QuesTek Innovations LLC

1820 Ridge Avenue, Evanston, IL 60201
(847) 328-5800

SERDP Strategic Environmental Research and Development Program
Improving Mission Readiness Through Environmental Research

Corrosion Resistant Steels for Structural Applications in Aircraft

SERDP Final Technical Report

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QuesTek Project SRP002
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a. NAME *(Last, First, Middle Initial)*
Olson, Gregory

b. RANK

c. TITLE

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a. NAME *(Last, First, Middle Initial)*
Rusk, Jennifer

b. TELEPHONE NO. *(Include Area Code)*

5. PRIOR COORDINATION

a. NAME *(Last, First, Middle Initial)*	b. OFFICE/AGENCY	c. TELEPHONE NO. *(Include Area Code)*
Smith, Bradley	SERDP Executive Director	
Pellerin, Charles	SERDP Pollution Prevention Program Manager	

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WHEN CLEARED, PLEASE FAX DD-1 ATTN: Jennifer Rusk (pho

if mailed: ATTN: Jennifer Rusk, 1155 Herndon Parkway, Suite 900, Herndon, VA 20170

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Smith, Bradley P.

d. TITLE
Executive Director, Strategic Environmental R&D Program

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1. BACKGROUND

Unlike chrome plating, where environmental and health problems are generally associated with the plating process, the problems with cadmium are intrinsic to the metal itself, creating occupational safety and health (OSH) risks and raising maintenance costs throughout the life of all cadmium plated parts. Furthermore, many of the major items that are cadmium plated, such as landing gear, are damage intolerant, and sensitive to hydrogen embrittlement during maintenance and stress corrosion cracking during use. This sensitivity makes stress corrosion cracking the primary failure mechanism for landing gear – a failure that often causes significant collateral damage to the aircraft, even though the failure usually takes place while it is parked. Therefore, no matter what coating is used to replace cadmium on landing gear and other major structures, these failures will remain a problem, becoming more frequent as weapons systems age. The only long-term answer to the problem is not a coating but a new steel that not only obviates the need for a coating but also eliminates these failures. This steel will be used not only in new landing gear designs, but also for sustainment of legacy systems, which is the reason that the Aging Landing Gear Life Extension program (ALGLE) is assisting in funding the development.

QuesTek's Materials by Design™ technology integrates processing/structure/properties/performance relations within a multilevel hierarchical system structure with computational design tools stemming from research integrating materials science, applied mechanics and quantum physics. This is illustrated in Figure 1.

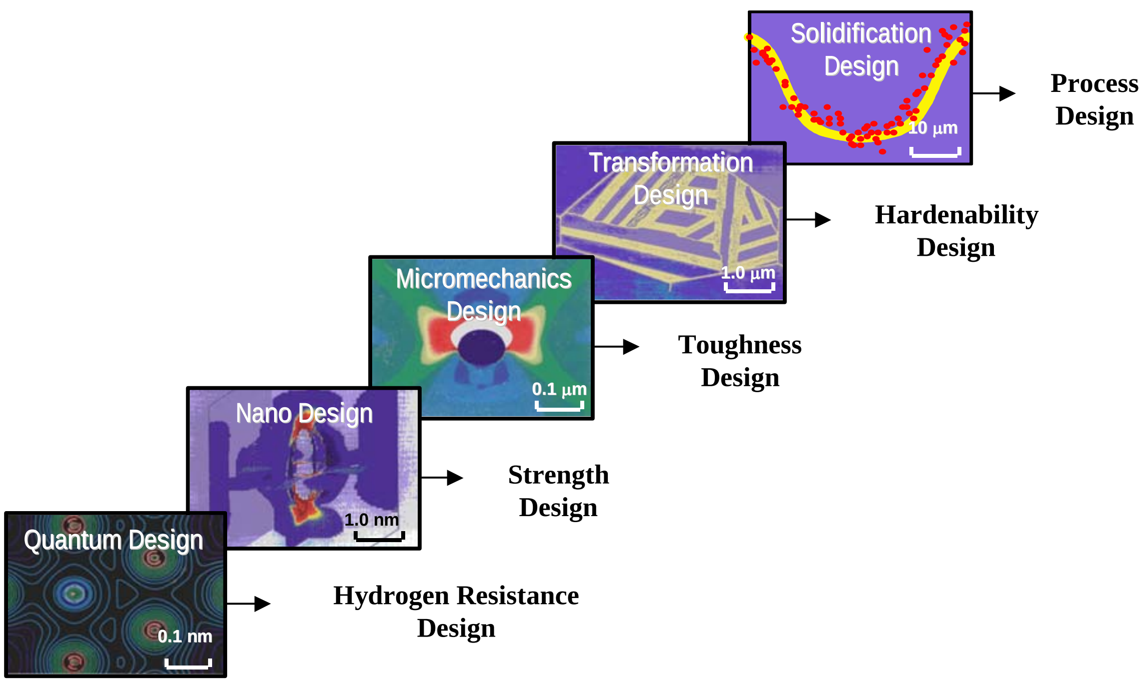


Figure 1 Hierarchy of design models

For Phase I, QuesTek's SERDP team analyzed the technical objectives and generated a system flow-block diagram, as shown in Figure 2, to streamline the material design process. The diagram denotes the hierarchy of microstructural subsystems underlying the set of material properties necessary for desired performance and the sequential stages of processing which govern their dynamic evolution. This systems view allows for the identification and prioritization of the essential structure/property and process/structure relations for which computational models are needed to support predictive design.

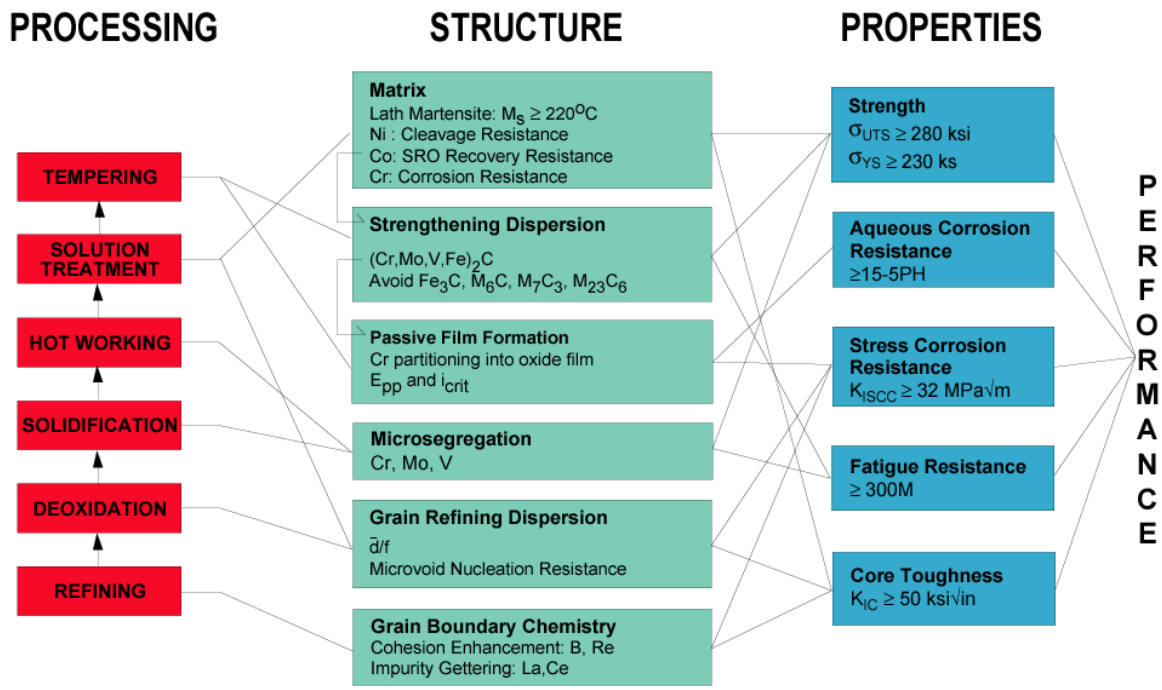


Figure 2. The system flow-block diagram for a structural stainless steel for aircraft applications.

The left of the flow-block diagram shows that the processing procedure is composed of conventional casting and heat treatment practice. At the right of the flow-block diagram, the key property objectives considered in the first prototype development are listed. The center of the flow-block diagram describes major structural features obtainable from the processing procedure and potentially capable of providing the proposed performance. The primary structural features in our first structural stainless steel design are:

- A strong and tough fine lath martensite matrix;
- A stable passive oxide film on the material surface for corrosion resistance;
- Nanoscale M_2C dispersion strengthening through tempering while avoiding other carbides to improve strength and toughness and provide efficient trapping to slow hydrogen transport;
- Fine grain refining dispersion to improve toughness; and
- Controlled grain boundary chemistry to improve toughness and hydrogen embrittlement resistance.

Each linkage in the flow-block diagram represents an individual material model. With the relationships illuminated by all the linkages, it is possible to perform an engineering design synthesis and achieve a system-wide optimization of the material composition and processing parameters.

These models have been integrated in the initial design of our new alloy. The same tools are now being applied to accelerate the full materials development cycle.

1.1 Objectives and Technical Approach

The use of Cd and hard Cr coating on structural aircraft components, mainly landing gear, is necessitated by the fact that current structural steels do not provide sufficient corrosion and wear resistance to meet performance requirements without them. The Phase I SERDP program has established the feasibility of designing a new structural alloy to meet these diverse requirements without coatings, and an interim program together with the first months of the Phase II effort have been used to optimize this alloy composition and processing. Based on discussions with several landing gear manufacturers, a list of desired properties for the alloy was generated and is given in Table 1.

Table 1 Property objectives for SERDP stainless steel replacement for 300M.

Property	Goal
UTS	280 – 300 ksi
YS	235 ksi
% elongation	10% min. longitudinal 7% min. transverse
RA	35% min. longitudinal 25% min. transverse
K_{IC}	50 ksi√in min.
Fatigue	Similar to 300M
Cleanliness	AMS 2300, ASTM E45
SCC	Superior to 300M
Corrosion Resistance	Better than 15-5 PH ASTM E85 (USN) Better than 13-8 Mo ASTM B117 (Civil/USAF)
Crack Growth	Better than 300M
Embrittlement Resistance	200 hrs @ 75% UTS post plating 200 hrs @ 45% UTS 5% NaCl

The desired alloy should also possess processability similar to the current 300M landing gear steel and be compatible with emerging coating processes such as HVOF for rework purposes.

In order to insert this material into aircraft structural applications a significant effort to determine processing standards for the alloy and determination of baseline mechanical and corrosion properties are required. The main objectives of our Phase II program are to:

1. Develop appropriate processing standards for alloy production processes, component manufacturing processes and overhaul and repair processes to provide the information required for manufacture of components of the alloy.
2. Provide adequate test data for mechanical behavior, corrosion resistance and embrittlement resistance and cost to illustrate the ability of the alloy to replace current aircraft structural steels without coatings using standard manufacturing techniques and at reasonable cost. This data will be sufficient to allow component level dem/val testing to proceed.

Typically such a program would span the better part of a decade and cost upwards of $10 million. In our program we integrated the mechanistic modeling components used to design the alloy to streamline the process optimization and facilitate the test program at significant reduced cost. The modeling activities were used to guide the selection of key process optimization experiments to minimize the amount of experimental studies required. In the generation of material data, fewer experiments are required because the impact of process variation on behavior of the alloy can be inferred from modeling as opposed to pure statistical data analysis. In the program collaboration with the appropriate stakeholders determined the balance between experiment and modeling acceptable to the user community.

The technical approach is designed to reach the objective of bringing the S53 alloy to the point of dem/val testing on landing gear components. It is based on our alloy development experience in general, and our chrome plating replacement experience in particular. In order to bring the technology to the dem/val stage it is necessary to produce a steel production specification and a heat treat specification to define the alloy, a steel properties and performance database to support the technical case for the new steel, and detailed cost data to support the business case.

The technical program is thus aimed at producing all the critical information to determine for the potential stakeholders whether the new S53 steel is technically and economically viable. Both performance and cost are critical to bringing the new steel to production. The property and performance measurements are based on the Hard Chrome Alternatives Team (HCAT) Joint Test Protocol (JTP) for landing gear, since, although ours is not a validation program, data in all of the areas covered in the JTP will be needed to provide an adequate database from which to proceed to a dem/val project. The cost evaluation portion of the program is based on the multiple needs of both DoD and OEM stakeholders for information on production, validation, and sustainment costs.

The program achieved the stated objectives by optimizing processing and parameters on a series of subscale prototype generations, using model predictions to estimate behavior at full production scale, and then producing a production scale melt and evaluating performance and processability on that material. The first prototype iteration evaluated grain refining dispersion control, the second evaluated martensite transformation stability and the third prototype iteration explored control of the DBTT through matrix alloying effects. The lessons learned in these studies were then incorporated into a final design that was produced in production quantity and also subscale to directly demonstrate scalability. Two additional subscale melts were also completed at this time to illustrate variation around the design composition. These were produced and evaluated under support from the ALGLE program to speed the estimation of alloy variability during qualification.

The implementation of new materials has always been a very long process, experimentally intensive and high cost. This fact has generally removed new materials as an option to solve certain technological problems. The time scale and investment required was incompatible with the resources available. This is one reason that solutions such as coatings and new processes have been very attractive alternatives to solve common materials problems such as wear or corrosion resistance. This however comes at a price including reliability, environmental impact and often cost. New technology, primarily computational modeling of materials, has enabled the design of new materials for demanding applications, avoiding the drawbacks of traditional discovery. However, the traditional cycle for implementation of new materials is based on the assumption that a discovered material is not well understood and requires significant testing and process studies to ensure success in a given application. This is based on a level of confidence that must be established statistically by testing a material that is not well understood to begin with.

In this program we accelerated the implementation of S53 by using the same modeling techniques that designed it and relying on the inherent predictability of a designed material. By streamlining the process optimization and reducing the experimental requirements to establish the required performance, this program has positioned the S53 alloy for insertion into demonstration and validation projects.

2. Project Accomplishments

2.1 Introduction

During the course of the SERDP program four design iterations (Series 3-6) were completed and evaluated. Each design iteration further refined the design specification and addressed issues identified in the earlier iterations. Each design iteration focused on achievement of the primary alloy properties of strength, toughness and corrosion resistance. The final iteration was produced at both prototype and commercial scale. This commercial specification, S53A, was evaluated for properties and manufacturability including machining, welding and coating processes. The S53A alloy meets UTS, toughness and corrosion resistance criteria of the design. The demonstrated YS is about 215-220 ksi compared to a project objective of 230 ksi. Since a great majority of landing gear components are designed to UTS, this issue should not limit the S53 alloy's applicability. Fatigue tests have shown comparable results to typical 300M data, even with the lower YS. In manufacturability evaluations, the only deficiency identified was poor annealed machinability. Investigation has identified high annealed austenite content as the primary factor and new mill anneal processes have been designed to alleviate this problem. The evaluation of these new procedures will be completed on the first production material evaluated in the ESTCP program.

2.2 Alloy Design and Process Optimization

2.2.1 Alloy Design and Production

Designs

QuesTek completed four design iterations during the course of the SERDP program. The specific compositions explored in each design iteration are given in Table 2. Design iteration 1 and 2 was completed under the SERDP SEED program, while the characterization of prototypes of the 2 series alloys was conducted under a project with the Aging Landing Gear Life Extension (ALGLE) program. The 3rd, 4th and 5th design iterations were conducted under the current program and these were then used to produce the first candidate commercial specification S53A. This 6th design iteration was produced at both prototype scale and commercial scale (17" diameter ingot). The 6 series alloys were design variants of S53A and their characterization was completed under an ALGLE project.

Table 2 S53 Alloy Design Iterations

Alloy	C	Co	Ni	Cr	Mo	W	Si	V	Ti	Nb
1	0.15	13.0	4.8	9.0	1.5	-	-	0.50	0.02	-
2A	0.18	12.5	2.8	9.1	1.3	-	-	0.29	0.03	-
2B	0.11	16.7	3.7	9.2	2.0	-	-	0.50	0.03	-
2C	0.23	12.5	2.8	9.0	1.3	-	-	0.30	0.03	-
3A	0.24	12.4	2.8	9.0	1.3	-	-	0.29	0.02	-
3B	0.24	12.4	2.8	9.1	1.3	-	-	0.37	0.03	
3C	0.24	12.4	2.8	9.0	1.3	-	-	0.34	-	0.03
4A	0.24	12.2	2.0	9.1	1.3	-	-	0.29	0.02	-
4B	0.25	12.4	2.7	8.2	1.3	-	-	0.29	0.02	-
4C	0.20	12.4	2.1	8.2	1.3	-	-	0.29	0.02	-
4D	0.19	14.2	2.8	6.8	2.4	1.3	-	0.28	0.02	-
4E	0.19	12.1	2.0	8.2	1.3	2.0	-	0.28	0.02	-
4F	0.21	14.2	2.6	8.2	1.3	-	0.6	0.29	0.02	-
4G	0.26	12.6	1.7	8.5	0.29	-	-	0.30	0.02	-
5B	0.24	13.0	5.1	8.9	1.7	-	-	0.29	0.03	-
5C	0.25	12.2	6.2	9.0	1.3	-	-	0.29	0.03	-

5D	0.22	15.3	4.6	8.5	1.5	0.5	-	0.28	0.03	-
5E	0.24	13.0	7.4	8.9	1.7	-	-	0.28	0.03	-
5F	0.24	13.0	8.7	8.9	1.5	-	-	0.28	0.02	-
S53A	0.22	14.0	7.0	9.0	1.0	1.0		0.30	0.02	
6F	0.21	14.0	5.5	10.0	2.0	1.0		0.30	0.02	
6M	0.20	8.0	6.0	9.0	2.0	2.0	0.7	0.30	0.02	

A summary of each design iteration is as follows:

3rd iteration design

The 3rd design iteration focused on the effects of grain refining distributions. Small additions of V, Ti, and Nb were specified to establish the MC carbide distribution that precipitates during forging and hotworking. These variations affect the relative composition of the (Ti,V,Nb)C FCC based carbide that is stable to high temperature. The size, number density and interfacial cohesion of these carbides has a strong effect on the ductile fracture behavior of the alloy. It is these carbide distributions that determine the grain growth of the alloy during high temperature processing in the austenite field. As shown in Figure 3, the preferred sequence is to homogenize the alloy in the absence of any carbide formation, initially hotwork the alloy in the predominantly MC carbide phase field and limit the other carbide phase fields to short exposures during finish forging. The alloy would then see a normalize at temperatures which would dissolve all but the MC grain refining dispersion. This provides a fine grained material with low residual stress and small relatively soluble carbides in the annealed state.

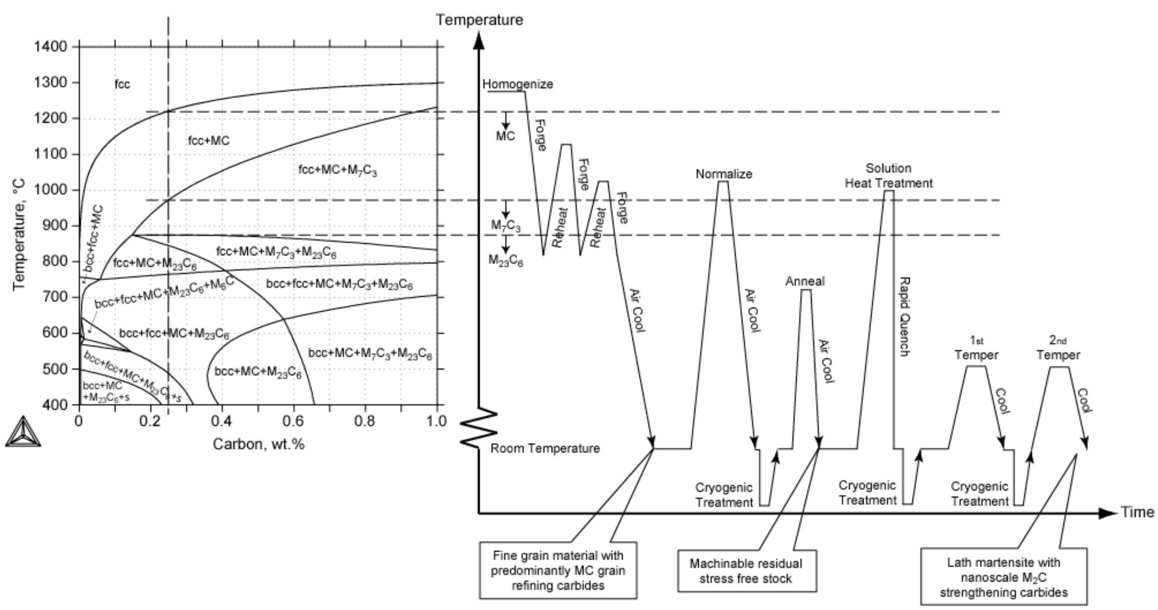


Figure 3 Typical processing path of S53 alloys in relation to equilibrium phase relations.

A very small amount of Ti is generally added deliberately as a deoxidizer. Residual Ti even in a very small amount can form Ti-rich carbides, as observed in S53-2A after homogenization at 1190°C for 12 hours. This will necessitate homogenization at even higher temperatures if we wish to eliminate MC during this processing step. The maximum temperature a typical manufacturer's equipment can reach, however, is 1250°C. As a consequence, the solution temperature of MC carbide should be lower than this limit. On the other hand, MC carbide can be used to refine grains. According to our previous experience, the amount of MC carbide should be around 0.1-0.2%. As a grain refiner, the MC carbide is also required to have a low coarsening rate.

Based on the above considerations, the effect of MC carbide formers Hf, Nb, Ta, Ti, V, W, and Zr on the solution temperature, volume fraction, and coarsening rate of MC were examined. Thermodynamic descriptions of HfC, TaC, and ZrC were taken from the pure substance database SSUB in Thermo-Calc, whereas NbC by W. Huang (1989), TiC by Jonsson (1996), VC by Huang (1990), and WC by Gustafson (1986) were either taken from different databases or from published papers.

The calculations show that HfC, TaC, and ZrC are much more stable than TiC. An addition of just a few wppm in S53 can cause the formation of MC carbides with solution temperatures higher than 1233°C. The stability of WC is much lower than that of TiC, so a W addition in the steels would dissolve in the FCC matrix instead of forming WC. The remaining elements are Nb, Ti, and V; their addition levels were selected in three designs according to the calculation results, as described below and summarized in Table 9

MC fraction, coarsening rate at 1000°C and solution temperature were calculated for each design. The MC coarsening rate was calculated according to Lee's model:

$$K = \frac{2\sigma V_m^{MC}}{RT}\left[\sum_i (k_i - k_{Fe})(k_i - 1)\frac{x_i^{fcc}}{D_i^{fcc}}\right]^{-1} \qquad i = \text{all components except Fe} \qquad (1)$$

In this equation, σ is the MC surface energy, and V_m^{MC} is the MC molar volume. x_i^{fcc} is the molar fraction of component *i*, k_i is defined as x_i^{MC} / x_i^{fcc}, and all compositions are calculated under equilibrium between FCC and MC at 1000°C. D_i^{fcc} is the diffusivity of component *i* in FCC and was calculated using DICTRA. Table 9 also gives the C and V contents in the matrix at 1000°C. C and V are critical for strengthening and for providing a high driving force for M_2C precipitation.

Table 3 Design of grain refiners Ti, V, and Nb in S53-2C.

Design	Ti (wt.%)	V (wt.%)	Nb (wt.%)	MC solution temperature (°C)	MC (%)	Coarsening rate $K/\sigma V_m$ (10^{-22} m^2 mol/J sec)	C and V in matrix (wt.%)	
3A	0.015	0.30	--	1187	0.10	0.44	0.221	0.275
	0.020	0.30	--	1214	0.12	0.47	0.219	0.270
	0.025	0.30	--	1235	0.14	0.51	0.216	0.265
3B	0.015	0.37	--	1189	0.15	0.91	0.216	0.323
	0.020	0.37	--	1215	0.18	0.78	0.213	0.316
	0.025	0.37	--	1237	0.20	0.69	0.211	0.311
3C	0.001	0.34	0.04	1188	0.16	1.36	0.215	0.295
	0.001	0.34	0.05	1205	0.18	1.27	0.213	0.290
	0.001	0.34	0.06	1221	0.21	1.20	0.211	0.285

The solution temperatures for Designs 3A and 3C are plotted in Figure 4 to illustrate the effect of variation in Ti or Nb content. The solution temperature for Design 3B is only about 2 degrees higher than that of Design 3A; the plots for 3A and 3B would nearly coincide in Figure 4. Figure 5 and Figure 6 show the MC fraction and coarsening rate at 1000°C as a function of Ti or Nb content.

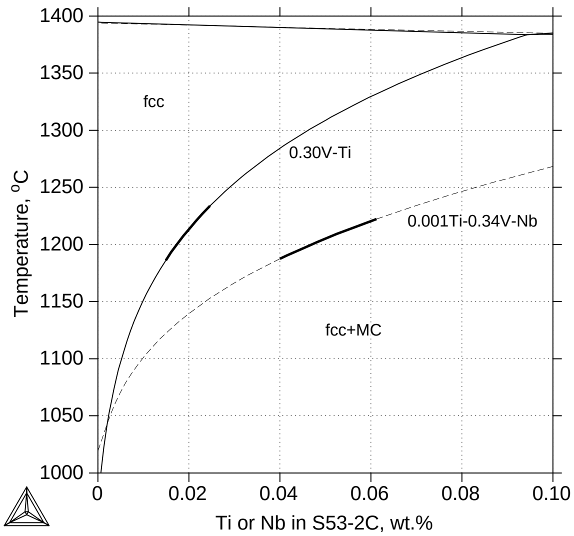


Figure 4 Solution temperature of MC carbide in S53-2C with different Ti, V, and Nb contents.

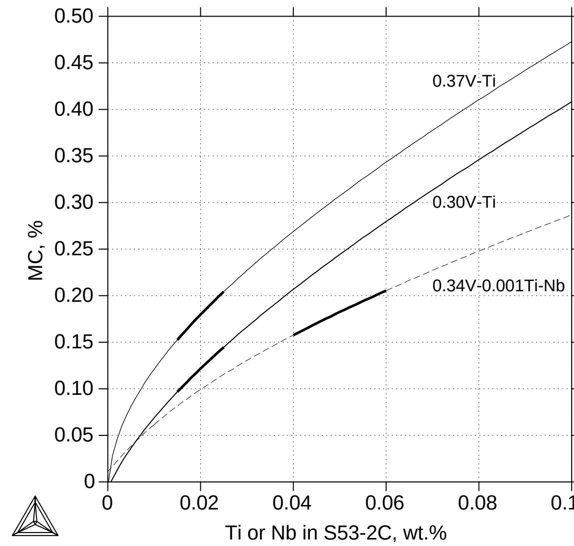


Figure 5 MC carbide fraction in S53-2C as a function of Ti or Nb contents at 1000°C.

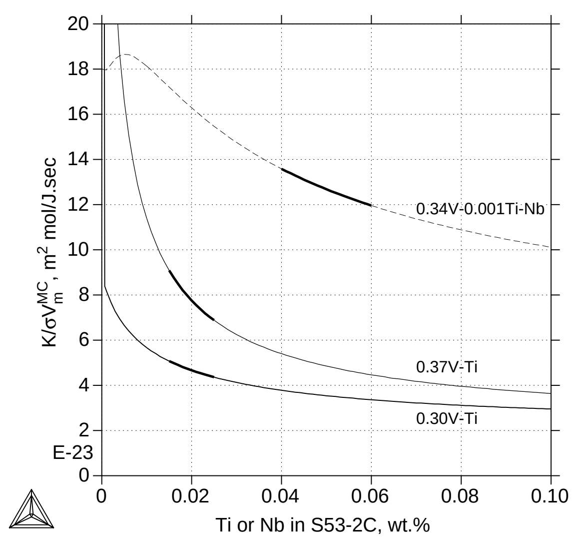


Figure 6 Coarsening rate of MC carbide in S53-2C as a function of Ti or Nb contents at 1000°C.

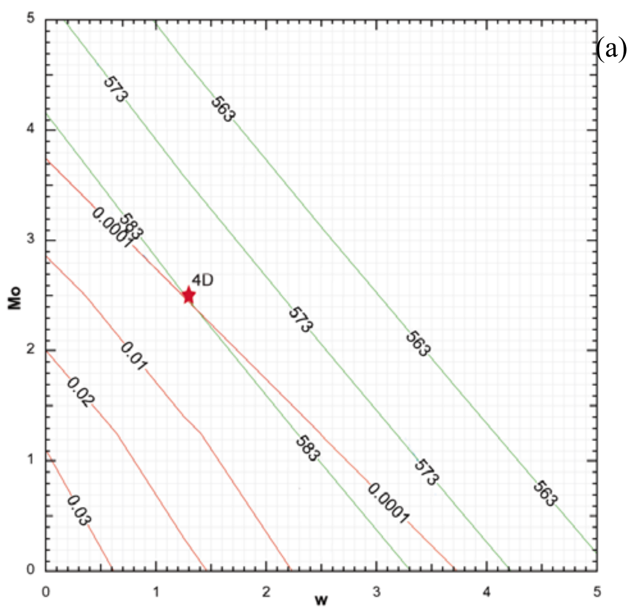
Based on these results, the compositions of S53-3 series designs 3A, 3B, and 3C were selected as shown in Table 2.

4th iteration design

The two primary goals in the design of the fourth generation alloy were first to increase the M_s temperature relative to that of the S53-2 designs, and second, to reduce the amount of cementite formed in the microstructure. In the second generation design, prototype alloy S53-2C contained an amount of retained austenite due to a relatively low M_s temperature. Thus, one objective in the fourth generation design was to increase the M_s temperature relative to the S53-2 series designs while maintaining or exceeding the previous design's mechanical properties. The formation of cementite in stainless steels has a detrimental effect on corrosion resistance due to localized depletion of matrix chromium content, and additionally can be detrimental to strength and toughness. Another purpose of the S53 redesign is to obtain information regarding Ni effect on cleavage resistance, Cr effect on corrosion, as well as Co effect on the enhancement of Cr activity. A series of seven prototype compositions in the fourth generation alloy, S53-4, were designed to address these issues.

The essential design strategy in S53-4 is to keep S53-2C's strength and improve M_s temperature over 2A's calculated value – 287°C. In order to avoid the retained austenite, not only should the Ms temperature be increased, but also the martensitic transformation hysteresis should also be narrowed, meaning faster transformation. Therefore, a new design parameter $M_s*\Delta S$ was applied in S53-4 design assuming a linear ΔG(T), equivalent to the parameter [ΔG(Ms) - ΔG(300)], which is directly related to the amount of the retained austenite at room temperature. The M_s temperature was altered primarily through variation of the alloy carbon and nickel content.

As previously discussed, cementite is a harmful phase that decreases both the strength and toughness and also reduces corrosion resistance. Tungsten and molybdenum can stabilize M_2C and effectively reduces the amount of equilibrium cementite. In addition, according to first principle calculations, tungsten has the effect of improving grain boundary cohesion and thus is beneficial to the stress corrosion cracking resistance Thus, in the second part of design, tungsten was added to minimize the equilibrium cementite. Silicon is also known to prevent/delay the (both full- and para-equilibrium) cementite formation. By adding some Si, we hope to see an increase in M_2C strengthening efficiency. However, we do not have the thermodynamics assessment of Si in cementite, and thus cannot do a quantitative analysis of Si effect on cementite. Prototype alloys were designed using both tungsten (-4D, -4E) and silicon (-4F) to reduce the cementite driving force. Figure 7 shows an example of the effect of tungsten on the equilibrium volume fraction of cementite, which is reduced to below 0.01 % while maintaining a high M_s temperature and high M_2C driving force.



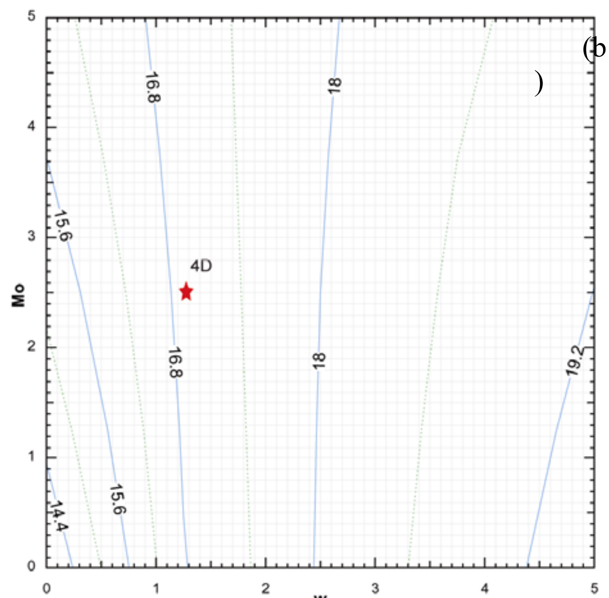


Figure 7 (a) Cementite driving force (red line) and M_s temperature (green line) as a function of Mo and W content for S53-4D. (b) M2C driving force (kJ/mol) as a function of Mo and W content in S53-4D.

5th iteration designs

Based on the toughness results of the S53-3 and S53-4 alloys a modeling activity for the Charpy V-notch toughness was completed and used in the S53-5 prototype designs. It is known that toughness is essentially inversely proportional to hardness; harder materials are usually more brittle. Nevertheless, hardness increased by grain refinement does not degrade materials toughness; rather, it improves the toughness[1]. Toughness is also very sensitive to alloy composition. Some elements in steel are beneficiary to toughness, but have to be limited due to other properties. Ni can significantly improve toughness[2], but it decreases the M_s temperature. Co is a strong secondary hardening enhancer, but it can reduce toughness dramatically due to its restricting cross-slip[3].

Therefore, a quantitative toughness model is necessary to enable us to determine the complex effects of various factors on toughness and achieve the optimum materials and processing design. The present work will focus on impact toughness of secondary hardening (SH) martensitic steels with ultra-high strength (UHS). Relevant information from literature will be studied. An impact toughness master curve model will be developed mainly based on QuesTek's experimental data of UHS secondary hardening steels.

One of the methods measuring the impact toughness is the Charpy V-notch (CVN) impact test, which determines the ductile to brittle transition behavior in terms of the fracture Charpy energy. Usually low fracture energy means a brittle fracture. The impact energy generally decreases with decreasing temperature as the yield strength increases and the ductility decreases. A sharp transition, where the energy changes by a large amount for a small temperature change, can occur when there is a change in the fracture mechanism. Physically, this transition corresponds to a fracture mode change from low-temperature cleavage or quasi-cleavage to elevated temperature microvoid coalescence[4]. The corresponding temperature is the so-called ductile to brittle transition temperature — DBTT, below which the material has poor toughness. This can be used as a guideline to determine the minimum service temperature.

There are different ways to define DBTT. A common way is to use the mean impact energy between the highest and lowest values, which turns to be effective in the present research. DBTT can be affected by many factors. According to experimental information, major factors are alloy composition (w), hardness (σ) and grain size (d). Hence, DBTT can be described as follows:

$$DBTT = DBTT_0 + \Delta DBTT(w) + \Delta DBTT(\sigma) + \Delta DBTT(d) \quad (2)$$

Here $DBTT_0$ is a constant for a certain type of steels. ΔDBTT(w) represents the shift of DBTT caused by alloy composition change. ΔDBTT(σ) is the shift of DBTT due to hardness change. ΔDBTT(d) gives the change of DBTT related to grain size.

Based on a large amount of test and power reactor data, Odette et al.[5] studied the relationship between irradiation hardening and embrittlement of pressure vessel steels. It indicates that the shift of DBTT is proportional to the change of yield strength as follows:

$$\Delta DBTT = 0.65 \sim 0.8 \Delta\sigma_{YS} \text{ (MPa)} \quad (3)$$

According to Questek's assessment of the relationship between strength and hardness for SH steels [6], yield strength (MPa) has a linear dependence on hardness (σ):

$$\Delta\sigma_{YS} = 1.44 \sim 1.54 \Delta\sigma \quad (4)$$

Thus, ΔDBTT is a function of the change of hardness as follows:

$$\Delta DBTT \approx f(\Delta\sigma) \quad (5)$$

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[1] S. Takaki, K. Kawasaki, Y. Kimura. Journal of Materials Processing Technology 117 (2001) 359-363.
[2] S. Floreen, H. W. Hayden, T. M. Devine. Metallurgical Transactions 2 (1971) 1403-1406.
[3] D. R. Squires, E. A. Wilson. Materials Science and Technology 10(1) (1994) 52-55.
[4] G. R. Odette. Journal of Nuclear Materials 212-215 (1994) 45-51.
[5] G. R. Odette, P. M. Lombrozo, R. A. Wullaert. Effects of Radiation on Materials: Twelfth International Symposium, ASTM STP 870 (1985) 840-860.

E^{US} (USE) represents the Upper-Shelf Energy that can be approximately described as a function of hardness:

$$E^{US} = f(\sigma) \quad (6)$$

As for the Lower-Shelf Energy (E^{LS}), it is reasonable to estimate it as 10% of E^{US} based on experimental phenomena:

$$E^{LS} = \frac{E^{US}}{10} \quad (7)$$

The most common function describing the relationship between the CVN energy and the temperature is the hyperbolic tangent (tanh) function[5]:

$$CVN = \frac{E^{US} + E^{LS}}{2} + \frac{E^{US} - E^{LS}}{2} \tanh\left(\frac{T - DBTT}{Const}\right) \quad (8)$$

Dividing this by USE, the normalized master curve is shown as:

$$CVN^1 = \frac{CVN}{E^{US}} = 0.55 + 0.45 \tanh\left(\frac{T^*}{Const}\right) \quad (9)$$

where T* = T – DBTT. Therefore, for a certain type of steels, their Charpy data should fall into the same master curve.

Room temperature charpy data from QuesTek's UHS martensitic steels along with CVN data from Aermet 100 and AF1410 steels[6,7] were used to optimize the model parameters through the least square optimization method. The optimized parameters are within reasonable range and the generated master curve is presented in Figure 8 in comparison with experimental data used for evaluation. Figure 8 indicates fairly good agreement between the model curve and the experimental data.

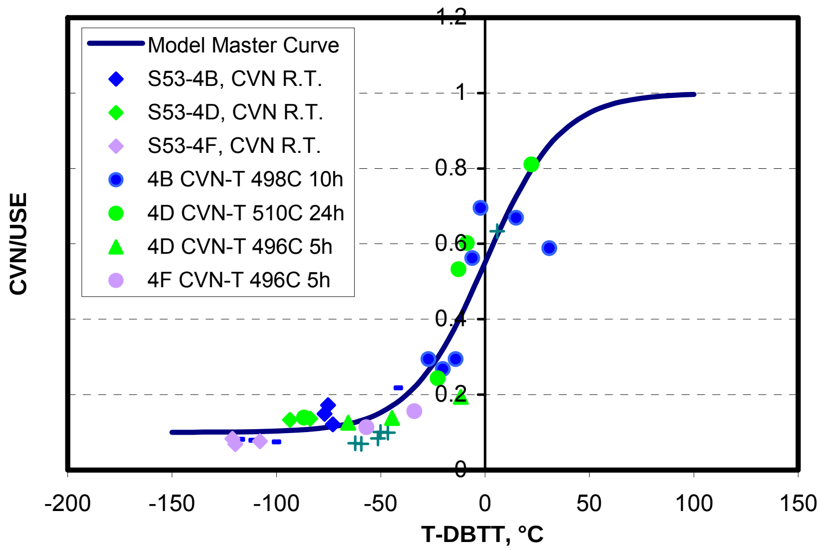


Figure 8 S53-4 CVN Data at Room and Elevated Temperatures in Comparison with the Master Model Curve.

[6] Aermet 100 Data Sheet, Carpenter Technology Corporation, Reading, PA.
[7] W. M. Garrison, Jr., N. R. Moody. Metallurgical Transactions 18A (1987) 1257-1263.

The output from the master curve model confirmed the assumption that the most effective alloy addition for increased toughness is Nickel. Thus one major goal of the S53-5 series was to span a wide range in Nickel content to better understand this effect. Unfortunately high Nickel contents in the alloy push the calculated M_s down. Although the 4 series alloys explored what M_s temperature was reasonable to ensure a fully martensitic matrix, it was not certain at what Ms temperature retained austenite would have a large effect on alloy properties. For this reason, we chose to let the designed M_s values fall far below the values designed in previous prototypes. Whereas the S53-4 series was designed to have an M_s of at least 290ºC, the S53-5 series had predicted M_s temperatures as low as 148ºC. This method allowed us to test Nickel's effect on toughness while concurrently testing the effect M_s has on microstructure and mechanical behavior.

As mentioned in the previous section, the S53-4 series proved to be only marginal in meeting the strength requirements of the program. For this reason all S53-5 series designs included at least 0.22 wt.% carbon, and the design hardness criteria was set to Rockwell C 54. The strength criteria were evaluated against the other design constraints using cross-plots and design tables.

In summary, the major goals and constraints of the S53-5 design were to:

- Explore high Ni compositions for increased toughness
- Explore low M_s compositions to better define required M_s temperature
- Keep strength above 54 HRC (keeping Carbon above 0.22wt.%)
- Keep Chromium at 9wt.%

6th iteration Design

Unlike the S53-4 and S53-5 series designs, the 6th iteration design was specifically attempting to meet all the program goals in a single composition, not explore a new composition space or define performance parameters. The primary design of the S53-6 series would become the prime candidate for commercial production and be evaluated in 3000 lb 17" VIM/VAR ingot for as well as in 300 lb prototype scale to evaluate the impact of scale-up. This candidate is noted at specification S53A to denote that it is the first commercial specification.

The primary design criteria for this specification was taken as:

- Low cementite
- Minimum segregation
- High corrosion resistance (high Cr, Mo)
- Sigma phase limit
- High toughness
- Grain size (low V)
- Si addition
- Low Co design

The S53-5 results indicated higher Ni contents were leading to retained (or precipitated) austenite and was limiting the yield strength in this alloy series.

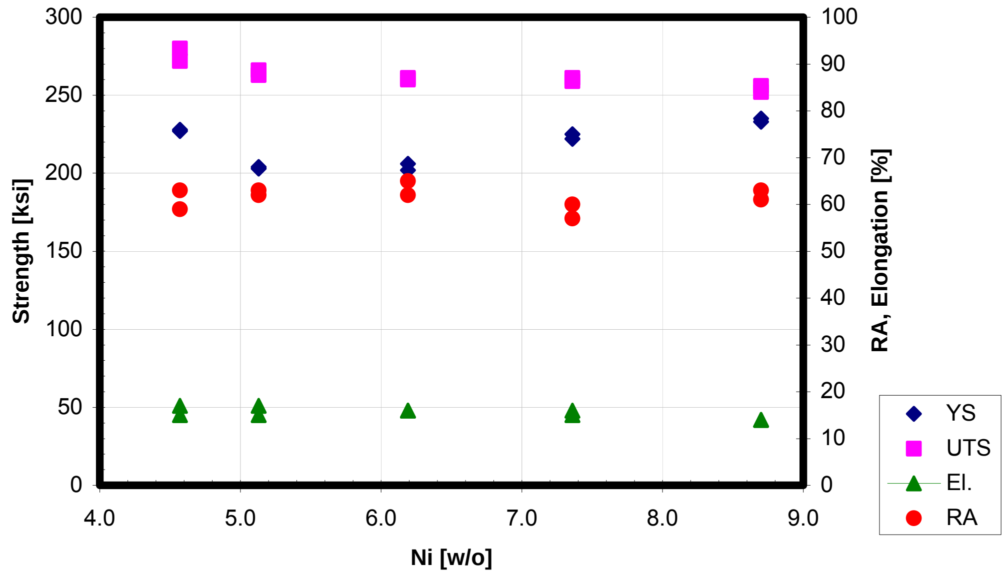


Figure 9 Tensile results for the S53-5 series alloys as a function of Ni content.

As seen in

Figure 9, there appears to be a valley in yield strength in the 5-6 wt.% Ni range. The mechanism behind this effect is most likely a complex interaction of the stability of retained or precipitated austenite on the tensile yield behavior due to martensitic transformation. To avoid this low YS behavior, S53A was designed to operate on the Ni rich side of the YS trough. Whereas S53-5E showed high toughness while lacking strength, and S53-5D shows decent strength while lacking toughness the S53A design became a balance of the two compositions.

The S53-6F design was undertaken to consider the possibility of a very high corrosion resistance alternative. This design increased Cr to 10 wt.% and Mo to 2 wt.%. With the additional Cr and Mo for corrosion resistance, the M_s temperature would be far lower than acceptable limits needed to ensure a complete or nearly complete martensitic transformation. To compensate for the difference, carbon was decreased to .21 wt.% and nickel was decreased to 5.5 wt.%. However, his put Ni in the aforementioned YS trough, the region from 5 to 7 wt.% where we had previously found anomalously low yield strengths.

The S53-6M alloy was designed to achieve low cementite, a silicon addition, and low cobalt. Adding silicon is a very effective way to reduce the predicted amount of cementite, however a silicon addition produces two additional design issues. The first issue, reduced M_s, was compensated by lowering Ni to 6 wt. % and lower carbon to .2 wt.%. The second issue, rising solution treatment and MC solvus temperatures, was also compensated for by the lower carbon. In the midst of these changes, cobalt was lowered to 8 wt.% to test its effects on Cr activity and on retarding dislocation recovery. Tungsten and Molybdenum were increased to 2 wt. % each to raise the M_2C driving force, not only aiding in this zero cementite design, but also helping to keep alloy strength with lower available carbon content.

Melt Processing

The solidification and homogenization processes in S53-3 were studied using the DICTRA software package for simulation of diffusion controlled transformations in multicomponent systems. For solidification, the chosen geometry, shown in Figure 10 represents a dendrite forming from the cooling liquid. As the temperature decreases, the liquid/FCC boundary moves to the left, until all of the liquid is consumed. Along with the FCC phase, carbide phases are also allowed to form. A half secondary dendrite arm spacing of 50 μm and a cooling rate of 0.75ºC/sec were chosen based on experimental data for small ingots of similar alloys.

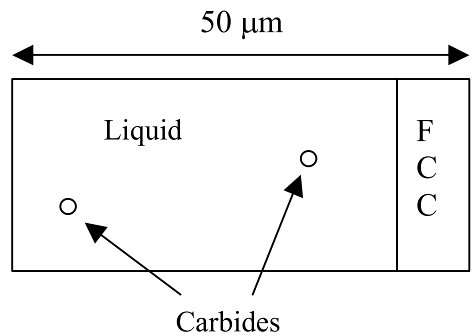


Figure 10 Geometry for DICTRA simulation of solidification in S53-3.

Since simulation results for all three alloys in the S53-3 series were very similar, most of the results reported here are for S53-3B. Figure 11 shows the solidification profile for this alloy, with the first solid forming at 1453ºC and the last liquid being consumed at 1163ºC.

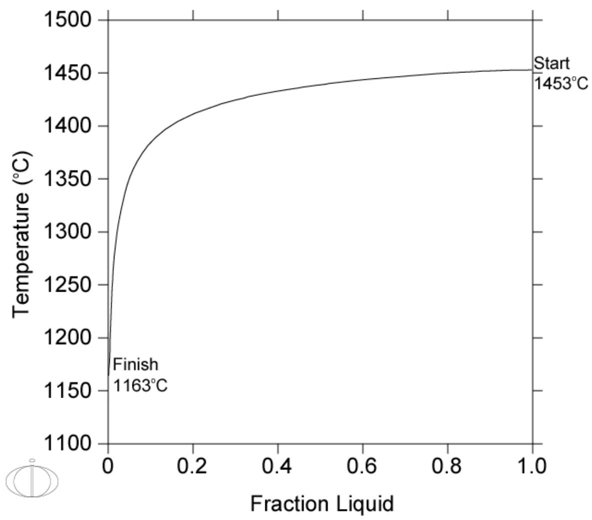


Figure 11 DICTRA solidification profile for S53-3B.

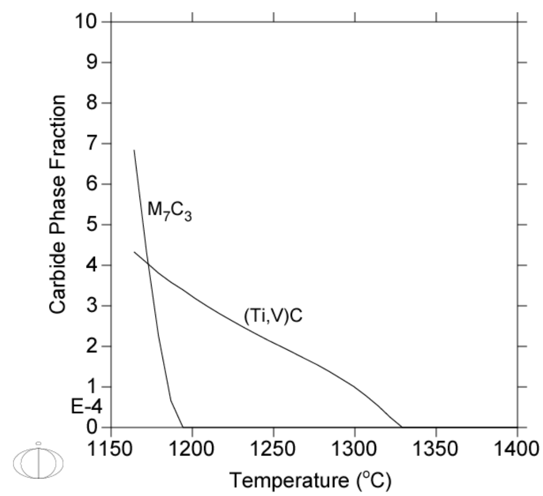


Figure 12 Appearance of carbides M_7C_3 and (Ti,V)C in S53-3B

Very small amounts of carbides M_7C_3 and (Ti,V)C form during the solidification process. Figure 12 shows the predicted phase fraction of these carbides as a function of temperature. The composition of liquid during solidification is shown in Figure 13. Note that as the temperature drops, the liquid becomes richer in Cr, Mo, V, and C, while the Co and Ni content of the liquid decreases. The Ti level first increases then decreases with decreasing temperature. These varying solute levels in the liquid determine the composition of the solid phases (FCC, M_7C_3, and (Ti,V)C) formed at any particular stage of the solidification process. The composition of the FCC phase at the end of solidification is shown in Figure 14, where it is seen that the composition at the dendrite edge (where the last liquid disappeared) is Cr- and Mo-rich. C and V levels are also higher here than at the dendrite center, although this is difficult to see in the figure. One representation of the level of microsegregation produced is the segregation index δ, where $\delta = C_{max}/C_{min}$. Values of δ for S53-3B are given in Table 9. Overall the level of solidification microsegregation is moderate compared to conventional stainless steels.

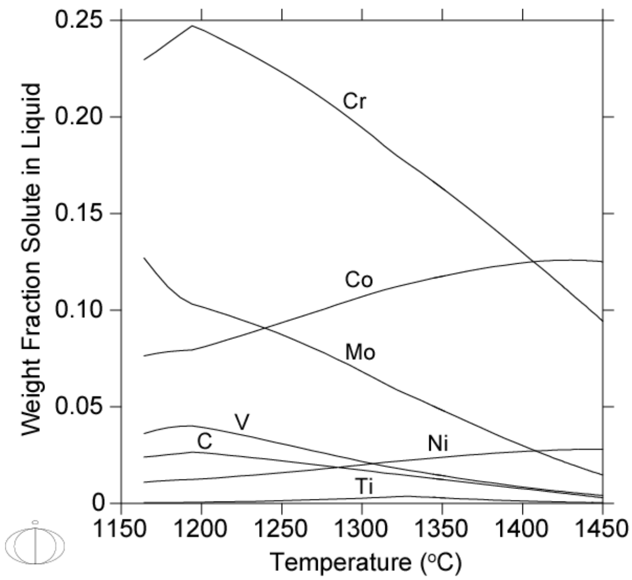


Figure 13 Liquid composition during solidification of S53-3B

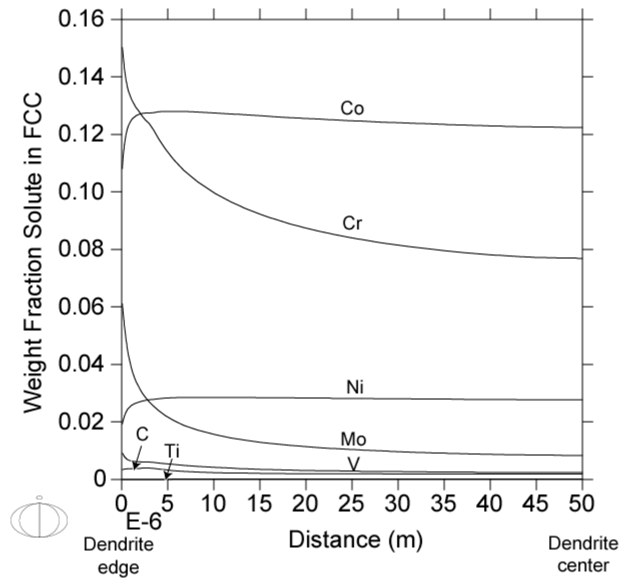


Figure 14 FCC composition at the end of solidification in S53-3B.

Table 4 Segregation indices δ for S53-3B

Element	C	Co	Cr	Mo	Ni	Ti	V
δ	2.53	1.15	2.04	7.28	1.46	1.16	4.40

Vacuum Arc Remelted (VAR) ingots of S53-3A, 3B and 3C (heats WK45, WK57, and WK58, respectively) were received from Allvac. A cross-section was taken from the middle of each ingot, polished, etched with Nital, and examined in the scanning electron microscope (SEM). The objective of the SEM examination was to locate the final solidification pools and to analyze the size and composition of these pools. The following Figures show one of the final solidification pools for each alloy along with the x-ray analysis of the pool. The final solidification pools are in the size range of 10-20 microns, consistent with the prediction of Figure 14. A Ti- or Nb-containing particle (most likely a carbide) is always found at the center of the final solidification pool, with moderate enrichment of Cr and Mo around the particle, indicating that Cr and Mo are likely to exhibit the highest levels of microsegregation. This is generally comparable to the predictions of the DICTRA solidification simulations.

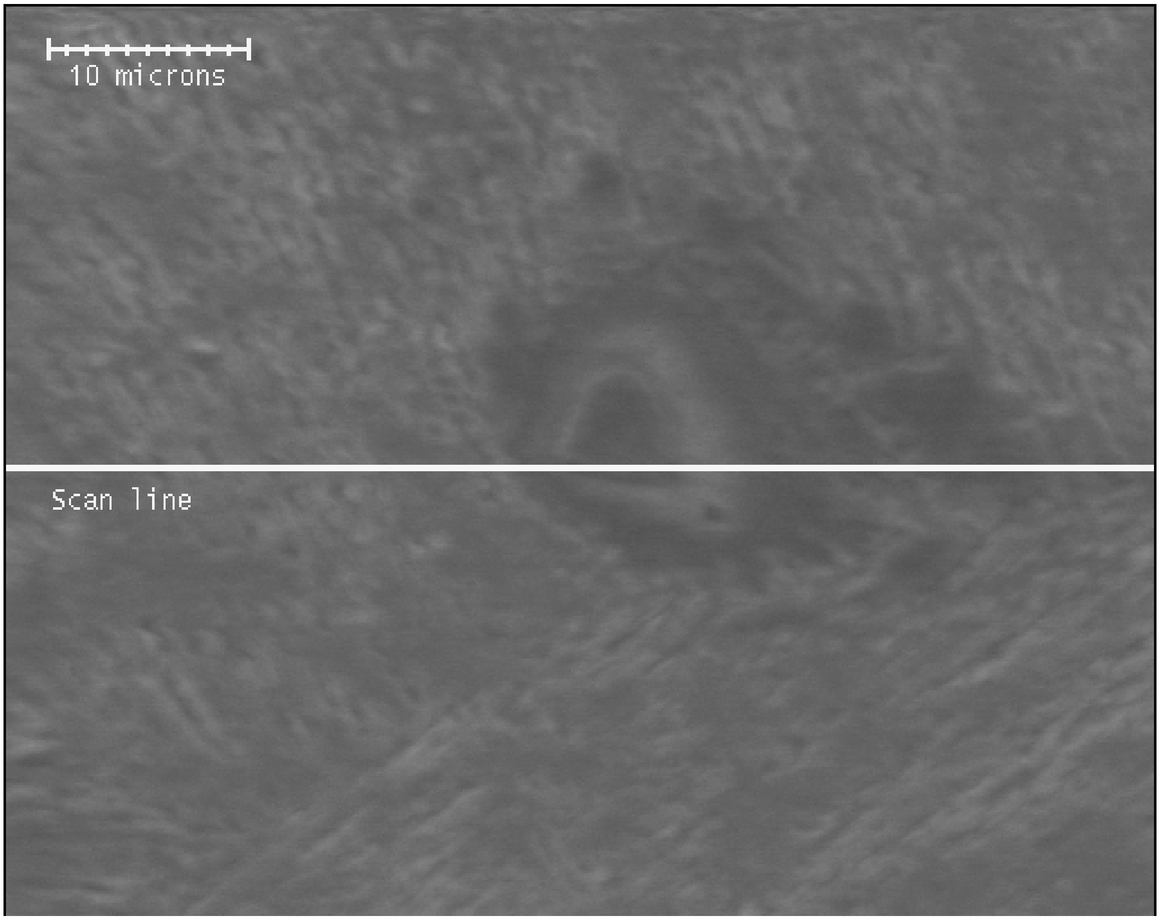


Figure 15 SEM micrograph of a final solidification pool in S53-3A with a superimposed location of the x-ray scan line

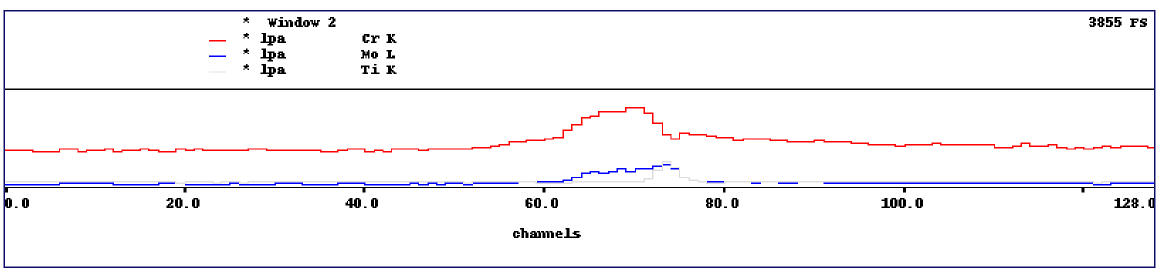


Figure 16 Cr (red) x-ray line spectrum associated with the x-ray line scan in Figure 15.

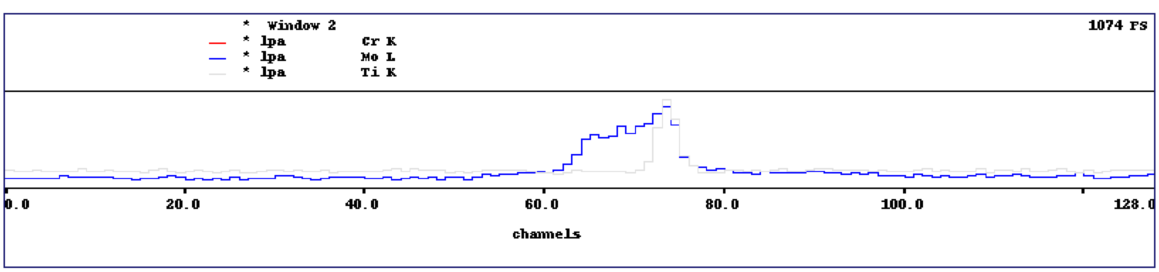


Figure 17 Magnified detail of x-ray counts shown in Figure 16 showing Mo (blue) and Ti (gray).

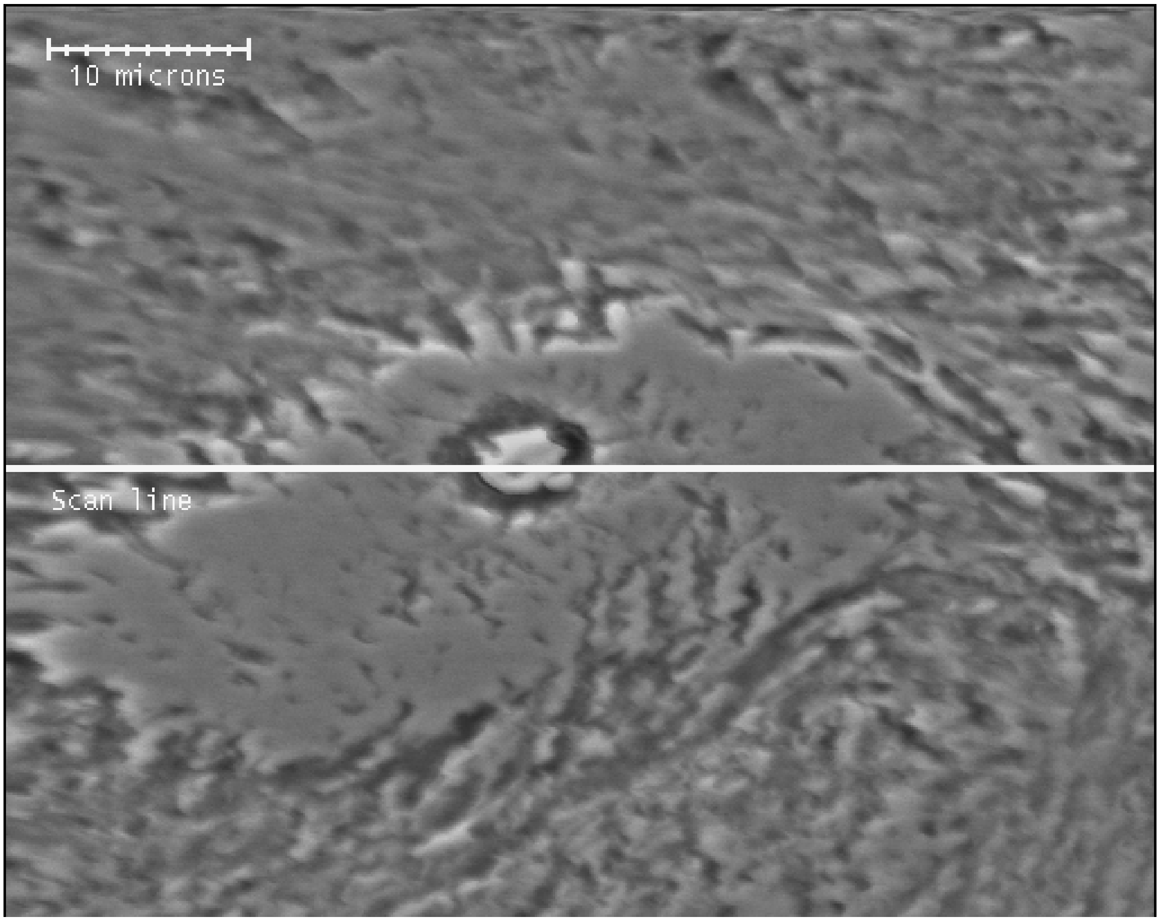


Figure 18 SEM micrograph of a final solidification pool in S53-3B with the superimposed location of the x-ray scan line.

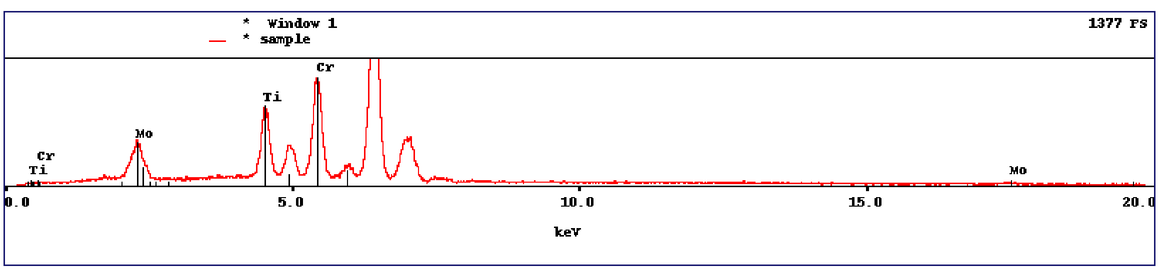


Figure 19 X-ray spectrum associated with the x-ray scan line shown in Figure 18.

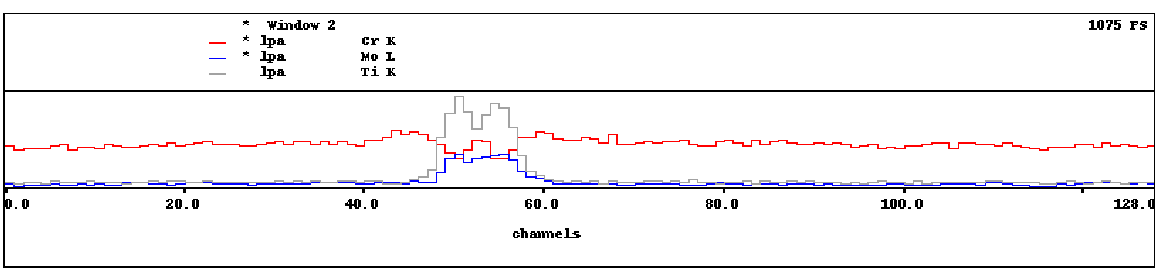


Figure 20 Cr (red), Mo (blue) and Ti (gray) x-ray counts along the x-ray scan line shown in Figure 18

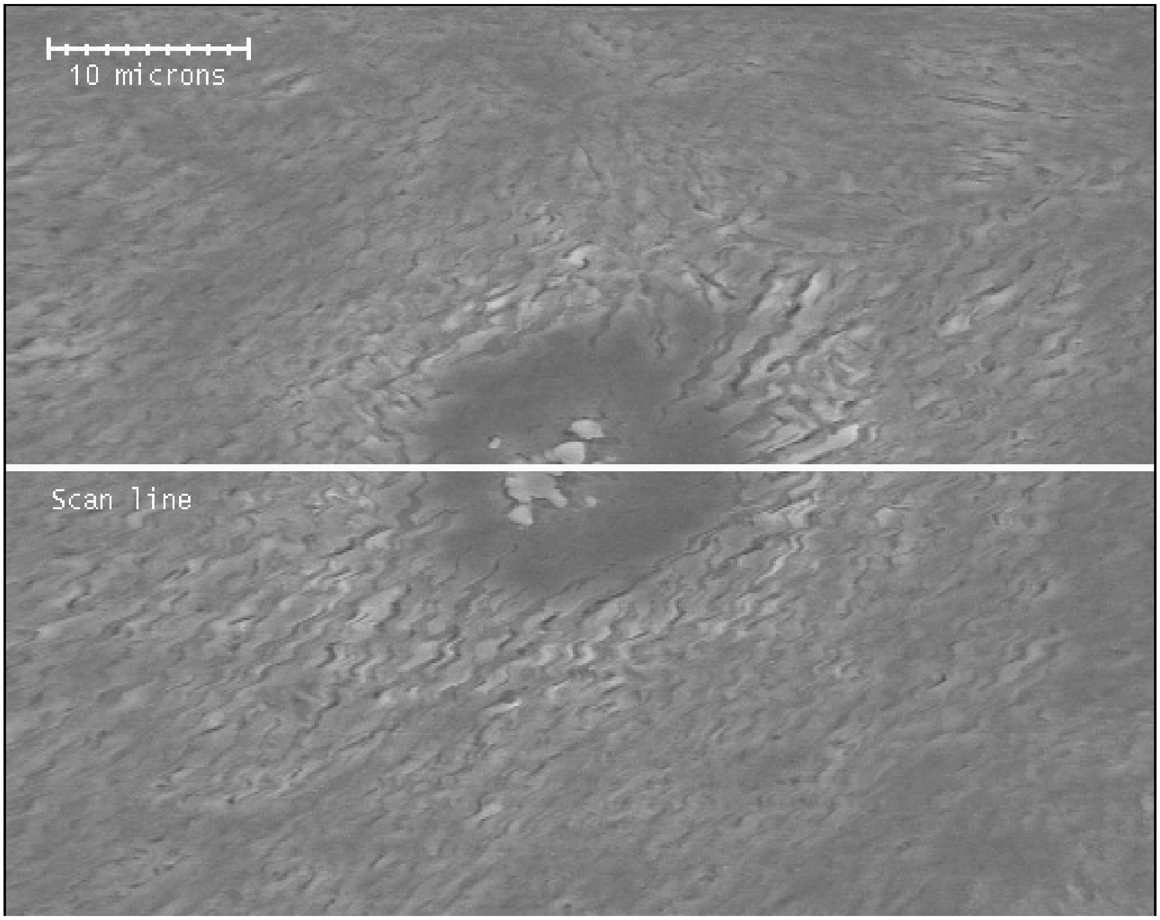


Figure 21 SEM micrograph of a final solidification pool in S53-3C with a superimposed x-ray scan line.

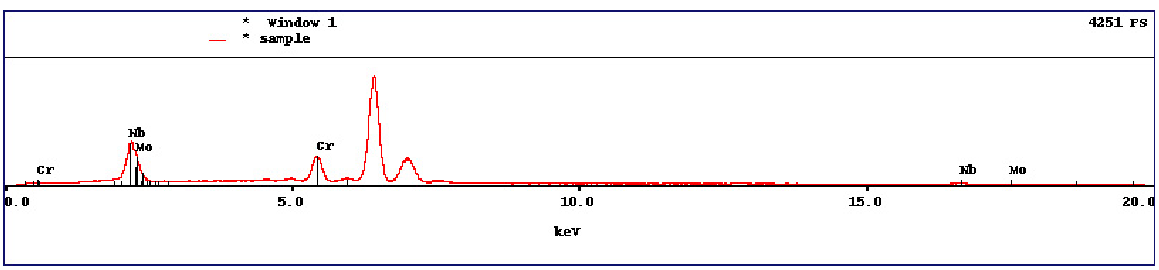


Figure 22 X-ray spectrum associated with the x-ray scan line shown in Figure 21.

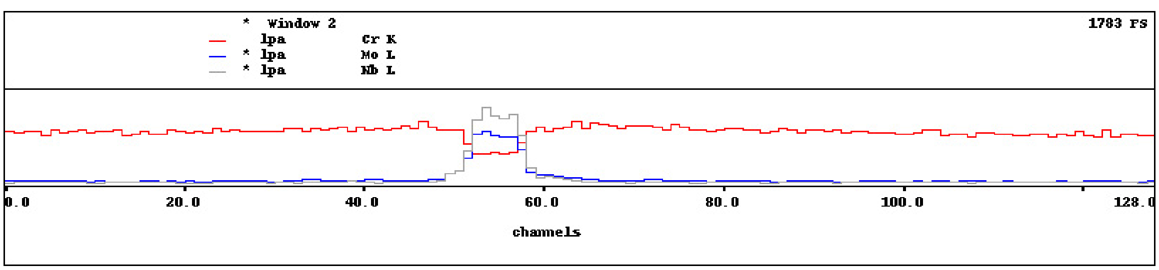


Figure 23 Cr (red), Mo (blue) and Nb (gray) x-ray counts along the x-ray scan line shown in Figure 21.

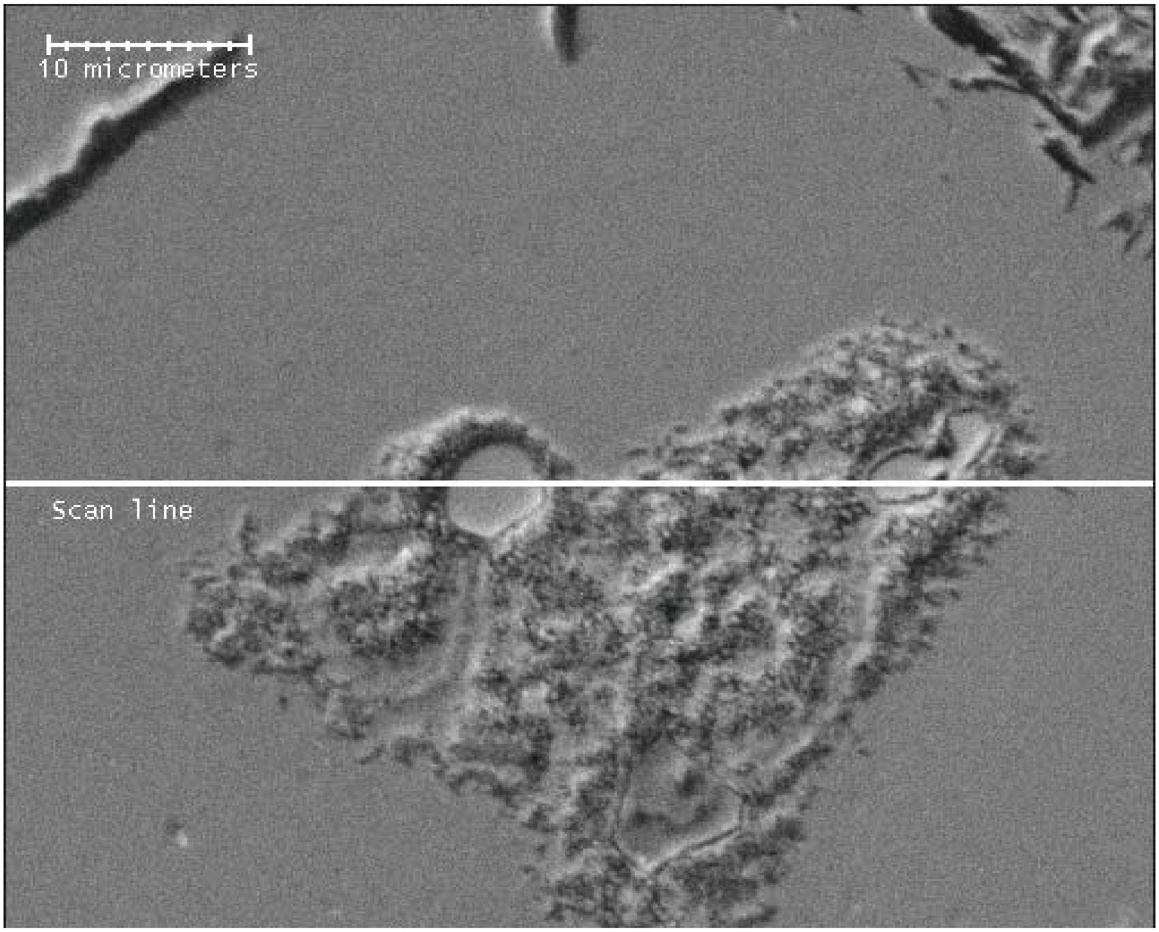


Figure 24 SEM micrograph of a final solidification pool in the S53A 17” dia. ingot with a superimposed x-ray scan line

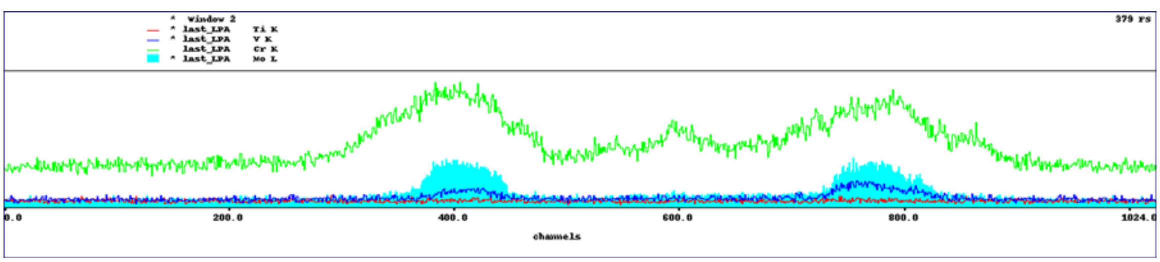


Figure 25 Cr (green), Mo (light blue), V(dark blue) and Ti (red) x-ray counts along the x-ray scan line shown in Figure 24

Homogenation/Hot-Working

Homogenization is required to reduce the level of microsegregation produced during solidification. Taking the composition profiles shown in Figure 5, homogenization simulations were run using DICTRA. A homogenization temperature of 1260ºC for S53-3B was chosen based on various experimental and simulation results as well as the furnace capability of our alloy producer. Figure 26 shows composition profiles for Cr and Mo as a function of distance along the dendrite for several different times at the homogenization temperature. Cr and Mo were selected for this plot since they have the highest absolute microsegregation levels (not necessarily the highest values of δ) in the S53-3 alloys. After just one hour at 1260ºC, the level of microsegregation has greatly decreased. After 12 hours, there is no noticeable difference between the maximum and minimum solute levels.

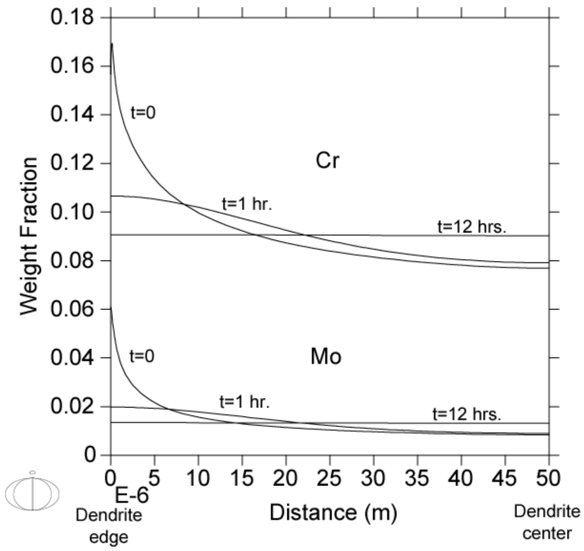


Figure 26 Cr and Mo composition profiles during homogenization at 1260ºC in S53-3B.

To compare homogenization results for different alloys, as well as to provide the most useful information for experimental work, it was decided to define a "homogenization time", a time after which an acceptable or perhaps experimentally insignificant level of microsegregation would remain. This homogenization time, called the "homogenization time at spec.", was chosen as the time required to bring the maximum and minimum solute levels to within the variation allowed in the material specification given to our alloy producer. For Cr and Mo, for example, these allowable variations are 0.4 and 0.2 wt.%, respectively. For a more stringent requirement, a "homogenization time at half spec." may be used, for which the allowable variations would be halved

For S53-3B, it was found that the homogenization time was limited by Cr, i.e, it took longer for the maximum and minimum Cr levels to come to within 0.4 wt.% (or 0.2 wt.% for half spec.) than for the other solute levels to come within their allowed variances.

Figure 27 shows the maximum (dendrite edge) and minimum (dendrite center) Cr levels as a function of time at 1260ºC. From this graph, it is seen that for S53-3B, the homogenization time at spec. is 6.2 hours (8.1 hours at half spec.).

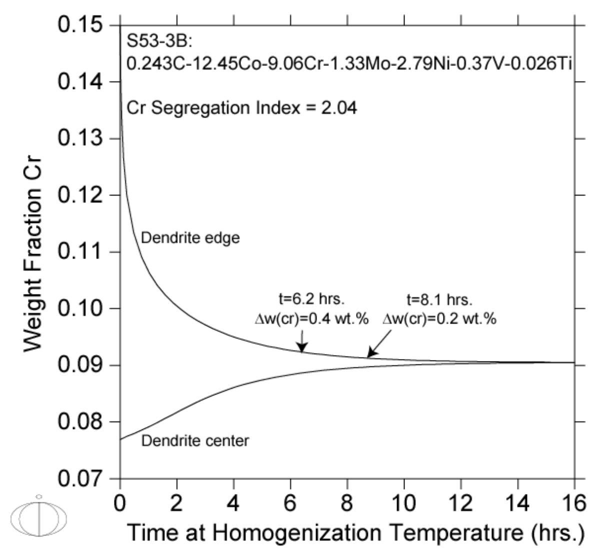


Figure 27 Determination of homogenization time for S53-3B.

The solidification and homogenization simulations described above for S53-3B were repeated for S53-3A and 3C. As mentioned, the results for all three alloys were very similar. There is a possibility, however, of selecting a homogenization temperature other than 1260ºC for 3A and/or 3C. The temperatures chosen for the simulations, along with the resulting homogenization times, are given in Table 2. This data is also given in graphical form in Figure 28 and Figure 29, showing the homogenization times at spec. and half spec. as a function of homogenization temperature.

Table 5 DICTRA homogenization times (in hours) at various temperatures for S53-3A (Heat WK45), 3B (Heat WK57) and 3C (Heat WK58).

Temp. (°F)	Temp. (°C)	S53-3A Spec.	S53-3A ½ Spec.	S53-3B Spec.	S53-3B ½ Spec.	S53-3C Spec.	S53-3C ½ Spec.
2100	1149					36.2	47.1
2192	1200					15.5	20.2
2246	1230					9.7	12.6
2250	1232.2	9.5	12.3				
2273	1245	7.8	10.1				
2300	1260	6.2	8.1	6.2	8.1	6.2	8.0

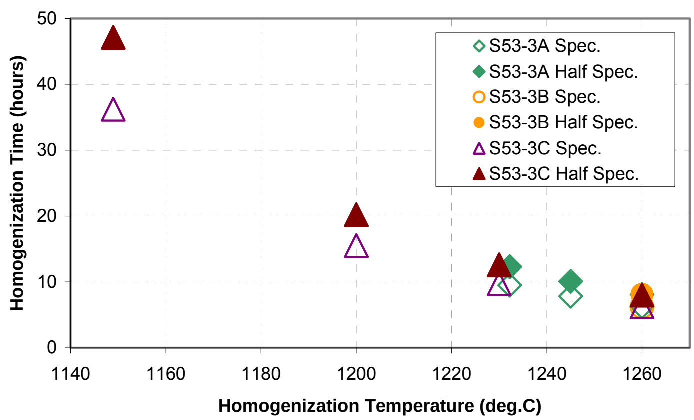


Figure 28 DICTRA homogenization times and temperatures for S53-3A, B and C.

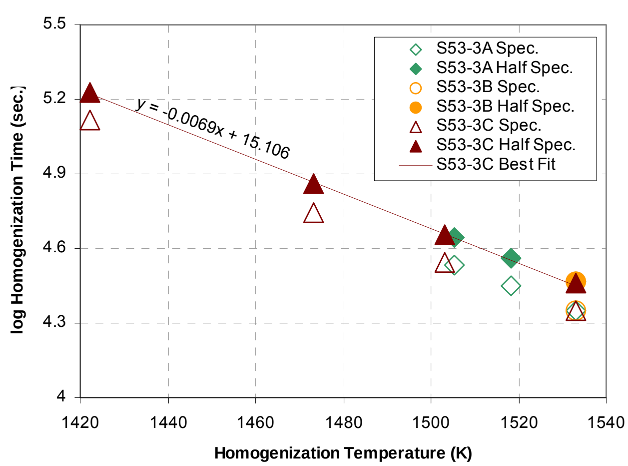


Figure 29 DICTRA homogenization simulation results. A best fit line is given for S53-3C, with the maximum allowed Cr composition difference at half the specification.

In moving to a larger production-scale ingot, segregation becomes a greater concern due to the lower cooling rate of the larger ingot. Solidification and homogenization simulations were conducted to better understand the effects of moving to a larger ingot and to define homogenization parameters for the S53A 17" dia. ingot. The as-cast VAR microstructure was examined using SEM to determine the dendrite size. Examination of both the 8" and 17" ingots, as shown in Figure 15 and Figure 24 respectively, demonstrate that the dendrite size scale is no larger than expected and the overall segregation is less than the modeling suggests. The solidification and homogenization process was simulated using DICTRA, with an assumed dendrite half-arm spacing of 200 μm based on examination of the as-cast structure. A cooling rate of 0.076°C/sec was used to simulate solidification of a 17” ingot.

The DICTRA simulation predicts that the most significant segregates will be chromium and molybdenum. The predicted composition profiles for these two elements after solidification are shown in Figure 30. The concentration of chromium at the dendrite edge is nearly double that of the dendrite center, and for molybdenum the concentration at the dendrite edge is approximately seven times higher that at the dendrite center.

Using the composition profiles predicted by the solidification simulation, the homogenization treatment was simulated using DICTRA. A homogenization temperature of 1260°C was chosen based on experience with previous generation alloys and known process equipment limitations. The compositions at the edge and center of the dendrite are shown as a function of homogenization time in Figure 31. After 24 hours of homogenization the total segregation is dramatically reduced. After homogenization, SEM analysis could not find any evidence of segregation.

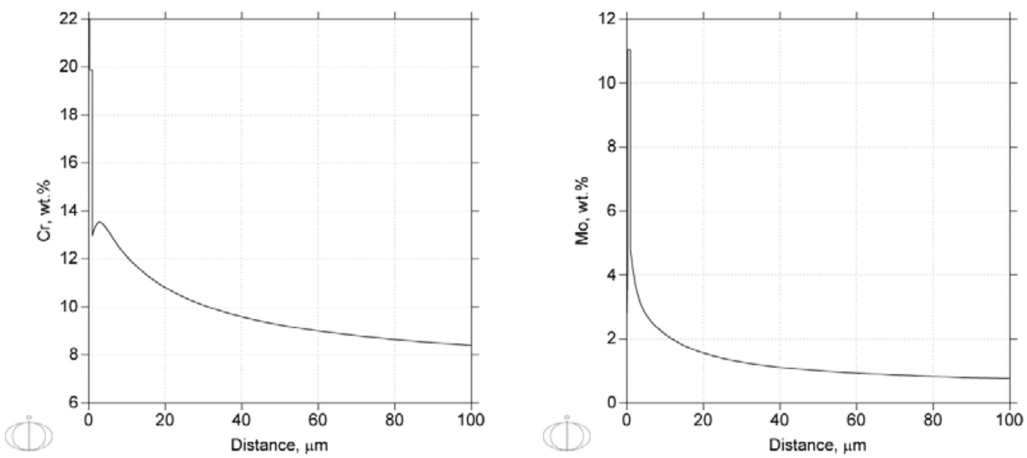


Figure 30 DICTRA solidification profiles for Cr and Mo in S53A, 17” ingot.

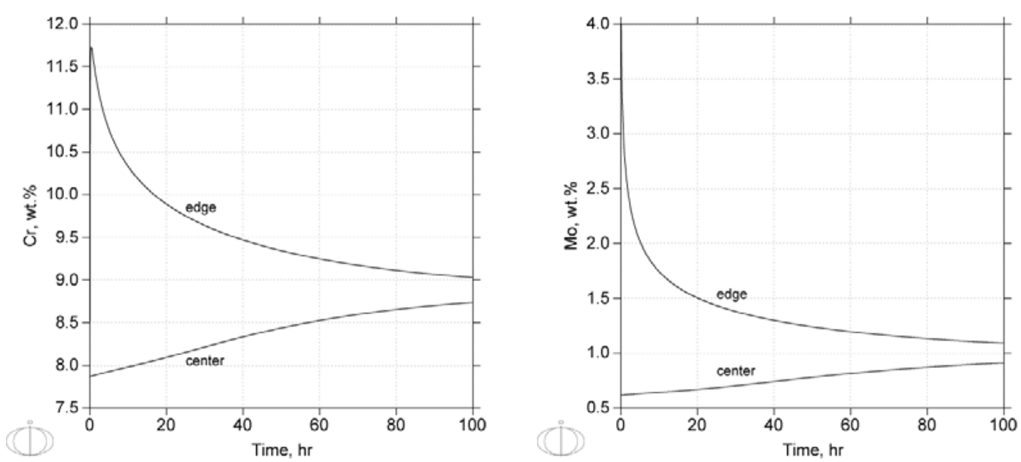


Figure 31 DICTRA homogenization simulation showing Cr and Mo content at dendrite edge and center as a function of homogenization time in S53A, 17” ingot.

Annealing

A study was undertaken to examine the annealing performance of S53A. The previously used annealing procedure at 732 °C gave poor machinability (see Machinability of Annealed Alloy) due to a combination of high hardness and retained austenite. In this study, the effects of annealing temperature were examined using dilatometry, with the goal of developing a new annealing process that gives lower hardness and reduced retained austenite.

In production, the annealing will typically be performed on relatively large-section pieces. To accurately predict behavior in these larger sections, the heating and cooling rates were controlled to approximate the behavior at the center of a solid 10" round bar. The cooling curve for this section size was obtained from *Phase Transformation Kinetics and Hardenability of Medium-Carbon Alloy Steels* by W.W Cias. Within the range of 800 to 500 °C, a cooling rate of 6 °C/min closely approximates the cooling curve for a 10" round.

Dilatometry specimens were manufactured from the previously annealed S53A. These samples were first encapsulated under argon, and then normalized at 1060 °C for one hour. The samples were furnace cooled at a rate of approximately 6 °C/min, with cooling rate control provided by opening the furnace door to various positions while monitoring temperature near the dilatometry samples. The microstructure at the end of the normalizing step was primarily austenite, with some grain boundary carbides formed during cooling, as shown in Figure 32. The average hardness of the normalized microstructure was 295 VHN.

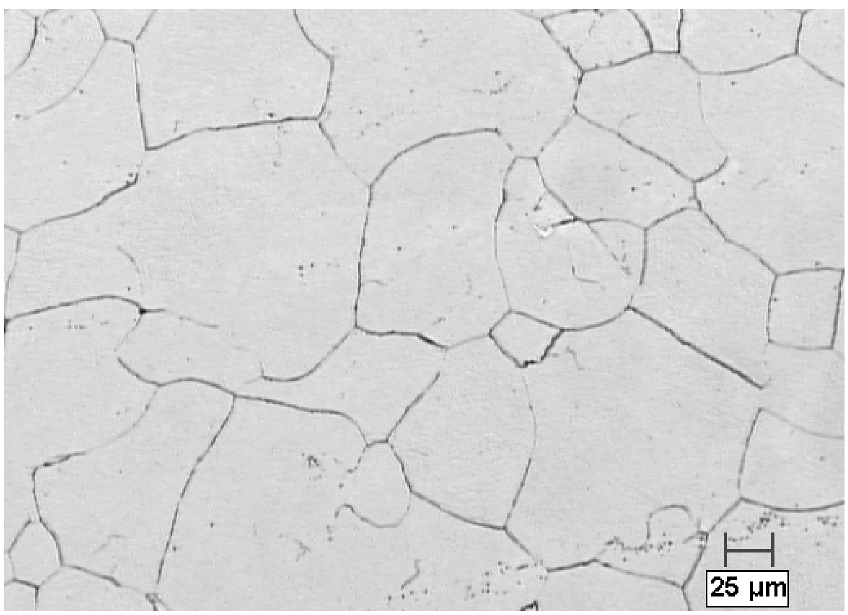


Figure 32 Microstructure of S53A after normalizing for 1 hour at 1060 °C and slow cooling. Microstructure is primarily austenite with grain boundary carbides. Nital etch.

To examine the effects of annealing temperature, a series of temperatures ranging from 650 to 800 °C were examined. Samples were heated at a rate of 6 °C/min to the desired annealing temperature, held for 4 hours, and then cooled at a rate of 6 °C/min. An example dilatometer trace is shown in Figure 33. During heat-up, a small amount of austenite reversion takes place, indicating that the microstructure after normalizing isn't fully austenitic. The amount of austenite reversion during heat-up increased slightly with increased annealing temperature. During the hold at the annealing temperature, a significant decrease in length takes place. The drop in length is initially very rapid, but flattens out at longer times, as shown in Figure 34. This decrease in length is believed to be primarily due to carbide precipitation, although some austenite precipitation likely occurs as well. During cooling, the austenite transforms to martensite at approximately 180 °C (see Figure 33). The measured M_s temperature after annealing was constant, within experimental uncertainty, at all annealing temperatures.

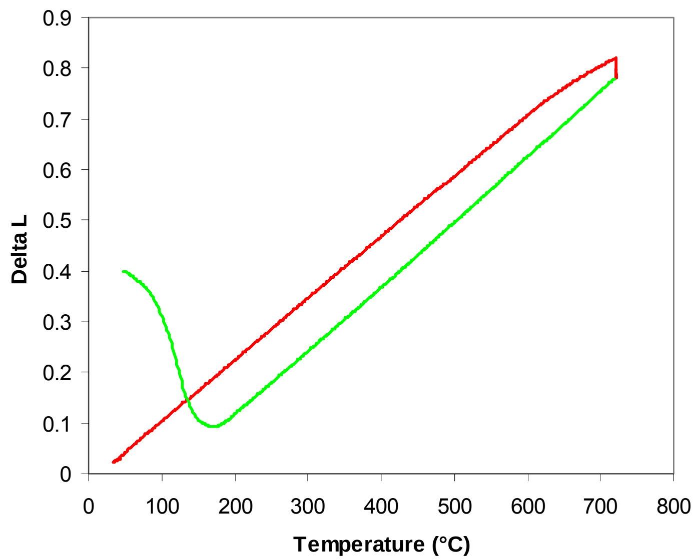


Figure 33 Length change as a function of temperature for sample annealed at 725 °C for 4 hours in the dilatometer. Red line is heat-up and hold, green line is cool-down.

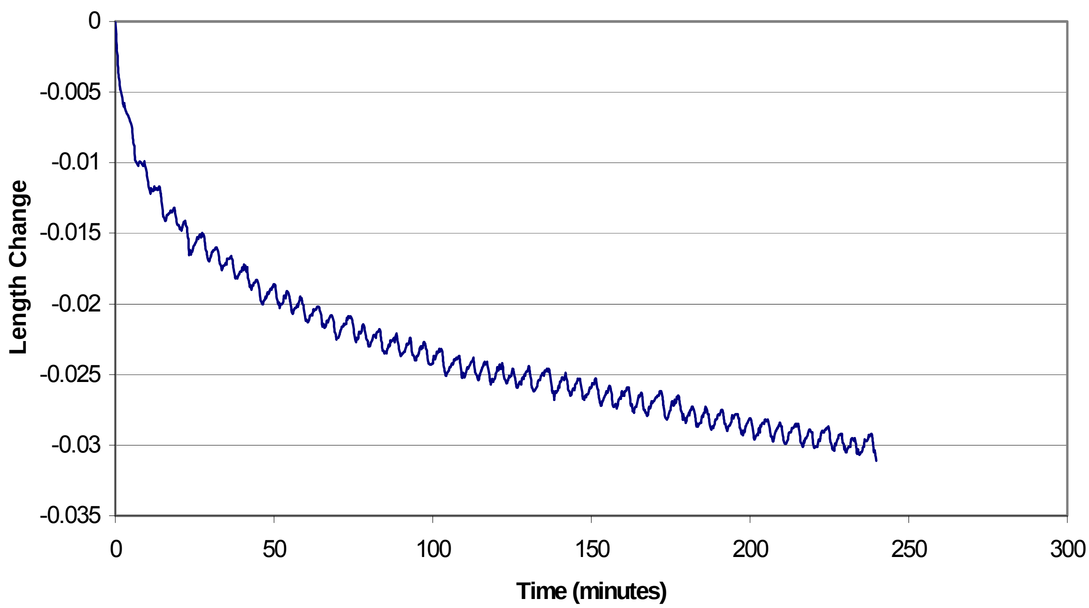


Figure 34 Length change as a function of time during hold at 750 °C.

After annealing, the microstructure of all samples was a mix of austenite, martensite, and carbides. A micrograph of a representative microstructure is shown in Figure 35. All annealing temperatures produced microstructures with very similar hardness, as shown in the chart in Figure 36. However, there is a significant difference in the standard deviation of the hardness measurements between annealing temperatures. This variation in hardness measurements on a given sample is due to the mixed austenite/martensite microstructure. Less variability in measured hardness is assumed to indicate a microstructure that is more uniformly martensitic. The standard deviation in measured hardness decreased with increasing annealing temperature, up to a temperature of 750 °C. At temperatures of 775 °C and higher, the standard deviation in measured hardness increased dramatically.

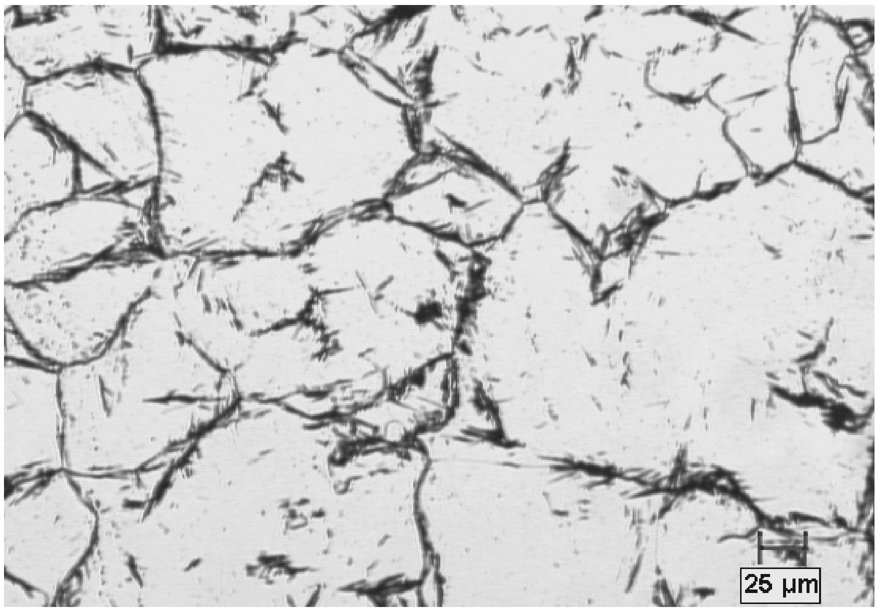


Figure 35 Microstructure of dilatometry sample held at 725 °C for 4 hours, followed by slow cool. Nital etch.

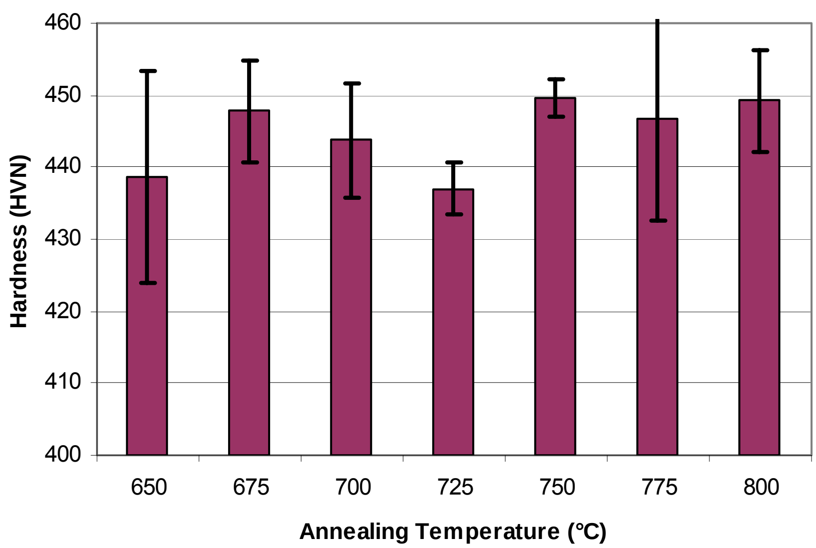


Figure 36 Measured microhardness after annealing for several annealing temperatures. Error bars represent the standard deviation of the microhardness measurements on a single sample.

Based on the results presented above, it was decided to utilize a two-step annealing procedure. A temperature of 725 °C was chosen for the first annealing temperature, since it gave the best combination of low hardness and low austenite content (based on observed deviation in measured hardness). For the first annealing step, samples were heated at 6 °C/min to 725 °C, held for 4 hours, then cooled at 6 °C/min to room temperature. For the second annealing step, samples were again heated at 6 °C/min to the annealing temperature, held for 4 hours, and then cooled at 6 °C/min.

Various temperatures were investigated for the second annealing step. In the second annealing step, it is desired to temper the martensite produced in the first annealing step while destabilizing the retained austenite and avoiding additional austenite precipitation. In the second annealing step, annealing at temperatures above 600 °C resulted in the precipitation of austenite. Annealing at 550 °C prevents austenite precipitation, and the carbide precipitation sufficiently destabilizes the retained austenite to allow martensite transformation upon cooling. This is shown in the dilatometry trace in Figure 37. The resulting hardness for several annealing temperatures is shown in Figure 38. Annealing at 550 °C results in a microstructure of uniform hardness, which indicates very little retained austenite. The microstructure of this sample is shown in the micrograph in Figure 39. Additionally, the average hardness is substantially reduced from that of the single-step anneal at 725 °C. The final two-step process chosen as the new annealing procedure is shown schematically in Figure 40. This procedure consists of 4-hour holds at 725 °C and 550 °C, with slow cooling after each step.

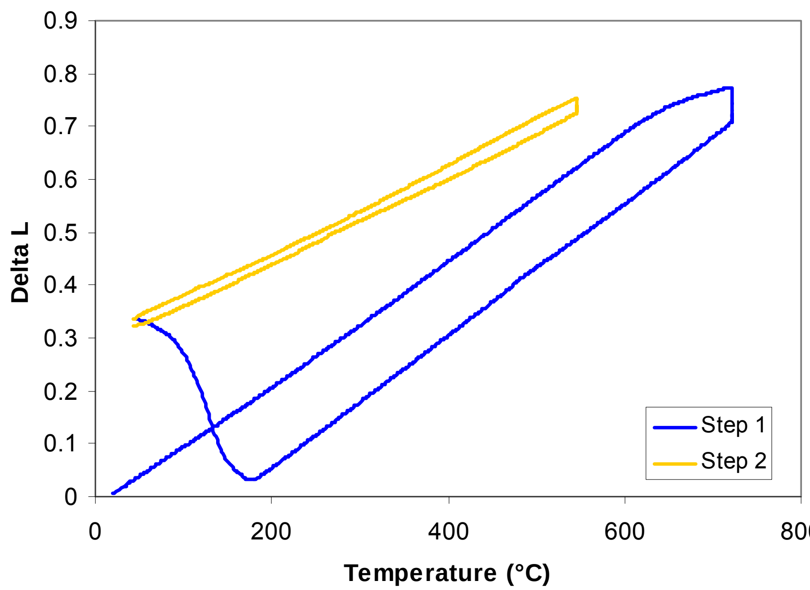


Figure 37 Dilatometry trace for two-step annealing procedure. The first annealing temperature was 725 °C, the second annealing temperature was 550 °C.

To verify that the new two-step annealing procedure successfully improves machinability, this cycle was applied to a 1" diameter round bar. The bar was first normalized in an argon atmosphere at 1060 °C for 1 hour, and then furnace cooled to simulate the slow cooling of a large-section part. The bar was then furnace heated to 725 °C, held for 4 hours, and allowed to furnace cool overnight. For the second annealing step, the bar was furnace heated to 550 °C, held for 4 hours, and furnace cooled to room temperature. The resulting hardness is shown together with the data for the two-step dilatometry specimens in . The measured hardness closely matches that of the dilatometer specimen annealed with the same process.

After annealing, the 1" diameter bar was subjected to a rudimentary machinability test. The bar was cut to produce a "puck" using settings optimized for material annealed using the old annealing procedure. Previously, a cutting speed of 50 f/min gave small, discontinuous chips. With the new annealing cycle, the same cutting speed produces a continuous chip or “curl”. The cutting speed could be increased to 70 f/min while still producing a continuous chip.

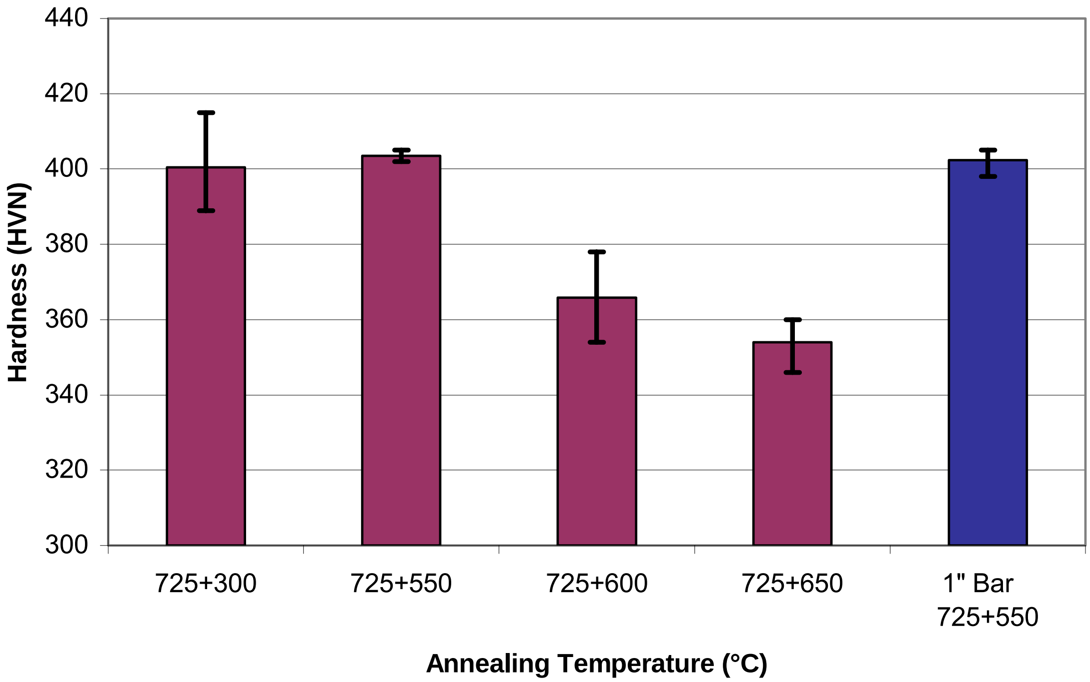


Figure 38 Measured microhardness after two-step anneal for several second-step annealing temperatures. Error bars represent the standard deviation of the microhardness measurements on a single sample.

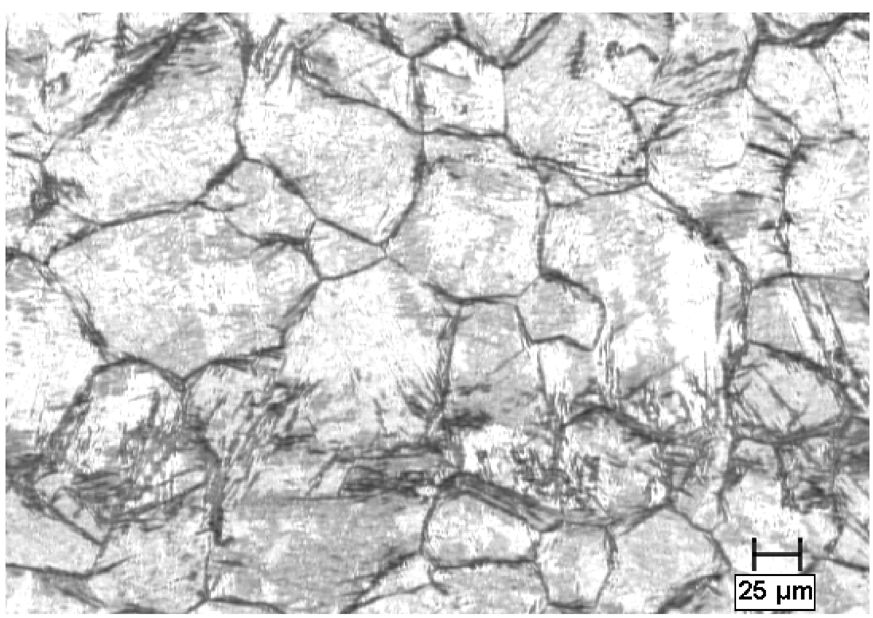


Figure 39 Microstructure dilatometry specimen treated to two-step anneal at 725 °C and 550 °C. Nital etch.

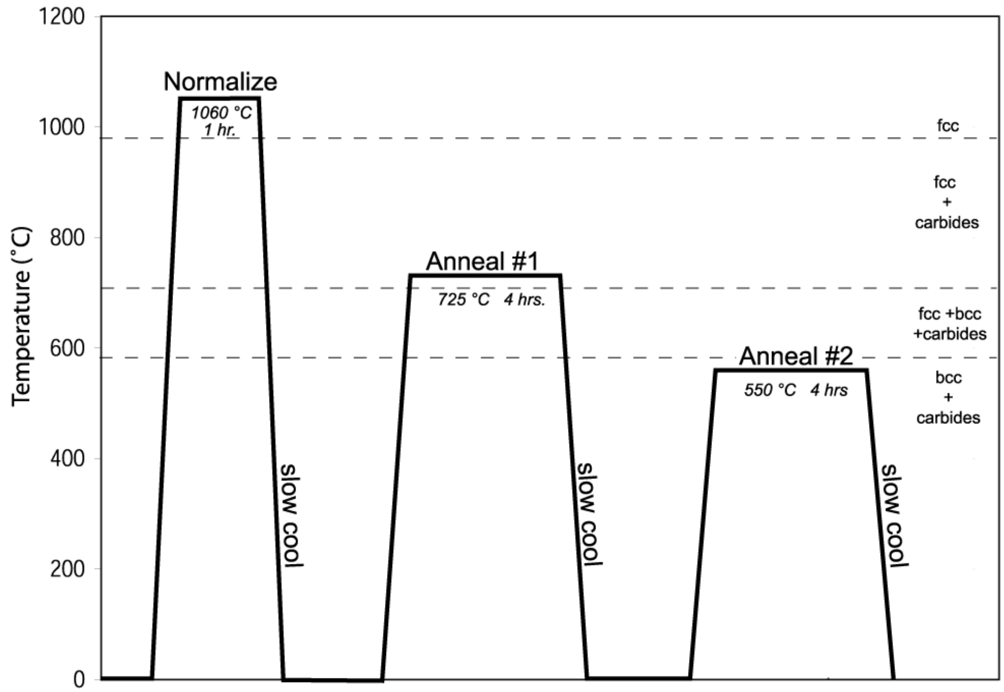


Figure 40 Schematic diagram of two-step annealing

2.3 Component Production

2.3.1 Machinability of Annealed Alloy

Specimen preparation

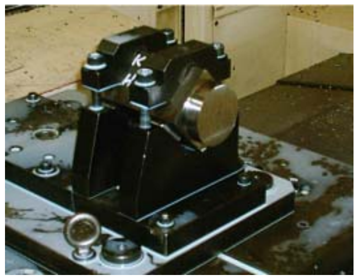
Raw material was supplied as eight square section bars, 3.5” x 3.5” x 24”, and two plates, 0.7” x 6” x 24” (Figure 41), in the annealed condition.

Figure 41 Raw materials supplied for machining studies.

Five of these bars were cut into three lengths of 7.75” each, resulting in 15 specimens (3.5” x 3.5” x 7.75” bars). On each bar, face and rounded end millings, and center drilling were done prior to machining. The machining coolant used was the Hangsterfer’s S-500CF, a chlorine-free, water soluble oil fluid.

(a) cutting

(b) mill facing



(c) rounded end milling

(d) center drilling

Figure 42 Specimen's preparation, specimen P/N SK-0110, S/N H0001.

The preparation of the specimens consisted of cutting (when required), end and face milling, and center drilling.

Interrupted and continuous turning

The starting point of the turning operations was the parameters used for the interrupted and continuous turnings of AerMet 100. The successive operations depended on the outcomes of the previous setting. The purpose was to select first the appropriate cutting insert, then, sequentially, the turning speed, the feed rate and the depth of cut in order to obtain an acceptable quality product and a high productivity rate. Table 6 gives the parameters usually used for the AerMet 100 in the annealed condition. They are similar to the 300M steel machining parameters in the normalized and tempered condition.

Table 6 AerMet 100 turning parameters

Operation	Tool and grade identification	Cutting speed (SFM)	Cutting feed (inch/revolution)	Depth of cut (inch)
Rough turning	DNMG442RP gr. KC9225	280	0.15	0.200
Drilling		250	0.005	N/A
Boring		--	--	--
Tapping		50	--	N/A

For all turning operations, the cutting tool characteristics (inserts grade and identification), turning speed, feed and depth of cut were recorded. Samples from the chips were also conserved to account for the performance of the cutting tools and the machining parameters.

Other observations like possible work piece deformation (TIR), number of pass before reaching an unacceptable wear of the inserts, etc. were collected.

The machine used for turning was a Dainichi MX95-2000, 50/60 horsepower CNC lathe, capable of a maximum spindle of 1200 RPM.

Interrupted turning transforms square specimen to round bar. An average of six passes were needed to achieve that goal, depending on the depth of cut. Continuous turning reduces the bar's diameter to the desired dimension before hardening. A pass is defined as one "back and forth" traveling of the tool where the tool does not cut at the "way back" to the original position.

All turning tools tested were indexable inserts. According to ANSI B212.4-2002 (Figure 43), indexable insert's characteristics are determined as follow:

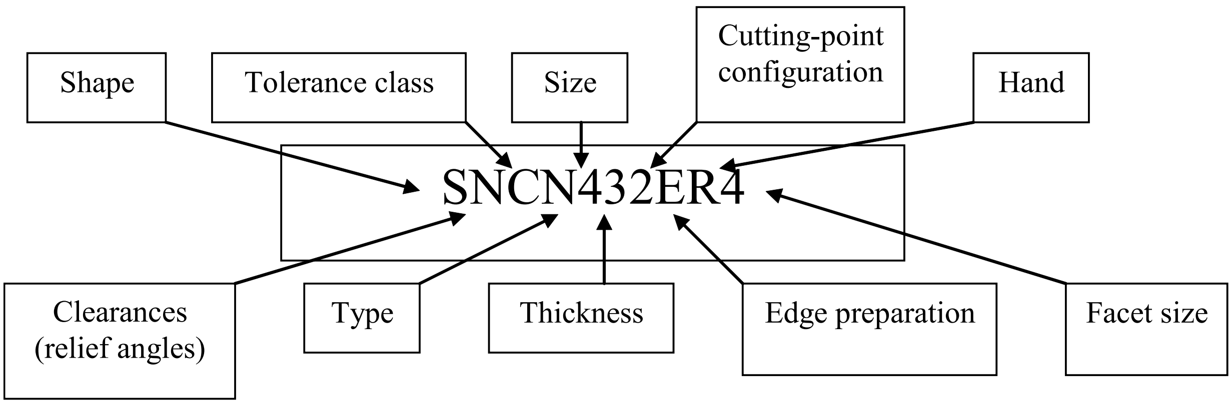


Figure 43 Indexable insert characteristics according to ANSI B212.4-2002.

Drilling and tapping

Drilling and tapping operations were conducted on a single OKK vertical milling machine. The model used was a MCV820 with a 20/25 horsepower unit and a spindle range of 25-3500 RPM.

The starting point of these operations was the parameters used for Aermet 100 drilling/tapping. Like turning, the successive operations depended on the outcomes of the previous setting. To optimize the operations, the appropriate drilling/tapping tool was first selected depending on the hole diameter, as well as the hole's depth. Then, the speed and the feed rate were selected and changed depending on the material behavior. Thus, a variety of holes and threads were drilled and tapped using different parameters as shown in Table 7.

For all drilling/tapping operations, the insert characteristics and the drilling/tapping parameters were recorded. A sample of the residual chips was also conserved to evaluate the cutting performance of each tool. Other observations like possible drill/tap wear, holes dimension, etc. were reported.

Table 7 Drilling and tapping parameters

Operation	Diameter/depth (inch)	Dimension (inch)	Bar condition
Drill holes	0.750	3.5 x 3.5 x 18.5 bar	Annealed
Drill holes	0.693	3.5 x 3.5 x 18.5 bar	Annealed
Tapping	0.693 holes to 0.7500-16 UNJF-3B	3.5 x 3.5 x 18.5 bar	Annealed
Drill holes	0.215	3.5 x 3.5 x 18.5 bar	Annealed
Tapping	0.215 holes to 0.2500-28 UNF-3B	3.5 x 3.5 x 18.5 bar	Annealed
Drill holes through thickness	0.125	3.5 x 3.5 x 18.5 bar	Annealed
Drill holes through thickness	1.375	0.7 x 6 x24 plate	Annealed

Table 8 summarizes the machining operations done on annealed specimens.

Table 8 Test matrix of annealed specimen

P/N	Dimension	Number of parts	Interrupted turning	Continuous turning	Drilling	Tapping
SK-0110	3.5” x 3.5” x 7.75”	6	√	√		
SK-0112	3.5” x 3.5” x 7.75”	5	√	√		
SK-0113	3.5” x 3.5” x 23”	1	√	√		
SK-0114	3.5” x 3.5” x 7.75”	2	√	√		
SK-0115	3.5” x 3.5” x 7.75”	2	√	√		
SK-0116	3.5” x 3.5” x 17.3”	1			√	√
SK-0117	0.7” x 6” x 24”	2			√	

One raw 23” long square bar (SK-0111) and the two plates (SK0117) were re-annealed. The scope of the re-annealing was to reduce the hardness of the material and make the machining easier. Only the bar was turned after the re-annealing, following the same procedure described in the section 0.

Figure 44 Re-annealed 24” long square bar

Table 9 summarizes the machining operations done on the re-annealed specimen. The detailed machining operations involved are described in a following section.

Table 9 Test matrix of re-annealed specimen

P/N	Dimension	Number of parts	Interrupted turning	Continuous turning	Drilling	Tapping
SK-0111	3.5” x 3.5” x 23”	1	√			

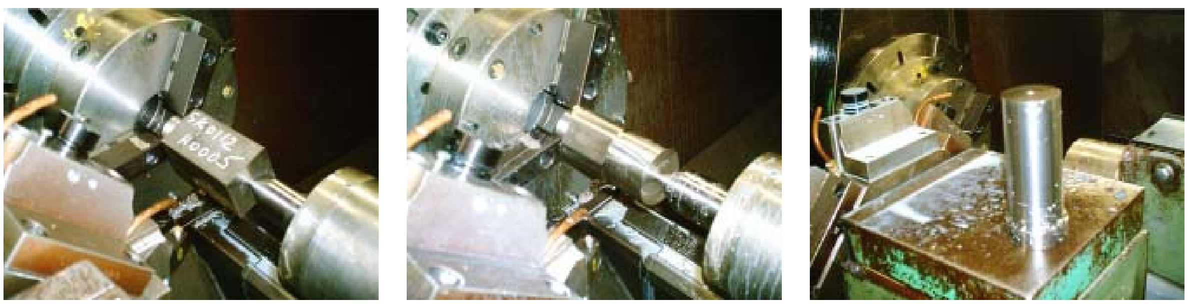
Metallographic study
Specimens 3.5” x 3.5” x 1” were cut from a bar of each heat treat lot to account for the decarburization layer thickness. Micro-hardness profiles were performed using a 300g load on an as-polished surface.

Microstructural observations were done using an optical microscope. Specimens were cut, mounted in bakelite and polished following the classic sequence (SiC abrasive paper with decreasing grit, diamond paste) to obtain a polish mirror. The specimens were then etched using a 5% nital solution.

Results

Even though the control of these operations was not required for this study, several comments can be made:

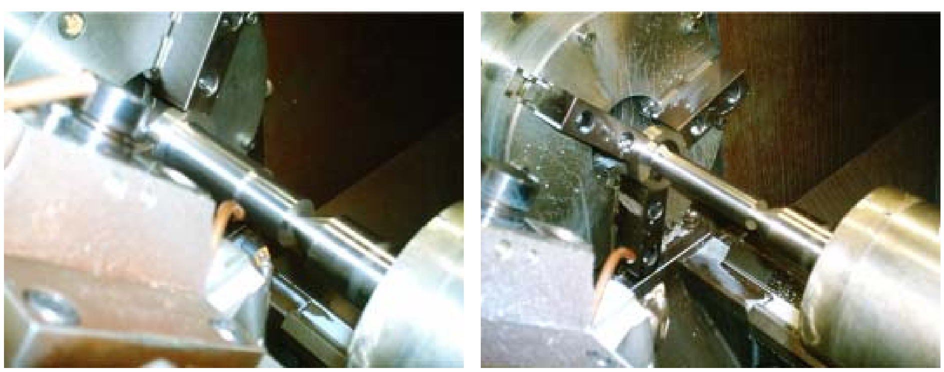
- **No major problems were observed during cutting, rounded end milling and center drilling.**
- Unlike low alloyed steel 300M and as high alloyed steel Aermet 100, face milling on Ferrium S53 without a good coolant flow gave bad results. The chips bonded on the insert and thus, made it wore prematurely.
- When using a good coolant flow with an appropriate insert, face milling speed as high as 600 RPM and feed rate as high as 12”/revolution were reached.



(a) first pass (b) intermediate pass (c) final result

Figure 45 Interrupted turning, specimen P/N SK-0112, S/N H0005

The annealed specimens were turned (interrupted and continuous turning) (Figure 45 and Figure 46), drilled and tapped (Figure 47). The following sections summarize the obtained results.



(a) intermediate pass (b) final pass

Figure 46 Continuous turning, specimen P/N SK-0110, S/N H0004

(a) SK-0116 H0001 bar (b) SK-0117 H0001 plate

Figure 47 Drilling and tapping

For each machining operation, a comparison between Ferrium S53 and the 300M and Aermet 100 machining parameters is done. General observations (insert wear, work piece deformation, etc.) are also made.

Interrupted and continuous turning

Table 10 and Table 11 summarize the turning trials done on the 7.75” long bars for respectively the interrupted and continuous turning.

Two basic diamond shapes inserts (80° and 55° inner angles, Figure 48) were tested during the interrupted turning. The performance of the inserts was more linked to the grade than to the shape.

The best results were found for the grades that are customized for high temperature materials, which are usually high alloyed materials. Grades EH520Z, CP200 and KC8050 are all grades that performed well during interrupted and continuous turning. These grades are all made with carbide based substrates either cemented carbides (EH520Z) or cobalt enriched surface carbides (KC8050) or micrograin carbides (CP200) that have a combination of hardness and toughness. These carbides are coated with high thermal and welding resistant materials deposited by techniques that improve the crater and flank wear as well as the built-up edge.

The turning speed, feed and depth of cut selected were lowered if compared with the 300M and AerMet 100 parameters. The usual speed for those two steels before hardening is 280SFM, the feed is 0.015ipr and the depth of cut is usually 0.200”. When using these parameters for Ferrium S53, inserts either wear very quickly or break.

Table 10 Annealed S53 optimum interrupted turning parameters

P/N	S/N	Insert grade	Insert identification	Insert characteristics	Turning speed (SFM)	Feed rate (inch/rev)	Depth of cut (inch)
SK-0110	H001	KC9240	CNMG120412RP		280	0.012	0.15
	H002	KC9240	CNMG120408MP		280	0.012	0.15
	H003	KC9225	CNMG123412RP		280	0.012	0.15
	H004	EH520Z	CNMG1204 12N-MU	Cemented carbides	280	0.012	0.15
	H005	AC3000	CNMG1204 12N-MU	*Usually used for Aermet 100*	280	0.012	0.15
	H006	EH520Z	CNMG1204 12N-MU	Cemented carbides	280	0.012	0.15
SK-0112	H001	KC5010	DNMG 442 MP		230	0.01	0.15
		N/A	1.42002R171 CM3		230	0.012	0.15
	H002	TP2000	DNMG 442-M3		230	0.01	0.15
		CP200	DNMG 442-MR3		230	0.01	0.15
	H003	CP200	DNMG432MF1		230	0.01	0.15
	H004	CP200	DNMG432MF1		230	0.01	0.15
	H005	9110	CNMG433FW		270	0.012	0.15
		KC8050	DNMG442RP		230	0.01	0.15
SK-0114	H001	EH520Z	DNMG432EMU	TiN/AIN PVD (ultra hard nanostructure- 4000H_v)	270	0.008-0.010	0.15
	H002	CP200	DNMP432MF1		270	0.008-0.010	0.15
SK-0115	H001	CP200	DNMP432MF1		250	0.01	0.15
	H002	CP200	DNMP432MF1		270	0.01	0.15

No unusual wear (green) | Excessive wear (yellow) | Broken insert (red)

Figure 48 shows crater and flank wears observed on different diamond shape inserts. The related chips are also shown. The wear was due to an overheating observed at the cutting point when the chips bonded on the insert or did not break in small fragments.

The chips form is correlated to the inserts wear. Small and fragmented chips are generally associated with a good insert while long chips reduce the life of an insert.

It was noted for Ferrium S53 that interrupted turning was easier than continuous. When the parts started to be round, the chips were hardly cut and stick on the insert inducing excessive wear.

The 55° angle inserts DNMG432MF1 grade CP200 (Figure 49a) and DNMG432EMU grade EH520Z (Figure 49b) gave the better results. These grades allowed the use of higher speeds (250-270SFM).

(a) CNMG120412N-MU gr. AC3000, 80° diamond shape, interrupted turning

(b) DNMG150408N-MU gr. EH510Z, 55° diamond shape, continuous turning

Figure 48 Inserts wear and associated chips

(a)

(b)

Figure 49 Grade CP200 (a) and Grade EH520Z (b)

Table 11 Annealed S53 optimum continuous turning parameters

P/N	S/N	Insert grade	Insert identification	Insert characteristics	Turning speed (SFM)	Feed rate (inch/rev)	Depth of cut (inch)
SK-0110	H001	EH510Z	DNMG150408N-MU		R: 280	0.012	0.15
		EH510Z	DNMG432MU		F: 230	0.012	0.15
	H002	-	-		-	-	-
	H003	EH520Z	DNMG432EMU	TiN/AIN PVD (ultra hard nanostructure-4000H_v)	R&F: 230	0.012	0.15
	H004	EH520Z	DNMG432EMU	TiN/AIN PVD (ultra hard nanostructure-4000H_v)	R: 280	0.01	0.15
		EH520Z	DNMG432EMU	TiN/AIN PVD (ultra hard nanostructure-4000H_v)	F: 230	0.01	0.15
	H005	EH520Z	DNMG432EMU	TiN/AIN PVD (ultra hard nanostructure-4000H_v)	R: 230	0.01	0.1
					F: 230	0.006	0.1
	H006	KC9225	DNMG150608RP		R: 230	0.01	0.15
		KC9225	DNMG442RP		R: 230	0.01	0.15
SK-0112	H001	5010	TO1698		230	0.01	0.15
		N/A	1.42002R171 CM3		230	0.012	0.15
	H002	TP2000	DNMG 442-M3		230	0.01	0.15
		CP200	DNMG 442-MR3		230	0.01	0.15
	H003	CP200	DNMG432MF1		230	0.01	0.15
	H004	CP200	DNMG432MF1		230	0.01	0.15
	H005	KC8050	DNMG442RP	Cobalt enriched substrate/multilayer alumina coating	230	0.01	0.15
SK-0114	H001	EH520Z	DNMG432EMU	TiN/AIN PVD (ultra hard nanostructure-4000H_v)	270	0.008	0.15
	H002	CP200	DNMP432MF1		270	0.008	0.15
SK-0115	H001	CP200	DNMP432MF1		250	0.01	0.15
	H002	CP200	DNMP432MF1		270	0.01	0.15

R: rough turningF: finish turning

No unusual wear | Excessive wear | Broken insert

The choice of the parameters was also dictated by the deformation induced on the part during the turning. Depending on the feed rate and depth of cut selected, the measured TIR varied between

0.015” and 0.040” for the 7.75 long bars. The TIR was higher when feed rate and depth of cut were increased as shown in Table 12.

Table 12 Deformation induced by turning

Grade	Speed (SFM)	Feed rate (inch/rev)	Depth of cut (inch)	TIR (inch)
EH 520Z	230	0.012	0.15	0.040
EH 520Z	230	0.010	0.15	0.015

Table 13 300M and Aermet 100 turning parameters

High strength steel	Turning	Insert grade	Insert Identification	Turning speed (SFM)	Feed rate (inch/rev)	Depth of cut (inch)
Aermet 100	Interrupted	AC3000	CNMG120412N-MU	280	0.012	0.15
	Continuous	KC9225	DNMG442RP	280	0.01	0.15
300M	Rough	N/A	N/A	280	0.015	0.2

As for interrupted turning, for continuous turning the parameters used were lower than those used for 300M as shown in Table 13. The feed rate and depth of cut used are lower (0.012ipr and 0.15” instead of 0.015ipr and 0.200”). However they are comparable with Aermet 100 steel parameters if using different inserts. The inserts used for Aermet 100 worn out very rapidly.

Table 14 summarizes the turning trials done on the 23” long bar.

Table 14 Annealed Ferrium S53 optimum interrupted and continuous turning parameters

P/N	S/N	Insert grade	Insert Identification	Insert characteristics	Turning speed (SFM)	Feed rate (inch/rev)	Depth of cut (inch)
SK-0113	H001	1005	CNMG432-QM		270	0.012	0.15
		EH520Z	DNMG432EMU	TiN/AlN PVD (ultra hard nanostructure-4000H_v)	230	0.015	0.125
		EH520Z	DNMG432EMU	TiN/AlN PVD (ultra hard nanostructure-4000H_v)	230	0.01	0.125
		8050	DNMG442RP		230	0.01	0.072
		8050	DNMG442RP		200	0.01	0.072
		EH510Z	DNMG432EEX		200	0.01	0.12

R: rough turning F: finish turning

Good insert (green) Broken insert (red)

The starting point was the best insert found (DNMG432EMU grade EH520Z) from the 7.75” long bars turning. As shown in Table 10, this insert was not successful. It broke after a turning length of 6.5” and 10.5” when the feed rate was respectively set up at 0.015”/rev. and 0.01”/rev. The turning of the 24” long bar took 4 different inserts. Most of them broke before turning a length of 10.5 inch.

Drilling and tapping

Different hole diameters have been drilled as shown in Table 15.

Table 15 Annealed Ferrium S53 optimum drilling parameters

P/N	S/N	Drill diameter	Drill insert	Drilling sequence	Drilling speed RPM (SFM)	Feed rate (mils/rev)	Depth (inch)
SK-0116	H001	0.738	TiN coated carbide-brazed Delta Sandvik R411.5-18732 D18.75 P-20	1 shot drilling	510 (100)	3	N/A
			TiN coated carbide-brazed Delta Sandvik R411.5-18732 D18.75 P-20	1 shot drilling	640	5.7	N/A
			TiN coated carbide-brazed Delta Sandvik R411.5-18732 D18.75 P-20	1 shot drilling	770	3.8	N/A
			TiN coated carbide-brazed Delta Sandvik R411.5-18732 D18.75 P-20	1 shot drilling	640	2.9	N/A
			TiN coated carbide-brazed Delta Sandvik R411.5-18732 D18.75 P-20	Incremental drilling	510 (100)	2.5	0.3
			TiN coated carbide-brazed Delta Sandvik R411.5-18732 D18.75 P-20	Incremental drilling	510 (100)	2.5	0.1
		0.687	Carbide	Incremental drilling	556	2.8	0.1
			Carbide	Incremental drilling	556	2.8	0.1
		0.216	Guhring firex coated carbide	Incremental drilling	1400 (80)	3.5	0.05
		0.125	Kennemetal SE carbide		1900	2.3	0.05
		0.125	Cobalt HSS		1900 (605)	2.3	0.0
SK-0017	H001	1.25	Iscar	1 shot drilling	650 (210)	1	0.075
						1.1	0.075
					650	1	0.075
		1.37	Twin bar		500 (180)	1.4	0.075
	H002	1.375	Iscar	Incremental drilling	1100	2.8	-
			Hertel	Incremental drilling	416 (150)	1.25	-
			HSS	Incremental drilling	160 (58)	0.75	-
			HSS	Incremental drilling	60	0.3	-
		1.250	Iscar	1 shot drilling	714 (233)	1.25	-

Good drill | Excessive heat or drill wear | Broken drill

It is worth noting that for hole smaller than 1", a one shot drilling was not possible for the Ferrium S53. Chips did not break inducing the jamming and/or overheating of the drills. Incremental drilling was then used successfully. It allowed the fracture of the chip and an intensive cooling of the material between the different steps.

Coolant-through high penetration carbide drills (with coolant ducts) seems to be the best choice for cooling improvement (twin bar).

For hole diameters larger than 1", a one shot drilling on the 0.7" thick plates could be done using an iscar or twin bar drills that gave the best results when using low parameters (low speed and feed). No wear was observed on these drills after drilling ten holes. For these larger hole diameters, the incremental drilling did not work since it has caused drill's wear or fracture.

Drilling parameters were much lower than the 300M and AerMet 100 parameters (Table 16).

Table 16   Drilling of 300M and Aermet 100

Operation	Speed (SFM)	Feed rate (mils/rev)	Drilling sequence
Drilling	250	5	one shot
Tapping	50	-	-


(a) long chip (unacceptable


(b) fractioned chip (good chips)

Figure 50 Drilling chips

Figure 50 shows an example of collected chips after drilling. Drill wear was observed frequently when the chips were not fractioned. The drilling was facilitated when the fractioned chips were very fine.

Tapping

Table 17 reports the tapping parameters used to tap different hole dimensions to thread sizes.

Table 17   Annealed Ferrium S53 optimum tapping parameters

P/N	S/N	Hole dimension (inch)	Tap dimension	Tap characteristics	Tapping speed RPM (SFM)	Feed rate (mils/rev)	Depth tapped (inch)
SK-0116	H001	0.216	¼-28	H.S.S.	100 (6.5)	3.57	0.2
		0.216	¼-28	Carbide	300 (19.6)	10.71	0.3
		0.738	¾-16	H.S.S. Spiral flutes	100	6.25	0.25
		0.738	¾-16	H.S.S. Type 4 Spiral flutes	100	6.25	0.4

		0.738	¾-16	Cobalt alloyed H.S.S. Type 4 Spiral flutes	100 (19.6)	6.25	0.75

Good tap | Tap's wear | Broken tap

As for drilling, only carbide and cobalt High Speed Steels gave the better results for tapping. Tapping speed were very low compared with the speed used for 300M and Aermet 100 (Table 12)

Conclusions and Recommendations

Turning
For interrupted and continuous turning, the following comments can be made:

- Turning annealed Ferrium S53 at 38 to 40 HRC is harder than turning 300M and AerMet 100 in the normalized and annealed condition.
- Interrupted turning was less difficult than turning the rounded bars. The inserts used for the interrupted turning were not adequate for the continuous turning.
- The inserts usually used for AerMet 100 did not perform well.
- The annealed and re-annealed Ferrium S53 hardens during turning inducing an unusual wear of the inserts.
- Turning the annealed 23" long bars with the inserts that perform well for shorter bars (7.75") was not successful.
- The coolant flow is very important, any lack or flow decrease leads to a very rapid insert wear due to a built up edge condition (welding of the chip and the insert).
- Lower speed is needed to have a reasonable inserts wear.
- A very important deformation (TIR) was noted on a 7.75" bar (0.040"), even with a low speed, which is not acceptable.
- Feed is found to be the most critical parameter to decrease the deformation (TIR) of the bars. Feeds as low as 0.006" are needed (compared with 0.012" for Aermet 100).
- Very good finishes after turning could be reached (34 Ra) with the most performing inserts.

Drilling and tapping
Again, it was noted that the control of the heating of the material during the cutting for drilling and tapping is very critical.

The speeds used for drilling and tapping are half the one used for 300M at the normalized and tempered condition. Higher speeds resulted in non-controlled chip sizes responsible of drill and/or hole damage. Feeds are equivalent to the one used for 300M.

- For small holes incremental drilling shall be done using coolant-through high penetration carbide drills
- For larger holes the one-shot drilling was possible providing the use of low feed rate and coolant-through drills

2.3.2 Heat Treatment

Executive Summary/Preferred Heat Treatment

S53 was designed as a secondary hardened martensitic steel. Care was taken in this design to achieve a robust heat treatment response following industry standard procedures. QuesTek did not want to create a material that relied on exotic heat treatments to achieve the mechanical properties needed for optimal performance. Experiments have shown this design work was successful, as S53 follows industry standard heating processes to reach its fully hardened state. The procedure for forging and annealed has already been discussed, see Section 1.2.2, hence this section will focus on the heat-treating of rough machined parts. The preferred heat-treating of a rough-machined component, as discussed in detail below, is as follows:

- Solution treat at 1922°F (1050°C) for 70 mins
- Gas or oil quench to room temperature (low pressure gas quench is fine)
- Immerse in liquid nitrogen (or subject to temperature equivalent) for 60 minutes, air warm
- Temper at 900°F (482°C) in two stages:
    - Temper 900°F (482°C) for eight hours, gas or oil quench
    - Immerse in liquid nitrogen (or subject to temperature equivalent) for 60 minutes, air warm
    - Temper 900°F (482°C) for eight hours, air cool

Solution Treatment

The solution treatment, or austenitization treatment, is needed to dissolve alloy carbides and transform the material entirely to the austenite phase. The material is then rapidly quenched to room temperature using gas or oil to achieve a martensitic transformation. Consider again the following diagram, first presented in Section 1.2.2.

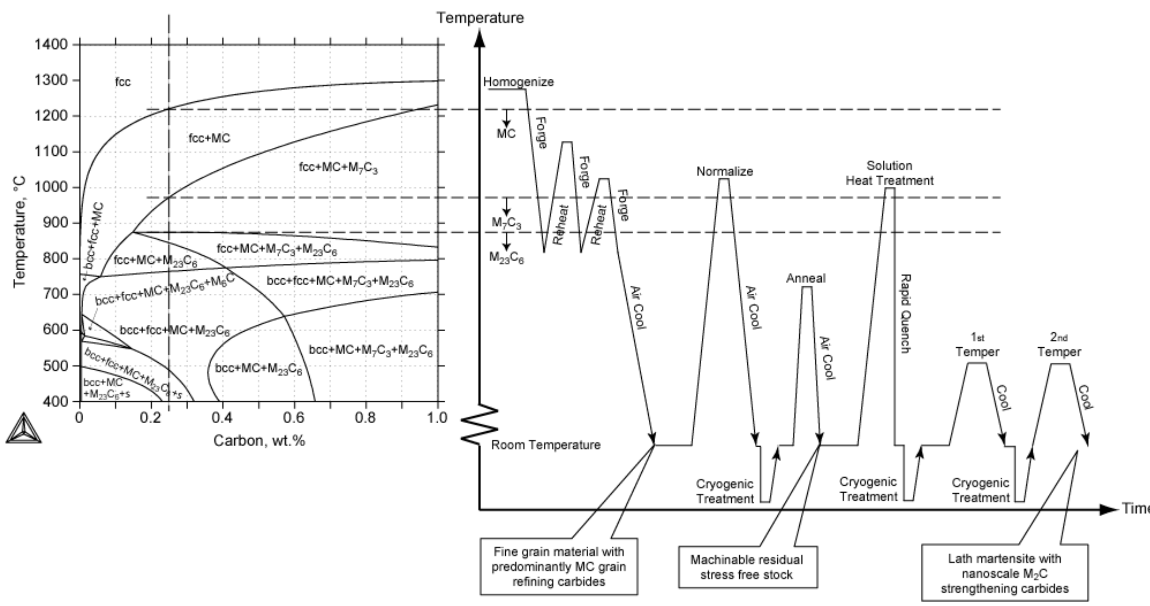


Figure 51 Typical processing path of S53 alloys

The solution heat treatment step dissolves all alloy carbides with the exception of the grain refining dispersion of MC carbides. QuesTek's *Computational Material Dynamics*, or CMD, software is used to predict the carbide solvus temperatures, and hence the appropriate solution temperature. The left side of Figure 51 shows thermodynamic calculations for the stability of the $M_{23}C_6$ and M_7C_3 carbides, and predicts a solution treatment temperature of just under 1000°C. Experiments have shown that the solution temperature needed to dissolve alloy carbides is generally 25°-50°C higher than the thermodynamic prediction, which is calculating an equilibrium condition. The solution treatment's duration is limited by grain growth, which occurs readily at these temperatures. Manufacturing lead times and costs are also reduced as the solution treatment time is shortened. Conversely, the solution treatment time must be long enough for practical use on large parts, as the intended landing gear application involves relatively large components. Hence the ideal solution heat treatment temperature is one that is high enough the alloy carbides dissolve within an hour, but low enough to avoid rapid grain growth. QuesTek has used small pucks of material solution treated at various temperatures, quenched, cyro-treated, and stage I tempered to evaluate the solution heat treatment response of all S53 prototype alloys. The stage I temper is simply heating the steel to 200°C for 1 hour. It was chosen in favor of secondary hardening to isolate the effect of the solution treatment step, avoiding the correlated effects of solution treatment and tempering. When evaluating the hardness at various solution treatment temperatures, one is essentially looking for the peak hardness condition. This is where all possible carbon has been put into solution during austenization and is contributing to strengthening in the quenched microstructure, but before grain growth starts to decrease alloy strength.

A series of representative solution treatment temperature curves are presented below to illustrate the behavior observed over the spectrum of alloys studied.

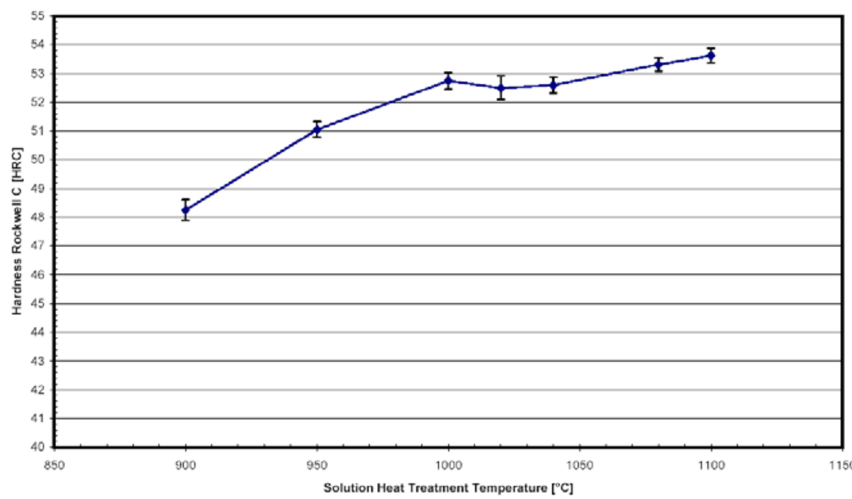


Figure 52 Solution Treatment response of S53-2C, 70 mins at temperature, oil quench, 1 hr LN_2, 200°C 1hr

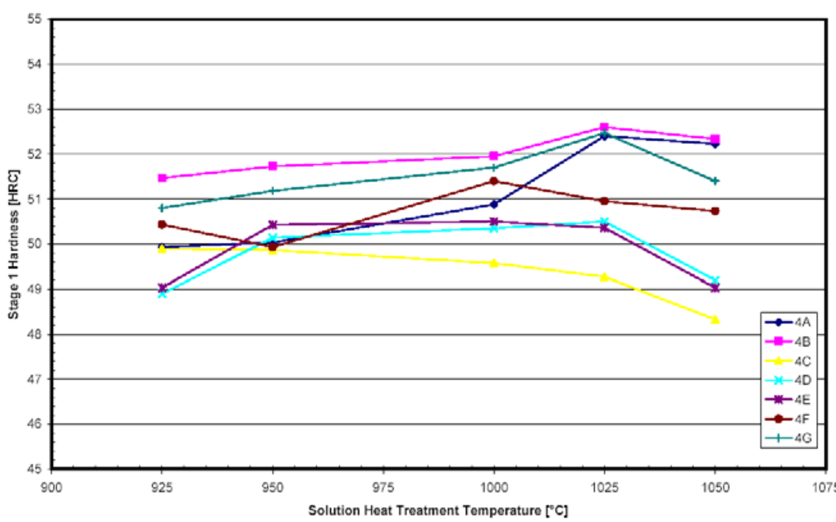


Figure 53 Solution Treatment response of S53-4 Series alloys, 70 mins at temperature, oil quench, 1 hr LN_2, 200°C 1hr

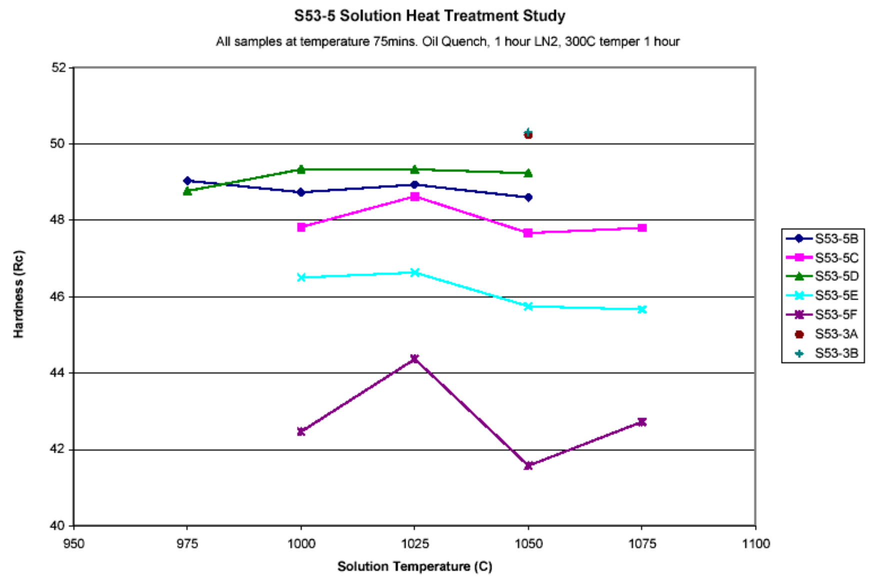


Figure 54 Solution Treatment response of S53-5 series alloys, 75 mins at temperature, oil quench, 1 hr LN_2, 300°C 1 hr

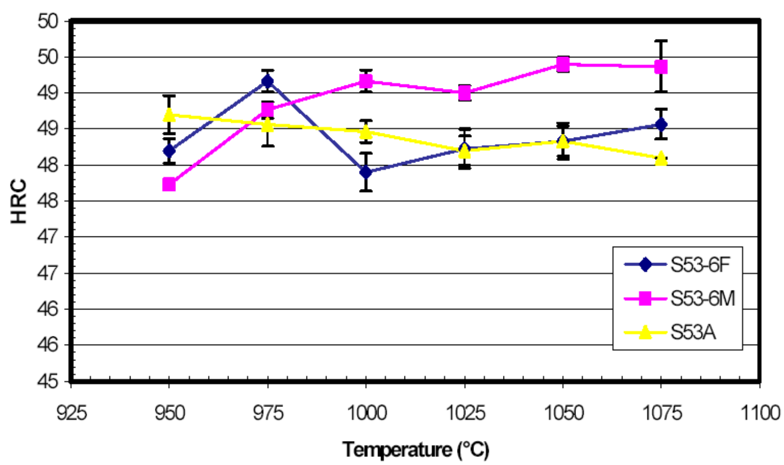


Figure 55 Solution Treatment response of S53-6 series alloys, 70 mins at temperature, oil quench, 1 hr LN_2, 200°C 1 hr

A solution heat treatment temperature of 1025°C was chosen for most alloys shown above, including the S53-2 series, S53-3 series, S53-4 series, and S53-5 series alloys. During testing of the S53-6 series alloys a solution treatment temperature of 1050°C was used on all three alloys. The primary reason for this change was that the six series alloys were designed with higher solution temperatures, allowing for the addition of more Mo, Cr, and/or W. Another reason for the change was S53A was produced in a large-scale 3000lb melt. It appears the relatively larger solidification structure that occurs in a 17" ingot creates inhomogeneities that are better dissolved moving to higher solution treatment temperatures. The switch to 1050°C solution treatment temperatures has not adversely affected grain size or mechanical properties and is still well within the range of commercial heat treaters' capabilities.

Vacuum heat-treating is recommended on components were little or no material is removed in the process of final machining. S53, as is all stainless steel, is prone to oxidation and decarburization if heat-treated in air. If sufficient stock is removed after heat-treatment, the solution treatment step may be completed in air, however, the exact amount of oxidation and decarburization may vary from part to part and amongst production facilities. Vacuum solution treatment followed by gas quenching is recommended.

S53 has high hardenability and generally shows a strong transformation to martensite upon quenching. High hardenability means that S53 may be quenched at slower rates that other common stainless steel, creating less distortion. Although a fast gas quench is preferred, on distortion critical parts a 2-3 bar gas quench should be sufficient to achieve the transformation. Future work is needed to fully understand quench rate sensitivity.

To measure the temperature at which prototypes transform to martensite, or martensite start temperature (M_s), dilatometry experiments were performed. Dilatometry involves precise measurement of expansion and contraction in a small sample. By measuring the length of a given sample and determining the temperature at which a shape change occurs, one can accurately determine the temperature at which the material transforms to martensite on cooling. M_s was measured using dilatometry on all alloy prototypes, the results are shown in Table 18.

Table 18 Measured Ms on all prototype alloys

Prototype	Ms (°C)
S53-1	175
S53-2A	265
S53-2B	225
S53-2C	253
S53-3A	250
S53-3B	240
S53-4A	275
S53-4B	285
S53-4C	310
S53-4D	300
S53-4E	300
S53-4F	300
S53-4G	320
S53-5B	200
S53-5C	180
S53-5D	240
S53-5E	165
S53-5F	<25
S53-A	85
S53-6F	72
S53-6M	129

A key number from Table 18 is 72°C, the Ms temperature for S53-6F. As this is the preferred prototype, it is of interest to note that the martensitic transformation does not begin until 72°C. For this reason, QuesTek requires that within one hour of quenching parts should be cyro-treated in liquid nitrogen (or temperatures equivalent) to ensure a complete martensitic transformation. Tensile tests have shown that the yield strength drops dramatically, as much as 50ksi, if the part is not subjected to a cyro-treatment. This is clearly a result of retained austenite, which may be rather high if the parts are not cooled below room temperature. QuesTek has run numerous tests at various sub-zero temperatures and cooled at various rates to determine if there is an optimal cyro-treatment beyond simply submerging the part in liquid nitrogen for one hour. These studies were performed on the most promising prototype, S53-6F, and are presented in Table 19 below. In each case the solution treatment was 1050°C 70 minutes with an oil quench, and the temper was 16 hours at 482°C broken into two 8 hour treatments with cyro-exposure in between. The samples were air warmed after the solution treatment cyro step (unless otherwise noted) and water warmed after the cyro step during tempering. The samples were air cooled after the second temper. Each data point in Table 2 represents the average of 2 samples unless otherwise noted.

Table 19 Various Cyro-treatments studied on S53-6F

YS (ksi)	UTS (ksi)	Cryo-treat after solution treat	Cryo-treat during tempering
215	289.5	ln2 1 hr	ln2 1 hr
225	288.8	ln2 3 hrs	ln2 1 hr
202.8	286.8	dry ice/methanol 1 hr (average of 4 samples)	dry ice/methanol 1 hr
209.8	288.3	dry ice/methanol 3 hrs (average of 6 samples)	dry ice/methanol 1 hr
188.5	284.5	dry ice/methanol 8 hrs	dry ice/methanol 1 hr
187.5	287.5	ice water 1 hr, dry ice/methanol 1 hr, ln2 1 hr	ln2 1 hr
218.5	289	ln2 3 hrs, water warm	ln2 1 hr
208	288	ln2 3 hrs	ln2 1 hr
191	286	ln2 3 hrs, evaporate off the ln2	ln2 1 hr
189.5	285	ln2 1 hr, dry ice/methanol 1 hr, ice water 1 hr	ln2 1 hr
175.5	283	ln2 slow ramp down and back up, 40 hrs	ln2 1 hr

Future work will continue to explore the effects of various cyro-treatments on S53, however it is certain that some type of cyro-treatment is needed. QuesTek has found consistent results when simple cyro-treatments are applied, and is confident S53 will have an easy to follow specification that results in good mechanical properties.

In summary, the solution treatment of S53 follows industry standard processes, and when optimized is expected to have a robust response over a broad range of component size and geometry.

Tempering

S53 is a secondary hardened martensitic steel. The section above "Solution Treatment" describes how the martensitic matrix is achieved. The second important piece is tempering, the heat treatment that precipitates alloy carbides to provide strength. S53 was designed to use a fine dispersion of M_2C carbides to provide resistance to dislocation motion and reach its strength requirements. These carbides were designed to be small (~3-5nm diameter) and are assumed to precipitate mostly from para-equilibrium cementite. As the material is heated from room temperature, cementite starts to form around 300°C. Even with rapid heating, a significant amount of cementite is formed before the alloy carbides start to precipitate. It should be noted that the tempering temperatures used on S53 are significantly higher than those used on many other commercial steels, including 300M. Whereas 300M requires a two-stage temper at 300°C, S53 utilizes a two stage temper at 482°C. This elevated secondary hardening temperature helps to alleviate concerns about grinding damage often seen in 300M.

Selecting the time and temperature combination used to temper S53 relied on several factors. First, the alloy chemistry was specifically designed (see Section 1.2.2.) to have a high driving force for the formation of the M_2C strengthening phase. Second, QuesTek designed compositions that avoided the formation of other carbide or intermetallic phases and limited the amount of residual cementite. Third, QuesTek studied the precipitation kinetics of the M_2C strengthening dispersion to ensure the alloy could meet its strength goals within a reasonable tempering time. Reasonable tempering times were taken as: no treatment shorter than 1 hour and no treatment longer than 24 hours. Given these constraints, QuesTek designed a secondary hardening response that performs well, reaching the desired strength level in a reasonable amount of time and avoiding other phases in the process.

To verify the microstructural features predicted, QuesTek used 3D Atom Probe Microscopy to study an early prototype and validate the predicted carbide size and composition. Essential to our alloy design is the achievement of efficient strengthening while maintaining corrosion resistance and effective hydrogen trapping for stress-corrosion resistance. All of these attributes are promoted by refinement of the strengthening M_2C carbide particle size to an optimal 3 nm size at the completion of precipitation. Atomic-scale imaging of such a carbide in the optimally heat treated S53-2C alloy using 3D Atom-Probe microanalysis (Figure 56) verifies that the designed size and particle composition have in fact been achieved.

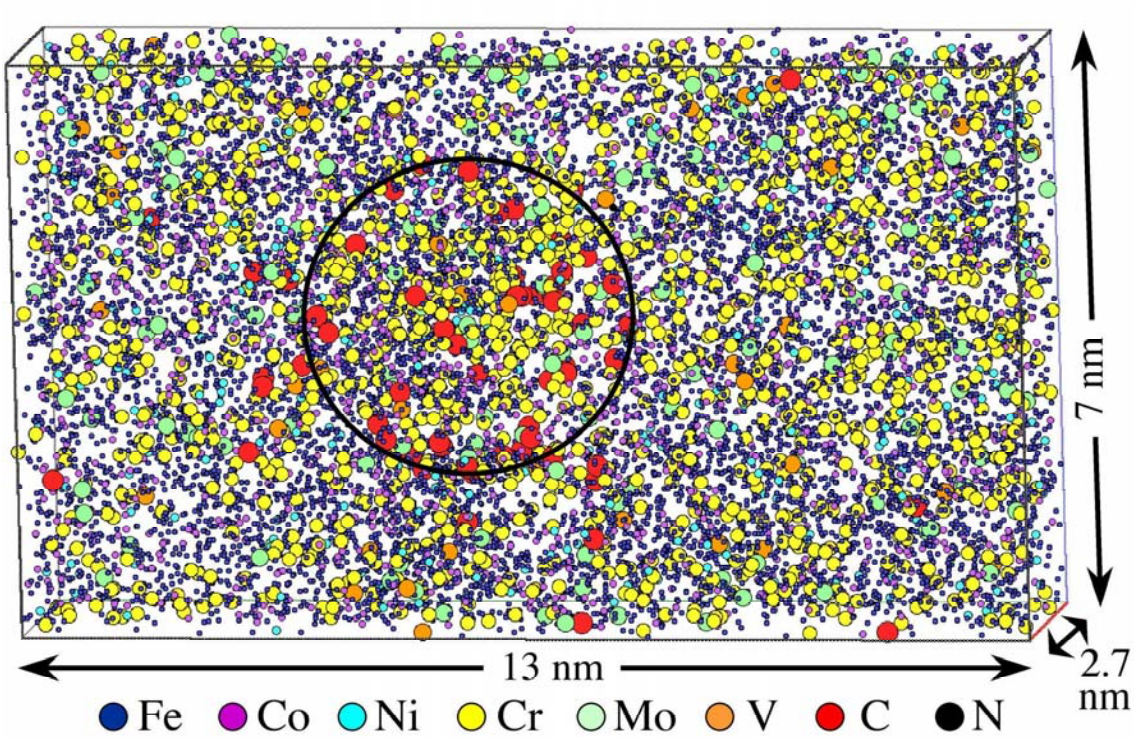


Figure 56 3D Atom-Probe image of M2C precipitate in S53-2C (Courtesy D. Isheim; NU FastScience Program).

Early in the program, QuesTek determined that multi-step treatments might boost mechanical properties, specifically yield strength, by reducing the amount of austenite in the steel. Multi-step tempering studies were conducted on alloys S53-2A (heat WK07) and S53-2C (heat WJ78) to assess the role of retained austenite in tensile properties. Test results are given in Table 20 and Table 21 below. These results show that, for S53-2A, tensile properties are for the most part independent of thermal processing, although some variation in yield strength was found, suggesting a risk of retained austenite. For S53-2C, the fact that yield strength increases after double and triple tempering indicates a strong likelihood of retained austenite when S53-2C is single-step tempered. This increased risk for S53-2C may correspond to its lower M_S temperature.

Table 20 Tensile properties of S53-2A with various temper treatments.

Sample #	YS [ksi]	UTS [ksi]	Elongation [%]	R.A .[%]	Solution Heat Treatment at 1025ºC	Temper Treatment at 496ºC
T23	194	262	17	66	SHT+OQ	12h
T24	194	262	16	62	SHT+OQ	12h
T25	217	264	17	62	SHT+OQ+LN2	12h
T26	199	263	16	66	SHT+OQ+LN2	12h
T27	203	261	17	65	SHT+OQ+LN2	6h+OQ+LN2+6h
T28	229	261	16	65	SHT+OQ+LN2	6h+OQ+LN2+6h
T29	203	261	15	64	SHT+OQ+LN2	4h+OQ+LN2+4h+ +OQ+LN2+4h
T30	203	263	15	64	SHT+OQ+LN2	4h+OQ+LN2+4h+ +OQ+LN2+4h

Table 21 Tensile properties of S53-2C with various temper treatments.

Sample #	YS [ksi]	UTS [ksi]	Elongation [%]	R.A. [%]	Solution Heat Treatment at 1025°C	Temper Treatment at 496°C
T11	149	312	11	28	SHT+OQ	12h
T12	173	314	6	7	SHT+OQ	12h
T13	209	292	17	66	SHT+OQ+LN2	12h
T14	216	294	16	60	SHT+OQ+LN2	12h
T15	225	295	13	42	SHT+OQ+LN2	6h+OQ+LN2+6h
T16	228	294	17	59	SHT+OQ+LN2	6h+OQ+LN2+6h
T17	223	295	18	64	SHT+OQ+LN2	4h+OQ+LN2+4h+ +OQ+LN2+4h
T18	223	293	17	63	SHT+OQ+LN2	4h+OQ+LN2+4h+ +OQ+LN2+4h

Based on the success in the early prototypes for increasing yield strength, double step tempers were used almost exclusively throughout the characterization of the 4-series, 5-series, and 6-series alloys. Triple step tempers were studied in one material, however this process was not shown to have any benefit over the double temper.

In addition to designing the tempering response of each alloy, QuesTek performed tempering studies on all alloy prototypes to experimentally determine the tempering kinetics and refine our models. Some prototypes were studied in more detail than others, including different temperatures and longer times, but all studies involved the same experimental procedure. Small pucks were solution treated in batches and then tempered accordingly to gather data. The pucks were then ground to remove the oxide and de-carb layers and tested using Rockwell C hardness indents. The Figures below show representative tempering data obtained throughout the SERDP program on various different prototypes. Special attention is warranted on the S53-6 series plot, as S53-6F has been chosen as the preferred alloy.

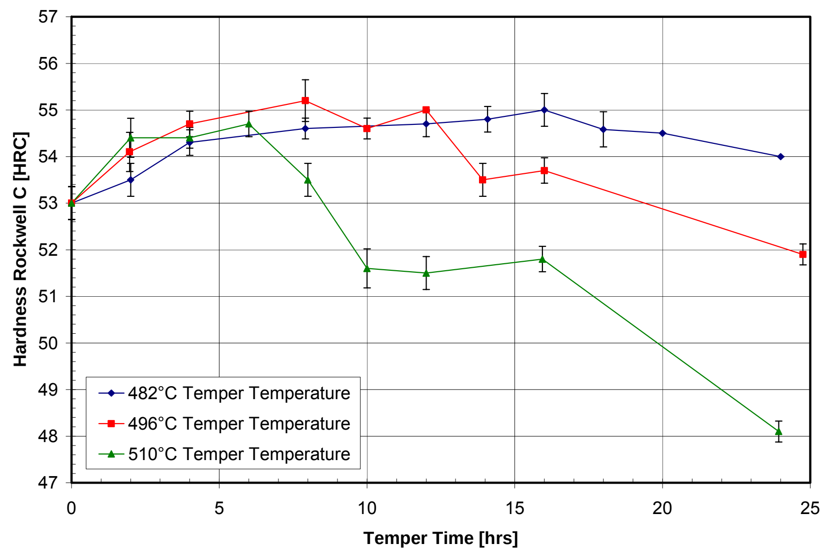


Figure 57 Tempering curve on S53-2C, Solution treated 1050°C 75 min, Oil quench, 1 hr LN_2

Of the tempering curves presented (Figure 57 through Figure 64) special attention is warranted on Figure 64, as it shows the tempering kinetics of the preferred prototype, S53-6F. One notices that at higher tempering temperatures, for instance 524°C, the material quickly loses strength with time. This is due to coarsening of the carbide dispersion beyond its optimal particle size and may likely also include the precipitation of austenite. As the tempering temperature is lowered, the peak hardness achieved increases. This is a result of increased driving force for M_2C formation at lower temperatures. The higher driving force creates a large dispersion of fine particles, leading to higher strength. Unfortunately, the time required to reach peak hardness dramatically increases at lower temperature, illustrated by the 48 hours needed to reach peak hardness at 468°C. Based on this tempering data, and knowing that two-stage tempers boost yield strength, QuesTek selected a two-stage 16 hour temper (8 hours plus 8 hours) at 482°C for the optimal tempering condition. Most mechanical property test specimens were then tempered to this condition.

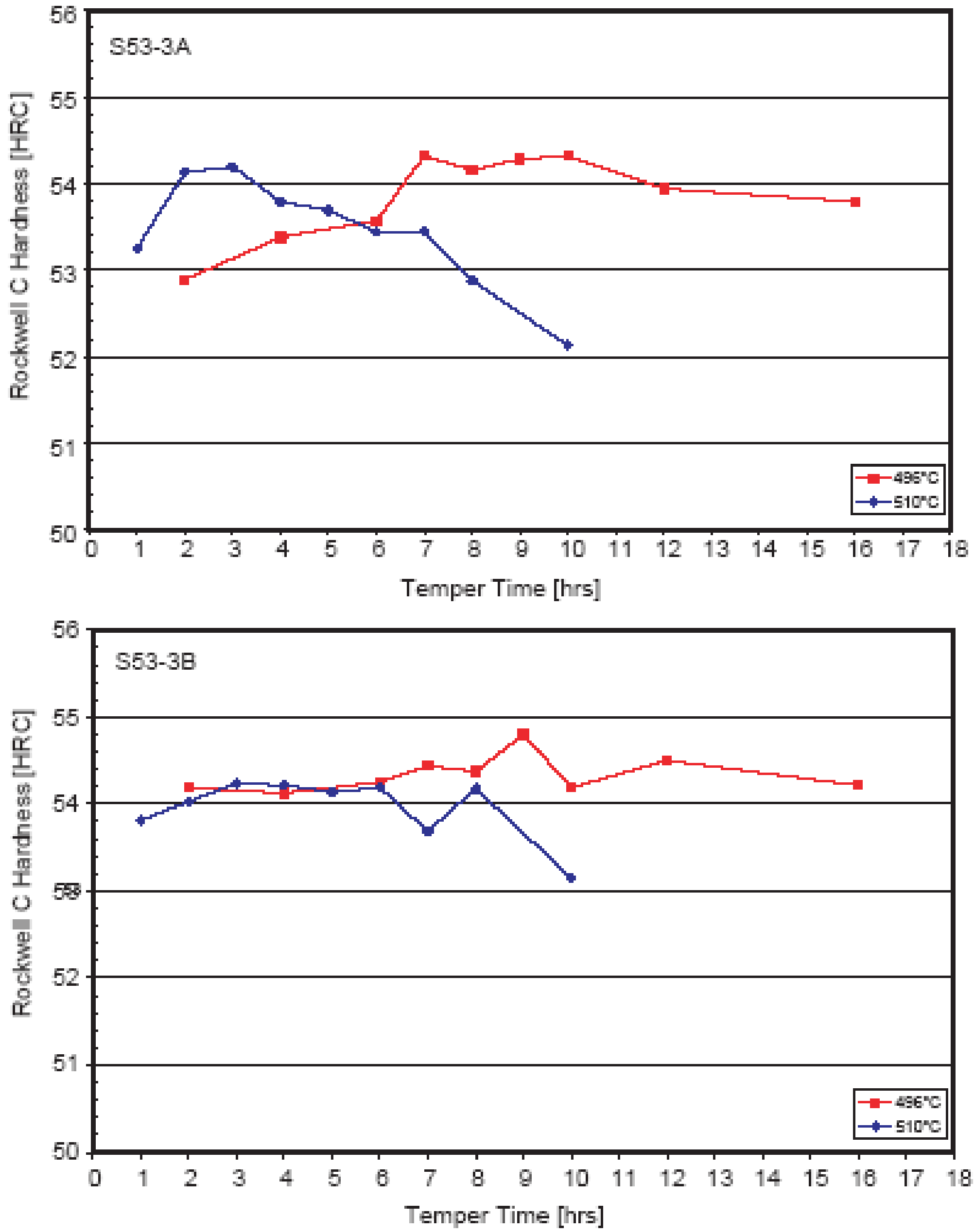
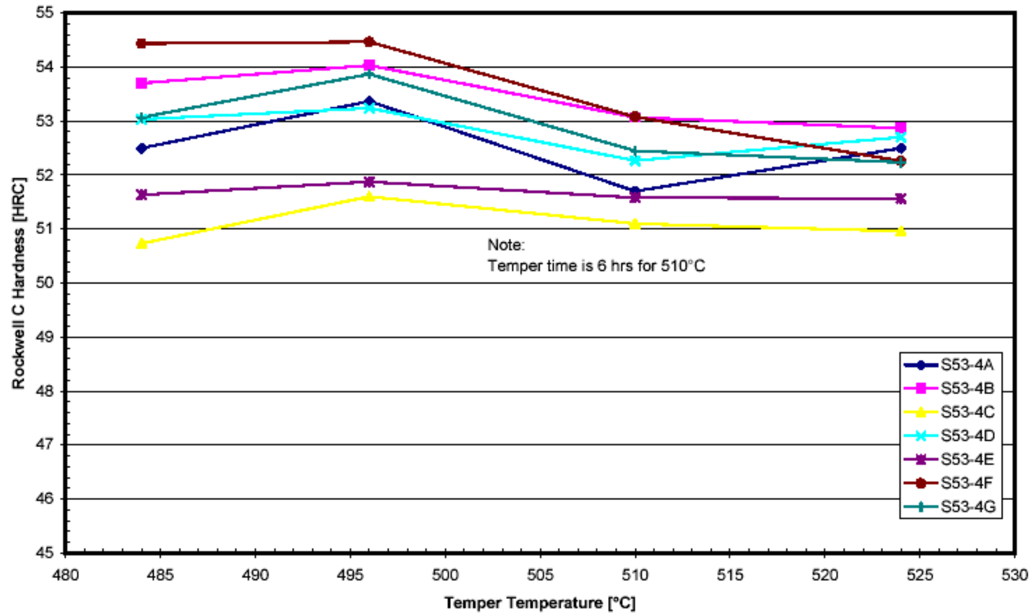
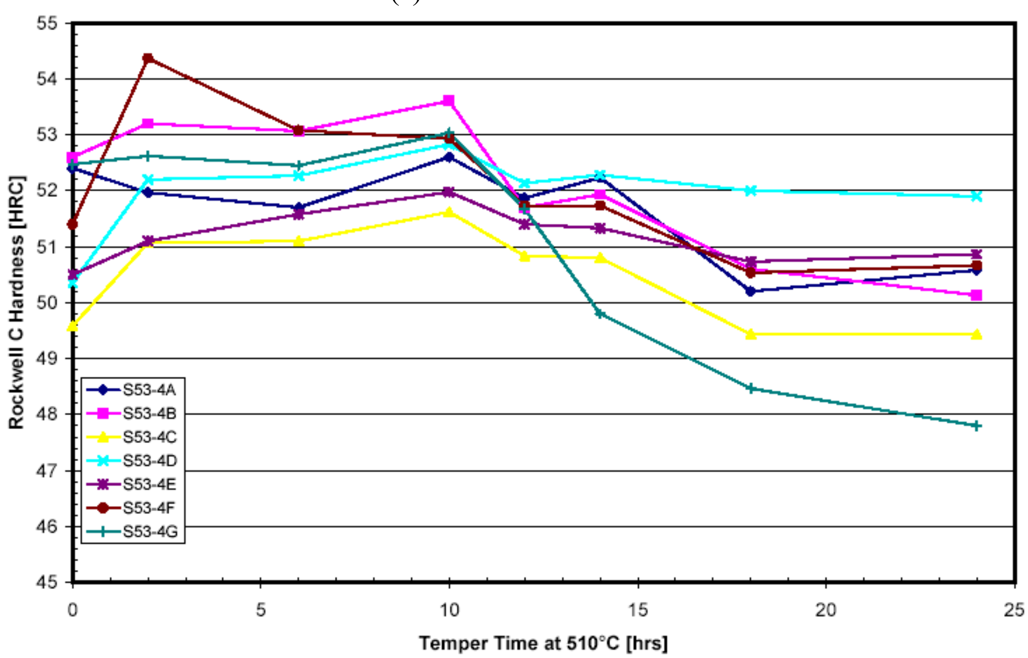


Figure 58 S53-3A and –3B Tempering Curves, Solution treated 1025°C 75 mins, Oil quench, 1 hr LN_2



(a) Isochronal 5 hours



(b) Isochronal 10 hours

Figure 59 Temper Curves at 5 hours (a) and 10 hours (b) for S53-4 Series alloys Solution treat at 1000°C (for –4C, -4D, -4E, and –4F alloys) or 1025 °C (for –4A, -4B, and –4G alloys) for 75 minutes, oil quench, 1 hr LN_2

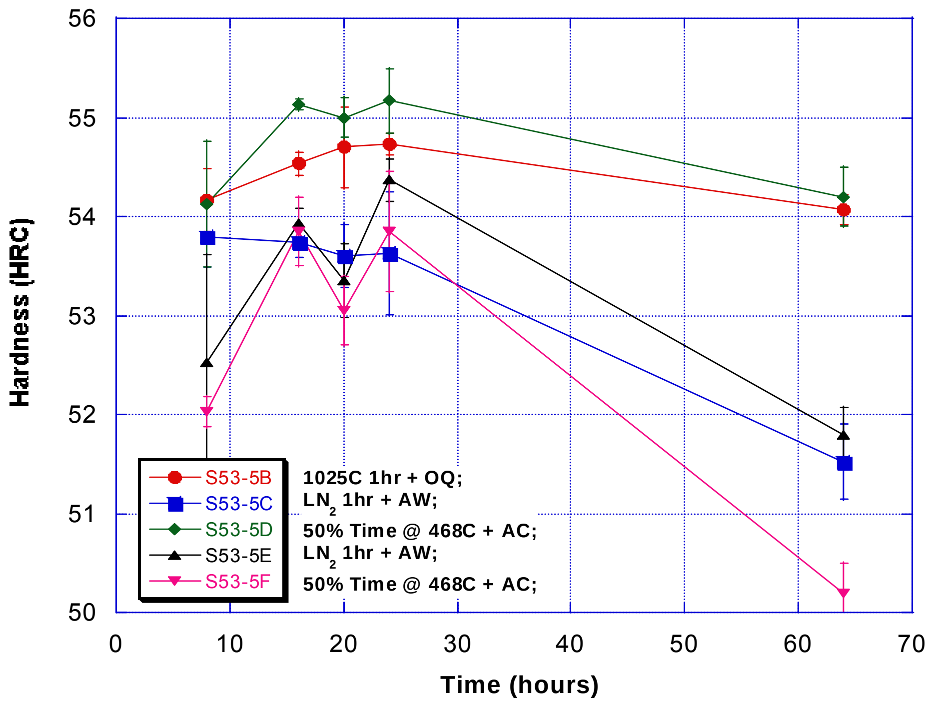


Figure 60 S53-5 Series tempering data, all treatments were double tempers, with time representing the total tempering time

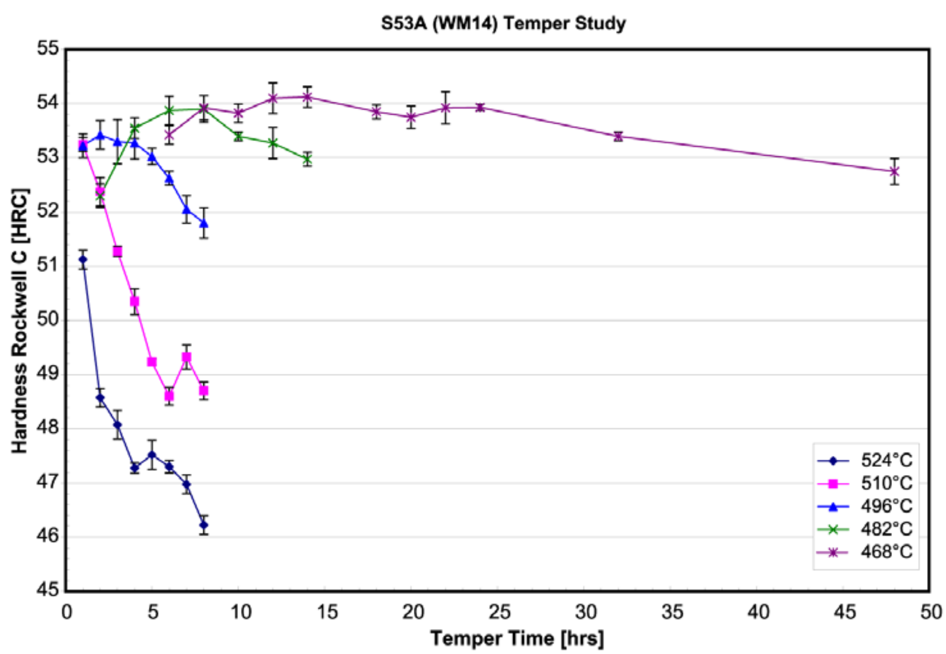


Figure 61 Rockwell C Hardness (HRC) as a function of tempering temperature and tempering time for S53A, heat WM14 (300 lbs), solution treated 1025°C, oil quench, 1 hr LN_2

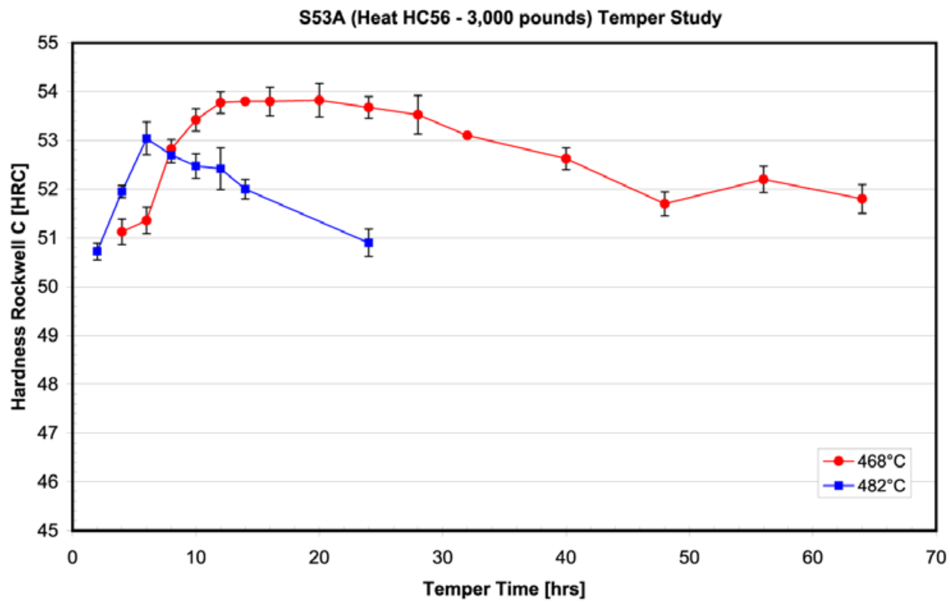


Figure 62 Rockwell C Hardness (HRC) as a function of tempering temperature and tempering time for S53A, heat HC56 (3,000lbs), solution treated 1050°C, oil quench, 1 hr LN_2

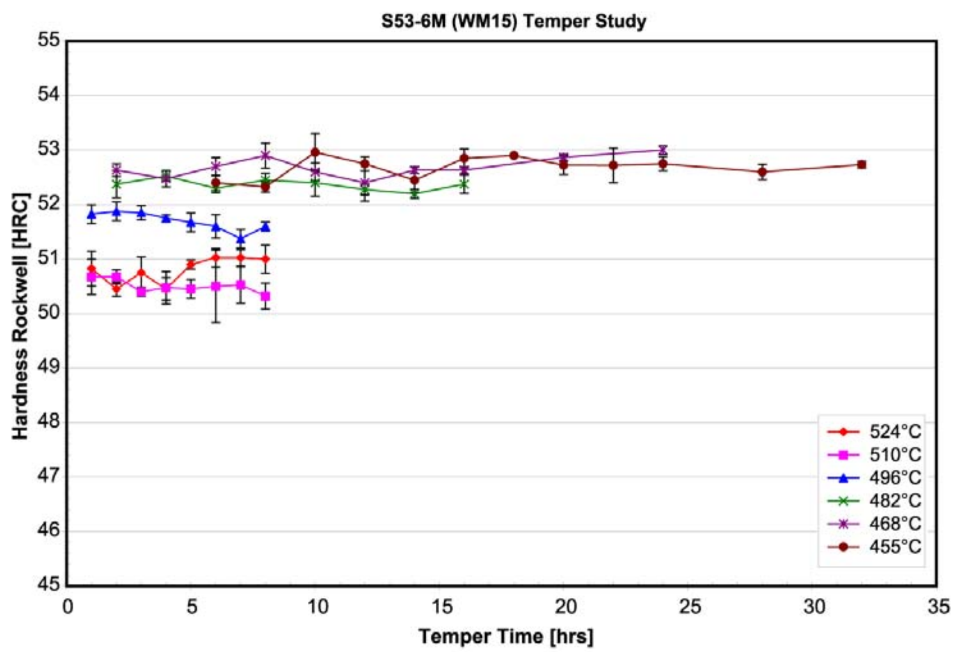


Figure 63 Rockwell C Hardness (HRC) as a function of tempering temperature and tempering time for S53-6M, solution treated 1050°C, oil quench, 1 hr LN_2

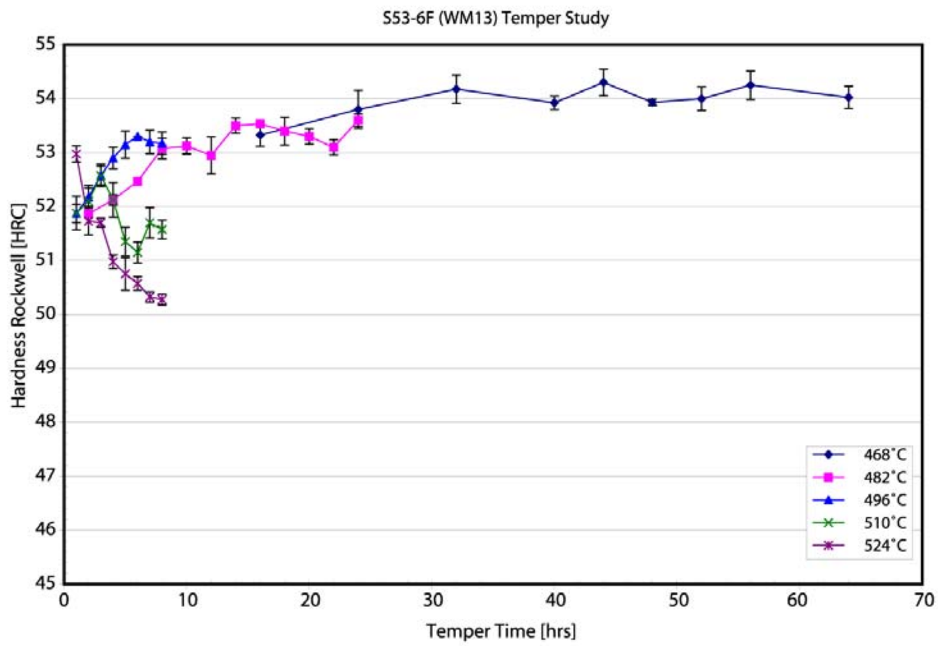


Figure 64 Rockwell C Hardness (HRC) as a function of tempering temperature and tempering time for S53-6F, solution treated 1050°C, oil quench, 1 hr LN2

Part of the characterization of S53A and S53-6F included Transmission Electron Microscopy (TEM) investigation at the sub-micron level to study cementite particles. Samples were polished to a mirror finish, etched with an appropriate solution, and coated with a thin layer of carbon. This carbon layer was then carefully removed from the substrate creating an extraction with a thin layer of the alloy. These extractions provided evidence of microstructural differences between the two materials.

Figure 65 is a representative micrograph taken from an extraction of S53-6F. Notice the plate shaped particles, some of which are highlighted with arrows for clarity. EDS and diffraction patterns confirm that this phase is cementite. Thermodynamic calculations predict that a small amount of cementite, 0.013 volume fraction, will be stable in S53-6F.

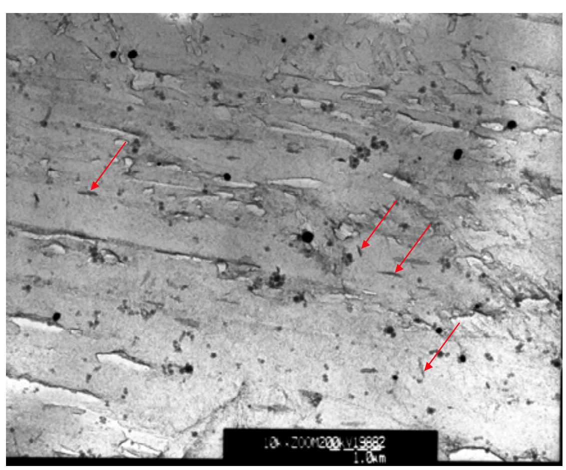


Figure 65 Representative TEM micrograph from S53-6F extraction replica

The thermodynamic predictions also indicate that cementite is more stable in S53A and predict a volume fraction of 0.02 in that alloy. Figure 66 is a representative micrograph taken from an extraction of S53A showing a similar overall microstructure to S53-6F. However there is clearly a higher volume fraction of cementite particles in S53A, as seen when comparing Figure 66 to Figure 65.

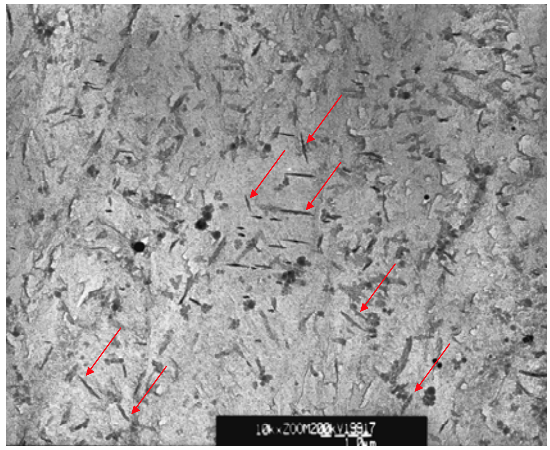


Figure 66 Representative TEM micrograph from S53A extraction replica

Undissolved cementite is detrimental to the performance of these stainless steels in a number of ways, and hence our designs attempt to limit or eliminate its presence. One well-described effect of undissolved cementite is tying up carbon that could otherwise be used for carbide strengthening. Aside from retaining valuable carbon, cementite is also suspected of limiting fracture toughness, likely because of its morphology. The Charpy V-notch Impact Energy tests previously described show a lower upper shelf impact energy for S53A as compared to S53-6F. Undissolved cementite may be limiting the fracture toughness of S53, creating another microstructural advantage for the preferred prototype, S53-6F.

Summary

To summarize, the preferred heat treatment for a rough-machined component, as discussed in detail above, is as follows:

- Solution treat at 1922°F (1050°C) for 70 mins
- Gas or oil quench to room temperature (low pressure gas quench is fine)
- Immerse in liquid nitrogen (or subject to temperature equivalent) for 60 minutes, air warm
- Temper at 900°F (482°C) in two stages:
    - Temper 900°F (482°C) for eight hours, gas or oil quench
    - Immerse in liquid nitrogen (or subject to temperature equivalent) for 60 minutes, air warm
    - Temper 900°F (482°C) for eight hours, air cool

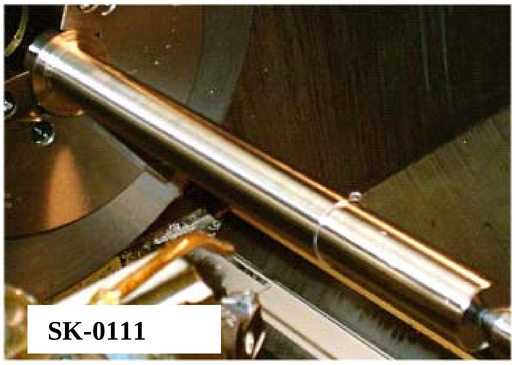
2.3.3 Finishing/Grinding

Specimen Preperation and Test Matrix

The bars turned as per the first part of this project were hardened and used for the turning and threading trials. The same parts used for the drilling in the annealed condition (plate) were used for the drilling in the hardened condition. Table 22 lists the samples tested.

Table 22 Specimens used for the tests

P/N – Dia (inch)	Number of parts	Turning	Threading	Drilling
SK-0110 – 1.50	6	X (parts prepared for the grinding trials)		
SK-0111 – 1.75	1	X		
SK-0112 – 3.00	5	X		
SK-0113 – 3.00	1	X		
SK-0114	2, three diam		X	
SK-0115 – 3.80	2	X		
SK-0117 – plate	2			X



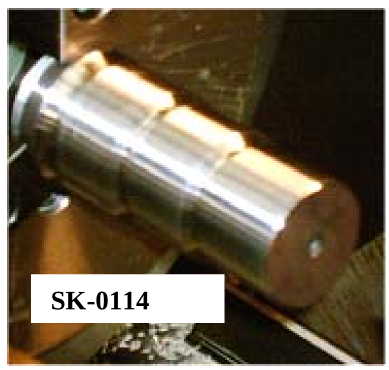


Figure 67 Specimens used for the different tests

At the end of the machining tests on the specimens in the annealed condition, these same specimens were hardened to 53-55 HRC as following:

- Solution heat treatment at 1000°C/1832°F (in vacuum)

- Cooling with a nitrogen gas ingress at an air-cooling rate. Sub-room temperature cooling to ensure full transformation of austenite to martensite.
- Age-hardening between 470°C (878°F) and 482°C (925°F), for at least 10 hours duration

Tests Conditions

Turning

The machine used for turning was a Dainichi MX95-2000, 50/60 horsepower CNC lathe, capable of a maximum spindle of 1200 RPM. Table 23 and Table 24 give the parameters usually used for the machining of 300M and AerMet100 steels.

Table 23 Aermet 100 turning parameters after quenching and tempering (53-55HRC)

Operation	Inserts grade	Cutting speed (SFM)	Cutting feed (inch/rev)	Depth of cut (inch)
Turning	Carbide	160F	0.010F	0.010F
Turning	Ceramic	N/A	N/A	N/A

F: Finishing, N/A: Not Available

Table 24 300M turning parameters after quenching and tempering (53-55HRC)

Operation	Inserts grade	Cutting speed (SFM)	Cutting feed (inch/rev)	Depth of cut (inch)
Turning	Carbide	160R/180F	0.010R/0.008F	0.075R/0.030F
Turning	Ceramic	550	0.006	0.030

R: Roughing, F: Finishing

The cutting tool characteristics (inserts grade and identification), the turning speed, the feed and depth of cut for each trial were recorded. Samples from the chips were also collected to account for the performance of the cutting tools and the machining parameters.

All turning tools tested were indexable inserts. According to ANSI B212.4-2002, indexable inserts characteristics are determined as follow:

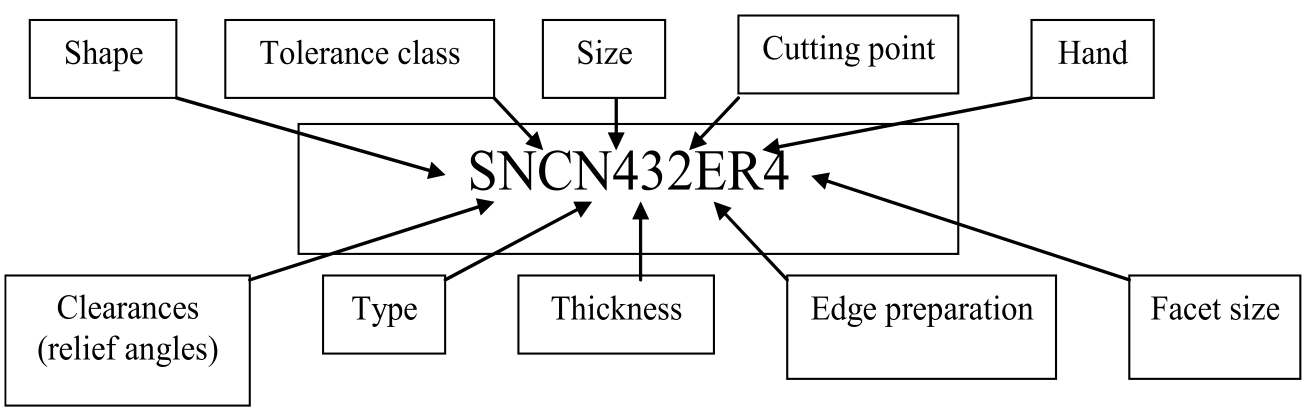


Figure 68 Characteristics of indexable inserts per ANSI B212.4-2002.

Inspection after turning

The surface finish of the parts was measured at the end of the turning.

For some parts, a Barkhausen Noise inspection was done to account for any detrimental effect on the condition of the steel due to inappropriate turning conditions. The inspection was done per HPS-119 (Ref.3.2.2) using automated installation. The acceptance criteria when using the data analysis provided by the View Scan software, is determined by the calculation of the ratio $\frac{MP_{\max}}{MP_{avg}}$. MP is the Magnetic Parameter provided by the Barkhausen signal.

When $\frac{MP_{\max}}{MP_{avg}} > 1.2$ the noise is too high, part is not acceptable. When $\frac{MP_{\max}}{MP_{avg}} \leq 1.2$ the part is acceptable.

Drilling and threading

Drilling and boring operations were conducted on a single OKK vertical milling machine. The model used was a MCV820 with a 20/25 horsepower unit and a spindle range of 25-3500 RPM.

The starting point of these operations was the parameters used for 300M drilling/threading. The successive operations depended on the outcomes of the previous setting.

Table 25 Drilling parameters

P/N	Operation	Diameter/depth (inch)	Dimension (inch)
SK-0117	Drill holes through thickness	0.25	0.7 x 6 x24 plate
SK-0117	Drill holes through thickness	0.75	0.7 x 6 x24 plate

To optimize the operations, the appropriate drilling tool was first selected depending on the hole diameter, as well as the hole's depth. Then, the speed and the feed rate were selected based on 300M machining parameters and changed depending on the material behavior and tool wear. Thus, a variety of holes and threads were done using different parameters as shown in Table 25 and Table 26. Table 27 reports the parameters widely used for 300M.

Table 26 Threading parameters

P/N	Operation	Diameter/depth (inch)
SK-0114	Threading	2.75-16UNF
SK-0114	Threading	3.00-16UNF
SK-0114	Threading	3.25-16UNF

For all the operations, the insert characteristics and the parameters were recorded. A sample of the residual chips was also collected to evaluate the cutting performance of each tool. Other observations like possible tool wear, etc. were reported.

Table 27 Drilling and Threading parameters for 300M quenched and tempered

Operation	Cutting Speed (SFM)	Cutting Feed (Inch per Revolution)
Threading	150	0.008
Drilling	80	0.005

Results

Hardness and dimensional deviation of the parts after hardening

Table 28 summarizes the hardness measured on the parts as received from the heat treater after hardening.

Table 28 Hardness of all parts as received after hardening heat treatment

P/N	S/N	Dimensions (inch)	Hardness After hardening			
			HRC1	HRC2	HRC3	Average
SK0110	H001	1.5 x 7.75	52.2	52.7	53.9	52.93
	H002	1.5 x 7.75	55.3	51.2	54.9	53.80
	H003	1.5 x 7.75	52.6	53.4	51.7	52.57
	H004	1.5 x 7.75	53.6	52.0	51.9	52.50
	H005	1.5 x 7.75	52.7	52.4	52.5	52.53
	H006	1.5 x 7.75	53.3	51.9	53.3	52.83
SK0111	H001	3.4 x 24	52.8	53.0	53.1	52.97
SK0112	H001	3 x 7.75	52.3	52.2	53.1	52.53
	H002	2.5 x 7.75	53.9	53.9	52.6	53.47
	H003	2 x 7.75	52.4	52.5	52.3	52.40
	H004	1.75 x 7.75	52.8	53.6	52.7	53.03
	H005	1.75 x 7.75	52.4	51.4	53.9	52.57
SK0113	H001	3 x 24	53.4	53.9	52.6	53.30
SK0114	H001	3.37 x 7.75	49.1	48.6	50.7	49.47
	H002	3.37 x 7.75	51.8	52.0	54.0	52.60
SK0115	H001	3 x 7.75	53.6	52.2	52.8	52.87
	H002	3 x 7.75	52.5	53.4	52.5	52.80
SK0116	H001	3.5 x 3.5 x 17.3	50.7	49.9	51.7	50.77
SK0117	H001	6 x 24 x 0.7	52.4	52.7	52.8	52.63
	H002	6 x 24 x 0.7	51.0	50.7	50.5	50.73

: Parts with hardness lower than 52.8 HRC (280 ksi)

More than 50% of the parts have hardness below 52.8 HRC, which is the equivalent to 280 ksi. Since the hardness is measured at the surface, the reading could be affected by the oxide layer formed obviously during the heat treatment.

The hardness was taken at GA on samples cut from two different diameters (1.75 and 3.0 inch) (e-mail Paul Trester September 26, 2003). The results were as shown in Figure 69a and Figure 69b. The measured hardness on the cross section is within the 53-55HRC range. The lowest values (53.3 to 53.9 HRC) were found on the 3.00 inch diameter, while the highest (54 to 54.8 HRC) were for the 1.75 inch.

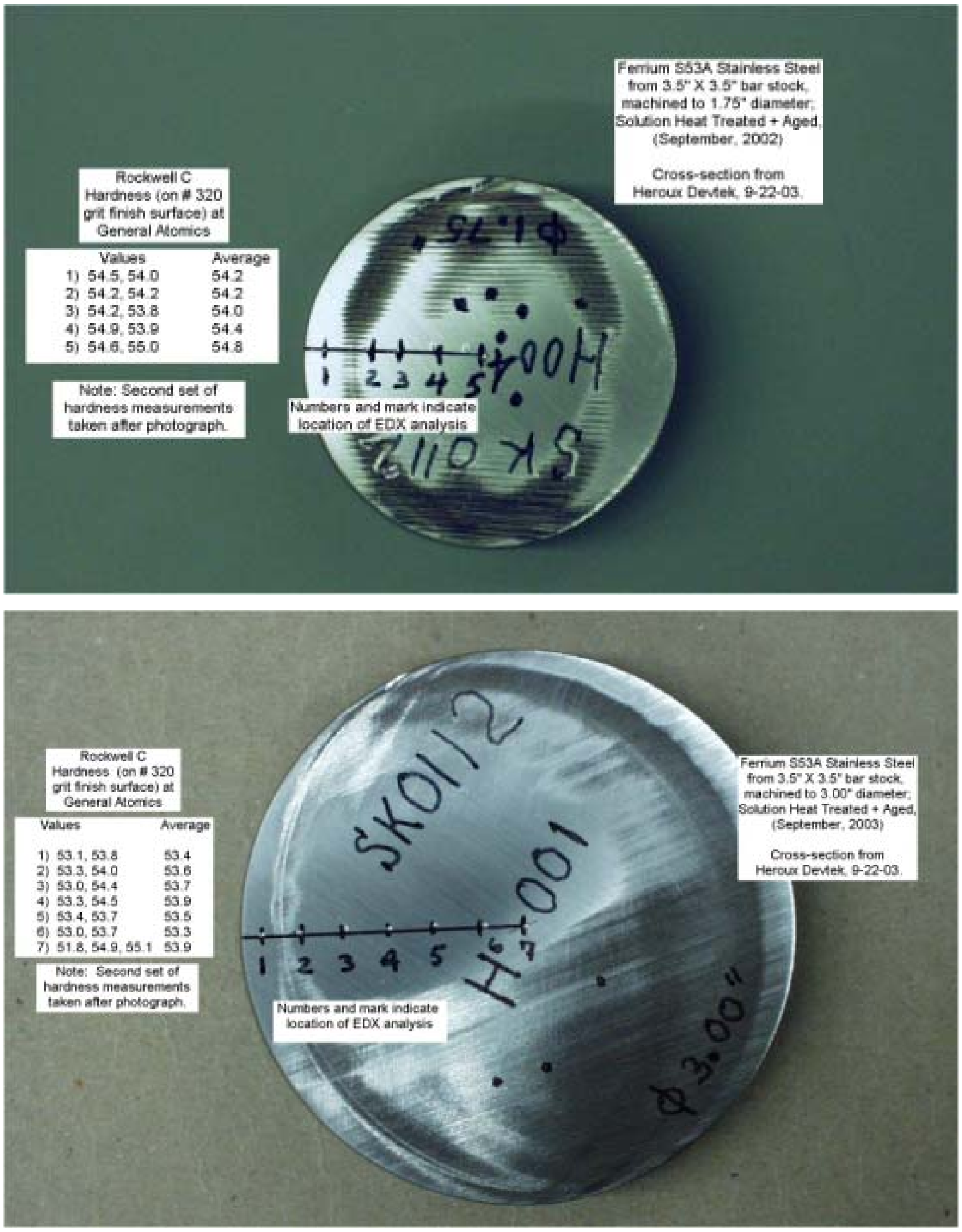


Figure 69 Hardness measured on the cross section of two samples cut from a 1.75 inch bar and a 3.00 inch bar

All 7.75 inch parts were 0.010 taller after heat treatments. Longer parts (24 inch, SK0111 and SK0113) extended by 0.020 inch. The deformation on the small bars was very important (around 0.020 inch TIR) and to make the parts straight before grinding, more than 0.010 inch by wall thickness had sometimes to be removed. This deformation is inherited not only from the heat treatment but also from the turning before the heat treatment.

For the long bars (24 inch) the deformation due to the heat treatment was 0.020 inch on the TIR.

Turning

As a general rule for all inserts, it was noted that the use of the 300M turning parameters in the quenched and tempered condition as shown in table 2, could not be achieved. If high speed are chosen, lower feed and depth of cut (DOC) had to be used.

The type and grade of inserts are very important. The following points were noted:

Unlike 300M, hardened Ferrium could not be turned with ceramics inserts. The advantage of using this type of inserts is that very high speeds could be used (600 SFM). That was not feasible with Ferrium and the inserts broke at the very first passes (figure 3). The heat generated at the insert/surface point was very high as revealed by the blue discoloration of the chips.

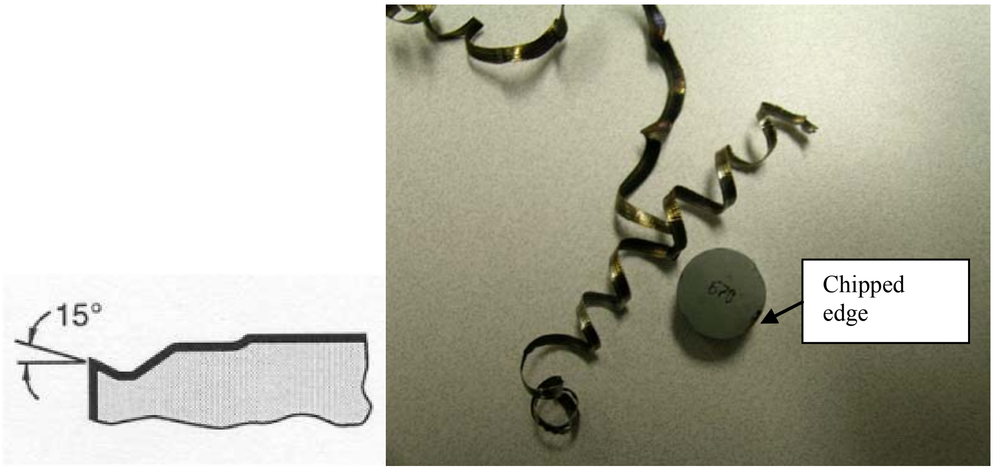


Figure 70 Ceramics insert and associated chips - the insert broke at the edge

Only tools with a positive cut (requiring positive insert and holder) permitted the use of the parameters listed above. A drastic decrease of the parameters, mainly feed and speed, (see table 8) is necessary when using neutral or negative cut tools. In positive tools the angle between the tool cutting point and the flank surface is a positive number. The tool is more positive when this angle is higher.

Carbide grades that worked the best for roughing and finishing were those that have a high deformation resistance associated with very hard and thermal resistant multi-layer PVD titanium aluminum nitride coatings (KC5010 and EH510Z). The KC7310 grade permitted the use of higher speed at the finishing step but could not withstand the roughing step that requires higher depth of cut.

Table 29 gives all the parameters used on the small bars with the various inserts used, and the resulting behavior of the inserts.

Table 29 Hardened Ferrium S53 turning parameters used for small bars

P/N	S/N	Insert grade	Insert identification	Turning speed (SFM)	Feed rate (inch/rev)	Depth of cut (inch)
SK-0110*	H001	KC5010	DNMG442P	120	0.005	0.010
		KC5010	DCMT432LF	120	0.008	0.003
		KC5010	DCMT432LF	80	0.0036	0.010
	H003	Ceramics	DOGA 150408	370	0.005	0.005
		KC5010	DNMG442P	120	0.005	0.010
		KC5010	DCMT432LF	120	0.008	0.005
	H004	KC5010	DNMG442P	120	0.005	0.010
		KC5010	DCMT432LF	120	0.008	0.005
	H005	Ceramics	DOGA 150408	370	0.005	0.005
		KC5010	DCMT432LF	120	0.008	0.005
	H006	Ceramics	DOGA 150408	370	0.005	0.005

P/N	S/N	Insert grade	Insert identification	Turning speed (SFM)	Feed rate (inch/rev)	Depth of cut (inch)
		KC5010	DCMT432LF	120	0.008	0.005
SK-0112	H001	KC7310	DNMG432P	260	0.008	0.020
				180	0.008	0.010-0.015
						0.020-0.025
						0.045
				150	0.008	0.045
				75	0.008	0.045
	H002	EH510Z	DNMG 432 EMU	150	0.008	0.060
		CP200	DNMG 150608-MR3	150	0.008	0.015
		EH510Z	DNMG 432 EEX	90	0.008	0.015
						0.040
	H003	EH510Z	DNMG 432 EEX	90	0.008	0.010
						0.060
	H004	EH510Z	DNMG 432 ESU	90	0.008	0.010
						0.040-0.060
						0.015
	H005	KC5525	DNGG 432 FS	90	0.008	0.010
						0.040-0.060
SK-0115	H001	KC5010	DCMT 432 LF	90	0.006	0.024
					0.008	0.035
				120	0.008	0.015
						0.060
	H002			90	0.006	0.090-0.024-0.015-0.010

R: rough turning F: finish turning

* SK-0110 are samples for the grinding trials, only a clean cut was done; then, a finish pass was done to reduce the high Barkhausen signal.

(green) No unusual wear (yellow) Excessive wear (red) Broken insert

Table 30 summarizes the turning trials done on the 23" long bar.

Table 30 Hardened Ferrium S53 turning parameters used for long bars

P/N	S/N	Insert grade	Insert Identification	Turning speed (SFM)	Feed rate (inch/rev)	Depth of cut (inch)
SK0111	H001	670*	RNG-45-T-0320	700	0.016	0.005
				500	0.012	0.03
		EH510Z	DNMG432EEX	120	0.008	0.06
				90	0.008	0.06
				90	0.008	0.02
				150	0.008	0.06
		KC5010	DNMG442MP	180	0.008	0.06
				150	0.008	0.06
				135	0.0096	0.06
				120	0.014	0.06
				120	0.008	0.06
		KC5525	DNMG 432 FS	120	0.008	0.06

P/N	S/N	Insert grade	Insert Identification	Turning speed (SFM)	Feed rate (inch/rev)	Depth of cut (inch)
		KC9125	DNMG432ND	120	0.010	0.06
			DNMG442RP	120	0.010	0.06
				120	0.008	0.06
SK0113**		EH510Z	DNMG 432 EEX	90	0.005	0.0125
		KC5510	DNMG432 MS	120	0.005	0.025
		1005	DNMG432-23	90	0.005	0.025

* Ceramic inserts
** Only a clean cut was done on the SK0113 to remove scale

Good insert (green) | Insert broken (yellow) | Excessive wear (red)

The maximum DOC (Depth Of Cut) achieved without unusual inserts wear or breakage was 0.060 inch for the roughing and 0.015 for the finishing. This has to be used with speeds lower or equal to 180 SFM for the finishing and 150 SFM for the roughing. If higher DOC were to be used for roughing, the speed had to be cut in half (90 SFM maximum). The maximum feed possible was 0.008 ipr (Inch Per Rotation) compared with the normally used 0.010 ipr for 300M. Above this value all inserts broke, whatever is the used speed.

The long bar SK0111 was turned much more easily in the hardened condition than in the re-annealed (Ref.3.1.2).

Inspection after turning
The Table 31 shows the surface finish obtained at the end of each trial. For the P/N SK0110, the pieces were turned twice because of a first high Barkhausen Noise signal (BNI) as noted in the table. The finish turning gave a higher Ra while the Barkhausen noise decreased.

Table 31 Surface finish at the end of the turning trial

		Ra (µinch)		Rt (µinch)		Rq (µinch)	
P/N	S/N	BNI rejected	BNI Accepted	BNI rejected	BNI Accepted	BNI rejected	BNI Accepted
SK0110	H001	30	69	170	258	35	77
	H002	33	N/A	185	N/A	39	N/A
	H003	21	55	128	297	25	67
	H004	53	56	274	246	62	65
	H005	46	63	258	234	55	70
	H006	45	71	226	244	52	79
SK0111*	H001	40/53/68					
SK0112*	H001	58-64					
	H002	58-61					
	H003	101-115					
	H004	87-96					
	H005	67-68					
SK0113	H001		88		391		100
SK0115	H001	-	17		112		20
	H002	-	16		110		18

*** For SK0111 and SK0112 no Barkhausen Noise inspection was done- finishes applied after the turning trials**

Table 32 shows the results of the Barkhausen Noise inspection (BNI) after turning. Only the P/N SK0110, SK0113 and SK0115 were inspected by BNI. For part SK0110 additional finish turning was done to decrease the high Barkhausen Noise. Table 33 provides the parameters used to decrease the signal.

Table 32 Barkhausen Noise inspection results

		$\frac{MP_{max}}{MP_{avg}}$ Axial Signal		$\frac{MP_{max}}{MP_{avg}}$ Circumferential signal	
P/N	S/N	Before finishing	After finishing	Before finishing	After finishing
SK0110	H001	1.1	1.2	1.7	1.2
	H002	1.1		1.3	
	H003	1.1	1.2	1.4	1.2
	H004	1.1	1.1	1.5	1.2
	H005	1.2	1.1	1.8	1.1
	H006	1.1	1.1	1.6	1.1
SK0113	H001	1.1	-	1.2	-
SK0115	H001	1.1	-	1.2	-
	H002	1.1	-	1.2	-

: Unacceptable ratio

The acceptance criteria is $\frac{MP_{max}}{MP_{avg}} \leq 1.2$

The BNI is used to account for any abusive mechanical operation on the steels. Operations that generate heat can induce either microstructural changes or high surface residual stresses. The BNI can differentiate the two situations since it gives high signal in both the circumferential and axial directions when microstructure changes, and a high signal in the sole direction of the stresses when only stresses are involved.

It can be noted that for turning the Ferrium steel parts, in all cases, only the circumferential signal is high which means that when the turning conditions are rough they induce surface residual stresses in the hoop direction but no microstructural changes.

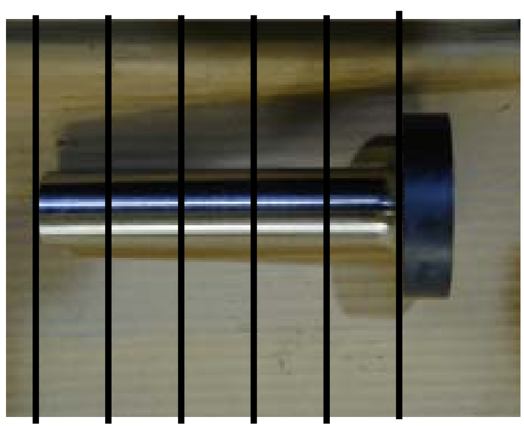


Figure 71 Different areas in SK0110 scanned during the Barkhausen Noise inspection as shown in Figure 72

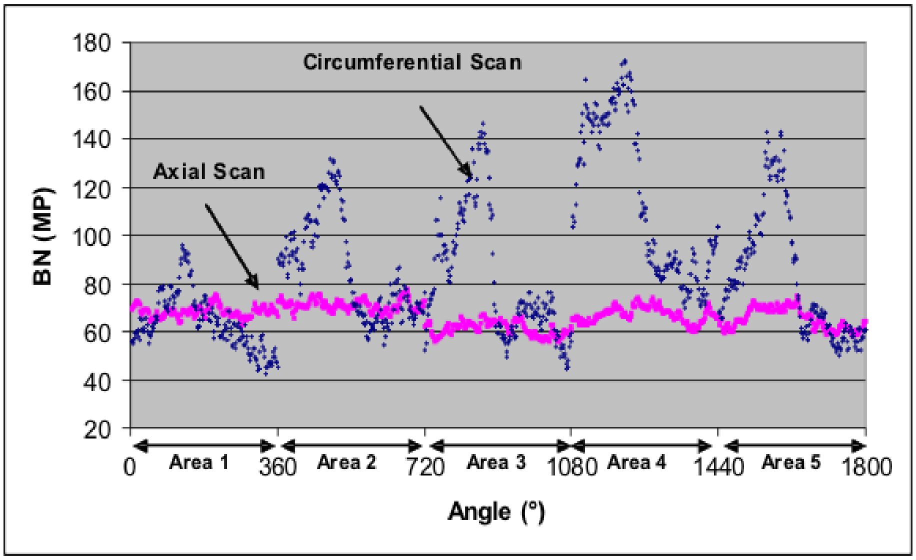
Figure 72(a) illustrates the type of signal obtained on different areas shown in Figure 71, when high stresses are induced during the turning (P/N SK0110, S/N H005). These stresses are in the direction of turning i.e. the circumferential direction as revealed by the scan. Figure 72b shows the Barkhausen Noise scan after finish turning using appropriate turning parameters (see Table 33), the circumferential signal decreases drastically which is a sign of the disappearance of the residual stresses in this direction.

Table 33 Turning parameters associated with acceptable Barkhausen signal compared with non acceptable conditions

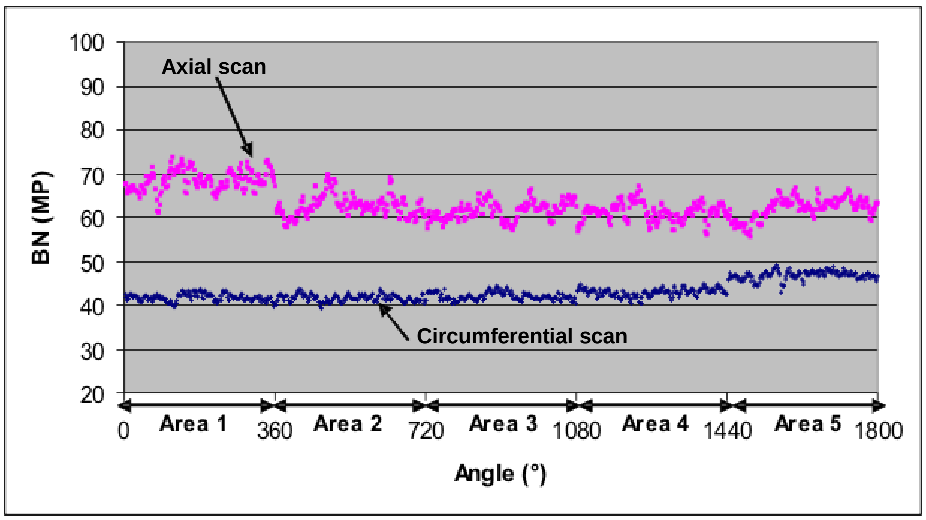
		Inserts (1)		Speed (SFM)		Infeed (ipr)		DOC (inch)	
P/N	S/N	Acceptable	N/Accept	Acceptable	N/Accept	Acceptable	N/Accept	Acceptable	N/Accept
SK0110	H001	DCMT432LF KC5010	Ceramics	120	370	0.008	0.005	0.005	0.005
	H002	DCMT432LF KC5010	Ceramics	120	370	0.008	0.005	0.005	0.005
	H003	DCMT432LF KC5010	Ceramics	120	370	0.008	0.005	0.005	0.005
	H004	DCMT432LF KC5010	DNMG442 KC5010	120	120	0.008	0.005	0.005	0.010
	H005	DCMT432LF KC5010	DNMG442 KC5010	120	120	0.008	0.005	0.005	0.010
	H006	DCMT432LF KC5010	DNMG442 KC5010	120	120	0.008	0.005	0.005	0.010
SK0113	H001	DNMG432EEX EH510Z		90		0.005		0.0125	
SK0115	H001	DCMT432LF KC5010		90		0.006		0.015	
	H002	DCMT432LF KC5010		90		0.006		0.015	

(1) DNMG inserts are less positive than the DCMT inserts

[red box] : Parameters providing non-acceptable Barkhausen Noise, DNMG442 is a neutral insert.



(a) Rough



(b) Finish turning

Figure 72 Barkhausen Noise response of P/N SK0110, S/N H005 a) rough turned b) finish turned – Axial scan Gain=50, Magn=35 Circumferential scan Gain=20, Magn=25

It can be seen that the Ferrium S53 can be turned to a very high surface condition when using appropriate parameters at the finish turning step. This is given by the results on SK0115, when using appropriate grades (PVD coated carbides), low speeds (90SFM) but higher infeed and depth of cut (0.015 inch) to increase productivity.

The use of higher speed (120SFM) and infeed (0.008ipr) could be done without breaking or inducing excessive wear to the insert, however, as it was demonstrated by the results on the S/N H004 through H006 of P/N SK0110, high surface stresses are then induced.

Drilling, boring and threading

As the drilling in the annealed condition, the drilling at the hardened condition could be performed without breaking the tools only when drills with cooling ducts are used. However, unlike the annealed condition, it was possible in the hardened condition to perform the drilling in one shot when using lower feed and speed for the larger holes (0.75 inch).

Drilling by increment of 0.030 inch permitted to increase the feed and speed and achieve the drilling of small holes without breaking the tool. Table 34 summarizes all the results. Figure 73 shows the part after performing the different tests.

Table 34 Hardened Ferrium S53 optimum drilling and boring parameters on P/N SK0117

Operation	S/N	Hole diameter	Drill insert	Drilling sequence	Drilling speed RPM (SFM)	Feed rate (mils/rev)	Depth (inch)
Drilling	H001	0.25	Carbide- no through coolant drill	1 shot drilling	1100 (72)	2.2	0.7
		0.75	Carbide through coolant-drill	1 shot drilling	400 (78.5)	1.4	0.7
	H002	0.268	Carbide through coolant-drill	Incremental drilling	1465 (103)	2.2	0.030
Boring	H001	1.375 to 1.500	TNMG322		380 (135)	1.5	0.025
		1.375 to 1.500			380	1.1	-

Legend	
(green)	Good drill
(yellow)	Excessive heat or drill wear
(red)	Broken drill

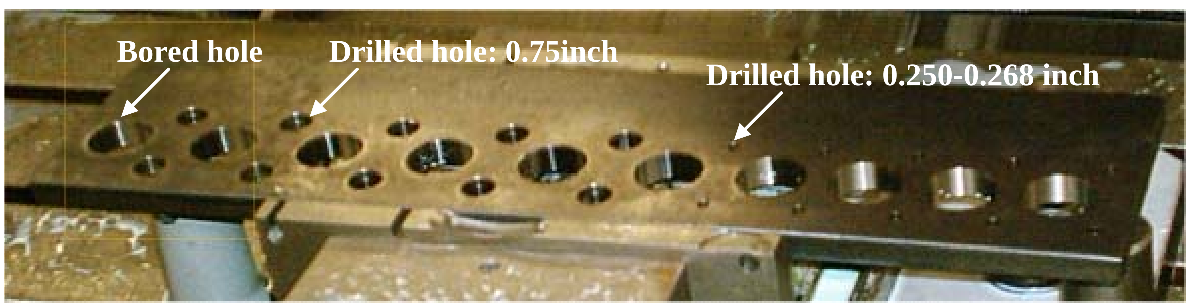


Figure 73 P/N SK0117 showing drilled and bored holes

Boring was conducted on the largest holes (1.375inch) using the same tools and parameters than 300M. No special behaviour was noted.

Table 35 reports the threading parameters used to make threads on three different diameters: 2.75, 3.00 and 3.25 inch.

No special behaviour was noted during the threading operation. The same parameters and tools used for 300M were chosen. Figure 74 shows the resulting part.

Table 35 Hardened Ferrium S53 threading parameters

P/N	S/N	Thread type	Tool Grade	Tool characteristics	Speed RPM (SFM)	Pitch (mils per rotation)
SK-0114	H001	2.75-16UNF	GC1020	carbide	100 (130)	0.0625
		3.00-16UNF				
		3.25-16UNF				

P/N	S/N	Thread type	Tool Grade	Tool characteristics	Speed RPM (SFM)	Pitch (mils per rotation)
	H002	2.75-16UNF	KC5010	carbide	100 (130)	0.0625
		3.00-16UNF				
		3.25-16UNF				

Figure 74 P/N SK0114 after the threading operation

Discussions and Recommendations

In the hardened condition, Ferrium S53 could be turned with a reasonable efficiency. Given the highest parameters that could be used without the loss of the tools, the efficiency is between 10 to 20% lower than quenched and tempered 300M. However very impressive finish could be reached (16-17 Ra) as well as safe surface residual stresses conditions.

Unlike 300M, Ferrium cannot be turned with ceramics insert. These inserts have the advantage to allow very high speeds (550SFM on 300M) for roughing and finishing without interruption. When trying to use them for Ferrium, excessive heat was generated and the inserts could not withstand the effort and chipped.

In all cases, carbide inserts should be used with very hard coating. The grades that showed best results are high deformation resistance carbides coated with very hard and thermal resistant multi-layer PVD titanium aluminium nitride (KC5010 and EH510Z).

The KC7310 grade allowed the highest speed for finishing. However, depth of cut higher than 0.015 induced the excessive wear or breakage of the insert. As a matter of fact this grade is less resistant to wear than the KC5010 and EH510Z (one layer of TiAlN coating). It is designed for finishing which explain its failure for higher depth of cut.

Usually steels in the hard quenched and tempered condition should be turned with grades that have high hardness to withstand wear because wear is the primary concern not toughness. Toughness is more an issue when the steel is machined in a milder condition. This does not apply to Ferrium since toughness remains an issue in the hardened condition as demonstrated by the systematic failure of the ceramics inserts. No explanation at this point could be given, but this should be related to the response of the Ferrium to the cutting effort.

High wear and high toughness is then required for the inserts used for the roughing and finishing of the Ferrium. If only one insert has to be used for both the roughing and finishing, the KC5010 and the EH510Z are recommended, even though lower speeds are required for the finishing (120 SFM max instead of 150 SFM).

The geometry of the tool is also another very important issue. It was shown that even using the good grade, a negative or neutral tool rapidly wears and induces high residual stresses. Negative, neutral inserts have a larger contact area with the surface to be machined than positive inserts. Thus, a higher cutting force is necessary. Positive inserts have less usable edge than negative, but higher free cutting action. Because they induce lower cutting forces they are more suitable for Ferrium. This rule seems to work well with Ferrium. Whatever grade used, geometry that induced lower cutting forces worked better with Ferrium.

The following Table 36 gives a synthesis of the turning parameters of Ferrium when using proper grades as established by this study compared with 300M and some data on AerMet 100.

Table 36 Optimum turning parameters for S53 compared with 300M and AerMet100

Alloy	Insert	Speed (SFM) (1)	Infeed (Inch per Revolution)	Depth of cut (inch)	BNI/Finish (2)
300M	Carbide KC5010	160R	0.010	0.075	
		180F	0.008	0.030	
	Ceramics	550R/F	0.006	0.030	
Aermet 100	Carbide	N/A	N/A	N/A	
		160F	0.010	0.010	
Ferrium S53	Carbide KC5010/positive	150R	0.008	0.060	
	Carbide KC7310/positive	180F	0.008	0.015	A/58-64Ra
	Carbide KC5010 OR EH510Z/positive	120F	0.008	0.005	A/55-71Ra
	Carbide KC5010/positive	90F	0.006	0.015	A/15-16Ra

(1) R: Rough, F: Finish (2) A: Acceptable

For the drilling, the use of drills with coolant ducts make the use of the same parameters than 300M possible. However, an incremental drilling is required for Ferrium when drilling small holes. This type of holes (0.750inch deep) can be done in one shot in the 300M. The Ferrium steel needs to be cooled down during the drilling and this is certainly related to its thermal properties. A steel with a lower thermal conductivity cannot evacuate the heat easily, which leads to the micro-welding of the chips inside the hole.

The effort shall then be focused on the cooling which explains also why using drills with cooling ducts is mandatory. It was not possible to account for the wear of the tools because of the too few number of tests done.

The threading was also done using the same parameters and tools than for 300M. No particular behavior was noted.

Conclusions

In the hardened condition, the machinability of the Ferrium steel was closer to that of the 300M and Aermet100 steels than in the annealed condition.

Threading and boring was conducted with the same conditions and using the same parameters as for 300M.

Drilling and turning have to be done with more precautions for Ferrium than for 300M since it is more difficult to evacuate the heat generated during machining. The Ferrium alloy induces wear or failure of the tools when using parameters optimized for 300M.

For turning lower feeds and depths of cut are needed. The use of the same insert for Ferrium and 300M is possible since it was shown that the most used carbide for 300M (KC5010) worked very well with Ferrium. The geometry of the tool should be chosen carefully, a positive tool should be used on Ferrium, so that a longer insert life and less steel surface residual stresses are obtained.

It is worth noting that all the tests were conducted on relatively small parts with very simple geometry. These results cannot account for larger parts and more complex geometry, however the basic requirements for machining the Ferrium steel are highlighted, and even these requirements are basic for machining any material, Ferrium would be less forgiving than 300M that has been used in this study as a comparison:

- Avoid the use of any parameter that would induce high cutting forces
- Always ensure a good heat exchange, then a high coolant flow whatever machining operation is involved since this would be unforgivable for Ferrium

2.3.4 Weldability

Approach

The weldability of the Ferrium S53A alloy was addressed by conducting weld experiments using the Gas Tungsten Arc (GTA) manual welding method and incorporating the use of a filler alloy of the same composition. The approach used produced two welded plate assemblies achieved by the joining of two abutted annealed plates. To evaluate the weld quality achieved, both radiographic and magnetic particle inspections were conducted. To evaluate the properties of welded assemblies, blanks suitable for the machining of tensile test specimens and Charpy V-notch type specimens were then excised. The rectangular blanks were partially machined, fully heat treated, ground to final dimensions for tensile and Charpy specimens and then tested.

Materials and Welding Experiment

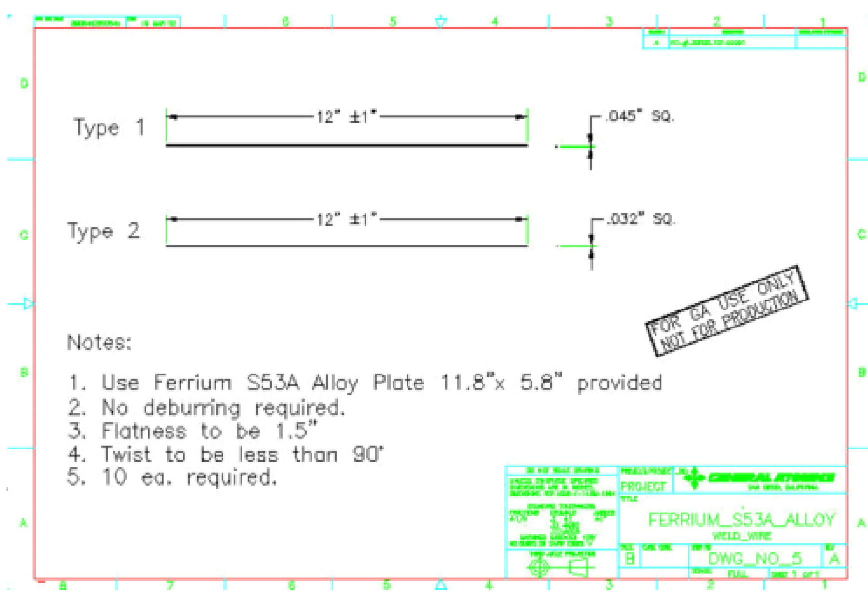


Figure 75 Design drawing of strips for use as weld wire.

Weld wire was simulated by fabricating thin strips from plates machined from rolled and mill-annealed plate stock. The two sizes fabricated are described in the drawing presented in Figure 75.

The test plates to be welded were machined from QuesTek provided S53A stock of rolled and mill-annealed plate of 0.7" nominal thickness. Machining was conducted at General Atomics on all surfaces to remove the decarburized zone of the stock plate. The test plates fabricated are described in the drawing presented in Figure 76. Following machining, the test plates were vacuum annealed to a QuesTek revised two-step annealing process. This thermal exposure was conducted for the purpose of maintaining consistency with test articles of another ongoing task to investigate machinability of annealed S53A alloy.

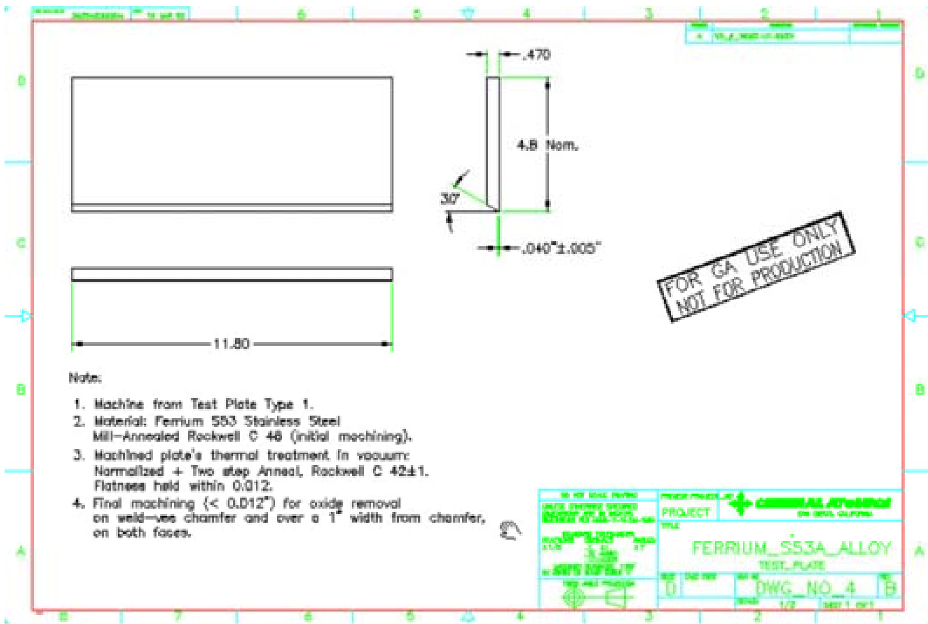


Figure 76 Design drawing of beveled-edge Test Plate for GTA welding experiment.

In Figure 77, the measured hardness values are presented for six test plates after they received the normalizing and Two-Step Anneal (November 2003) conducted by Midwest Heat Treating Company for QuesTek. A hardness survey was conducted on the as-annealed faces of the subject plates. Three measurements were made on the plate face near the center. At the top of Figure 77, in a software pre-set table, which is associated with the Newage Hardness Testing instrument, details are entered, which are relevant to the test plates and hardness procedure. The bar graph provides the hardness values measured on the six plates. All the values were approximately of between 41 and 43HRC. No evidence of an unusual trend or gradient was found. Essentially, the Normalize + Two-Step Anneal process established a Rockwell C hardness of 42 +/- 1 in the machined test plates of Ferrium S53A stainless steel.

Plates # 1 through # 4 exhibit modest warpage and on a flat QA table, the out-of-flatness was measured to be less than 0.012. These four plates were selected for use in the welding of two assemblies. The discoloration of the test plate surfaces varied from dull metallic to matte purple-gray. From this appearance, the vacuum pressure of the thermal treatments was between 10^{-3} and 10^{-4} Torr, it is estimated. A machine cut of up to approximately 0.010" was necessary to remove the slight warpage in the plates and to enable removal of the thin oxide film from the weld chamfer edge and nearby surfaces.

Two test plates are shown abutted to one another in Figure 78. This set-up represents the positioning used at the time of the GTA welding. Figure 79 presents the drawing that specifies all the important procedures for weld preparation, cleaning surfaces, hydrogen removal bake, GTA welding, and post weld inspections.

S53A Ferrium HRC Survey			
Date:	11/03/03	**Part Name:**	Ferrium S53A Alloy
Part Number:	Machined Plates #'s 1 through 6	**Type:**	Vacuum Atm.
Special Order:	Plates Machined by GA	**By:**	Midwest Thermal Co.
Comment:	HRC Survey by GA- 12/2/03	**Comment:**	Normalized + Two-step Anneal
Comment:	HRC Survey of Face	**Comment**	3 HRC Readings/plate

Scale:	HRC
Average:	42.3
Std. Dev:	1.0

Plate No.	1	2	3	4	5	6
Reading 1 (HRC)	43.2	41.3	42.4	43.1	40.1	42.6
Reading 2 (HRC)	42.7	42.0	42.7	42.9	40.6	43.3
Reading 3 (HRC)	42.9	42.6	42.8	43.2	41.0	42.9

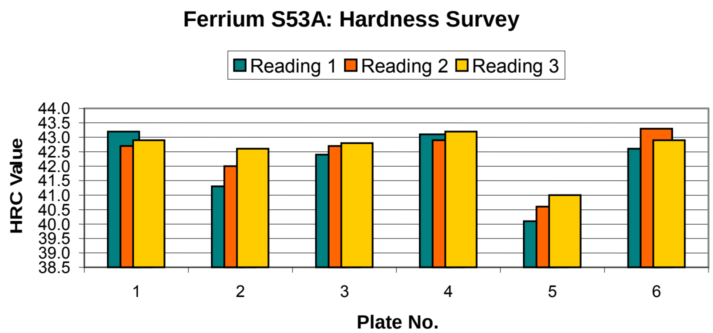


Figure 77 Hardness survey of machined plates after annealing.

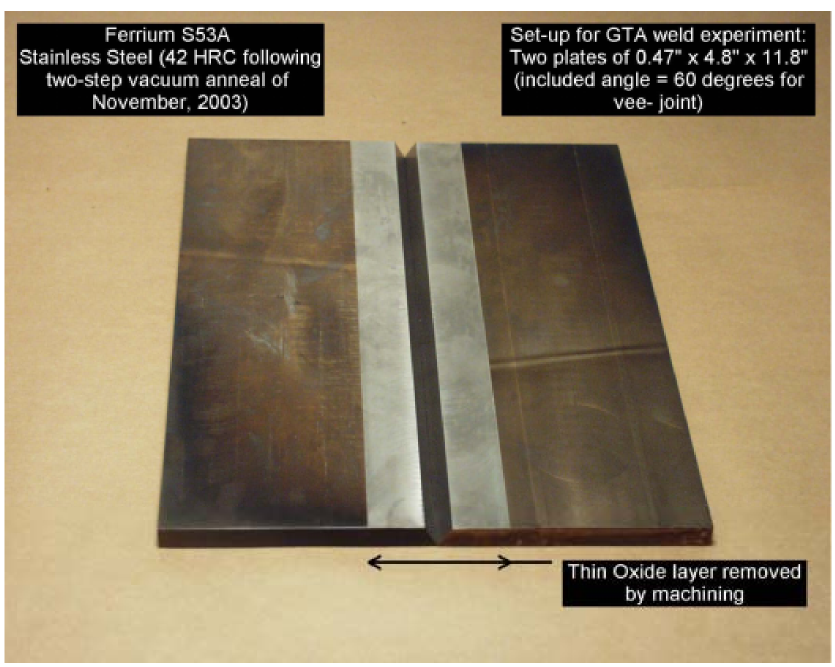


Figure 78 Photograph of two Test Plates abutted in position for the GTA welding experiment.

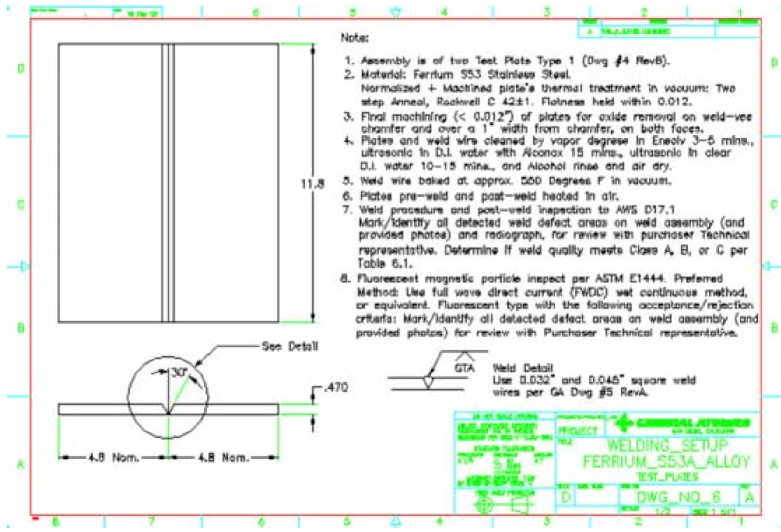


Figure 79 Design drawing (including weld specification and inspection) for GTA welding of two Test Plates.

The set-up fixturing used to hold two test plates during the GTA welding was a commercial Weld Test Fixture type #130100 manufactured by TIG Depot Co., of Kansas. The fixture employs a trough design that enables a flow of argon gas beneath the root region of the abutted plate assembly. Test plate clamping was achieved by bolted cover plates positioned over the S53A test plates. C-clamps were used at the opposite end of the cover plates; this modification enabled fixturing the 12" long test plates so they could extend ~ 3" beyond the fixture's length. MC Precision Welding Co. conducted the GTA welding. Mr. Milt Cruz was the weldor.

In Figure 80, the manual GTA welding of Assembly # 1 is shown in progress. For Assembly # 1, no preheating was provided to the test plates. No post-weld thermal treatment was conducted.

Figure 80 Photograph of set-up and GTA manual welding of Assembly # 1.

The GTA welding system used was a Thermal Arc commercial unit type 3000TSW. The electrical characteristics of welding were: direct current; straight polarity; 17 volts with current varying between the range of 10 and 150 amperes. Typical steady-state amperage was between 125 and 140A, for filler passes. The torch used incorporated a 1/16" diameter electrode (tungsten – 2wt.% thoria alloy) with a pointed tip for the root pass and first two fill passes. A 3/32" diameter electrode was used for subsequent fill passes. The ceramic cup, which surrounded the electrode, was a # 8 standard size. The gas lenses used were sizes 1/16" for the 1/16" diameter electrode and 3/32" for the 3/32" diameter electrode. Argon was the shielding inert gas used and the flow rate was 20 cubic feet per minute. The same flow rate was used for the backing gas during the root pass, but the rate was then decreased to 5 cfm for the fill passes. The GTA manual technique incorporated fill deposition in the form of stringer beads.

Results

For the Weld Assembly # 1, there were a total of ten passes (one root pass and nine fill passes) needed to build a weld crown thicker than the 0.463" thickness test plates. The thicker wire size was used for conducting the fill passes.

Temperature of the weld zone was periodically measured by pushing a metal-sheathed thermocouple against the weldment. Temperatures were typically within the range of 145˚F (63˚C) and 350˚F (177˚C). After the completion of the welding and a five minute wait, the temperature near the pass-finish measured 205˚F (96˚C), and at the pass-start location, it was 157˚F (69˚C).

As a result of the high forces induced by the weld metal shrinkage , the welded test plate assembly could not be fully restrained by the narrow cover plates. The weld assembly bowed and lifted progressively, by the stressing of the fixture, bolts and clamps, with each fill pass, to develop a permanent convex vee shape on the crown face. For the ~ 9.5" wide assembly, the lift from the initial flat condition was 0.29" at one edge and 0.15" at the other. The assembly was permitted to air cool overnight before unclamping.

Visual inspection revealed no indications of cracks or voids. The root over the last four inches of length did not reveal any drop-through. This lack-of -penetration zone was estimated to be shallow and less than 0.010" in depth.

Radiographic and Magnetic particle inspections (see Figure 79 for specification details) were conducted at Decisive Testing Inc., San Diego, CA. The weldment was found to be free of cracks, porosity and inclusions and would therefore meet the Class A type weld quality. The four-inch length of root pass without drop-through was a negative feature. However, this zone would eventually be machined away and therefore not pose a practical problem for the fabrication of the CVN test specimens from this locality of the welded assembly.

Figure 81 presents a view of the crown face of Weld Assembly # 1. In Figure 82 a view is shown of the root side, after sawing and flattening of blanks to be used for fabrication of test specimens (transverse-weld tensile type and Charpy CVN type). Flattening of the blanks was conducted by a three-point bending method at room temperature in a frame that included loading by a hand-pumped hydraulic ram. No indication of cracking was heard or observed during flattening of the blanks.

There were two cross-sections prepared by metallographic methods to enable direct examination for defects and to reveal the weld and the heat-affected zone (HAZ) microstructures. Both mounts exhibited no evidence of defects. The hardness of ~ 39HRC was indicative of an austenite microstructure in the weld zone.

The GTA welding of Weld Assembly # 2 was conducted using an approach similar to the welding of the # 1 assembly. However, there were two parameters that were intentionally changed; a pre-heating of the weld fixture and of the test plates was incorporated, and a post-weld thermal treat of the welded assembly was added.

Figure 81 Photograph of GTA Weld Assembly # 1; Weld -Crown Side.

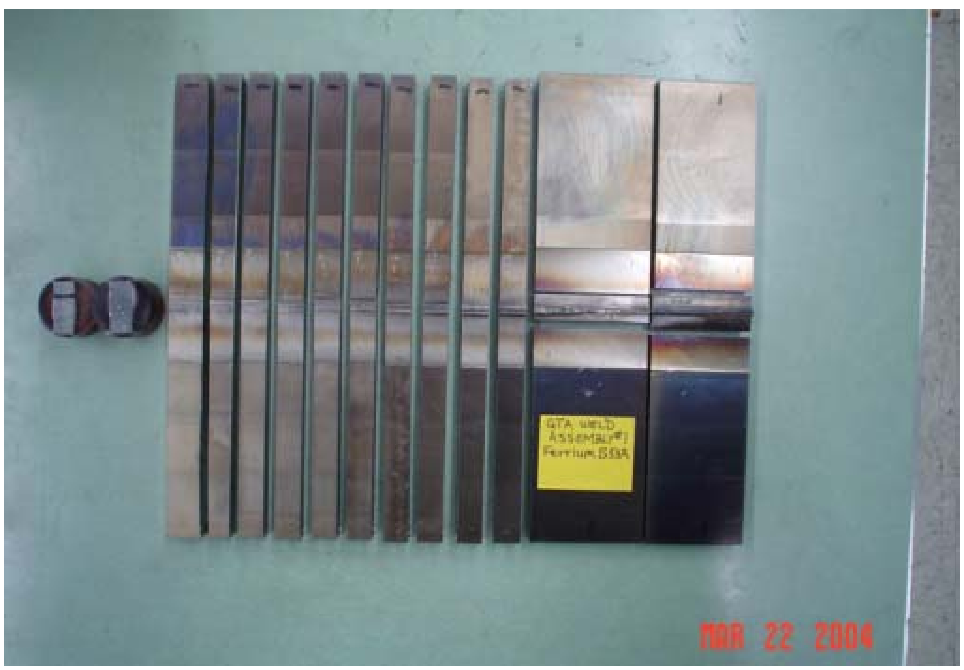


Figure 82 Photograph of Weld Assembly # 1 (Root Side) after sawing specimen blanks and flattening; two metallographic mounts of cross-sections.

Note: the metallurgical rationale behind this approach for the Weld Assembly # 2 was as follows: The pre-heat at ~415˚ F (213˚C) of the test plates would minimize the occurrence of austenite transformation to martensite in the weld zone during the root pass and subsequent fill passes. A post-weld thermal treatment was added to temper any fresh martensite formed in the weld or HAZ and to reduce residual stresses from the welding. The post-weld exposure would be in vacuum at a temperature ~ 932˚F (500˚C) for ~4-hours followed by a power-off cooling rate (reaching ~287˚C after 1.5 hrs. of cooling). The post-weld thermal treatment should provide for: A) relief of residual stresses, B) over-tempering of any martensite phase, C) allow austenite present to convert to ferrite and carbides. Upon cooling, there may be a small percentage of retained austenite and some transformation to fresh martensite mixed within the predominant microstructure consisting of over-tempered martensite, ferrite and carbide phases. This over-all condition would then be non-conducive for occurrence of delayed -cracking phenomena in the interim processing when the following occur: weld- inspection, blank sawing, blank flattening and transportation to QuesTek for the rough machining of tensile and CVN specimens and finally the full heat treatment to the 53HRC condition prior to test.

The GTA Welding of Assembly # 2 was accomplished successfully and with results quite similar to the appearance of Assembly # 1. The weldability of the S53A alloy plate, for both assemblies, was found to be very good by the selected manual GTA method. The welder was able to deposit the weld metal with good control of the weld bead. Hand feed of the thin strips (which simulated conventional filler wire) was controllable and did not present any practical difficulties. The welder felt that any welder knowledgeable in the art of manual GTA welding should be successful in the welding of S53A alloy.

The pre-heated plates at 415˚F (213˚C) from the furnace and installed on the preheated fixture. Never the less, by the time of the tack welding commenced, and the root closure pass, the plate temperature had cooled to 265˚F (130˚C). The root closure pass for assembly # 2 was conducted with a 3/32" diameter electrode and with use of the thicker weld filler strips. Also, the gap was increased between the two plates at the time of tack welding. These modifications from the assembly # 1 welding resulted in the achievement of weldment underbead along the total length of ~ 12 ". However, the root underbead was less uniform (undulations were present) than for Assembly # 1.

Thermocouple measurements after fill passes determined the weld crown was near 400˚F (205˚C) at the end and 235˚F (113˚C) at the pass start location. This temperature range would be well above the Ms temperature of the S53A alloy during welding. Between each pass, the welder brushed (stainless steel hand-held brush) off the heat tint developed on the weld. The weld consisted of 12 passes, the root closure pass and 11 fill passes. The welding of Assembly # 2 occurred over a time period of two-hours. It took ½-hour to unclamp Assembly # 2 from the fixturing and install the Assembly within the furnace and resume heat up. Based upon the Furnace thermocouple contacting the plate, the temperature decreased to 127˚F (53˚C) before heating ensued to bring the assembly to 932˚F (500˚C), for the ~ 4hr post-weld thermal treatment.

The visual examination revealed no indications of cracking. The radiography and the MFPI revealed a clear weldment, free of porosity, inclusions and /or cracking. These observations are consistent with a Class A weld rating. However, one non-uniform drop-through underbead region which occurred at about two-thirds length was recorded as a defect. This non-uniform zone was attributed to the use of the larger electrode diameter for the root pass and in part to a necessary procedure where the assembly was rotated 180-degrees (in-plane), and then reclamped, to enable the root-closure weld, over the entire 12" assembly length, to be made with the presence of inert backing gas. With the fixture length shorter than the test plates, the inert backing gas was flowing only within the trough of ~ 8" length. The official interpretation for the non-uniform root topography was a defect zone. From a practical engineering standpoint, the condition was quite acceptable for the ongoing investigation because the entire root weld zone of the assembly is machined away in the fabrication of test specimens.

The Figure 83 view shows the root side of Weld Assembly # 2, after the sawing and flattening of blanks for fabricating test specimens (transverse-weld tensile type and Charpy CVN type). Flattening was conducted by three-point bending at room temperature in a frame that included loading by a hand-pumped hydraulic ram. No indication of cracking was heard or observed in the flattening of the blanks.

One cross-section was prepared by the metallographic method. The etched surface of the cross-section can be viewed in the mount shown in Figure 83.

In Figure 84, a photograph is shown of three typical sawn and flattened test specimen blank from Weld Assembly # 2; each blank is oriented differently to reveal a different side. The metallographic mount face shows the cross-section of the weld. The etched microstructure distinguishes the weld zone from the HAZ.

In Figure 85, a macrograph is shown of the same cross-section presented in Figure 84. The etched microstructure reveals features of the weldment, the HAZ and the parent alloy. In the photomicrograph, at a higher magnification, presented in Figure 86, the prior austenite phase grain boundaries in the HAZ (right side of photo) of the parent plate. Direct examination at magnifications of between 10X and 400X revealed no defects in the weldment or the heat-affected zone (HAZ) microstructures. A hardness of ~ 39HRC was measured in the weld zone.

Figure 83 Photograph of Weld Assembly # 2 (Root Side) after sawing specimen blanks and flattening; metallographic mount of cross-section.

Figure 84 Photograph of typical sawn and flattened test specimen blanks, presented to show three views; Metallographic Mount shows outline of polished and etched weld zone in cross-section.

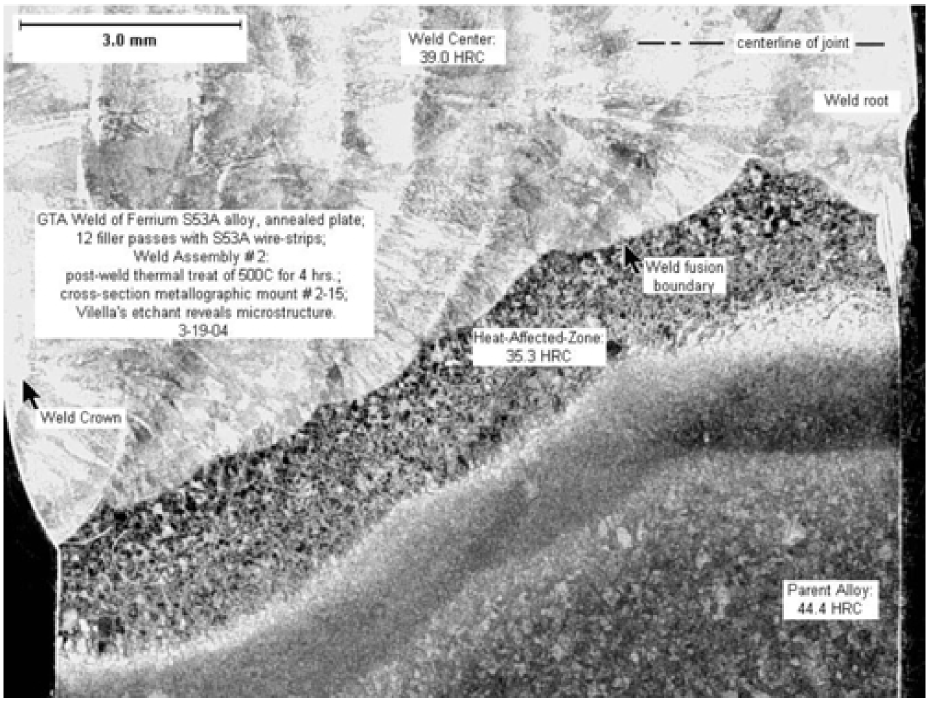


Figure 85 Macrophotograph of cross-sectioned weldment, etched to reveal microstructure of weld, HAZ, and parent alloy.

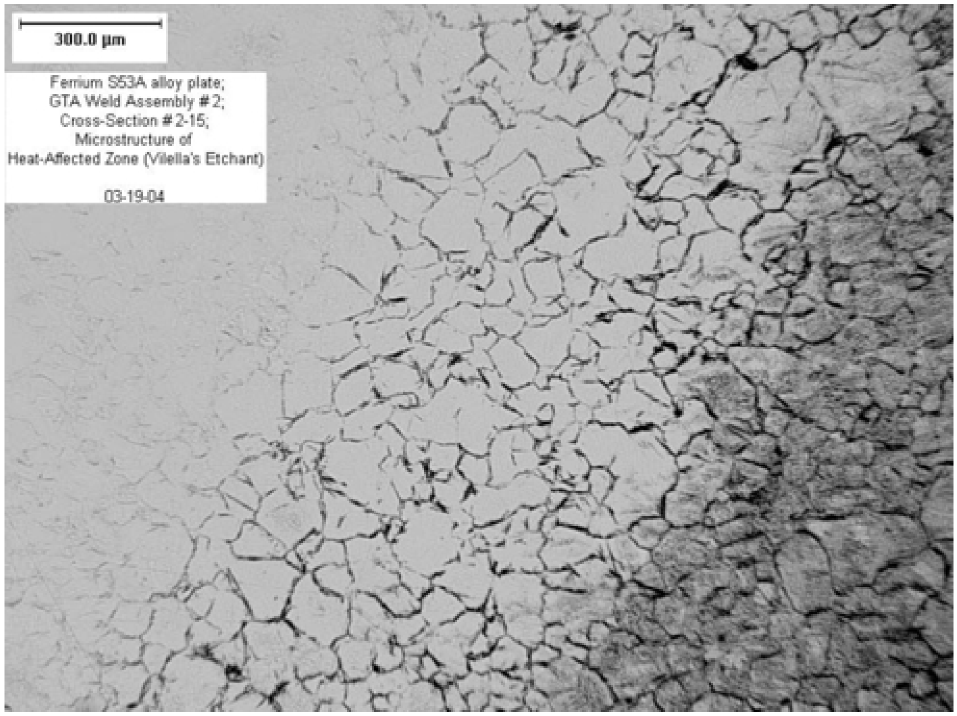


Figure 86 Photomicrograph of polished and etched cross-section of Weld Assembly # 2; weld zone (minimal etching) to left and to the right the HAZ (prior austenite grain boundaries revealed by etching).

Mechanical properties of fully heated treated specimens excised from the weld were completed and are shown in Table 37. The heat treatment for these specimens was as follows:

- 1050°C 70 min Solution Treatment
- Oil Quench
- 1hr LN_2 – Air warm
- 482°C 8hr temper + water quench
- 1hr LN_2 – Air warm
- 482°C 8hr temper + Air cool

The weld metal samples were taken from the weldment with enough margins to insure the final specimen was completely contained in the weld and did not contain any root pass or capping pass material. CVN specimens were oriented with their notch both longitudinal and transverse to the weld direction, but the resulting CVN energy was insensitive to orientation. The base metal comparison samples were taken from weld plate material far from the weld to avoid any HAZ material.

Table 37 Mechanical properties demonstrated in the weld metal in comparison to base metal of the S53 alloy excised from the plate.

	Base Metal	Weld Metal
UTS (ksi)	276	275
YS (ksi)	226	220
Elong.%	15	9
CVn (ftlbs.)	7	6

2.3.5 Surface Treatments

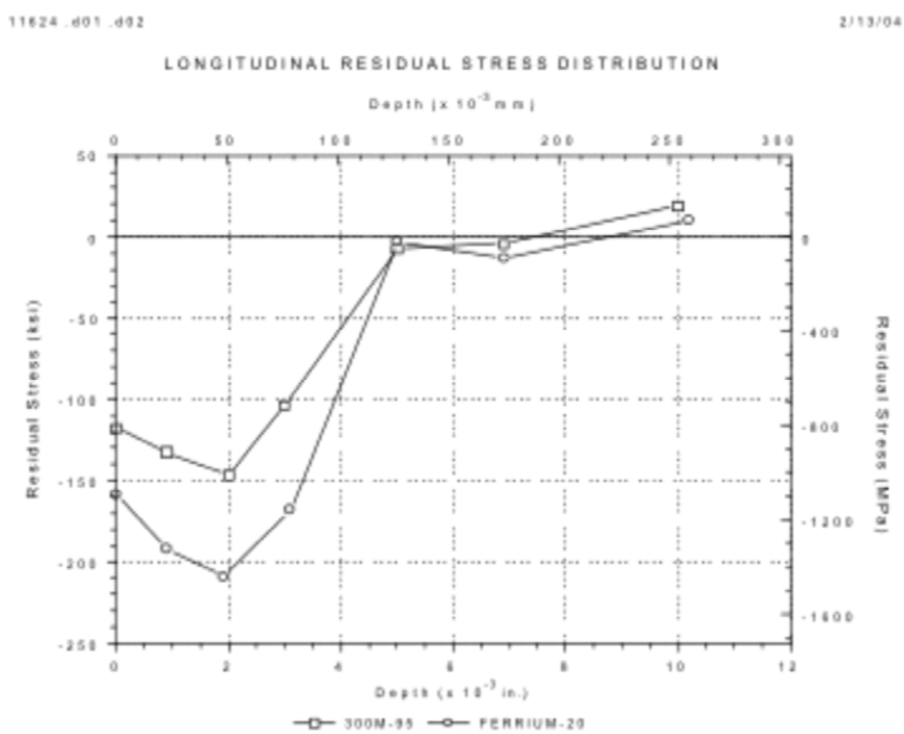
Shot Peening

Shot peening is a common cold working procedure used extensively on landing gear components made from 300M low alloy steel. The benefits of shot peening are :

- Improved fatigue life
- Improved resistance to stress corrosion cracking

Since any new material being qualified for landing gear components will require shot peeing it is imperative that the new material , when shot peened, produce residual stresses similar in magnitude and depth when compared to 300M low alloy steel.

An investigation was conducted on 300M and S53A fatigue coupons using X-ray diffraction techniques. The fatigue coupons are nominally 3.7 inches in length with a 0.25 inch diameter gage zone. The gaze zone was shot peened in accordance with SAE AMS-S-13165. The coupons were then sent to Lambda Research for X-ray measurements in accordance with SAE HS-784. The graph below presents residual stress magnitude and depth in 300M and S53A.



Shot peening of S53A produces similar residual stress profile when compared to 300M low alloy steel. Therefore the current shot peeing procedures developed for 300M can be used for S53A.

Coating/Plating/HVOF/Nitriding

Landing gear components use hard coating such as, chrome plate, for wear and to a lesser extent corrosion protection. These hard coatings will continue to be used regardless of substrate material and it is essential that S53 be compatible with current plating/coating processes and procedures. The coatings/platings must also adhere to the substrate surface equally as well as they do on 300M and the fatigue debit from the coatings must be similar to the 300M fatigue debit.

An investigation was conducted using the following platings/coatings:

- Hard chrome plate per MIL-STD-1501
- Sulfamate Nickel plate per MIL-STD-868
- High Velocity Oxygen Fuel (HVOF) coating per Praxair parameters

Table 38 Plating type and thickness for fatigue test specimens

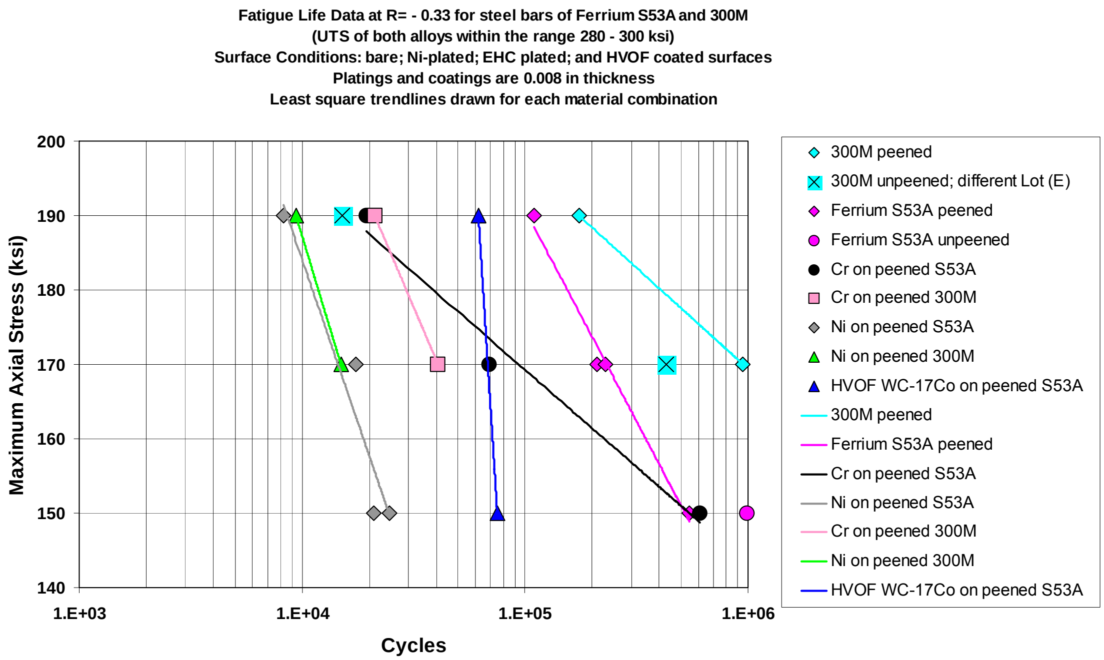
300M-1,-3	Item 1	Two	none	8 Sulfamate Ni (electroplate)	MIL-STD-868 and QQ-N-290
300M-5 and -6	Item 2	Two	none	8 Hard Chrome (electroplate)	MIL-STD-1501 and QQ-C-320
Ferrium -7,-8,9,-10 and -11	Item 3	Five	none	8 Sulfamate Ni (electroplate)	MIL-STD-868 and QQ-N-290
Ferrium-13,-14,-15,-16 and -18	Item 4	Five	none	8 Hard Chrome (electroplate)	MIL-STD-1501 and QQ-C-320
300M-7,-9,10,-11,and -16	Item 5	Five	5 Sulfamate Ni (electroplate)	3 Hard Chrome (electroplate)	MIL-STD-868 and QQ-N-290; MIL-STD-1501 and QQ-C-320
300M-18,-19,-20,-23 and -25	Item 6	Five	10 Sulfamate Ni (electroplate)	3 Hard Chrome (electroplate)	MIL-STD-868 and QQ-N-290; MIL-STD-1501 and QQ-C-320
300M-26,-30,-31,-32 and –33 -35,-38 and –39 extras	Item 7	Five	16 Sulfamate Ni (electroplate)	4 Hard Chrome (electroplate)	MIL-STD-868 and QQ-N-290; MIL-STD-1501 and QQ-C-320
TOTAL: 29					

Table 39 HVOF coating and thickness

Ferrium S53A	1	8 WC-17Co (HVOF thermal spray)		- 0.33	150
Ferrium S53A	1	8 WC-17Co (HVOF thermal spray)		- 0.33	190
Ferrium S53A	1	8 WC-17Co (HVOF thermal spray)		- 0.50	190 and higher by Step-Test Method See Note 1
Total	3				

Testing Sequence and Results

Plated and coated coupons were tested to determine adherence and fatigue debit on S53. Stress levels used during testing ranged from 150 ksi to 220 ksi. These levels were chosen based on data from 300M testing. Thus a direct comparison between 300M and S53A could be made.



Results of testing demonstrated that the platings and coating performed as good on S53A as on 300M. Adherence of the platings and coating met all requirements. No unacceptable failures were observed. Fatigue debit due to platings/coating was very similar to 300M fatigue debit as shown the S-N graph.

Based on testing S53 can be plated and/or coated with current processes and procedures without any negative effects on substrate, fatigue life or the plating/coating.

2.4 Alloy Summary Data

2.4.1 Alloy Property and Performance Data

Static Properties

Summary

The three static properties studied extensively in S53 are yield strength, ultimate tensile strength, and Charpy impact energy. The static property goals established in Figure 2 and Table 1 include 230ksi yield strength, 280ksi ultimate tensile strength, and 50ksi√in fracture toughness. QuesTek has used Charpy impact energy testing as a quick and inexpensive method to determine fracture toughness. While the two properties do not always scale together, we have evaluated fracture toughness in enough conditions to verify that using impact energy is a suitable alternative. Figure 87 summarizes all data gathered across the various generations, and plots this data against 300M as a reference. One notes that the S53-6 series, specifically S53-6F, meets the ultimate tensile strength and impact energy requirements. The yield strength of S53-6F is a bit lower than 300M, QuesTek hopes that further thermal treatments will be able to reduce or eliminate this difference. These static properties essentially meet the program goals, and indicate S53 should be able to serve as a drop-in replacement in many 300M applications.

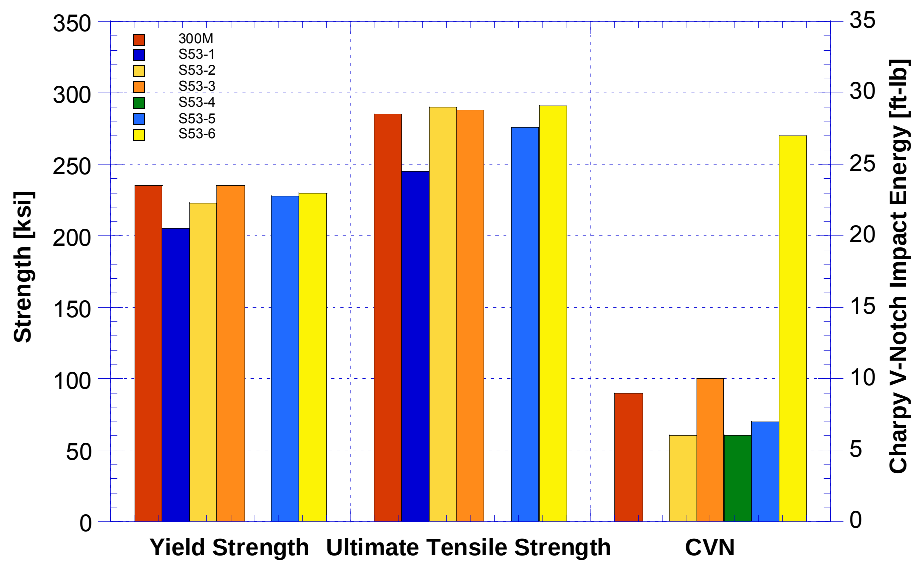


Figure 87 Mechanical properties of various S53 series, along with 300M for reference

Static Properites by Series

Mechanical properties were measured on each S53 prototype produced. The data not only served to benchmark progress toward the program goals, but also served as valuable calibration data for our models. Each property will be discussed individually, however it is clearly the combination of properties that is key to meeting the program goals. Figure 87 includes data that was gathered in identical conditions and is a fair presentation of the best results from each alloy series. Below is a property specific discussion of performance throughout the various prototypes.

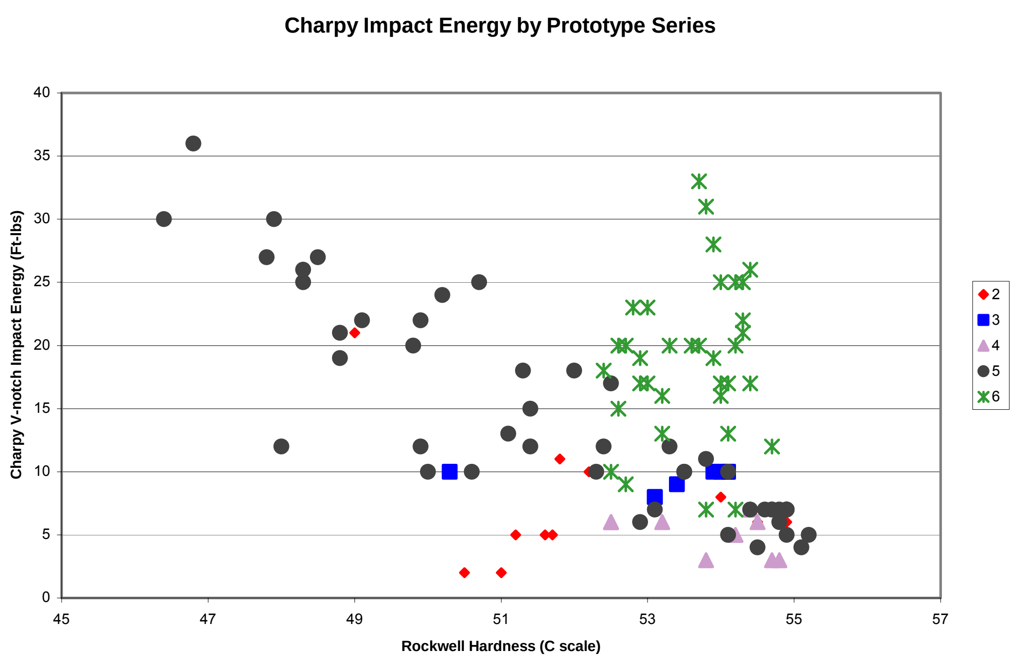


Figure 88 Impact Energy of S53 prototypes vs. hardness, by alloy series

Charpy Impact Energy
Charpy V-notch Impact Energy testing was used to evaluate toughness in the various prototypes produced. Early in the program (series 1, 2, and 4 specifically) many of the prototypes were failing in a brittle manner, indicating they had a ductile to brittle transition temperature (DBTT) above room temperature. Using the 4 and 5 series alloys to calibrate a DBTT model QuesTek was able to push the DBTT well below room temperature and achieve excellent room temperature toughness in the 6th series. Details of this modeling effort were discussed in section 1.2.1. Figure 88 displays the measured Charpy V-notch Impact Energy (LT orientation) for all the prototypes produced versus hardness, delineated by series.

Figure 88 shows a general trend, well understood in the literature, of decreasing impact energy with increasing hardness. The S53-6 series alloys falls outside of this general trend because of the large shift in DBTT inherent in their design. This shift in DBTT was also experimentally measured by heat-treating multiple samples to an identical condition and breaking them at various temperatures above and below room temperature. Figure 89 clearly indicates that while S53-2C and S53-4D are both on the lower shelf of toughness at room temperature, S53-6F is on the upper shelf. Additionally, S53-6F still retains 10ftlbs of impact energy at -80°C, approximately equal to the specified minimum of 300M at room temperature.

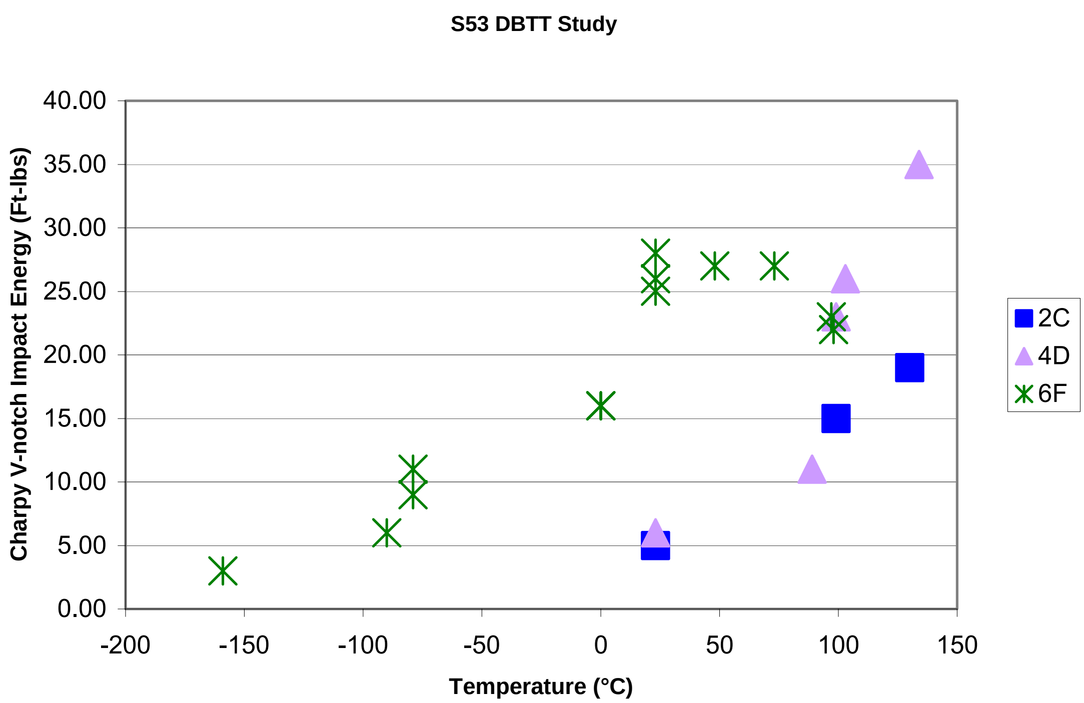


Figure 89 DBTT study of selected S53 prototypes

To present the large amount of data shown in Figure 88 in a complete manner, the following set of figures (Figure 90 through Figure 94) detail the measured impact energy for each alloy by series.

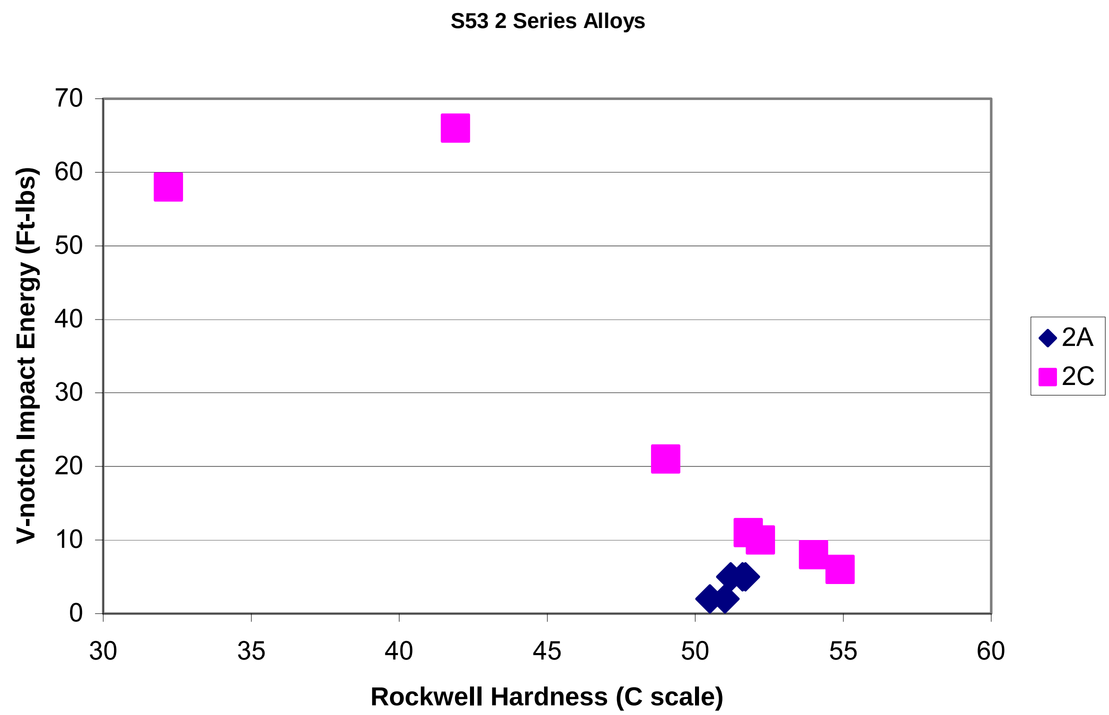


Figure 90 Charpy V-notch Impact Energy vs. Hardness for S53 2 series alloys

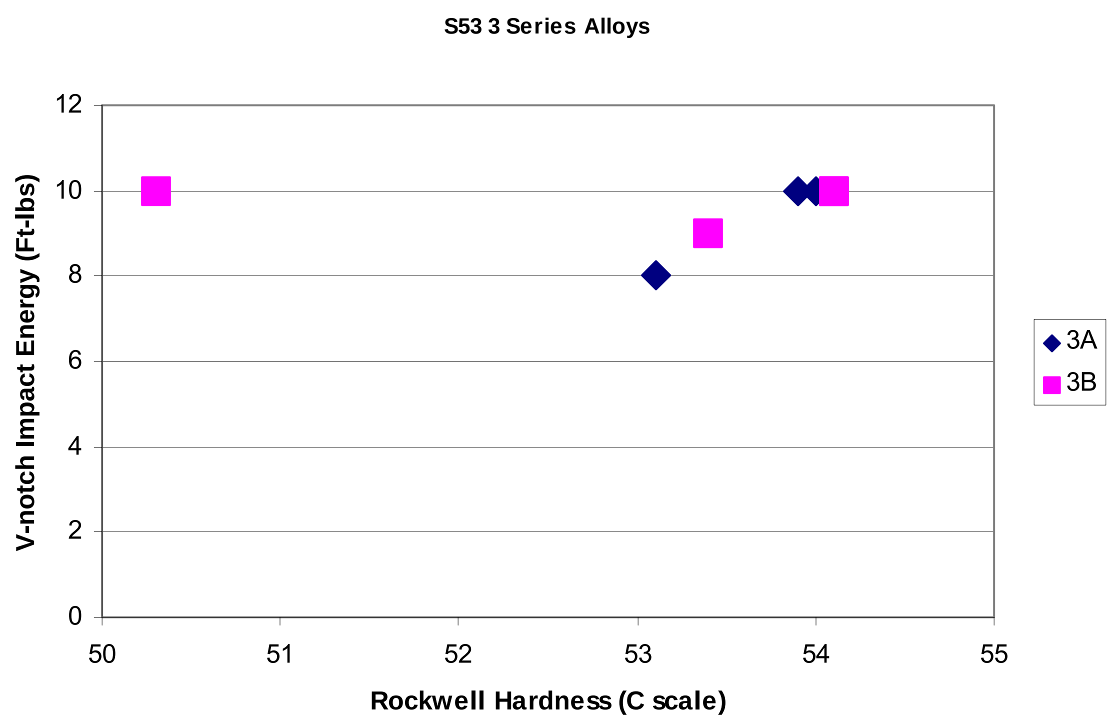


Figure 91 Charpy V-notch Impact Energy vs. Hardness for S53 3 series alloys

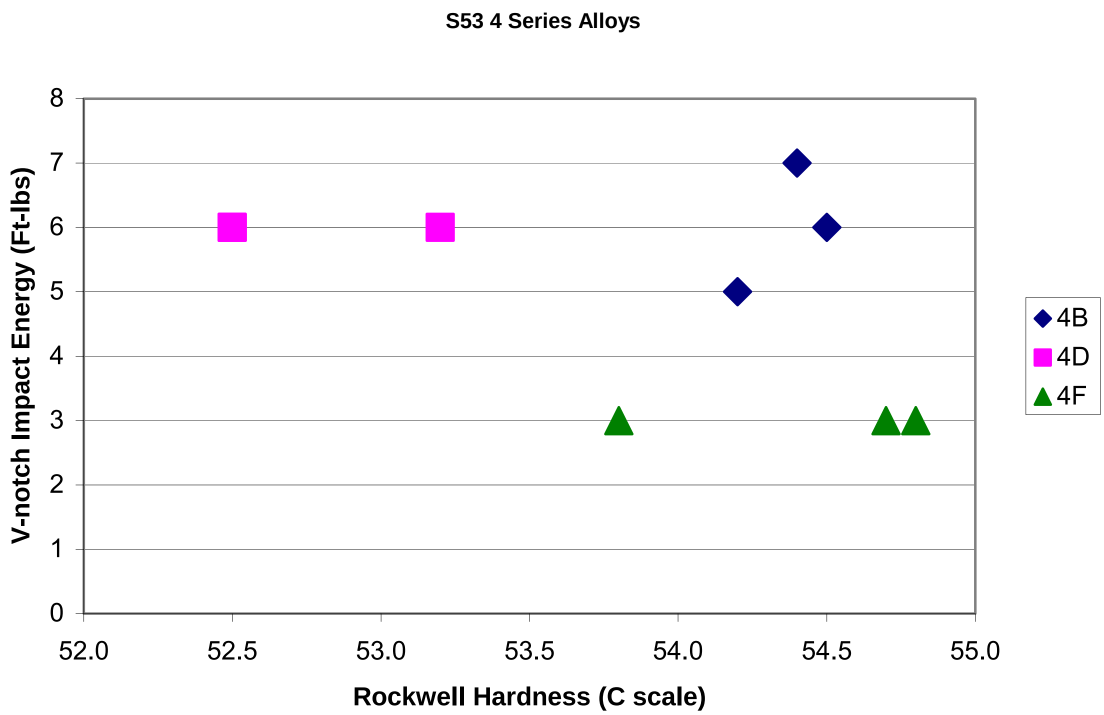


Figure 92 Charpy V-notch Impact Energy vs. Hardness for S53 4 series alloys

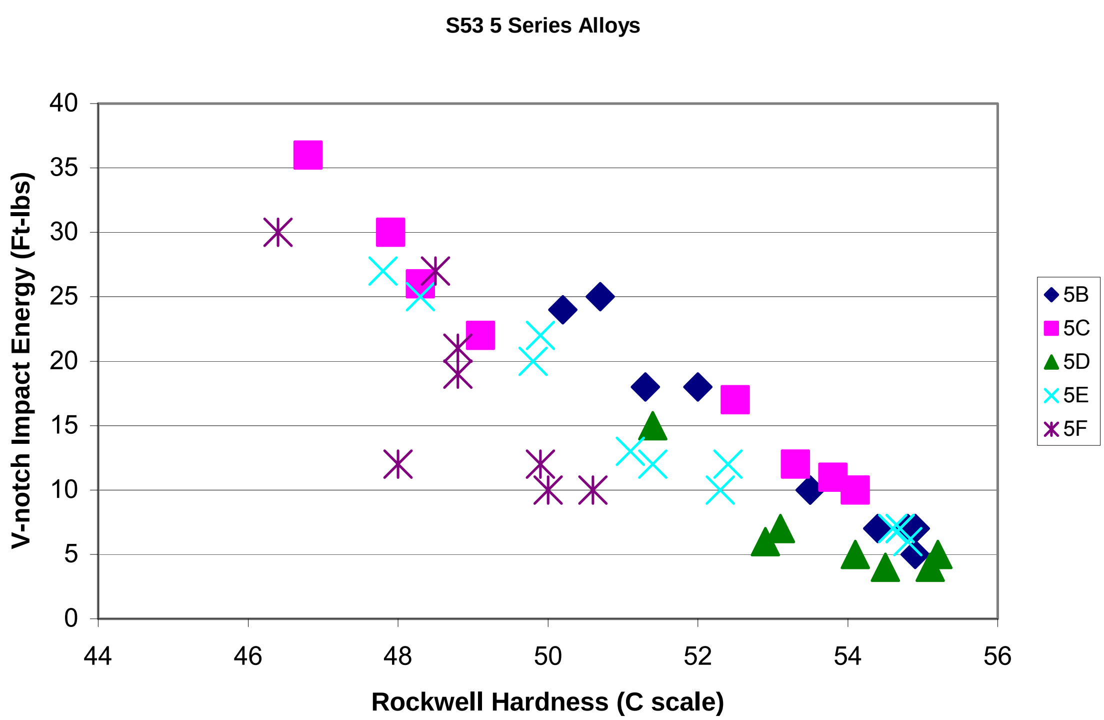


Figure 93 Charpy V-notch Impact Energy vs. Hardness for S53 5 series alloys

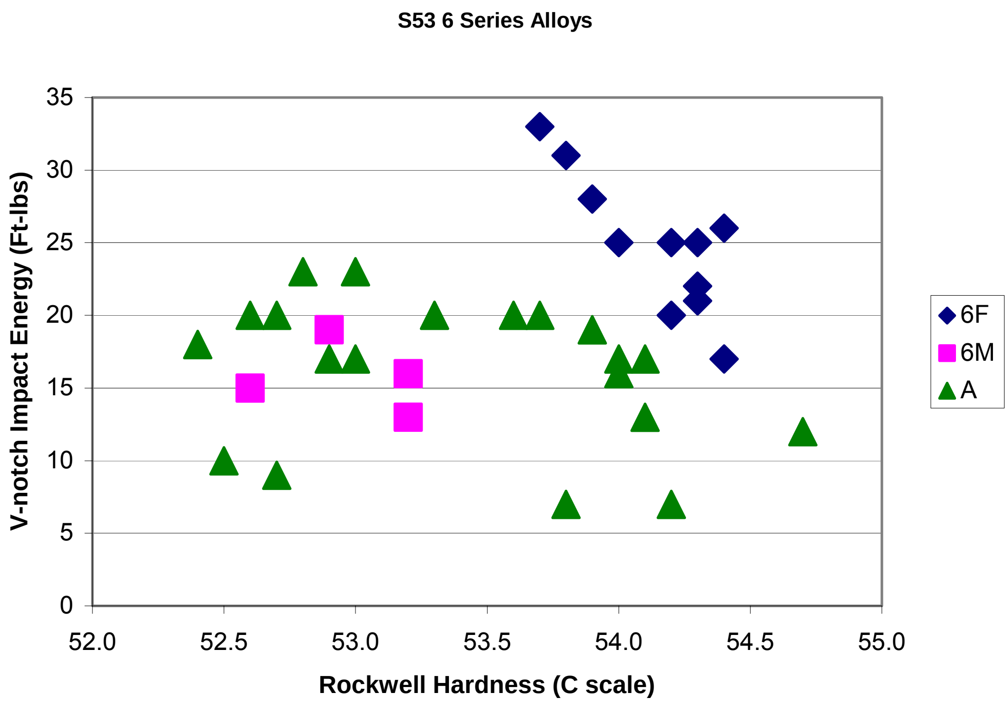


Figure 94 Charpy V-notch Impact Energy vs. Hardness for S53 6 series alloys

The Charpy impact energy of S53-6F, as shown in Figure 94, is 25-30 ftlbs. when hardened to the desired level of ~54 Rockwell C. This impact energy far surpasses the typical values for 300M, which are 8-10 ftlbs. The alloy redesign for the 6 series prototypes succeeded in decreasing the ductile to brittle transition temperature to well below room temperature, allowing S53 to easily exceed its impact energy and toughness goals.

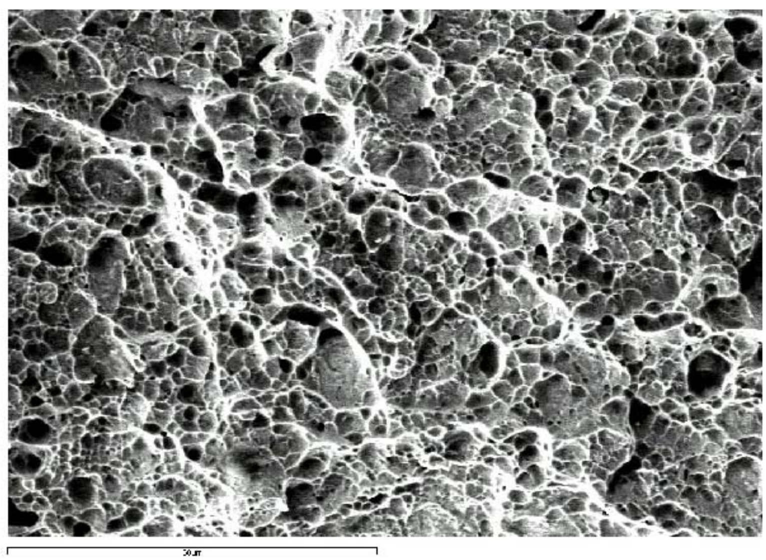


Figure 95 Typical SEM fractograph from S53A Charpy impact specimen, showing ductile fracture. Scale bar represents 30 μm

The ductile failure mode of the 6 series alloys is shown in a representative micrograph, Figure 95. The fracture surface shows microvoid coalescence, indicating ductile fracture behavior. Similar behavior was observed in all sixth-generation S53 alloys over a wide range of process conditions. No intergranular fracture was observed in any alloy under any process condition.

No significant difference in tensile properties was found between 300 lb and 3,000 lb heats of S53A, however, a significant reduction in impact energy was observed in the large scale heat. The 300 lb (WM14, 8" ingot) heat showed noticeably higher upper shelf impact energy as compared to the 3,000 lb (HC65, 17 ingot) heat. The actual compositions of these heats are virtually identical, with only very slight differences in major alloying additions, but there does exist a substantial difference in the nitrogen content of the heats. It is believed the difference in impact energy is due to the high nitrogen content of heat HC56, rather than related to differences in ingot size. A similar difference in impact energy was observed in the S53-2 prototype series, as shown in Figure 96. Prototype alloys S53-2A and S53-2C were both produced in 8" 300 lb. ingots, and the alloys had similar compositions. However, the nitrogen content in S53-2A was substantially greater, and a reduction in impact energy was observed similar to that in heat HC56. To prevent this reduction in impact energy, the maximum allowable nitrogen content in all future productions will be specified to be less than 10 ppm. In Figure 96 the master curve represents the response expected for an ideal microstructure with the alloy grain size, strength and composition. As can be seen the higher the N content of the alloy, the lower the alloy falls below the "ideal" master curve. As can be seen the lower N alloys do follow a line below the master curve. This is primarily due to cementite in the microstructure that limits toughness but is not explicitly accounted for in our current master curve analysis. Although S53 designs have been developed to minimize cementite in the final microstructure, at the high Cr contents required for corrosion resistance, some residual cementite is inevitable.

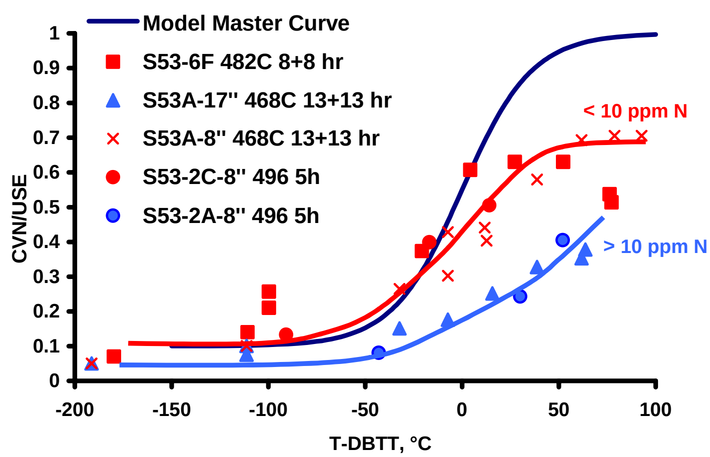


Figure 96 Normalized Charpy impact energy as a function of normalized temperature, showing the reduction in energy due to high nitrogen content.

Tensile

The other static property that is key for S53 replacing 300M in landing gear applications is strength. S53 was designed to have an ultimate tensile strength of 280ksi and a yield strength of 230ksi. Figure 97 shows the tensile data for all S53 prototypes studied. It is clear that in some heat treatment conditions on certain alloys S53 can meet the program goals in both ultimate strength and yield strength.

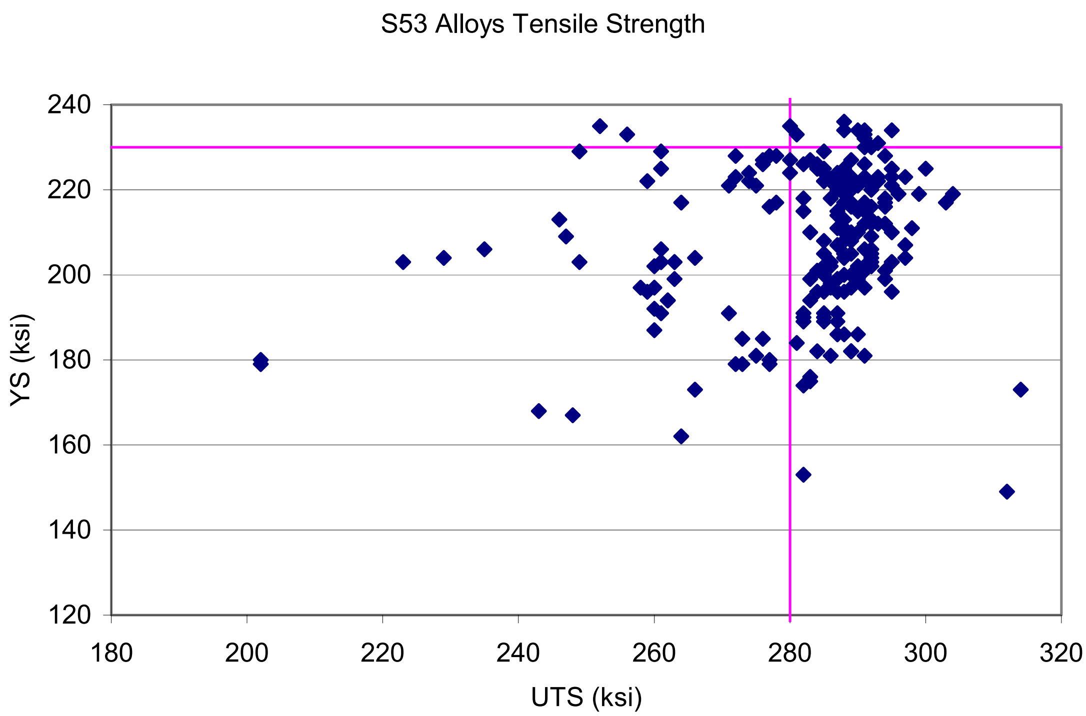


Figure 97 All S53 alloys, tensile data plotted as UTS, YS. Pink lines indicate program goals.

The preferred prototype, S53-6F, has shown YS/UTS combinations as high as 231,292ksi. However these numbers have been difficult to reliably repeat. QuesTek has developed heat treat specifications that can consistently achieve 215 ksi yield strength and 289 ksi ultimate tensile strength. Future work will focus on ways to consistently achieve the 230ksi yield strength known to be possible.

Fracture Toughness

Although Charpy Impact Energy was used to evaluate toughness through most of the prototypes, plain strain fracture toughness (KI_c) was also tested in select conditions. The fracture toughness goal for the program is 50ksi√in or greater, coupled with significant stress corrosion cracking resistance. (For detailed information on the stress corrosion behavior of S53 see later part of Section 1.4) As the early prototypes were generally low in toughness, the design goal was not met until the redesign for the 6 series alloys moved the DBTT below room temperature. Fracture toughness greatly improved and is now well above program goals, as seen in Figure 98. (All values are for LT orientation.)

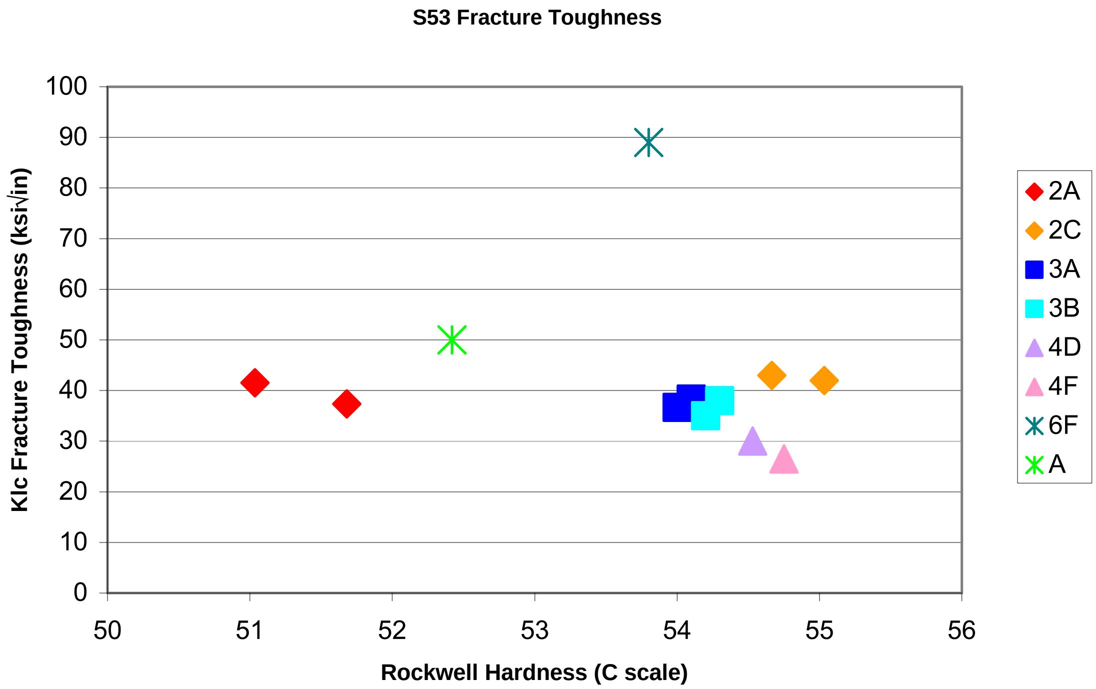


Figure 98 Fracture Toughness for various S53 prototypes vs. hardness

The measured fracture toughness of 89ksi√in in S53-6F is well above the typical values seen in 300M. This increase in fracture toughness may allow for a redesign on some components, or simply provide a more flaw tolerant design as compared to 300M.

Fatigue

Preliminary fatigue testing was done on two S53 variants. Both shot peened and unpeened coupons were tested. The goal of this preliminary testing was to provide a quick assessment of the new S53 material with two slightly different chemistries.

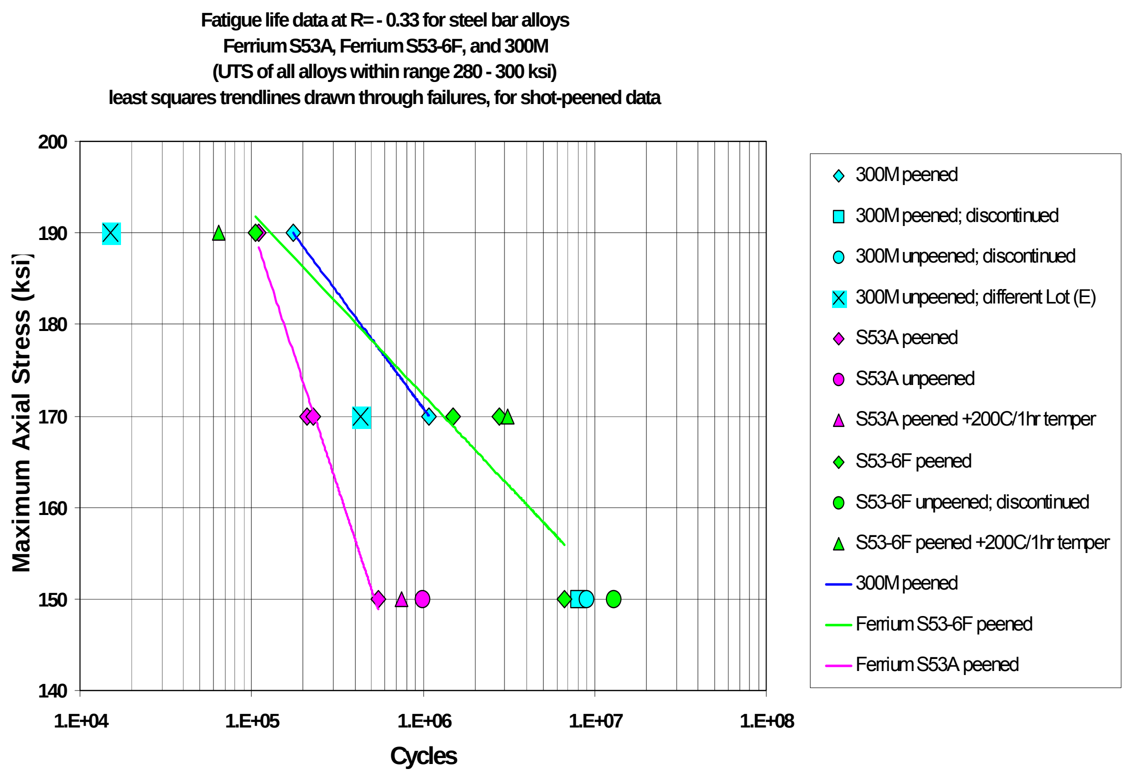
Testing Sequence and Results
Fatigue testing was carried out in accordance with Table 40.

Table 40 Fatigue test parameters.

Fatigue Specimen Code Number: (Shot-Peened specimen gage is coated with 0.63-inch length patch.)	Number of Fatigue Specimens to be tested for specific loading condition	Thickness of Plating or Coating: (mils)	Axial-Fatigue Stress Ratio = (σ min./ σ max.) (see Notes 2 - 4)	Specified Maximum applied Tensile Stress: (Ksi)
300M- 91	1	Un-peened; No coating	- 0.33	150
Ferrium - 1 (S53A alloy)	1	Un-peened; No coating	- 0.33	150
Ferrium S53-6F alloy: S53-6F -12	1	Un-peened; No coating	- 0.33	150
300M - 24	1	Peened:	- 0.33	150

		No coating		
Ferrium - 2 (S53A alloy)	1	Peened: No Coating	- 0.33	150
Ferrium S53-6F alloy: S53-6F-9	1	Peened: No Coating	- 0.33	150
300M- 29	1	Peened: No coating	- 0.33	170
Ferrium - 6 (S53A alloy)	2	Peened: No Coating	- 0.33	170
Ferrium S53-6F alloy: S53-6F-10	2	Peened: No Coating	- 0.33	170
300M- 34	1	Peened: No coating	- 0.33	190
Ferrium - 12 (S53A alloy)	1	Peened: No Coating	- 0.33	190
Ferrium S53-6F alloy: S53-6F-11	1	Peened: No Coating	- 0.33	190

Results of fatigue testing demonstrated that S53A has a lower fatigue life than 300M. However S53-6F did have a fatigue life very similar to 300M has shown in the S-N graph below.



Conclusions
Preliminary fatigue testing has shown that the new stainless steel alloy S53 does have fatigue lives comparable to 300M. Additional testing will be conducted to create fatigue allowables for S53. From a fatigue standpoint it appears that S53 could be used as a drop-in replacement for 300M.

Corrosion Resistance

introduction

Corrosion resistance is the key to S53 replacing 300M in landing gear components and eliminating the need for toxic Cadmium coatings. The general corrosion resistance of S53 must provide resistance to stress corrosion cracking in order to make the alloy a structural stainless steel. The specific design criteria used in this program was stress corrosion cracking (KIscc) of at least 35ksi√in. Initial estimates showed corrosion resistance equivalent, or similar, to 15-5PH would be sufficient to provide needed stress corrosion cracking resistance in a high toughness stainless steel. Whereas environmental exposure tests are costly and can take years to complete, QuesTek opted to use cyclic polarization testing in a 3.5% salt-water solution to accelerate corrosion experiments. Using common alloys 300M and 15-5 PH as standards, QuesTek was able to evaluate overall corrosion rate and pitting behavior of various S53 prototype alloys and design adequate corrosion resistance for the final alloy. **The overall corrosion rate of S53-6F, as measured from the accelerated test in mils per year, is not statistically different from 15-5 PH steel.**

Experimental Procedures

The test procedure for the cyclic polarization tests is as follows:

Test coupons were ground and allowed to air passivate for approximately 24 hours. Each coupon was then immersed into the test solution at ambient temperature, and allowed to stabilize for 22-30 hours. The cyclic polarization tests were conducted using an EG&G Model K0235 Flat cell, which utilizes a saturated silver/silver chloride reference electrode. An EG&G Model 273 Potentiostat/Galvanostat was used to make the measurements, along with the EG&G Model 352 corrosion software. A scan rate of 0.8 millivolts/second was used in order to provide adequate stability to the measurements.

In addition to the cyclic polarization tests, QuesTek also evaluated different passivating solutions by treating small coupons then submerging them in 3.5% salt-water for 96 hours. This study was performed on both S53A and S53-6F using six different passivation techniques, the majority of which included a chromate wash. Table 41 below outlines the different passivation conditions studied:

Table 41 Passivating Solutions Tested on S53A and S53-6F

Passivation	Chromate
70 ml HNO3 30 ml H2O 125F for 30 minutes	5g Na2Cr2O7 2H2O 95 ml H2O 145F for 30 min
70 ml HNO3 30 ml H2O 125F for 30 minutes	
25 ml HNO3 75 ml H2O 2.5 g Na2Cr2O7 2H20 125F for 40 minutes	5g Na2Cr2O7 2H2O 95 ml H2O 145F for 60 min
100 ml 10% M/V citric acid 131F for 12 min	5g Na2Cr2O7 2H2O 95 ml H2O 145F for 60 min
33 ml HNO3 65 ml H2O 2 g Na2Cr2O7 2H20 0.3 g (NH4)6Mo7O24	5g Na2Cr2O7 2H2O 95 ml H2O 145F for 60 min

129F for 40 minutes	
100 ml 10% M/V citric acid 140F for 18 min	6g Na2Cr2O7 2H2O 94 ml H2O 160F for 60 min

Observations were made twice daily throughout the 96 hours, documenting relative corrosion and pitting behavior.

Results and Discussion

The overall corrosion rate of various S53 prototypes and two standard materials, as measured by independent third party cyclic polarization testing and reported in mils per year, is presented in Table 42

Table 42 Corrosion Rates Determined by Cyclic Polarization

Alloy/Condition	Overall Corrosion (mpy)
300M	7
S53-2A	0.52
S53-2C	0.4
S53-4A	0.45
S53-4B	1.05
S53-4D	1.12
S53-4F	0.62
15-5 PH	0.26
S53A	0.56
S53-6F	0.33
S53-3A Peak	0.51
S53-3A Stage I	0.38
S53-4A Overage	0.88

These corrosion rates are compared graphically in Figure 99. Notice the order of magnitude difference between non-stainless 300M and the various S53 prototypes.

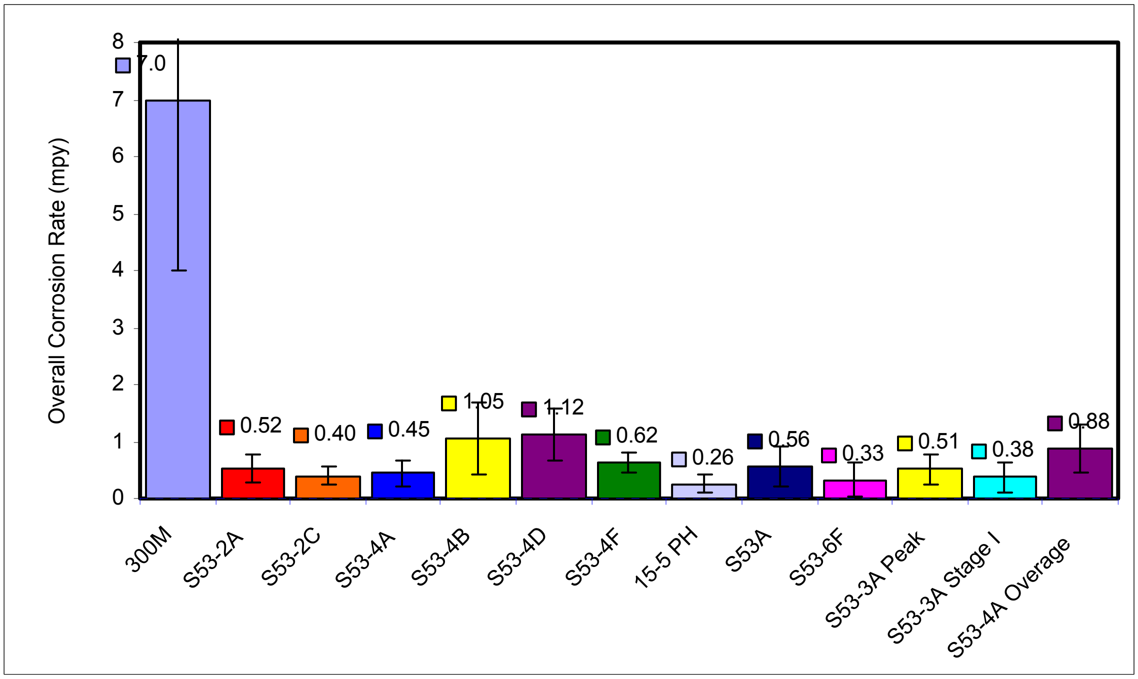


Figure 99 Corrosion Rates Determined by Cyclic Polarization

The cyclic polarization tests confirmed the designed corrosion resistance of the S53 prototypes as compared to non-stainless 300M. In addition, the tests also confirmed predicted differences among the prototypes; specifically that the best corrosion resistance would belong to S53-6F and the worst to S53-4D. S53-6F has the highest Cr content of any version of S53, and has become the preferred version based on its combination of corrosion resistance and mechanical properties.

The last three conditions presented in Figure 99(labeled Peak, Stage 1, and Overage) were tested to evaluate how various microstructures effect corrosion resistance. S53-3A was used to test the difference between secondary hardening (labeled as "Peak") and low temperature Stage I tempering (labeled as "Stage I"). In Stage I tempering, the steel is tempered at 200°C for 1 hour, precipitating only epsilon carbides. This creates a very different microstructure than the secondary hardened steels, which first precipitate para-equilibrium cementite that later dissolves in favor of M_2C carbides. Stage I alloys were presumed to have better corrosion resistance, as cementite is typically detrimental to corrosion resistance. The cyclic polarization results support this conclusion, but show that the difference is not drastic. (only .13 mils per year) One can conclude that secondary hardening is not a huge drawback over stage I hardening.

A second microstructural feature studied was the effect of overaging, or tempering much longer than would be appropriate for optimal hardness. As the material is over tempered the carbides grow and consume more of the corrosion inhibitors Cr and Mo. When the material is hardened to at or near its peak condition, the carbides are so small (less than 10 nanometers) that the constituent elements still participate in passivating film formation and aide in overall corrosion resistance. Significantly overaging a sample of S53-4A showed that the corrosion rate nearly doubles in the overaged state. (0.88 mils per year vs. 0.45 mils per year) Studying the effects of Stage 1 and overaging heat treatments on corrosion resistance has ensured that the microstructure designed and used in S53 is suitable for this corrosive environment.

The passivation study outlined previously in the Experimental Procedure section showed the effect of six different passivation treatments on S53. The study showed that in all cases S53 is stable in salt water after passivation. Many hours or days were needed to initiate corrosion, which in nearly every case started as crevice corrosion initiated at the bottom of the sample in contact with the glass dish. The passivation study identified a citric acid passivation with a dichromate wash (see the last passivation solution in Table 41) as the best solution for prohibiting corrosion. It is also of interest to note that while a dichromate wash is recommended for optimal corrosion resistance, it is not required. A simple passivation procedure of submerging S53 in 50% nitric acid (in water) at room temperature for 80 minutes also yields acceptable corrosion resistance.

A final note on corrosion resistance in S53 is that the material seems susceptible to pitting, especially when coupled against more noble materials. When using S53 in landing gear design, one must be cognizant to design in such a way that the material is not exposed to excess voltage that can drive active corrosion. The measured open circuit potential of S53 is approximately –0.7 volts. (vs. SCE) Corrosion becomes active and begins to dramatically effect mechanical properties when exposed to –1.0 volts (vs. SCE) or more. Further tests are needed to determine pitting rates and corrosion behavior in component geometries and environments; these tests are planned in late 2005 through 2006.

Stress Corrosion

Summary

Resistance to stress corrosion cracking is a key factor allowing S53 to replace 300M for landing gear components. The combination of improved fracture toughness and strong corrosion resistance allows S53 to outperform cadmium coated 300M in this key mechanical property. To measure a materials resistance to stress corrosion cracking, one may test for the threshold stress intensity parameter using a rising step load test in a corrosive environment. The threshold stress intensity parameter, commonly abbreviated K_{Iscc}, is 60 ksi√in in S53-6F at open circuit potential. **This result, well above the design minimum of 29 ksi√in., indicates that S53 has adequate resistance to stress corrosion cracking for uncoated use in landing gear components across most air and sea environments.**

Experimental Procedures

The rising step load stress corrosion tests were run by industry renowned LRA Labs in Newport Beach California. The test set-up can be seen in Figure100.

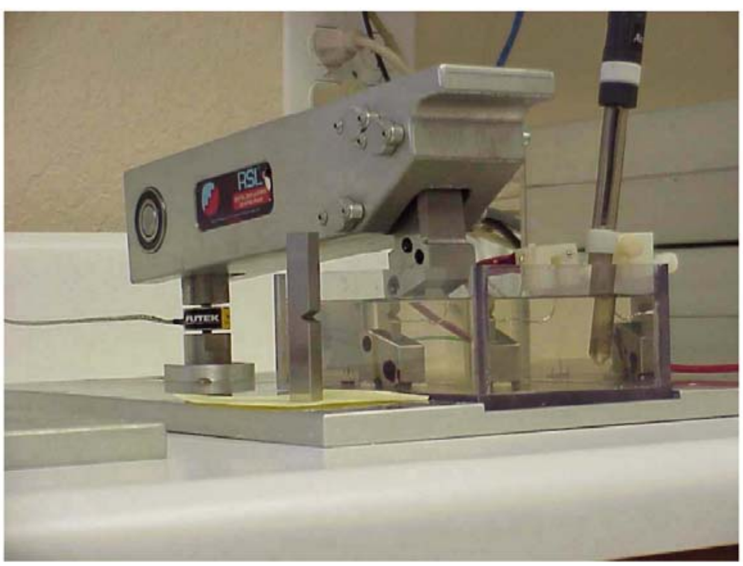


Figure100 RSL Apparatus

The test uses single edged notched bend specimens, which are first fatigue pre-cracked to yield a sharp crack. The samples are then submerged in the test environment and tested for K_{Iscc} in accordance with ASTM F1624. (Note: this provides the same value for the threshold stress intensity as the long-term method found in ASTM E1681.) Testing is performed in a 3.5% salt-water solution and a Saturated Calomel Electrode (SCE) is used to reference the applied potential. The Rising Step Load (RSL) apparatus then incrementally increases load at a given strain rate, in this case 7 x 10^{-8} s^{-1}. The applied potential can be varied to find the open circuit potential, (OCP) the potential at which the sample exhibits active corrosion and rust formation. By varying the applied potential below the OCP one can measure the stress intensity parameter the steel would likely experience in service.

Results and Discussion

The rising step load method was used to test stress corrosion cracking in two versions of S53: S53A and S53-6F. Unfortunately the fracture toughness in S53A was lower than desired, leading to relatively low stress corrosion cracking values. The fracture toughness, measured as 50 ksi√in., resulted in stress corrosion cracking ranging from 14 to 18 ksi√in. The other version of S53 tested, S53-6F, was tested in a high toughness condition and exhibited excellent stress corrosion cracking behavior. Fracture toughness of 89 ksi√in was measured in ambient conditions with corresponding stress corrosion cracking of 60ksi√in measured near OCP. In S53-6F, the measured OCP is just above –0.7V vs. SCE. At –0.5V vs. SCE active corrosion was observed.

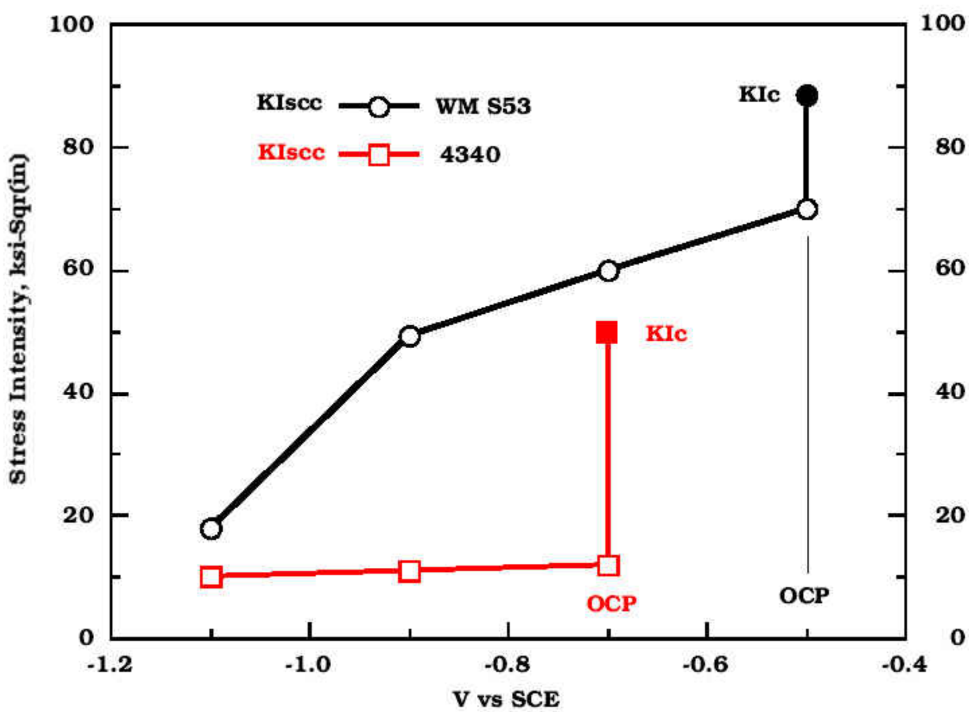


Figure 101 K_{Iscc} as a function of potential for S53-6F vs. common alloy 4340

The strong general corrosion resistance of S53 leads to good stress corrosion cracking resistance. This is especially apparent in Figure 101 when S53 is compared to common non-stainless steel, 4340. Non-stainless steels, including 300M, show dramatic decreases in toughness in corrosive environments. It is for this reason current landing gear is cadmium coated. S53 represents a brand new alternative to coated landing gear. As the stress corrosion cracking measured in the S53-6F is well above the program design goal of 29ksi√in., S53 is predicted to have adequate stress corrosion cracking resistance for uncoated use in landing gear components across most air and sea environments.

2.5 Cost and Value Metrics – Decision Tool

A decision tool has been created that can be used by DoD organizations to analyze the full cost of implementing clean technologies, and in particular by Ogden ALC to evaluate S-53 replacements for 300M.

Up to this point the primary cost analysis tool has been the ECAM model that is used by CTC. This tool works well, but because it was developed primarily to analyze process changes such as waste handling, it concentrates mainly on process costs. In analyzing materials substitutions, costs and cost savings can be dominated by other factors, such as the costs of qualifying and implementing the alternative technology and the savings that result from better performance. To incorporate all of these factors an Excel-based tool has been developed that we call C-MAT (Calculation for Material Alternative Technologies).

Most analyses (such as ECAM) simply compare the cost of processing using the current technology with the cost of processing using the new technology. The C-MAT tool, on the other hand, calculates the cost (or cost saving) that results from *implementing and using the new technology*. Thus it includes the way that the new technology is implemented – e.g whether 300M components are replaced with S-53 all at once, at scheduled overhaul, or only on failure. Because new materials technologies are usually implemented gradually, the tool permits phasing out the old technology while phasing in the new.

2.5.1 Description of the C-MAT decision tool

The C-MAT tool is based on an Excel spreadsheet and is described fully in the User Manual of Appendix ??. The tool can be used for both manufacturing and overhaul, and it can be applied to specific components (such as a strut), to systems of components (such as a landing gear or engine), or to an entire site (such as providing an analysis of the elimination of cadmium in an entire depot).

In order to carry out the analysis, we define Scenarios for the baseline technology and its replacement. Each Scenario is defined in an Excel workbook comprising a series of worksheets that contain the cost factors for each type of cost:

- Direct manufacturing (or overhaul) cost
- Indirect costs (including component and spares inventories)
- Capital costs (note that capital costs can also apply to the baseline if continuing to use the old technology requires expenditure on new plant or pollution control equipment)
- Depreciation (which can be turned off or set to the standard accounting methods of straight line, declining balance, double declining balance and sum-of-year's digits)
- Environmental costs (including waste disposal, water treatment, air handling, testing, etc.)
- Adoption costs, which include
    - Qualification tests
    - Specification development
    - Drawing changes
    - TO modifications
    - Costs of shutting down old technology plant (such as plating lines)
    - Training costs
    - Cost of money and cost of time-in-process
- Service failure costs, which include
    - Direct damage
    - Collateral damage
    - Investigation costs
    - Insurance and legal costs
- Cost of replacement components

Since a number of these costs vary with overhaul rate the Scenarios take into account changes in overhaul frequency that result from improved performance. Where a new technology substantially changes the risk of service failure (as S-53 does because of its substantially higher K_{1SCC}) the financial impact of this change can also be taken into account.

Any number of Scenarios can be constructed (either from a blank, or null Scenario, or from a previous scenario) and saved, and then compared with the baseline to permit options to be rapidly evaluated. This allows the user to use the tool as a true Decision Tool, rather than simply as a cost analysis tool, in which he can compare the costs and financial risks of different ways to make the changeover to the new technology, or compare the cost implications of different technologies that might provide different levels or performance or different probabilities of service failure.

Each of the costs and production rates can be assigned a estimate of accuracy that provides an estimate of the spread in the final financial calculations. This is in contrast to most other models, which produce "exact" numbers that in reality are frequently ill-defined. This accuracy estimate provides a picture of financial risk and gives a measure of the likelihood that the endeavor will produce an overall cost saving or a long-term loss.

A master workbook, the C-MAT workbook, computes the financial impact of the materials change by summing the costs of phasing out the old technology and phasing in the new, and subtracting this total from the costs of continuing to use the old approach. So as to accommodate both OEM manufacture and depot overhaul, the tool outputs the financial results in terms of both cash flow (with different OEM pricing options) and cost reduction. The tool produces the standard financial value measurements:

1. **Cost savings and cash flows** over a 15-year period.
2. **Net Present Value (NPV)** – This is the value today of the up-front investment and implementation costs together with the future income stream of cash flow or cost reduction. It is determined by the standard discount rate (i.e. the amount by which the value of money is assumed to decrease every year).
3. **Internal Rate of Return (IRR)** – This quantity is related to NPV and is the rate of return that the same investment would need to earn to have a NPV equal to that of making the technology change. In essence, IRR is a way of comparing potential uses for the same money.
4. **Return on Investment (ROI)** – This is the annual income divided by the initial investment. This is the most common definition of ROI; some analyses use a cumulative form that divides total profit by total investment, which therefore increases over longer measurement periods.
5. **Payback Period** – This is the time (in years) until the cumulative cost crosses the zero axis (for a money-saving investment, of course).

The tool has been provided to Doug Wiser and to Craig Edwards of Ogden ALC, both in Windows and in Macintosh format.

2.5.2 Cost evaluation of S-53 for landing gear component replacement

C-MAT analysis has been applied to a specific component that Ogden is considering replacing with S-53 – the KC-135 Main Landing Gear Drag Brace Strut. This item (shown in Figure 102) is a hollow bar made of 300M steel. It is subject to interior corrosion and stress-corrosion cracking, and it is very difficult to inspect. Given the age of the KC-135 fleet Ogden is concerned that it may become a source of increasing failures over the coming few years, especially with our increasing use of combat aerial refueling.

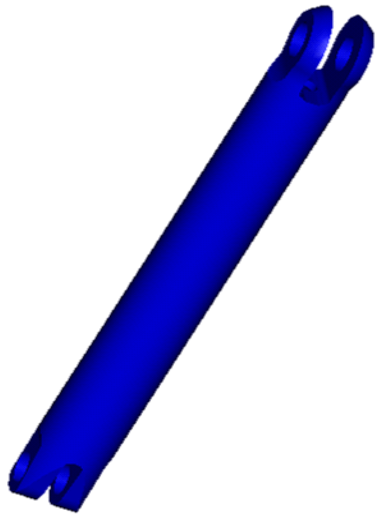


Figure 102 KC-135 MLG Drag Brace Strut.

This was a particularly good test of the model since General Atomics had already carried out an analysis of replacement of this part for Ogden[8]. It was therefore possible to compare the two models directly to ensure that the C-MAT model was working correctly.

GA assumed that the 300M drag brace strut would be replaced with a new S-53 strut as each landing gear came in for overhaul. The result of a direct comparison between the GA and C-MAT models using the same assumptions on component cost, repair cost and repair rate is shown in Figure 103. The solid line (GA calculation) and blue bars (C-MAT) are the cumulative annual costs of using the present technology. The dashed line (GA) and the red bars (C-MAT) are the cumulative costs for S-53 components. It can be seen that the two models are in close agreement, showing that the C-MAT calculation is being done correctly.

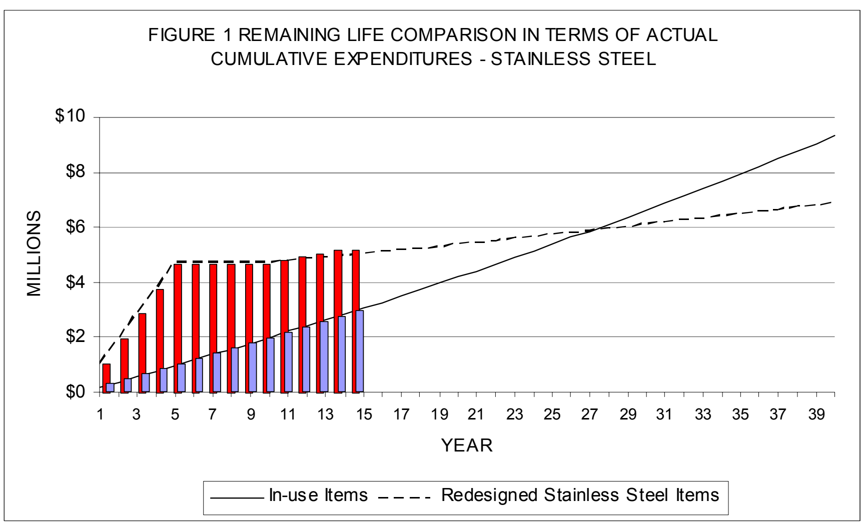


Figure 103 Comparison of GA computations and C-MAT model for KC-135 Drag Brace Strut.

[8] "Cost Comparison Between the Redesigned KC-135 MLG Drag Brace Strut and the Existing Strut", Todd Walker, General Atomics (February 2002).

Note that the C-MAT model runs out to 15 years, as that is the maximum time period over which most decisions are considered. This may be extended in later versions, as there are situations where one must measure the long-term costs and benefits of diffusing a technology into more and more weapons systems over a long time period. In fact, as we have begun to apply the model to other situations and to consider the true costs and benefits of environmental changes, we see that one must often take into account the impact of clean technology across an entire weapons system or overhaul site, rather than solely to the specific component in question. This is because materials changes are usually made gradually as users become comfortable with the alternative. A gradual replacement is also a way to reduce risk. A change in a single component may have little impact by itself, but the effect of adopting the technology can become system-wide in the long run as it migrates into broader use.

Table 43 Parameters used in financial calculations.

Parameter	Baseline Cd plated 300M	S-53	Notes
Discount rate	4%	4%	For depreciation
Cost of money	4%	4%	For inventory
Inflation rate	0%	0%	
# fielded items	356	356	
Overhaul cycle	5 yrs	-	
Annual repair rate	71	-	GA assumed no repair as no corrosion
Annual condemnation rate	15	-	
Direct repair cost	$1,564	$0	
Component cost	$5,288	$7,033	33% cost increase (reflecting alloy cost differential)
Inventory	5% items in service		
Service failures	1 per 8 years for $1 million, 1 per year at $15,000	33% (1 per 24 years at $1 million, 1 per 3 years at $15,000)	33% probability of SCC and corrosion failure.

Table 43 gives the parameters used in the calculation. Note that the environmental costs of Cd plating and chromate conversion were not included in the GA calculation, and are relatively low for this small item in any case. There are no environmental costs (except for cleaners) for the S-53 component.

The NPV based on the same Scenario is shown in Figure 104, which plots NPV taken over 0 – 15 years. NPV depends on the time over which the calculation is made. If one only measures NPV over a few years the up-front costs (in this case the cost of replacement parts) overwhelms the long term benefits (lower maintenance cost). Since the cumulative cost of adopting S-53 goes below that of the existing technology in 27 years, the NPV in 15 years is still negative.

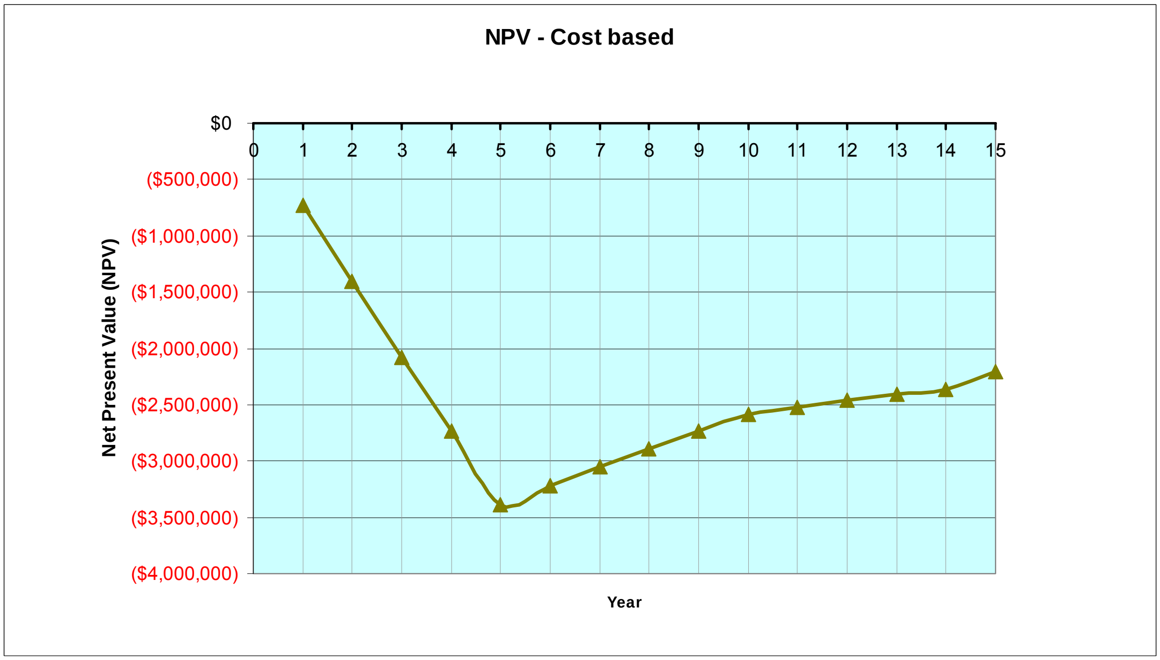


Figure 104 Net Present Value of GA Scenario, taken over a period of up to 15 years.

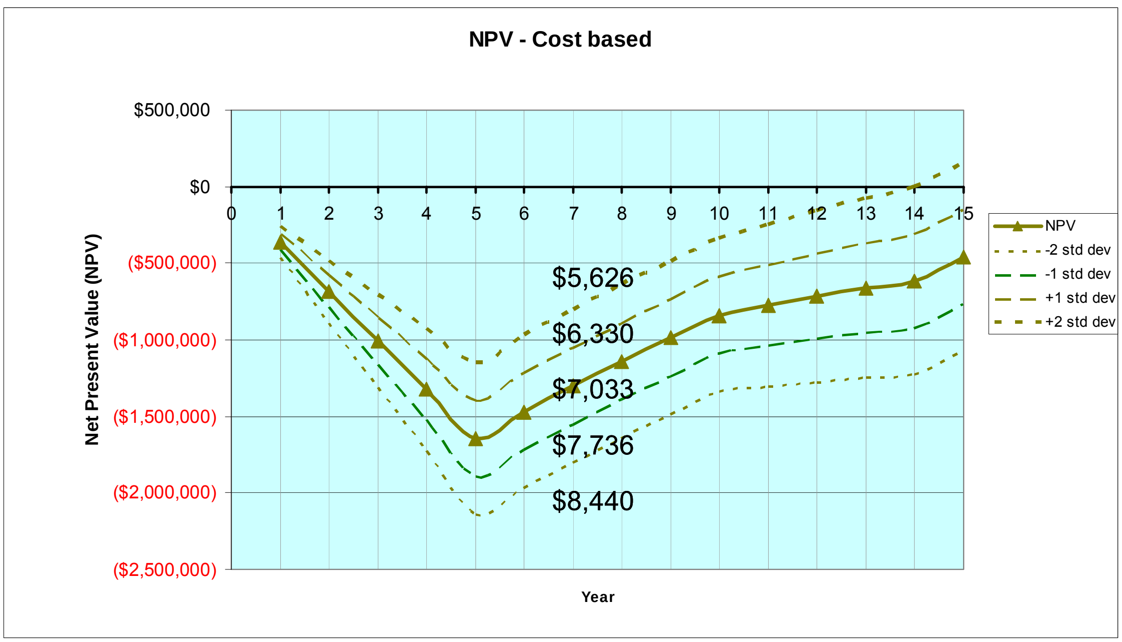


Figure 105 Effect on NPV of different component cost assumptions.

C-MAT permits one to quickly examine the effect of different assumptions and errors in those assumptions. For example, GA assumed an S-53 component cost of $12,000 vs the current cost of $5,288. A more realistic cost would be $7,033, which is a 33% increase that reflects the material cost differential (assuming the same manufacturing cost). The effect of varying the cost assumptions is shown in Figure 105. Even at the lowest cost for S-53 the payback is still very slow.

However, the reason that Ogden wishes to make the change is the risk of catastrophic failures from stress corrosion cracking, which they fear will rise over the coming years, given the age of the system, the difficulty of measuring corrosion on the ID of the part, and the impossibility of detecting stress corrosion cracks on components in the field. There has been only one major Class B failure (damage >$500,000) in the past 10 years resulting from this part. However, if we now allow for the possibility of increased failures – one corrosion failure/year resulting in $15,000 in damage and one major SCC failure every 8 years, resulting in $1 million in damage – the picture looks very different (Figure 106). This figure shows the effect of including uncertainties in the estimates. The payback period is now 7-10 years and the NPV over 15 years rises to $3 million.

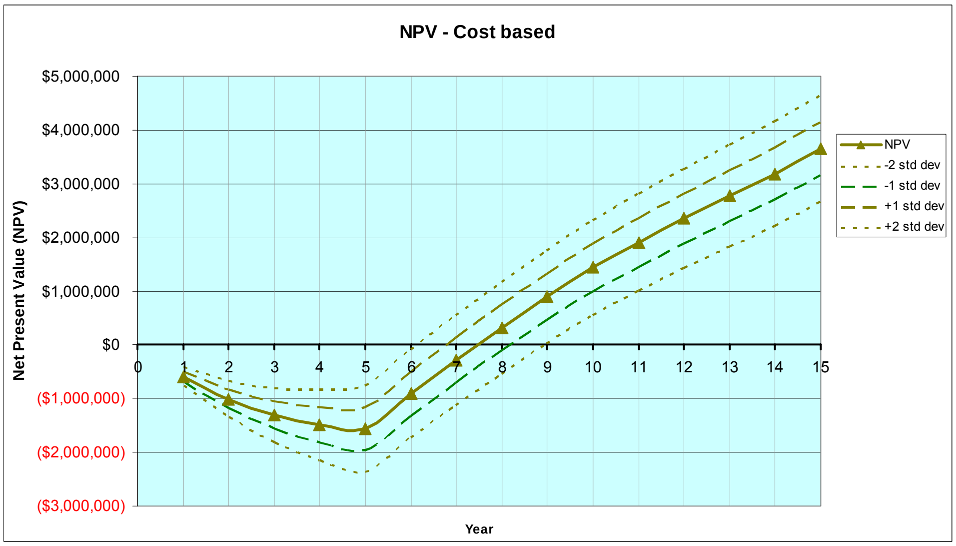


Figure 106 Effect of including likely corrosion and SCC failure costs.

Combining this with a more reasonable component cost of $7,033 instead of GA's original $12,000 value makes the change even more attractive (Figure 107). The change starts paying for itself very quickly as the cost of new items is balanced out by the reduction in failure cost.

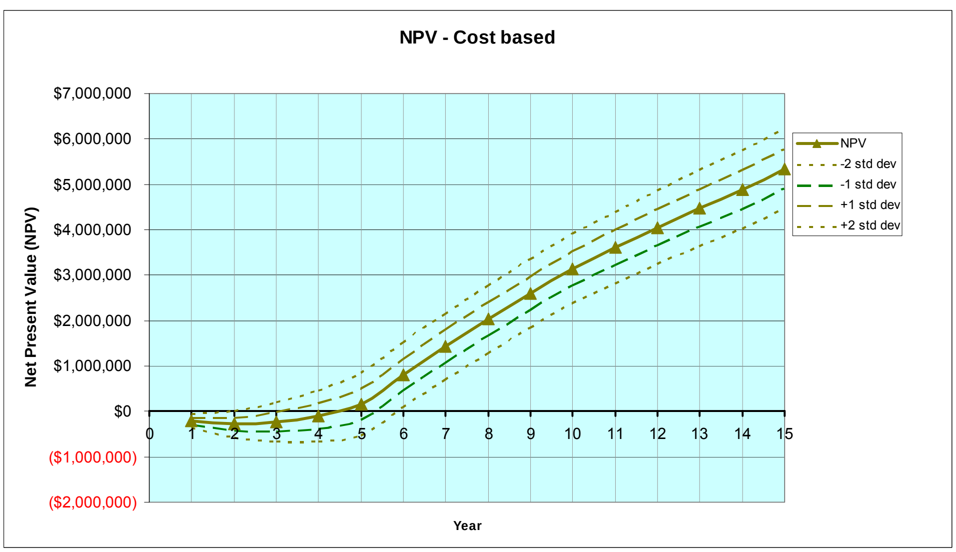


Figure 107 Effect of including corrosion and failure cost, with a more reasonable component cost of $7,033.

The cumulative cost for this situation is shown in Figure 108. This shows the payback over 15 years.

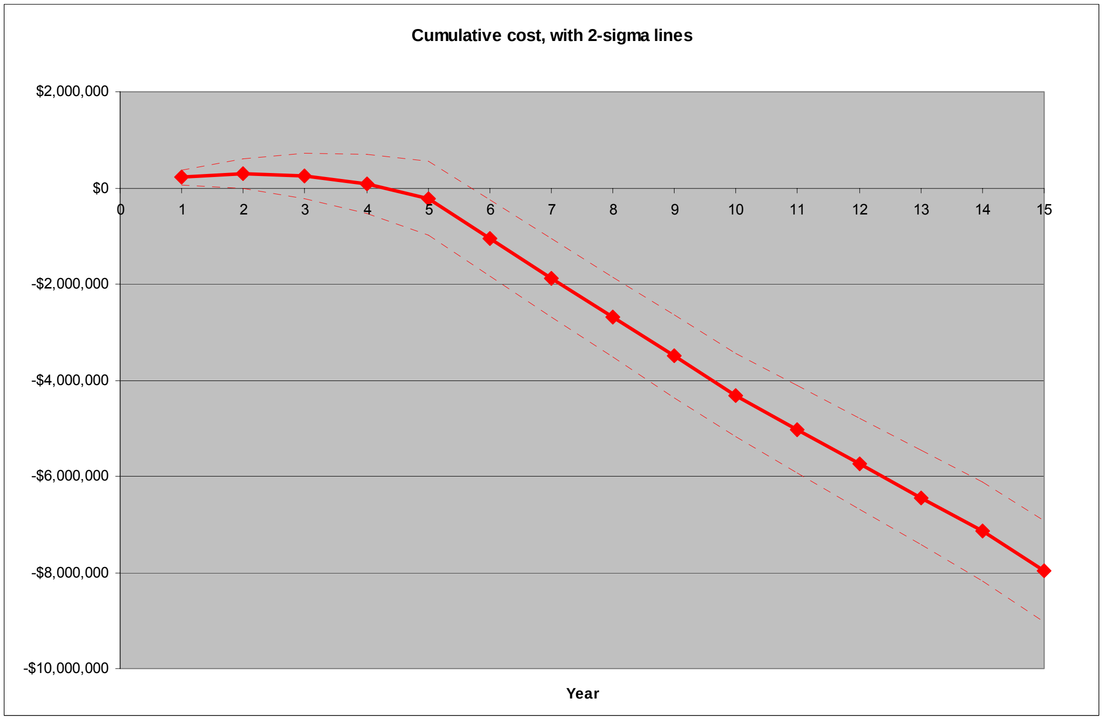


Figure 108 Cumulative cost of including lower component cost and failure cost.

3. Conclusions and Transition

3.1.1 Final Assessment

The SERDP program had completed 4 design iterations and evaluated the S53 alloy to production scale ingot processing. Alloy producability has been investigated and optimal processing conditions evaluated.

For S53 to be a viable replacement for 300M in landing gear applications it must demonstrate equal mechanical properties (tensile, yield, elongation, RA, fatigue) and improved corrosion and stress corrosion cracking properties. The evaluation in the SERDP program has demonstrated desired goals for ultimate tensile strength, ductility, fracture toughness and fatigue. Corrosion and stress corrosion tests have met program goals but identified a higher sensitivity to pitting corrosion attack. The program has determined adequate weldability, compatibility with coating and surface modification processes, and machinability in the fully hardened state. The current alloy design did not meet the yield stress goal of 230 ksi, demonstrating typical values of about 215 – 220 ksi. A yield stress deficit will not affect the design of a great majority of landing gear components since ultimate tensile stress generally sets the design. Of greater concern is lower fatigue due to the low yield stress. The fatigue studies did not show a fatigue debit over the 300M baseline alloy. Machinability evaluations of the S53 alloy in the annealed state indicates that additional annealing process development will be needed to reduce tool wear and increase stock removal rates to commercially viable levels. Annealed S53 contains a significant amount of retained austenite and will likely require cryogenic treatment in the annealing cycle as is common for many commercial high-strength stainless alloys such as Custom 465.

3.1.2 Transition Planning

In transition of the S53 alloy to commercial application in aerospace structures the first objective is to develop an appropriate specification. AMS specification of the alloy will require three production heats of the alloy processed using similar parameters. A draft specification was developed in the SERDP program and serves as the basis for the development of a candidate AMS specification. Beyond an AMS specification most flight critical components will require A-basis MIL-HNDBK-5 allowables (now superseded by AR-MMPDS-01. QuesTek can apply AIM technology developed by DARPA to predict A-basis allowables.

Appendix A
CMAT USER MANUAL

C-MAT

Calculation for Material Alternative Technologies

User Manual

DoD EPA DOE SERDP
Strategic Environmental Research and Development Program
Improving Mission Readiness Through Environmental Research

ROWAN TECHNOLOGY GROUP
Linking Global Technologies with Markets

About C-MAT

C-MAT is a Microsoft Excel-based spreadsheet Decision Tool for assessing the cost-effectiveness of new technology alternatives for materials or process substitution. It is part of a comprehensive Implementation Assessment package to evaluate production readiness, technology gaps, cost and risk of adopting new technologies. For more information go to http://www.rowantechnology.com/implementation.htm

The development of this software tool was funded by the Strategic Environmental Research and Development Program (SERDP) of the US Department of Defense.

Requirements: Microsoft Excel spreadsheet software. This software has been checked for harmful viruses. This spreadsheet utilizes macros and Microsoft Visual Basic (VBA) programming. Tools/Macro/Security must be set to Medium or Low to use automatic features of this software.

For information or assistance contact:

Keith Legg, Rowan Technology Group

Phone: 847-680-9420; email: klegg@rowantechnology.com

Copyright

Version 2.0
Release date, December 2003
Developed in Microsoft Excel 2002

TABLE OF CONTENTS

CHAPTER 1 GETTING STARTED

C-MAT is a financial tool to aid in the cost-benefit analysis of materials alternatives. It can be used to evaluate the relative costs and savings entailed in replacing one material or coating with another, both for the original equipment manufacturer (OEM) and for subsequent maintenance, repair and overhaul (MRO) operations.

This C-MAT cost benefit modeling software is part of a broader package of analysis tools and methodologies called Implementation Assessment, which generates a complete picture of a new technology and what it will take to bring it to production:

- Technology Analysis
  - Its degree of development
  - Technology gaps that must be filled for it to be brought to production
  - What will be required to bring the technology to production
- Cost-Benefit Analysis (this C-MAT decision tool), which includes
  - Development cost
  - Implementation cost
  - Performance-based life-cycle cost savings (e.g. fewer overhauls and service failures)
- Risk Analysis, including
  - Technology risks
  - Financial risks
  - Performance risks

Details on Implementation Assessment, can be found on the Rowan web site at http://www.rowantechnology.com/implementation.htm

Updates and other information on the C-MAT Decision Tool may be found on the HCAT workgroup site at http://www.materialoptions.com

Although every attempt has been made to make this software as simple to use as possible, we recognize that it is, of necessity, quite complex in order to accommodate the many options involved in materials substitution. It may therefore have a rather steep learning curve. Should you wish to have a C-MAT analysis or full Implementation Assessment done for your application, please contact Keith Legg, Rowan Technology Group; Phone: (847) 680-9420, e-mail: klegg@rowantechnology.com.

Each spreadsheet page includes an e-mail button. Please let us know if you come across difficulties, errors or annoyances, or if there are common situations that should be incorporated into the model.

CHAPTER 2 INSTALLATION

C-MAT does not require any special installation procedures. The program consists of three basic files:

1. C-MAT.XLS - This is the master file that serves as the portal to the various scenarios that you can set up for your cost analyses
2. Scenario00.XLS - This is the 'Null Scenario", which is the basic Scenario spreadsheet that contains no data. You can build any scenario from Scenario00.XLS by inputting the relevant data and choosing among the various options for what you wish to include.
3. C-MAT.CHM - This is the Help File for the spreadsheets.

If you intend to carry out cost analyses for several items it is recommended that you create a folder on your computer for each new item and copy these three files in the folder. Then you can choose any number of variations and scenarios that describe or analyze the costs in different ways (e.g. including or excluding inventory or service failures, incorporating different sets of estimates for poorly-known costs, etc.).

Security

C-MAT requires macros to run properly. Be sure that your Excel Security is set to Medium so that the macros built into this spreadsheet are able to run. To change Security settings:

- Open Excel itself (not the C-MAT spreadsheet)
- Click on Tools\Options and click the Security Tab
- Click the Macro Security button and the Security Level tab.
- Click the Medium box.

When you open C-MAT or any Scenario file Excel will display a box asking if you wish to enable or disable macros. Click Enable Macros. With some versions of Excel, the program will ask this question several times while opening C-MAT (once for each Scenario file it opens). You must enable macros each time.

CHAPTER 3 NAVIGATION AND DATA ENTRY

Navigation

In general you can only move the cursor to either yellow data entry cells, buttons, list boxes and check boxes. All other parts of the spreadsheets are locked to prevent accidental overwriting of the calculation. When you hit Enter after entering data in a cell the spreadsheet will take you to the next cell. You can reach other data entry cells using the cursor or mouse. The various buttons and check boxes will take you to whatever part of the spreadsheet you need to be to enter the data. Note that if you do not see all the available lines or columns you may not be viewing the entire page because the top section of the page, containing the column headings, is usually locked so that you can always see them. Some of the rows in the movable bottom section of the page may be hidden beneath this stationary top section. If this happens, simply drag the bar at the far right all the way to the top so that you see all the available rows. Likewise, drag the bar beneath the bottom right of the screen to the right or left to view the information from all the columns.

You will be moved to the appropriate sheet as you press different buttons. You can go to a specific sheet by clicking the labeled tabs at the bottom of your screen.

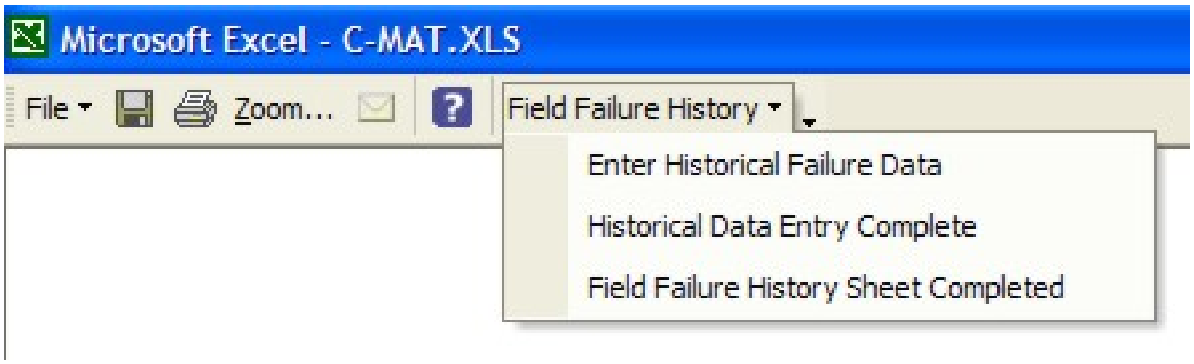
Data Entry

You can enter data in any yellow cell by clicking on it and typing. (Note that $ and % signs are added automatically - do not type them.) Every time you enter data and press the Enter key the data will be entered and the cursor will move to the next yellow cell. You cannot enter data into any other color cell - they are all locked to prevent their being accidentally overwritten. You can change any previously entered data just by clicking on the appropriate cell and retyping the entry, or by double-clicking in the cell and editing it directly.

Note: Data entry is not complete until you press Enter. You will not be able to use the buttons or list boxes until you press Enter after entering data in a cell.

The Toolbar

Each C-MAT and Scenario sheet has a toolbar containing a drop-down menu of File options, Save and Print buttons, a Zoom option, an e-mail button to contact Rowan Technology Group, and a context-sensitive Help button. In addition there is a menu button with a drop-down menu that allows you to jump to different places within the sheet, or back to the main navigation sheet (see below).



Moving within and between sheets

All sheets include a menu item named with the sheet name that takes you to detail entry areas, back to the beginning of the sheet, or back to the primary entry sheet (i.e. the Scenario Choose sheet in C-MAT.LXS or to the Assumptions, Inputs sheet in any Scenario. e.g. In the attached figure from the C-MAT spreadsheet the Field Failure History button does the following:

Enter Historical Failure Data - Takes you to the section of the sheet in which you can enter detailed data

Historical Data Entry Complete - Takes you back from detailed data entry to the top of the sheet

Field Failure History Sheet Completed - Takes you back to the Scenario Choose sheet.

CHAPTER 4 OVERVIEW OF THE FINANCIAL MODEL

The Decision Tool is based on a financial model of the entire manufacturing and qualification process, including all of the costs of testing, qualification, and paperwork changes, and the costs of service failure (if desired).

The model is designed to be used by different types of organizations:

- Original Equipment Manufacturers (OEMs) – These users will be primarily concerned with manufacturing cost changes, liability and warranty cost changes, and changes in revenue streams. OEMs are most likely to base decisions on cash flow and profitability.
- Maintenance, Repair and Overhaul (MRO) organizations – These users (such as military depots) will be primarily concerned with maintenance cost changes, environmental cost changes, and reduction of both technical and financial risk. MROs are most likely to base decisions on cost savings.

The tool provides both tabulated and graphical outputs to assist in decision-making.

Data Input

The financial details are contained in the worksheets of each Scenario spreadsheet. Each worksheet is designed so that the user can enter either detailed financial information (ensuring that important costs and savings are included) or enter the data in a simple summary form. Each sheet also includes various model projections as well as the ability to enter separate data in each category for each year manually.

Each sheet includes a cell for an estimate of the accuracy and variability of the information (where accuracy is defined as 95% probability, or two standard deviations).Ideally this number will be determined based on existing cost data. Where prior data cannot be used, it should be assigned a reasonable value that reflects the accuracy with which it is known.

Note: Since the final calculation takes the difference between the cash flows in the different Scenarios, it does not matter whether the user inputs the actual costs or simply the difference between the baseline and the alternative Scenarios.

Then the user simply enters the change in cost in each category. Higher costs or incomes are entered as positive numbers, while reductions in cost or income are entered as negative numbers. However, actual production and overhaul numbers do of course need to be entered in the alternative Scenarios, not the difference (since the difference will normally be zero).

Treatment of Inflation

Inflation is entered into the C-MAT.XLS spreadsheet, since it is a universal number. To eliminate any consideration of inflation, the Inflation Rate value is set to zero. Inflation is incorporated into the following costs:

- Direct Manufacturing
- Indirect Business
- Environmental
- Field Failure

It is not incorporated into Capital Cost and Adoption Cost since these items are assigned by year by the user. It can be incorporated into the following at a different rate, since costs of large items may not follow the inflation rate directly:

- MRO new component purchase
- Revenue

Tabular and Graphical Output

All of the measures of value (except Payback Period) depend on the length of time over which they are measured. The primary output is provided in the form of graphs of NPV, ROI, and IRR as a function of time. This permits the user to understand how the value measures change with time. The primary financial measures (cash flow, capital/adoption costs, operating costs, gross revenues, and cumulative cost and cash flow) are also provided graphically. Each scenario also contains graphical outputs of all the financial items in the model.

Graphical outputs usually include the upper and lower bound values derived from the estimates of accuracy. This shows the spread in expected values as a function of time.

Scenarios

A Scenario is simply a financial picture of the costs associated with a particular change. It includes all the costs estimates associated with

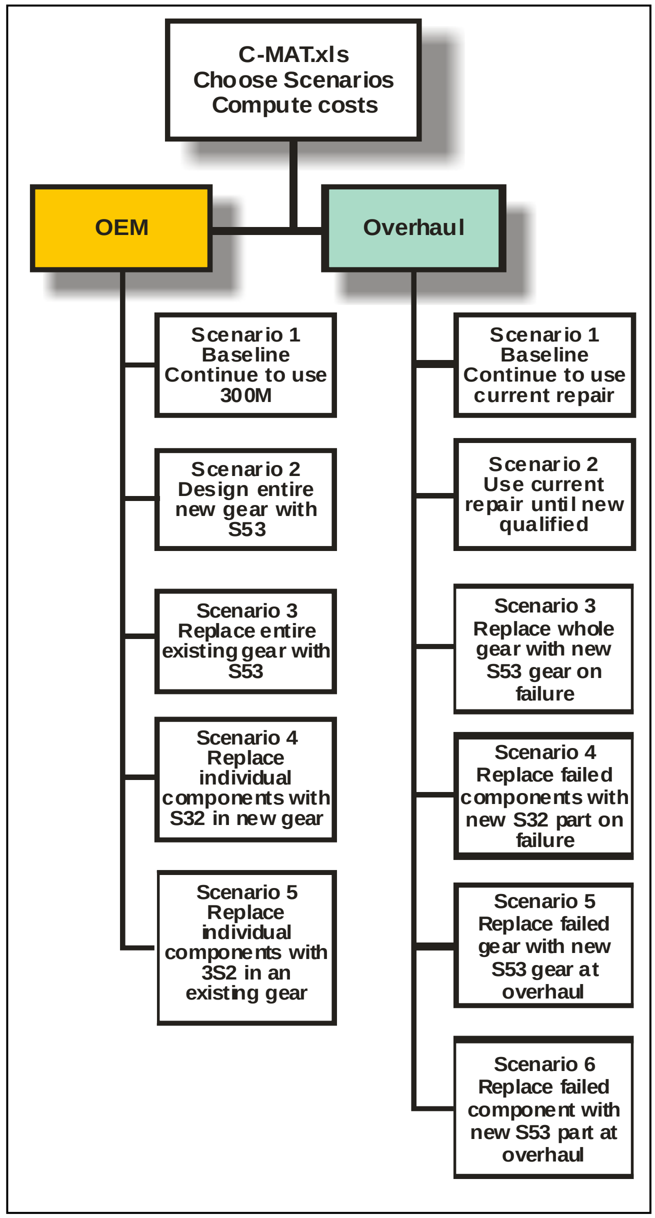
- Changing the material
- Manufacturing (both direct and indirect costs)
- Capital expenditures for new equipment
- Purchasing new components
- Environmental compliance
- Adopting the new technology (qualification, paperwork, drawing changes, etc.)

It also incorporates

- When the change is made (immediately, on failure, at overhaul, etc.)
- How the change is made (replace the whole item or a part)

One Scenario must always be the baseline – i.e. what is done today. The tool allows the user to generate up to 99 Scenarios covering different types of situations, items, or cost estimates. 25 of these are readily accessible in the model sheets. This allows you to compare a number of "what-if" scenarios to determine which option is the least expensive or carries the lowest financial risk.

Basic models for some of the most likely Scenarios are provided. The user can readily build new a new Scenario off an existing one or from a blank Scenario sheet (i.e. a sheet with no existing data).



Details of model cost items

In its general form, this decision tool financial model is designed for use by people who need to evaluate the costs and savings involved in switching from an existing technology to a new technology. This particular version of the tool is intended for use by OEMs and military maintenance depots considering a change from existing steel used in aircraft components (e.g. 300M used in landing gear) to a new high strength stainless steel (designated S53).

Capital Costs

Capital costs include any costs for permanent machinery and equipment needed to adopt the new technology, including

- Production equipment such as specialized machining or finishing equipment.
- Manufacturing tooling such as specialized jigs and fixtures.
- Process control equipment such as heat treating temperature measurement or control equipment
- New equipment for NDI QC or QA.
- Pollution prevention or environmental controls.
- Buildings and land

Other machinery or equipment with an expected life in excess of 5 years.

Depreciation

Depreciation covers the loss in value of a capital asset over time. Although it is not a direct cost, it should generally be incorporated into the cost structure. (Depreciation can be set to “None” to exclude depreciation from the calculations.) Depreciation can be thought of as annual contributions to a “fund” for the purchase of new capital equipment when the original equipment wears out. In order to calculate depreciation cost the equipment must be assigned an initial cost, V_o, a life, L, and a residual or salvage value, V_s, at the end of its life.

There are various ways of calculating D_n, the annual depreciation for the Year n. The model permits a choice of the following standard methods:

- None – In this case depreciation is not taken into account.
- Straight line – This method simply depreciates the asset value by an equal annual amount from the initial cost to the residual value

$$D = \frac{V_O - V_S}{L}$$

- Sum of the years’ digits – This is a common method of weighting depreciation toward the beginning of the asset’s life to more closely reflect its real loss of value.

$$D = \frac{2L(Vi - Vr)}{L(L+1)}$$

- Declining balance – This is another common means of weighting the decline in an asset's value toward the beginning of its life. The formula is a great deal more complex than either of the above. Depreciation for Year n is defined as (initial cost - total depreciation from prior periods) * rate

  where

  rate = 1 - ((salvage / initial cost) ^ (1 / life)).We can express this as

  $$D_n = (V_o - \sum_{1}^{n-1} D_i)\,(1\text{-}(V_s/V_o)^{1/L}$$

  For the first period, however D_1 = initial cost * rate.

- Double Declining Balance – This method weights the decline in value more heavily toward the beginning of the asset's life. Depreciation for Year n is defined as

  ((initial cost-salvage) - total depreciation from prior periods) * (2/life)

  We can express this as $D_n = ((V_o - V_s) - \sum_{1}^{n-1} D_i)\,(2/L)$

Direct Manufacturing

Direct manufacturing is the direct cost of manufacturing or overhaul

- Materials
- Machining
- Coating and finishing
- Heat treating
- New component purchase.

Indirect Business

Indirect business costs include

- Inventory
- Insurance
- Legal costs
- Training of personnel
- Cost of money
- Cost of sales
- Factory space
- Depreciation

- Indirect costs related to existing technology

Environmental

Environmental costs include

- Regulatory and compliance costs (federal, state, city)
- Pollution prevention equipment maintenance
- Waste management and disposal.

Adoption

Adopting a new technology involves a great many paperwork, testing, qualification, and other costs, such as

- Materials qualification testing
- Process development costs - component specific
- Component recertification
- Specification development
- Configuration control
- Support documentation, drawing changes
- Changes to travelers and other paperwork
- Approval paperwork
- Development of manufacturing, repair, testing, and QC procedures
- Engineering related to capital equipment installation
- Costs related to decommissioning equipment
- Costs related to personnel changes.

Field Failure (C-MAT.XLS)

Failures in service (field failures) can represent a major cost that is directly attributable neither to OEMs (unless it relates to warranty)nor to MRO facilities. However, it is a direct cost to airlines and the defense department as a whole.

The model allows the user to input failure mode and cost data for prior years so as to calculate the failure costs due to each of these failure modes, as well as the standard deviations of the various costs. Costs that can be included (on a category by category basis) include both direct incident costs and indirect costs. Direct costs include:

- Component replacement
- Repair costs not directly attributable to MRO operations, e.g. transport to repair center, etc
- Subsystem replacement cost, e.g. brakes, lights, etc.
- Collateral damage
- Complete loss of aircraft or crew (including the cost of replacement

crew training)

- Accident investigation cost.

Most of these direct costs are borne by users (airlines or the Defense Department). Indirect costs include:

- Legal and liability costs
- Warranty replacement and repair
- Insurance cost changes (including self-insurance costs and deductibles)

Most of these indirect costs are borne by OEMs.

These historical cost data are included in the C-MAT.XLS workbook since they are common to all scenarios.

Failure Probability (Scenario)

Changes in component materials and treatments can affect the probability of failure from various common causes. For example, adopting a corrosion-resistant steel or a better corrosion inhibiting coating would be expected to reduce corrosion failures and the incidence of stress-corrosion cracking.

The program takes into account changes in the probability of failure due to several common causes:

- Stress corrosion cracking (environmental embrittlement)
- Corrosion
- Hydrogen embrittlement (as a result of repair operations)
- Fatigue
- Wear
- Overload
- Other

Changes in the probability of these failure modes can be estimated or calculated from test data. Because the failure probabilities may change with each scenario (e.g. between baseline and new materials), failure probabilities are changed in the Scenario spreadsheets.

Production rate

Production rate is used for both OEM and for MRO operations. It is simply the number of items manufactured or overhauled annually.

Overhaul rate

Overhaul rate is calculated based on the number of items in service and the overhaul cycle (time between overhauls), as well as the percentage of unscheduled overhauls and repairs. The model allows for the option of retiring items from service on overhaul (as might be done when replacing items made from existing materials with items made with a new material). Newly purchased items are assumed not to be overhauled until their first overhaul cycle (except for unscheduled repairs).

Note that the overhaul cycle may change with a new technology, which may require more of less frequent overhauls.

Revenue

Revenue is based on production rate (OEM or MRO) and price. This allows for input of different pricing models for the different technologies, as well as for the possibility of increased (or decreased) sales as a result of adopting the new technology.

Revenue calculation permits decisions to be made on the basis either of cost (as a user would typically do) or of profitability (as an OEM or overhaul operation would typically do). The distinction is important since the two methods of decision making are radically different. For example, an OEM would be expected to maximize profit by reducing total cost (including liability and warranty cost as well as production cost), while a user would be expected to minimize cost (including adoption and service failure costs as well as production cost).

Value calculations (C-MAT.XLS)

In order to determine whether or not a technology change is financially beneficial we must compare our financial results using the new technology against our financial results using the current technology. The decision tool therefore calculates the difference between the revenue streams and costs of the new and existing technologies. In fact, since it usually takes several years to put a new technology completely into place, the tool permits the user to create a “technology adoption” Scenario as the sum of two scenarios:

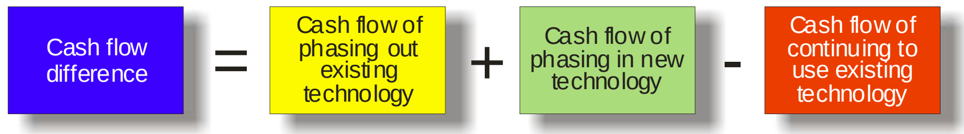
1. Maintaining the current technology until the new technology is on-line and then phasing it out
2. Qualifying the new technology and phasing it in.

Financial results can be expressed either in terms of increased profitability (see Cash flow-based model) or in terms of decreased costs (see Cash flow-based model)

This model takes into account total cash flow, including revenue derived either from sale of components or from overhaul operations. It is intended primarily for use by OEMs and commercial overhaul shops. The following are calculated for each year:

- NPV of total cash flow
- IRR of total cash flow
- ROI, determined as the ratio NPV(operating cash flow)/NPV(capital investment + adoption costs)
- Payback Period, defined as the point at which cumulative differential cash flow becomes positive.

Cost-based model). All results are calculated over a 15-year time scale.



Discount Rate

The discount rate (i.e. the percentage by which future cash flows are discounted) simply says that income received N years in the future has its value reduced by a percentage equal to the discount rate over N years.

The discount rate may reflect the actual cost of money (loan interest rates) or it may be a nominal rate assumed by an organization for the purpose of financial calculations. OMB Circular A-94 ("Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs", October 1992) states: "Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7 percent. This rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years. Significant changes in this rate will be reflected in future updates of this Circular."

Financial Value Measurements

This decision tool includes the standard discount rate-based measures of value. Cost savings can be treated exactly the same as cash flows.

Net Present Value (NPV) – NPV is the value today of a future cash flow. NPV is the primary measure of value recommended by OMB. For cash flows (positive and negative) over n years:

$$NPV = \sum_{i=1}^{n} \frac{cash\ flow_i}{(1 + discount\ rate)^i}$$

Note that cash flows that are received further into the future are worth less than those received earlier. The NPV of the single cash flow in Year i is simply the amount of money that would have to be invested up-front and compounded at the discount rate to have a value equal to the cash flow in Year i.

Internal Rate of Return (IRR) – Closely related to NPV, IRR is the choice of discount rate that would be required to make the NPV become equal to zero. IRR requires an initial investment that generates a future series of cash flows. The IRR is the interest rate that would be required for the initial investment to produce the same NPV as the cash flows. Thus the higher the IRR value, the greater the return on the investment.

IRR requires at least one negative cash flow (cost) and at least one positive cash flow (income). Since Microsoft Excel uses an iterative method to calculate IRR, the answer may not always converge, even when supplied with a guess as the starting point for the iteration. In that case the program produces an error. The iterative method also often produces extreme results that are clearly incorrect. Sometimes a better guess will correct these errors, but if not they should simply be ignored.

Return on Investment (ROI) – This is simply the annual return on the investment expressed as a percentage:

$$ROI = \frac{Annual\ net\ cash\ flow}{Investment}$$

For most technology adoption projects the investment takes place over several years. We have defined the ROI for Year n as:

$$ROI_n = \frac{Cash\ flow_n}{\sum (Capital + Adoption\ Costs)}$$

In the decision tool investment is defined as the sum of all capital investment and adoption cost.

Payback Period – Payback Period is the time required to recoup the investment. There are subtly different ways this can be defined. The most common definition, which is the one we use, is that Payback Period is the point at which cumulative cash flow becomes positive. (This is called the "simple" payback period since it does not discount the cash flows). One might also define Payback Period as the time at which NPV becomes positive. (Cash flow will almost always be negative in the initial period because of the cost of adopting the alternative.)

Note: It is necessary to check the number provided by the software against the graph of Cumulative Cash Flow and Cumulative cost to ensure that the correct crossover is chosen.

Cash Flow-Based Model

This model takes into account total cash flow, including revenue derived either from sale of components or from overhaul operations. It is intended primarily for use by OEMs and commercial overhaul shops. The following are calculated for each year:

- NPV of total cash flow
- IRR_n of operating cash flow, including any required Baseline investments needed to keep using the current technology. The initial cost taken for IRR is the total Capital cost + Adoption cost of Scenarios A and B. IRR_n is the IRR taken from Year 1 to n, assuming all investment is in Year 1.
- ROI_n, determined as (Year n operating cash flow + Baseline investments)/(Total capital investment + adoption cost)
- Payback Period, defined as the point at which cumulative differential cash flow becomes positive.

Cost-based Model

The cost-based analysis does not consider revenues that an organization derives from adopting the new technology, but considers only costs and cost savings (as well as depreciation). The following are calculated for each year:

- NPV of total cost savings
- IRR_n of operating cost savings, including any required Baseline investments needed to keep using the current technology. The initial cost taken for IRR is the total Capital cost + Adoption cost of Scenarios A and B. IRR_n is the IRR taken from Year 1 to n, assuming all investment is in Year 1.
- ROI_n, determined as (Year n operating cost savings + Baseline investments)/(Total capital investment + adoption cost)
- Payback Period, defined as the point at which cumulative differential cost becomes positive.

Uncertainty in the Estimates

Since the various costs cannot be known precisely, the final values are also subject to uncertainty. To take this uncertainty (error) into account the variances of the numbers are added to obtain an estimate of the total variance of the calculation. (This assumes a normal distribution of probabilities.)

For a normal distribution, the standard deviation is square root of the variance:

$$\sigma = \sqrt{V}$$

and when summing independent variables, each with a variance, V_i the variance of the sum is simply the sum of variances:

$$V_i = \sum_i V_i$$

The variance of the difference of two variables is also the sum of the variances, which is why uncertainties can become relatively large when taking the difference between similar values, as we do in most cost evaluations.

When independent variables with variances are multiplied and divided the situation becomes more complex. If

$$x = k\,\frac{a.b}{c.d}$$

then the relative variance of the sum is the sum of the relative variance, i.e.,

$$\frac{\sigma_x^2}{x^2} = \frac{\sigma_a^2}{a^2} + \frac{\sigma_b^2}{b^2} + \frac{\sigma_c^2}{c^2} + \frac{\sigma_d^2}{d^2}$$

which leads to

$$\sigma_x^2 = \left(k\,\frac{a.b}{c.d}\right)^2 \left[\frac{\sigma_a^2}{a^2} + \frac{\sigma_b^2}{b^2} + \frac{\sigma_c^2}{c^2} + \frac{\sigma_d^2}{d^2}\right]$$

Thus, when a variable is multiplied by a constant, the variance of the result is the original variance multiplied by the square of the constant. If

$$x = k.a$$

then

$$\sigma_x^2 = k^2.\sigma_n^2$$

Further, if

$$x = k.a.b$$

then

$$\sigma_x^2 = k^2.\left[b^2.\sigma_a^2 + a^2.\sigma_b^2\right]$$

and if

$$x = k.{}^{a}\!/_{c}$$

then

$$\sigma_x^2 = \left(k\frac{a}{c}\right)^2\left[\frac{\sigma_a^2}{a^2} + \frac{\sigma_c^2}{c^2}\right] = k^2.\left[\frac{\sigma_a^2}{c^2} + \frac{\sigma^2.\sigma_c^2}{c^4}\right]$$

To provide an estimate of the accuracy of the result and how they vary with assumptions, the value curves also contain lines for one and two standard deviations above and below the mean.

CHAPTER 5 WHAT TYPE OF ANALYSIS DO I NEED?

The C-MAT decision tool allows for several types of analysis, which cover most material alternative situations:

1. OEM production
2. Repair and Overhaul
3. Technology replacement on specific components
4. Technology replacement over an entire manufacturing/overhaul site

OEM Production

There is little difference between OEM and MRO usage since both are different types of production. For OEM production, of course, the "Enter MRO New Component Sheet" and "Enter Overhaul Rate" would usually not be used. In most OEM situations the Cash Flow based Value Calculations will be likely to be the most relevant.

Repair and Overhaul

There is little difference between OEM and MRO usage since both are different types of production. In most, but not all, situations DoD depots will probably find the Cost based Value Calculations to be the most relevant. However, depots and commercial repair operations may find the Cash Flow based Values to be more useful when the aim is to determine, not how much money will be saved, but how the technology change will affect overall revenues.

Replacement on Specific Components

Where the technology is to be changed on specific components all the component-related cost data is entered directly into the sheets. Note that the Direct Cost sheet permits calculation of the direct cost for an assembly as well for a single item. In the case of an assembly, all other costs can be calculated as averages or as the total cost for the assembly itself. Inventory costs would then be treated as the total inventory cost for all items in the assembly, if the assembly itself is not inventoried.

Replacement Over an Entire Site

You may wish to adopt a technology over an entire site or assess its impact over an entire industry. Most of the cost items in the model are identical in both component-specific or site-specific replacement.

The only place where there is a definitive difference is in the Direct Manufacturing cost. This sheet in the Scenario spreadsheet has a separate column for site-wide costs in the Simple Data Entry area and a separate section in Detailed Data Entry area, which is reached by clicking the "Use Detailed

Component Calculation or Site Cost" checkbox. This permits annual costs to be assigned or calculated for the entire site rather than for a single components.

In all other cost sheets enter annual costs. Note that for site replacement, in most cases production rates will not be a relevant measure, although in some cases it may be possible to determine total system production rates - e.g. aircraft or engines. For Production rate it will usually necessary to enter manual Production rates. In the MRO New Component Purchase spreadsheet, enter the average item cost and number of items, or the total annual purchase cost.

CHAPTER 6 THE C-MAT SPREADSHEET

This is the master sheet that inputs the underlying values of constants to be used in all Scenarios.

The C-MAT file opens at the About C-MAT sheet. Clicking the Start Program button will take you to the Scenario Choose (see page 30) sheet.

Note: On opening it may take a few seconds to a minute or two to read in the information on existing Scenarios, during which the Scenario names and information will be loaded onto the sheet. Once this is complete the file can be used.

Introduction to the C-MAT spreadsheet

(Calculation for Material Alternative Technologies)

The C-MAT spreadsheet takes data from the Scenarios you choose and calculates cash flow, revenue, cost, etc. over a 15-year period to produce the following measures of Value as a function of the time period over which they are calculated:

- Net Present Value, NPV
- Internal Rate of Return, IRR
- Return on Investment, ROI
- Payback Period. PP

These value measurements are described in the Financial Model Overview (See Chapter 4, page 5).

C-MAT also serves as a gateway into the Scenario spreadsheets in which you construct the various Scenarios (see page 7) you want to compare (e.g. current repair technology versus new repair technology, or two alternative new technologies). The easiest way to enter data into the proper sections of the Scenario spreadsheet is to begin at Scenario Choose (see page 30) tab of the C-MAT sheet, which you can enter by clicking the Start Program button.

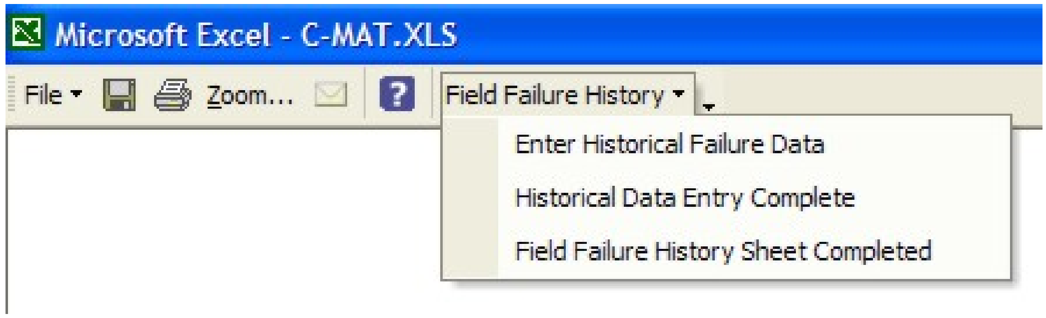
You can get help on the details of any Sheet tab by clicking on the appropriate Index item in the Help Index.

Navigation

For information on spreadsheet navigation, see Navigation and Data Entry (see Chapter 3 page 3).

Toolbar

The toolbar buttons are reduced to those you actually need. Buttons with a down-arrow to the right have a set of menu choices.



File button options:

- Save - Save the spreadsheet (Note: this is the same as the adjacent Disk icon)
- Save As - Save the spreadsheet with a different name (used to create a new spreadsheet from an existing one)
- Save and Close - Exit the spreadsheet after saving
- Close without Saving - Do not keep changes

Save button (disc icon): Executes Save command, overwriting existing data with the data currently in the spreadsheet.

Print button (printer icon): Brings up printer options that depend on your printer.

Note: Print areas are set up to print the relevant areas of the spreadsheets. The default is to print the current sheet. Clicking the Print Entire Workbook option will print all of the pages of your spreadsheet.

Zoom button: Brings up a box allowing you to choose the magnification of the spreadsheet so that you can see an area of interest at any convenient size.

e-mail button (envelope icon): This will use your e-mail program to address an e-mail to Rowan Technology Group if you need assistance.

Help button (question mark icon): Brings up context-sensitive help. Other Help pages can be displayed or you can Search for specific information.

Context-sensitive button: This button, which varies from page to page, permits you to jump to a specific place in the worksheet for detailed data entry. For example, on the Field Failure History sheet the button has the following options:

- Enter Historical Failure Data - Takes you to the correct location to enter the details of historical failure costs
- Historical Data Entry Complete - Returns to the beginning of the Field Failure History worksheet after entering details
- Field Failure History Sheet Completed - Returns to the Scenario Choose page.

Cost Summary (C-MAT)

Note: This spreadsheet does not become visible until you carry out a calculation by choosing Scenarios and clicking the Save and Calculate button on the Scenario Choose sheet.

This sheet has no user inputs. It calculates the difference between the Cost Summary sheets of each of the Scenarios used in the model, as follows:

Cost differential = ScenarioA Cost + ScenarioB Cost - Baseline Cost

and

Variance of Cost = Variance of ScenarioA Cost + Variance of ScenarioB Cost + Variance of Baseline Cost

The variance equations are described in the Financial Model Overview (See Chapter 4 on page 5).

The Cost Summary includes a table for each of the Scenarios in the calculation as well as for the differential costs. All of the costs and revenues are tabulated as a function of time.

Positive Cash Flow numbers are increases in Cash Flow, indicating a financially viable technology alternative.

Positive Cost numbers, on the other hand, are increases in cost, indicating an alternative that is not financially viable.

The data from this sheet are fed into the Graphs and Value Summary (see page 26) sheet to produce the measures of value - NPV, IRR,ROI and Payback Period.

Input constants

Note: These values are constant for all scenarios

Constants for the calculation

Type of production	OEM Overhaul/repair
Annual inflation rate	4%
Discount rate	2.0%
Cost of money	3.0%

Access this page by clicking the Insert Constants button on the Scenario Choose page.

Type of Production: Click on OEM or Overhaul/Repair. The chosen type will show as blue with white text.

Input the following into the yellow cells:

> **Annual inflation rate**: Enter the percentage rate. It will automatically be shown as %. This number can be set to zero if you simply wish not to take inflation into account, or it can be set to an anticipated rate or a standard rate used in your organization. Default value = 0%.
>
> **Discount rate**: The discount rate is the standard cost of money used in calculations of net present value and internal rate of return. Most organizations use a standard value for financial calculations. Default value = 3.5%.
>
> **Cost of money:** This is the cost of borrowing money for your organization (which may be chosen as identical to the Discount Rate or may be chosen to match your particular requirements). It is used in calculating the cost of money in inventory cost and in-process time, both of which are based on the cost of tying up money in inventory or production items.

When you have finished click the "Constants Entry Complete" button to return to the Scenario Choose page. The "Done" box will automatically be checked.

Input field failure cost and history

The direct and indirect costs of service failure can be a major factor in evaluating the value of a new technology. Service failure can result in a wide range of costs, from the cost of replacement of the failed component to extensive collateral damage, or even loss of the entire aircraft and crew. If the new technology can significantly reduce the number of Class A or Class B accidents, the savings can far exceed any other saving.

Indicate manual entry or automatic calculation based on historical data (see Instructions)

Enter data here Use historical data / Use manual entry here

Typical # items in service	70							
Manual input cost accuracy for # failures and cost	40%		40%					
Failure cause	**Mean # failures per year**	**# failures per year per item in service**	**Mean cost of a failure for this cause**	**# failures per year per item in service**	**Mean cost of a failure for this cause**	**Expected failure cost per year per item in service**	**Variance of failure cost per year per item in service**	**Std Dev of failure cost per year per item in service**
Stress corrosion cracking (in-service)	0.5	0.0071	$250,000	0.007142857	$250,000	$ 1,786	255,102	$ 505
Corrosion (other than stress corrosion cracking)	1	0.0143	$15,000	0.014285714	$15,000	$ 214	3,673	$ 61
Hydrogen embrittlement (following maintenance operations)		0.0000		0	$0	$ -	-	$ -
Fatigue		0.0000		0	$0	$ -	-	$ -
Wear (including fretting)		0.0000		0	$0	$ -	-	$ -
Overload		0.0000		0	$0	$ -	-	$ -
Other		0.0000		0	$0	$ -	-	$ -

Field failure cost can be input in one of two ways Choose the method you wish to use in the box beneath the large arrow. Your choice will be displayed to the left of the box. The choices available to you are:

1. **Use manual entry here** : Enter the data for each major cause follows:

   - **Cost accuracy -** Enter percentage accuracy for failures/year and average cost/failure in top two cells
   - **# failures per year per item in service -** Average annual failures for this cause divided by number of items in service
   - **Mean cost of a failure for this cause -** Average cost of this type of failure

The data are summarized for each major cause:

Stress corrosion cracking

Corrosion

Hydrogen embrittlement (as a result of plating)

Fatigue

Wear

Overload

Other

If the annual cost for each cause is known it can be entered in the table. If only the total is known it can be entered under "Other".

Costs are entered in terms of Cost/year/item in service - i.e. annual service failure cost divided by number of items in service - and average cost of a failure for each cause (or total failure cost divided by number of fielded items.

Note: If you choose the manual entry method, be sure to estimate (or better calculate on the basis of historical data) the accuracy of the annual number of failures and mean costs (based on two standard deviations, or 95% probability). These accuracies are entered in the yellow boxes above the data entry columns.

2. Use historical data: The most complete and accurate data is obtained by entering the data in the form of a summary of actual costs over one or more years. **To use this approach you must have sufficient data - several failures per year** . To do this click on the "Use historical data" choice. Then click on the Field Failure History menu button and choose Enter Historical Failure Data This takes you to a table into which you can enter all the relevant data for failures related to the item under consideration. These costs include MRO costs such as item replacement, collateral damage, loss of entire aircraft, etc., and OEM costs that include warranty and legal costs. The program calculates annual cost per year per item in service, average cost of each failure, and standard deviation and variance in the data. Not all cells in each row need to be filled. A large number of options are given to ensure that the most important costs are included. Simply fill in as much information as is relevant for each incident.

On each line, the reason for failure is selected from the pull-down box. **Note - Entering the year is important since the calculation uses this data to determine the span of time over which the failures occur and hence to compute the annual failure costs.**

Average # items in service these years =

Year (####)	Incident ID	Weapons system	Failed component description/Part #	Reason for failure
				Corrosion (other than stress corrosion cracking)
				Hydrogen embrittlement (following maintenance
				Stress corrosion cracking (in-service)
				Stress corrosion cracking (in-service)
				Stress corrosion cracking (in-service)
				Corrosion (other than stress corrosion cracking)

At the top of each column of direct and indirect costs is a check box. If checked, this column of data is included in the cost estimate. If unchecked, it is omitted. This permits the user to carry out "What if" analysis or to easily modify the scenario to permit certain types of costs and exclude others.

Indirect incident costs					
☑	☑	☑	☑	☑	
Legal and liability cost	**Warranty replacement and repair**	**Insurance deductible**	**Insurance premium increases**	**Other**	**Total cost of incident to your organization**
					$800
					$1,000
$400	$700				$1,400
					$400
					$700
					$500

The results of the chosen data entry method are automatically calculated in the remaining columns of the table at the top of the sheet.

Graphs and Value Summary

Note: This spreadsheet does not become visible until you carry out a calculation by choosing Scenarios and clicking the Save and Calculate button on the Scenario Choose sheet.

This sheet provides the following measures of value from the **differences** in outcome between the baseline and the Scenarios (i.e. Adopting and Using the New Technology minus Continuing to Use the Old Technology). For a worthwhile project differential (sometimes called "incremental") Cash Flow should become positive over time (higher cash flow), while differential Cost should become negative (lower cost). At the beginning, of course, investments in equipment and adoption costs will lead to negative differential cash flows and positive differential costs.

- **Net Present Value (NPV)** - This is the value today of a series of cash flows (or cost reductions) in the future, the future cash flows (cost reductions) being discounted in value according to the Discount Rate.
- **Internal Rate of Return (IRR)** - This is the value that the Discount Rate in the NPV calculation would have to be in order to make the NPV = 0. This is the rate of return that you would have to get on your investment to equal the return in the Model. Note: Excel calculates IRR iteratively, and the value will not converge under certain circumstances, such as if the NPV is negative. Therefore you should ignore any non-converging IRR values.
- **Return on Investment (ROI)** - This is the annual return that you will expect to receive on the money invested in the new process. It is defined as (Annual Operating Cost Saving or Operating Cash Flow Increase in Year n)/(Sum of Capital Costs and Adoption Costs from Year 1 to n). ROI is relevant only after all investments have been made and a positive cash flow from the new technology is established.
- **Payback Period** - This is the time at which the project has paid for itself. We define this as the point at which the Cumulative differential Cash Flow (or Cumulative differential Cost) crosses the zero axis.

For a detailed description of these financial measures and how they are calculated see Chapter 4 page 5.

Note that each of these values varies, depending on the length of time over which the calculation is made. In general a changeover to a new technology will entail high initial cost and lower life-cycle cost. Therefore the NPV and other measures tend to be negative when measured over short times, and become positive when measured over long times. At the top of the sheet are tables for NPV, IRR, ROI (all calculated for time periods of 5, 10 and 15 years), and payback period (defined as that period over which cumulative cash flow or cost changes from negative to positive.

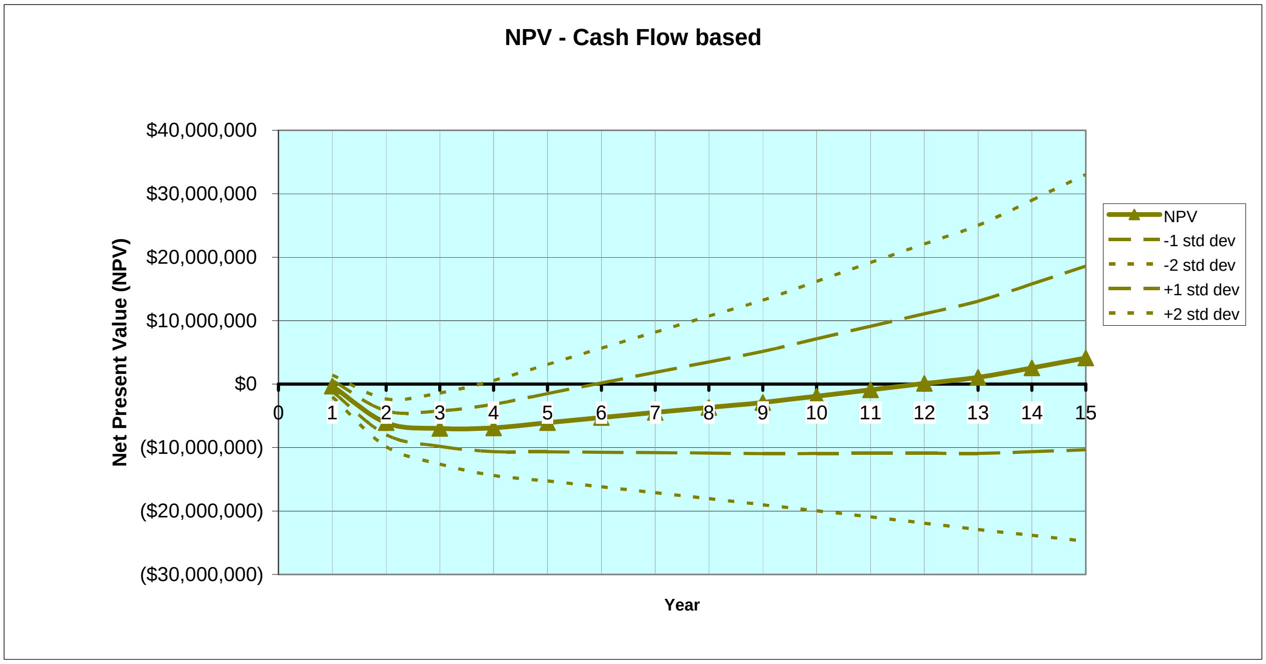
The values are calculated on two different, but related, bases:

1. **Cash Flow -** this is the basis that is most applicable for a commercial operation, since it takes into account both revenues and costs. Cash Flow differential is defined as ScenA Cash Flow + Scenario B Cash Flow - Baseline Cash Flow; i.e. the higher the Cash Flow for the new technology the larger the payback.

2. **Cost Savings -** this is the basis most appropriate for a government organization or captive MRO facility. It is based on cost savings alone, and excludes revenue. Cost differential is defined in the opposite manner to Cash Flow, as Baseline Cost - ScenA Cost - ScenB Cost; i.e. the lower the Cost for the new technology the larger the payback.

Replacement of 300M or 4340M with S-53 in landing gear				
Scenario08.xls	vs	Scenario09.xls	+	Scenario11.xls

Value based on cash flow				
		5 year	10 year	15 year
Net Present Value		($6,083,876)	($1,891,094)	$4,128,679
Internal rate of return				6%
Return on investment		8%	11%	18%
Payback period (years)	3.7	**11.1**	>15 years	
	min	**expected**	max	



Summary tables

Summaries of the primary financial data are given in two small tables, which can be copied and attached to graphical outputs or incorporated into reports.

Value based on cost savings

15 year

-2 sigma	Value	+2 sigma	
NPV	($9,556,697)	$9,540,713	$28,638,123
IRR		9%	19%
ROI	9%	29%	48%
Payback period	4.7	9.4	>15 years

Value based on cash flow

15 year

-2 sigma	Value	+2 sigma	
NPV	($24,764,639)	$4,128,679	$33,021,996
IRR		6%	23%
ROI	-11%	18%	48%
Payback period	3.7	11.1	>15 years

Inputs

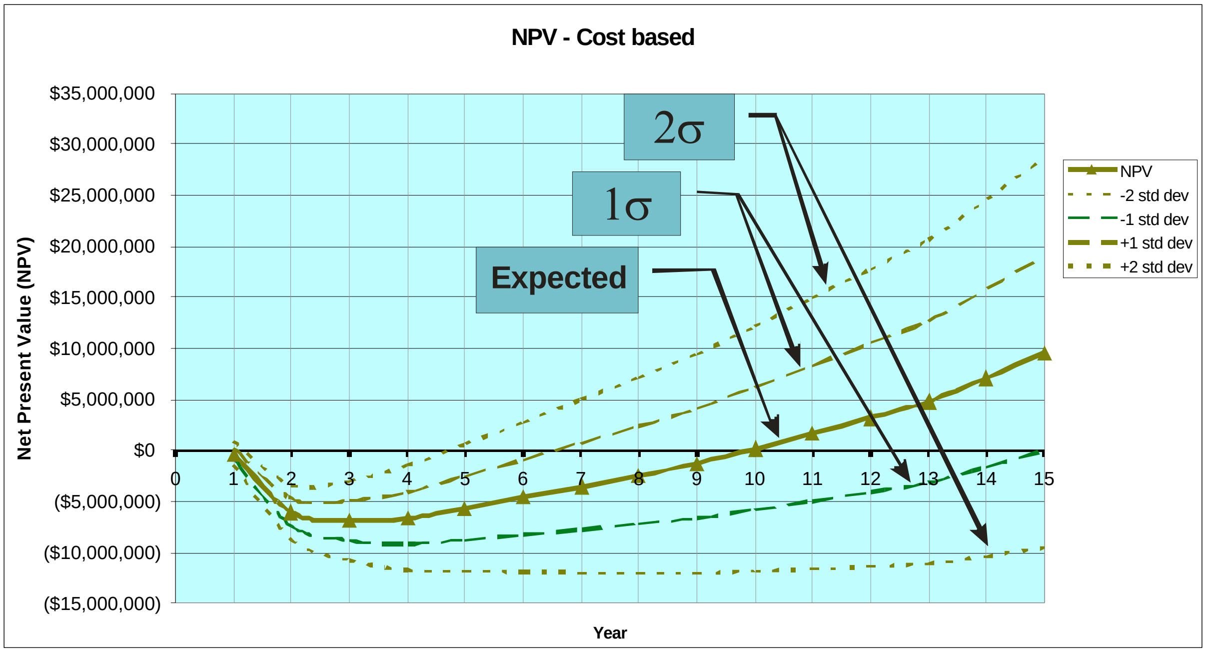
Because IRR is calculated by an iterative technique, the calculation may not always converge. When the calculation fails to converge it yields either a #NUM! or a #DIV/0! error, and is plotted as zero on the graph. Since IRR values are essentially meaningless in negative cash flow situations they are also plotted as zero on the graph. To improve the likelihood of convergence it is possible to supply the calculation with a guess. A starting value guess (from -99 to +99) can be typed into the yellow cells found beneath the IRR graphs in order to optimize the range of calculation.

Graphs

The left column of graphs is cash flow-based; the right column is cost-based.

Each graph includes lines for +- 1 and 2 standard deviations.

Any graph can be copied and pasted into reports and summaries.



These are the graphical outputs (by year) of the data from the Cost Summary for the following value parameters:

- Net Present Value, NPV - This is not the NPV for Year n, but is **the NPV of Cash Flows or Costs from Year 1 to Year n**. It should generally be negative at the beginning, where the investments are made, and then grow over time.
- Return on Investment, ROI - This is the ROI for Year n based on the investment from Year 1 to Year n. It should generally grow at the beginning and stabilize over time.
- Internal Rate of Return, IRR - As with NPV this is **the IRR required for the Capital and Adoption Cost investments to produce the cumulative Cash Flows or Costs from Year 1 to Year n**. It should grow at the beginning and stabilize over time.

The graphs also include the Primary Financial Data Graph, with the accuracy (2 standard deviations) expressed as error bars:

- Cash flow
- Investment and adoption costs
- Gross revenues
- Total operating costs
- Cumulative cost and cash flow

Primary costs are graphed in the Cost Data Summary, which displays the following:

- Investment/Adoption Costs

- Operating Costs
- Field Failure Costs
- Direct Manufacturing Costs

In addition there are graphs, with 2 sigma lines, for:

- Cumulative Costs
- Cumulative Cash Flow

Data tables

Tables of the numbers from which the graphs are plotted can be seen by clicking the See Detailed Value Data Button beneath the IRR graphs.

Scenario Choose

This sheet allows you to input the constants for the calculations that will be common to all Scenarios, and to choose and modify the scenarios.

A scenario is a set of costs and production information that describes a production situation. A certain number of pre-defined scenarios have been created for demonstration purposes, but new ones can be created from scratch from the Null Scenario (Scenario00.XLS) or by modifying existing Scenarios to accommodate your particular situation. The following pre-defined scenarios exist:

- The current OEM manufacturing technology
- The current MRO technology
- Adopting the new technology immediately
- Adopting the new technology by replacing components on overhaul

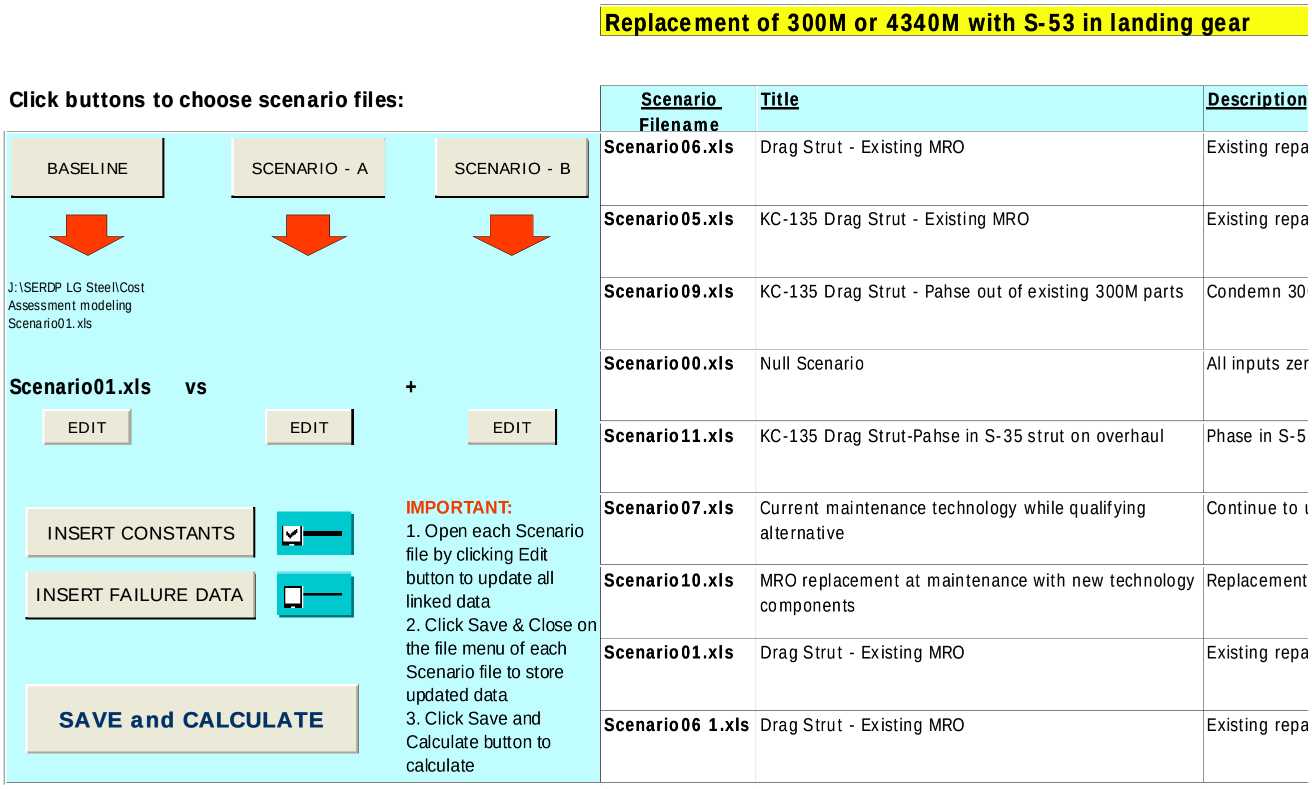
Layout of the sheet

The left side of the sheet contains the control buttons for information input and calculation.

The right hand side summarizes all the existing Scenarios in the folder that contains the Decision Tool file C-MAT.XLS. You will find the filename, Title, brief Description, and Notes for each of the Scenarios in the C-MAT folder. This information is read in when the C-MAT file is opened. The purpose of this listing is to permit you to see all the available options in choosing your Scenarios.

Note: If you do not see all the available files you may not be viewing the entire page - some of the rows in the bottom section of the page may be hidden beneath the top section, or the filenames may run off the bottom of the page. If this happens, simply drag the bar at the far right up or down to see everything. Likewise, drag the bar beneath the bottom right of the screen to the right or left to view the information from all the columns.

Title: At the top, in the yellow box, is the title you choose to give the calculation. Go here first to name the calculation. This name will appear at the top of each Scenario sheet.



Insert Constants and Failure Data

For details on these sheets, see Insert constants on page 21 and Input field failure history on page 23.

It is good practice to clear the checkmarks in the Done boxes by clicking before you begin. After you have finished inserting the constants and failure data these boxes will be automatically checked. Clicking the Insert Constants button will take you to the sheet for inputting the constants that will be the same for all Scenarios in this calculation. Clicking the Insert Failure Data button will take you to the Field Failure History sheet where you can input historical service failure data.

Choosing Scenarios

The Tool allows you to compare the costs of adopting the technology in different ways, compared with the cost of continuing with the present method. The current method is termed the Baseline. Because adoption of a new technology usually entails a changeover period, the adoption Scenario can be made up of two different Scenarios:

- phasing out the Baseline over a period of time as the new approach is brought on-line (ScenarioA)
- bringing the new technology into full production (ScenarioB).

The total cost is therefore the sum ScenarioA + ScenarioB.

For details on creating and modifying Scenarios see Introduction to the Scenario spreadsheet on page 35.

Baseline

- Click the Baseline button. This will bring up a file browsing window. Browsing to the proper folder will bring up a list of the available Scenarios in the folder. You can refer to the list at the right of the Scenario Choose sheet for details on the existing Scenarios.
- If you intend to use an existing Baseline, click on the appropriate filename, which must be of the form "ScenarioNN.XLS", where NN is the Scenario number - 01 to 99. The full path and filename will appear beneath the red arrow as a check that you have chosen the correct file.
- If you are going to create a new Baseline, click on either Scenario00.XLS (the Null Scenario) or an existing Scenario that you intend to modify.
- To modify the Scenario click the Edit button. This will open the Scenario for editing. In doing so it will read into the Scenario the current values for the information you have entered on the Constants and Field Failure History sheets.

Scenarios

- If you wish to use or modify an existing Scenario, click on the Scenario - A (or Scenario - B) button and choose the relevant file as above.
- If you wish to create a new Scenario, you can either create it from an existing Scenario (which is usually the quickest approach) or you can enter all the data from scratch.
- To modify an existing Scenario, click the Scenario - A or B button, choose the Scenario you wish to modify, click the Edit button to open it, and immediately click Save As on the File menu and save it with a new name (number). Then modify the file and click File\Save of the File Save (disc) icon. For details see Building a New Scenario from an Existing One on page 41.
- To enter data from scratch, choose Scenario00.XLS, which is the blank Scenario. Open and immediately save it (using Save As from the File menu) with a new Scenario number, e.g. Scenario12.XLS, before making any changes. This will ensure that you have a copy of each of your Scenarios and that you retain Scenario00.XLS as the Null Scenario. (Should you accidentally enter data into Scenario00.XLS you can just delete the data and resave.)
- Always remember to click Save or File\Save As to save changes if you want to keep any modifications you have made.

Note: If you wish to compare a baseline with an alternative with no phase-in, just choose ScenarioB to be the Null Scenario, Scenario00.XLS.

Since the Decision Tool permits you to enter either actual costs or the cost difference with respect to the Baseline (see Scenario Spreadsheets - Assumptions, inputs, page 40), you can enter Scenario00.XLS as the baseline and enter relative data for the Scenario. However, you must be sure to include any costs in the Baseline that will not be in the Scenarios. For example, if continuing to use the existing technology means that you must update your plant to meet current regulatory standards, this must be included in the Baseline.

Note: You can access and change any Baseline or Scenario file independently without opening C-MAT by double-clicking the Scenario file name from the usual Windows file menus.

Save and Calculate

When this button is pressed it initiates the following actions:

- All the links between files are updated
- Two new Sheets become visible: Cost Summary and Value Summary, Graphs
- The workbook recalculates the cost difference (Scenario A + Scenario B - Baseline) and places the information on the Cost Summary (page 21) sheet
- The Value Summary, Graphs (page 26) sheet is updated with the new calculation

To see the results of the calculation click on the lower sheet tabs to see the Cost Summary or Value Summary sheets.

Note: This is quite a long calculation and may take a minute or two to complete.

If you with to save the various global costs and Scenario choices you have entered into C-MAT.XLS be sure to save the file using the FileSave icon or the File\Save As menu option. (Note that you can also quit without saving.)

CHAPTER 7 THE SCENARIO SPREADSHEETS

Each Scenario contains a model for production and cost.

Note: It is important to remember that ***any given Scenario can only refer to a single technology*** . Thus it can be for the baseline or the new technology, but cannot mix the two. This is because all costs can only be for a single technology. If you intend to adopt the new technology by phasing out the old method while phasing in the new, this is done by the use of a two Scenarios - one handling the old technology phase-out and the other the new technology phase-in.

VERY IMPORTANT BASIC CONCEPT

Each Scenario can only include a *single* technology. It may refer to:

- **The baseline - how things are done today**
- **Phasing out the old technology**
- **Phasing in and/or using the new technology**

Thus you *cannot* include phasing in the new technology while phasing out the old in a single Scenario.

For more information see Introduction to the Scenario Spreadsheet on page 35.

Introduction to the Scenario spreadsheet

The Scenario spreadsheet is the file that holds all the information about a Scenario, except basic data that pertains to all Scenarios (which is entered into the C-MAT spreadsheet, page 21). Any Scenario can built from the Scenario00.XLS file, which contains no data, or by modifying an existing Scenario (see Building a new Scenario from an existing one on page 41).

A Scenario file comprises a set of worksheets for each type of cost. The primary navigation page is the Assumptions, inputs (page 40) page, from which you can navigate to all data input points in the sheet. Checkboxes on this page also keep track of what sheets have been changed (checked boxes) and what have not.

When you open a Scenario file you will be warned that it contains macros. You must click Enable Macros for the file to work. The Scenario spreadsheet opens at the About C-MAT page. Click the Start Program button to go to the Title page where you can enter the basic information about the Scenario. Clicking the Input Data button takes you to the Assumptions, Inputs page, which is the primary navigation page for the spreadsheet.

Another way to enter data into the proper sections of an existing Scenario spreadsheet is to begin at the C-MAT sheet. When you open a Baseline or Scenario file from the C-MAT spreadsheet Scenario Choose (page 30)page, it takes you immediately to the correct Scenario sheet Assumptions, inputs (page 40) page.

IMPORTANT

Be sure to save your Scenarios with filenames of the form ScenarioNN.XLS, where NN is between 01 and 99. Save in the same folder as the master file, C-MAT.XLS and the Help file C-MAT.CHM.

Navigation

The main data entry sheets are set up as shown below:

Title:	**Replacement of 300M or 4340M with S-53 in landing gear**
Scenario:	**Scenario00**
Scenario Title:	**Null Scenario**

Upper bound	
Lower bound	
Standard deviation	
Variance	-

Cost accuracy (%)

Total turnaround time (days)

Payment net (days)

Category	SITE COST Annual cost	Direct manufacturing cost per item Cost/item	Cost/lb Cost/lb	Weight	Cost/hr Cost/hr	Hours	Scrap, rework %	Total	Variance
Standard Overhaul:									
Total materials and parts (except MRO comps)								$ -	-
Total machining								$ -	-
Total plating and finishing								$ -	-
Total heat treating								$ -	-
Quality control								$ -	-
Utilities								$ -	-
Other								$ -	-
Repair:								$ -	-
Total materials and parts (except MRO comps)								$ -	-
Total machining								$ -	-
Total plating and finishing								$ -	-
Total heat treating								$ -	-
Quality control								$ -	-
Utilities								$ -	-
Other								$ -	-
								$ -	-
☐ Use simple Component Calculation or Site Cost			Total from simple calculation - Overhaul					$ -	-
☑ Use detailed Component Calculation or Site Cost			Total from simple calculation - Repair					$ -	-
☐ Use detailed calculations for an assembly of up to 25 items			Total from detailed calculation - Overhaul & Repair					$ -	

Calculate steel price

Most Scenario sheets contain two sections - a Simple Data Entry area located at the top left of the sheet and a Detailed Data Entry area located to the right. You can jump to the Detailed Data Entry area by clicking the yellow Detailed data entry checkbox. This will check the detailed data option and take you to the appropriate part of the sheet. To return to the Simple Data Entry area use the Detailed Data Entry Complete menu option under the right hand toolbar button that has the same name as the sheet. To return to the main Assumptions, Inputs page click this same button but choose the "...sheet completed" menu option.

You can enter data in any yellow cell by clicking on it and typing. (Note that $ and % signs are added automatically - do not type them.) Every time you enter data and press the Enter key the data will be entered and the cursor will move to the next yellow cell. You cannot enter data into any other color cell - they are all locked to prevent their being accidentally overwritten. You can change any previously entered data just by clicking on the appropriate cell and correcting the entry either by retyping, or by double-clicking in the cell and editing directly in the cell, or by editing the number in the Excel "Formula Bar" at the top of the page.

Note: You can use the Data Graphs, which graph the Year-by-year Data, to make sure that the Scenario you are constructing is behaving as expected - production starts and stops in the correct years, cost numbers are reasonable, etc.

You can obtain help on the details of any Sheet tab by clicking on the Help button (which is context-sensitive), and where necessary the appropriate Index item in the Help Index.

Differences between simple and detailed calculations - accuracy of data input

A number of the sheets in the Scenario permit you to enter broad-brush data in a simplified form or detailed information with a greater degree of flexibility. You can use either method on any sheet - you do not need to use the same method on all sheets. The final result of the calculation will be the same whether the data are entered in the simple or the detailed sheet. However, the statistical calculations are somewhat more accurate on the detailed sheets because variance calculations are more detailed. In general, this does not lead to large differences, and it has little practical effect given the precision with which one is likely to know the accuracy of input data in any case. The accuracy assigned to input data is intended to be only a guide as to how confident you are of the variability of the numbers from year to year so as to estimate the overall level of confidence in the final result.

Note: You can enter data in both the Simple and Detailed areas of the spreadsheet. The program will use whichever data set is checked.

Adoption

Adoption Costs are the various costs paperwork and engineering associated with adopting the alternative. These costs are likely to arise during the first few years (principally in the first 2 years). These costs include:

- Qualification testing for materials, components, and systems, including flight tests
- Development and approval of specifications, QC procedures, repair procedures, etc.
- Engineering related to equipment installation
- Training
- Paperwork costs such as configuration control, drawing changes, contract modifications, manuals, routing documents, etc.
- Costs related to decommissioning old equipment and transferring or laying off personnel.

Simple Calculation

Click on the "Use Simple Calculation" button and enter costs for each category in the appropriate year. A category may have costs in several years.

Title	**Replacement of 300M or 4340M with S-53 in landing gear**
Scenario	**Scenario01**
Scenario Title	**Drag Strut - Existing MRO**

Cost accuracy (%) 20% **Stan**

Category	**Total annual adoption cost** Year 1	Year 2	Year 3
Materials qualification testing	$ 55,000		
Process development costs - component specific			
Component recertification			$ 150,000
Specification development		$ 35,000	
Design and Configuration control			
Support documentation, drawing changes			
Changes to travelers and other paperwork			
Additional paperwork, approvals			
Repair procedures			
Engineering related to capital equipment installation			
Costs related to decommissioning equipment			
Costs related to laying off personnel			
Costs associated with hiring new personnel			
Other costs			
☑ Use simple calculation		**Total from sim**	
☐ Use detailed calculation or more years		**Total from detai**	

Detailed Calculation

Click the "Use Detailed Calculation" checkbox and enter costs in the appropriate year in the fifteen-year time frame. Most adoption costs will fall in the first 5 years, but you are not limited in when these costs can be entered. Enter the accuracy of the cost estimate in the Accuracy % box in the same row. In addition to the categories provided you can include any additional costs under "Other costs". Click "Detailed Data Entry Complete" in the right-hand drop-down menu to return to the front of the sheet or the "Adoption data complete" item to return to the Assumptions, Inputs page.

(Note: Only Year 1 is shown in the accompanying picture.)

				Standard deviation		3,905
				Variance		15,250,000
	Total adoption cost	$ 240,000		Total annual cost		$ 55,000
Category	Category detail					Year 1
	Annual costs	Total	Accuracy (%)	Variance (%%)		
Materials qualification testing						
	Development/optimization	$ -		0		
	Materials testing	$ 30,000	20%	9,000,000		$ 30,000
	General performance testing (corrosion, fatigue, embrittlement, etc)	$ 25,000	20%	6,250,000		$ 25,000
	System performance testing (rig, flight, engine, vehicle, shipboard, etc.)	$ -		0		
				0		
Process development costs - component specific				0		
	Inspection and NDI	$ -		0		
	Machining, grinding and finishing	$ -		0		
	Process steps (machining, coating, heat treating, coating, finishing, stripping, grinding, et	$ -		0		
	Production equipment reprogramming	$ -		0		
	Training	$ -		0		

Assumptions, inputs

This is your starting point for inputting data to your Scenario. You can start with a blank sheet (the Null Scenario, which is called Scenario00.XLS) or you can build your Scenario by modifying an existing one (see Building a New Scenario from an Existing One on page 41).

Summary of assumptions and inputs

Button	Done
ENTER CAPITAL INVESTMENT	☑ Done
ENTER DIRECT PROD. COST	☑ Done
ENTER MRO NEW COMPONENT	☑ Done
ENTER INDIRECT COST	☑ Done
ENTER ENVIRONMENTAL COST	☑ Done
ENTER ADOPTION COST	☑ Done
ENTER FIELD FAILURE COST	☐ Done
ENTER REVENUE/PRICE	☑ Done
ENTER PRODUCTION RATE	☑ Done
ENTER OVERHAUL RATE	☑ Done
GO TO TITLE PAGE	

Item	Value		Input location
Scenario #	Scenario00		
Scenario name	Null Scenario		
Description	All values zeroed		
File name	C:\Office Backup\Cost Benefit Analysis\C-MAT files\Basic files\Scenario00.xls		
Type of Production	2	Overhaul/Repair	C-MAT spreadsheet
Annual inflation rate	5.0%		C-MAT spreadsheet
Discount rate	4.0%		C-MAT spreadsheet
Cost of money (annual)	4.0%	Annual cost of money	C-MAT spreadsheet
Cost of money (daily)	0.011%		
Production start year	0		Production Rate sheet
Production stop year	0		Production Rate sheet
Retirement start year	0		Overhaul Rate sheet
Retirement stop year	0		Overhaul Rate sheet
Overhaul/repair cycle (years)	0		Overhaul Rate sheet
Type of depreciation	2	Straight Line	Capital investment sheet

The information on the right of the picture above is some of the basic information contained in this Scenario. If any of these pieces of information is wrong, you can see which sheet to go to in order to correct it.

To the right of this table is a large table (not shown here) containing all the primary settings used in the Scenario, broken out by Scenario Sheet. This provides a quick check to ensure that you have set up the Scenario in the way you had intended without the need to check each sheet individually.

Below this table is a series of Notes lines on which you can record any relevant information or notes to help you construct the sheet or remind you of its contents.

To fill in all the data for your Scenario do the following:

1. Make sure that each of the small boxes is **unchecked** before you begin (click on them to uncheck). This will help you keep track of where you are.
2. The large buttons at the left will carry you through the entry of all the relevant data. When you press any of the large buttons you will be taken

to the data entry sheet for that item.

3. When data entry is complete, press the "... data complete" button on the right-hand menu item of that sheet. The program will return you to the **Assumptions, inputs** sheet and check the small checkbox to the right of the big button to show you that you have entered data for that sheet. If the data are not complete (for example, you need to go look something up), you can just uncheck the box to remind you that you need to return to that sheet later.
4. You can enter or change Scenario Title data by clicking the Go To Title Page button.

Important note: Data can be entered in two ways

Absolute numbers	Actual costs and revenues are entered. This allows you to keep track of the full cost data for your Scenario.
Numbers relative to the baseline	Since the value measurements are calculated from the difference between each Scenario and the baseline, you can simply input the difference between the two - i.e. if the baseline is $1,000 and your Scenario will cause a cost change (or relative cost) of $200, then you can just enter $200 for a cost increase or -$200 for a cost decrease. You can even enter Investment Costs, for example, in absolute numbers, and Direct Production Costs in relative numbers. You simply have to be consistent in each category. Care must be taken with relative costs, however. For example, if the new scenario also causes a change in overhaul frequency, then it is important that this change is not made in the Scenario whose cost is taken as the zero cost baseline. Also if a baseline cost is avoided, such as a capital cost for environmental equipment upgrades if the new scenario is not adopted, then that must be added into the baseline cost, even if the baseline is the zero-cost scenario.

Note: All cells that can take manual data input are yellow. Data cannot be entered into any other cells.

Building a new Scenario from an existing one

It will usually be the case that each Scenario will have a lot in common with another (especially the baseline). To modify a Scenario do the following:

1. Note: **Scenario00.XLS** is defined as the "Null Scenario", which has all cells set to zero, with default values for items such as the discount rate. This is a good Scenario to choose for your first Scenario since it ensures that you do not accidentally incorporate previous data. This Scenario is also used as Scenario B if you do not wish to add two Scenarios for comparison with the baseline (see Scenario Choose on page 30).
2. Some other likely Scenarios may be predefined with a basic model. You

can just adjust the numbers in these.

3. Open the Scenario file from which you intend to build the new Scenario.
4. **Immediately save it with the new name** to make sure you do not overwrite the existing Scenario. Note Scenario names are defined as ScenarioNN.XLS, where NN is the Scenario number (00, 01, 02, ... 99).
5. Uncheck any checkbox for a category that will change.
6. Use the **Assumptions, inputs** page to guide you through data entry.
7. Resave the spreadsheet.
8. Remember to change the Title page data to reflect the new Scenario number and information.

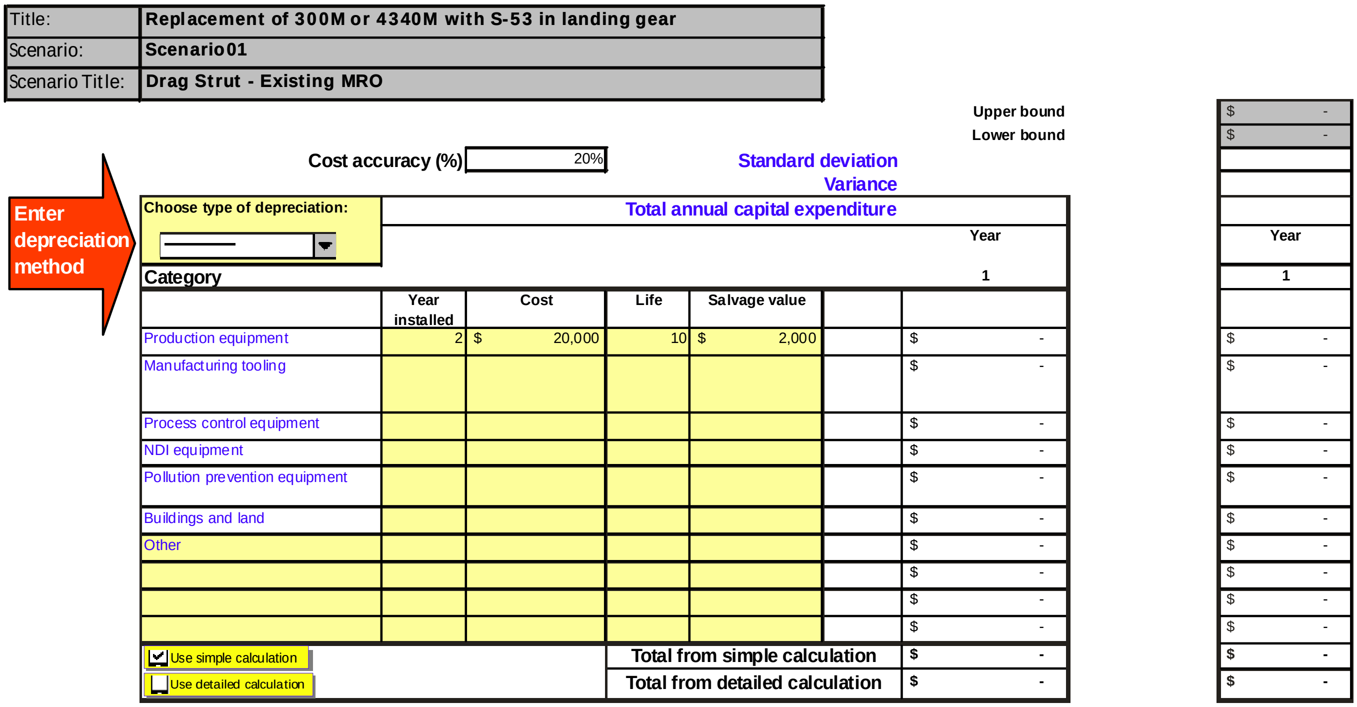
The following are the predefined Scenarios, set up with a particular model and ready for data input. These Scenarios are for a specific problem - replacement of 300M landing gear components with a new high strength stainless steel called S53. **This list may change depending on user needs.**

Predefined Scenarios

Scenario00.XLS	Null Scenario
Scenario01.XLS	OEM Baseline - manufacture with 300M
Scenario02.XLS	Manufacture of existing 300M gear for limited time while qualifying S53
Scenario03.XLS	New OEM design and manufacture with S53
Scenario04.XLS	Replacement of existing technology items with S53
Scenario06.XLS	MRO Baseline - maintenance of 300M gear
Scenario07.XLS	Maintenance of existing 300M gear for limited time while qualifying S53
Scenario08.XLS	Replacement of entire gear or components at maintenance
Scenario09.XLS	Replacement of entire gear or components on failure

Capital Investment

This sheet summarizes the costs for capital equipment - generally equipment with a lifetime in excess of 5 years.



Title:	Replacement of 300M or 4340M with S-53 in landing gear
Scenario:	Scenario01
Scenario Title:	Drag Strut - Existing MRO

Upper bound $ -
Lower bound $ -

Cost accuracy (%) 20%

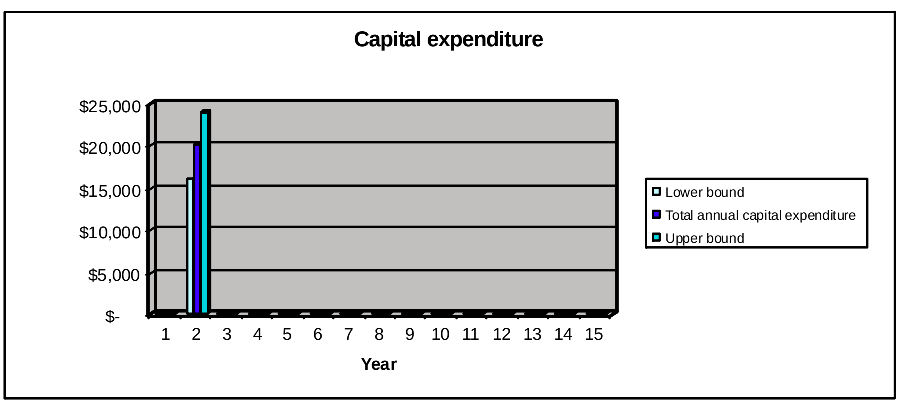
Standard deviation
Variance

Enter depreciation method

Choose type of depreciation:

Total annual capital expenditure

Category	Year installed	Cost	Life	Salvage value		Year 1		Year 1
Production equipment	2	$ 20,000	10	$ 2,000		$ -		$ -
Manufacturing tooling						$ -		$ -
Process control equipment						$ -		$ -
NDI equipment						$ -		$ -
Pollution prevention equipment						$ -		$ -
Buildings and land						$ -		$ -
Other						$ -		$ -
						$ -		$ -
						$ -		$ -
						$ -		$ -
Use simple calculation			Total from simple calculation			$ -		$ -
Use detailed calculation			Total from detailed calculation			$ -		$ -



Simple Calculation

The Simple Calculation is shown in the figure above. It allows you to input a summary of the types of equipment and other capital items required in the Scenario.

Depreciation method

This determines how depreciation is to be handled for all items. The options are

- None
- Straight line

- Sum of the Year's Digits
- Declining Balance
- Double Declining Balance

The last three methods are designed to accelerate depreciation into the early years. For details see Overview of the Financial Model on page 5.

Input Data

Year installed - This can be any year from 1 to 15.

Cost - Item cost

Life - Expected life of the item (1 - 15 years)

Salvage value - The remaining value of the equipment at the end of its life.

Cost accuracy - Defined as 95% probability (2 standard deviations). If cost is estimated at $10,000 and you are 95% sure that it will be between $9,000 and $11,000 then accuracy is $1,000/$10,0000 or 10%. This makes the standard deviation 5% (or $5,000) and the variance 25,000,000 (variance = square of standard deviation).

Detailed Calculation

The Detailed Calculation allows you to input each item individually, and choose a type of depreciation for each one. Clicking on Detailed Calculation will check the box and take you to the Detail section of the spreadsheet (see below).

Clicking on the Detailed Calculation button will check the Detailed Calculation box and take you to a section of the spreadsheet in which you can enter details of all capital equipment, including Year installed, Cost, Life, Salvage value, Cost accuracy, and type of depreciation on an individual basis (see picture below).

							Total annual capit
Category	**Category detail**						
Capital expenses							
		Year installed	**Cost**	**Life**	**Salvage value**	**Cost accuracy (%)**	**Depreciation method**
Production equipment							
	Manufacturing and processing equipment						Straight Line
	Ancillary equipment (cleaning tanks, air handling, compressors, etc.)						Straight Line
Manufacturing tooling							
	Manufacturing equipment						Straight Line
	Jigs and fixtures						Straight Line
Process control							
	Process control equipment						Straight Line
	Robotics						Straight Line
NDI							
	Test and evaluation equipment						Straight Line
Pollution prevention							
	Air handling equipment						Straight Line
	Water processing equipment						Straight Line
	Waste processing and handling equipment						Straight Line
Buildings and land							
	Building purchases						Straight Line
	Land purchases						Straight Line
Other (or specific items)							
	Add items here						Straight Line
							Straight Line
							Straight Line

When you have completed detailed data entry you can either Click on Detailed Data Entry Complete under the Capital Investment menu item to return to the front of the sheet, or Capital Investment Data Completed to return to the Assumptions, Inputs sheet.

Cost Summary

This sheet has no user inputs.

This sheet summarizes the costs and variances calculated in the various cost sheets:

- Capital Investment
- Depreciation
- Direct Manufacturing/Maintenance
- Indirect Business
- Environmental
- Adoption Cost of new technology
- Purchase of New Components
- Field (Service) Failure

It then combines them to produce overall financial performance numbers:

Definitions:

Total Annual Cost	Sum of all annual costs
Cumulative Cost	Sum of Total Costs for current and prior years
Investment/Adoption costs	Capital Investment + Adoption Cost
Operating Cost	Depreciation + Direct Manufacturing/Maintenance + Indirect Business + Environmental +Purchase of New Components + Field Failure = Total Annual Cost - Investment/Adoption Cost
Gross Revenues	Revenue (from Revenue sheet)
Operating Cash Flow	Gross Revenue - Operating Cost
Cash Flow	Gross Revenue - Total Annual Cost
Cumulative Cash Flow	Sum of Cash Flows for current and prior years
Discounted Cash Flow	Cash Flow discounted by the discount rate defined in C-MAT Input Constants sheet
Cumulative Discounted Cash Flow	Sum of Discounted Cash Flows for current and prior years

Direct Manufacturing

Direct manufacturing (OEM or MRO) costs are entered here. This includes:

- Materials
- Machining
- Plating and finishing
- Heat treating
- QA/QC
- Utilities

Costs can be entered in three different ways:

1. **Simple -** Enter direct manufacturing costs for components in general categories. Data may be entered either per item or as an annual cost for the whole site.
2. **Detailed -** Enter details for a large number of individual items and categories. This method includes the ability to cost an assembly of up to 25 items by entering the data for each item.
3. **Site Cost -** Rather than inputting the cost of operations on components this option allows you to input direct operational costs for an entire site that may produce or process many different items. This method would be used to evaluate an entire production plant or overhaul facility.

Note: Inflation is built into this sheet and can be eliminated only by setting its value to zero in the C-MAT.XLS spreadsheet.

Note: Repair items are a subset of overhaul items. Thus you should input Repair Cost as the cost ***over and above*** the cost of standard overhaul. ***The total overhaul and repair cost of an item is thus the Overhaul Cost + the Repair Cost.***

Overhaul vs. repair

It is assumed that all items brought in for maintenance are overhauled, incurring standard overhaul costs. Of these some items may need to be repaired (see Overhaul Rate sheet on page 69). The Repair cost is therefore the additional cost of repair over and above that of standard overhaul.

Title:	**Replacement of 300M or 4340M with S-53 in landing gear**
Scenario:	**Scenario00**
Scenario Title:	**Null Scenario**

Upper bound	
Lower bound	
Standard deviation	
Variance	-

Cost accuracy (%)			
Total turnaround time (days)		Payment net (days)	

Category	SITE COST	Direct manufacturing cost per item							
			Cost/lb		Cost/hr		Scrap, rework		
	Annual cost	Cost/item	Cost/lb	Weight	Cost/hr	Hours	%	Total	Variance
Standard Overhaul:									
Total materials and parts (except MRO comps)								$ -	-
Total machining								$ -	-
Total plating and finishing								$ -	-
Total heat treating								$ -	-
Quality control								$ -	-
Utilities								$ -	-
Other								$ -	-
Repair:								$ -	-
Total materials and parts (except MRO comps)								$ -	-
Total machining								$ -	-
Total plating and finishing								$ -	-
Total heat treating								$ -	-
Quality control								$ -	-
Utilities								$ -	-
Other								$ -	-
								$ -	-
			Total from simple calculation - Overhaul					$ -	-
			Total from simple calculation - Repair					$ -	-
			Total from detailed calculation - Overhaul & Repair					$ -	

☐ Use simple Component Calculation or Site Cost
☑ Use detailed Component Calculation or Site Cost
☐ Use detailed calculations for an assembly of up to 25 items

Calculate steel price

Use the yellow check boxes to choose simple, detailed, or assembly methods of inputting data. Use the simple method if you plan to use general cost categories rather than price items individually and in detail.

Cost accuracy is the estimated accuracy of your entries (with 95% confidence). e.g. if the cost is between $900 and $1,100 then enter $1,000 cost and 10% for the accuracy

Costs can be entered in four different ways, depending on the item:

1. Annual site cost (total direct line item costs over the entire site)
2. Total cost per item
3. Cost/lb (or /kg) and weight
4. Cost/hour (day, etc) and time

Note that for utilities or any other items costed in other units (such as kilograms or liters) enter Unit Price in the Cost/lb column and enter # of Units in the Weight column, e.g.

- for water or chemicals enter Cost/gal in the Cost/lb column, and Gallons in the Weight column
- for electricity enter Cost/kWh in the Cost/lb column, and kWh in the Weight column

Note: Include in hourly cost both direct labor (salaries) and indirect labor (labor-related taxes, insurance, etc.).

The following categories of costs are included:

- Materials
- Machining
- Plating and finishing
- Heat treating
- Quality control
- Utilities
- Other costs - additional items can be included as needed

Notes:

- These are **Direct Costs** only - Labor, materials, etc. Do not include indirect costs or major new purchased items, which are included in the Indirect Manufacturing (page 60) and MRO New Component Purchase (page 75) sheets.
- If an item includes both fixed costs and hourly costs, both can be entered and both will then be included in the cost. **(Note: if all the cost is entered as, say, Cost/hr and Hrs then do not include Cost/item as well, since this will double the value, unless the item contains a fixed cost (e.g. purchase price) plus an hourly cost (e.g. assembly labor cost).)**
- Note that the Standard Deviation is half the Cost Accuracy and that the Variance is the square of the standard deviation.

Scrap and rework

In addition to the normal manufacturing cost, the percentage cost of scrap and rework can be added to any category as a percentage of the total cost of that category. For example, if plating has a high rework frequency, then the percentage of additional cost (which would also probably be the same as the percentage of rework items) should be entered in the Scrap, rework column. Examples:

- if half the items need plating rework, enter 50 in the Total plating and finishing Category/Scrap, rework column
- if on average it takes two tries to get an acceptable product, enter 100 (i.e. 100% have to be reworked)
- if half the items are finally rejected as scrap at the end of

manufacture, enter 50 in all Categories

- if half the items are scrapped on testing at the end of heat treating, enter 50 in all categories for all processes prior to and including heat treating.

Cost of money

Direct cost calculations also permit you to include the cost of money while the item is being manufactured or overhauled. Cost of money is the cost of tying up Direct Costs at the Cost of Money rate from the time the money is expended to the time payment is received. You can include this cost by filling in the Total Turnaround Time and Payment Net boxes.

- Total Turnaround is the time an item spends from the beginning of manufacturing or receipt for overhaul to the time of shipment
- Payment Net is the time from shipment to receipt of payment

It is assumed that the total cost is accumulated linearly, so it can be treated as though all the expense is incurred at the middle of the turnaround period. The cost of money is therefore taken as the Direct Manufacturing cost multiplied by the daily cost of money, taken over a period equal to half the Process Time plus the Payment Net.

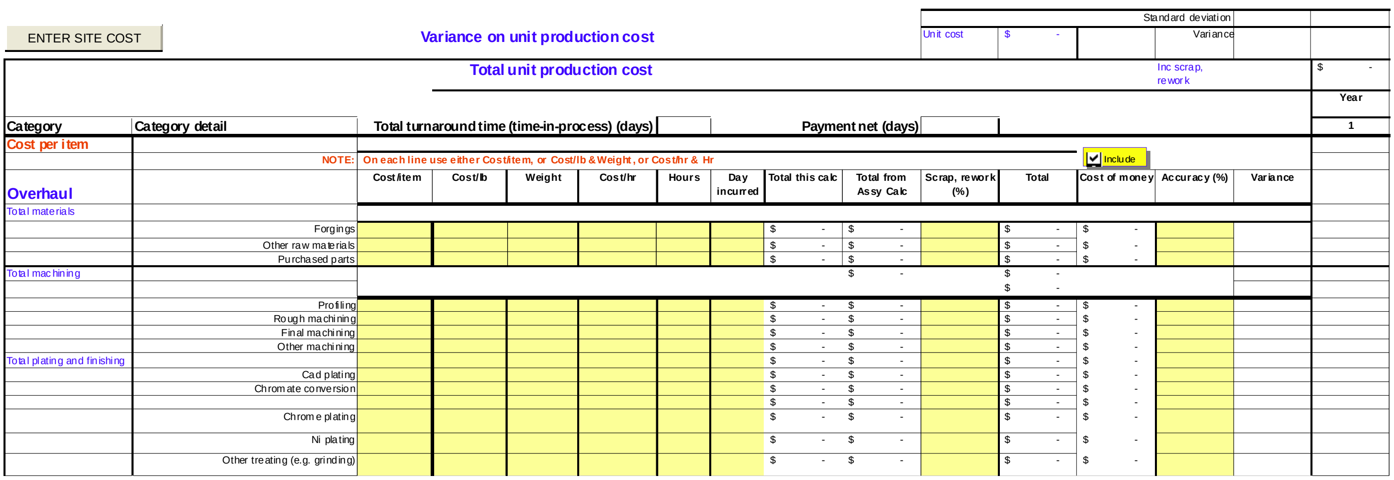
Detailed calculations

Reach this area of the spreadsheet by clicking on the yellow checkbox labeled "Use Detailed Calculation". This leaves the Simple Data entries on the spreadsheet but uses only the Detailed Data entries in the calculation.

When you have finished entering data click the "**Detailed Data Entry Complete**" button to return to the beginning of the Direct Cost sheet; or click the "**Direct Manufacturing Data Complete**" button to return to the Assumptions, Inputs sheet.

Notes:

- You can enter details of direct costs in the same way as for the Simple Calculation, including the scrap and rework rates.
- Items in gray text are not expected to change with the new steel. However, you may make entries into these areas.
- Each item entered must have its own Accuracy. If left blank, it will be assumed that the number is precise (Variance=0).
- If you are carrying out the cost analysis for an entire site, click the Enter Site Cost button to go directly to the Site Cost Detail area.



ENTER SITE COST

Variance on unit production cost — Standard deviation; Unit cost $ -; Variance

Total unit production cost — Inc scrap, rework $ -

Total turnaround time (time-in-process) (days) | Payment net (days) | Year 1

NOTE: On each line use either Cost/item, or Cost/lb & Weight, or Cost/hr & Hr — Include

Category	Category detail	Cost/item	Cost/lb	Weight	Cost/hr	Hours	Day incurred	Total this calc	Total from Assy Calc	Scrap, rework (%)	Total	Cost of money	Accuracy (%)	Variance
Cost per item														
Overhaul														
Total materials														
	Forgings							$ -	$ -		$ -	$ -		
	Other raw materials							$ -	$ -		$ -	$ -		
	Purchased parts							$ -	$ -		$ -	$ -		
Total machining									$ -		$ -			
											$ -			
	Profiling							$ -	$ -		$ -	$ -		
	Rough machining							$ -	$ -		$ -	$ -		
	Final machining							$ -	$ -		$ -	$ -		
	Other machining							$ -	$ -		$ -	$ -		
Total plating and finishing								$ -	$ -		$ -	$ -		
	Cad plating							$ -	$ -		$ -	$ -		
	Chromate conversion							$ -	$ -		$ -	$ -		
								$ -	$ -		$ -	$ -		
	Chrome plating							$ -	$ -		$ -	$ -		
	Ni plating							$ -	$ -		$ -	$ -		
	Other treating (e.g. grinding)							$ -	$ -		$ -	$ -		

Scrap and rework

As in the Simple Calculation the cost of scrap and rework can be included. However, the scrap/rework rate associated with each cost can be assigned separately so that processes that generate more rework can be assigned a higher rate. Note that if an operation generates a particular scrap rate, then all prior operations must also generate at least the same scrap rate since scrapping the item requires that you must repeat all the operations to that point on its replacement. Rework may entail repeating one or several operations.

Cost of money

The Turnaround Time and Payment Net entered at the top of the Simple Calculation sheet are carried into the Detailed Calculation. Each cost can be assigned to a time in the manufacturing process by entering the day in the "Day incurred" column. You can even enter expenses that occur prior to the start of manufacturing (e.g. purchase of a forging) by entering a negative time in the "Day incurred" column for days **prior to** manufacturing start. The cost of money for each Direct Manufacturing cost is accumulated from the day on which the cost is incurred to the end of the Payment Net period. If no day is entered in the "Day incurred" column, cost will accumulate from the beginning of production (Day 0).

The cost of money can be included by checking the yellow checkbox at the top of the "Cost of money" column, or excluded by unchecking the box.

Detailed calculations for an assembly

A additional calculation tool is provided to assist in calculating the cost for an assembly. This area of data entry is reached by clicking the yellow checkbox labeled "Use detailed calculation from an assembly of up to 25 items". Enter the data for each item in any of the boxed columns (see figure below). The sum for each Category is brought over to the column labeled "Total from Assy Calc" in the figure above and used in place of the Detailed Data in the left-hand columns of the figure above. **However, each data item does still use the Scrap, rework % and the Accuracy % estimate in the right-hand columns of the figure above**. To aid in entering this Scrap, Rework and Accuracy data, clicking the "Assembly Data Entry Complete" button will bring you to the top of the Scrap, rework column.

Direct manufacturing cost per item, which is composed of up to 25 types of parts		$	-					
	These elements unlikely to change	**System direct manufacturing cost**	**Part 1**					
		Assy #	**Part #**					
		Descrip.	**Descrip.**					
Cost element	**Sub-element**		# of parts in system					
Manufacture/Overhaul		**Total**	**Cost/lb**	**Weight**	**Cost/hr**	**Hours**	**Cost/ item**	**Total**
Total materials	Forgings							
	Other raw materials							
	Purchased parts							
Total machining								
	Profiling							
	Rough machining							
	Final machining							
	Other machining							
Total plating and finishing	Cad plating							
	Chromate conversion							
	Chrome plating							
	Ni plating							
	Other treating (e.g. Sermetel)							

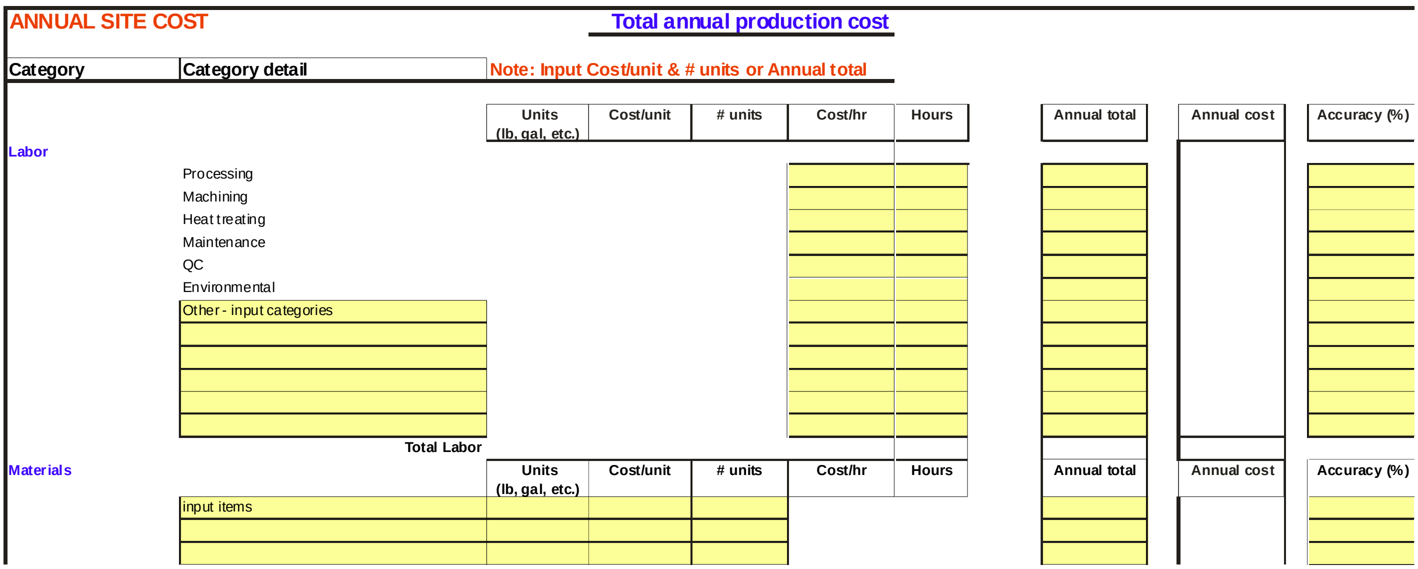
Manual input by year

Note that the spreadsheet also permits you to enter data manually for each year, rather than calculating it from production data. This is particularly useful for Site Cost models (see below), where the annual cost may vary over time depending on anticipated workloads.

Site Cost

If the cost calculation is being done over an entire site then you may use either Simple or Detailed Site data.

- Simple Site Cost - Click the "Use Simple Component Calculation or Site Cost" button. Enter data in the first data entry column of the Simple Calculations area (note that for an entire site it is not necessary to distinguish between repair and overhaul, only to account for total cost in the different categories).
- Detailed Site Cost - Click the "Use Detailed Component Calculation or Site Cost" button. Click the "Enter Site Cost" button at the top left of the Detailed Calculation area to move to the Annual Site Cost area.



Note: Annual direct costs can be calculated from annual usage or they can be entered as annual totals.

As with all other calculations you may enter estimates for the accuracy of the data, which may be drawn from historical variations or from expected accuracy. You may also enter the total direct site cost manually by year.

Calculate steel price

This button allows you to use a tool to calculate the price of alloy components when using a alternative alloy. This tool allows you to compute the expected price for the steel or for forgings, based on raw materials costs and production costs. This calculation also permits you to estimate the cost of a new component based on its weight. Click on the "Calculate Steel Price" button to go to the correct part of the sheet and enter data. The steel price data is not entered automatically into the rest of the sheet since the price to the user may depend on a great many factors. Return to the Simple Calculation area of the sheet by clicking on the "Steel Price Entry Complete" button.

Environmental

Environmental costs include

- Regulatory, compliance, and reporting costs
- Pollution control equipment
- Waste management and disposal
- Utilities

Simple Calculation

The Simple Calculation allows you to enter costs of three types

1. Fixed costs - items such as regulatory and compliance costs that are independent of the volume of waste generated.
2. Costs per item produced - such as environment-related utilities, wastewater treatment and disposal, and waste chemicals disposal
3. Costs that are directly related to manufacturing costs

Each type of environmental cost can be entered broadly or in detail. The simple entry method is done by clicking on the yellow "Use Simple Calculation" checkbox.

Variance Cost accuracy (%)	

	Total annual environmental cost		
Category			
	Fixed annual cost	**Cost per item produced**	**% manuf costs**
Regulatory and compliance (federal, state, city)			
Pollution prevention equipment maintenance			
Waste management			
Other			
☐ Use simple calculation	$ -	$ -	0%
☑ Use detailed calculation			

Detailed Calculation

Detailed information can be entered by checking the yellow "Use Detailed Calculation" checkbox. Because of the large number of possible items that can be included in Environmental Costs there are three sections, in a long column, as shown below:

1. Fixed costs - entered as an annual cost

2. Costs per item - entered as a cost for each item manufactured or overhauled
3. Costs as a percent of Direct Manufacturing costs - entered as a percent of Direct Manufacturing costs.

In each case the Accuracy is entered as a percentage of the cost. Thus, even for an indirect cost that is 1% of Direct Manufacturing cost, if it could be from 0.5% to 1.5% its accuracy is 50% (i.e. 50% of the cost).

Each section provides a number of lines for entry of other types of Indirect Costs.

As with other costs, you can enter total Environmental Cost in each category manually by year.

Annual fixed costs

	Upper bound				$ -
	Lower bound				$ -
	Standard deviation				$0
	Variance				0
	Total cost per item				$ -
Category	Category detail				Year 1
	Annual fixed costs Note: The following may be incorporated as a combination of fixed costs and as a percentage of Production costs, Sales, or Production/Overhaul volume	Total annual	Accuracy (%)	Variance	
Regulatory and compliance (federal, state, city)	Permitting (except items covered in Capital Investment)			0	0
	Labeling			0	0
	Licensing			0	0
	Record keeping			0	0
	Reporting			0	0
Pollution prevention equipment maintenance and running costs	Air handling			0	0
	Water treatment			0	0
	Chemical storage			0	0
	Chemical clean-up and recycling			0	0
	Testing			0	0

Annual item-related costs

Annual item-related costs		Total per item	Accuracy (%)	Variance	Year 1
Chemicals handling	Storage			0	0
	Treatment			0	0
	Disposal			0	0
	Record keeping			0	0
Utilities for chemicals handling	Water			0	0
	Electricity			0	0
	Gas			0	0
	Water treatment			0	0
				0	0
				0	0

Annual direct manufacturing related costs

Annual direct manufacturing-related costs		% manuf costs per item	Accuracy (%)	Variance	Year 1
Chemicals handling	Storage			-	0
	Treatment			-	0
	Disposal			-	0
	Record keeping			-	0
Utilities for chemicals handling	Water			-	0
	Electricity			-	0
	Gas			-	0
	Water treatment			-	0
				-	0
				-	0

Field Failure Probabilities

Note: Because they pertain to all Scenarios, baseline costs associated with In-service Failures (or Field Failures) are put into the C-MAT.XLS spreadsheet (see Input field failure history on page 23).

Field failures are failures that occur in service as a result of fatigue, wear, corrosion, stress corrosion cracking, etc. This item allows you to include or exclude any particular failure cost item.

It is assumed that changing the technology may affect the probability of failures due to a particular cause, but will not affect the cost of any failure that does occur. For example, a fatigue failure of a strut will have the same cost regardless of how likely it is to occur.

Into each Scenario you input how you expect the Field Failure probabilities to change. For example, if the new technology eliminates corrosion then it would change the Corrosion Failure probability to zero. However, it might also eliminate or reduce stress corrosion cracking and maintenance embrittlement failures. In addition test data might show an increase or decrease in fatigue life or wear rate, which would affect the Fatigue Failure Probability or Wear Failure Probability as well.

Options

Include or exclude field failures

Field failure can be included in some scenarios and excluded in others to assess its importance or to meet the requirements for different cost-benefit analyses. This choice is made by clicking on the relevant item in the box to the right of the red arrow. The clicked item will change to white text on a blue background.

Likelihood of occurrence with this technology

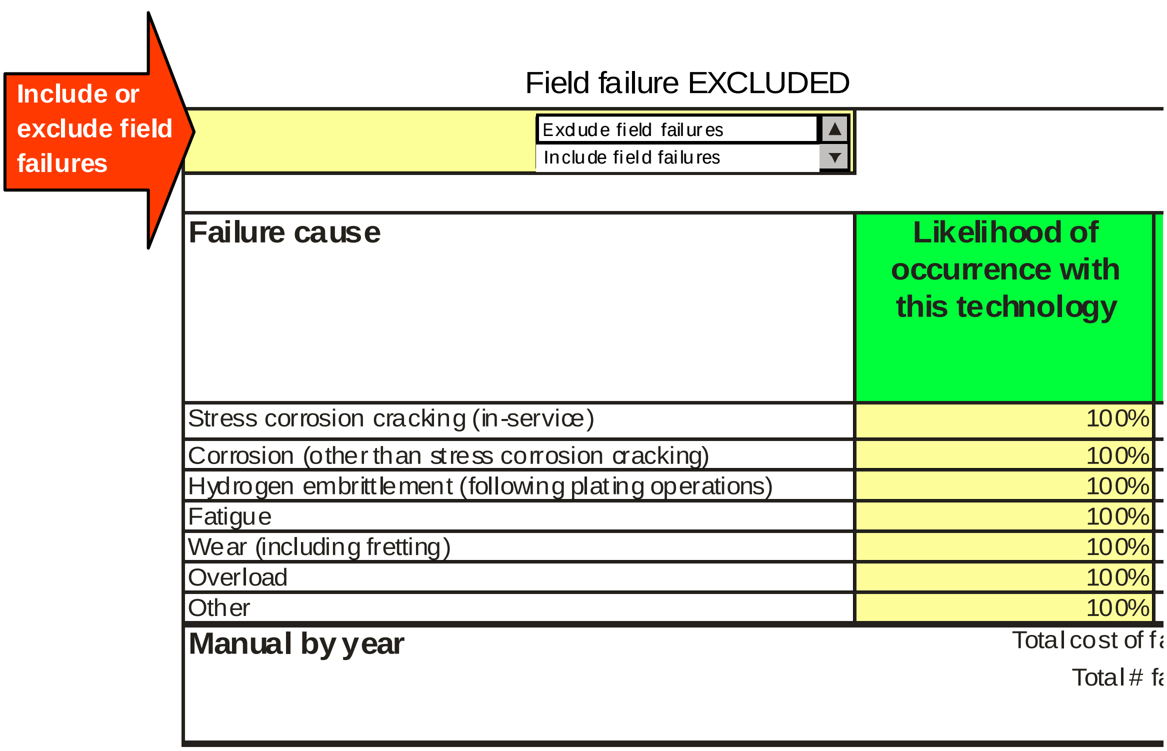
Enter here the Likelihood of occurrence **compared to the baseline**. In baseline (current technology) Scenarios these numbers should all be 100% (entered as 100 - the percentage sign is added automatically). The number of failures per year per item in service for this cause determines the actual failure rates. The variance in the failure cost is already included. We do not include an error in the probability of failure.

Causes included in the model are:

Stress corrosion cracking (SCC), environmental embrittlement (in service)
Corrosion (other than SCC)
Hydrogen embrittlement (typically shortly following maintenance or repair operations)
Fatigue
Wear
Overload
Other

Setting Likelihood of Occurrence

If the chance of failure is:	Likelihood of Occurrence is:
Unchanged	100
Eliminated	0
Only a quarter as high	25



Graphs (Scenario)

The following items are graphed by year:

- Cash Flow
- Cost Breakdown by category
    - Capital Investment
    - Depreciation
    - Direct Manufacturing/Maintenance
    - Indirect Business
    - Environmental
    - Adoption Cost of new technology
    - Purchase of New Components
    - Field (Service) Failure
- Capital Cost
- Depreciation Cost
- Direct Manufacturing Cost
- Adoption Cost
- Direct Manufacturing Cost per Item
- Adoption Cost
- Environmental Cost
- Indirect Cost
- Failure Cost
- Gross Revenue
- Production Rate
- Overhaul Rate
- Total Items in Service at End of Year

Indirect Manufacturing

Indirect costs include the many non-manufacturing costs that are required to run the business, such as:

- Inventory
- Insurance
- Legal and insurance
- Cost of money
- Cost of sales
- Indirect costs related to baseline processing (e.g. Cd plating)
- Factory space costs (including loans, rent, maintenance and utilities)
- Depreciation of existing equipment

Simple Calculation

Indirect costs are typically composed of different kinds of costs, each of which can be entered:

1. Fixed costs - items such as rent, factory space, and insurance
2. Costs per item produced - such as shipping
3. Costs that are directly related to manufacturing costs - such as cost of money

Note: Labor Overhead costs, which are directly related to labor hours (such as payroll taxes), should be included in Direct Manufacturing.

Each type of indirect cost can be entered broadly or in detail. The simple entry method is done by clicking on the yellow "Use Simple Calculation" checkbox.

The cost of money for carrying inventory may be included in the model or excluded through the choice box, but this still adds the direct cost of purchasing and warehousing inventory.

Note: Inventory can only be calculated in detail if you use the Detailed Calculation. In the Simple Calculation it is merely an annual cost.

Variance
Cost accuracy (%)

Category	Total annual indirect cost		
	Fixed annual cost	Cost per item produced	% manuf costs
Inventory			
Insurance			
Legal			
Training			
Cost of money			
Cost of sales			
Indirect base process costs			
Factory space			
Depreciation			
Other			
☑ Use simple calculation ☐ Use detailed calculation	$ -	$ -	0.0%

Enter Inventory

Exclude cost of money for inventory
Include cost of money for inventory

Detailed Calculation

Detailed information can be entered by checking the yellow "Use Detailed Calculation" checkbox.

Note: Because of the large number of possible items that can be included in Indirect Costs there are three identical sections, in a long column, as shown below, instead of side-by-side (as above):

1. Fixed costs - entered as an annual cost
2. Costs per item - entered as a cost for each item manufactured or overhauled
3. Costs as a percent of Direct Manufacturing costs - entered as a percent of Direct Manufacturing costs.

Enter data into the appropriate section for each cost Category. If a category contains fixed and variable elements, enter both in the appropriate sections and they will be added.

In each case the Accuracy is entered as a percentage of the cost. Thus, even for an indirect cost that is 1% of Direct Manufacturing cost, if it could be from 0.5% to 1.5% its accuracy is 50% (i.e. 50% of the cost).

On any of the cost sections, click on the Enter Inventory button to go to the correct place in the spreadsheet and enter inventory data. Any of these buttons will bring you to the same location.

Annual indirect costs

Enter annual cost and accuracy with which cost is known (95% certainty, or two standard deviations).

Upper bound	$	1,001,670
Lower bound	$	560,944
Standard deviation		$110,182
Variance		12,139,970,121
Total cost per year	$	780,307

Category	Category detail	Total annual	Accuracy (%)	Variance	Year 1
	Annual fixed costs				
	Note: The following may be incorporated as a combination of fixed costs and as a percentage of Production costs, Sales, or Production/Overhaul volume				
Inventory	Production inventory	Enter Inventory			
	Spares inventory				
Insurance		10,000	5%	62,500	
Legal				-	
Training	Production			-	
	Inspection, NDI			-	
	Engineering			-	
	Other			-	0
					0
Cost of money	Other than inventory and time-in-process				0
				-	0
Cost of sales					0
				-	0

Per-item indirect costs

Enter cost per item produced (OEM fabrication or overhaul) and cost accuracy. The program will compute the annual cost from the data.

Per-Item costs Note: Do not include cost items already included elsewhere as direct		Total per item	Accuracy (%)	Variance	Year 1
Inventory	Production inventory	Enter Inventory			400
	Spares inventory				0
					0
Insurance		100	50%	625	2,000
					0
Legal				-	0
					0
					0
Training	Production			-	0
	Inspection, NDI			-	0
	Engineering			-	0
	Other			-	0
					0
Cost of money	Other than inventory and time-in-process			-	0
					0
Cost of sales				-	0

Indirect costs related to direct production

Enter the cost as a percent of direct manufacturing cost (per year or per item, since the percentage will be the same in either case).

Annual direct manufacturing-related costs Note: Do not include cost items already included elsewhere as direct		% Annual Direct Manuf	Accuracy (%)	Variance	Year 1
Inventory	Production inventory	Enter Inventory			
	Spares inventory				
					0
Insurance				-	0
					0
Legal				-	0
					0
					0
Training	Production			-	0
	Inspection, NDI			-	0
	Engineering			-	0
	Other			-	0
					0
Cost of money	Other than inventory and time-in-process	300%	5%	0	768,707
					0
Cost of sales				-	0

Inventory costs

The Inventory Costs portion of the sheet can be reached from any of the Enter Inventory buttons provided. Detailed inventory calculations can only be used in the Detailed Calculation.

> **Note:** Inventory cost of money can be included or excluded using the yellow checkbox beneath the Simple Calculation at the top of the sheet. Excluding cost of money does not exclude inventory purchase or warehousing costs.

Inventory is broken down into inventory cost of the items being manufactured/overhauled and the inventory cost of ancillary parts such as maintance kits. Inventory cost consists of:

- Cost of purchasing inventory items - While this is a direct cost included in the MRO New Component Purchase (page 75)and Production Rate (page 74)sheets, the number of inventory items required is calculated here.
- Cost of money to hold items in inventory - Inventory ties up money that could be profitably invested elsewhere. The cost of money is the interest cost for the replacement value of the inventory (i.e. the replacement value multiplied by the cost-of-money interest rate).
- Cost of warehousing - Storage, tracking, etc.

Several options are provided for determining inventory levels of primary items being manufactured or overhauled (picture below):

1. Annual addition or subtraction from an initial number - used for building up or reducing inventory
2. Maintaining inventory proportional to (as a percentage of) the number of items in service - the most common way of maintaining a stable inventory
3. Adding a percentage of production to inventory - useful for building up inventory with new production
4. Maintaining inventory to meet demand immediately - this is used to establish the inventory level needed to immediately supply a new item from inventory for each item (or a percentage of items) brought in for repair. This level is based on the number of items in overhaul at any time. Define a base inventory and define what percentage of the demand you need to meet.
5. Manual input by year.

An option is to put items withdrawn from inventory into service. This has the effect of reducing the number of new production or overhaul items and is used to draw down inventory when changing technologies eliminates the need for the existing inventory.

Items in inventory				
Items already in inventory (Year 0)	**20**			
Annual addition or removal from inventory				
Annual addition/removal rate	6			
Addition/removal start year	3			
Addition/removal stop year	7			
# items in inventory - calculated		☐ Automatic calculation		20
Maintain inventory as % items in service	5%	☐ % items in service		
Add % of production to inventory	10%	☐ Add % to production		20
Maintain as % of production	10%	☐ Maintain as % of production		
Maintain inventory to meet demand immediately		☐ Meet immediate demand	Base inventory 0 % demand to meet 20	
Manual input # in inventory		☑ Manual input		20
Number of items required in inventory				
# items that need to be added to (subtracted from) inventory				
Items purchased for inventory				
# items to be withdrawn from inventory		☐ Put withdrawn items into service		
Total items in inventory at end of year				20

Excess Inventory

Inventory costs for components used in manufacture or overhaul of primary items are added in the table shown below, which is located directly beneath the Items in Inventory table shown above. This table calculates the inventory costs. For primary manufactured or overhauled items these costs are calculated automatically and only the warehousing cost need be added. As with primary items there are several options for how the ancillary parts inventory is to be maintained. These components need not use the same inventory model as primary items. Choose only one method for each component type:

1. Base inventory plus immediate demand inventory (a checkbox can include or exclude this column)
2. Annual purchase/reduction
3. Maintain as % of items in service
4. Maintain as % production
5. Add as % of production to inventory

Cost (second column) is the cost of each inventory component, kit, etc. Inflation is included. Warehousing cost can also be included.

Inventory cost
(cost of warehousing + cost of money+purchase cost of accessories)

☑ Include

Item	Cost (Year 1)	Number per component	Base inventory required (# items)	Immediate demand inventory (Year 1)	# purchased /year for inventory
This component (purchase cost on MRO new component purchase sheet)			0	1	
Maintenance kits	$0	2	20	7	
Other accessories (insert)				0	
				0	
				0	
				0	
				0	
				0	

Manual input of total parts inventory and warehousing

(table continued)

Maintain inventory as % items in service	Maintain inventory as % production	Add % of production to inventory	Ware-housing cost/item	Cost of money	Cost accuracy (%)
				$0	20%
				$0	20%
				$0	
				$0	
				$0	
				$0	
				$0	
				$0	
				$0	20%
			Total components + other parts	**$600**	
			Total other parts	$0	

Title

Scenario	**Scenario01**
Title	**Drag Strut - Existing MRO**
Description	Existing repair of 300M component
Comments	Existing repair. Demonstration scenario

Organization	
User	
Date	

This sheet contains the basic information that you will use to identify the Scenario. Enter the information by clicking on the cell and typing. To change information double-click on the cell to put the cursor into the text and change as needed.

Scenario: This is just the Scenario filename, ScenarioNN. Remember to use two digits, from 00 to 99

Title: A short title that will identify what this set of Scenarios is about.

Description: A short description of this specific Scenario

Comments: Whatever comments you will need to later understand what assumptions you put into this Scenario, where the data came from, or any other useful notes.

Organization, User, Date: User-identifying information.

When you have entered all the information you wish to record, click the Input Data button. This will take you to the Assumptions, Inputs sheet, which is the jumping-off point for data entry.

Setting the production rate and number of items in service

Production rate is the term used both for OEM (new item) production and for MRO (overhaul) production:

- For OEMs Production Rate is the number of items manufactured per year
- For MRO organizations Production Rate is the number of items overhauled per year

Notes:

- The choice of OEM or MRO models on the C-MAT constants page changes how the calculations are made, so that the Production Rate page outputs either OEM or MRO production.
- All data in a Scenario must relate only to the technology of that Scenario, because all the costs can only relate to one technology. Do not, for example, mix taking old technology parts out of service and replacing them with new technology parts in the same Scenario. To do this, you must define a Scenario to phase out old technology production and overhaul and another to phase in new technology and overhaul. This why the C-MAT spreadsheet permits comparison of the baseline with the sum of two Scenarios.
- Be sure to be consistent in your definition of "item". An item can be a single component (such as a piston rod), a subassembly (such as a hydraulic actuator), or a complete assembly (such as an entire landing gear). Your choice of "item" should include all costs that may be affected by the use of the new technology. Thus, if a new material for a pin requires a different assembly method for an assembly, then choose the assembly as the "unit". Of course, if qualifying the use of the new technology for the pin requires a complete landing gear endurance test, but does not change manufacturing, assembly, or maintenance of other items, then you can still consider the pin as the "item", but include the endurance test as part of the Adoption Cost.

The number of items in service, OEM production, and item retirement rate are interrelated and all affect the overhaul rate:

Items in service in Year N = Items in service in Year 0 + Sum(items added) - Sum(items retired)

MRO Production Rate = (# items in service)/(maintenance cycle) + # unscheduled maintenance items

The number of items in service may vary with the changing size of a fleet or it may be kept constant by replacing retired items. If fleet size is intended to be kept constant then you must be sure to balance new purchases with retirements, either automatically (which the program can do) or by balancing new production and retirement rates.

The necessary information is entered in several sheets:

- Overhaul Rate sheet (page 69)
  - items already in service in Year 0
  - retirement rate (constant rate, retire on overhaul, or manual input)
  - repair cycle (time between repairs, years)
  - unscheduled overhaul rate
- Production Rate sheet (page 74)
  - OEM production rate (constant rate, replace retired items, or

manual input)

- MRO New Component Purchase (Page 75)
  - used only to input the cost **<u>to the MRO organization</u>** of new components
- Revenue sheet (page 76)
  - used to input the price, either
    - selling price per item, for OEMs, or
    - overhaul charge per item, for MROs
  - price can be entered as constant (with or without inflation or other escalator), as cost plus, or as manual input

- Choice of OEM or MRO is entered on the C-MAT Constants sheet (page 21)since this is a constant for any Scenario in the model.

OEM production

- Set the Decision Tool to OEM on the C-MAT Constants sheet (page 21)
- For a new program set the production rate on the Production Rate sheet (page 74). It can be set constant, with start and stop dates, or it can be input manually.
- Set a pricing model on the Revenue sheet (page 76)using a constant, cost-plus, or manual model.

MRO production

- Set the Decision Tool to MRO on the C-MAT Constants sheet (page 21)
- Enter the repair cycle, retirement rate, and unscheduled repair rate on the Overhaul Rate sheet (page 69). If production is to be ramped up or down set the start and stop years to do this correctly
- Set the OEM production rate on the Production Rate sheet (page 74) to reflect changes in fleet size or to replace retired items. Check fleet size (Items in service) on the graph to ensure it matches your expectations, and adjust retirement rate or OEM production rate to correct as necessary.
- Set the Purchase Price on the MRO New Component Purchase sheet (page 75).

Overhaul Rate

This sheet calculates overhaul/repair rates based on the number of items in service and the overhaul cycle:

- Overhaul rates (number of items overhauled per year). This includes scheduled and unscheduled overhauls.

- Schedules overhaul items are brought in for overhaul at a rate determined by the number of fielded items and the Overhaul Cycle. For example, if there are 150 items in the field and the overhaul cycle time is 10 years, then 15 items will come in for overhaul each year.
- Repair rates (number of parts requiring significant repair). For convenience this is provided as a separate cost category since, while most items may require a standard overhaul, some proportion may require significant repair as well. **Note:** ***Items requiring repair are a subset of items brought in for overhaul***. Thus Repair items cannot exceed Overhaul items, which can happen in the formulae if large numbers of items are condemned and retired from service. In this case it is necessary to define the number of items needing repair either manually or as a percentage of Total Overhauls.
- Items brought in from service outside the usual overhaul cycle are shown in the Unscheduled Overhauls section of the spreadsheet.

Note: Remember that each scenario is specific to a particular technology. So, if this is a Scenario for the existing baseline technology, then only production using that technology is included. **Do not mix parts using different technologies in the same Scenario.**

- The number ***put into service each year*** is automatically brought in from the Production Rate sheet (page 74).
- Enter the number of items ***in service*** at Year 0.
- Enter the number ***removed from service*** each year:
  - For constant annual number of removals enter Annual Retirement Rate, Start and Stop years and click the Automatic Calculation from Above box.
  - To retire items from service on overhaul (as you might if replacing with a new design) click the Retire from Service on Overhaul box and input the Start Year as the first year in which the retirements are to begin. **Note:** In this type of scenario, the number of overhauls and repairs ***must be zero*** beyond the Start Year.
  - To enter retirement numbers for each year click the Manual Input box and enter the numbers for each year in the yellow cells.
- Enter the ***Repair Cycle*** (time between overhauls) under Repair cycle (years).

Overhauls required:

- ***Unscheduled Overhauls*** can either be entered as
  - A percentage of items in the field - click the % of Items in the Field box and enter the percentage number (the % sign is added automatically).

- An annual average - click the Annual Average box and enter the annual number of unscheduled overhauls.
- A number for each year - click the Manual Input box and enter the data for each year on Line 28 (yellow cells).

- ***Overhaul Rate Accuracy*** is entered as a percentage in the topmost yellow box, as in all other sheets.

Repairs required:

- Items requiring repair are a subset of overhaul items - i.e. they are those items that are found to require more than a standard overhaul. Therefore ***repair numbers cannot exceed overhaul numbers***.
- Repair numbers may be defined as:
  - A percentage of total overhauls
  - A percentage of scheduled overhauls only
  - A percentage of unscheduled overhauls (e.g. most unscheduled overhauls may be for major repair)
  - Annual average
  - Manual input (enter number by year into yellow cells).

Note: You may enter different ways of handling overhaul and repair on the same sheet. The method taken up by the model is the one that is checked.

Once you have completed data entry look at the graphs of Overhaul Rate and Items in Service at Year End to ensure that these are what you expect.

Click the Overhaul Data Complete menu item under the Production Rate toolbar button to return to the Assumptions, Inputs sheet. This will mark the Overhaul Rate sheet as complete.

				Standard deviation	-
				Variance	-
Repair rate accuracy (%)				Repair rate	-
Overhaul rate accuracy (%)				Standard deviation	-
				Variance	-
				Overhaul rate	-
					Year 1
Items in Service					
Items already in service (Year 0)					
Items added to service (from Production rate sheet)					0
Annual retirement rate					
Retirement start year					
Retirement stop year					
Items retired from service - calculated	☑ Automatic calculation from above				0
Original items retired from service on overhaul	☐ Retire from service on overhaul	Start year			0
Items retired from service - manual input	☐ Manual input				
				Total retired from service	0
Original items remaining in service (new items retired)				0	0
Cumulative new items in service (from Production Rate sheet)					0
Total items in service at end of year				0	-
Overhauls required:					
Existing items returned for repair					-
New items returned for overhaul (or supplied from inventory)	Overhaul cycle (years)				-
Constant overhaul rate			per year		-
Manual input of overhaul rate					
Total scheduled overhauls					-
Unscheduled overhauls per year	☐ % of items in the field				-
Unscheduled overhauls per year	☐ Annual average				-
Unscheduled overhauls per year	☑ Manual input				
Total unsheduled overhauls					-
Repairs (overhaul items requiring significant repair):					
Repairs as percentage of Total Overhauls	☑ % of Total Overhauls				-
Repairs as percentage of Scheduled Overhauls	☐ % of Scheduled Overhauls				-
Repairs as percentage of Unscheduled Overhauls	☐ % of Unscheduled Overhauls				-
Annual average repairs	☐ Annual Average				-
Annual average repairs	☐ Manual Input				
Total repairs					-

Overhaul of new items

Whenever a new item is purchased it enters the overhaul cycle and is returned for overhaul at the end of the overhaul cycle. If it is life-limited it will then be retired at a certain age. As a result, calculations will often show a periodic rise and fall in overhauls reflecting the times when new items were introduced. This is normal and is generally only a small effect. A table below the charts in the spreadsheet tracks when new items are purchased and come in for overhaul. These numbers are used in the model calculations.

Production rate accuracy (%)		**Standard deviation**	-
		Variance	-
Overhaul/Repair		**Production rate**	**0**
			Year
			1
OEM production			
Annual OEM production rate			
Production start year			
Production stop year			
Calculation of OEM production	☑ Automatic calculation		0
Manual input of production	☐ Manual input		
Replace retired items	☐ Replace retired items		0
Items purchased for inventory			0
Total new items to be purchased			0
Total new items put into service			0
Cumulative new items put into service			0
Total overhaul items			0

Production Rate

This sheet is used for the input of **OEM Production Rate** numbers or of **replacements for items removed from service or purchased for inventory**.

It displays the Production Rate on Line 8 , showing either

- the OEM Production Rate (number of items manufactured annually) calculated in this sheet, or
- the MRO Production Rate (number of items overhauled annually), from the Overhaul Rate (page 69) sheet

Note: Production Rate displayed at the top of this sheet is OEM rate in OEM scenarios and Overhaul Rate in MRO scenarios. The type of production is selected in the Input Constants (page 21)sheet of the C-MAT spreadsheet.

OEM Scenarios:

Automatic calculation: For a steady production rate, enter the Production Rate, Start Year, and Stop Year in the boxes and click the "Automatic Calculation" button.

Manual input: Input the expected rates for each year in the boxes on Line 17 and click the "Manual input" button.

Replace retired items: This is used to automatically calculate the production needed to maintain a constant fleet. The number of retirements is calculated in the Overhaul Rate (page 69) sheet and these retirement numbers are added to the Production Rate sheet to maintain the number of fielded items constant.

Items purchased for inventory: The numbers in this row are automatically brought in from the Inventory section of the Indirect Business (page 60) sheet.

All new purchases are brought into the MRO New Component Purchase (page 75) sheet to calculate the new component purchase costs.

As in all other sheets the accuracy of the estimates can be entered in Production Rate Accuracy (%).

Overhaul Scenarios:

This sheet may be left blank unless OEM purchases are required (e.g. to replace retired items or manufacture additional items for the fleet). Overhaul production rate data will be brought in automatically from the Overhaul Rate (page 69) sheet. If you wish to replace retired items, then click the Replace Retired Items box.

Click the Production Data Complete menu item under the Production Rate toolbar button to return to the Assumptions, Inputs sheet. This will mark the Production Rate sheet as complete.

MRO New Component Purchase

This sheet is primarily intended for use by MRO organizations and allows you to enter the following by checking the appropriate yellow box:

- The cost of new components purchased from the manufacturer
- The cost may remain constant or have a constant inflation (which need not be the same as the standard inflation rate)
- Alternatively you can enter data for each year manually.
- Note that ancillary materials and parts (such as parts kits) are entered in the Direct Manufacturing (page 47) sheet.

Note: The number of new items per year is determined from the Production sheet and Inventory section of the Inventory sheet.

	Cost accuracy (%)		Standard deviation	$0
			Variance	$0
		Overhaul/Repair	Annual purchase cost	**$0**
				Year
				1
Number of items purchased (or # withdrawn from inventory)				0
Purchase price				
	☑ Constant cost	Current cost		$0
	☐ Annual % change	Annual % change		$0
	☑ Manual input			
Cost				**$0**
Total new items purchased (from Production sheet)				0
Cumulative new items purchased				0

Revenue

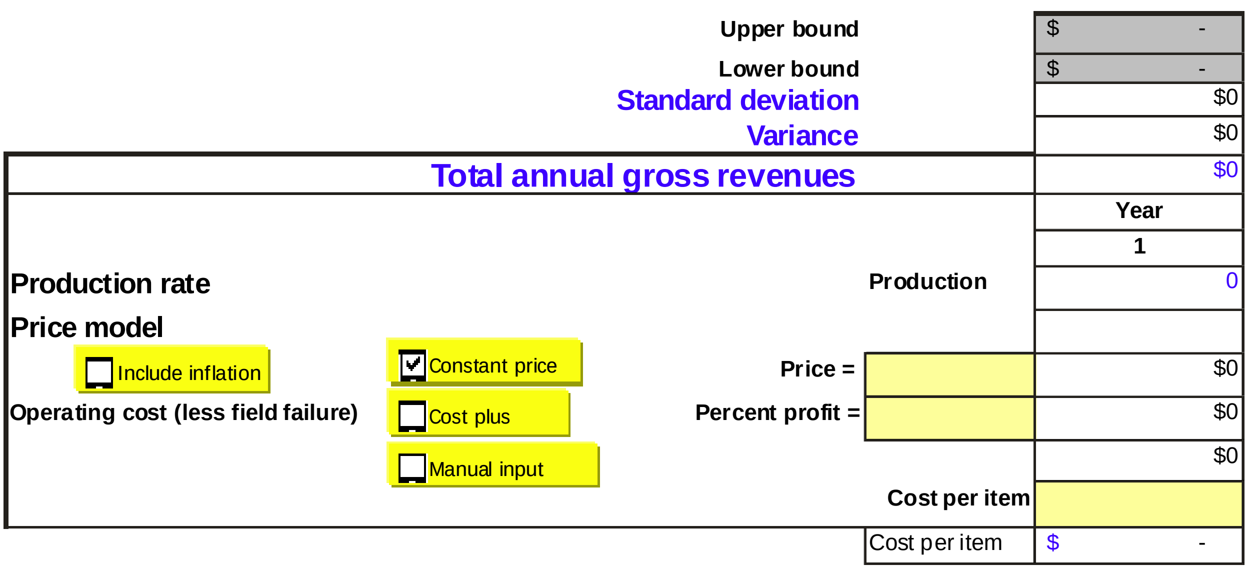
This sheet is used for calculations based on Revenues rather than cost savings. This is likely to be the preferred method for most OEMs, but it may also be used by MRO facilities and by depots, which are increasingly being required to operate as businesses.

Price (per new item or per overhaul) can be entered in three ways:

- ***Constant price*** (with and without inflation included) **-** click the Constant Price box and enter the price.
- ***Cost plus*** **-** click the Cost Plus box and enter the percentage "profit" over cost. Cost is defined as Operating Costs (Direct manufacturing, MRO new components, Environmental, Indirect Business, and Field failures and Depreciation if included)
- ***Manual input*** **-** click the Manual Input box and enter the per-item Price for each year on Line 16.

It is assumed that price is a defined quantity and has no variance attached to it. The Revenue Variance displayed in the sheet derives from the variance in number of items sold or overhauled.

Click the Revenue Data Complete button to return to the Assumptions, Inputs sheet. This will mark the Revenue sheet as complete.



CHAPTER 8 THE COST MODEL

Overview of the financial model

The Decision Tool is based on a financial model of the entire manufacturing and qualification process, including all of the costs of testing, qualification, and paperwork changes, and the costs of service failure (if desired).

The model is designed to be used by different types of organizations:

- Original Equipment Manufacturers (OEMs) – These users will be primarily concerned with manufacturing cost changes, liability and warranty cost changes, and changes in revenue streams. OEMs are most likely to base decisions on cash flow and profitability.
- Maintenance, Repair and Overhaul (MRO) organizations – These users (such as military depots) will be primarily concerned with maintenance cost changes, environmental cost changes, and reduction of both technical and financial risk. MROs are most likely to base decisions on cost savings.

The tool provides both tabulated and graphical outputs to assist in decision-making.

Data input

The financial details are contained in the worksheets of each Scenario spreadsheet. Each worksheet is designed so that the user can enter either detailed financial information (ensuring that important costs and savings are included) or enter the data in a simple summary form. Each sheet also includes various model projections as well as the ability to enter separate data in each category for each year manually.

Each sheet includes a cell for an estimate of the accuracy and variability of the information (where accuracy is defined as 95% probability, or two standard deviations). Ideally this number will be determined based on existing cost data. Where prior data cannot be used, it should be assigned a reasonable value that reflects the accuracy with which it is known.

Note that, since the final calculation takes the difference between the cash flows in the different Scenarios, it does not matter whether the user inputs the actual costs or simply the difference between the baseline and the alternative Scenarios. Then the user simply enters the change in cost in each category. Higher costs or incomes are entered as positive numbers, while reductions in cost or income are entered as negative numbers. However, actual production and overhaul numbers do of course need to be entered in the alternative Scenarios, not the difference (since the difference will normally be zero).

Tabular and graphical output

All of the measures of value (except Payback Period) depend on the length of time over which they are measured. The primary output is provided in the form of graphs of NPV, ROI, and IRR as a function of time. This permits the user to understand how the value measures change with time.

The primary financial measures (cash flow, capital/adoption costs, operating costs, gross revenues, and cumulative cost and cash flow) are also provided graphically. Each scenario also contains graphical outputs of all the financial items in the model.

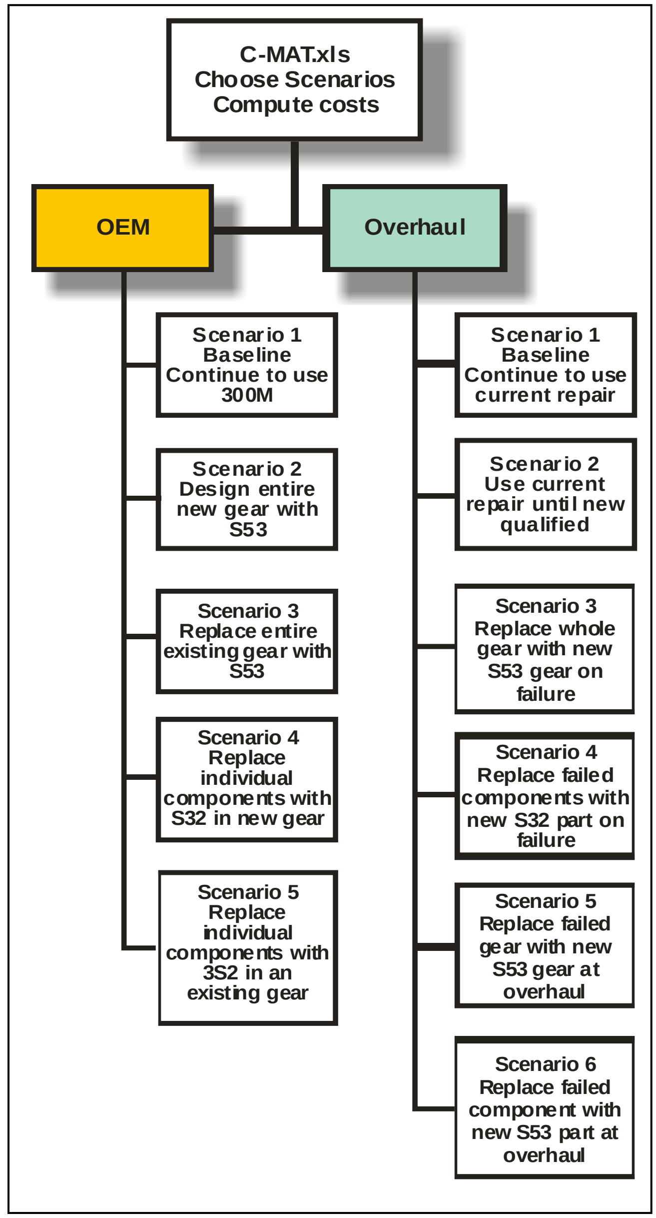
Scenarios

A Scenario is simply a financial picture of the costs associated with a particular change. It includes all the costs estimates associated with

- Changing the material
- Manufacturing (both direct and indirect costs)
- Capital expenditures for new equipment
- Purchasing new components
- Environmental compliance
- Adopting the new technology (qualification, paperwork, drawing changes, etc.)

It also incorporates

- When the change is made (immediately, on failure, at overhaul, etc.)
- How the change is made (replace the whole item or a part)



One Scenario must always be the baseline – i.e. what is done today. The tool allows the user to generate up to 99 Scenarios covering different types of situations, items, or cost estimates. 25 of these are readily accessible in the model sheets. This allows you to compare a number of “what-if” scenarios to determine which option is the least expensive or carries the lowest financial risk.

Basic models for some of the most likely Scenarios are provided. The user can readily build new a new Scenario off an existing one or from a blank Scenario sheet (i.e. a sheet with no existing data).

Details of model cost items

In its general form, this decision tool financial model is designed for use by people who need to evaluate the costs and savings involved in switching from an existing technology to a new technology. This particular version of the tool is intended for use by OEMs and military maintenance depots considering a change from existing steel used in aircraft components (e.g. 300M used in landing gear) to a new high strength stainless steel (designated S53).

Capital costs

Capital costs include any costs for permanent machinery and equipment needed to adopt the new technology, including

- Production equipment such as specialized machining or finishing equipment
- Manufacturing tooling such as specialized jigs and fixtures
- Process control equipment such as heat treating temperature measurement or control equipment
- New equipment for NDI, QC or QA
- Pollution prevention or environmental controls
- Buildings and land

Other machinery or equipment with an expected life in excess of 5 years.

Depreciation

Depreciation covers the loss in value of a capital asset over time. Although it is not a direct cost, it should generally be incorporated into the cost structure. (Depreciation can be set to “None” to exclude depreciation from the calculations.) Depreciation can be thought of as annual contributions to a “fund” for the purchase of new capital equipment when the original equipment wears out. In order to calculate depreciation cost the equipment must be assigned an initial cost, V_o, a life, L, and a residual or salvage value, V_s, at the end of its life.

There are various ways of calculating D_n, the annual depreciation for the Year n. The model permits a choice of the following standard methods:

- None – In this case depreciation is not taken into account.
- Straight line – This method simply depreciates the asset value by an equal annual amount from the initial cost to the residual value

  $$D = \frac{V_O - V_S}{L}$$, for all years

- Sum of the years’ digits – This is a common method of weighting depreciation toward the beginning of the asset’s life to more closely reflect its real loss of value

$$D = \frac{2L(Vi - Vr)}{L(L+1)}$$

- Declining balance – This is another common means of weighting the decline in an asset's value toward the beginning of its life. The formula is a great deal more complex than either of the above. Depreciation for Year n is defined as

  (initial cost - total depreciation from prior periods) * rate

  where

  rate = 1 - ((salvage / initial cost) ^ (1 / life)). We can express this as

  $$D_n = (V_o - \sum_{1}^{n-1} D_i)(1\text{-}(V_s/V_o)^{1/L}$$

  For the first period, however D_1 = initial cost * rate.

- Double Declining Balance – This method weights the decline in value more heavily toward the beginning of the asset's life. Depreciation for Year n is defined as

  ((initial cost-salvage) - total depreciation from prior periods) * (2/life)

  We can express this as

  $$D_n = ((V_o - V_s) - \sum_{1}^{n-1} D_i)(2/L)$$

Direct manufacturing

Direct manufacturing is the direct cost of manufacturing or overhaul

- Materials
- Machining
- Coating and finishing
- Heat treating
- NDI
- New component purchase.

Indirect business

Indirect business costs include

- Inventory
- Insurance
- Legal costs
- Training of personnel
- Cost of money

- Cost of sales
- Factory space
- Depreciation
- Indirect costs related to existing technology.

Environmental

Environmental costs include

- Regulatory and compliance costs (federal, state, city)
- Pollution prevention equipment maintenance
- Waste management and disposal.

Adoption

Adopting a new technology involves a great many paperwork, testing, qualification, and other costs, such as

- Materials qualification testing
- Process development costs - component specific
- Component recertification
- Specification development
- Configuration control
- Support documentation, drawing changes
- Changes to travelers and other paperwork
- Approval paperwork
- Development of manufacturing, repair, testing, and QC procedures
- Engineering related to capital equipment installation
- Costs related to decommissioning equipment
- Costs related to personnel changes.

Field failure (C-MAT.XLS)

Failures in service (field failures) can represent a major cost that is directly attributable neither to OEMs (unless it relates to warranty) nor to MRO facilities. However, it is a direct cost to airlines and the defense department as a whole.

The model allows the user to input failure mode and cost data for prior years so as to calculate the failure costs due to each of these failure modes, as well as the standard deviations of the various costs. Costs that can be included (on a category by category basis) include both direct incident costs and indirect costs. Direct costs include:

- Component replacement
- Repair costs not directly attributable to MRO operations, e.g.

transport to repair center, etc

- Subsystem replacement cost, e.g. brakes, lights, etc.
- Collateral damage
- Complete loss off aircraft or crew (including the cost of replacement crew training)
- Accident investigation cost.

Most of these direct costs are borne by users (airlines or the Defense Department).

Indirect costs include:

- Legal and liability costs
- Warranty replacement and repair
- Insurance cost changes (including self-insurance costs and deductibles)

Most of these indirect costs are borne by OEMs.

These historical cost data are included in the Costcalc.XLS workbook since they are common to all scenarios.

Failure probability (Scenario)

Changes in component materials and treatments can affect the probability of failure from various common causes. For example, adopting a corrosion-resistant steel or a better corrosion inhibiting coating would be expected to reduce corrosion failures and the incidence of stress-corrosion cracking.

The program takes into account changes in the probability of failure due to several common causes:

- Stress corrosion cracking (environmental embrittlement)
- Corrosion
- Hydrogen embrittlement (as a result of repair operations)
- Fatigue
- Wear
- Overload
- Other.

Changes in the probability of these failure modes can be estimated or calculated from test data.

Because the failure probabilities may change with each scenario (e.g. between baseline and new materials), failure probabilities are changed in the Scenario spreadsheets.

Production rate

Production rate is used for both OEM and for MRO operations. It is simply the number of items manufactured or overhauled annually.

Overhaul rate

Overhaul rate is calculated based on the number of items in service and the overhaul cycle (time between overhauls), as well as the percentage of unscheduled overhauls and repairs. The model allows for the option of retiring items from service on overhaul (as might be done when replacing items made from existing materials with items made with a new material). Newly purchased items are assumed not to be overhauled until their first overhaul cycle (except for unscheduled repairs).

Note that the overhaul cycle may change with a new technology, which may require more of less frequent overhauls.

Revenue

Revenue is based on production rate (OEM or MRO) and price. This allows for input of different pricing models for the different technologies, as well as for the possibility of increased (or decreased) sales as a result of adopting the new technology.

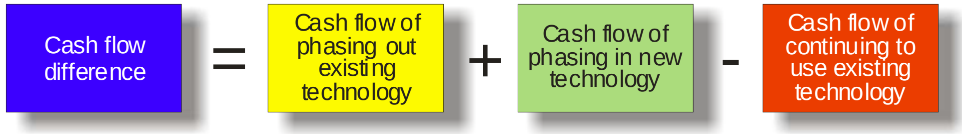
Revenue calculation permits decisions to be made on the basis either of cost (as a user would typically do) or of profitability (as an OEM or overhaul operation would typically do). The distinction is important since the two methods of decision making are radically different. For example, an OEM would be expected to maximize profit by reducing total cost (including liability and warranty cost as well as production cost), while a user would be expected to minimize cost (including adoption and service failure costs as well as production cost).

Value calculations (C-MAT.XLS)

In order to determine whether or not a technology change is financially beneficial we must compare our financial results using the new technology against our financial results using the current technology. The decision tool therefore calculates the difference between the revenue streams and costs of the new and existing technologies. In fact, since it usually takes several years to put a new technology completely into place, the tool permits the user to create a “technology adoption” Scenario as the sum of two scenarios:

1. Maintaining the current technology until the new technology is on-line and then phasing it out
2. Qualifying the new technology and phasing it in.

Financial results can be expressed either in terms of increased profitability (see Cash flow-based model) or in terms of decreased costs (see Cash flow-based model). All results are calculated over a 15-year time scale.



Discount rate

The discount rate (i.e. the percentage by which future cash flows are discounted) simply says that income received N years in the future has its value reduced by a percentage equal to the discount rate over N years.

The discount rate may reflect the actual cost of money (loan interest rates) or it may be a nominal rate assumed by an organization for the purpose of financial calculations. OMB Circular A-94 ("Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs", October 1992) states: "Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7 percent. This rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years. Significant changes in this rate will be reflected in future updates of this Circular."

Financial value measurements

This decision tool includes the standard discount rate-based measures of value:

- **Net Present Value (NPV)** – NPV is the value today of a future cash flow. NPV is the primary measure of value recommended by OMB. For cash flows (positive and negative over n years:

$$NPV = \sum_{i=1}^{n} \frac{cash\ flow_i}{(1 + discount\ rate)^i}$$

  Note that cash flows that are received further into the future are worth less than those received earlier. The NPV of the single cash flow in Year i is simply the amount of money that would have to be invested up-front and compounded at the discount rate to have a value equal to the cash flow in Year i.

- **Internal Rate of Return (IRR)** – Closely related to NPV, IRR is the choice of discount rate that would be required to make the NPV become equal to zero. IRR requires an initial investment that generates a future series of cash flows. The IRR is the interest rate that would be required for the initial investment to produce the same NPV as the cash flows. Thus the higher the IRR value, the greater the return on the investment.

  IRR requires at least one negative cash flow (cost) and at least one positive cash flow (income). Since Microsoft Excel uses an iterative method to calculate IRR, the answer may not always converge, even when supplied with a guess as the starting point for the iteration. In that case the program produces an error. The iterative method also often produces extreme results that are clearly incorrect. Sometimes a better guess will correct these errors, but if not they should simply be ignored.

- **Return on Investment (ROI)** – This is simply the annual return for the investment expressed as a percentage:

$$ROI = \frac{\textit{Annual net cash flow}}{\textit{Investment}}$$

For most technology adoption projects the investment takes place over several years. We have defined the ROI for Year n as:

$$ROI_n = \frac{\textit{Cash flow}_n}{\sum (\textit{Capital} + \textit{Adoption Costs})}$$

In the decision tool investment is defined as the sum of all capital investment and adoption cost.

- **Payback Period** – Payback Period is the time required to recoup the investment. There are subtly different ways this can be defined. The most common definition, which is the one we use, is that Payback Period is the point at which cumulative cash flow becomes positive. (This is called the "simple" payback period since it does not discount the cash flows). One might also define Payback Period as the time at which NPV becomes positive. (Cash flow will almost always be negative in the initial period because of the cost of adopting the alternative.)

  Note: It is necessary to check the number provided by the software against the graph of Cumulative Cash Flow and Cumulative cost to ensure that the correct crossover is chosen.

Cash flow-based model

This model takes into account total cash flow, including revenue derived either from sale of components or from overhaul operations. It is intended primarily for use by OEMs and commercial overhaul shops. The following are calculated for each year:

- NPV of total cash flow
- IRR_n of operating cash flow, including any required Baseline investments needed to keep using the current technology. The initial cost taken for IRR is the total Capital cost + Adoption cost of Scenarios A and B. IRR_n is the IRR taken from Year 1 to n, assuming all investment is in Year 1.
- ROI_n, determined as (Year n operating cash flow + Baseline investments)/(Total capital investment + adoption costs)
- Payback Period, defined as the point at which cumulative differential cash flow becomes positive.

Cost-based model

The cost-based analysis does not consider revenues that an organization derives from adopting the new technology, but considers only costs and cost savings (as well as depreciation). The following are calculated for each year:

- NPV of total cost savings
- IRR_n of operating cost savings, including any required Baseline investments needed to keep using the current technology. The initial cost taken for IRR is the total Capital cost + Adoption cost of Scenarios A and B. IRR_n is the IRR taken from year 1 to n, assuming all investment is in Year 1.
- ROI_n, determined as (Year n operating cost savings + Baseline investments)/(Total capital investment + adoption costs)
- Payback Period, defined as the point at which cumulative differential cost becomes positive.

Uncertainty in the estimates

Since the various costs cannot be known precisely, the final values are also subject to uncertainty. To take this uncertainty (error) into account the variances of the numbers are added to obtain an estimate of the total variance of the calculation. (This assumes a normal distribution of probabilities.)

For a normal distribution, the standard deviation is square root of the variance:

$$\sigma = \sqrt{V}$$

and when summing independent variables, each with a variance, V_i the variance of the sum is simply the sum of variances:

$$V_i = \sum_i V_i$$

The variance of the difference of two variables is also the sum of the variances, which is why uncertainties can become relatively large when taking the difference between similar values, as we do in most cost evaluations.

When independent variables with variances are multiplied and divided the situation becomes more complex:

If

$$x = k\frac{a.b}{c.d}$$

Then the relative variance of the sum is the sum of the relative variance, i.e.:

$$\frac{\sigma_x^2}{x^2} = \frac{\sigma_a^2}{a^2} + \frac{\sigma_b^2}{b^2} + \frac{\sigma_c^2}{c^2} + \frac{\sigma_d^2}{d^2}$$

Which leads to

$$\sigma_x^2 = \left(k\frac{a.b}{c.d}\right)^2 \left[\frac{\sigma_a^2}{a^2} + \frac{\sigma_b^2}{b^2} + \frac{\sigma_c^2}{c^2} + \frac{\sigma_d^2}{d^2}\right]$$

Thus, when a variable is multiplied by a constant, the variance of the result is the original variance multiplied by the square of the constant:

If

$$x = k.a$$

Then

$$\sigma_x^2 = k^2.\sigma_n^2$$

Further, if

$$x = k.a.b$$

Then

$$\sigma_x^2 = k^2.\left[b^2.\sigma_a^2 + a^2.\sigma_b^2\right]$$

And if

$$x = k.{}^{a}\!/_{c}$$

Then

$$\sigma_x^2 = \left(k\frac{a}{c}\right)^2\left[\frac{\sigma_a^2}{a^2} + \frac{\sigma_c^2}{c^2}\right] = k^2.\left[\frac{\sigma_a^2}{c^2} + \frac{\sigma^2.\sigma_c^2}{c^4}\right]$$

To provide an estimate of the accuracy of the result and how they vary with assumptions, the value curves also contain lines for one and two standard deviations above and below the mean.

Appendix B
NITRIDING TRIALS

Low Temperature Plasma Nitriding

Introduction

As S53 is implemented in various landing gear components traditional methods of providing wear resistance such as hard chrome (HCr) or high-velocity oxy-fuel (HVOF) may be able to be replaced by utilizing nitrided surfaces. Although HCr and HVOF coating may be eventually required for rework in overhaul repair, initial nitrided S53 surfaces may provide adequate wear resistance for landing gear applications of interest. Anticipating this need, preliminary nitriding trails were performed to test the feasibility of using low temperature plasma nitriding to surface harden S53 and provide the needed boost in wear properties.

Nitriding is a common thermochemical process whereby nitrogen is introduced to the steel work piece, hardening the outer case. Common techniques include gas nitriding, plasma nitriding, and liquid nitriding. Of the three, plasma nitriding is the most controllable and consistent process and was selected for use in this study. Low temperature nitriding, under 1000°F, allows the tempering kinetics of S53 to line-up with nitriding process conditions, ideally combining nitriding and tempering into a single operation during production.

As nitriding has been commercially available for many years, the microstructural mechanisms behind the process are well understood. Nitriding results differ from steel to steel based on alloy composition, alloy microstructure, and thermal behavior. It is common for steels to form a “white layer” or compound zone on the outer case of the material. This layer may be γ’, ε, or a combination of the two phases. In any case, it is a different phase from the matrix structure of steel, and as such has radically different properties. The desired property is hardness, as these compound zones are extremely hard and generally boost sliding, abrasive, and rolling wear. Unfortunately the resulting compound structure is not corrosion resistant, and dramatically decreases the corrosion resistance of the overall system by inhibiting passive film formation and providing initiation sites for corrosion products.

Based on the desire to maintain corrosion resistance during nitriding, QuesTek attempted to nitride S53 under conditions that would avoid the white layer and result in a single diffusion zone. The intention was to introduce nitrogen into the case without creating another structural phase, simply maintaining the martensitic structure of the steel. If successful, S53 would obtain an extremely hard case for increased wear resistance, but not sacrifice corrosion resistance. QuesTek worked with four different companies to run nitriding trials, each group experimenting on 5 prototype alloys of S53. Nitriding behavior was similar across all five S53 prototypes tested. Preliminary trials resulted in the formation of compound zones, however with process refinement a successful run was performed that eliminated the white layer. This treatment validated the hypothesis that S53 could be surface nitrided without a resulting white layer and produced a case hardness of 71 HRC. Despite this success, preliminary corrosion testing indicated a decline in corrosion resistance on the nitrided surface. Further work is needed to quantify the loss in corrosion resistance due to nitriding.

Experimental Procedures

Five different prototype alloys were selected for the nitriding study: S53-3A, 3B, 4D, 5B, 5C. These alloys were selected based on their varying chemical composition. This tested nitriding behavior over a range of Chromium content to demonstrate if small changes in material chemistry affected nitriding behavior. QuesTek worked closely with each vendor to design nitriding recipes that would be likely avoid compound layer formation, introduce a significant amount of nitrogen into a diffusion zone, and be consistent with the tempering kinetics of the steel. As a first approximation, 16 to 24 hours at 900°F (482°C) was chosen for the tempering of the S53 variants in the present study. 900°F is slightly lower than most commercial plasma nitriding processes, however the extended duration of the S53 heat treatment allows the use of the lower temperature while still producing reasonable case depths.

Samples were solution treated, quenched, and cryogenically treated at QuesTek before they were sent to the nitriding facilities. Samples were not tempered, as the nitriding process itself was designed to act as the tempering treatment. Small sample pucks, approximately .7"x.7"x.3" were used for this study. The samples had a machined and polished surface on all sides, representative of a surface finish one would typically see on wear sensitive components.

Nitriding was performed by inducing a plasma on the samples at temperature. Typically plasma nitriding involves a mix of N_2 and H_2, with 20% N_2 : 80% H_2 as a common ratio. To avoid compound layer formation QuesTek used lower concentrations of N_2, as low as 2-5%. Because S53 has a high affinity for nitrogen, significant amounts of nitrogen were introduced into the samples even at low nitrogen concentrations.

Characterization of the nitrided samples was performed at QuesTek and primarily involved using microhardness traces to evaluate case depth and light optical microscopy to evaluate case microstructure. Corrosion resistance was not typically evaluated, however a simple 3.5% salt-water bath exposure was used when desired.

Results and Discussion

Initial trials at elevated N_2 partial pressures were successful in increasing the case hardness of S53. Figure B1 shows microhardness traces for all 5 prototypes tested after plasma nitriding with 25% N_2 gas. Note case depth is only 100 μm deep. (or 0.004") This is typical of commercial practice, which generally achieves rather shallow cases depths. Near surface hardness was measured as high as 1400 VHN, or 74 HRC. Unfortunately, most of the case depth, about 55μm in this instance, is a compound layer with a different structure than the martensitic microstructure of the steel. Figure B2 demonstrates the brittle compound layer, as small microcracks can be seen throughout the case. Literature data suggests compound layers destroy corrosion resistance, often turning stainless steel into unusable rust collectors. Anecdotal evidence from our simple 3.5% salt water tests support this conclusion. Figure B2 also demonstrates the huge boost in hardness from nitriding, as the microhardness indents (all made with the same load) shrink significantly near the surface. The indents in the compound layer (indents 1-6) are especially small, corresponding to 1200-1400 VHN hardness. Indent 7, no longer in the compound zone, still shows elevated hardness over the matrix material, representing a nitrogen diffusion zone.

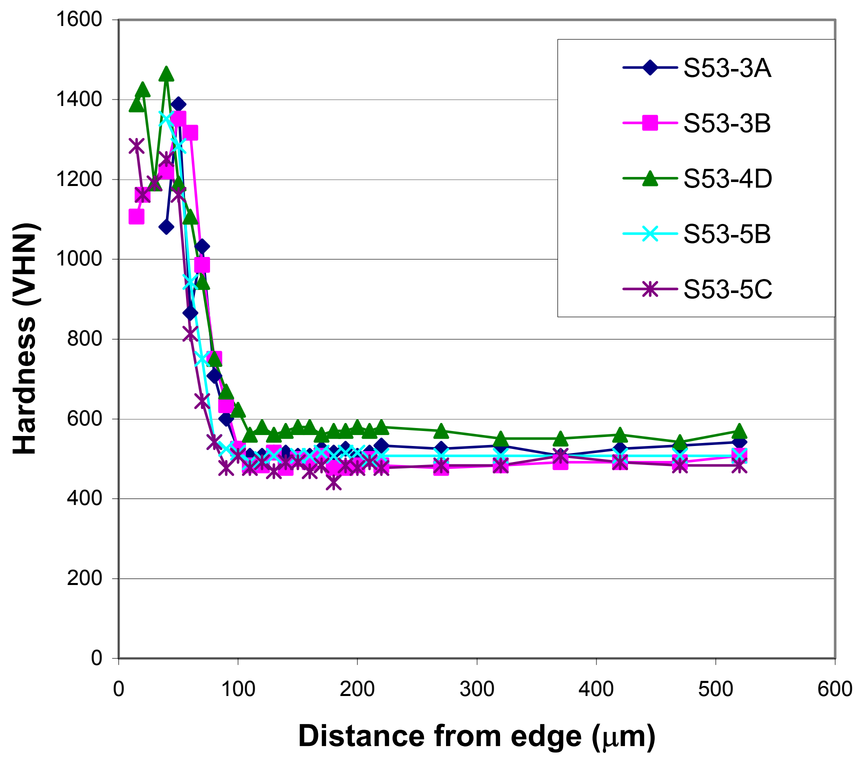


Figure B1- Microhardness traces taken from high N_2 concentration plasma nitriding trial for all 5 prototype alloys tested

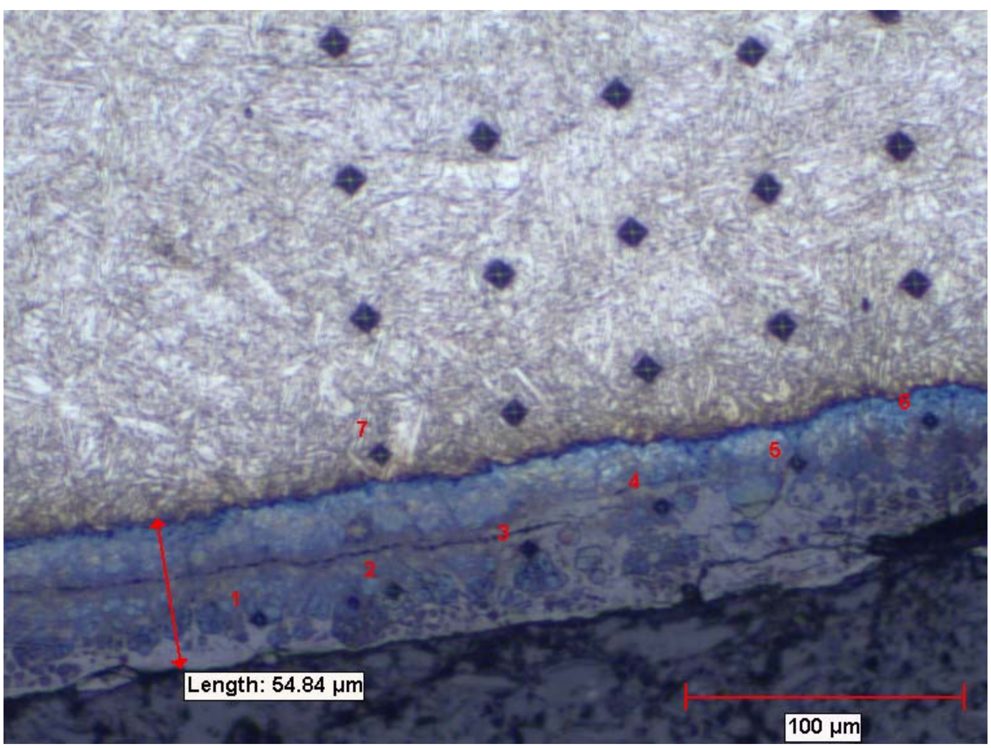


Figure B2- Microstructure of S53-4D after high N_2 plasma nitriding, note compound layer on surface approximately 55 μm deep

Further development resulted in a process in which the compound layer was avoided completely, resulting in only a diffuse zone of nitrogen. Figure B3, a representative micrograph of a sample from this run, shows a martensitic structure up to the edge of the sample. Note the diffuse zone etches differently in the acidic etch due to the high fraction of carbonitrides, but the underlying martensitic structure is not different from that of the matrix, unlike Figure B2.

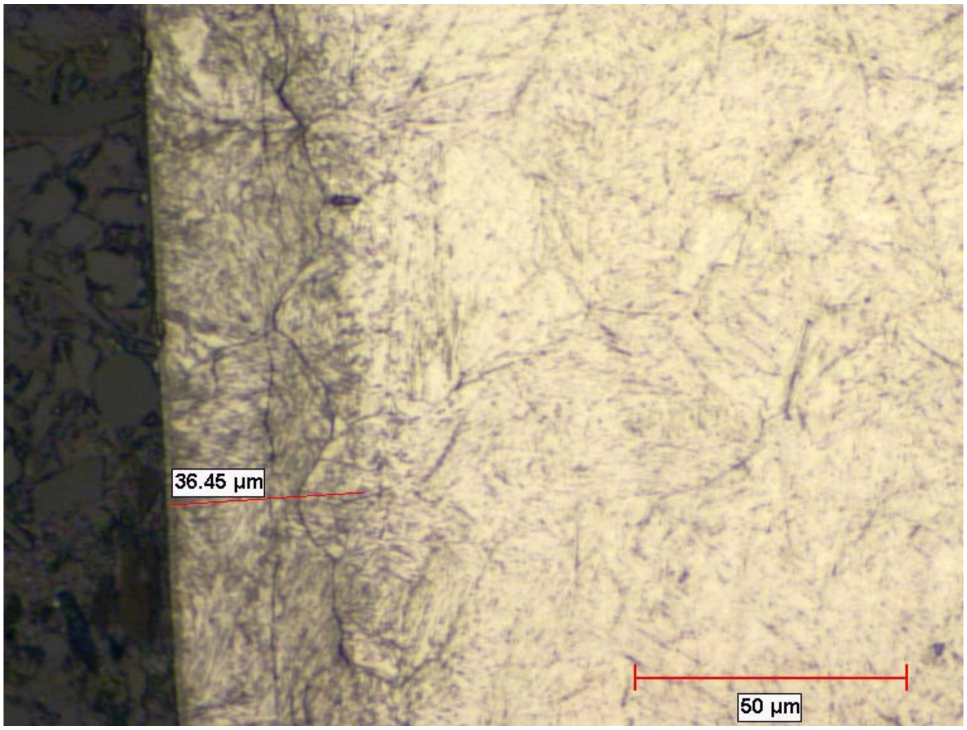


Figure B3- S53-5B Nitrided surface, successfully avoiding compound layer (notice martensitic structure is maintained up to black mounting media)

Not only was this process successful in avoiding compound layer formation, it was also successful in boosting the case hardness. Figure B4 shows the resulting microhardness trace on the sample shown in Figure B3. The case profile is rather steep, resulting in a case depth of only 50µm. (0.002") Further process development may be needed to extend the case depth, however it should be noted that case depths deeper than 0.005" might be difficult to achieve. No wear tests were performed on nitrided samples, however the expectation is a 71 HRC case with uniform microstructure into the core will achieve many of the same benefits seen from HCR or HVOF coatings.

To evaluate what effect this diffuse zone of nitrogen may have on corrosion resistance samples were submerged in 3.5% salt water and compared to control specimens. The nitrided samples, even those that avoided compound layer formation, showed significantly more corrosion than the control samples. More quantitative studies are needed to fully evaluate the effect nitriding has on corrosion resistance, but preliminary screening tests show corrosion may be an important issue. It is likely that in production nitriding may be specified only on surfaces requiring increased wear resistance and that all other surfaces be masked to avoid nitriding. This would boost wear resistance where needed, yet allow the remaining areas of the part to maintain their corrosion resistance.

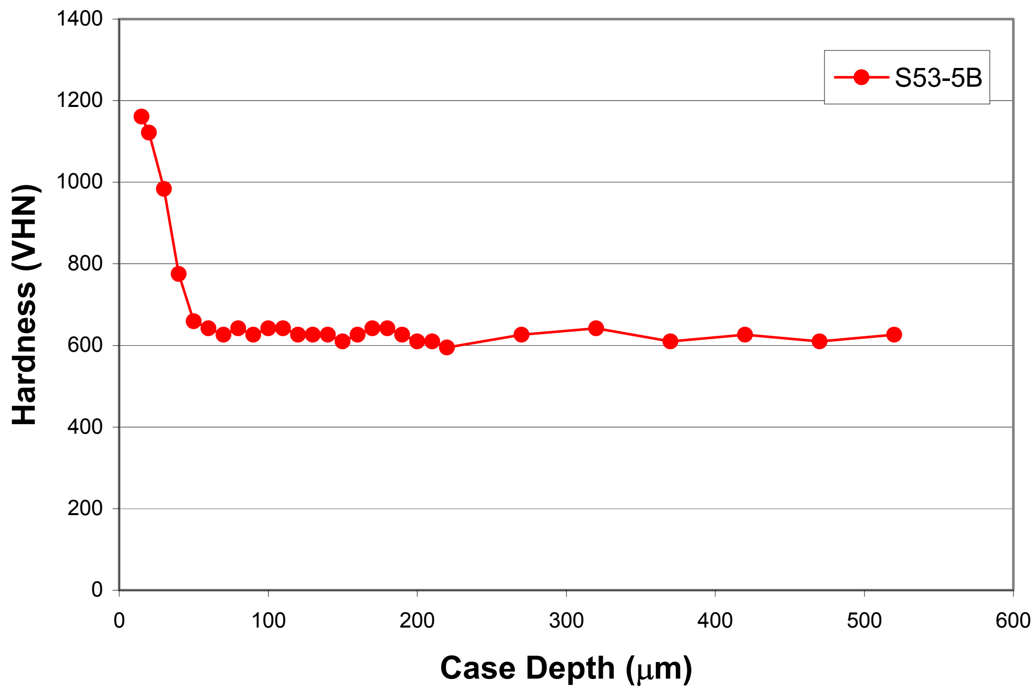


Figure B4- S53-5B Microhardness profile when compound zone is eliminated

Conclusion

This study has shown that low temperature plasma nitriding is a feasible approach to increase surface hardness in S53. The preferred process to date avoids compound layer formation and results in surface hardness of 71 HRC. More testing is required to quantify the benefits to wear resistance and debits to corrosion resistance after nitriding. Pending the results of these tests, plasma nitriding may be a suitable alternative to HCR or HVOF coatings on S53 components.