Processing Information

Manufacturing and Thermal Processing of *Ferrium*® S53®

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1. Purpose:
   a. This document provides introductory information regarding manufacturing and thermal processing of parts made from QuesTek-designed *Ferrium* S53 steel. This information is intended to assist purchasers, fabricators and users in their application engineering of S53 to design and produce specific parts or components; those individuals and companies remain wholly responsible for the outcome of their decisions and processes. This document does not supersede applicable Reference Documents and Standards such as those listed below.
2. Reference Documents and Standards:
   a. UNS S10500
   b. MMPDS-05
   c. CINDAS ASMD/ASMH
   d. SAE AMS 5922A
   e. SAE AMS 2759/3 for thermal processing
   f. SAE AMS 2759/9 for hydrogen bake out parameters
   g. SAE AMS 2759/11 for stress relieve parameters
3. Summary:

   S53 is a new ultra-high-strength, corrosion-resistant, secondary-hardening martensitic steel that is produced by vacuum induction melting followed by vacuum arc remelting (*i.e.,* VIM/VAR). S53 can be a “drop-in upgrade” for 300M (BS S155), 4340 and 4330V steels in many structural aerospace and other applications by providing superior resistance to corrosion, fatigue, corrosion fatigue, stress corrosion cracking, and grinding burn damage. When compared to steels such as 300M, 4340 or 4330V, some key overall processing differences to consider (described further below) include:

   a. The much greater resistance of S53 to general corrosion and to stress corrosion cracking (SCC) may eliminate the need for cadmium plating.
   b. In general, S53 will be more difficult to machine and will require slower speeds and feeds; preliminary information is provided herein.
   c. Forging dies used for 4340, 4330V or 300M can probably be re-used with S53, but it will probably be necessary to forge S53 at significantly higher hot fire temperatures (e.g. 2300°F - 2350°F, or 1260°C - 1288°C) and/or use additional reheats in the forging process than when the same dies are used to forge 4340, 4330V or 300M.
   d. In general, S53 has very high hardenability. Therefore, slower cooling rates or larger cross section parts can typically be completed, and using vacuum heat treating with gas quenchants is very feasible when making many parts. This may permit some parts to be final-machined in the normalized-and-annealed condition, with only minor lapping or other operations completed afterwards.
   e. The high solution treatment temperature of S53 (1985°F, or 1085°C) can increase the propensity of parts to sag during thermal processing, so it is important to adequately support parts (especially long horizontal sections) or hang long parts vertically as feasible during thermal processing.
   f. Operations such as shaft straightening (if required) should preferably be done after the 1st sub zero treatment but prior to the 1st temper. S53 achieves full mechanical strength after tempering, and thus trying to straighten parts after tempering will be more difficult.
   g. It will typically be far more difficult to impose grinding burn damage on S53 parts, due to its higher tempering temperature (934°F or 501°C). And inspection for grinding burn damage (in the unlikely event that it occurs) cannot be made with a conventional Nital etchant; instead more aggressive etchants or Barkhausen noise inspection methods should be utilized.

h. A solution nitriding process is available for S53, allowing surfaces to be hardened to ~60 HRC.

i. Paint adhesion is significantly improved by using pre-primer adherence compound AC-131 (also known as Boegel). Use of this pre-primer is highly recommended on painted S53 parts.

4. Forging

a. Please contact QuesTek to discuss your specific S53 forging application or for vendor referrals, *especially when forging from ingot stock input*. Forging of S53 has been done successfully at a number of vendors on a variety of geometries and sizes, including heavier than 1,600 lbs (725 kg). S53 parts have been successfully forged using the general guidelines outlined below.

b. The suggested procedure for forging S53 parts from billet and bar stock follows (if *higher* forging temperatures are preferred, then use the procedure in part "c" below):

i. Hot fire at approximately 1800°F to 2050°F (982°C to 1121°C), and forge with no requirement on forging reduction ratio. Higher temperatures tend to improve forgability but may promote undesirable grain growth (enlargened grains can be reduced if the forging reduction ratio exceeds 4:1, the majority of which is completed in the final pass).

ii. Cool to room temperature after forging operations are complete.

iii. Normalize forgings by heating to 1976°F (1080°C) +/- 36°F (20°C), holding for 60 minutes, - 15, + 15 minutes, and then air cool to room temperature.

iv. Refrigerate forgings to -100°F (-73°C) or below holding for a minimum of 60 minutes, followed by air warming to room temperature.

v. Anneal forgings by heating to 1256°F (680°C) +/- 25°F (14°C) for 8 hours, - 0.5, + 2 hours, and then air cool to room temperature.

vi. The hardness should be less than 327 HB.

c. The suggested procedure for forging S53 parts from billet and bar stock at *higher* hot-fire temperatures, or from ingot stock that has been fully homogenized, is:

vii. Hot fire at 2300 to 2350°F (1260 to 1288°C), and forge with a minimum of 4:1 forging reduction ratio. The majority of the 4:1 forging ratio should be completed in the final pass in order to meet the grain size requirements.

viii. Cool to room temperature after forging operations are complete.

ix. Normalize forgings by heating to 1976°F (1080°C) +/- 36°F (20°C), holding for 60 minutes, - 15, + 15 minutes, and then air cool to room temperature.

x. Refrigerate forgings to -100°F (-73°C) or below holding for a minimum of 60 minutes, followed by air warming to room temperature.

xi. Anneal forgings by heating to 1256°F (680°C) +/- 25°F (14°C) for 8 hours, - 0.5, + 2 hours, and then air cool to room temperature.

xii. The hardness should be less than 327 HB.

xiii. Confirm that mechanical properties (UTS, YS, elongation, RA, and K_{IC}) have been achieved on representative sample material after being fully heat treated.

d. Avoid hot-fire temperatures between 2150°F (1177°C) and 2250°F (1232°C), in order to avoid coarsening of the grain pinning dispersion particles, which could lead to grain growth.

e. Forging dies used for 4340, 4330V or 300M can probably be re-used with S53, but it will probably be necessary to forge S53 at significantly higher hot fire temperatures (e.g. 2300°F - 2350°F, or 1260°C - 1288°C) and/or use additional reheats in the forging process than when the same dies are used to forge 4340, 4330V or 300M. It is highly recommended that the forge vendor either complete a modeling analysis of the die stresses (using DeForm, Forge, or other software), or complete some internal forging evaluations (typically hand forgings) to get a sense of the material flow. Contact QuesTek for more information and to obtain flow stress data.

f. After completing the heat treating steps of normalizing, refrigerating (sub zero) and annealing listed above, the forgings can be rough and/or final machined. The parts will thereafter need to undergo the further heat treatment identified below.

5. Cold Working / Cold Forming

   a. There have been no prior attempts to cold-forge S53. The very high ductility and toughness of S53 suggests it should be capable of cold working. A simple, short trial run to make a few parts using S53 would probably yield the best information, preferably with the use of an older die nearing retirement in the unlikely event that any die damage occurs. For more information, please contact QuesTek.

6. Machining

   a. S53 bar stock is typically shipped from the producer/mill in a normalized-and-annealed condition, with typical hardness of ~33-35 HRC, and with decarburization and surface defects removed. Forgings that have been heat treated as listed above should also have a typical hardness of ~33-35 HRC.

   b. In general, S53 will be more difficult to machine in the normalized-and-annealed condition than 300M, 4340 or 4340V. See **Table 1** for a comparison of relative rate factors for typical machining operations of annealed S53 (at 35 HRC) vs. normalized and annealed 4330V (at 27 HRC). Machining parameters for S53 forgings that have been normalized-and-annealed should be similar to bar stock from the producer/mill in the normalized-and-annealed condition.

   c. Tools used for cutting and drilling are typically those used for 400 series stainless steel, with coolant through the tool. Use a radius tool and not a chamfered tool, since sharp corners appear to wear or chip faster in S53. Always use a rigid setup for both tool holding and work holding.

   d. Contact QuesTek to receive additional machining studies and documentation. Available resources include a machinability investigation that provides more specific guidance on tool inserts, speeds and feeds, and a related ITAR-distribution-restricted report from the National Center for Defense Manufacturing and Machining (NCDMM; www.ncdmm.org) dated Jan. 22, 2010 entitled "Manufacturing Evaluation of Innovation & Advanced Materials. Latrobe Specialty Steel – C61 & S53 Materials".

7. Welding

   a. Please contact QuesTek to discuss your specific S53 welding application. It has been successfully demonstrated that S53 is readily weldable (but few large-scale S53 weldments have been made, to QuesTek's knowledge). For example, two pieces of S53 plate of 0.4" thickness were welded using the gas tungsten arc manual welding method and incorporating the use of a filler alloy of the same composition; testing of the material transverse to the weld following the full heat treatment process revealed no debit in strength properties of the base or the weldment.

   b. A post-weld thermal bake of an S53 weldment is not required, but is recommended:

      i. If welding was performed on S53 in the normalized-and-annealed state (as received from the producer/mill, or after a forging is normalized and annealed), then the parts must receive the full heat treatment defined in Section 9.

      ii. If welding was performed on fully heat treated parts as outlined in Section 9, then the parts should receive a post-weld thermal bake of 392°F (200°C) for 1 hour.

   c. S53 has been Friction Welded with successful results. Inertia Welding of S53 also appears feasible, but to QuesTek's knowledge this has not yet been demonstrated.

   d. It may be possible to braze non-structural S53 joints using a Silicon Bronze filler.

8. Allowances for and Control of Heat Treat Growth and Runout (Distortion):

   a. Dimensional changes should be taken into account as the preferred manufacturing and machining paths for parts are being determined. The heat treat growth/permanent expansion of S53 is uniform and should be ~0.002"-0.003" per inch. The extent of distortion (runout) will vary depending on the machining stresses and processes induced during manufacturing, as well as the specific fixturing, and quench rate during heat treatment. Very little distortion has been observed on aerospace parts manufactured to date.

   b. If it is desired to stress-relieve a machined part in the mill-annealed condition as a means to help prevent distortion during further thermal processing (*e.g.* if significant forces were imposed on the part during machining), then either of two options are recommended:

i. Produce the part in a rough-machined state with adequate stock material (e.g. 1/8”) on all surfaces so that oxide scale can be removed, and then stress-relieve the part at ~1200°F (649°C) for 2 hours, followed by cooling in air. Then complete all final machining operations prior to the solution treatment, quench, sub-zero treatment and temper steps, in order to remove the oxide scale formed at 1200°F (649°C). This option will be the most effective option to stress-relieve parts.

ii. Produce the part in a fully- or nearly-fully-machined state prior to solution treating, and then stress-relieve the part at 700°F (371°C) for 2 hours or 525°F (274°C) for 4 hours, followed by cooling in air.

c. If it is anticipated that a straightening operation may be required to <u>correct</u> distortion caused by quenching after solution treatment, then the part’s distortion will preferably be measured and any corrective steps taken after the solution treatment, quench and 1st sub zero treatment steps have been completed, but before the 1st temper:

i. If excessive distortion exists after the solution treatment, quench and 1st sub-zero treatment, then it is recommended to heat the part to 392°F (200°C) in air for 1 hour, hot-straighten the part (temperature determined by amount of force required to straighten part; temperature should be maintained below 700°F (371°C) to avoid any tempering or decarburization; small oxide layer may form at this temperature), and allow the part to air cool. The two temper cycles, and intermediate 2nd sub-zero treatment, described below must then be applied.

ii. NOTE: This is only a recommendation. If it is not convenient to measure distortion and straighten a part before tempering, then users can investigate hot-straightening parts with greater force after tempering. It may be possible to hot-straighten S53 parts of modest size after the tempering cycles are completed. The temperature used should be determined by amount of force required to straighten the part and should be maintained below 700°F (371°C) to avoid over-tempering or decarburization. A small oxide layer may form at this temperature. Allow the part to air cool to room temperature after hot straightening. A stress relieve process should then be completed to relieve any residual stress induced during the hot straightening process.

9. <u>Heat Treatment</u>

a. <u>General Information</u>

i. S53 can be solution treated and tempered in either vacuum, air or other media as described below, and selection of the process can depend on factors such as: industry application; ability and desire to final-machine a part after tempering; size or weight of part; achievable quench rates; etc.

ii. As with other martensitic alloys, it is recommended that fillets and rounded corners be used as feasible to limit any sharp corners or edges of parts made from S53, since sharp edges or corners can serve as crack initiation points if a severe quench is used.

b. <u>Selection of Vendor:</u>

i. A number of heat treat vendors have experience processing S53. Where possible/feasible, QuesTek recommends that these vendors be selected for the production of initial prototype parts since they often have well-developed processes. Contact QuesTek for more information about these vendors.

c. <u>Cleaning</u>:

i. Immerse parts for a minimum of 15 minutes in alkaline solution or other approved degreasing method in order to remove oil, grease and other surface contaminants prior to heat treating.

d. <u>Part Loading</u>:

i. Parts should be loaded with no contact or stacking.

ii. It is recommended that shafts and long-sectioned parts be hung vertically, as possible, or be adequately supported. The higher solution heat treatment temperature of S53 vs. 4340 (for example) can increase the propensity of S53 parts to sag during this high temperature processing step.

iii. It is recommended that an extra carrier piece be added with a thermocouple to mimic the largest cross-section thickness and serve as the working thermocouple. If desired, one or more additional carrier pieces can be included to validate the hardness and microstructure produced during thermal processing.

e. <u>Solution Treatment</u>:

i. Recommended Practices for Selected Solution Treatment Method

1. Solution Treating in <u>Vacuum</u> is generally preferred for aerospace parts, and when the parts will not be final-machined on all contact points or load-bearing/fatigue-limiting surfaces. To achieve optimum results, evacuate the chamber to at least 10^{-4} torr. Using 10^{-3} torr or other less severe vacuum levels may also yield acceptable results, but can result in a small amount of surface decarburization (e.g. ~0.001 - 0.002”).

2. Solution Treating in <u>Air</u> can be an acceptable alternate method when all contact points or load-bearing/fatigue-limiting surfaces will be final-machined to sufficiently remove the oxide/decarburization layer of ~0.060” that will likely occur, or for example when the size or weight of the part precludes solution treatment in vacuum.

3. Solution Treating in <u>Endothermic Gas</u> can be an acceptable alternative method when all contact points or load-bearing/fatigue-limiting surfaces will be final-machined to sufficiently remove the decarburization layer that will likely occur, or for example when the size or weight of the part precludes solution treatment in vacuum. To prepare the endo gas, a suggested starting point is to achieve a carbon potential of 0.1485 wt% C with reference to graphite or 0.4030 wt% C with reference to pure Fe; this can result in a decarburization layer of ~0.030” thickness. These parameters have not been fully optimized and users are encouraged to perform tests before solution treating S53 in endo gas.

ii. Heat parts from room temperature to 1940°F (1060°C) in the following recommended manner, achieving uniform temperatures as feasible:

1. Pre-heat the part, preferably at 600°F (315°C). This preheat step is highly recommended in order to minimize the coarsening of non-desirable carbides that will be more difficult to put back into solution during subsequent solution treatment steps. In no case should the pre-heat temperature be greater than 932°F (500°C).

2. Heat from 600°F (315°C) to 1985°F (1085°C) as fast as possible in order to minimize carbide precipitation/growth, but decrease the ramp rate as the temperature nears 1940°F (1060°C) so as to not significantly exceed 1985°F (1085°C). If solution treating in air and using a separate pre-heat furnace, then first stabilize the main/gantry furnace at 1985°F (1085°C) +/- 27°F (15°C) before loading the parts from the pre-heat furnace directly into the main/gantry furnace.

One example heat-up cycle is:

1. Heat from room temperature to 600°F (315°C) at a rate of 800°F/hr (444°C/hr), and allow the part to fully equilibrate at 600°F (315°C).
2. Heat from 600°F to 1900°F (315°C to 1038°C) at a rate of 1800°F/hr (1000°C/hr).
3. Heat from 1900°F to 1985°F (1038°C to 1085°C) at a rate of 1000°F/hr (556°C/hr).

iii. Once the thickest section of the part has equilibrated at 1985°F (1085°C) +/- 27°F (15°C), hold for 60 minutes, + 10, -0 minutes.

f. <u>Quenching after Solution Treatment</u>

i. Quench directly from 1985°F (1085°C) at the fastest rate possible (while considering possible distortion effects) so that the part temperature drops below 122°F (50°C) within 15-30 minutes using either of these two methods:

1. Oil or liquid quenchant, such as when the solution treatment step is performed in air or endo gas, or when the vacuum chamber has an integrated liquid quench tank. The temperature of the oil or liquid quenchant should not exceed 120°F (49°C). Use caution when quenching with water, especially large parts with large variations in section thickness.

2. Inert gas (Argon, Nitrogen, Helium, etc.), such as when the solution treatment step is performed in vacuum. This may require using Helium at 10 bar pressure for larger parts, although using Nitrogen at 2-4 bar pressure may suffice for smaller / thinner parts.

ii. NOTE: It is important to quench S53 fast enough in order to maximize the resulting UTS, YS, K_{IC} and in particular CVN.

1. Necessary quenching rates will differ based on part geometry, section thickness and desired properties achieved. A higher quench rate will typically result in higher mechanical properties, but also more distortion. Using higher gas quenching pressures or using an oil/liquid quench may be desirable especially for thick-sectioned parts, whereas using lower gas quenching pressures and cooling rates may be acceptable for smaller parts. Please contact QuesTek for questions regarding specific quenching procedures based on your part geometry.
2. There has been a documented decline in CVN impact energy for S53 when quench rates (i.e. times to reach 122°F) after the solution treatment exceed the 15-30 minute guidelines provided above. Longer quench times (e.g. over 45 minutes to reach 122°F) tend to also reduce the 0.2% YS (but typically not 0.4% YS). However no degradation in tensile strength or fracture toughness has typically been observed when quench rates after the solution treatment have been as long as 60 minutes to reach 122°F.

g. 1^{st} Sub Zero Treatment (Refrigerate):

i. Within 2 hours of quenching from solution treatment temperature, cool parts to -100°F (-73°C) or below and hold for 1 hour, +2, -0 hours, followed by air warming to room temperature.

ii. When doing this step, moisture condensation should be considered; one example of a way to reduce condensation is to seal the parts in a bag with inert gas prior to refrigerating.

iii. If an extended period of time is going to elapse between the 1^{st} sub zero treatment and tempering (e.g. 1 day or longer), it is recommended to complete a snap temper at 392°F (200°C) for 60 minutes to prevent cracking.

h. 1^{st} Temper:

NOTE: The tempering directions listed below should be closely adhered to. While S53 is a high hardenability steel that achieves near full martensitic transformation even at slow quench rates from the solution treatment temperature, there is still some retained austenite present (even after sub zero treatment).

i. Recommended Practices for Selected Tempering Method

1. Tempering in Vacuum is generally preferred for all aerospace parts, and when the parts will not be final-machined on all contact points or load-bearing/fatigue-limiting surfaces. To achieve optimum results, first evacuate the chamber to at least 10^{-4} torr; using 10^{-3} torr or other less severe vacuum levels may also yield acceptable results, but can result in a small amount of surface oxidation. Then backfill the chamber with an inert gas such as argon or nitrogen to 700 microns +/- 100 microns (in order to help accelerate the heat-up and promote temperature uniformity within the furnace).
2. Tempering in Air or in Salt Bath can be an acceptable method when up to ~0.01" of material will be removed from all contact points or load-bearing/fatigue-limiting surfaces during final machining, or if the part can be plated or covered, or if for example the size or weight of the part precludes tempering in vacuum. In addition, some color tinting of exposed metal will probably occur. One option to prevent or minimize oxidation, decarburization and color tinting during an air or salt bath temper is to apply copper-plating or stop-off paint to these surfaces (this should be applied after the solution treatment step since these materials will likely breakdown at the solution treatment temperature). To our knowledge no S53 parts have yet been tempered in a salt bath, but this is expected to be an acceptable method.

ii. Temper at 934°F (501°C) +/- 12°F (7°C), holding for 3 hours, +0.5, -0.5 hours

i. Quenching after 1^{st} Temper

i. Quench directly from 934°F (501°C) at the fastest rate possible (while considering possible distortion effects) so that the part temperature drops below 122°F (50°C) within 30-45 minutes using either of these two methods:

1. Oil or liquid quenchant, such as when the solution treatment step is performed in air or endo gas, or when the vacuum chamber has an integrated liquid quench tank. The temperature of the oil or liquid quenchant should not exceed 120°F (49°C). Use caution when quenching with water, especially large parts with large variations in section thickness.
2. Inert gas (Argon, Nitrogen, Helium, etc.) such as when the solution treatment step is performed in vacuum.

ii. NOTE: It is important to quench S53 fast enough in order to maximize the resulting UTS, YS, K_{IC} and in particular CVN.

1. Necessary quenching rates will differ based on part geometry, section thickness and desired materials properties. A higher quench rate will typically result in higher mechanical properties, but also more distortion. Using higher gas quenching pressures or an oil/liquid quench may be desirable especially for thick-sectioned parts, whereas using lower gas quenching pressures and cooling rates may be acceptable for smaller parts. Please contact QuesTek for questions regarding specific quenching procedures based on your part geometry.

2. There may be some leeway to use slower cooling rates than the 30-45 minutes recommended above (even an air cool quench of small parts may be feasible) but caution should be used when exploring quench rates longer than 30-45 minutes after the 1st temper. S53 is particularly sensitive to the quench rate after the solution treatment, but somewhat less sensitive to the quench rate after the 1st temper, in order to maximize resulting properties.

j. 2nd Sub Zero Treatment (Refrigerate):

i. Within 2 hours of quenching from 1st temper step, cool parts to -100°F (-73°C) or below and hold for 1 hour, +2, -0 hours, followed by air warming to room temperature.

ii. When doing this step, moisture condensation should be considered; one example of a way to reduce condensation is to seal the parts in a bag with inert gas prior to refrigerating.

iii. If an extended period of time is going to elapse between the 2nd sub zero treatment and tempering (e.g. 1 day or longer), it is recommended to complete a snap temper at 392°F (200°C) for 60 minutes to prevent cracking.

k. 2nd Temper:

i. Recommended Practices for Selected Tempering Method

1. Tempering in Vacuum is generally preferred for all aerospace parts, and when the parts will not be final-machined on all contact points or load-bearing/fatigue-limiting surfaces. To achieve optimum results, first evacuate the chamber to at least 10^{-4} torr; using 10^{-3} torr or other less severe vacuum levels may also yield acceptable results, but can result in a small amount of surface oxidation. Then backfill the chamber with an inert gas such as argon or nitrogen to 700 microns +/- 100 microns (in order to help accelerate the heat-up and promote temperature uniformity within the furnace).

2. Tempering in Air or in Salt Bath can be an acceptable method when up to ~0.01” of material will be removed from all contact points or load-bearing/fatigue-limiting surfaces during final machining, or if the part can be plated or covered, or if for example the size or weight of the part precludes tempering in vacuum. In addition, some color tinting of exposed metal will probably occur. One option to prevent or minimize oxidation, decarburization and color tinting during an air or salt bath temper is to apply copper-plating or stop-off paint to these surfaces (this should be applied after the solution treatment step since these materials will likely breakdown at the solution treatment temperature). To our knowledge no S53 parts have yet been tempered in a salt bath, but this is expected to be an acceptable method.

ii. Temper at 900°F (482°C) +/- 18°F (10°C), holding for 12 hours +2, -1 hour

iii. Cool to room temperature. **DO NOT QUENCH**.

1. If tempering in vacuum, cool the part by slowly circulating gas within the chamber (at rate equivalent to air cool).

2. If tempering in air or salt bath, cool the part in air.

iv. If the part was tempered in air or salt bath, or solution treated in air or endo gas, then machine away as desired any oxide/decarburization layer that occurred. In addition, a sandblast and oil spray procedure is recommended prior to further processing or packaging.

l. Inspection of Heat Treatment:

Inspection criteria will need to be developed for the specific heat treatment process. An example of inspection requirements based on the heat treatment process discussed in Section 7.e is that the carrier piece/test coupons achieve these minimum property requirements:

i. Surface hardness greater than or equal to 53 HRC (59 HR45N or 87 HR15N).

ii. Typical microstructure (typical micrograph shown in **Figure 1**).

iii. If test coupons are provided, mechanical testing should meet the minimum properties provided in SAE AMS 5922. Typical properties are shown in **Table 2**.

iv. Any oxide layer formed from solution treating in air or endothermic gas may sometimes be left "as is" if that portion of the part is not a contact point or load-bearing/fatigue-limiting surface.

v. Any oxide layer formed from tempering in air or salt bath may sometimes be left "as is" if that portion of the part is not a contact point or load-bearing/fatigue-limiting surface.

m. Nitriding and Carburizing Processes

i. The surface of S53 can be hardened to ~60 HRC using a solution nitriding process. **Figure 2** shows representative results. Contact QuesTek for more information.

ii. QuesTek does not have any experience with carburizing S53, and does not recommend doing so. Efforts to carburize S53 will be experimental.

10. Final Machining and Warm Working

a. If necessary, perform final straightening or hot working of parts as outlined in Section 8.c.

b. In general S53 will be more difficult to machine in the heat-treated condition than 300M, 4340 or 4340V. See **Table 3** for a comparison of relative rate factors for typical final machining and grinding operations of heat treated S53 (at 54 HRC) vs. heat treated 4330V (at 27 HRC).

11. Peening and Other Final Cold Working Processes

a. Recommended shot peening parameters for S53 are currently being developed. Existing shot peening parameters established for steel 300M may be appropriate to apply to S53. Preliminary recommendations for shot peening S53 are: cast steel shot size of 230; 0.006-0.010 Almen Intensity; and 200% coverage. Shot peening should be in accordance with SAE AMS 2430 or 2432. Contact QuesTek for more information.

12. Etching and Other Inspection

The following details have been observed successfully using the listed corresponding etchants and techniques:

a. Grinding burn damage is difficult to inflict on S53 parts, and grinding burn observations cannot be made with a conventional Nital etchant. Instead we recommend:

i. Ralph's or Marble's etchant can be used because they are much more aggressive than Nital etchant and will penetrate the chromium oxide layer and the high alloy content. The duration of the immersion or swab time to use Marble's or Ralph's etchant to inspect for grind burn damage on S53 should be similar to that of using a Nital etch to inspect a low alloy steel. The goal is to uniformly etch the outside of the S53 part immediately after polishing the sample; if there are any light areas, those are areas that need to be further inspected to determine if it is an area with bainite/austenite/dissolved carbides present (i.e. non-uniform structure).

ii. Barkhausen noise inspection techniques can be used to inspect grinding burn damage on S53, and BNI inspection standards are currently being established for S53.

b. Other microstructural detail observations (inclusions, martinistic substructures, primary carbides, lath packets, retained austenite and carbides, etc.) are also optimized with the use of Ralph's or Marble's etchant, when used immediately after polishing the sample.

c. Grain size detail observations are optimized with the use of oxidation etch.

d. Macrostructural detail observations (macroinclusions, segregations, etc.) are optimized with the use of 50% HCl in H_2O solution, etched at 160°F for 30 minutes.

e. S53 can be inspected using magnetic particle inspection per ASTM-E1444 or fluorescent penetrant per ASTM-E1417.

13. Passivation

    a. It is recommended that all S53 parts be passivated (including prior to plating or painting) in order to promote the development of a stable chromium oxide layer. Passivating S53 parts can be done in manner similar to that done to stainless steels, and the recommended procedure is:

        i. Ultrasonically clean parts by immersion for 15 minutes in an alkaline solution to yield a pretreatment surface free of all foreign matter including oil, grease, rust, scale and fingerprints. If ultrasonic cleaning is unavailable or if the part size necessitates an alternate method, than a solvent degrease followed by alkaline soak is an acceptable substitute.

        ii. Rinse parts in distilled water after cleaning, and then dry all surfaces.

        iii. Passivate parts in accordance with AMS 2700, Method 1, Type 6 or 8. Rotate the parts in the bath frequently.

        iv. Thoroughly rinse the parts in distilled water immediately after removal from the passivating bath, and then dry the parts completely.

    b. An optional post treatment bake-out cycle may be performed within 4 hours hour of completing the passivation treatment. The recommended post treatment bake-out cycle is 375°F (191°C) +/- 25°F (14°C) for 4 hours +5, -0 hours, followed by air cool.

14. Coatings and Additional Final Processes

    a. Electroplating and Related Processes:

        i. S53 parts have been successfully electroplated with additional surface protection options such as: Cr; Ni; duplex Ni+Cr; Zn-Ni; Cd; Al, including Alumiplate and Ion Vapor Deposition (IVD) aluminum; and WC-Co powder by HVOF thermal spray.

        ii. Surface finishing options that have not been tested on S53, but that are expected to yield satisfactory results, include: Ag; Ni-Cd; Zn; Mn; phosphating platings; and others.

        iii. Hydrogen absorption from electroplating and other processes must be removed by a thermal bake-out treatment to minimize possibility of hydrogen embrittlement and delayed-failure phenomena. A conventional bake-out cycle of 375°F (191°C) for 23 hours followed by air cool has been demonstrated to diffuse hydrogen out of S53 that was absorbed during Cr, Ni, duplex Ni+Cr, Cd and Al electroplating operations. The M_2C carbides in S53 are strong hydrogen traps, and if more extensive bake-out efforts are desirable then multiple 23-hour bake-outs at 375°F (191°C) can be considered. Hydrogen embrittlement relief bake-out processes should conform to AMS 2759/9, and begin within 4 hours hour of plating operations.

    b. Painting Process Recommendations:

        i. Grit blast the part at moderate pressure such as ~30–45 psig (in order to minimize grit embedding) in accordance with MIL-STD-1504. Alumina grit blast is suggested.

        ii. Clean with alkaline solution. If an alkaline solution is unavailable, a soap and water solution may suffice.

        iii. Apply a thin film of a primer adherence compound conversion coating AC131 (also known as "Boegel") on a clean and prepared surface in order to produce high adhesion and a chemical bond between the metal and the primer coating. The application of AC-131 is typically done by spraying a fine mist to produce a very light coating, and in accordance with SAE AMS 3175. AC-131 is manufactured by 3M Inc. (having acquired AC Tech Inc.) and should be available directly from 3M's distributor as well as distributors such as E.V. Roberts (www.evroberts.com). Using the light blue vs. clear type of AC-131 can make it easier to see how much AC-131 has been applied.

        iv. Prime and paint with epoxy- or polyurethane-based organic coatings. Primer can be applied in accordance with MIL-PRF-85582 within 8 hours of pre-primer AC131 application. Paint can be applied in accordance with MIL-PRF-85285 and should be applied within 4 hours of primer application.

    c. Consideration should be given to the time and temperature of any coating process so that the parts are not over tempered. Contact QuesTek for any questions.

15. Packaging and Storage:

a. Parts (especially bare metal surfaces) should be protected from corrosion prior to shipment using a light oil spray or other approved method.

b. The parts should be prepared for shipment in accordance with commercial practice and in compliance with applicable rules and regulations pertaining to the handling, packaging, and transportation of the product to ensure carrier acceptance and safe delivery.

c. While S53 is a corrosion resistant steel, consideration should be given to surface preparation/treatment for the usage environment including extended outdoor exposure.

Machining Operation	Speed (surface feet per minute, SFM): **4330 N&T**	Feed Rate: (in/Rev) **4330 N&T**	Depth of Cut: (in) **4330 N&T**	Speed (surface feet per minute, SFM): **Ann. S53**	Feed Rate: (in/Rev) **Ann. S53**	Depth of Cut: (in) **Ann. S53**	**Multiplying Factor**** to determine time required to machine an equivalent amount of Annealed S53 steel (Relative to either 4330 N&T or 300M steels)
Interrupted OD Turning	360	0.008	Rough: 0.12; Fine: 0.06	140	0.008	Rough: 0.12; Fine: 0.06	2.6
Continuous OD turning	360	0.008	Rough: 0.12; Fine: 0.06	140	0.008	Rough: 0.12; Fine: 0.06	2.6
OD turning @ Finer control (for ~60 µin Ra)	280	0.012	Rough: 0.038; Finish: 0.030	220	0.012	Rough: 0.038; Finish: 0.030	1.3
OD Threading	262	0.0625	0.002	262	0.0625	0.002	1.0
ID drilling	393	0.002	N/A	393	0.002	N/A	1.0
ID turning	220	0.01	Rough: 0.025; Finish: 0.005	180	0.01	Rough: 0.025; Finish: 0.005	1.2
ID deep- boring (@ET&M)	232	0.0044	N/A	232	0.0022	N/A	2.0 (Note: Tool wear rate on S53 = 3 x wear rate on 4330V)
Face milling	275	0.17	0.32	140	0.11	0.32	3.0
Face milling (@ ET&M)	500 (4 in. dia.)	0.015 per tooth	N/A	160	0.014	N/A	3.3
End milling	150	0.02	0.02	150	0.02	0.02	1.0
Drilling: diameters							
0.75 inch	285	0.00076	N/A	162	0.0015	N/A	0.9
0.37	141	0.00076	N/A	141	0.00076	N/A	1.0
0.338	133	0.00073	N/A	133	0.00073	N/A	1.0
0.1875	118	0.0005	N/A	94	0.00063	N/A	1.0
Tapping: thread size							
7/16-14	13	0.0714	N/A	13	0.0714	N/A	1.0
3/8-24	13	0.0416	N/A	13	0.0416	N/A	1.0

**** Determined by multiplying (Tool Turning Speed) x (Feed Rate) x (Depth-of-Cut) for each alloy and dividing the value for 4330V by the value for S53.**

Table 1: Rate Factors Comparing Performance of Annealed S53 (35 HRC) with Normalized and Tempered 4330V (27 HRC) Steel for Machining Operations Typically Used to Fabricate Parts Prior to Heat Treatment

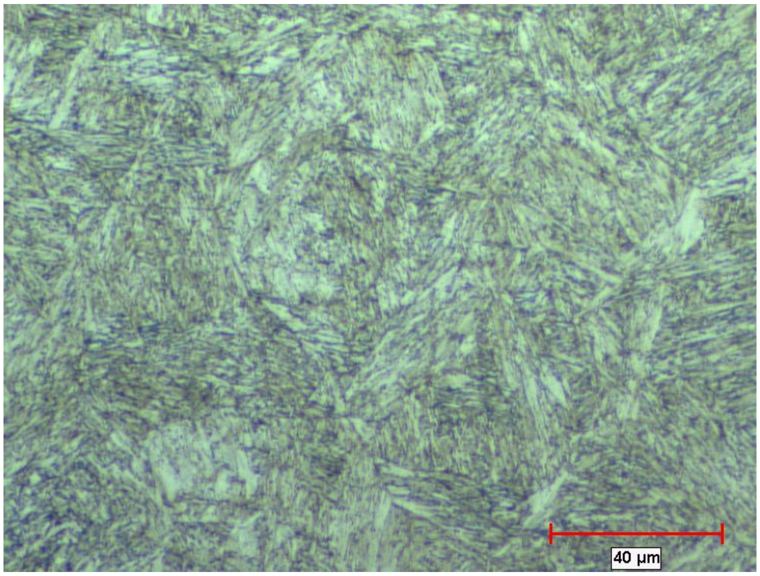

Figure 1: Typical Microstructure of S53.
After heat treating as described in this document (and no solution nitriding). Sample was etched with a 2% Nital solution.

YS (ksi)	UTS (ksi)	El (%)	Ra (%)	Hardness (HRC)	CVN (ft-lb) at RT	K_{IC} $\left(\text{ksi}\sqrt{\text{in}}\right)$
225	288	15	57	54	18	65

Table 2: Typical mechanical properties of S53.

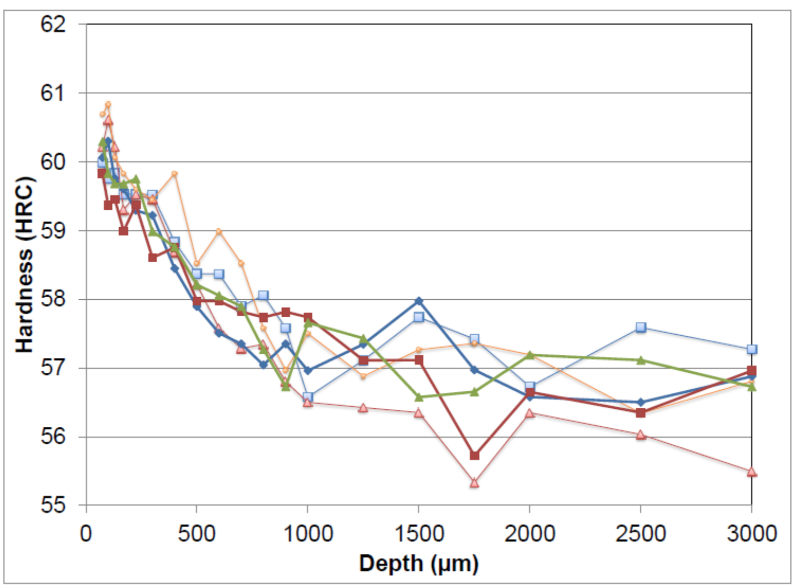

Figure 2: Representative Hardness Profiles of Solution-Nitrided S53.

Machining Operation	Speed (surface feet per minute, SFM): **300M (54HRC)**	Feed Rate: (in/Rev) **300M (54HRC)**	Depth of Cut: (in) **300M (54HRC)**	Speed (surface feet per minute, SFM): **S53 (54HRC)**	Feed Rate: (in/Rev) **S53 (54HRC)**	Depth of Cut: (in) **S53 (54HRC)**	**Multiplying Factor**** to determine time required to machine an equivalent amount of hardened S53 steel (Relative to either 4330 N&T or 300M steels)
OD turning (carbide); Rough	160	0.010	0.075	150	0.008	0.060	1.7
OD turning (carbide); Fine (~ 60 µin =Ra)	180	0.008	0.030	180	0.008	0.015	2.0
OD Grinding (finishing for low residual stress): Alumina wheel							~ 1.0

**** Determined by multiplying (Tool Turning Speed) x (Feed Rate) x (Depth-of-Cut) for each alloy and dividing the value for 300M by the value for S53.**

Table 3: Rate Factors Comparing Heat Treated S53 (at 54 HRC) with Heat Treated 4330V (at 47 HRC) Steel for Typical Final Machining and Grinding Operations