Microstructural Characterization of Ti-6Al-4V and its Relationship to Sample Geometry

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Approval Page

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Abstract

A problem exists with a part produced by forging made by Shultz Steel of Ti-6Al-4V in the variance of properties throughout the part. There is one specific region that exhibits the most variance. The purpose of the report is to determine any microstructural differences within the region of interest in the part. When microstructures of the inner section and outer section of the part were looked at it was determined that they exhibited a martensitic structure. There was a noticeable difference in the lath structure between sections. The outer region contained larger more widely spread laths of an average length of 99.92 μm while the inner region consisted of finer and shorter grains more closely packed with an average length of 75.89 μm. It was then deduced that the cooling rate between the inner section and outer section was the most likely cause for these differences. Further testing will be conducted consisting of tensile testing, box micrographs, and Electron Backscatter Diffractometry (EBSD).

Acknowledgements

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Introduction

Problem

Shultz Steel produces a component for use in landing gear of large aircraft. This component when forged and heat treated exhibits significant variation in tensile properties specifically yield strength within the part and from lot to lot. Repercussions of the problem of significant variability include: possibility of part failure in application and more frequent testing that ultimately increases the cost of manufacturing the component. There is the need for material characterization as well as tensile testing to determine the extent of the problem.

The product that is exhibiting the variation (Figure 1) consists of a relatively complicated body that necks into a large rectangular end. The primary area of interested as denoted in Figure 1 by the star occurs along the die parting line where the material goes from a thin cross-section relative to the larger rectangular area. Due to this and the plastic

deformation associated with moving material from a thin region to thicker region leads to the hypothesis that there may be an issue related to flow. If this is the case then there may be the need for retooling to change the orientation or placement of the die parting line to alleviate the stress associated with plastic deformation. Any findings and suggestions made by this project will be considered by Shultz Steel and possibly incorporated into a Root Cause and Corrected Action (RCCA) which Shultz Steel will undertake.

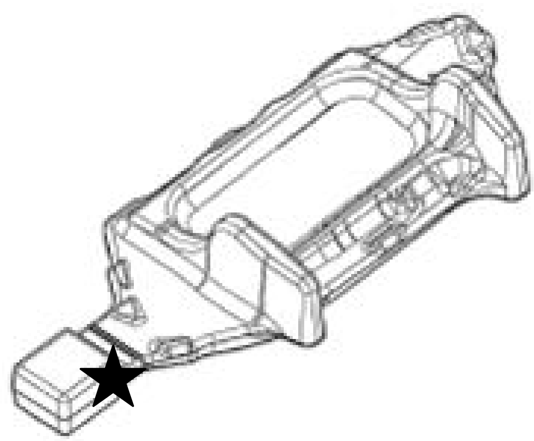


Figure 1. Problematic product with the star indicating the location of the most variance

Application

Shultz Steel is a forging company dedicated to the production of parts for commercial and military aircraft. Primary processes conducted by Shultz Steel include, but are not limited to: vacuum arc remelting, open and closed die forging, non-destructive testing (NDT), heat treating design and execution, and tooling and part design. Vacuum arc remelting is done in one of four furnaces with a 36,000 lb melt capacity. Open and closed die forging is done to conduct ingot breakdown to reforge stock and produce the final parts. These processes are conducted on one of Shultz Steel's six presses. Heat treatments are conducted using one of six furnaces with the options for cooling rates determined by quenching tanks and in ground hearths. NDT is performed through submersing testing and magnetic and ultrasonic particle testing. The alloys that Shultz Steel works with are titanium, nickel, aluminum, and ferrous alloys. Parts made by Shultz Steel are used in static and dynamic structural components primarily for applications in the aerospace industry specifically with use in aircraft.

Ti-6Al-4V

Ti-6Al-4V is an alpha-beta titanium alloy. This alloy contains a mixture of alpha and beta phases with the beta phase accounting for 10-50% at room temperature. The alloy Ti-6Al-4V is a difficult alloy to work due to the fact that its formability is poor even in the annealed condition making it challenging to forge. To control the properties of Ti-6Al-4V heat treatment is used that controls the amount of beta phase present and the form that it takes. A common heat treatment consists of a solution treatment at 900-1200°F that precipitates the alpha phase. The result of this precipitation treatment is a fine mixture of alpha and beta contained within a matrix of the beta phase. Beta matrix phases may be either retained or transformed [(1)].

Properties

Titanium and its alloys serve as a bridge between the ideal properties of aluminum and steel. Due to its high strength and low densities these alloys provide superior properties. Along with its high strength and low density titanium alloys also exhibit superior corrosion resistance due to the formation of a passive film and as such have applications in fields other than the aerospace and aircraft industries. Table I shows the properties of Ti-6Al-4V that are relevant. Note that these properties are general and are not necessarily exhibited by the part used for this project.

Table I. Different properties of Ti-6Al-4V emphasizing mechanical properties

Property	**Ti-6Al-4V**	
	Annealed	Solution + Aging
Density (lb/in^3)	0.160	0.160
Ultimate Tensile Strength (ksi)	130-144	170
0.2% Yield Strength (ksi)	120-134	160
Elongation (%)	14	10
Reduction in Area (%)	30	25
Hardness	36 HRC	41 HRC
Modulus of Elasticity (10^6 psi)	16.5	-----------
Poisson's Ratio	0.342	------------

Preliminary testing done by Shultz Steel confirms that tested parts exhibit mechanical properties within the range of the annealed Ti-6Al-4V. However, the parts tested exhibit the entire range of the yield strength creating variability between and within parts of the tensile properties.

There is a phenomena created with the size of the tensile test sample to the tensile strength it exhibits. Table II shows the difference in tensile strength of a square bar with regards to changing section size of the bar.

Table II. Relationship between tensile strength and section size of solution treated and aged titanium Ti-6Al-4V

Property	**Section size of Square bar (in)**		
	1 in.	2 in.	3 in.
Tensile Strength (ksi)	155	145	135

This shows that with an increasing section size the tensile strength can exhibit significant variance. Furthermore, beta annealing can decrease strength by 5-15 ksi. The exact amount is dependent on prior grain size, average crystallographic texture, and testing direction. To remedy this solution treating and aging can increase the tensile strength while lowering fracture toughness in Ti-6Al-4 [2].

Microstructures and Effects on Properties

Literature suggests that microstructure and grain morphology affects the tensile and mechanical properties of Ti-6Al-4V. Controlling morphology of the sample can be done through heat treatment and cooling rates. As suggested low to intermediate cooling rates (Figure 2) create an α-β lamellar structure with α-phase lamellae in a β-phase matrix. The formation of α-lamellae is a diffusion controlled nucleation and growth mechanism of the α-lamellae into the β-grains.

Cooling rate (K s^{-1})	Phase composition Ti–6Al–4V
48	$\alpha'(\alpha'')$
40	$\alpha'(\alpha'')$
18	$\alpha'(\alpha'')$
9	$\alpha + \alpha'(\alpha'')$
7	$\alpha + \alpha'(\alpha'')$
3.5	$\alpha + \alpha'(\alpha'')_{trace} + \beta$
1.2	$\alpha + \beta$
0.08	$\alpha + \beta$
0.04	$\alpha + \beta$
0.024	$\alpha + \beta$
0.008	$\alpha + \beta$
0.004	$\alpha + \beta$

Figure 2. Influence of cooling rate on phase composition

As cooling rates increase the length and thickness of the α-lamellae decrease which leads to higher yield strengths. A common α-β microstructure with α-lamellae (Figure 3a) shows the finer α-lamellae and how cooling rate affects the structure of the phases in the resultant microstructures. With increased cooling rates the α-lamellae's thickness and length decreases (Figure 3b). Since parts cool faster towards the outside of the part due to diffusion of heat through the part it is expected that towards the center of the part the α-lamellae should be thicker and longer (Figure 3c) since cooling will occur slower [3].

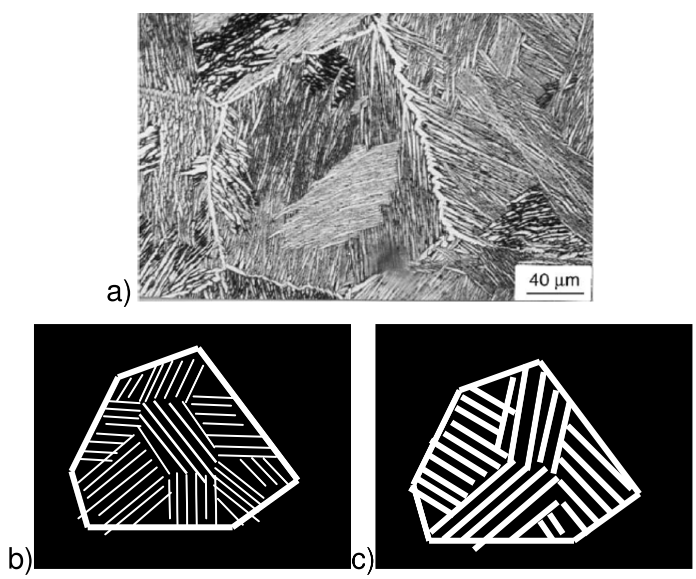


Figure 3. a) Common α-β microstructure exhibiting α-lamellae in a β-matrix, b) Diagram of increased cooling rate with finer and shorter α-lamellae, c) Diagram of decreased cooling with longer thicker α-lamellae.

Forging

Forging is a process by which metal is plastically deformed into a desired shape. This may be a process of hammering the material into a pre-forge shape or a press operation where the material is formed into the final shape in the forging process. For titanium alloys and specifically Ti-6Al-4V these processes are done at elevated temperatures. Temperatures for this operation range from 1400 °F to 1800 °F and are significantly higher than that for aluminum alloys. Another influencing factor for the forging process is the strain rate for the process. In the pre-forge application which use hammers this strain rate exceeds 12,000 mm/mm/min and for the press operation utilizing hydraulic presses this is typically 50 mm/mm/min but can sometimes exceed this value (4).

Temperature and Strain Rate Effects on Properties

The temperature at which forging operations utilize and the strain rates associated with the type of press used can influence the flow stress that can in turn lead to an influence on the mechanical properties. In the case of titanium alloys die cooling, which is where the die temperature that ultimately affects the part is lowered due to a malfunction, can severely inhibit properties by increasing the flow stress. When the temperature is plotted against flow stress for varying strain rates (Figure 4) it can be seen that at lower temperatures the flow stress increases dramatically and there is a significant effect between temperature and strain rate on the flow stress.

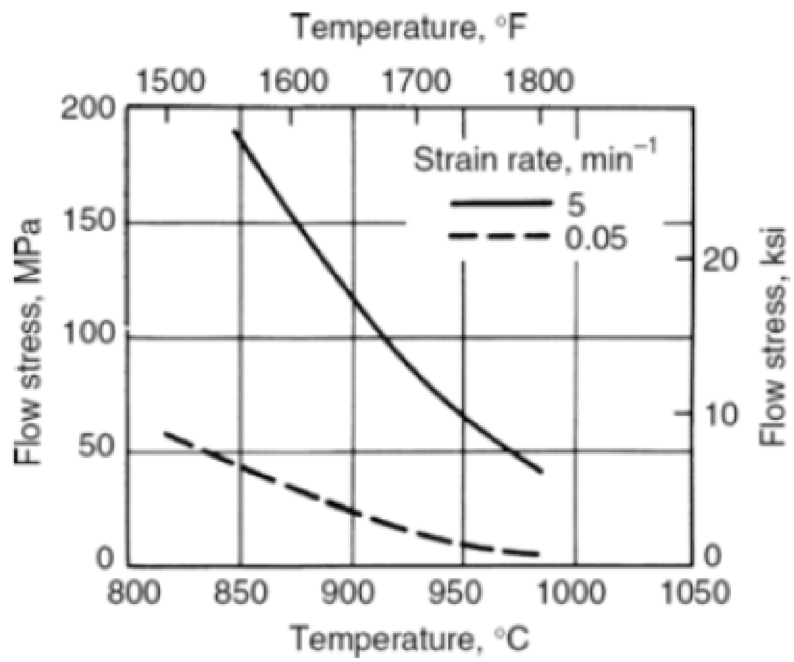


Figure 4. Relationship between strain rate and temperature and its effects on flow stress for Ti-6Al-4V

For example, by decreasing temperature from 1800 °F to 1550 °F the flow stress increases more than three times. Furthermore, by holding temperature constant and varying strain it is seen that there is a significant difference between the amounts of flow stress depending on the strain rate. It is also important to note the interactions between strain rate and temperature. The curves do not exhibit the same slope and so a variation can alter the flow stress significantly. As would be expected a higher strain rate has a steeper curve than a lower strain rate and thus it should be noted that forging operations should, if possible be done at a lower strain rate.

Titanium alloys are very sensitive to processing parameters as seen in Figure 3. Therefore a decrease in temperature can significantly alter the flow stress creating a smaller temperature range for working the materials. This must also be balanced with Ti-6Al-4V having a high resistance to deformation, high forging loads, and multiple forging operations that can all lead to potential failure specifically in the form of cracking. This is due to the fact that the higher the flow stress the more likely the material is to fail. To overcome the limitations different process: isothermal forging and hot die forging are used.

Types of Processes

Isothermal and hot die forging are used to prevent failure during the forging of Ti-6Al-4V by increasing the die temperature to reduce die chill and in turn reduce flow resistance of the workpiece by maintaining the work piece at a temperature closer to the forging stock. Different methods are used to heat the die during the process and include: induction heating, gas-fired infrared heating, and resistance heating. These operations are implemented into the die increasing tooling cost and making the cost of retooling more expensive.

Isothermal forging is a process that typically uses large induction coils placed around TZM dies (Figure 5). To control the induction heating of the coils thermocouples are buried in the dies and utilized to control the heating of the coils maintaining the dies at a constant temperature. In order to protect the pres platen die stacks are put between the die and platen to reduce the effects of the die's heat on the platen. With an increase in temperature at the press platen comes problems with the functionality of the press' hydraulican as well as possibly compromising the dimensional stability of the platen.

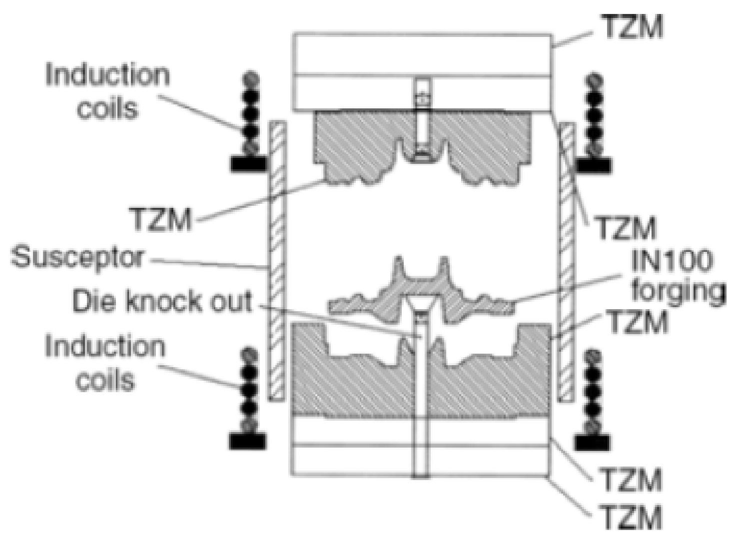


Figure 5. Depictionof a typical induction heated isothermal forging process

The same heating can also be incorporated in the form of gas-fired infrared heaters (Figure 6). Within this figure there is also a resistance-heated plate located beneath the dies to maintain thermal stability.

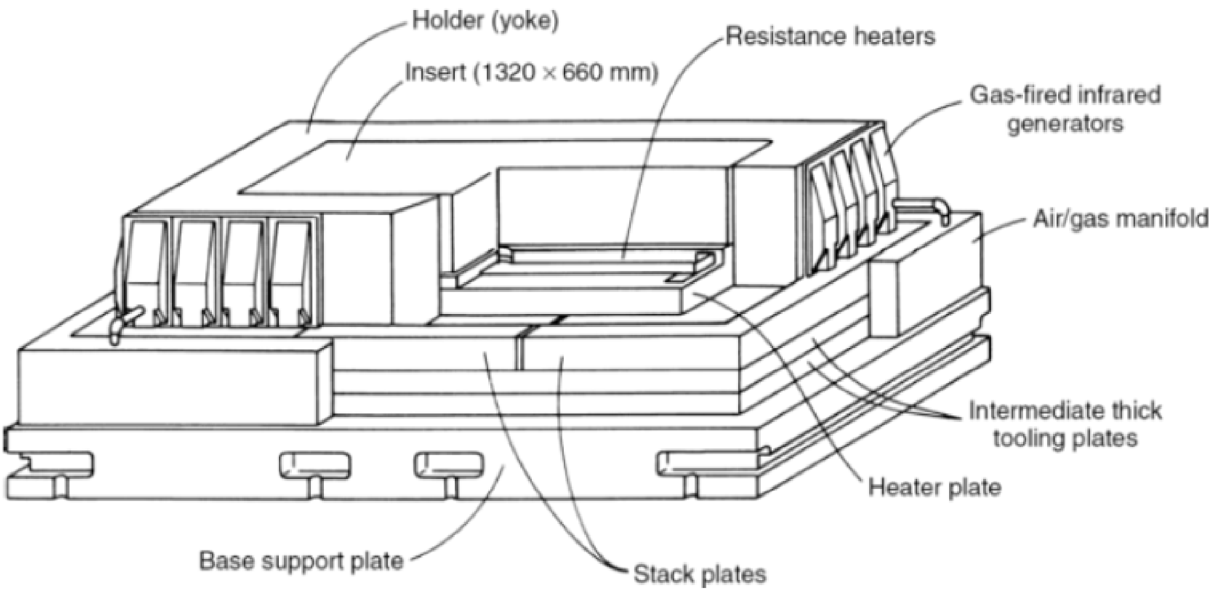


Figure 6. Gas-fired infrared heating system for hot-die forging

Due to these processes the forging stock is able to remain at higher temperature during the duration of the forging process to help alleviate some of the flow stress associated with the plastic deformation of the forging process. This heating is also incorporated with slower forging speeds to further limit the amount of flow stress during plastic deformation of the part [(4)].

Types of Forging Approaches

Typically multiple processes are used in the forging of products with two predominant metallurgical approaches for forging titanium alloys. These two approaches consist of forging the part with the workpiece temperature below the β_T most commonly known as "conventional" or alpha-beta forging and forging the alloy with workpiece temperature above the β_T temperature known as beta forging. The two techniques mentioned may be utilized during different processes and are used to control the microstructural properties of the product.

Alpha-beta forging the temperature of the dies is kept below 1000 °F and this is used to work the piece where both the alpha and beta phases are present to maintain a microstructure consisting of the two phases. For the microstructure associated with this technique there are deformed or equiaxed primary α in a transformed β matrix. The purpose of this approach is to optimize strength and ductility while maintaining adequate high or low cycle fatigue properties. Since this is done at low temperatures the amount

of working done on the material can significantly alter the microstructure of the final product. Figure 6 shows a microstructure characteristic of this approach with the primary α in the transformed β (Figure 7).

Figure 7. Alpha-beta forging showing equiaxed primary alpha in transformed beta in Ti-6Al-4V

The second technique as mentioned above is beta forging where the majority or all of the forging work is done above the β_T. When practiced in industry the technique usually involves supratransus forging in the first and intermediary steps with the final and finish forging operations completed below the β_T. The final subtransus work is done at a variety of temperatures consistent with desired properties.

When plastically deforming a product using the beta forging technique most of the effects from the prior operations are diminished due to recrystallization by heating the alloy above the β_T. Microstructures found using this approach are called Widmanstatten (Figure 8) which is an acicular primary α morphology in a transformed β matrix [5].

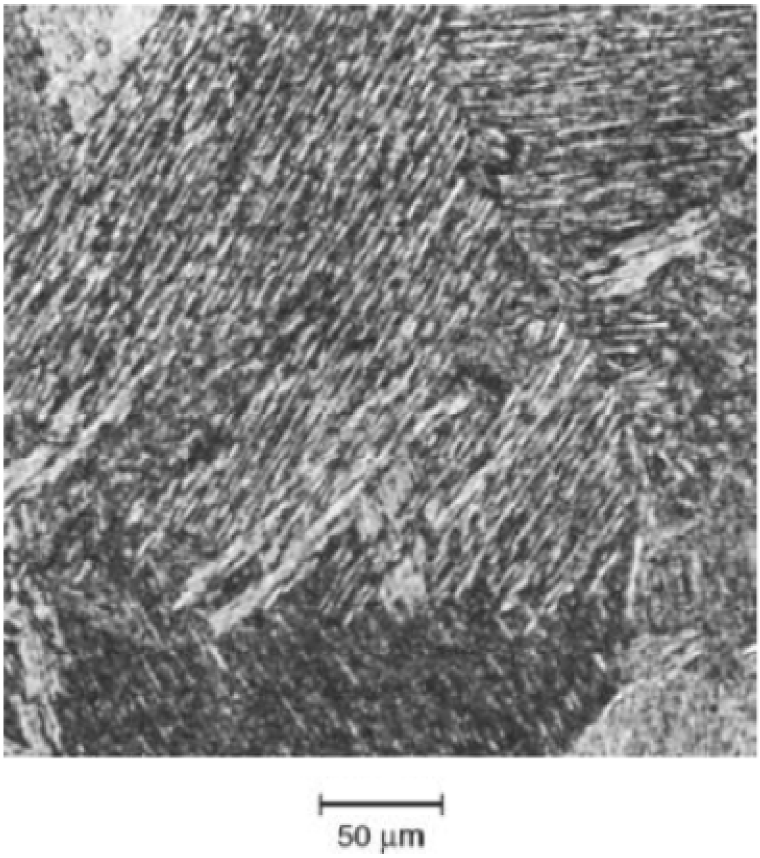


Figure 8. Beta forging of Ti-6Al-4V showing the Widmanstatten morphology

Experimental Procedure

Location of Sample Cuts

Samples obtained from Shultz Steel were taken from three regions as outlined in Figure 9. The ideal region was an area known to have near ideal properties to the specifications. A secondary region was also taken to compare a larger feature to the ideal region and problematic region. As stated before the problematic region consists of the rectangular protrusion from the end of the part where there is a possible problem with the flow of material from a thin to thick cross-section.

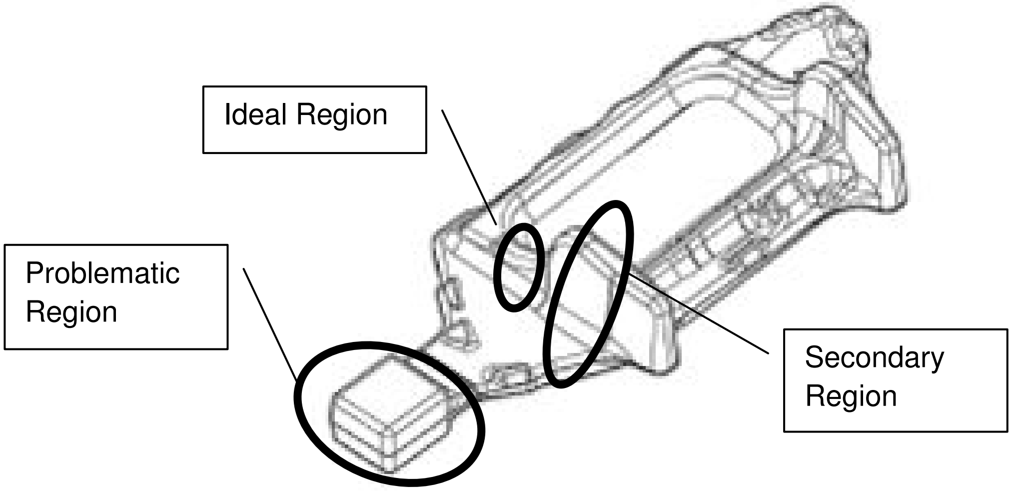


Figure 9. Depiction of location of sample areas with labels

For this project the problematic region is looked at. Different sections will be taken corresponding to the die parting line as well as the problematic area of the problematic region. Figure 1Figure 10 shows a Solidworks model of the problematic region. A metallographic sample was taken from the problematic area designated by a star. Further samples were taken in line with the problematic area closer to the edge of the part. Other samples were taken further into the problematic region close to the edge to attempt to correlate some microstructural difference between the regions. The die parting is represented by a black line located axially through the part. It should be noted that the only two sections analyzed were sections B and C.

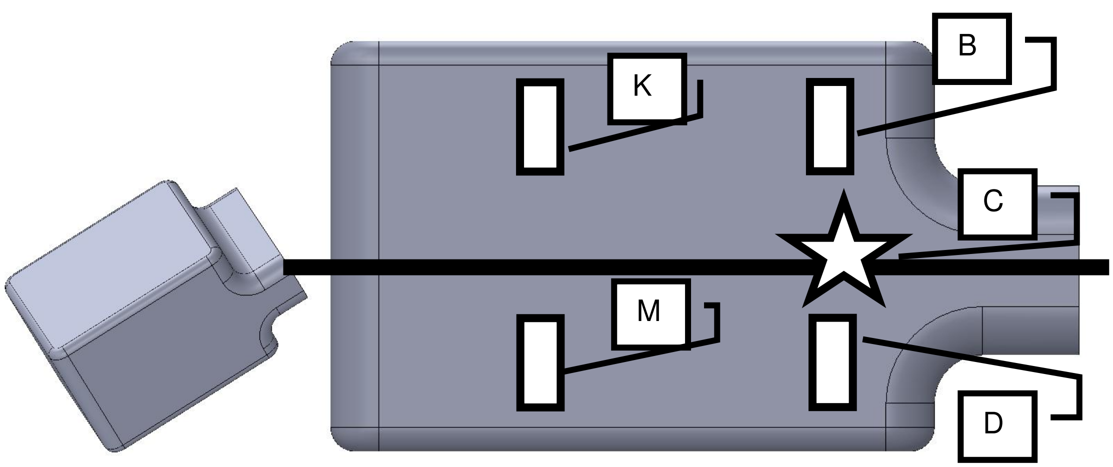


Figure 10. Problematic region and cuts taken for metallography designated by rectangles with the primary region of interested designated by a star

Sample Preparation

Samples were obtained and cut with a wet abrasive saw in order to make them easier to work with. These samples had rough dimensions of 1” x ½” x ¼”. The surface measuring 1” x ½” was first ground to be planar. From there the sample was ground using a succession of abrasive paper in the following grits: 240, 400, 600. When it was determined the samples were ready a 6 μm polishing pad was used using suspended colloidal silica. When scratches from the abrasive paper were polished out a 1 μm final polish was used to completely polish the samples. To etch the samples Kroll’s reagent was used. This is a solution made of 1.5 mL HF, 4 mL KNO_3, and 94 mL of H_2O. Kroll’s reagent is a standard microetchant for use with α + β alloys.

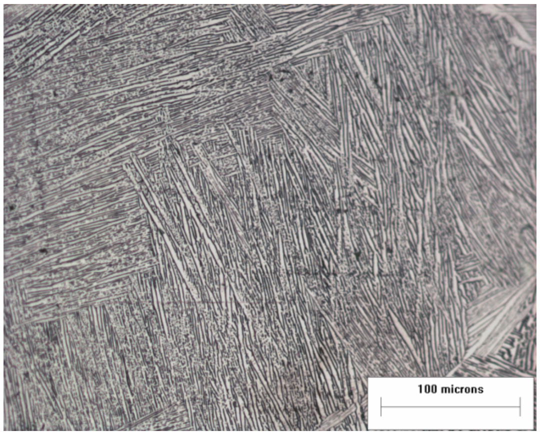
Sample Analysis

To quantitatively analyze the samples the software ImageJ was used. This software provided a quantitative assessment of the size and length of the lathes in the micrographs. In order to analyze the microstructures quantitatively five micrographs were taken of each etched sample at 200x. Using these micrographs ImageJ was calibrated to microns for the micrographs. Threshold levels were then set for each micrograph so that the features being measured were the lathes. Finally, using the “analyze particles” tool the micrographs were analyzed quantitatively and the data analyzed.

Results

Microstructures

After polishing and etching the samples it was noticed that the expected lamellar structure was not present. Rather, there was a lathe martensitic structure. Another thing noticed was that these microstructures differed depending on location relative to the edge of the part. Towards the middle of the part (Figure 11a) the lathes are slightly thinner and denser. However, towards the edge of the part (Figure 11b) there is wider spacing between lathes and they are slightly thicker.

a) 

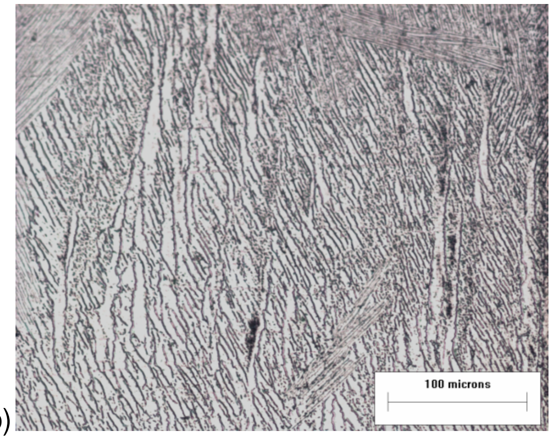
b) 

Figure 11. a) Microstructure of Section C (problematic area) at 200x showing a martensitic microstructure and b) Microstructure of section B (closer to the edge of the part) at 200x showing a slightly different martensitic structure.

Quantitative Analysis

Quantitative analysis of the lathe length proved to be more accurate than expected. As seen in Figure 11 the lathe length for most of the lathes in the two microstructures corresponds to data found in Table III. Using this data it can be seen that for all of the micrographs taken of Sample B the average lengths of the lathes in the micrographs correspond well to what appears to be the average lathe length in the photos. One thing to note is the standard deviations for the measurements. Sample B has a lower and thus more desirable standard deviation due to have a larger sample size. Measurements by ImageJ were taken on over 300 lathes in Sample B as compared to around 200 for Sample C.

Table III. Quantitative data representing the average length of the lathes

Sample	Average Length	Standard Deviation
B1	98.61	19.99
B2	98.22	12.77
B3	98.02	16.08
B4	100.35	13.93
B5	104.39	20.34
B-Average	**99.918**	**2.663732344**
C1	101.82	46.87
C2	65.85	29.11
C3	68.92	18.87
C4	71.38	22.74
C5	68.46	27.93
C-Average	**75.286**	**14.96218834**

A graphical representation (Figure 12) shows the average lathe length for the different micrograph for each section as well as the average length for all the micrographs in a section shown as the dark black bar. As can be seen in the first micrograph for Section C there is some outlier data. This shows an increased lathe size as compared to the other micrographs.

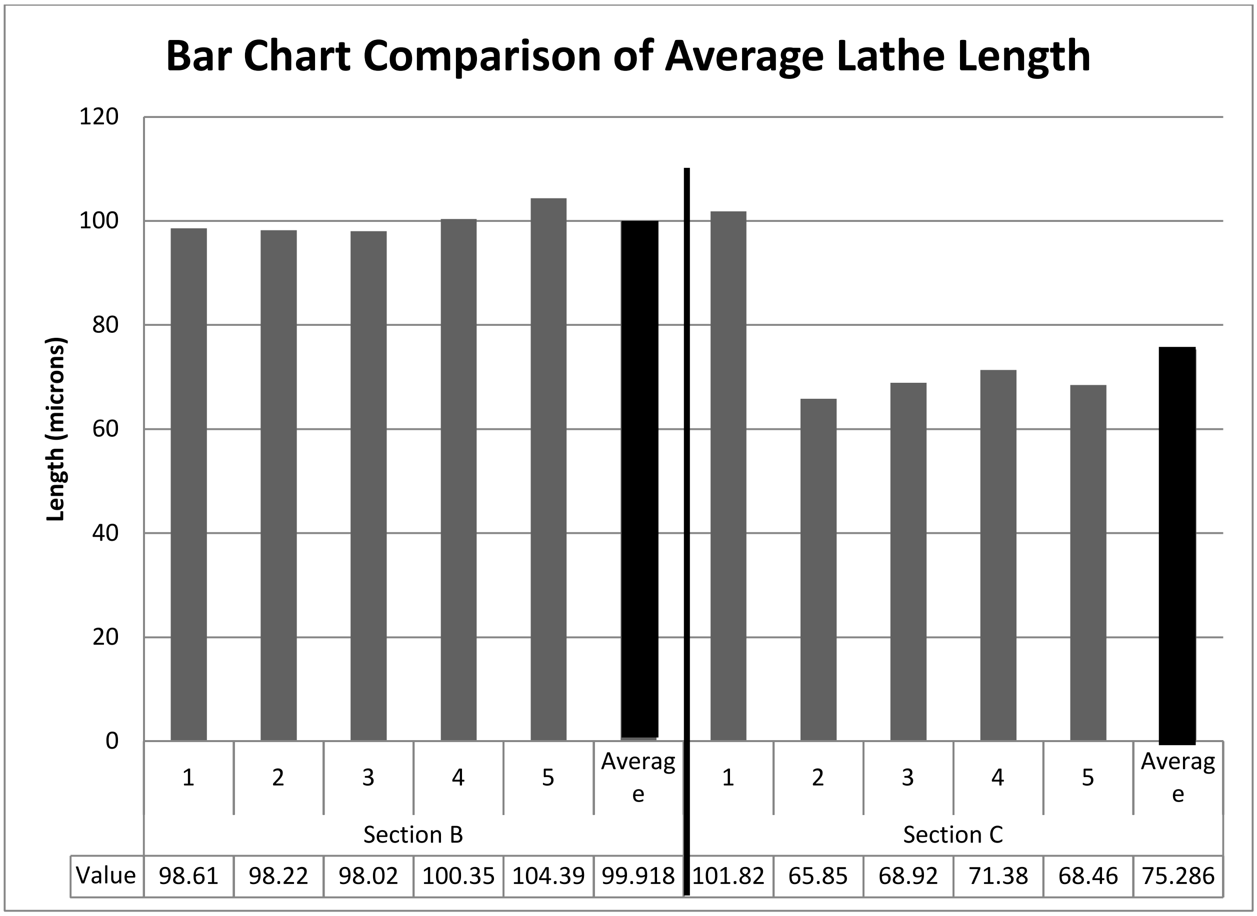


Figure 12. Bar chart for comparison of average lathe lengths in Samples B and C

To better represent the data from a statistical standpoint Figure 13 shows a scatter plot of the average lathe length for each section with an included standard deviation error bar. Here it is more easily seen that the outlier in Section C data exists and creates the large standard deviation shown.

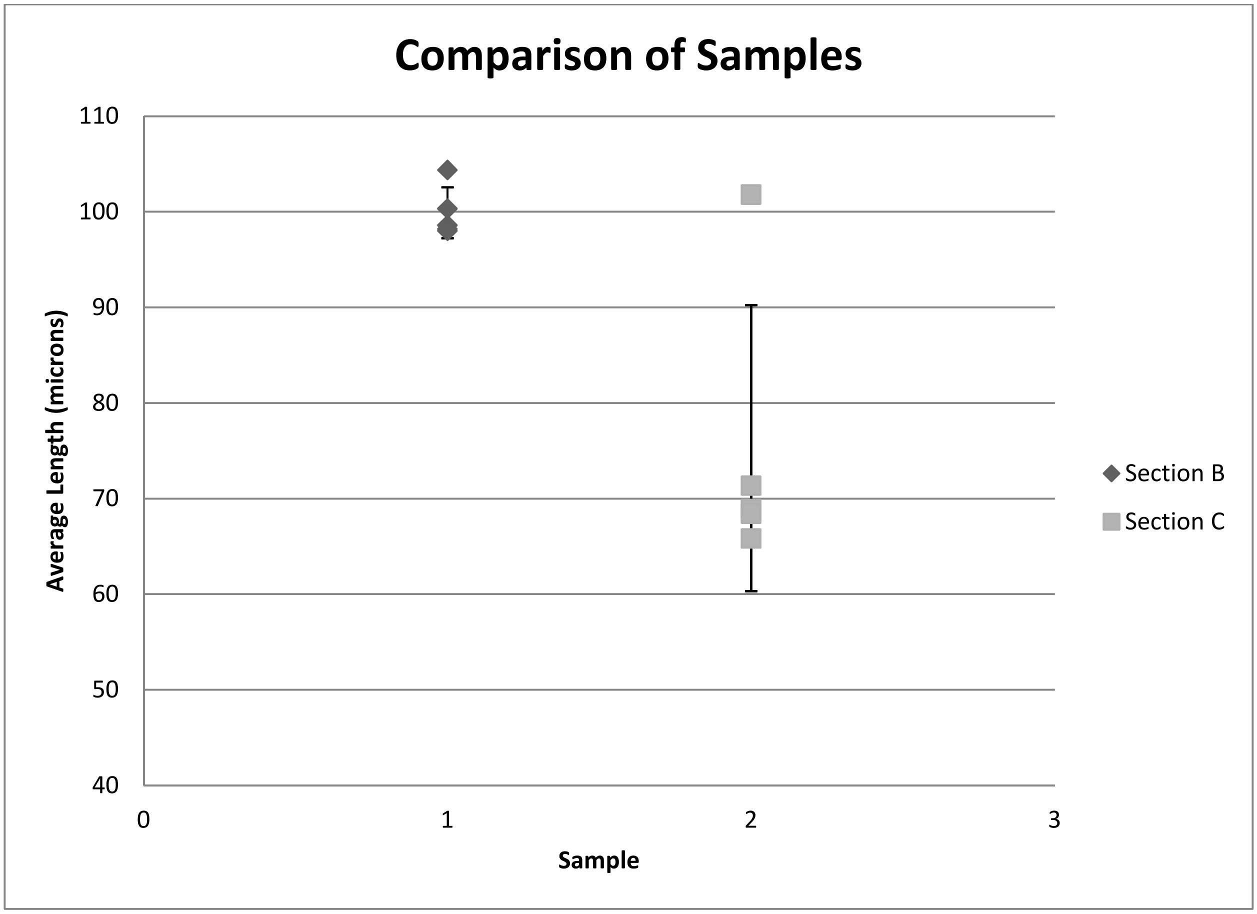


Figure 13. Scatter plot of the different sections with standard deviation error bars included

Discussion

Microstructures

As seen in Figure 11 the microstructures from the two sections differ if only slightly to the eye. What can be seen is that the outer region has coarser but less dense α lathes in a transformed β matrix, while the inner region has a finer and denser group of α lathes. This held true for all of the micrographs taken of the two sections. One possible reason for this has to do with the cooling rate distribution throughout the sample.

Since this is the thickest region in the part it may have cooled more quickly in the outer area of the problematic region than the inner. If this is the case then what would be expected is the coarser and less dense distribution of the α lathes than the slower cooled inner region of the part. However, since this is just one orientation of the sample it cannot be certain that the entire inner area of the problematic region shows this trend.

Also, since this was a small section it does not necessarily portray the same microstructural properties as other areas in section of the part.

This then leads to the need for further testing. Since another area of interest is the variation of tensile properties and how this relates to the microstructure and grain orientation this project will be continued on. Tensile tests will be conducted to determine the amount of variance. To characterize this variance box micrographs will be prepared to give a three dimensional view of the area of interest. Further work will be done using an Electron Backscatter Diffractometer (EBSD) to characterize grain orientation. The results of the EBSD will also help to characterize any problems associated with the flow of the material during plastic deformation of the forging process.

Quantitative Data

The quantitative data presented suggests that from the orientation being viewed there is a difference in the size of the α lathes in the material. As is seen in Table III and correlated to the microstructures in Figure 11 section B has significantly larger grains. Since the lathe lengths for section C was more difficult to calculate which leads to the significant variance in the data. The reason for this problem is that the density and closeness of the α lathes is more difficult for analytical software to distinguish. Thus with microstructures having close and fine lathes the software has difficulty interpreting the α lathes, the software can determine them to be larger than they are or not include them at all in the analysis.

Conclusions

- There is a significant difference in microstructures between inner and outer regions of thicker section in a part produced by Shultz Steel
- This difference comes in the form of the density and size of the α lathes in a martensitic structure
- Further testing will be conducted to reveal the amount and to determine the reason for variance that includes: tensile testing, box micrographs, and EBSD

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