Microstructure and Tensile Properties of Close-die Forged Ti-6Al-4V Aircraft Engine Mount

A Senior Project presented to
The Faculty of the Materials Engineering Department
California Polytechnic State University, San Luis Obispo

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Bachelor of Science

by

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Abstract

The microstructural characteristics of a Ti-6Al-4V close-die forging that passes yield strength specifications are examined and found to be consistent with literature recommendations. Originally, the intent was to compare the microstructure of a forging that passed specification to the microstructure of a forging that did not pass specifications using the imaging software ImageJ. Due to time and safety constraints considering the COVID-19 pandemic, the data that is presented is incomplete data on only the forging that passes specifications. There are no comparisons between the forging that did not pass and the forging that passed.

Keywords: Titanium, Metallography, Ti-6Al-4V, Close-die Forging, ImageJ, Weber Metals, Grain Morphology, AMS 4928

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Contents

List of Figures

List of Tables

Introduction

Company Information

Weber Metals is an aluminum and titanium forging company located in Paramount, California. Their headquarters is home to the largest operating presses in North America, with capabilities up to 60K tons. Weber Metals supplies products for commercial and military aerospace applications, space programs, and certain electronics/semiconductor components. The company can produce closed-die forgings up to 4000 pounds and open-die forgings up to 11,000 pounds. These parts are then cut, heat treated, and machined. Parts are generally not machined to final dimension at Weber Metals, they are sent to customers for final processing.

Problem Statement

Weber Metals is investigating engine mount forgings that are only marginally passing inspection for yield strength during tensile testing. Available literature indicates that a fine microstructure consisting of equiaxed alpha and transformed beta will result in the best tensile properties in all directions. In accordance with AMS 4928, a specification for titanium forgings, the yield strength must be at least 125 ksi. Samples from the parting line of the component at a specific location do not meet specifications. This has been noted in multiple components that were forged using closed-die forging.

The team will investigate sample orientation, location within the component, and microstructural morphology and yield strength. The team will then relate the results of the investigation to the yield strength of the sample. This project will find distinguishing characteristics in the microstructures that show a strong correlation with tensile properties. Testing methods and analysis techniques used to accomplish this will include polarized light metallography and tensile testing. The safety issues to be addressed during the execution of this project include the use of hydrofluoric acid and sodium cyanide while performing metallography, and general lab safety procedures during tensile testing.

Titanium 6Al-4V

Titanium 6Al-4V is by all measures the most widely used titanium alloy [1]. Most of it is used in the aerospace industry where the combination of high strength and low weight make it a desirable material for aircraft. Ti-6Al-4V is an alpha + beta alloy, a subclass of titanium alloys. The alpha and beta refer to the relative amounts of alpha and beta phases present in the microstructure of the bulk alloy. The high strength of Ti-6Al-4V is possible due to precipitate strengthening mechanisms made possible by the dual presence of alpha and beta phases.

Alloy Composition

Given the importance of Ti-6Al-4V in failure critical applications such as aerospace or surgical implants, the elemental composition of Ti-6Al-4V is tightly controlled. Elements considered impurity elements such as nitrogen or carbon have a weight percentage maximum limit. The primary alloying elements, aluminum and vanadium are added in strict known percentages (Table I).

Table I. Common Impurity Element Maximum Limits and Alloying Elements in Weight Percent in Ti-6Al-4V [1]

Al	**V**	N	C	H	Fe	O
6.0	**4.0**	0.05	0.10	0.01	0.3	0.2

Mechanical Properties

Components that are forged from Ti-6Al-4V can display a range of properties depending on the processing the components underwent. As brought up in the problem statement, the property of note is yield strength. A typical range for forged Ti-6Al-4V is 120 ksi to 134 ksi [1]. It is worth noting that the relationship between yield strength and fracture toughness is inversely proportional, much like how in most metals, yield strength and ductility are inversely proportional.

Heat Treatment of Ti-6Al-4V

Above the beta-transus temperature, grain growth occurs at exceedingly fast rates, leading to undesirable microstructures and mechanical properties [2]. As a result, most processing steps and heat treatments of Ti-6Al-4V occur in the sub-transus region, though there are exceptions, noted below. Weber Metals performs all forging operations in the sub-transus range, and as such any heat treatments involving super-transus temperatures will not be discussed in this paper. Major reasons for heat treating include reducing residual stresses, balancing ductility, machinability, and dimensional stability, increasing strength, and optimizing fracture toughness, fatigue and creep strength for the given application [3].

As with many dual-phase alloys, Ti-6Al-4V can be solution treated and aged to increase strength. Solution treating generally occurs around 1760°F (960°C). Once the part has reached uniform temperature, it is then quenched to room temperature, and subsequently aged for 2 to 8 hours between 995 and 1250°F (535 and 675°C). The resulting microstructure can range from primary alpha and tempered alpha prime, to a mixture of alpha and beta grains depending on the aging parameters [3]. A microstructure of primary alpha and alpha prime offers higher strength properties, while alpha and beta microstructures lend themselves to higher ductility and toughness [4]. In the case of the forging investigated, small, equiaxed primary alpha grains surrounded by a matrix of transformed beta produces the highest mechanical properties (Figure 1) [4] [5].

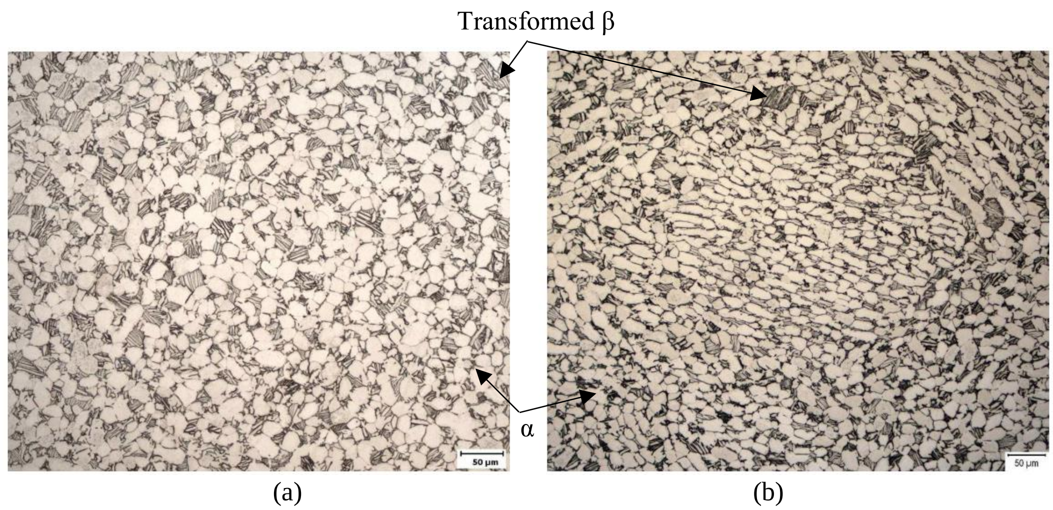

Figure 1. Solution treated and aged Ti-6Al-4V following a sub-transus solution treatment and aging process. An equiaxed primary alpha morphology (a) is typical of a forging that has been mill or recrystallization annealed. On the other hand, the microstructure in (b) exhibits some elongation, an indication of cold work, or forging with no annealing step. [5]

Annealing processes work to relieve stress from the part and generally result in lower strength and higher ductility [3]. Ti-6Al-4V annealing heat treatments fall into 4 main types: beta, recrystallization, duplex, and mill annealing. Recrystallization annealing is a straightforward process of heating the part to temperature, and then allowing the part to air or furnace cool to room temperature. A typical resulting microstructure is that of equiaxed α with β at the grain boundary triple points [3].

Mill annealing is a heat treatment that occurs during a hot work in the α + β region. The microstructure is constantly being deformed and recrystallized, and then allowed to air cool once the processing is completed. The resulting microstructure contains a matrix of partially recrystallized α with a small volume fraction of β particles [2].

The continuous cooling transformation diagram for Ti-6Al-4V offers insight to the relative amounts of phases after a given cooling rate (Figure 2) [6].

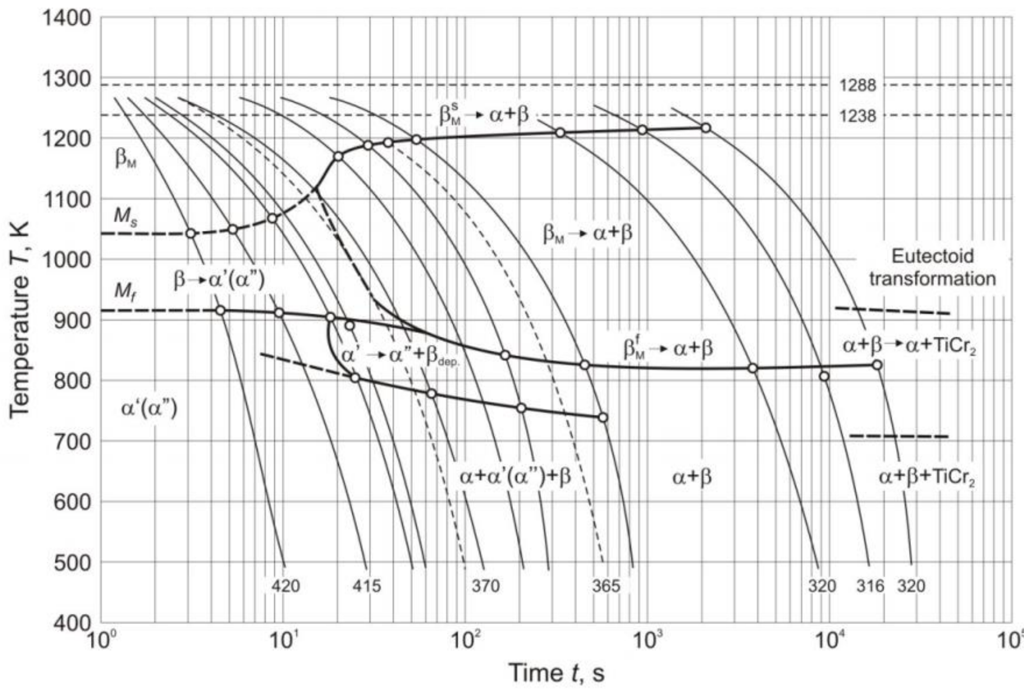

Figure 2. Continuous cooling diagram for Ti-6Al-4V featuring common cooling rates [6]. It should be noted that α'' refers to a strain-induced phase [7].

Duplex annealing, as the name implies, is a two-step heat treatment. In this case, the part is solutionized at approximately 60 °F (15 °C) below the beta-transus. The part is air cooled, and then aged for 2 to 8 hours at temperatures between 1000 and 1250 °F (540 and 675 °C). Depending on the specific aging parameters, the microstructure can range from primary α and Windmanstätten α – β, or a uniform and fully Windmanstätten microstructure (Figure 3) [2].

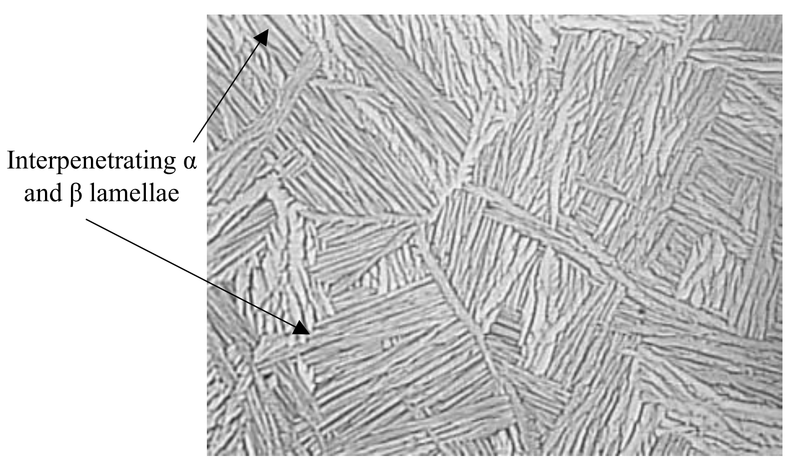

Figure 3. Fully Windmanstätten microstructure, formed as the result of a duplex anneal [2].

As noted earlier, this microstructure lacks the high yield strength necessary (125 ksi). Therefore, any duplex anneal must be managed to produce a microstructure with higher properties.

Orientation

Mechanical properties and deformation characteristics ultimately rely on slip systems and methods of deformation at the crystallographic scale. The mechanical properties of Ti-6Al-4V are not only dependent on the overall morphology of the grains, but also on the orientation of those grains in relation to the stress axis. The HCP structure of alpha titanium contains three primary slips systems, denoted as basal, prismatic, and first-order pyramidal (Figure 4) [8].

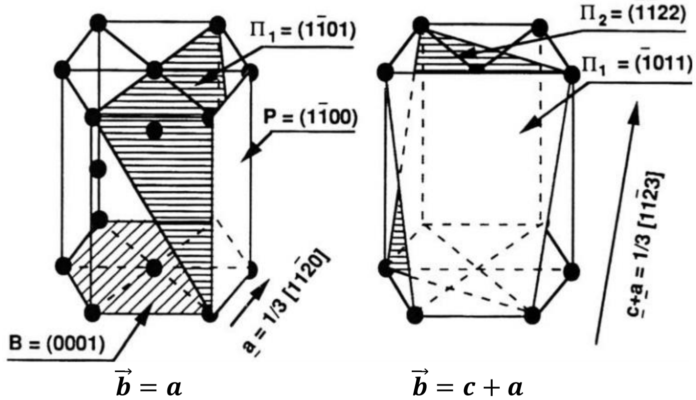

Figure 4. Slip systems in hexagonal (hcp) metals: basal (B), prismatic (P) and first-order pyramidal (Π_1) planes containing the Burgers vector *a*; first and second-order (Π_2) pyramidal slip planes containing the Burgers vector *c* + *a* [8].

The favored type of gliding can be determined from the orientation of the grain (Figure 5). Further, an analysis of the Schmid's factor of each grain can help predict the nature of the slip [8]. Presently, however, no conclusive method of anticipating the precise stress at which the slip systems are activated [8] [9].

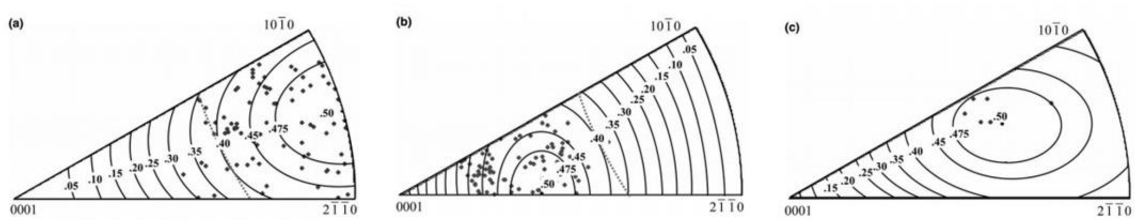

Figure 5. Unit triangle with iso-curves of Schmid's factor for (a) prismatic, (b) basal and (c) first-order pyramidal gliding with in superposition experimental data [8].

Thus, further investigation on the practical impacts of grain orientation, and the distribution of orientations on yield strength is needed before this insight can be put to use [8] [9].

Forging

Overview

Modern forging is defined as the compressive plastic deformation of material between dies [10]. Forging is a primary metalworking process, meaning it comes after the metal has been extracted from the ore, melted to remove impurities, or add alloying elements, and cast.

Forging is often classified by the temperature at which the part is forged. These classifications are relative to the melting temperature of the metal. Cold forging occurs at 25% or less of the melting temperature of the metal, which usually includes room temperature. There is less workability of the metal in this temperature range. Warm forging is between 25 and 65% of the melting temperature, and the workability in this range is even lower than cold forging due to holes at grain boundaries. These holes are formed as dislocations move through the grains and hit grain boundaries. Tensile stresses cause the holes to grow larger, and if the stresses are large enough, they can cause fracture of the piece. Hot forging occurs while the metal is softened, but still below the melting temperature. This process gives the best workability of the metal, but it can be hard to control the final dimensions of the piece due to uneven cooling and contraction after forging [10].

Open-Die Forging

Open-die forging, one of the two main types of forging, is also called hand-forging because it mimics the first forging process discovered where blacksmiths would hammer metal by hand to shape and increase the strength of components. In this type of forging the die does not enclose the work piece.

Open-die forging is cost efficient for small production batches and preferable for large or bulky parts. It can also be used as a preliminary step to closed-die forging to reshape or resize parts to better fit the die or following process [11]. Open-die forging can yield continuous grain flow, which is important for consistent properties across the part [12]. For the engine mount being investigated, Weber Metals ran three different preforms in attempts to increase grain flow in the problem area. These included short transverse, long transverse, and shorter overall partial forgings. The short transverse preform was expected to yield the best results, but the long transverse performed slightly better with recrystallize anneal and mill anneal [5]. The goal is to maintain preform properties because the loss of properties occurs in the closed-die forging step. The ability to modify grain flow for specific applications of the part is a major advantage of open-die forging. A photo showing grain flow in a forging can be found in Figure 6.

Figure 6. Cross section of a forged part that has been etched to depict grain flow [13]. The vertical lines through the longitudinal body represent the grain flow.

Grain flow is the elongation of the metal grains and any impurities or inclusions in the alloy during processing. The anisotropic properties of metals, such as fatigue strength, impact toughness, and ductility, can be greatly impacted by grain flow [13]. The three different preforms were part of Weber Metals preliminary investigation into increasing grain flow in hopes of increasing strength in the problem area.

Closed-Die Forging

Closed-die forging utilizes a custom die that has been designed for a specific piece. The design and manufacturing of these dies can be expensive, making the initial cost of closed-die forging much higher than open-die. However, the cost of each forged part is lower, the process is more efficient, and the overall cost lowers with every part produced, which means that closed-die forging is preferable for larger production orders [10]. The engine mount being investigated in this project undergoes closed-die forging after the preforms are made by open-die forging.

Closed-die forging generally needs less further processing. Open-die forged parts need to be machined or undergo some other type of secondary processing. The dies for closed-die forging can be designed to incorporate finer progressive detail so less secondary processing is needed, which can save cost.

Forging of Ti-6Al-4V

Titanium is susceptible to oxidation, so it needs to have a protective coating on it while forging. These are typically liquid glass coatings that fuse with the surface of the metal and prevent oxygen, nitrogen, hydrogen, and carbon from contaminating the part. Some literature reports the use of graphite as a lubricant that can prevent the wear on die and improve metal flow during forging [14].

Titanium alloys frequently undergo multiple rounds of forging due to the differences in microstructures and properties that are dependent on the forging temperatures. Body-centered cubic structure has higher ductility and lower pressure requirements, so the initial forging is usually done above the beta-transus. However, forging at this temperature can lead to excessive grain growth so the final forging is done just below the beta-transus [14]. The forging of the engine mount is done completely below the beta-transus.

Experimental Procedure

Safety

The safety precautions taken throughout the execution of this senior project include general lab safety measures and etchant safety procedures. General lab safety procedures were observed at all times, while etchant safety procedures were utilized during the etching step of sample preparation.

General Lab Safety

During all operations in the Materials Engineering department's lab spaces, long pants, closed-toe shoes, and safety glasses are required, even when no processes or machines are in operation. Long pants and closed-toe shoes protect participants from injuries that may occur from falling materials or splashes from mild chemicals. Safety glasses protect the wearer from any airborne particles that may cause damage to the eyes.

Food and drink were prohibited from lab areas at all times, preventing chemical contamination, and reducing the possibility of spills and unnecessary clutter in the workspace. Personal belongings were stored in designated areas to further reduce clutter and keep floorspace clear and safe.

In addition, at least two people were present for all lab activities. This ensured that a partner was present and able to call for help in the event of an emergency.

Etchant Safety

All etchant mixing and usage occurred in a fume hood. While producing the etchants, solutes were always added to solvents. A lab coat, nitrile gloves, chemical splash goggles, and a face shield were used to protect against spills and splashes. Because hydrofluoric acid was used, calcium gluconate topical cream was kept nearby at all times when utilizing etchant. This cream is meant for use on suspected splash areas on any exposed skin in the event of a spill or accident. Calcium gluconate binds with the fluorine in the acid to prevent excessive bone damage. Use of the cream was not needed throughout the project.

Designated chemical waste bins were used for proper disposal of the etchants and associated solid waste, such as the applicator swabs. When not in use, etchants were stored in a chemical storage cabinet separate from any other chemicals that might cause a dangerous reaction. Any container used for storing hydrofluoric acid, or Kroll's reagent, which contains hydrofluoric acid, was made of a polymer that would not react with the etchant. Glass containers were avoided due to their reactivity with hydrofluoric acid.

Sample Locations

A total of eight sections from two separate forgings were provided by Weber Metals. The samples were differentiated by which forging they were from, their location from the forging, and the depth from which they were taken.

Forgings differed by means of production process. The forging that did not meet specifications was produced by closed die forging. The forging that did meet specifications was produced by open die forging.

From each forging, samples were extracted from one of the prolongs, at the centerline of the forging and at 1/4-inch offset from the centerline, as well as from the single tang end – again at the centerline and 1/4-inch offset (Figure 7).

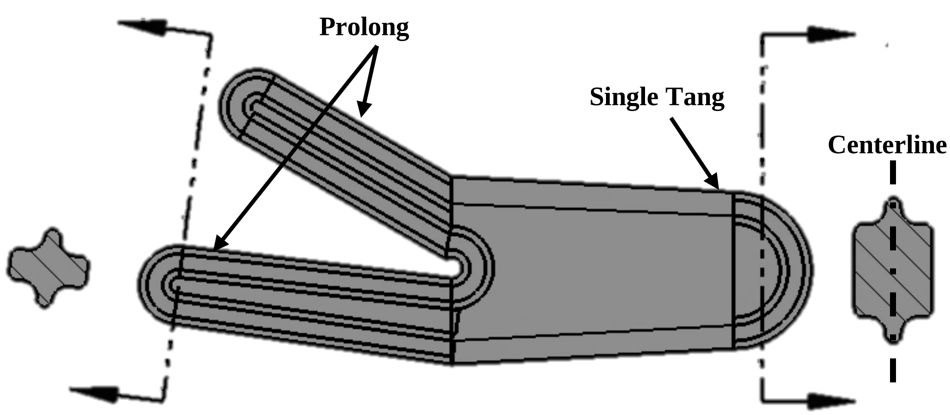

Figure 7. Sample locations from the engine mount.

The forgings used for producing samples were classified as either "Passing" or "Failing" based on the results of tensile testing performed by Weber Metals on samples from the centerline of the corresponding single tang.

Three metallographic samples from each location were then produced to investigate the microstructural characteristics of each sample. The directions of the sample were chosen relative to the forging, and align with either the longitudinal (L), long transverse (LT), or short transverse directions (ST) **Figure 8**.

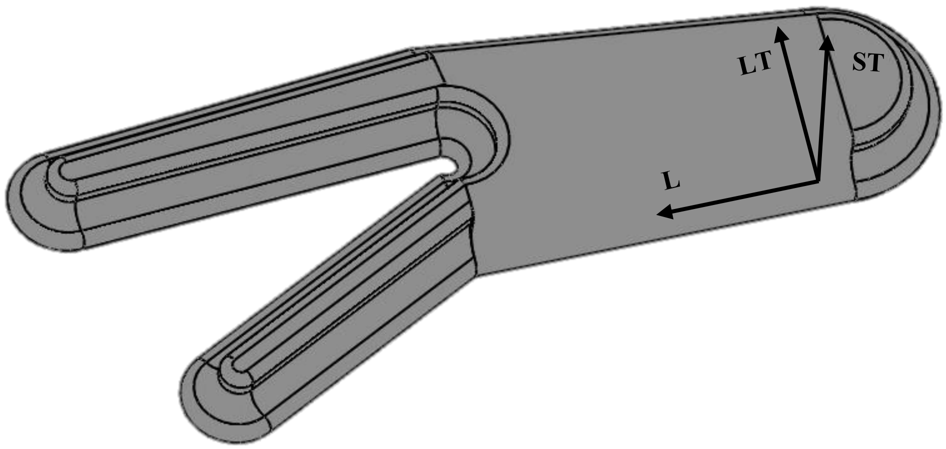

Figure 8. Schematic displaying the directional view of the component with respect to sample labelling.

A total of twenty-four mounted samples were produced from the eight original sections received from Weber Metals. Noted on each mounted sample was the section the sample came from and the direction of view the sample represented (**Table II**).

Table II. Sample Numbers Matched with Forging of Origin, Location in Forging, and Distance with Respect to Centerline

Section Number	Met Specifications	Location	Centerline Distance
1	Met	Tang	At
2	Met	Tang	Offset
3	Not Met	Tang	At
4	Not Met	Tang	Offset
5	Met	Prolong	At
6	Met	Prolong	Offset
7	Not Met	Prolong	At
8	Not Met	Prolong	Offset

Sample Preparation

The original eight samples received from Weber Metals were further sectioned into three samples on an abrasive cold saw with an epoxy bonded SiC abrasive wheel to present microstructures from the three directions of investigation. This resulted in a total of twenty-four samples for microstructure analysis.

Each sample was mounted in Bakelite and polished using SiC abrasive paper of increasing grit from 240-1000. Further refinement of the sample surface was performed on polishing pads utilizing diamond particle suspensions of decreasing particle size from six microns to three microns.

When the samples were polished to a satisfactory condition, they were etched using Kroll's reagent until features of the microstructure were visible.

Image Analysis

Images were collected using optical microscopy and analyzed with the software ImageJ. Processing the photos using ImageJ allowed the team to collect data on the grains visible in the image. Grain size, grain aspect ratio, and volume fraction of the types of grains in the microstructure were recorded (Figure 9).

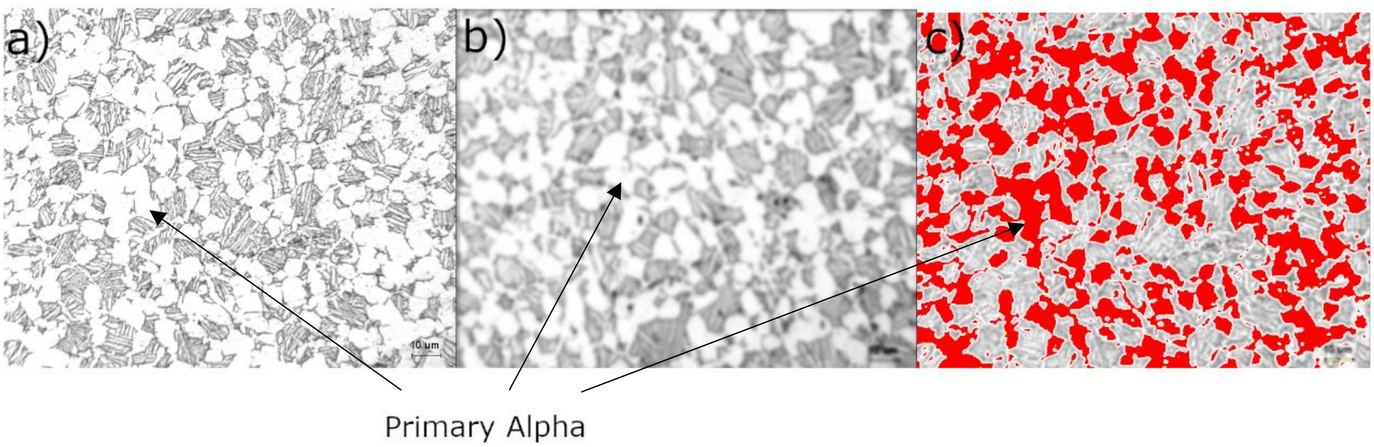

Figure 9. Figure illustrating the image processing steps necessary to recording grain data using ImageJ. a) shows the unaltered image. b) Shows the image processing necessary to exclude light regions within the transformed beta grains from the particle measurement. c) An ellipse was fitted to each particle (represented by a red region) using ImageJ and data about each ellipse was recorded.

Results

Impact of COVID-19

The following results are incomplete. Of the twenty-four planned images, eight images were captured. All the images captured were from forgings that met specifications. As a result, the data presented only represents data from a forging that met specification.

Grain Data

Data was collected by performing a simple average of the microstructural characteristics. The microstructural properties observed agree with properties literature suggests are optimal characteristics (Table III and IV).

Table III. Section Number and Direction of View Displayed with Average Grain Size and Percent Volume Fraction Primary Alpha

Sample and Direction	Average Area (μm^2)	Percent Volume Fraction ($\%vol$)	Average Grain Diameter (μm)
Sample 2 L	42.8	38.5	7.39
Sample 2 LT	36.5	20.0	6.82
Sample 3 L	50.9	36.9	8.05
Sample 3 LT	54.7	31.2	8.35
Sample 3 ST	76.1	31.7	9.84
Sample 5 L	33.0	21.2	6.48
Sample 5 LT	21.3	17.8	5.21
Sample 5 ST	43.7	32.3	7.46

Table IV. Section Number and Direction of View Displayed with Average Grain Aspect Ratio

Sample and Direction	Average Major Axis (μm)	Average Minor Axis (μm)	Aspect Ratio (Min/Maj)
Sample 2 L	11.0	5.81	0.53
Sample 2 LT	9.88	5.31	0.54
Sample 3 L	7.91	4.15	0.52
Sample 3 LT	8.41	4.37	0.52
Sample 3 ST	9.57	4.71	0.49
Sample 5 L	7.21	3.07	0.43
Sample 5 LT	9.08	4.66	0.51
Sample 5 ST	8.20	4.28	0.52

Discussion

The results from gathering partial data on a single forging that met specifications serve as a starting point for comparison to other forgings. The results gathered are consistent with literature which proposes that high strength values are highly correlated with a large volume fraction of primary alpha with a grain diameter under 15 microns [15]. Also consistent with literature is the overall shape of the particles. Equiaxed primary alpha grains are correlated with higher yield strength. The data for the forging that passed specification shows that the grains show some directionality though it is not extreme (Table IV).

Summary

Due to unexpected limitations from COVID-19, not enough data was collected to make results statistically significant, and therefore no conclusions can be drawn from the work done during this project.

Future Work

Further work for this project should include completing the testing plan that was started as described in the Experimental Procedure. Comparisons can be made between the microstructural properties of forgings that met specifications and forgings that did not meet specifications.

Including tensile testing data for each sample and comparing that to the micrographs would make the analysis more robust. Correlating the yield strength values found in tensile testing data with the percent volume fraction of primary alpha could confirm the patterns described in literature. Knowing which microstructures correspond to yield strengths above 125 ksi (in accordance with AMS 4928) would allow for greater understanding of the mechanical properties of those microstructures and allow for more accurate forging methods to produce the desirable microstructures.

A separate team performed additional analysis on this project in the form of Electron Backscatter Diffraction (EBSD) testing. EBSD is a technique that maps the crystallographic orientation of individual grains relative to the sample surface. For further details, contact Blake Gaspar at Weber Metals.

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