Effects of Initial Forging Temperatures, Cooling Rates and Carbon Content on Primary Alpha Formation in Ti-6Al-4V

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By

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Abstract

Ti-6Al-4V is an alpha-beta titanium alloy system, which contains both alpha and beta phases at room temperature. Both alpha and beta phases provide Ti-6Al-4V a range of different properties for a range of applications. In order to improve the energy efficiency and better satisfy customers' requirements of less than 52% primary alpha phase, Weber Metals sponsored this project to study the effects of carbon content, forging temperature, and cooling rates on primary alpha formation in Ti-6Al-4V alloys. There has been a lot of discussion as to whether or not carbon, a known alpha stabilizer, will affect the microstructure in small percentages. High and low carbon Titanium forgings, .025%C and .007%C respectively, were received from Weber Metals and were sectioned to approximately 1 in^3. Prior to heat treatment the samples were drilled to fit a .062-inch thermocouple that would monitor the rate at which the Titanium cooled, as cooling rates affect how the microstructure forms. Samples were heat treated at 1725°F, 1750°F, 1775°F and 1800°F and cooled with three different cooling methods, and analyzed metallographically using Photoshop. Weber Metals uses an image-processing tool for quick estimates on alpha and beta phase content. Photoshop is a powerful tool that will speed up their analysis process and give more accurate readings on microstructures. Carbon content was found to have no statistically significant effect on the microstructures, while air cooling produced the least primary alpha within the cooling rate grouping, only by about 6%. Finally, as the heat treatment temperature increased the primary alpha formed decreased significantly.

Keywords: titanium, primary alpha, Ti-6Al-4V, materials engineering, forging, cooling rates, carbon content, β-transus, quantitative metallography.

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Introduction

Problem Statement

The current challenge with Titanium forging is controlling the amount of primary alpha phase present. It has been indicated that too much primary alpha phase can cause properties to change from forging properties to plate properties. Forgings have better strength from the center of the part, as the grains are not elongated during processing like that of rolled plates. Available literature in this area has shown the forging temperature, cooling rate, and carbon content will affect the amount of primary alpha in the final microstructure. To address this problem, the following project will investigate the microstructures of various forging temperatures, cooling rates and carbon contents and give a quantitative analysis and approximation of primary alpha in the microstructure. The specific goals of the project are to obtain an average of less than 52% primary alpha phase. Testing methods and analysis techniques to accomplish the project goals will be quantitative metallography analysis using Photoshop, and statistical analysis of the received data with Minitab.

Weber Metals

Weber metals, is one of the biggest aluminum and titanium forging specialists in the United States. Weber metals estimated completion of the titanium expansion project in 2010. Weber Metals has invested over thirty million dollar to expand their capabilities in converting ingot to billets and hand forgings up to 20000 lbs (9071 kgs) and 25ft (7.62m) long. State of the art computer controls on their presses and automated manipulators reduce variability and lead time. The benefit to their customers is optimizing material utilization for their titanium forgings.

Titanium Background

In 1791, Titanium was discovered by William Gregor of Cornwall, Great Britain, who treated ilmenite with hydrochloric acid. Titanium was named by chemist Martin Heirich Klaproth after the titans from Greek mythology[1]. Titanium was not practically used for a long time, due to the issue of impurity and the difficulty with processing titanium. In early 1910, the

purification processing was achieved by Matthew Albert Hunter at Rensselaer Polytechnic Institute by heat treating titanium tetrachloride ($TiCl_4$) with sodium in a steel pot (Reaction 1[2]).

$$4\,Na + TiCl_4 \rightarrow 4\,NaCl + Ti \qquad \text{Reaction 1}$$

As the cost of producing and processing titanium decreased, the commercial production of titanium in United States increased from zero to more than 6 million kg/year in 1956[3]. On the other hand, titanium alloy development progressed rapidly. Titanium alloys have high specific strength, high operating temperature, and high corrosion resistance in seawater. The density of titanium alloys is about 55% than that of steel. Ti-6Al-4V alloys accounts for more than half of the current U.S. titanium market[4]. Figure 1 shows the Titanium-Aluminum phase diagram, which is used in understanding how the microstructure will form. Now, titanium alloys have accumulated industrial practices and design applications for engineering purposes due to their superior properties.

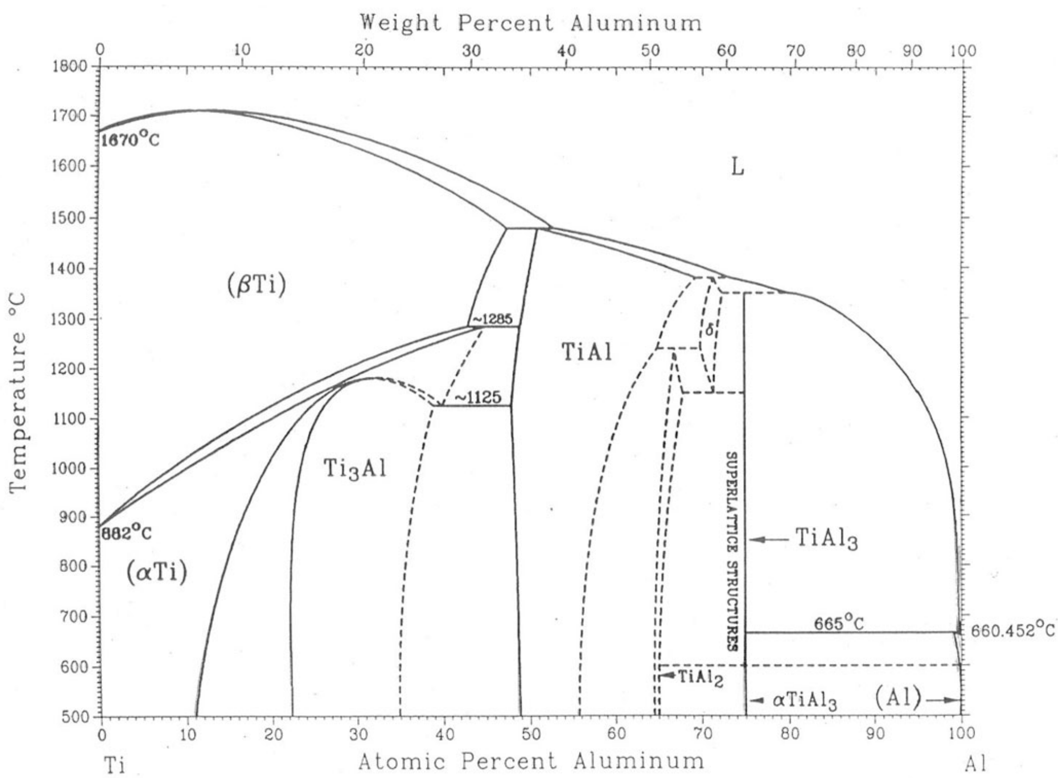

Figure 1. Titanium aluminum phase diagram used in producing titanium ingots[5]

Ever since its large scale production titanium has been chosen for engineering purposes. Forging can give some beneficial properties to titanium, though it must be carefully worked to ensure that there are not drastic property fluctuations in thicker or thinner sections[6].

Titanium is much more difficult to process compared to most steels. All steps taken during processing can have an effect on the final properties. Oxygen, nitrogen, and carbon can impair ductility and impact toughness as well as lower the overall quality of titanium forgings. Hydrogen absorption can also be a big problem if it exceeds a specified quantity; a more significant problem is that hydrogen is not limited to being a surface contaminant[3].

Titanium Phases

Titanium has two main phases, α and β. In pure titanium, α is the low temperature stable phase and β is the high temperature stable phase. A temperature called the β-transus (Figure 2) is the point where α transforms into β upon heating.

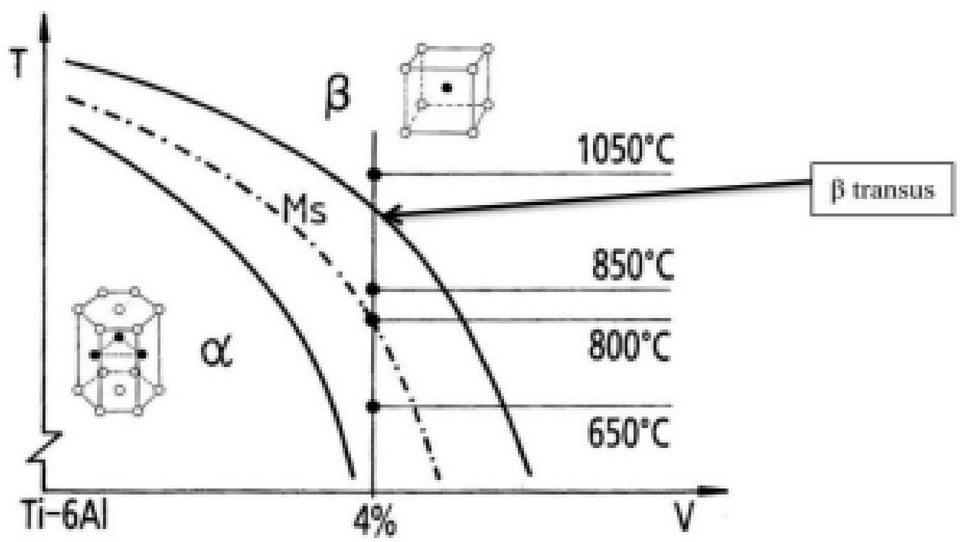

Figure 2. Representative phase diagram for Ti-6Al-4V. Temperatures are only approximate[7].

Alpha Ti

The low temperature α phase has a hexagonal close packed (HCP) crystal structure (Figure 3). Interstitial atoms such as carbon, nitrogen, or oxygen increase the c/a ratio. Interstitial atoms produce a non-ideal packing arrangement that leads to slip favored on prism planes rather than on basal planes.

Due to the nature of α, this phase gives limited plastic deformation due to HCP having only three independent slip systems required for plastic deformation[7]. Although the packing density of an HCP slip plane is significantly higher, deformation is harder than in BCC materials with a lower slip plane packing density. The crystal structure of α-Ti results in good strength and creep resistance. Single crystalline α-Ti also exhibits clear strength differences based on

orientation also due to being HCP. Young's modulus perpendicular to the basal plane is about 1.5x greater than parallel to the basal plane.

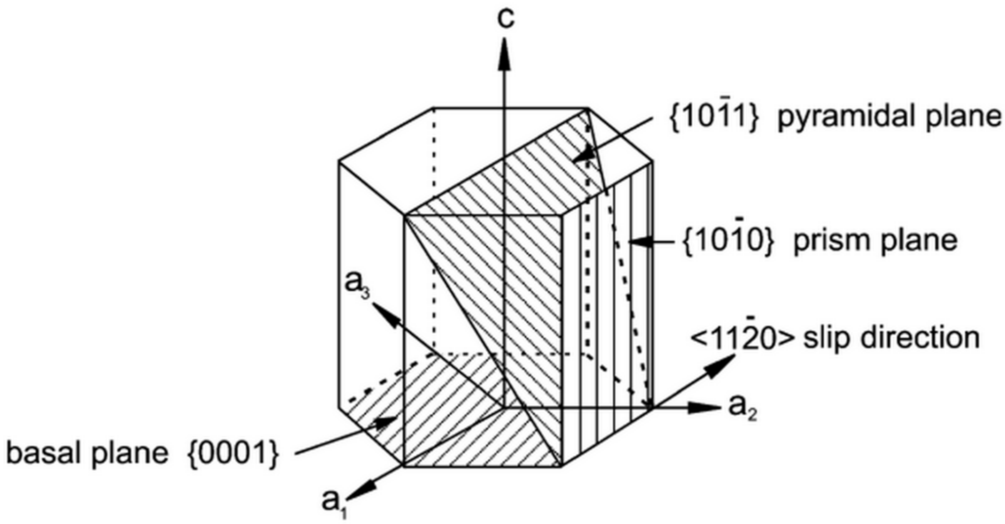

Figure 3. Slip systems of hexagonal crystal lattices[7].

Beta Ti

Above the β transus in pure titanium, α-Ti transforms into the body centered cubic (BCC) β phase (Figure 4). Ductility is greater in β-Ti due to BCC having more slip systems than HCP, as well as a shorter slip path. More slip systems and a shorter slip path length contribute to β-Ti's increased ductility over α-Ti, even though BCC's packing density on slip planes is less[8].

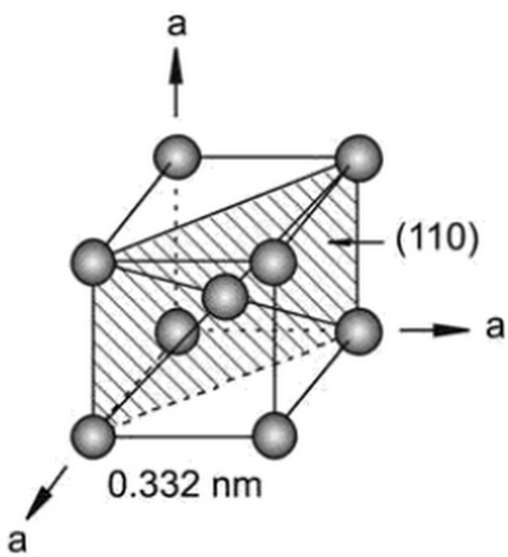

Figure 4. Crystal structure of bcc beta phase[7].

Alpha-Beta Ti

Cooling from the β phase field results in the most densely packed BCC planes to become the basal planes of HCP α. The distance between the HCP basal planes is slightly larger than the distance between BCC planes, causing a contraction of two axes. The slight change in distance distorts the HCP lattice, leading to a non-ideal lattice ratios. An increase in volume is observed when cooling from β-Ti to α-Ti (Figure 5). This leads to a basket-weave like structure upon cooling below the β-transus. Slower cooling results in a coarser basket-weave structure (Figure 6a), faster cooling a finer basket-weave structure (Figure 6b).

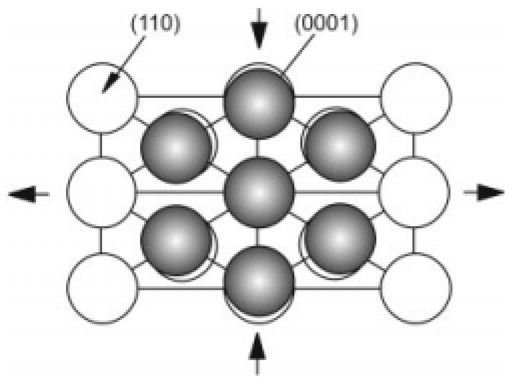

Figure 5. Beta to alpha transformation according to Burgers relationship[7].

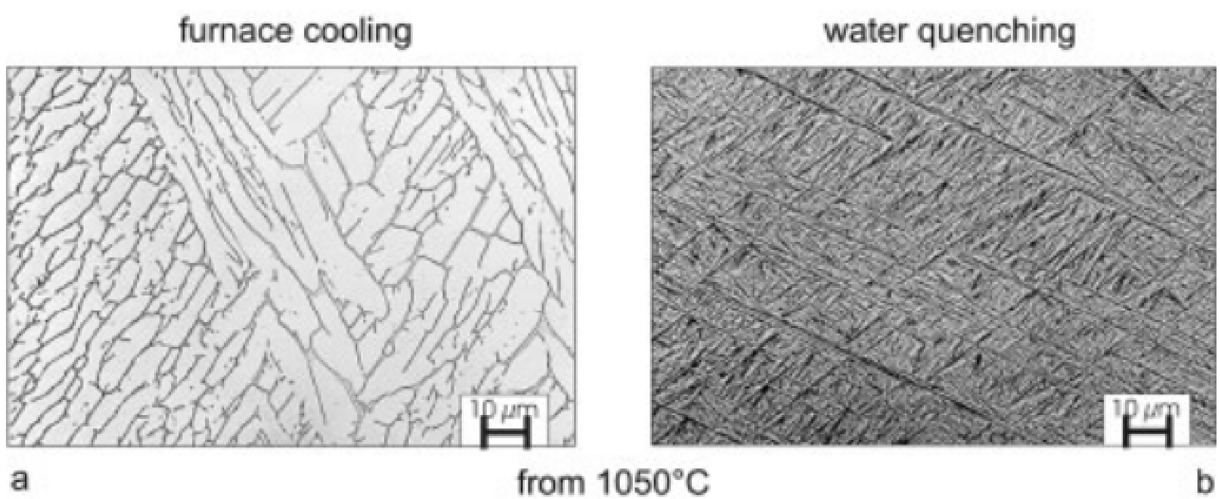

Figure 6. Microstructure of Ti-6Al-4V after slow cooling (50°C/h) and water quenching from 1050°C[7].

Classifying Alloys

Titanium alloys are the bridge between steel alloys and aluminum alloys. It is about half as dense as steel with higher strengths achievable and only about 60% more dense than aluminum with about twice the strength. It is nonmagnetic, nontoxic, and biologically

compatible making it useful for surgical-implant devices. Other important characteristics of titanium alloys depend on the class of alloy. For alpha and alpha-beta alloys their outstanding properties are derived from their heat treatments and aging. Fine equiaxed alpha, is associated with high tensile strength, good ductility, and fatigue-crack resistance. Acicular alpha is associated with good creep strength, high fracture toughness, and resistance to fatigue crack propagation that occurs by heating above the β-transus and subsequent beta transformation during cooling and aging. Finally, an intermediate microstructure can be achieved by processing alpha alloys close to the β-transus. The objective of an intermediate microstructure with acicular and equiaxed alpha is to provide good creep strength without excessively compromising fatigue strength[9]. Figure 7 shows general trends for titanium families.

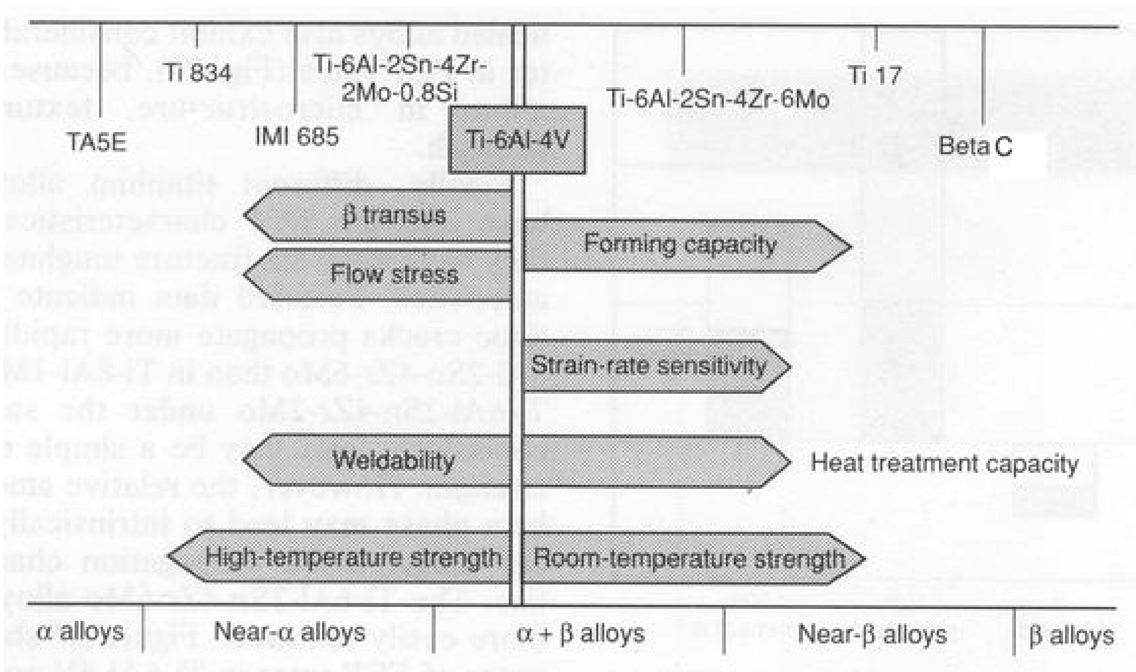

Figure 7. General characteristics of the different titanium alloy families[6].

Alpha Alloys

The α alloys often contain Al, Sn, or both. Al has a solid solution strengthening effect on titanium, but reduces ductility. Sn is neutral in its effect on the phase diagram, but Sn strengthens titanium without a significant loss in ductility. Alpha alloys are mainly used for high service temperature situations. They are almost exclusively alpha phase. They are not heat treatable. Though they cannot be heat-treated they are annealed to relieve internal stresses.

Some α alloys have extra low levels of interstitials (ELI), such as Ti-5Al-2.5Sn-ELI. These alloys retain ductility and toughness at cryogenic temperatures because of the lack of a ductile-brittle transformation shown in BCC alloys show. Therefore these α alloys are used in certain cryogenic applications.

Beta Alloys

The β alloys are also called metastable β alloys. They contain one or more β stabilizers like Mo, V, or Cr in sufficient quantity to suppress the martensitic transformation that forms acicular alpha from within the retained beta[6]. Beta alloys contain significant alloying to retain the beta phase at room temperatures. These alloys are treatable to even higher strengths than Ti-6Al-4V[10]. In beta alloys thermomechanical processing affects not only the microstructure but also the decomposition of the metastable beta phase during the aging process. The increased dislocations after mechanical working of the beta alloys leads to heterogeneous nucleation of an equilibrium phase which can suppress formation of a crowded omega phase, though this phase is not normally seen in commercial production of titanium.

Alpha-Beta Alloys

Ti-6Al-4V is an α + β alloy and the subject of this project; the α + β alloys are the most commonly used titanium alloys. A representative microstructure can be seen in Figure 8. Microstructures of Ti-6Al-4V under three cooling rates and at four temperatures[6]. For this project (b), (f), and (j) are the expected microstructures when heat treated from below the beta-transus. They contain α and β stabilizers so that the alloys have a mixture of α and β at room temperature. These alloys can be strengthened by heat treatment. The heat treatment procedure involves heating to a solution-treating temperature, quenching, and then aging. At the solution-treating temperature, primary α and β are formed. Upon quenching from the solution-treating temperature metastable β may be retained, or the β may transform into α by nucleation and growth of acicular alpha within the beta region.

Of α + β alloys, Ti-6Al-4V is the most widely used. It has an excellent combination of strength, toughness, and corrosion resistance. Since this project involves Ti-6Al-4V, the remainder of this report will address Ti-6Al-4V specifically.

Titanium Stabilizers

For titanium alloys the main reason for alloying is to affect the α- and β-transus. Some elements stabilize the alpha crystal structure while others stabilize the beta structure. Table I lists some of the common alloying elements and their effect on the alpha and β-transus. The transus varies with the levels of impurities such as carbon, oxygen, nitrogen, and hydrogen.

Table I. Ranges and Effects of Some Alloying Elements Used in Titanium

Alloying element	Range (wt %)	Effect on structure
Aluminum	2.0 -7.0	alpha stabilizer
Tin	2.0 - 6.0	alpha stabilizer
Vanadium	2.0 - 20.0	beta stabilizer
Molybdenum	2.0 - 20.0	beta stabilizer
Chromium	2.0 - 12.0	beta stabilizer
Copper	2.0 - 6.0	beta stabilizer
Zirconium	2.0 - 8.0	alpha and beta stabilizer
Silicon	0.05 - 1.0	Improves creep resistance

Aluminum is the primary alpha stabilizer in titanium alloys. Other alloying elements that favor the alpha crystal structure and stabilize it by raising the alpha-beta transformation temperatures include gallium, germanium, carbon, oxygen, and nitrogen[8].

Carbon is a unique element to have in titanium. In high enough quantities it is considered to be an alpha stabilizer, while at low concentration it is considered to be an impurity. Carbon widens the temperature between the α-transus and the β-transus.

Ti-6Al-4V Microstructure

Ti-6Al-4V can be strengthened by heat treatment and aging. The heat treatment procedure involves heating to a solution-treating temperature (initial forging temperature), quenching and then aging. At the solution treating temperature, primary alpha and primary beta phases are formed. Based on different cooling rates, primary beta phase may transform into metastable beta phase, or it may produce a mixture of acicular alpha + beta phase structure.

In this project, alpha-beta forging is applied, which means the initial temperatures are lower than β-transus temperature. The alpha-beta forging allows both alpha and beta phases present to maintain a microstructure consisting of the two phases. Different initial temperatures and cooling rates provide different microstructures in the alloy sample (Figure 8.). As the cooling rate increases, the grain size decreases. It also predicts that holding the initial

temperature closer to the β-transus, more percentage of primary alpha phase contained in the sample.

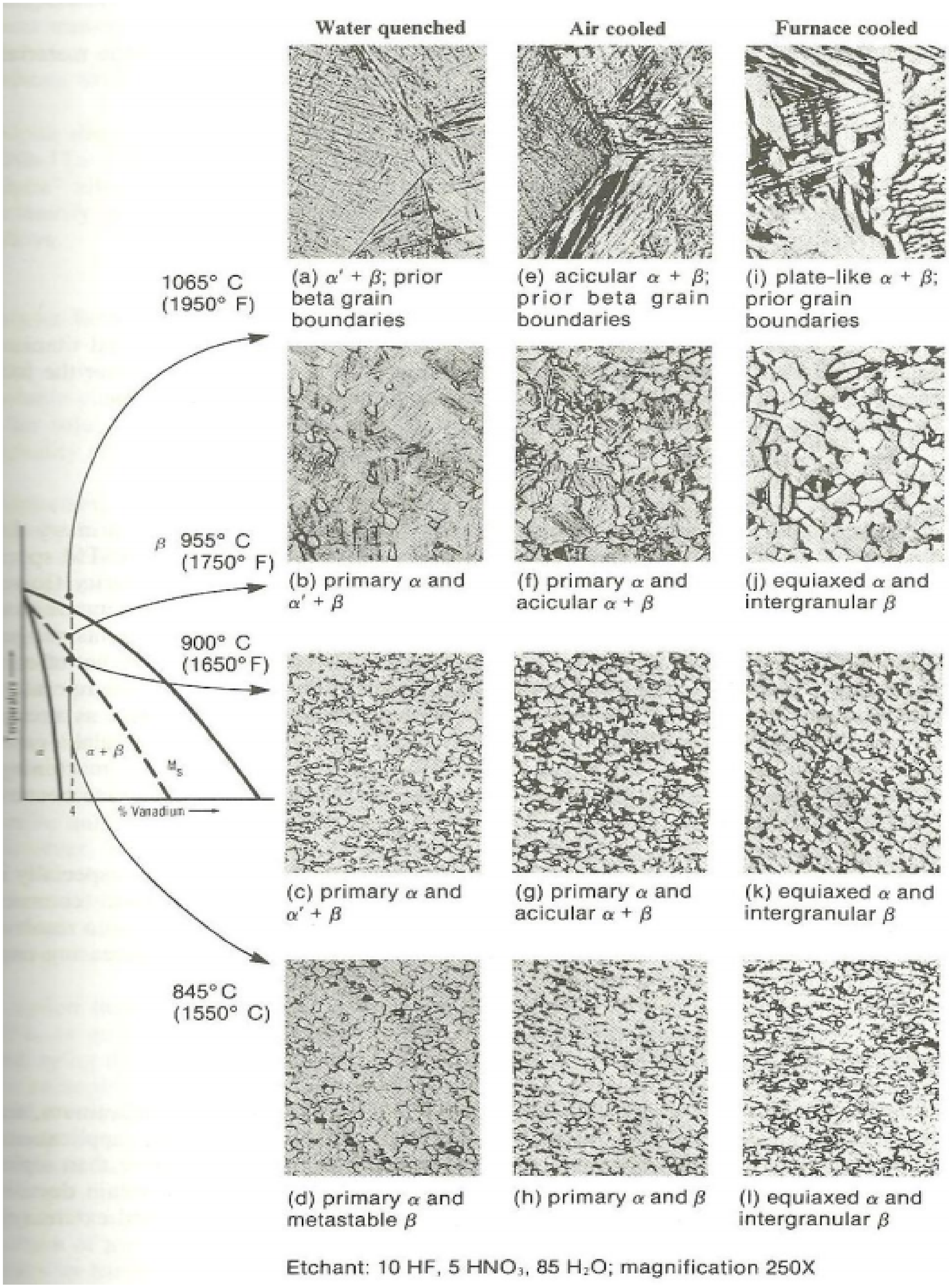

Figure 8. Microstructures of Ti-6Al-4V under three cooling rates and at four temperatures[6]. For this project (b), (f), and (j) are the expected microstructures when heat treated from below the beta-transus.

Titanium Forging

Titanium is unique in that all of the combined process variables readily affect the final microstructure. Microstructural control is basic to successfully process titanium alloys. Grain boundary alpha, beta fleck (solute rich regions), and elongated alpha can interfere with optimal property development. The titanium ingot structures can also carry over into the final product. There are several important factors in the processing of titanium and titanium alloys. The biggest four are: amounts of specific alloying elements and impurities; melting process used to make the ingot; method for mechanically working ingots into mill products; and the final step employed in working, fabrication, or heat treatment[8].

Primary Working

The purpose of primary hot working is to produce a uniform and fine two-phase microstructure of globular α in a matrix of α and β from cast ingots. This is accomplished by initial hot working and heat treatment in the single-phase β region followed by transformation of structure into equiaxed α + β by deformation below the β-transus.

Forging is a common wrought processing method for manufacturing titanium products and is typically conducted in the α + β region. Forging sequences and heat treatment can be used to control the microstructure and resulting properties. Knowledge of the β-transus is necessary for successful forging and heat treatment; the closer the forging is conducted to the β-transus, the more β is available to transform on cooling. The exact form of the globular α and transformed β structures produced by processing depends on the β-transus temperature.

Experimental Procedure

Safety

During this project a safety check-in was required every time before working in the lab. During the lab section, close-toed shoes, long pants, and safety goggles would remain on at all times. Since all of the samples were heat treated between 1725°F and 1800°F, gloves, thermally insulated aprons, face shields, and tongs were used to handle the hot samples. Kroll's reagent[i] and 2% Hydrofluoric acid (HF) were used in this project to etch heat-treated samples. All

[i] 5-7% Nitric acid, 2-4%Hydrofluoric acid, balanced water.

samples were etched under the hood with gloves, apron, and tongs. Hydrofluoric acid in an extremely dangerous etchant which can cause damage to skin and bones.

Sample Preparation

Two kinds of Ti-6Al-4V alloys with different carbon contents were supplied by Weber Metals, one was .007% C and the other .025% C (Table II). Both alloys were primary worked at the same condition. Both alloys were sectioned to twelve one-inch cubes for each alloy. A half-inch deep, 0.0625 diameter hole was drilled in 12 of the samples in order to use a high temperature thermocouple to measure the cooling rates.

Table II. Compositions of Two Kinds of Ti-6Al-4V Alloys

Alloys	Aluminum (Al)	Vanadium (V)	Iron (Fe)	Carbon (C)
Low Carbon	6.260%	4.230%	0.220%	0.007%
High Carbon	6.570%	4.280%	0.200%	0.025%

Heat Treatment

All of the samples were heat treated at 1725°F, 1750°F, 1775°F, and 1800°F for half an hour to solution treat the equilibrium alpha-beta phases. Three different cooling methods were applied to the samples, air cool, open furnace cool, and water quench shown in Figure 9. In order to measure the temperature of each sample, a k-type high temperature thermocouple connected to a data logger was required (Figure 10). The high temperature thermocouple was wrapped around the titanium samples (Figure 11), which ensured that the thermocouple measured the temperature at the center of each sample and prevented the thermocouple from falling out of the samples while transferring them in and out of the furnace. Water quenched samples were further heat treated at 900°F for thirty minutes, in order to observe the microstructure. Table III shows the design of experiment of this project. There is one sample was heat treated in each condition.

Table III. Design of Experiment

Cooling Method	Air Cool								Water Quench								Open Furnace Cool							
Temperature	1725		1750		1775		1800		1725		1750		1775		1800		1725		1750		1775		1800	
Carbon Content	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H

Figure 9. Basic setup of open furnace cool

Figure 10. High temperature thermocouple and data logger.

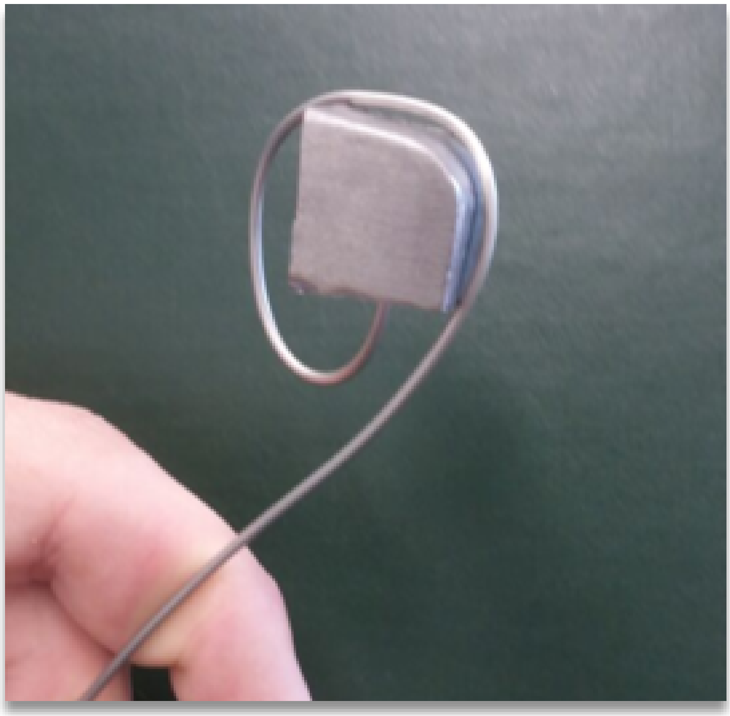

Figure 11. Thermocouple was installed inside of the sample and wrapped around the sample.

Quantitative Metallography

Weber Metals uses an image analysis process when they want a quick estimate of the composition of the microstructure and is used in conjunction with their lab technicians. Images of confirmed microstructural compositions were sent to us by Weber Metals and using those images we developed a method for analyzing the amount of alpha and beta phase present in our samples using Photoshop. This method was quick and effective at measuring the different phases and is a good alternative to the point count method, which entails overlaying a grid of 100 points over the image and determining how many lay on alpha or beta.

Heat-treated samples were sectioned across the center to avoid edge effects. After mounting all of the samples in Bakelite they were ground using abrasive paper with 240, 320, 400, 600 grits. Samples were polished through 6 micron diamond, 1 micron diamond and final polished with 0.05 micron alumina. Kroll's reagent was used to etch the samples, which is a standard etchant for use with alpha-beta Titanium alloys. To quantitatively analyze the samples, the software Photoshop was used. Four tiff images were taken around the center of each sample at 200x by optical microscope (Figure 12). Tiff images store better the pixel information than jpg images, which provides more accurate results when doing quantitative metallography analysis in

Photoshop. Images were set to be black and white first. This allows us to analyze the image of a grey scale ranging from 0-255, where 0 is black and 255 is white. Then the contrast was set to 100%. This is done in order to distinguish the difference between black and white more clearly, which provided a more accurate percentage of each phase. Lastly, in the level function, the white level was brought down so there was at least some pixels that were completely white. Then the black was used to help set the midtone. Since the midtone stays equidistant from the black and white levels the black level was used to move the midtone since beta needed to be brought out. By using the histogram we can select from the midtone and drag the cursor toward the black end of the histogram. Doing so makes the histogram act like an integral and counts the area, or number of pixels, under the curve. In the percentile region of the histogram it will display the percent of pixels selected, this is our percent beta. Subtracting this from 100 will give us the primary alpha formed.

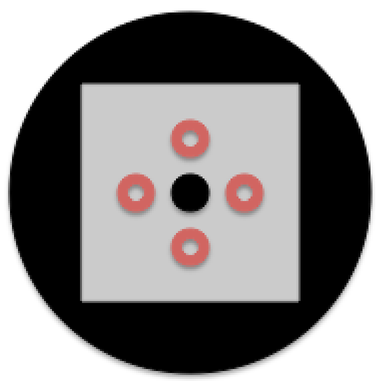

Figure 12. Four images were took around the center of each sample.

Results

Cooling Rates

Cooling rates for water-quenched samples seen in Figure 13 were step like nature. For the water quenched samples this meant some assumptions on how the curve would look if the data logger were able to sample faster and more accurately. The data logged seems to follow a log function similar to that of Figure 14 which is the curve for the furnace cooled samples and Figure 15 which is the curve for air cooled samples. An assumption was made here that the cooling rates all should look similar as the rate at which the samples cool is constantly changing throughout the cooling period. To get a specific cooling rate a secant line was drawn through the highest

temperature and 900°F. 900°F was chosen as the second point as that was the lowest heat treatment temperature found to be used in literature and where it is said that diffusion and microstructural changes stop taking place. Since both the air-cooled and furnace cooled data looks the same we can safely assume this. The final rates we calculated were 190.8°F/s, 8.50°F/s, and 1.3°F/s for the water quenched, air cooled, and furnace cooled samples respectively.

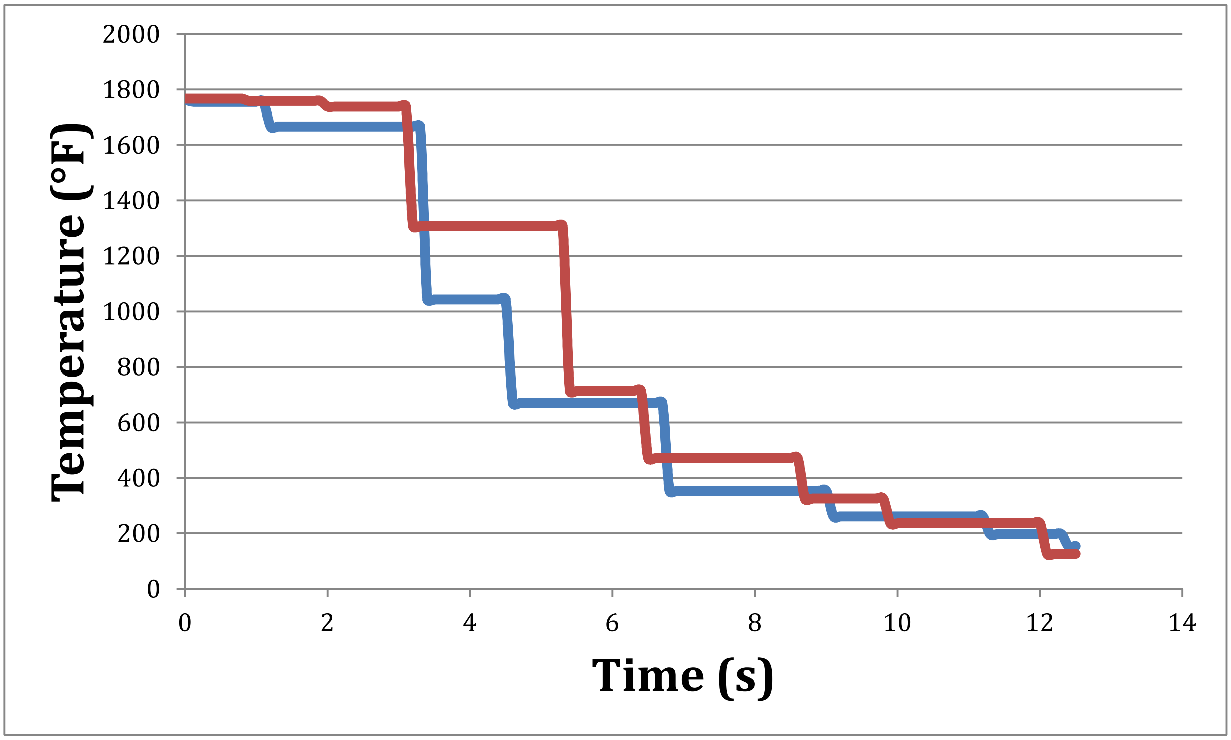

Figure 13. Graph of temperature versus time of the water quenched samples. The red line is a high carbon sample and the blue line is a low carbon sample.

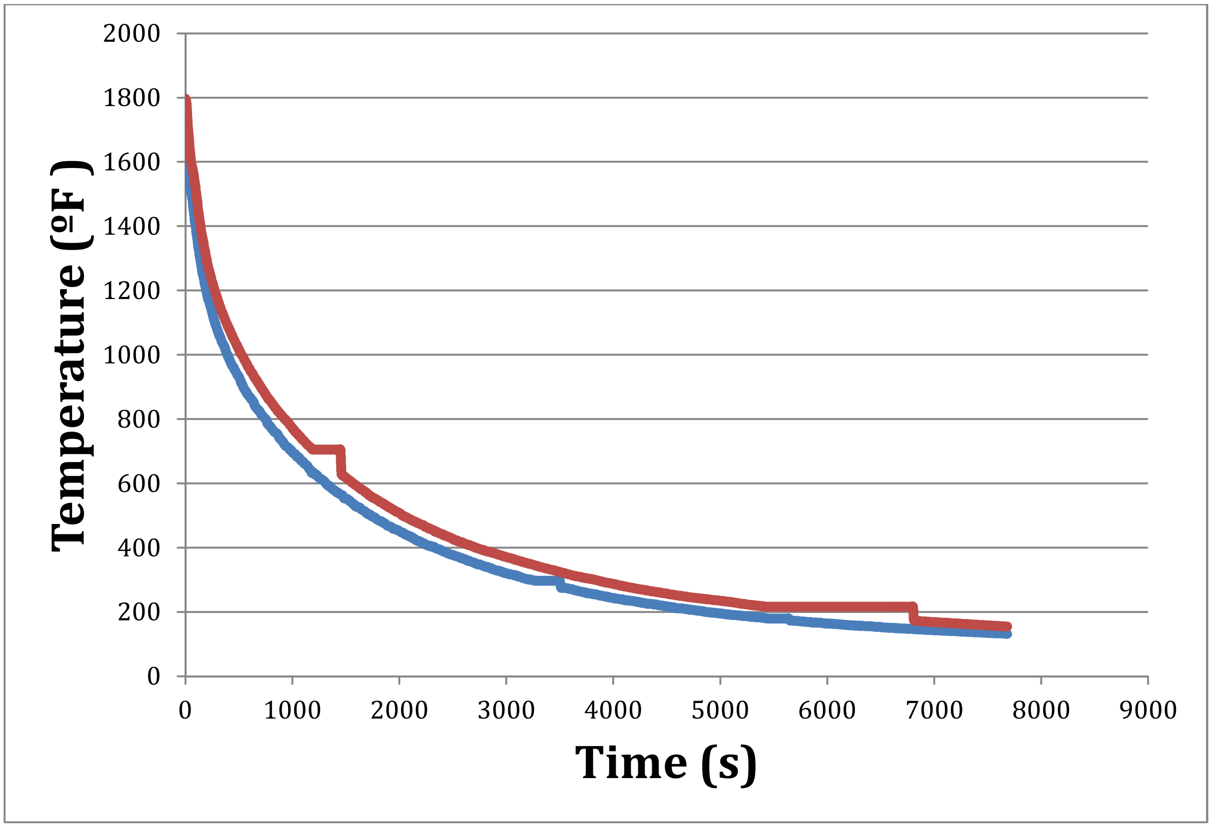

Figure 14. Graph of temperature versus time for furnace cooled samples. The blue line is a high carbon sample and the red line is a low carbon sample.

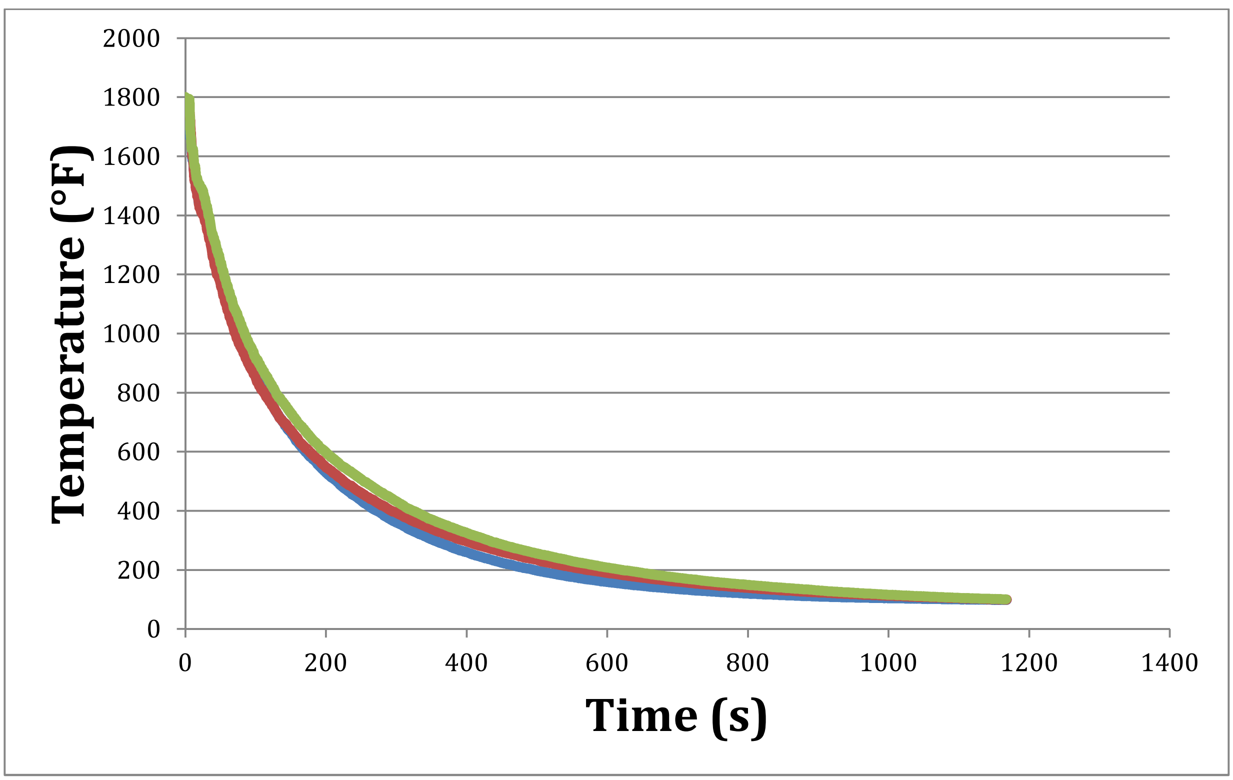

Figure 15. Graph of temperature versus time for air-cooled samples. The blue line is a 1750 F low carbon sample. The redline is a 1775 F high carbon sample. The green line is a 1800 F high carbon sample

Quantitative Metallography

Table IV is the raw data from Photoshop analysis, average values for alpha and beta are displayed along with their corresponding heat treatments. A one-way ANOVA (unstacked) with a confidence interval of 95% was run on the data for Carbon content, Cooling rate, and Initial forging temperature. Four images were taken per sample and using the same Photoshop method were averaged and a mean was found.

Carbon Content	Temperature	Cooling method	Average β%	α%
Low	1800	Air cooled	87.3	12.7
		Furnace cooled	69.8	30.2
		WQ+Temp	86.8	13.2
	1775	Air cooled	73.9	26.1
		Furnace cooled	75.5	24.5
		WQ+Temp	67.2	32.8
	1750	Air cooled	74	26
		Furnace cooled	62.2	37.8
		WQ+Temp	73.6	26.4
	1725	Air cooled	56.9	43.1
		Furnace cooled	48.7	51.3
		WQ+Temp	57.3	42.7
High	1800	Air cooled	74.3	25.7
		Furnace cooled	83.8	16.2
		WQ+Temp	64.5	35.5
	1775	Air cooled	79.1	20.9
		Furnace cooled	75.7	24.3
		WQ+Temp	68.3	31.7
	1750	Air cooled	69.2	30.9
		Furnace cooled	57.8	42.2
		WQ+Temp	72	28

Table IV. Raw Data of Photoshop Analysis

Carbon Contents

Carbon is an alpha stabilizer. So we would expect to find more alpha present in all samples with the high carbon designation compared to those with the low carbon designation. Figure 16 compares two microstructures that received the same cooling rate

and heat treatment. There is a slight decrease in alpha formation in the high carbon sample which is unusual, but when all images were processed and analyzed there was no difference in the means.

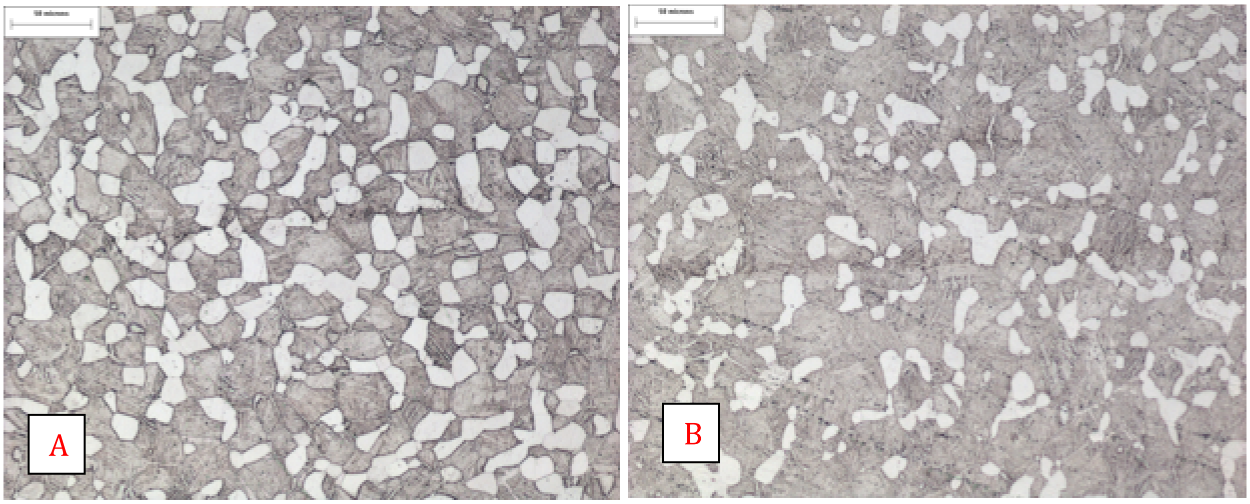

Figure 16. Microstructure of samples heat treated at 1775 F and air cooled. (a) Low carbon content, (b) High carbon content.

In Figure 17 it is shown that there is no statistically significant difference between the different Carbon contents. The group for each mean consisted of all samples with a high or low carbon designation. The assumption here is that the other two factors will effect each group equally. The mean primary alpha for the Low Carbon samples is 30.55% and the mean for the High Carbon samples is 32.16%. A p-value of .471 and with less than a 2% difference in the mean we do not reject the null hypothesis that carbon content does not affect primary alpha formation. We can conclude that there was no statistical difference between the two.

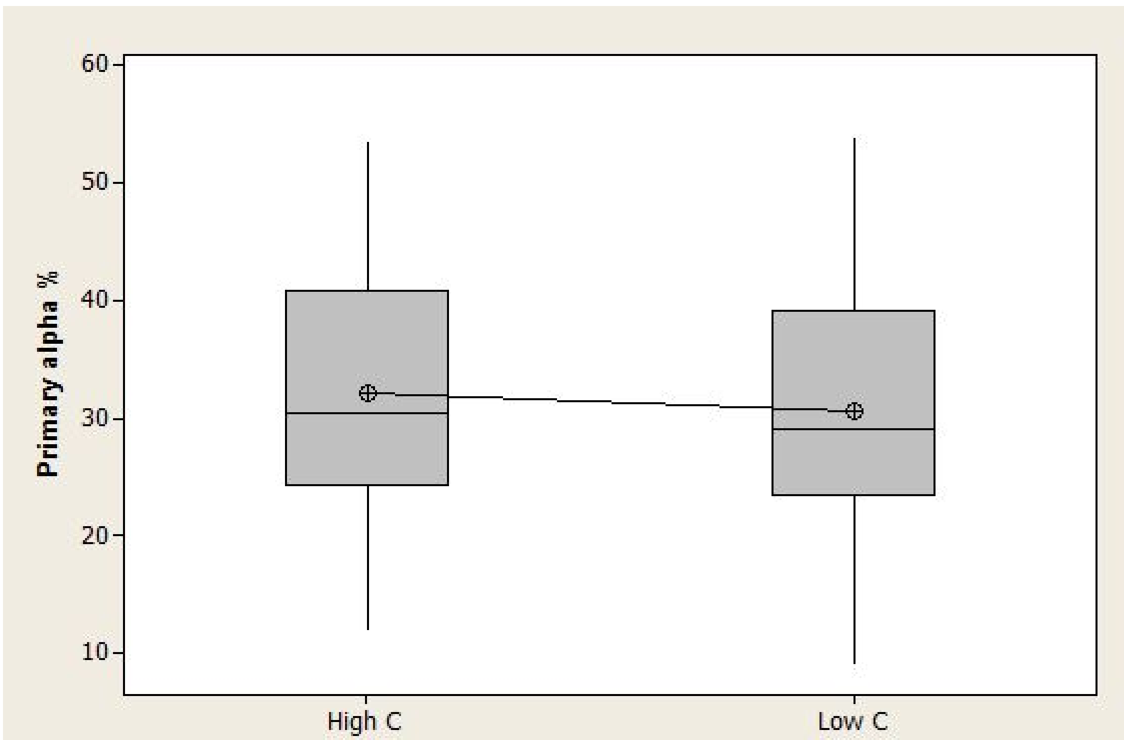

Figure 17. Boxplot of carbon content and primary alpha percentage. Plot was made in Minitab with a one-way ANOVA and 95% Confidence Interval.

Cooling Rates

Cooling rates can greatly affect how alpha and beta form in titanium. Figure 18 shows three microstructures that received a different cooling rate but the same heat treatment and have the same carbon content. In these images there does not seem to be much of a difference in how much primary has formed. All of the alpha globules are roughly the same size leading to the conclusion that the cooling rate has no effect on the

microstructure. This is somewhat true. The water quenched microstructure does not have a statistically different mean than the air cooled or furnace cooled. But, the air cooled and furnace cooled are statistically different from one another.

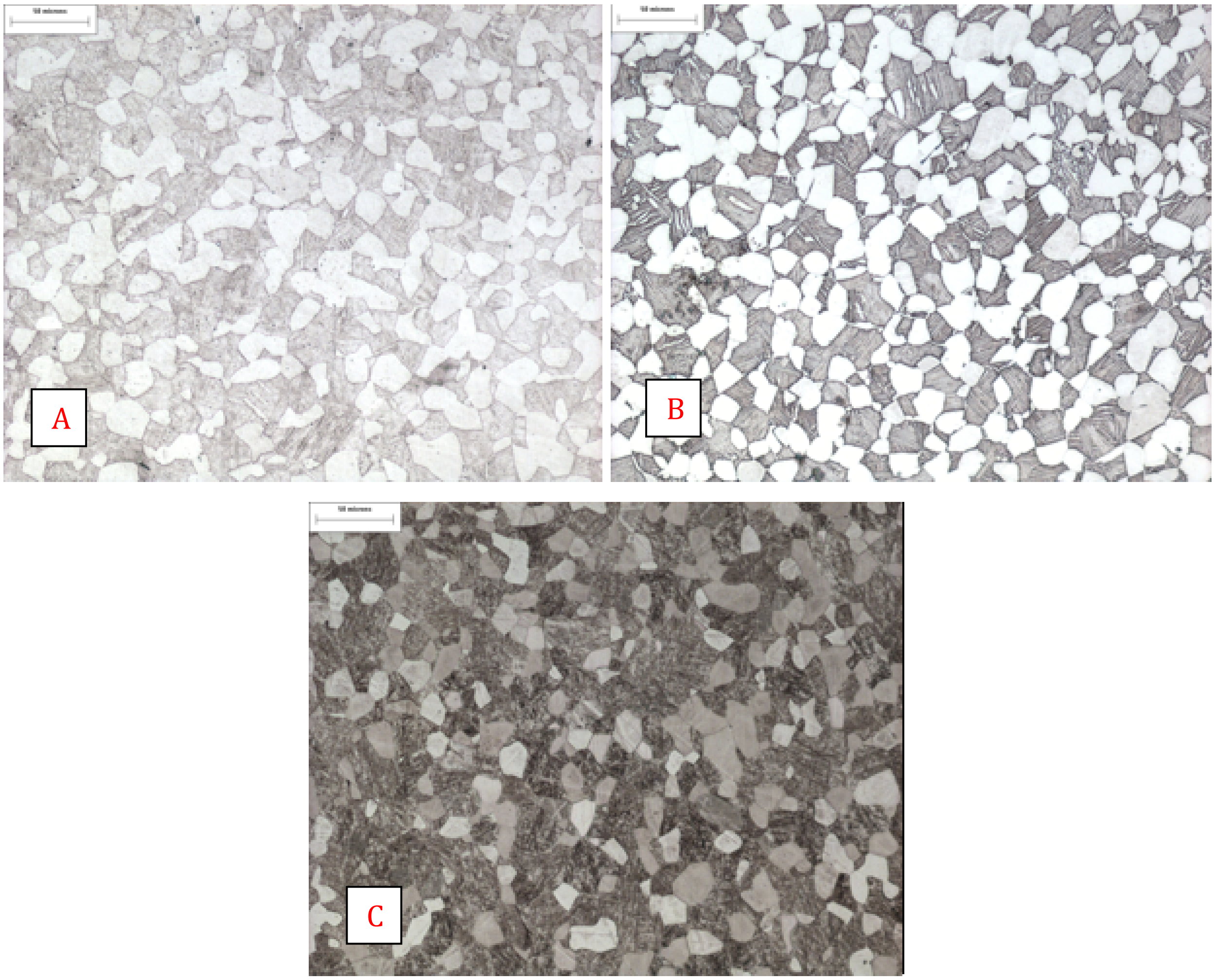

Figure 18. Microstructure of low carbon samples heat treated at 1775 F. (a) air cooled, (b) furnace cooled, (c) water quenched and tempered.

For the air cooled, furnace cooled, and water quenched samples the mean was 28.3%, 34.8%, and 31.0% primary alpha respectively as seen in Figure 19. The group for each mean consisted of all samples with an air cooled, furnace cooled, or water quenched designation. A p-value of .053 tells us that at least one of the means is statistically different. The difference in means is between air-cooling and furnace cooling but not water quenching and the other two. This is interesting as many sources say to water quench titanium before further heat treatments but we found no difference in our twenty-four samples[6].

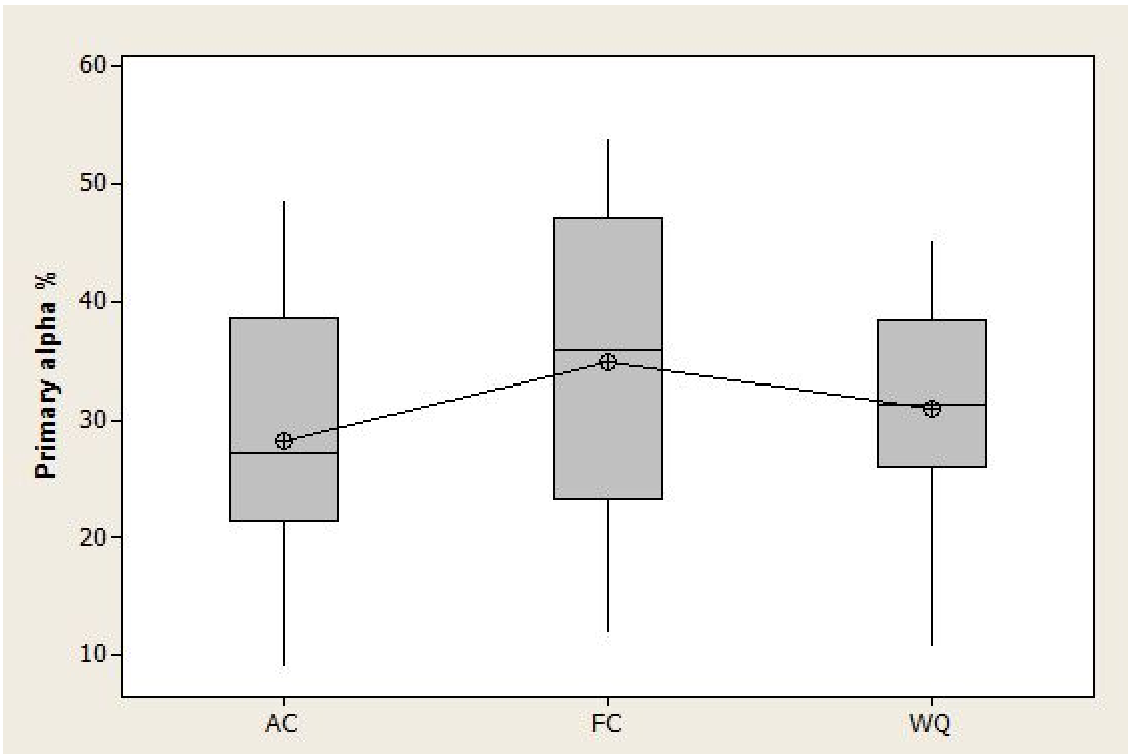

Figure 19: Boxplot of cooling rates and primary alpha percentage. Plot was made in Minitab with a one-way ANOVA and 95% Confidence Interval

Initial Forging Temperature

Temperature is another factor that can help produce great differences in the microstructure of titanium. Figure 20 shows four microstructures that received the same cooling rate and have the same carbon content but a different heat treatment. The trend in the reduction in alpha phase present is quite noticeable. The 1800 °F microstructure has small globules of alpha whereas the 1725 °F still has large globules. Across the board the higher temperatures have significantly less alpha compared to their lower temperature counterparts.

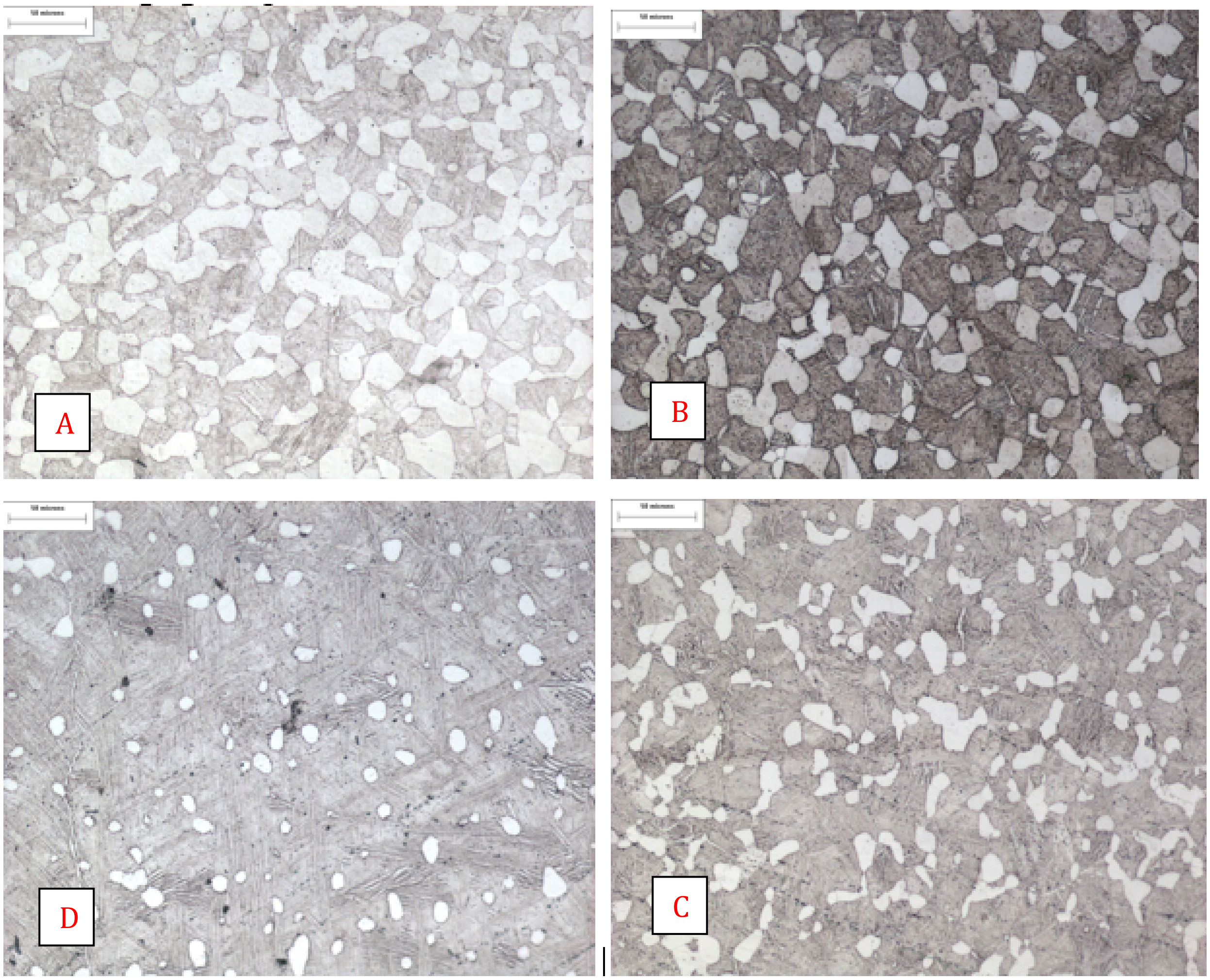

Figure 20. Microstructure of low carbon air cooled samples heat treated at (A) 1725 F, (B)1750 F, (C) 1775 F ,(D) 1800 F.

For the Initial forging temperature, otherwise known as the solutionizing temperature, there was a large difference in the means of the groups as seen in Figure 21. The 1725°F, 1750°F, 1775°F, and 1800°F groups had means of 44.6%, 31.9%, 26.7%, and 22.2% primary alpha respectively.

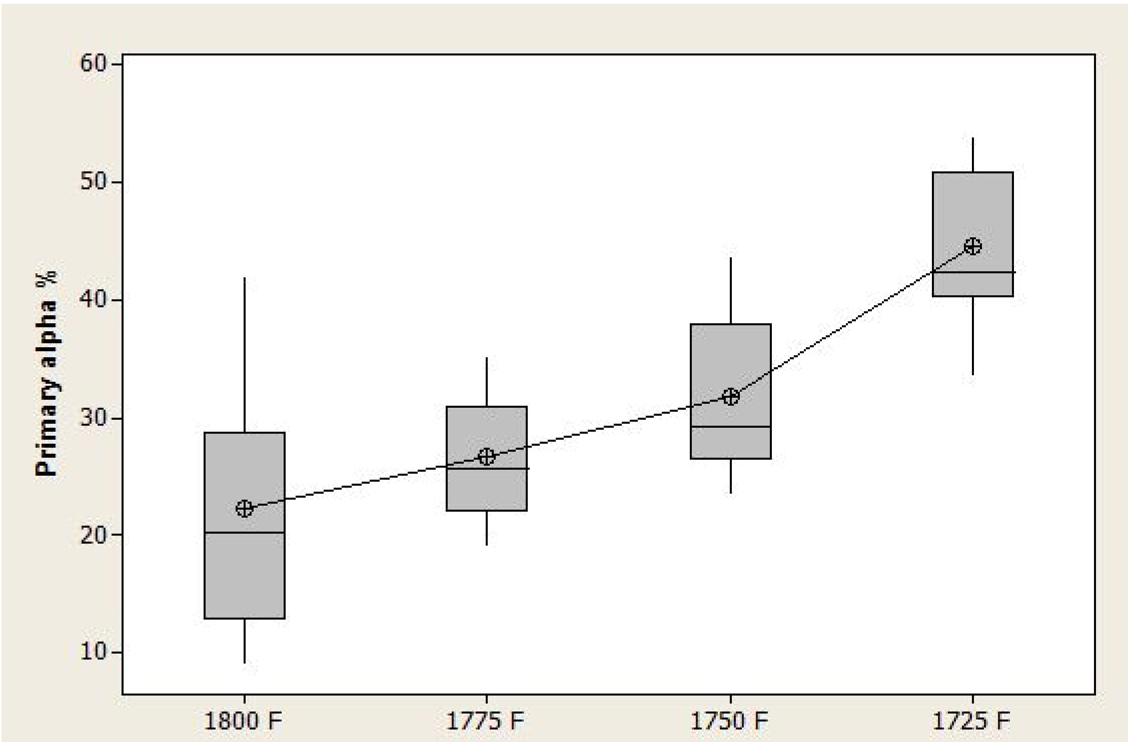

Figure 21: Boxplot of forging temperatures and primary alpha percentage. Plot was made in Minitab with a one-way ANOVA and 95% Confidence Interval

The group for each mean consisted of all samples with a 1725 ºF, 1750 ºF, 1775 ºF, or 1800 ºF designation. All of the boxplots show some variance but this is to be expected, as there was only one true sample for each specific carbon content, heat treatment, and forging temperature. This means that the more images we take the closer we will be to finding the composition of that sample but not the composition of other samples treated the same way. The variance was reduced by taking multiple images of the microstructure to gain a better understanding of the composition of each specific sample, but more than four images will lower the variance even more.

Discussion

Carbon Content

For this project we were mainly concerned with how carbon affects the primary alpha formation in the microstructure of Ti-6Al-4V. Being the most widely used titanium alloy, it is important to know how the composition of the forging will affect the final microstructure. Carbon is listed as an alpha stabilizer so it would seem that more carbon would result in higher amounts of primary alpha formation. The difference between the high and low carbon is .018%. This is the largest difference in carbon content that Weber Metals could easily produce. Even though the samples tested in this project had a large difference in carbon content there was no statistical difference that we could find. The two forgings had similar compositions of every other element other than carbon. Carbon could still be an alpha stabilizer but just not at these low percentages.

Cooling Rates

In processing titanium there can be many methods of cooling. Much of Weber Metals titanium is air cooled, but some is water quenched, and some is partially furnace cooled. Weber Metals wanted to know if how they cooled their titanium affected the final microstructure they would eventually send out to customers. We can say that air-cooling gave statistically lower primary alpha versus furnace cooling. This is good as doing furnace cooling is inefficient and costs extra time and money for little to no benefit. More testing would need to be done to compare water quenching versus air-cooling and when analyzed in Minitab they were both in the same group, though their means were different by about 3%. Further testing could reveal if that is significant or not.

Initial Forging Temperature

What we were calling the initial forging temperature was really the solutionizing temperature. The beta transus temperature for the low and high carbon forgings was 1825 ºF and 1850 ºF respectively. This was the factor in our test that made the largest difference in the microstructure. We consistently found that the higher the temperature heat treatments had more beta phase present and less primary alpha phase present. Looking at the phase diagram for Ti-6Al-4V in Figure 2 this makes sense. When heating the samples for solutionizing they would sit in the alpha-beta region on the phase diagram. The closer to the beta transus you get the more beta phase you will form when you cool your sample. Up to 22% more beta phase formed in the

1800 ºF samples versus the 1725 ºF samples. Titanium is sensitive to drastic changes in cooling rates. Since all the samples had fairly stable cooling curves beta formed preferentially because of the higher temperature.

Conclusions

1. The carbon content of these two forgings, .007%, and .025% is not enough to see any statistically significant change in primary alpha formation in the titanium samples we prepared.
2. The cooling rates did not make a large difference, only a 6% increase, in the amount of primary alpha formed.
3. Solutionizing closer to the β-transus significantly changes the way the final microstructure will form.

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