Effects of Beta Stabilizers on Quench Delay Susceptibility of Ti-6Al-4V

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Abstract

Tensile samples of Titanium 6Al-4V (Ti-6Al-4V) were machined from forgings containing rich and poor amounts of beta stabilizers in their compositions. The tensile samples were each heat treated two times. In the first round of heat treatments, the samples were either beta solution treated (BST), or solution treated (ST). Each sample was water quenched with varying quench delays of 10, 20, and 30 seconds. BST treated specimens were then overaged at 1350°F for 2 hours and air cooled (BSTOA); while the ST treated samples were aged at 990°F for 6 hours and air cooled (STA). Following heat treating, the tensile samples were chemically milled to remove the alpha case layer from the surface, and then tensile tested using an Instron Tensile Testing System. Beta stabilizer rich bars that were BSTOA treated with a quench delay of 10 seconds resulted in an average ultimate tensile strength (UTS) of 154 ksi, and average yield strength (YS) of 144 ksi. Beta stabilizer poor, BSTOA treated bars with the same quench delay of 10 seconds, resulted in similar average UTS and YS values of 155 and 145, respectively. Increasing quench delays of BSTOA treated bars to 30 seconds did not alter the resulting average mechanical properties. The beta stabilizer rich bars that were STA treated with a 10 second quench delay resulted in average UTS of 167 ksi and average YS of 154 ksi. Mechanical properties were slightly lowered for beta stabilizer poor, STA treated bars with 10 second quench delays; resulting in average UTS of 166 ksi and YS of 152 ksi. Average properties of both beta rich and beta poor samples that underwent STA heat treatments dropped when the quench delays were 30 seconds.

Key Words

Alpha Case, Alpha Phase, Alpha Stabilizer, Beta Phase, Beta Solutionizing, Beta Stabilizer, Beta Transus, Forging, Solution Treating, Materials Engineering, Thermo-mechanical Processing, Quench Delay, Quench Delay Susceptibility.

Important Terms

- **Alpha Case:** Surface layer of alpha phase formed on titanium alloys from the diffusion of oxygen at elevated temperatures.
- **Alpha Phase:** hexagonal close packed phase of titanium alloys.
- **Alpha Stabilizer:** Alloying element that raises the beta transus temperature by stabilizing the alpha phase at higher temperatures (Al, O, N, C, Ga, Ge, La, and Ce).
- **Beta Phase:** Body centered cubic phase of titanium alloys.
- **Beta Solution Treating:** Heat treating titanium alloys above the beta transus temperature.
- **Beta Stabilizer:** Alloying element that lowers the beta transus temperature by stabilizing the beta phase at lower temperatures (Fe, V, Cr, Si, Mo, Nb, Re, Ta).
- **Beta Transus:** Transition temperature of titanium from which the alloy goes from the alpha phase to the beta phase.
- **Isomorphous Beta Stabilizer:** Beta stabilizer that lowers the beta tranus with increasing concentration and is completely soluble in the beta phase (V, Mo, Nb, Re, and Ta).
- **Eutectoid Beta Stabilizer:** Beta stabilizer that forms eutectoid systems with increasing concentration (Fe, Cr, and Si).
- **Forging:** Mechanical shaping processes that uses localized compressive forces.
- **Solution Treating:** Heat treating below the beta transus temperature in the alpha-beta phase; this is the first step in age hardening heat treatments.
- **Thermo-mechanical Processing:** Process of mechanically deforming metals that utilizes both work hardening and heat treating.
- **Quench Delay:** Time elapsed between solution treating and quenching of a metal.
- **Quench Delay Susceptibility:** Extent of mechanical property loss due to extended quench delays.

Introduction

Weber Metals, Inc. (Paramount, CA) is an aluminum and titanium forging company that produces high quality products for commercial and military aerospace applications. Other applications of products produced at Weber Metals include space programs, jet engine components, and parts for the electronics and semiconductor industry.[1] Equipped with more than ten forging presses, including the 4th largest press in the nation, Weber Metals is capable of forging a large range of metal alloys from readily forged aluminum alloys to titanium alloys, which are among the most difficult engineering alloys to forge. A photograph of a titanium component produced by Weber Metals is shown in **Figure 1.**

Figure 1: Photograph of a titanium component produced at Weber Metals, Inc.[1]

During the production process, the alloys are subjected to various forging techniques and heat treatments that force the stock material to the desired shape and then reduce the residual stress that develops within the material. The microstructures of the resulting forgings depend greatly on the amount of work put into the alloys, forging process parameters, and the thermo-mechanical processing (TMP) techniques used during production. Using their extensive knowledge of aluminum and titanium alloys, the metallurgists at Weber Metals can tailor the mechanical properties of the alloys to the desired specifications of the components or applications.

The most widely used titanium alloy is Ti-6Al-4V due to its high strength-to-weight ratio and excellent corrosion resistance, which offers the best overall performance among titanium alloys for aerospace applications[2]. A significant problem that Weber Metals experiences daily while forging Ti-6Al-4V is a loss in mechanical properties due to quench delays that exceed 10 seconds after forging is complete. This project hopes to address this problem and increase the minimum quench delay time after forging by varying the amounts of beta stabilizers within the alloy and measuring the resulting mechanical properties.

Allotropic Phases

Titanium is an allotropic element that exists in two distinct phases: the hexagonal close-packed (HCP) alpha phase, and the body-centered cubic (BCC) beta phase. In general, titanium alloys exhibit the alpha phase at low temperatures. The alpha phase is the most difficult to deform and therefore is not generally encouraged during forging. At elevated temperatures, above about 900°C (1650°F), the beta phase is present and is much easier to deform. The temperature at which a particular titanium alloy completely transforms from the alpha to beta phase is known as the beta transus.[2] The beta transus is an important parameter for the forging process as many TMP procedures are done relative to its value. When alloying titanium with aluminum, intermetallic compounds such as Ti_3Al and TiAl can form and are known as titanium aluminides, which maintain ordered HCP and tetragonal crystal structures, respectively. **Figure 2** shows the titanium-aluminum phase diagram; with increasing aluminum content the beta transus increases.

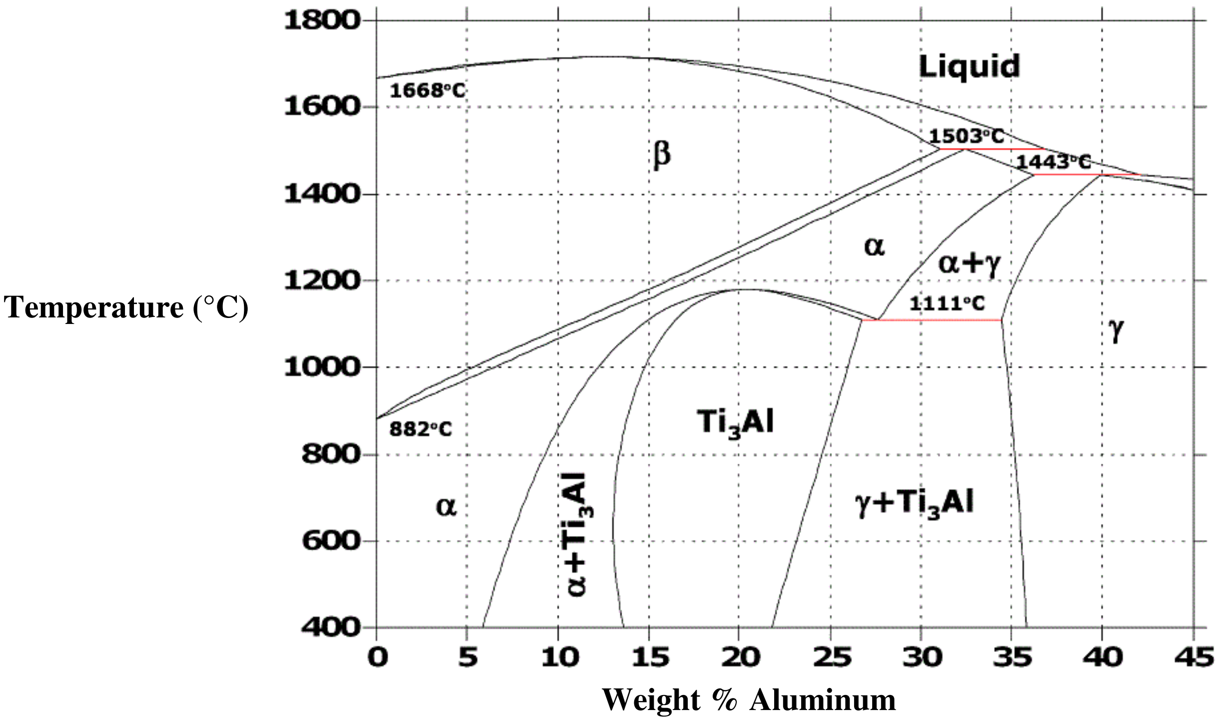

Figure 2: The Titanium-Aluminum phase diagram.[3] The beta transus temperatures increases with the addition of the alpha stabilizer aluminum.

Other alloying elements such as oxygen, nitrogen, iron, and vanadium can stabilize either the alpha or beta phase of the material. Alpha stabilizers which include aluminum, oxygen, nitrogen, carbon, gallium, germanium, lanthanum, and cerium act to stabilize the alpha phase; that is, they raise the beta transus temperature of the alloy so that the alpha phase is stable at higher temperatures. Beta stabilizers, which lower the beta transus temperature by making the beta phase stable at lower temperatures, are divided into two sub-categories: isomorphous and eutectoid beta stabilizers. Isomorphous beta stabilizers consist of vanadium, molybdenum, niobium, tantalum, and rhenium, all of which are entirely soluble in the beta phase. Eutectoid beta stabilizers such as iron, chromium, and silicon form eutectoid systems with titanium.[3] If enough concentration of these elements is added to the matrix of a titanium alloy, the beta transus can be lowered to room temperature. Tin and zirconium are considered neutral because

when present in titanium alloys they neither raise nor lower the beta transus. The effects of the addition of different alpha and beta stabilizers on the beta transus temperature is shown in **Figure 3** by four phase diagrams.

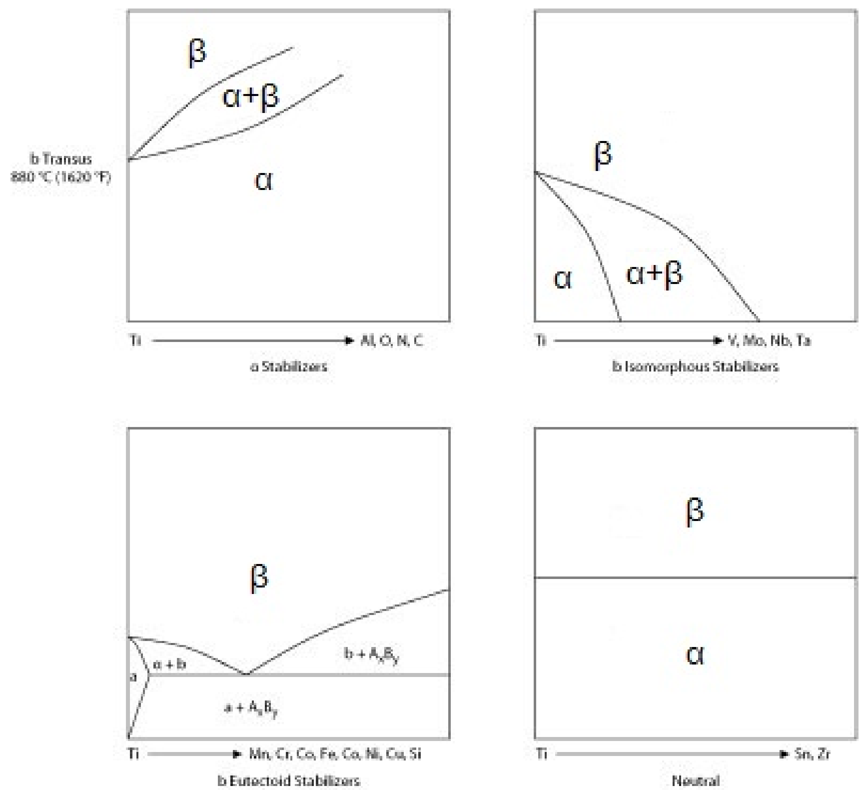

Figure 3: Effects on the beta transus temperature of titanium alloys with the addition of alpha and beta stabilizers.[4]

Referring to **Figure 3**, the top left phase diagram shows an increase in the beta transus with the addition of alpha stabilizers. The top right phase diagram shows a decrease in the beta transus with increasing concentration of isomorphous beta stabilizers. In the bottom left, an observable eutectoid system is developed with increasing eutectoid beta stabilizers. Finally, in the bottom right, the beta transus is not affected by the addition of neutral tin and zirconium.[4]

Titanium Alloy Classes

Titanium alloys are divided into three main groups based on the allotropic phases present at room temperature. The first group is the Alpha/Near-Alpha alloys that contain high levels of alpha stabilizers to maintain the HCP alpha phase at elevated temperatures. These alloys are the most difficult titanium alloys to forge and have moderate strength because of the high percentage of alpha phase in the material; however, they do perform well at elevated temperatures. Alpha-Beta alloys, which include Ti-6Al-4V, are the most widely used titanium alloys. They contain high amounts of beta stabilizers so that some of the BCC beta phase is stable at room temperature. By having both alpha and beta phases present, they are generally more readily forged than alpha alloys and have intermediate to high strength, as well as good fracture toughness[2]. The third class of titanium alloys is Beta/Metastable Beta alloys. These alloys contain high amounts of beta stabilizers that cause the majority of the material to be in the beta phase at room temperature. Generally, Beta/Metastable Beta alloys are the easiest to forge among titanium alloy classes and are known to have high strength, good fracture toughness, and excellent fatigue properties[2]. For each alloy class, the desired mechanical properties can be optimized using specially design forging and TMP techniques.

Forging

Forging is a metal shaping process in which localized compressive forces are utilized to achieve a desired form. Although titanium alloys are much more difficult to forge than other non-ferrous alloys such as aluminum alloys, they can be forged using all of the forging methods currently available. Open-die or hand forging and closed-die forging are the two main forging methods used at Weber Metals to produce titanium components. Selection of the forging

technique is determined by the desired final shape and resulting microstructure of the forging. In many cases more than one type of forging is utilized to finalize the product. Open die forging is more commonly used to produce small quantities of preform shapes while closed die forging is used to produce large quantities of high tolerance, precision forgings. A photograph of a closed die forge press is shown in **Figure 4.**

Figure 4: Photograph of a closed die forge press located at Weber Metals, Inc.[1]

Forging processes are characterized by the temperature at which the metal is being forged. The more general characterizations include hot and cold forging; however for titanium alloys, the forging processes can be characterized by the phases that are present at the forging temperatures. For instance, the temperatures during beta-forging exceed the beta transus while the metal is being worked and are achieved by leaving the stock metals in a large furnace until the center of the stock is up to temperature. During alpha-beta forging, the temperature of the part is just below the beta transus, but not low enough for the alloy to be completely in the alpha phase. The

higher the temperature, the less force is required by the press for forging. For this reason beta-forging is normally the easiest and most desired forging process.

It is also important to note the effects of the die temperature as well as the effects of deformation rates when forging. Dies used while forging titanium must be pre-heated with natural gas flames to facilitate the forging process and reduce the amount of temperature loss in the worked metal.[2] Titanium alloys are highly sensitive to strain at rapid rates, for this reason ensuring that deformation rates are slow is important. This reduces the stress that develops within the metal and reduces the likelihood of splintering the forging. However, in many cases the effects of temperature loss while forging are more apparent and damaging than elevated strain rates. Because of this, many forging companies, including Weber Metals, utilize moderate deformation rates while forging titanium alloys to balance out the effects of both occurrences.

Ti-6Al-4V

The alloy used in this project is Ti-6Al-4V because it is the most widely used titanium alloy and is also the most commonly used alloy by Weber Metals. It is composed of a titanium matrix alloyed with 6 weight percent aluminum and 4 weight percent vanadium, along with other beta and alpha stabilizers. Applications of the alloy include aerospace components (airframes, engine casings, landing gear), and medical implants such as heart valves and bone replacements. The alloy is characterized by high strength, low weight, and excellent fracture toughness which makes it well suited for aircraft components that strive to reduce weight. The unique resistance to corrosion displayed by Ti-6Al-4V and its high strength-to-weight ratio also gives it an advantage over other materials as medical implants. Titanium alloys readily create a stable layer of TiO_2 that passivates the metal, and protects it from corrosion from oxygen-rich environments such as aqueous solutions or blood from the human body. Ti-6Al-4V is classified as an Alpha-

Beta alloy because it contains both the alpha and beta phases at room temperature. A representative microstructure of Ti-6Al-4V taken at 200x magnification is shown in **Figure 5.** The lighter colored grains are the alpha phase while the dark colored grains are the beta phase of the material.

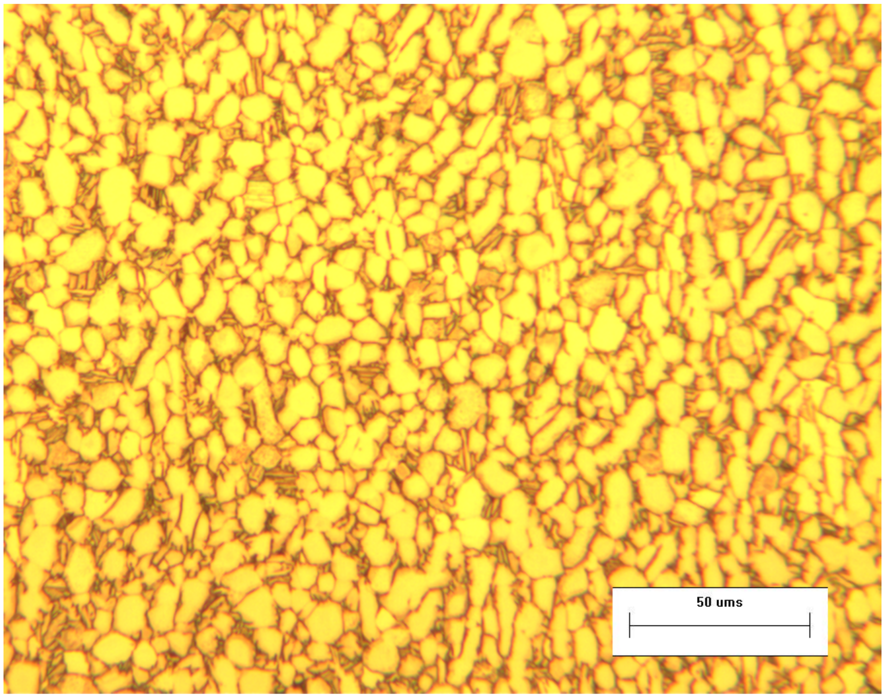

Figure 5: Representative microstructure of Ti-6Al-4V taken at 200x magnification. The lighter colored grains are the alpha phase while the darker colored grains are the beta phase of the material. For clarity, the sample was etched using Kroll's Reagent.

Because of the portions of beta phase that are stable at room temperature, the alloy is more easily forged than pure titanium and alpha alloys; this is important for shaping processes as they require much less load from the forging equipment which reduces cost by conserving time and energy. Ti-6Al-4V has a large solubility range of beta stabilizers; alloys with high concentrations are considered beta stabilizer rich while alloys with low concentrations are deemed beta stabilizer poor. This project hopes to reduce the effects of quench delay by varying the amounts of beta stabilizers in Ti-6Al-4V from poor to rich concentrations while holding the forging process constant and testing the resulting mechanical properties.

Realistic Constraints[5]

The project has two realistic constraint categories that it most adequately addresses: economics, and manufacturability. The main focus of the project is to reduce the amounts of parts that are scrapped because of mechanical properties that fall below specifications. The failed mechanical properties are due to extended quench delays of Ti-6Al-4V forgings, in which the loss of internal heat in the metal changes the microstructure. By reducing the amounts of scrapped parts the company, Weber Metals, will save money in both material and capital costs such as power usage and labor hours.

To do this, the alloys quench delay susceptibility will be improved by running a design of experiment that tests mechanical properties of tensile bars that contain different beta stabilizer concentrations and quench delay times after heat treating. The theory of the experiment is that with increased beta stabilizer concentration, the forgings will be able to maintain the desired phase longer, thereby improving the quench delay susceptibility.

Experimental Procedure

The design of the experiment (DOE) included three factors: relative beta stabilizer concentration (rich and poor), heat treatment (BSTOA and STA), and quench delay time (10, 20, and 30 seconds). Each of the twelve sections of the DOE was repeated four times, totaling 48 samples. To begin, two billet sources of stock Ti-6Al-4V needed to be found at the maximum and minimum solubility of beta stabilizers for the particular alloy. This proved to be a challenge for Weber Metals because the majority of the Ti-6Al-4V stock material available to the company contains the same composition of alpha and beta stabilizers. For this reason, two billets of stock

material that are only relatively different in beta stabilizer content were chosen. The alloy compositions of the relatively beta stabilizer rich and poor billets are shown in **Table I**.

Table I: Billet Material Compositions (weight %)

Beta Stabilizer Content	Al	V	Fe	C	N	O
Rich	6.42	4.27	0.24	0.025	0.01	0.19
Poor	6.56	4.00	0.16	0.016	0.009	0.19

The beta transus of each Ti-6Al-4V billet material was determined using light optical microscopy (LOM), which is the one of the most accurate methods to determine the beta transus temperature; therefore, these values were used for determining heat treating temperatures. The beta transus temperatures of the beta rich and the beta poor heats was 1815°F and 1795°F, respectively. Interestingly, the resulting beta transus temperatures show that the beta rich heat has a higher beta transus than the beta poor heat. This contradicts the expected trend in which the beta rich heat has the lowest beta transus temperature; however, there is some uncertainty in these temperature values. There are multiple ways of determining the beta transus of titanium alloys, all of which will most likely result in different values. The most accurate method of determining the beta transus temperature is by metallographically observing the phases present after heat treating and quenching; however, this can be time consuming and in many cases is relatively subjective. That being said, the purpose of this experiment is not to study the effects of beta transus temperatures on quench delay susceptibility; rather, this experiment intends to study the effects of beta stabilizers on quench delay susceptibility of Ti-6Al-4V.

Once the stock materials were identified, they were forged to simulate a typical forging that would occur at Weber Metals. From each of the forgings, 24 round tensile bars were turned on computer numerical control (CNC) lathe, totaling 48 bars. Each of the bars was labeled on the ends of the threads for traceability purposes. The gage lengths of the tensile bars were 0.250 inches in diameter and about 2.3 inches long; the threaded ends of the bars used a 9/16 inch x 12 thread. An image of a machined tensile bar is shown in **Figure 6**.

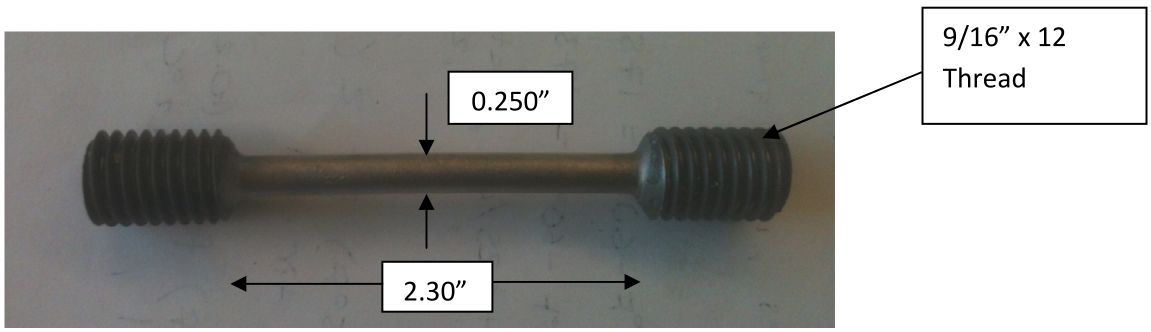

Figure 6: Photograph of one of the many round tensile bars machined from the Ti-6Al-4V forgings.

Heat Treating

Once machining the tensile bars was completed, heat treating in a high temperature furnace began. The two sets of 24 bars from both the beta rich and poor forgings were split into groups of 12. Each bar was then heat treated in two rounds. In the first round of heat treatments, 12 of the bars from each composition were beta solution treated (BST), and the remaining 12 were solution treated (ST). Because of the differing beta transus temperatures between beta rich and poor heats, the heat treating temperatures of BST and ST treated bars were different. Beta rich bars were BST treated at 1890°F for 30 minutes while the beta poor bars were done at 1870°F. As for ST treatments, beta rich heats were done at 1755°F for one hour while beta poor heats only were exposed to 1735°F. Following heat treating, the bars were water quenched at varying

quench delays. The heat treating instructions are shown in **Table II**. Within each of the four groups of 12 bars, three smaller groups of 4 bars were quench delayed 10, 20, and 30 seconds each. In the second round, BST treated bars were then overaged at 1350°F for 2 hours and air cooled (BSTOA); while the ST treated bars were aged at 990°F for 6 hours and air cooled (STA).

Table II: Heat Treating Instructions

Heat Treatment Designation	**Heat Treatment Steps**
BSTOA	1) Beta Solution Treat at Beta Transus plus 75°F (±15°F) for 30 (+5/-0) minutes, water quench after specified delay (holding in air) 2) Overage at 1350°F (±25°F) for 2 (+.25/-0) hours, air cool
STA	1) Solution Treat at Beta Transus minus 60°F (±15°F) for 1 (+.25/-0) hour, water quench after specified delay (holding in air) 2) Age at 990°F (±10°F) for 6 (+.25/-0) hours, air cool

During heat treating, a section of the DOE was ruined by the overheating of the high temperature furnace. More specifically, the four beta stabilizer rich bars that were BSTOA treated and quench delayed 20 seconds were exposed to temperatures as high as 1960°F when they were only intended to be at 1890°F. The Hall-Petch relationship indicates that the four samples that were overheated in the furnace will likely be affected by grain growth. In titanium, increasing the grain size dramatically drops the hardness of the material, as well as the yield strength.[6]

Alpha Case Layer

Titanium has a great affinity for oxygen and will absorb oxygen in the atmosphere at elevated temperatures. Because the furnace was open to the atmosphere, a high concentration of oxygen was present within the furnace. When alloyed with titanium, oxygen is an alpha stabilizer that raises the beta transus temperature. During heat treating, diffusion of oxygen from the atmosphere of the furnace into the surface of all the tensile samples caused an alpha case layer to develop on the surface of the bars. Alpha case is a low ductility phase of titanium and causes brittle failure of the bars during tensile testing. For this reason, the alpha case layer needed to be removed by chemical milling. A cross sectional image of a Ti-6Al-4V microstructure with an alpha case layer present after BSTOA treating is shown in **Figure 7.** The alpha case layer, shown by white grains, covers the entire outer surface of the cross section and is slightly over 200 microns in depth.

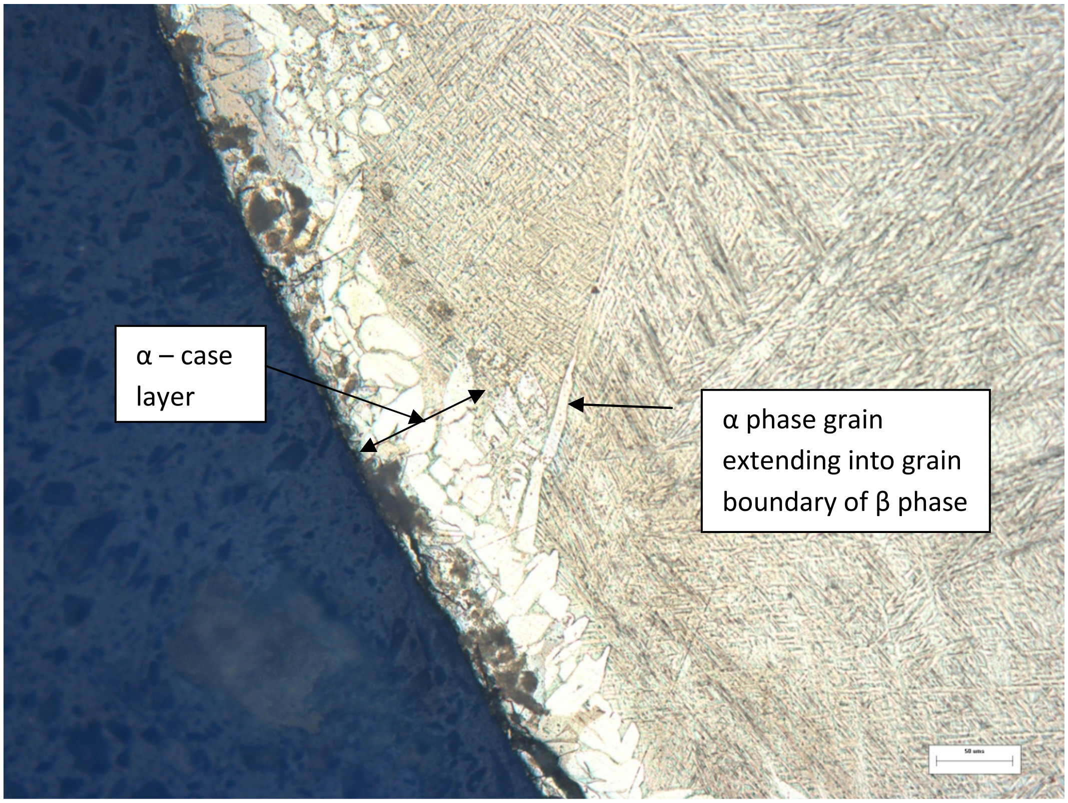

Figure 7: Microstructure of a BSTOA treated sample of Ti-6Al-4V that contains an alpha case layer shown by white alpha grains. Note the alpha case grain that extends into the grain boundaries of the beta phase creating a brittle failure zone.

We can also see an example of the brittle failure zone in the microstructure of **Figure 7** by a particular alpha grain that extends into the grain boundary of the beta phase. If the bar were to break at the location of this alpha grain, the fracture would propagate through the entire cross section and result in brittle failure with much less ductility than expected. This problem was avoided by sending the tensile bars back to Weber Metals for chemical milling. Three thousandths of an inch was removed from the surface of the gage lengths of the bars to completely remove the alpha case layer; totaling six thousandths of an inch taken from the diameter of the gages. The threads of the bars were protected from the chemicals by dipping them in a thermoplastic resin which is liquid at room temperature (known as Plasti-Dip) and allowing it to set on the threads. When the bars returned from Weber Metals, the Plasti-Dip was

removed, and the bars were tensile tested using an Instron Tensile Testing system. The Inston Tensile Testing system, model number 3369, contains an 11000 lb capacity load cell. The strain rate of each tensile sample was 0.10 in/min up until 1% elongation; once 1% elongation was reached, the extensometer was removed and the strain rate increased to 0.5 in/min till fracture. Yield strength, ultimate tensile strength and elongation % were recorded for each tensile sample.

Results

The four beta stabilizer rich tensile samples that were BSTOA treated and quench delayed 20 seconds were exposed to temperatures as high as 1960°F for 30 minutes, when they were only intended to be at 1890°F. According to the Hall-Petch relation, the overheating caused grain growth within the bars that will significantly reduce the yield strengths of those samples. For this reason, this section of the DOE was removed from the experiment. The loss of this section is not a big concern because the extremes of quench delays of beta rich samples that were BSTOA treated were still present. Therefore we can inquire about the general trends of the extended quench delays. The average tensile properties of the BSTOA treated samples are listed in **Table III.**

Table III: Average Tensile Properties of BSTOA Treated Samples

Beta Stabilizer Composition	Quench Delay Time (seconds)	UTS (ksi)	YS (ksi)	Elongation (%)
Poor	10	154.93	145.46	4.09
	20	154.78	145.23	4.10
	30	155.20	144.90	6.91
Rich	10	153.96	143.92	3.26
	20	-	-	-
	30	152.42	146.39	3.38

In the BSTOA treated samples, the average tensile properties are similar for both beta rich and poor heats, regardless of quench delay time. Ultimate tensile strengths and yield strengths of these samples only differ around 1-2 ksi each. Elongations of the samples also only slightly increase as quench delays increase. A representative stress-strain plot for a BSTOA treated sample is shown in **Figure 8**.

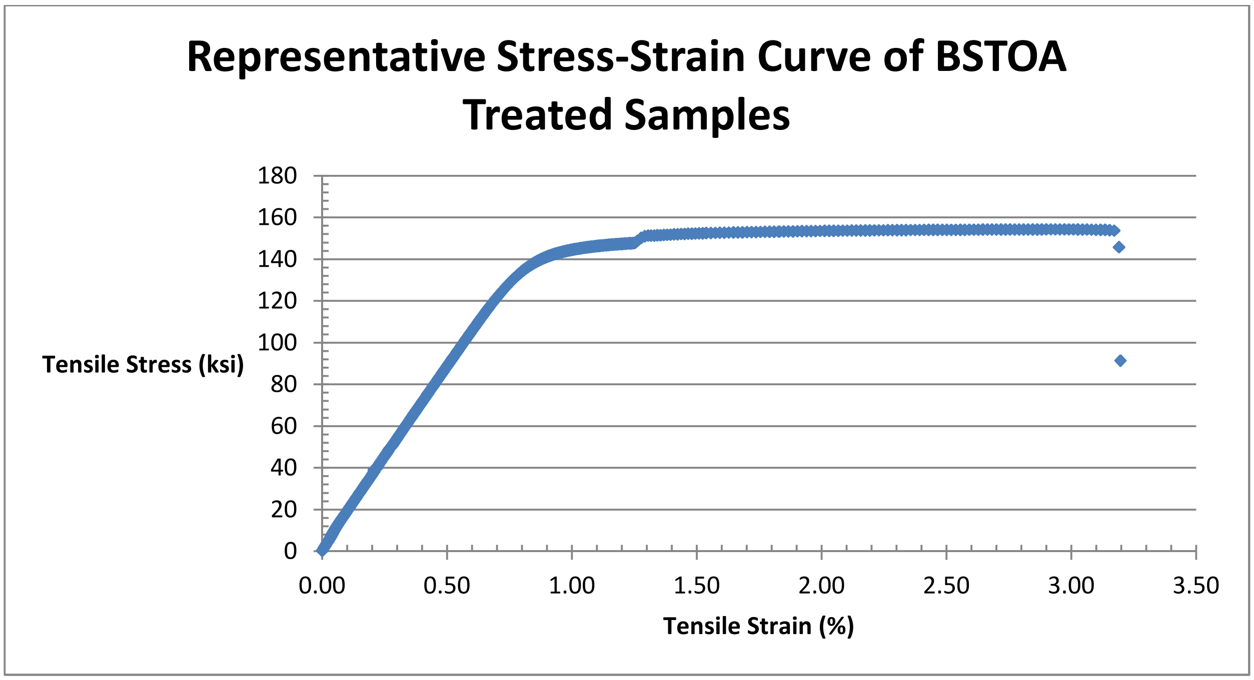

Figure 8: Representative stress-strain plot of a BSTOA treated tensile sample.

The average tensile properties of the STA treated samples are listed in **Table IV.** The STA treated tensile samples differ much more in average tensile properties with increased quench delay times. The beta rich tensile samples show a 7 ksi drop in UTS and a 5 ksi drop in YS when quench delays go from 10 to 30 seconds. The beta poor tensile samples show a similar trend in which the tensile samples show a 6 ksi drop in UTS and a 5 ksi drop in YS. Elongation also increases for both beta rich and poor samples with increased quench delay time.

Table IV: Average Tensile Properties of STA Treated Samples

Beta Stabilizer Composition	Quench Delay Time (seconds)	UTS (ksi)	YS (ksi)	Elongation (%)
Poor	10	165.59	152.31	7.11
	20	159.38	147.42	8.35
	30	159.00	146.79	9.58
Rich	10	166.64	154.13	3.69
	20	162.25	149.15	5.49
	30	161.05	148.74	6.77

A representative stress-strain plot for a STA treated sample is shown in **Figure 9**.

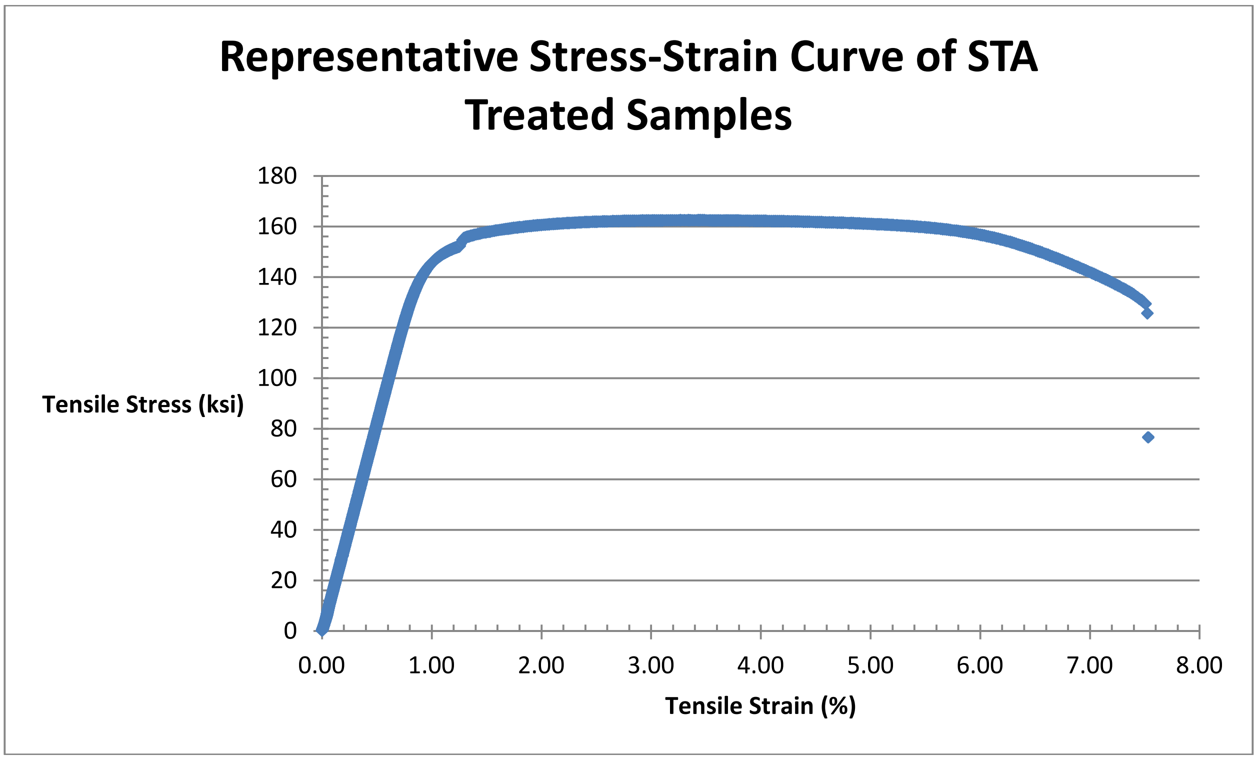

Figure 9: Representative stress-strain plot of a STA treated tensile sample.

Interactions Plots

Interactions plots were separately created for both the BSTOA treated tensile samples and the STA treated tensile samples to further explain the data. **Figure 10** is an interaction plot of

average ultimate tensile strengths against quench delay time for BSTOA treatments that compares beta poor and rich tensile samples.

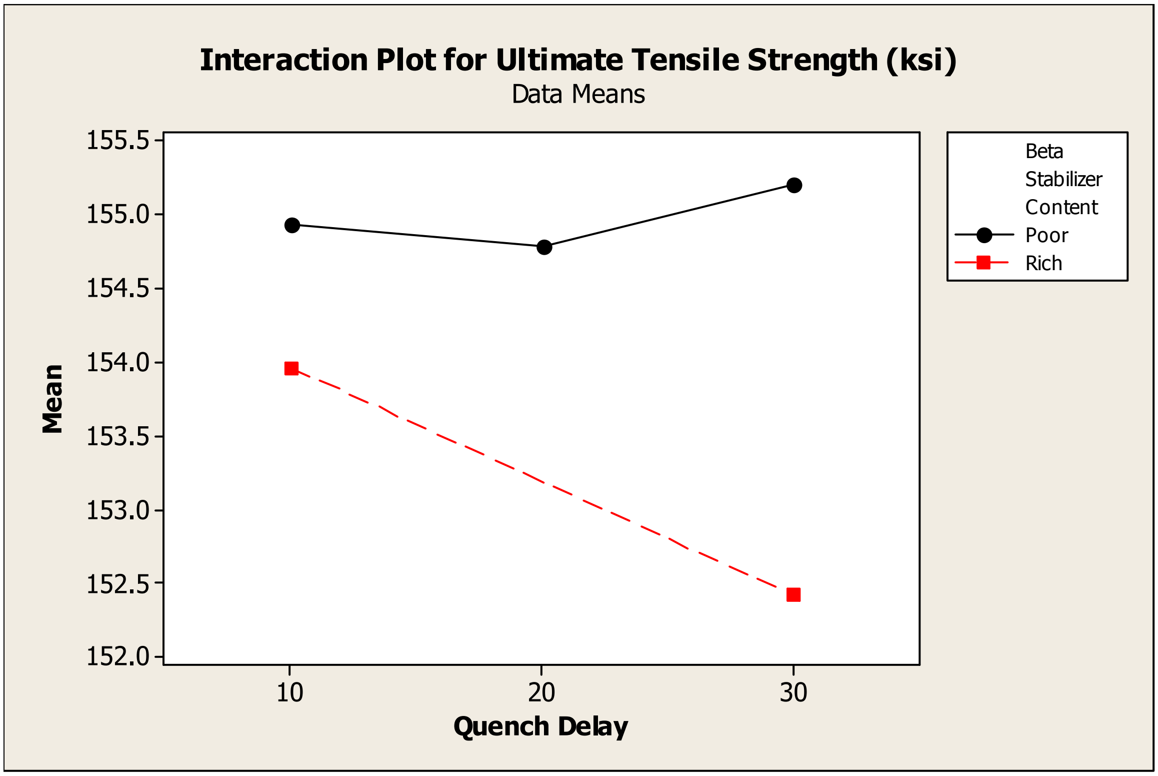

Figure 10: Interactions plot of average ultimate tensile strengths against quench delay time of beta rich and poor tensile samples that were BSTOA treated.

From **Figure 10,** beta poor samples show no significant change in average ultimate tensile strength with increasing quench delay times. Beta rich samples seemingly drop in average UTS when quench delay times increase from 10 to 30 seconds; however, this drop in UTS is only about 1.5 ksi, which is not statistically significant. **Figure 11** shows a similar interactions plot of average yield strength against quench delay time for BSTOA treated samples.

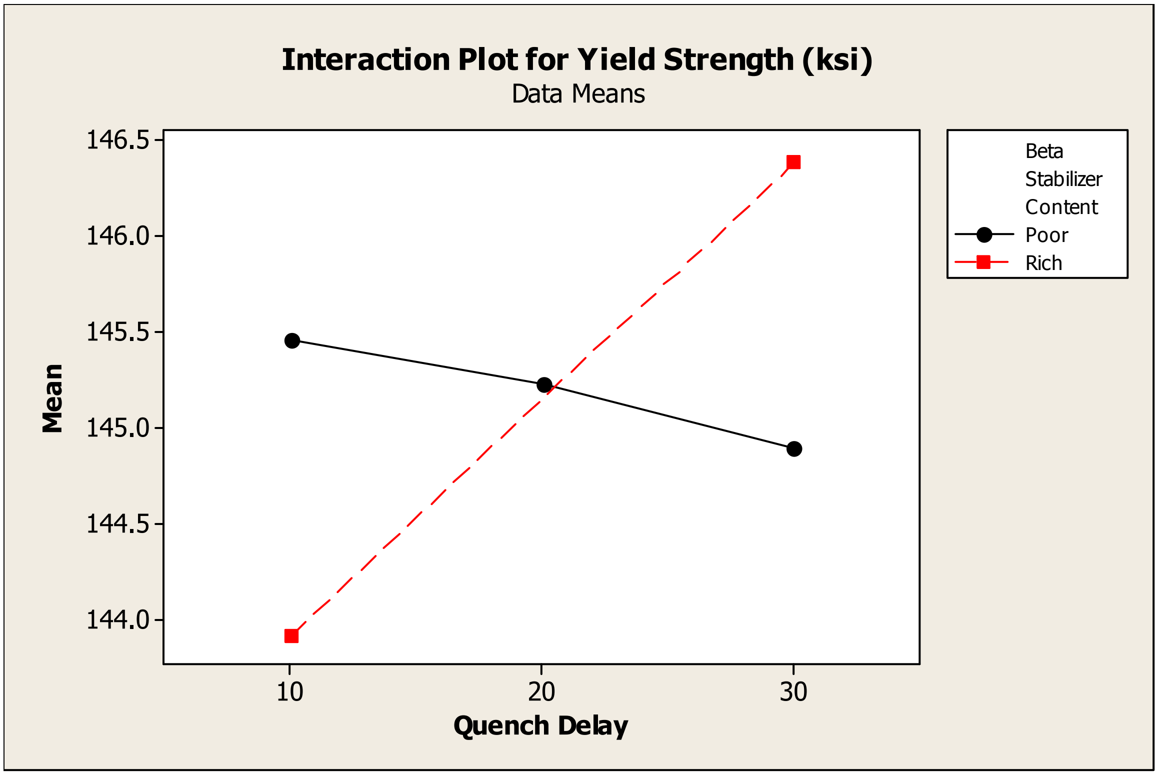

Figure 11: Interactions plot of average yield strength against quench delay of beta rich and poor tensile samples that were BSTOA treated.

In **Figure 11,** the average yield strength of beta poor, BSTOA treated samples, slightly reduces with increasing quench delay, and the beta rich samples increase in yield strength with increasing quench delay. Again the ranges of these changes are within 2 ksi and therefore are not statistically significant. An interaction plot of average ultimate tensile strength against quench delay time for beta rich and poor, STA treated samples, is shown in **Figure 12.**

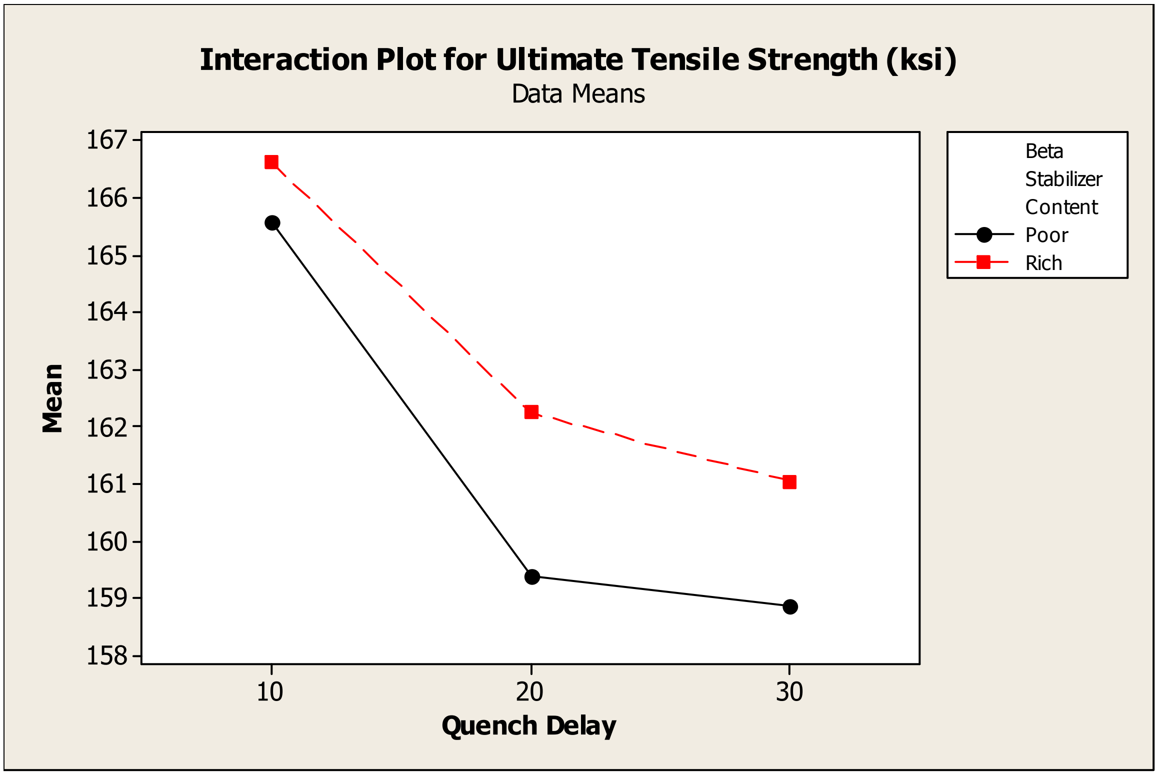

Figure 12: Interactions plot of average ultimate tensile strength against quench delay of beta rich and poor tensile samples that were STA treated.

Figure 12 shows similar trends for average UTS of both the beta rich and poor tensile samples that were STA treated. At 10 second quench delays, the tensile samples exhibit much higher average UTS, and then drop significantly when quench delays are 20 and 30 seconds. The average UTS drop for beta rich samples that were STA treated is about 7 ksi, while the beta rich samples show an average UTS drop of about 5 ksi. **Figure 13** shows a similar trend for the average yield strength of STA treated samples. Beta rich, STA treated samples resulted in a 6 ksi drop in YS when quench delays go from 10 to 30 seconds. Beta poor, STA treated samples also show a 5 ksi drop in YS when quench delays go from 10 to 30 seconds.

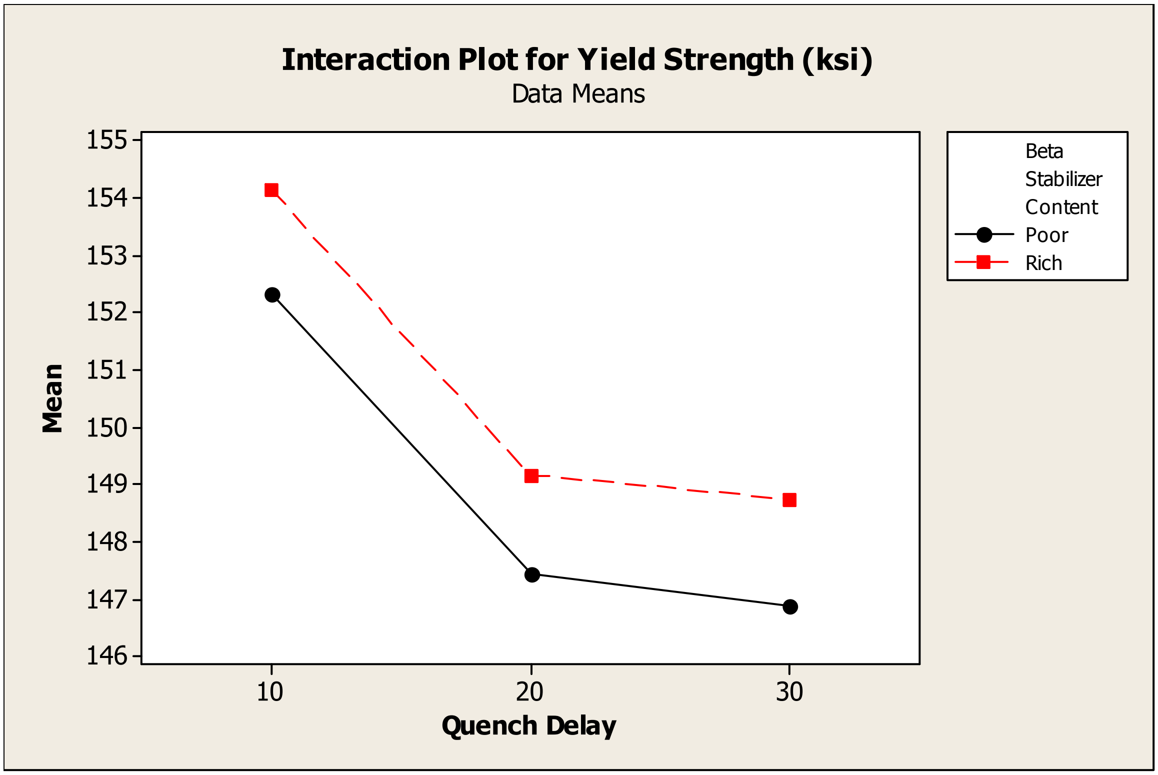

Figure 13: Interactions plot of average yield strength against quench delay of beta rich and poor tensile samples that were STA treated.

<u>Discussion</u>

The results of this experiment show that beta stabilizer rich forgings are not significantly less quench delay susceptible than beta stabilizer poor forgings, regardless of heat treatment. The interactions plots of the BSTOA treated samples actually show the opposite trends than expected by the experiment; in which beta stabilizer poor forgings are less quench delay susceptible. However, these results are not statistically significant because they only vary around 2 ksi for both UTS and YS.

In the interactions plots of the STA treated samples, similar trends for both the beta rich and poor samples are observed, indicating that they are equally quench delay susceptible. However, the beta rich samples resulted in slightly better UTS and YS for all quench delay times. This may be an indicator that for STA treatments, increasing beta stabilizer concentration does reduce quench delay susceptibility of Ti-6Al-4V; but for this experiment, the data is not statistically significant enough to prove this.

One thing that was observed in the experiment was that BSTOA treatments were less quench delay susceptible than STA treatments. With increasing quench delay times, BSTOA treated samples showed no significant drop in tensile properties, while STA treated samples showed drops in UTS and YS of more than 5 ksi. **Figure 14** can explain this occurrence with a representative phase diagram of titanium alloys. BST treatments are shown by the top red line, and ST treatments are shown by the bottom red line. Because the beta solution treatments were done 75°F above the beta transus temperature, the samples were well into the beta phase. A quench delay of 30 seconds may not have been enough time for the alpha phase to precipitate out of solution and alter tensile properties. The solution treatments were done well below the beta transus temperature, and therefore the alpha phase must have been present in the microstructure.   Increasing quench delay after solution treating would only further allow the alpha phase to precipitate and grow, which would reduce tensile properties as shown by the data.

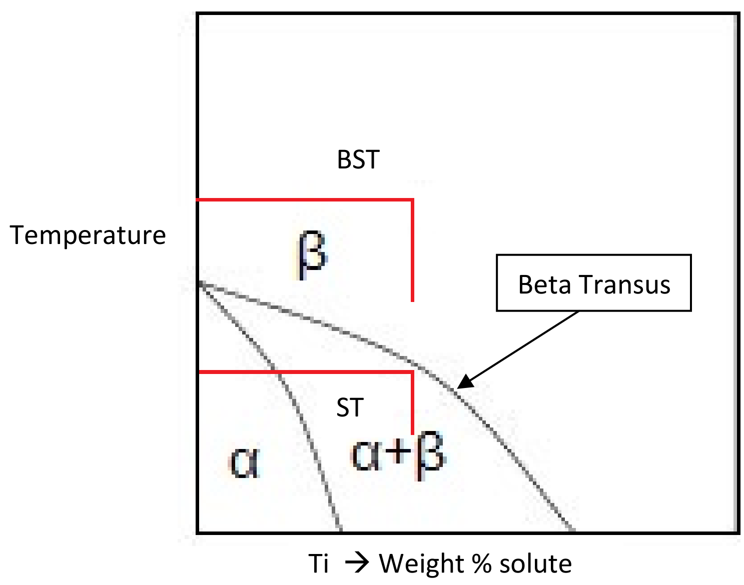

Figure 14: Representative phase diagram of titanium alloys that shows the effects of quench delays on the phases present after BST and ST treatments. BST quench delays are shown by the top red line, and ST quench delays are shown by the bottom red line.

In the future trials of this experiment, many things could be done to help the project show better results. Most importantly, the compositions of the beta rich and poor heats need to be more controlled.

This can be achieved by keeping the compositions of alpha stabilizers constant and increasing the difference in beta stabilizer concentrations between the two heats. Secondly, by extending the maximum quench delay from 30 seconds to a minute, the effects of quench delay will be more observable in both BSTOA and STA treatments. Finally, all sections of the DOE need to be represented in the data. Losing a section in this experiment could have caused an important aspect of the project to be overlooked.

Conclusions

1. Beta stabilizer rich forgings are not significantly less quench delay susceptible than beta stabilizer poor forgings.
2. BSTOA heat treatments are less quench delay susceptible than STA heat treatments.

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