Research Article

Tensile Properties of Thermal Cycled Titanium Alloy (Ti–6Al–4V)

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The effect of thermal cycling on tensile properties and microstructural characterization of Titanium (Ti–6Al–4V) alloy which were subjected to various types of thermomechanical treatments especially stress relief annealing and solution treated aging were studied and results presented. The specimens were thermally treated at a temperature of 427 °C for up to 1500 cycles. The test setup used for thermal treatment of the specimens was a specially designed experimental setup. After thermal treatment the specimens, were prepared for a tensile test to get the desired tensile properties. It was noticed that the maximum tensile strength of the specimen was observed when reached at 250 cycles and thereafter marginally increasing up to 1000 cycles. After 1000 cycles the tensile strength of the specimen decreases. Similarly, the hardness of the specimen increases up to 1000 cycles and then decreases after 1000 cycles, while elongation increases marginally when the cycle increases. Solution-treated aged specimen attains greater strength and hardness when compared to stress relief annealed specimen. With the increased number of cycles, the strength of the specimen when treated with stress relief annealing and solution-treated aging specimen increases. It was observed that the hardness and strength values decrease after 1000 cycles. With an increasing number of cycles, the tensile elongation increased. When compared with both the treatment processes the solution-treated aged specimen shows better results after thermal cycling.

1. Introduction

Titanium alloys are recognized for their high tensile strength and toughness properties even at extreme temperatures. Usually, they are a mixture of titanium as metal and some other chemical elements. The present study, an alpha-beta titanium alloy which has high specific strength as well good corrosive resistance properties. Due to its wide range of applicable properties like lightweight in nature, high specific strength, thermally stability, and corrosion resistance; Ti–6Al–4V alloy is being used in various applications on demand in aviation and automobile industries. These days titanium and its alloys are widely used in applications like spacecraft, missiles, aircraft frames, aircraft engines, marine applications, military [1, 2], chemical [3–6], armor plate applications, metallurgic [7] sports equipment [8], automotive components [9], surgical devices, medical implants [7, 10], and petrochemical production [11]. The alloy Ti–6Al–4V is widely acceptable and viable for structural applications in aerospace or aviation vehicles. PVD coatings have been shown to improve mechanical properties, biocompatibility, osseointegration, wear, and corrosion resistance in Ti–6Al–4V and SS 316 LVM substrates [12, 13]. Out of all titanium alloys, Ti–6Al–4V is the most preferable to use in engine components, airframe, and aerospace components. Ti–6Al–4V can also be represented as Ti–6Al–4V. Ti–6Al–4V alloys are heat treated in two different forms [14] in order to get an optimum combination of machinability, and structural stability by annealing and also for an increase in strength by treating with solution and aged and also for ductility. Researchers have identified that Ti–6Al–4V will behave as superplastic material under the temperature condition

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between 750°C and 950°C with a strain rate of $5 \times 10^{-4}$s$^{-1}$ [15, 16]. Reports say that in titanium alloy after heat treatment, the α in the α-β phase-field will not transform while cooling to room temperature still the presence of α-phase affects the % of elongation of the β phase. The alloy’s mechanical properties also depend on the transformation of β-phase to α′ martensite and ultrafine refinement of α and β grains. This transformation is possible by solution treatment and aging process, which improves the tensile strength of alloy without reducing the ductility. This process produces a 20% increase in the strength of the annealing process [17–19]. Between the temperatures of 930°C to 980°C good refinement of α grain is notorious because of this refinement strength of the alloy increases. Above 980°C, the strength decreases due to the rapid growth in prior β grains [20, 21].

Li et al. [22] reported that when heat treated at 950°C and then cooled in the furnace increased the strength and elongation of Ti–6Al–4V alloy than the base metal. Despite this, it has resulted in a decreased hardness value than the base metal. Wang et al. [15] observed that the strength of titanium alloys was higher when tested in a condition of 950°C for 1 hour, WQ + 540°C for 4 hours followed by air cooling (AC) than when treated at 970°C for 1 hour, WQ + 540°C for 4 hours, AC. Researchers have proven that when alloys are heat-treated by thermal cycles ductile properties of the alloys could be improved. By treating an alloy with thermal cycling will result in the strengthening of mechanical properties along with improved ductility [23]. Hu et al. investigated the effect of heat treatment on microstructure and tensile properties of Ti–6Al–4V alloy. As the annealing temperature was increased, α′ martensite decomposed into the α + β phase, whereas the width of the lamellae increased, resulting in an increase in ductility and a reduction in strength [24]. The influence of heat treatment on the microstructural evolution and mechanical characteristics of Ti–6Al–4V alloys produced by selective laser melting (SLM) was studied. The ductility of the as-fabricated −1133 K sample was substantially higher than that of the as-fabricated sample. This was attributed to the precipitation of micro/nanoscale and thermal phases, which was accompanied by columnar grain equiaxial transition [25]. A strong association was found between α lath width and microhardness levels. The solution air-cooled plus aged samples had the finest refinement in α-β morphology, with homogeneous equiaxed grains. The tensile characteristics of the solution air-cooled plus aged samples were comparable to those of the EBM printed samples and exceeded ASTMFI472 requirements [26]. The CCT diagram clearly shows that β transfers to α′ martensite occurs in both sections of the SLM process. However, a higher energy density occurred at the surface, resulting in a greater remelt depth and a greater number of effective thermal cycles in the preceding layers. As a result, the martensite size in the SLM samples reduced from the core to the surface. Hence, titanium and its alloys play a vital role in all kinds of structural applications. In the case of high fidelity applications, the material is often subjected to thermal cycling with temperature and time in various cycles. In the present work Ti–6Al–4V alloy is heat treated in two different forms and thermal cycling is carried out in specially designed equipment with different cycles ranging from 500 to 1500 cycles.

### 2. Concept of Thermal Cycling Testing

Thermal cycling is the process with two extreme temperatures being applied to a material in a cyclic manner of relatively high rates of change, to observe the latent defects. This test is used for modulating the temperature which is used to improve the strength and performance of a variety of materials. It is considered to be one of the most severe among environmental stress carrying a test to evaluate a material or product’s behavior toward reliability. As many industries are looking towards improved material performance in typical world situations, this test determines the material withstand capability when exposed to alternating high and low extreme temperatures. The workpiece is heated and cooled in cycles throughout this thermal cycling process until the material undergoes molecular reformation. This reorganization helps in relieving stresses, reduces particle structure, and tightens the material throughout making the metal more uniform. Additionally, the material’s properties for distributing heat and conducting energy will be improved. The steel is heated until it reaches its maximum non-magnetic state and then cooled by air until it acquires its magnetic property.

The time it takes for each metal varies, viz., for 1080 steel it takes a few seconds. In general, an instrument in continuous working condition will experience wear and tear till its performance is gradually compromised in real-time sequences. So, it may fail or require maintenance in time as needed sooner or later. When it is combined with thermal cycling it brings favorable results which contrasts to experience failure later than sooner. The applications of this type of technology are broadly used in aircraft, medicals, industries, automotive and railroad cars. The advantages of the thermal cycling process include relieving internal stress in forged or cast materials, reducing maintenance and repair costs, extending the life of surgical instrumentation.

#### 2.1. Forced Air Cooling

In this process, warm air is pulled out rapidly which increases the effective cooling rate and thus avoids condensation also which in turn is also used as a dehumidifying effect. In this process, effective surface area will be increased. As air is a medium to cool the component/material in thermal cycling, for advanced applications forced air is blown towards the specimen to cool till it cools back to normal and the cycle is repeated for thermal cycling. Air at a pressure of 3 bars will be sprayed over the specimen to cool for 2 minutes to attain room temperature. In our case, two minutes is the dwell time. Some advantages of forced air cooling are microstructure of the metal can be improved and also increase in microhardness can be observed [28, 29].

### 3. Experimental Procedure

A specific approach was adopted for studying Ti–6Al–4V alloy and its tensile properties. Figure 1 shows that the flow chart of the experimentation process. At first, specimens were prepared for the heat treatment process. Later the specimens were processed with two different heat treatment methods. One for stress relieving and annealing, and the
other for Solution treating and aging (STA). In a later stage, the heat-treated specimens were subjected to thermal cycling. The results of tensile properties were compared before and after thermal cycling.

An experimental study was conducted using high-precision instrumentation to acquire accurate test values. At a room temperature, the tensile tests were carried out using the UTM machine of Model Unitek 9410. Hardness measurement was done by using the Vickers hardness testing method on Zwick 3212 on the same specimen as used for the tensile test.

3.1. Specimen Preparation. The specimen is prepared from a Ti–6Al–4V plate. It is machined by using a wire cut EDM machine. It is a type of metal removal process where the metal is removed using an electric spark. The spark will remove the material as the spark-erosion technique is applied in this principle. EDM is mostly used for metal components especially electrically conductive metals or heat-treated metals like high carbon steels, Inconel, Titanium alloys, and AMC [30–32]. The specimen is prepared by ASTM E8/E8M specifications. The geometry of the tensile specimen is shown in Figure 2.

3.2. Heat Treatment of the Ti–6Al–4V Alloy. To study the tensile behavior, Ti–6Al–4V alloy specimens were subjected to heat treatments (Stress Relief Anneal, Solution treated, and Aged). Primarily, the specimens of stress relief anneal are heated to a temperature of 538°C for 1 hour and it is furnace-cooled to reach the atmospheric temperature as shown in Figure 3.

As part of the preparation of an alloy, annealing is used to relieve stress in the material, hence increasing its tensile strength and ductility. Then, the specimens are heated at a temperature of 950°C for 1 hour and it is quenched in water as part of the STA process. After the quenching process with a delay of 2 seconds, the aging process is performed at 524°C for 4 hours, and then it is forced to air cool outside the furnace to reach an atmospheric temperature shown in Figure 4. This process is termed as solution treatment and aging, which increases the strength and hardness of the material.

3.3. Thermal Cycling Test Setup. Thermal cycling testing is also termed as temperature cycling process. It is generally performed to determine material’s resistance when exposed to extreme high and low temperatures cyclically as alternating the high and low temperatures. This is performed for checking thermal mismatch in the alloys as they can cause certain kinds of failures and damages like cracking etc.

So before performing this test, the specimen has been heat-treated. The test setup of the thermal cycling test has been shown in Figure 5. The apparatus can be controlled using the Program Logic Control (PLC) unit. Using this apparatus, the specimens are thermally cycled. For exposing the specimen to extreme temperatures rapidly. A pneumatic actuator is attached to the specimen works in a translation motion as required, in and out of the muffle furnace. The temperature of the muffle furnace has been maintained constantly at 427°C with a dwell time of 2 minutes. The dwell time of 2 minutes is programmed in PLC, to operate the pneumatic actuator (5).

For force cooling of the specimens, samples are exposed to air (as a medium) under 3 bars of pressure. For a proper test result, it is estimated to be 1500 cycles per test. So systematically the test specimens are exposed to 1500 cycles.
3.4. Tensile Testing. In tensile testing of a specimen, a sample is fully loaded under controlled tension until it fails. With this test, we knew about the strength properties and ductility of the material before and after the thermal cycling test. The apparatus used for the tensile test is a UTM with the following specifications:

Model: Unitek 94100 with a Load range of 0 to 100 kN, Maximum cross head stroke of 1000 mm, Clearance between columns of 450 mm, Crosshead displacement measurement with 0.01 mm, Cross head speed of 0.25 to 250 mm/min, Power supply: 230 VAC, 50 Hz Single Phase.

The specimen with dimensions of 130 mm as length and a diameter of 10 mm has been used for testing. The specimen is shown in Figure 6. The deformations due to elongations and load applied have been recorded down at various time intervals with the help of computer. From the values observed through the experimentation, the elastic modulus ($E$), yield strength, % of elongation has been calculated and noted.

The specimen is inserted into the grips of the testing machine to hold the test piece, and then, the load is applied to observe the elongations through which mechanical properties can be calculated. The reading is taken frequently as yield point is approached. The universal testing machine is shown in Figure 7.

4. Results and Discussion

A titanium alloy was subjected to stress relief annealing and STA to study the thermal cycling effects on tensile properties. On UTM, tensile test was performed at room temperature with the specimens after and before heat treatment and temperature cycling. The results of the effect of with heat treatment and without heat treatment were presented in this section.
4.1. Effect of Thermal Cycling on the Ti–6Al–4V Alloy without Heat Treatment (WHT). The specimens were first gone through thermal cycling without heat treatment. The test results were plotted into graphs and are presented in Figures 8 and 9. By analysis, it is observed that the tensile strength of the specimen increases with the increase in a number of cycles until 1000 thermal cycles. The maximum tensile strength has been observed at 1000 cycles. Ultimate tensile strength (UTS) of 920 mpa and yield strength (YS) of 885 MPa and elongation of 26%. After 1000 cycles, ultimate tensile strength (UTS) is observed to be in decreasing trend. As the number of cycles increases, the % of elongation of the alloy under study shows a steep decreasing trend. The hardness of specimen shows a similar trend as in the case of tensile strength is maximum at 1000 cycle and decreases after 1000 cycles as shown in Figure 10. Among the three mentioned thermal cycles, 1000 cycles showed 374.6 HV0.5 which is the highest value among the three thermal cycle conditions. The lowest values have resulted in 500 cycles as 356 HV0.5, and at 1500 cycles as 369 HV0.5 respectively. The Without Heat Treated (WHT) thermal cycle process yielded a 4.9% and 1.5% increase in hardness value for 1000 cycles while comparing the 500 and 1500 cycles, respectively.

4.2. Effect of Thermal Cycling on Ti–6Al–4V Alloy Stress Relief Anneal (SRA). The specimens have been tested with thermal cycling after SRA heat treatment, for which results were presented in this section. The results have been presented in the form of plotted graphs as shown in Figures 11 and 12. By analysis, it is observed that the tensile strength of the specimen after heat treated with an annealing process for stress relief increases with the number of cycles, with a maximum tensile strength at the 1000th cycle. After 1000 cycles, ultimate tensile strength (UTS) decreases. Ultimate tensile strength (UTS) of 935 MPa and yield strength (YS) of 896 MPa and elongation of 26%. A similar trend can be observed here by the results of WHT. The % of elongation of the alloy shows an increase in ductile nature.

The maximum hardness of the specimen has been noted at the 1000th cycle after which the trend line decreases as shown in Figure 13. Among the three mentioned thermal cycles, 1000 cycles showed 381 HV0.5 which is the highest value among the three thermal cycle conditions. The lowest values have resulted in 500 cycles as 368 HV0.5 and at 1500 cycles as 376 HV0.5 respectively. The stress relief anneal (SRA) thermal cycle process yielded a 3.4% and 1.3% increase in hardness value for 1000 cycles while comparing the 500 and 1500 cycles, respectively.
4.3. Effect of Thermal Cycling on Ti–6Al–4V Alloy after Solution Treated Aged (STA). The specimens have been tested with thermal cycling after STA heat treatment, for which results were presented in this section. The results have been presented in the form of plotted graphs as shown in Figures 14 and 15. After analyzing the results, it can be observed that an increased maximum tensile strength at 1000 cycles after which a decline of UTS can be noted. The % of elongation of the alloy decreases with an increased number of cycles but points to an increase in ductile nature. Ultimate Tensile Strength (UTS) of 1530 MPa and Yield Strength (YS) of 1420 MPa and elongation of 29%. The maximum hardness of the specimen has been noted at the 1000th cycle after which the trend line decreases as shown in Figure 16. Among the three mentioned thermal cycles, 1000 cycles showed 471 HV0.5 which is the highest value among the three thermal cycle conditions. The lowest values have resulted in 500 cycles as 443.6 HV0.5, and at 1500 cycles as 456.4 HV0.5 respectively, which shows that there is an increase in the hardness when compared to WTH and SRA results. The Solution Treated Aged (STA) thermal cycle process gave a
5.8% and 3.1% increase in hardness value for 1000 cycles while comparing the 500 and 1500 cycles, respectively. 

When compared between the heat treatment processes, the STA process was shown with a 20.46% and 19.1% increase in WHT and SRA processes at 1000 cycles, respectively. The tensile test also proved that the Solution treated aged (STA) process showed a higher percentage of improvement in ultimate tensile strength (UTS) 39.86%, yield strength (YS) 37.67%, and elongation of 10% than without heat treatment (WHT). Similarly, Solution treated aged (STA) has shown ultimate tensile strength (UTS) of 39.56%, yield strength (YS) of 36.90%, and 10% of elongation higher than the stress relief anneal process at 1000 cycles.

(vii) Among all heat treatment conditions, the solution treated aged process showed improved hardness value when compared to the other two without heat treated and stress relief anneal processes with a percentage of 20.46% and 19.1% at 1000 cycles, respectively.

(viii) While heating, the material microstructure will have movements of dislocation density. This dislocation density movement will result in the entanglement of dislocation, which will result in the formation of high distortion energy. This energy leads to nucleation and recrystallization of grains to fine grains in titanium alloys.

(ix) These fine-grain formations have resulted in the higher hardness value of the solution treated aged process at 1000 cycles.

5. Conclusions

In the present study, the Ti–6Al–4V alloy has been processed with two different kinds of heat treatment processes i.e., stress relief annealing (SRA) and solution treated aged (STA). After heat treatment, thermal cycling of 500, 1000, and 1500 cycles with two minutes dwell time was applied and carried over the specimens. After heat treatment and thermal cycling, the tensile test and hardness test were conducted at room temperature. 

The following conclusions are drawn from the present study:

(i) At 1000 cycles, without heat treatment conditions recorded the higher ultimate tensile strength of 920 MPa and yield strength of 885 MPa, and the percentage of elongation is 26%.

(ii) Similar results were observed for stress relief anneal with ultimate tensile strength of 935 MPa, yield strength of 896 and percentage of elongation is 26% and solution treated aged with ultimate tensile strength of 1530 MPa and yield strength of 1420 MPa and percentage of elongation is 29% at 1000 cycles.

(iii) Solution treated aged process shown a higher percentage of strength improvement with ultimate tensile strength of 39.86%, yield strength of 37.67% and percentage of elongation 10% than without heat treatment. Similarly, solution treated aged has shown ultimate tensile strength of 39.56%, yield strength of 36.90%, and 10% of elongation higher than the stress relief anneal process at 1000 cycles.

(iv) Among all three heating conditions and displays, the solution treated aged process with higher strength and elongation.

(v) Among the three mentioned thermal cycles, 1000 cycles showed 374.6 HV0.5, 381 HV0.5, and 471 HV0.5 for without heat treated, stress relief anneal, and solution treated aged, and 1000 cycles had the highest value among the three thermal cycle conditions in their heat-treatment process.

(vi) The lowest values have resulted in 500 cycles for all three heat treatment conditions. They were 356 HV0.5, 368 HV0.5, and 443.6 HV0.5 for without heat treated, stress relief anneal, and solution treated aged, respectively.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication.

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