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STUDY OF THERMAL BEHAVIOUR ON TITANIUM ALLOYS (TI-6AL-4V)

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Abstract

Titanium is recognized for its strategic importance as a unique lightweight, high strength alloyed structurally efficient metal for critical, high-performance aircraft, such as jet engine and airframe components. Titanium is called as the "space age metal" and is recognized for its high strength-to-weight ratio. Today, titanium alloys are common, readily available engineered metals that compete directly with stainless steel and Specialty steels, copper alloys, nickel based alloys and composites. Titanium alloys are needed to be heat treated in order to reduce residual stress developed during fabrication and to increase the strength. Titanium (Ti-6Al-4V) alloy is an alpha, beta alloy which is solution treated at a temperature of 950 ºC to attain beta phase. This beta phase is maintained by quenching and subsequent aging to increase strength. Thermal cycling process was carried out for Ti-6Al-4V specimens using forced air cooling. Heat treated titanium alloy specimen was used to carry out various tests before and after thermal cycling, The test, like tensile properties, co-efficient of thermal expansion, Microstructure, Compression test, Vickers Hardness was examined by the following test. Coefficient of Thermal expansion was measured using Dilatometer. Tensile test was carried out at room temperature using an Instron type machine. Vickers's hardness measurement was done on the same specimen as used for the microstructural observation from near the surface to the inside specimen. Compression test was carried out at room temperature using an Instron type machine. Ti-6Al-4V alloy is a workhorse of titanium industry; it accounts for about 60 percent of the total titanium alloy production. The high cost of titanium makes net shape manufacturing routes very attractive. Casting is a near net shape manufacturing route that offers significant cost advantages over forgings or complicated machined parts.

Keywords: Titanium alloy, thermal behaviour, quenching, heat treatment, Vickers hardness.

1. Introduction

Titanium has been recognized as an element (Symbol Ti; atomic number, 22; and atomic weight 47.88). However, commercial production of titanium did not begin until the 1950's. At that time, titanium was recognized for its strategic importance as a unique lightweight, high strength alloyed structurally efficient metal for critical, high-performance aircraft, such as jet engine and airframe components. In the aerospace industry, titanium alloys have been widely used because of their lower weight higher strength (or) high temperature stability. The worldwide production of this original exotic, "Space Age" metal and its alloys have since grown to more than 50 million pounds annually. Increased metal sponge and mill product production capacity and efficiency, improved manufacturing technologies, a vastly expanded market base and demand have dramatically lowered the price of titanium products.

Today, titanium and its alloys are extensively used for aerospace, industrial and consumer applications. In addition to aircraft engines and airframes, titanium is also used in the following applications: missiles; spacecraft; chemical and petrochemical production; hydrocarbon production and processing; power generation; desalination; nuclear waste storage; pollution control; ore leaching and metal recovery; offshore, marine deep-sea applications, and Navy ship components; armor plate applications; anodes, automotive components, food and pharmaceutical processing; recreation and sports equipment; medical implants and surgical devices; as well as many other areas. Ti-6Al-4V alloy, by virtue of their excellent specific strength, is attractive for structural applications in aerospace vehicles. Hence, Titanium plays vital role in all applications. However, these alloy often subject to thermal cycling by various cycles with time and temperature.

Titanium -6Al-4v alloy is an alpha + beta alloy, which generally contains alpha and beta stabilizers and is heat treatable to various degrees. Alpha stabilizers (such as Al only) are not heat treatable and Beta alloys, which are metastable and contain beta stabilizers (such as Vanadium), are used to completely retain beta phase upon quenching. This can be solution treated and aged to achieve a significant increase in strength. This alloy is fully heated treated in section sizes up to 15mm and is used up to approximately 400 ºC. Over 70% of all Titanium alloy grades melted on a sub grade of Ti-6A1-4v which is used in aerospace, airframe and engine components. Ti-6Al-4v alloys are heat treated for two different methods [1] in order to get the optimum combination of ductility, machinability and structural stability by annealing and to increase the strength by solution treating. The heat treated tensile specimens were subjected to thermal cycling up to 1250 cycles. The present study reports that the Thermal Cycling increases the strength of the heat treated specimens to a considerable level and the micro structural changes for the thermal cycled specimens were displayed. Scanning electron microscope (SEM) was used to investigate the micro structural changes. Compression tests are essential to characterize the flow properties of the alloy at the different temperatures used in warm working. Hence the present study has been carried out on the behaviour of Ti-6Al-4V alloy in the temperature 750 ºC by means of compression test. Coefficient of thermal expansion was analysed with the help of dilatometer at temperature 450 ºC.

Titanium and its alloys have very attractive properties, e.g., high strength to weight ratio and excellent corrosion resistance, which enable them to be used in the fields of aerospace, biomedical, automotive, marine and military [1-7].The demand for the use of titanium and its alloys in many areas of applications has increased over the past years by the necessity for weight reductions that enhance the efficiency and greatly reduce the fuel consumption when used in the transportation systems, e.g. aerospace and automotive applications [3, 7].The excellent corrosion resistance and biocompatibility make Ti and its alloys a material of choice compared with other metallic implant materials [4-6]. In addition to applications of titanium in healthcare instruments such as wheelchairs, equipment for handicapped persons such as artificial limbs and artificial legs are currently making use of the unique properties of titanium alloys.Ti-6Al-4V alloy has an excellent combination of strength, toughness and good corrosion resistance and finds uses in aerospace applications, pressure vessels, aircraft turbine and compressor blades and surgical implants. Although in use for a number of years, Ti-6Al-4V alloy still attracts attention of researchers from both fundamental and practical points of view [3].

2. Previous Works

Ti is also widely used in such industries as automobile [8, 9], chemical [10-13], medical [14, 15], metallurgic [11, 16], military [17, 18], and sporting goods [15]. The rapid advance of the application of Ti in the past several decades has been matched by a dramatic growth of the Ti industry. It was estimated that the worldwide demand for Ti would be over 136,000 tons (or, 300 million pounds) by 2015 [19]. Sarasota Maintenance Superintendent, Jim Basilotto said: "We treated some of the school buses and then brought them back after 10,000 to 14,000 miles. They had less than 2% wear. That ended the test" [20].

The primary source of the increasing popularity of the is its superior properties such as high strength/weight ratio, high compressive and tensile strength, low density, high fatigue resistance in air and seawater, and exceptional corrosion resistance [10, 13, 21, 22]. Other reasons include its availability in the earth’s surface and price stability [10, 11]. The detailed information about the properties of Ti is readily available in the literature [10, 22- 24].

Among all Ti machining methods, drilling (or hole making) is very important. It accounts for a large percentage of all machining processes and is essential for many applications [25, 26]. It is usually one of the final steps in the fabrication of mechanical components and has considerable economical importance [27].

Wear mechanisms in machining Ti may vary according to different tool/work piece material combinations. Notching, non-uniform flank wear, crater wear, chipping, and catastrophic failure are the prominent failure modes when drilling Ti [28-30]. Li et al. [31] reported that WC-Co drills performed better than HSS tools because of lower thrust force and torque. The WC-Co spiral drills (a kind of twist drill with an advanced geometric design with S-shaped chisel edge and lower negative rake angle than that of the conventional twist drill) produced lower cutting force and torque than WC-Co twist drill. Kim, D et.al reported that, when drilling Ti/graphite stacks, the torque with HSS-Co tools was at least 40% higher than that with carbide tools [32]. Kim et al. [33] reported that the typical thrust force and torque profiles varied with a cutting depth as the drill penetrated the composite material when drilling Ti/composite stacks. Thrust force increased proportionally to an optimal depth then it dropped to a lower level for higher depth of cut. The thrust force was the maximum as the drill penetrated Ti and the maximum torque occurred when the drill lips cut both composite and Ti simultaneously.

Tool wear in Ti drilling is very sensitive to change in feed rate [23, 28, 34]. As feed rate increased, tool wear increased and drill life declined [31]. Zhu and Wang [35] reported that a drill material with higher hardness and higher density was more wear-resistant. For example, carbide tools might be required instead of HSS tools to improve the tool life when the hardness level of Ti was above 38 Rockwell [22]. Yang and Liu [23] listed some potential cutting tool materials (which could be used to improve the tool life during Ti drilling) such as boron-based tool material, CBN tool, WBN-CBN composite tool, and WC-Co alloys. In their review paper, Ezugwu [28] mentioned that WC-Co grades of cemented carbide and polycrystalline diamond were the best tool materials to machine Ti.

Because the thermal properties of Ti are poor, use of cutting fluids (or coolant) is very important to improve the tool life. Cutting fluids containing phosphates were found to perform better [28, 36]. Chlorine in cutting fluids might cause stress-corrosion cracking [37]. It was also found that sulphur compounds led to sulphur attack on turbine blades made of Ti [28].

Amin et al. [37] tried furnace heating of the work piece of titanium alloy to reduce chatter and improve machinability but furnace heating and subsequent mounting of the hot job on the machine is not a practical method to be employed in real life situation.

Thermally enhanced machining is the process that uses an external heat source to heat and soften the work piece. As a result, the yield strength, hardness and strain hardening of the work-piece reduce and deformation behaviour of the hard-to-machine materials (especially ceramics) changes from brittle to ductile. This enables the difficult-to-machine materials to be machined more easily and with low machine power consumption which leads to increase in material removal rate and productivity [38].

Some researches offer alternative methods in enhancement of machinability of titanium alloys (such as longer tool life, higher surface finish, lower cutting force and lower vibrations). They focus on the benefits of thermally assisted machining in improving the machinability of such alloys. It is due to the fact that the flow stress and strain hardening rate of materials normally decrease with increasing temperature due to thermal softening [39].

3. Thermal Cycling Process

3.1. Thermal cycling

Thermal cycling is a temperature modulation process developed to improve the performance, strength and longevity of a variety of materials. Probably best described as "advanced cryogenics", thermal cycling has been applied chiefly to metals to-date, although the process is also beneficial to Ti-6Al-4V, It is currently used by a number of industries where enhanced material performance is desired. During the thermal cycling process, materials are alternately cold and (sometimes) heated until they experience molecular reorganization This reorganization "tightens" or optimizes the particulate structure of the material throughout, relieving stress, and making the metal denser and more uniform (thereby minimizing flaws or imperfections). The tight structure also enhances the energy conductivity and heat distribution characteristics of the material.

To see an actual example of Thermal Cycle Metal, as expected, an instrument will wear until its performance is eventually compromised. It will fail, or require maintenance sooner or later. Due to the beneficial results created by thermal cycling, however, it will fail later than sooner. The applications for this new technology are extensive (aircraft, automotive, building, industrial, medical, military, railroad cars, etc.), and will be limited only by the imagination. Vehicle braking system fades, or brake fade is the reduction in stopping power that can occur after repeated application of the brakes, especially in high load or high speed conditions. Brake fade can be a factor in any vehicle that utilizes a friction braking system, including automobiles, trucks, motorcycles, airplanes, even bicycles. Thermal cycling reduces brake fade. Brake fade is caused by a build-up of heat in the braking surfaces and the subsequent changes and reactions in the brake system components. During high speed police chases, repeated sharp brake applications to control the vehicle produce brake temperatures in the 900-1200 degree range. Thermal cycled brakes remain cooler, minimizing the heat surface build-up. Finished, component parts and raw materials can be treated in a customized process that takes 2 to 10 hours to complete.

Advantages of thermal cycling process

- Optimizes the molecular particulate structure of materials
- Is not a surface treatment, application, or coating
- Enhances the material throughout, and cannot wear off
- Does not alter the appearance or coloration of materials
- Cannot be applied unevenly
- Does not require secondary processes to be effective
- Does not alter the dimensions of materials or components
- Improves other dipping and coating-type processes
- Improves the yield strength, reduces breakage
- Reduces wear, extends life
- Significantly reduces harmonic amplification (Vibration Signature)
- Improves heat conduction for better distribution & cooling
- Relieves stress inherent in forged or cast materials
- Enhances corrosion and chemical resistance
- Substantially extends the life of Surgical Instrumentation, Instrumentation trays and Containers
- Substantially reduces maintenance and repair costs.

3.2. Forced air cooling

Forced air cooling was used to cool the thermal cycled specimen. Air at a pressure of 2.5 bar was sprayed to cool the specimen for 2 minutes to attain an atmospheric temperature.

Advantages of forced air cooling:-

- Instead of water, forced air cooling, using we can improve microstructure of the titanium alloy.
- Micro hardness also increases.
- Aircraft manufacture: simulation of space flights.

4. Experimental Procedure

The experimental methodologies adopted in the present work are to study the Titanium thermal properties. To conduct the various tests titanium specimens were heat treated by two methods annealing and solution treated, then treated specimen carried out thermal cycling. Finally, heat treated specimen results was carried out before and after thermal cycling. The experimental study has been developed by high precision instrumentation, so as to have accurate results to compare with theirs. Tensile tests were carried out at a crosshead speed of 30mm/m at room temperature using an Instron type machine.

Micro structural observations were carried out on the cross sections of the tensile specimens using an SEM Vickers hardness measurement was done on the same specimen as used for micro structural observation from near the surface of the inside specimen. In the present work, the micro structural changes occurring during the high temperature deformation of the alloy at the lowest temperature of 750 ºC and their effect of thermal behaviour have been studied. Using dilatometer Coefficient of thermal expansion was examined between the range of temperature 50 to 400 ºC and results were analysed. The experimental procedure is given in the flow chart form as shown in Fig. 1.

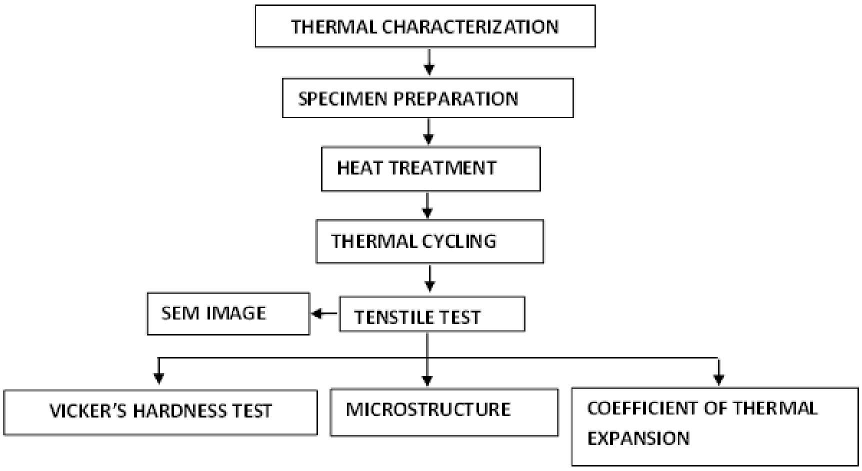

Fig. 1. Experimental procedure flow chart.

4.1. Specimen preparation

The Ti-6Al-4V plate is machined into a dimension as shown in Fig. 2.

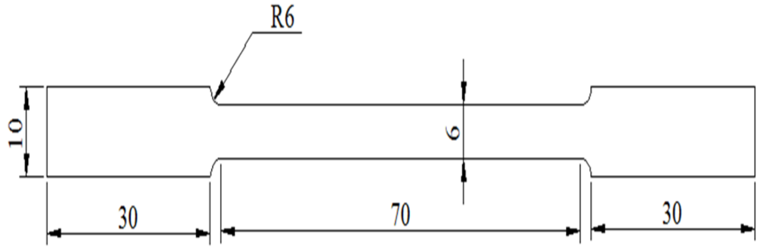

Fig. 2. Geometry of tensile specimen.

4.2. Heat treatment

In order to study the thermal behaviour of Ti-6Al-4V, it cannot be used directly. Hence, they are subjected to post heat treatments such as Solutionizing, aging and annealing in a muffle furnace. The muffle induced electric furnace has the following specifications: Temperature: 1200 ºC, Operation: 230 V/AC, and Type: K type Chrome alumel upto1200 ºC.

In solution heat treatment, the test specimens were heat treated to 950 ºC and quenched in caustic soda for 10 minutes. After completing the Solutionizing, the same specimens were treated with aging. Aging the specimens at 450 ºC temperature for a period of time 4 hours .After the heat treatment is over the specimens were quenched in the atmospheric air (Air quenched) .Aging increases the strength and hardness .Annealing is the another method of heat treatment which used for the tensile specimens, the test specimens were heat treated to 750 ºC and quenched in atmospheric air (Air quenched).Annealing increases strength and ductility.

4.3. Thermal cycling

The thermal cycling experimental setup is shown in Fig. 3. After completing the heat treatment, thermal cycling is started. The specimens are thermally cycled in a specially designed thermal cycling apparatus .The Pneumatic piston actuator was built to cycle the tensile specimen in and out of the furnace .The Temperature was maintained in the furnace at 300 ºC .The thermal cycle imposed had dwell time of 2 minutes in and out of the furnace .Samples were cooled by forced air cooling at a pressure of 2 bar

Samples were systematically exposed up to 1250 cycles in order to investigate the tensile properties and micro structural changes. After completing the thermal cycling process various tests is evaluated the test like tensile test, Microstructure Micro hardness, coefficient of thermal expansion and the Vickers hardness test. Using these results studied the thermal behaviour before and after thermal cycling. The photographic image of the thermal cycling experimental setup is shown in Fig. 4.

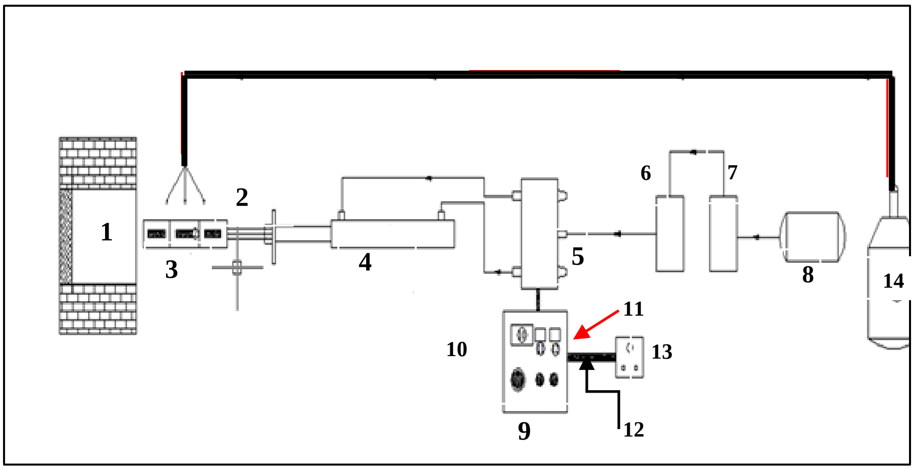

Fig. 3. Thermal cycling experimental setup.

(1- Furnace, 2- Specimen, 3- Compartment, 4- Pneumatic cylinder, 5- Compact valve, 6- Filter, 7- Regulator, 8- Compressor, 9- Control panel, 10- Counter, 11- Timer, 12- Timer, 13- Main switch, 14- Compressor.)

Fig. 4. Photographic image of thermal cycling experimental setup.

4.4. Testing

Tensile test

The tensile test is conducted in "UNIVERSAL TESTING MACHINE" having the following specifications: Model: Unitek 9410, Load range 0 to 100 kN, Maximum cross head stroke: 1000 mm, Clearance between columns: 650 mm, Cross head displacement measurement: 0.1 mm, Cross head speed: 0.5 to 250 mm/m, Power supply: 1 HP, 230 V AC, 50 Hz.

The round specimen is used for testing. The specimen is shown in Fig. 5. The specimens can be made out of the Ti-6Al-4V.The load and elongations were noted down at various instants. The elongations were measured using a computer. The elastic modulus, yield strength, % of elongation was calculated and recorded. In general, the experimental procedure for any testing machine would involve measurement of the original length and thickness of the specimen. The specimen is inserted into the grips of the testing machine, and then the load application is started. The reading is taken frequently as yield point is approached. During the initial stages of plastic deformation the load rises rapidly. Later values are evaluated. The elongation values then measured. The universal testing machine is shown in Fig. 6.

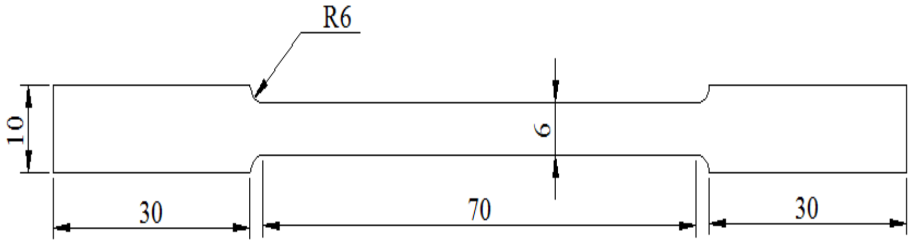

Fig. 5. The round specimen for tensile test.

Fig. 6. The universal testing machine.

5. Results and Discussion

Tensile behaviour of thermal cycled titanium (Ti-6Al-4V) Alloy

Heat treated (annealed and solution treated) and thermal cycled titanium alloy were subjected to tensile tests, co-efficient of thermal expansion, vicker's Hardness and SEM image. A Tensile test was carried out at room temperature using a Universal testing machine; Coefficient of thermal expansion was carried out at room temperature using Dilatometer. The tensile behaviour of different heat treated and thermal cycled specimens were studied.

5.1. The effect of thermal cycling of Ti-6Al-4V alloy after annealing

From Figs. 7 and 8, it is inferred that, the tensile strength of the annealed specimen increases with the number of cycles. After 1000 cycles, ultimate tensile strength decreases. Tensile strength remains almost constant between 250 to 1000 cycles. The elongation of the alloy decreases with increased No of cycles. Hardness of annealed specimen decreases after 1000 cycles as shown in Fig. 7 and % of elongation decreases as shown in Fig. 8.

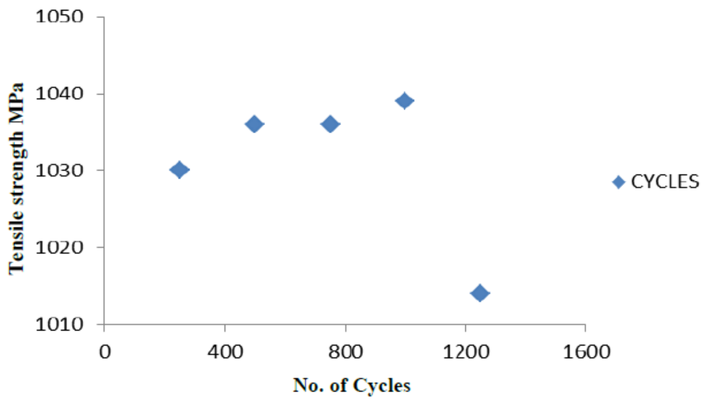

Fig. 7. Ultimate Tensile strength vs. the number of cycles for annealed specimen.

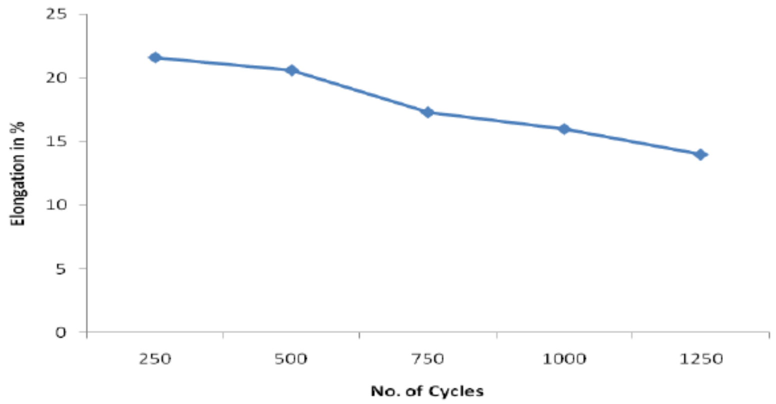

Fig. 8. The % elongation vs. the number of cycles for annealed specimen.

5.2. The effect of thermal cycling of Ti-6Al- 4V alloy after solution treated

Figure 9 shows the tensile behaviour of specimen. The ultimate tensile strength of titanium alloy is increasing at a higher rate when the number of cycles increases. The Tensile strength of the specimen increases at a higher rate after 250 cycles and decreases marginally after 1000 cycles. Elongation of the specimen decreases at higher cycles as shown in Fig. 9.

Finally, Fig. 10 shows that the ultimate tensile strength can be more in the solution treated specimen while compared with annealed specimen and tensile strength, % of elongation decreases after 1000 cycles.

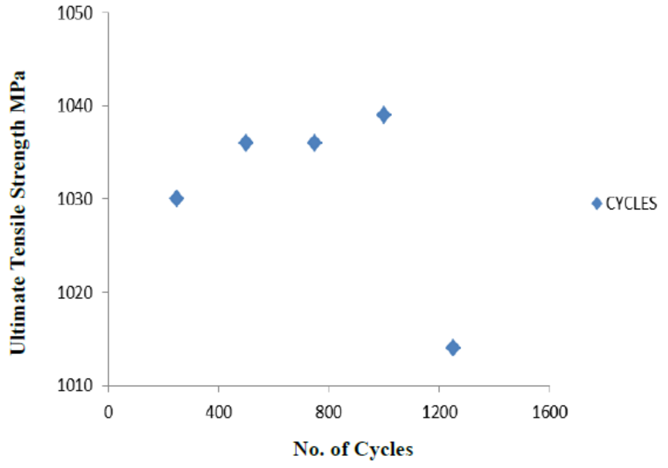

Fig. 9. Ultimate tensile strength vs. the number of cycles for annealed specimen.

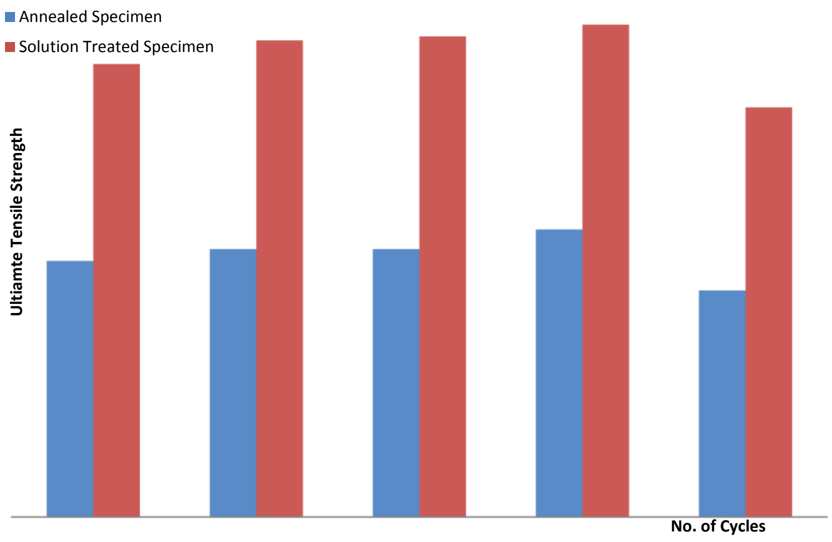

Fig. 10. Ultimate tensile strength vs. the number of cycles for heat treated specimen.

6. Conclusions

In the Present study, Titanium alloy (Ti-6Al-4v) is heat treated for two different methods in order to get the optimum combination of ductility, machinability and structural stability by annealing and to increase the strength by solution treating. Titanium (Ti-6Al-4V) alloy is an alpha, beta alloy which is solution treated at a temperature of 950 ºC to attain beta phase. This beta phase is maintained by quenching and subsequent aging to increase strength. Thermal cycling process was carried out for Ti-6Al-4V specimens for 250-1250 cycle at 450 ^{0}C and 2 minutes dwell time. Heat treated (annealed and solution treated) and thermal cycled titanium alloy specimens were subjected to compression tests for different strains (0.1 – 0.5), at constant strain rate of 1.0 s^{-1}. Compression test and tensile test were carried out at room temperature using a Universal testing machine. The flow behaviour of different heat treating and thermal cycled specimens was studied. The Comparative study of the flow behaviour of titanium alloy was made. The optimum Thermal Cycling was identified in the material.

The following conclusions related to Flow behaviour of Titanium alloy (Ti-6Al-4v) are drawn from the present study.

- Thermal Cycling increases the strength of the heat treated specimens to a considerable level.
- The strength of the annealed specimen and solution treated specimen increases with increased number of cycles.
- After 1000 cycles, the ultimate tensile strength and Vicker's hardness decrease.
- Solution treated specimen shows better result when compared to annealed specimen
- 750 thermal cycled Titanium (Ti-6Al-4V) alloy was found to have more strength.
- Solution treated specimen shows higher value when compared to annealed specimen.

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