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Thermal Cycling In (α+β) Ti6Al4V Alloy

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ABSTRACT

Thermal cycling experiments of Ti6Al4V alloy in forged condition were perform in two phase (α+β) region and single phase β to two phase (α+β) regions. The tensile tests, microstructure observation and hardness were carried out before and after the cycling treatments. Thermal cycling in two phase (α+β) region between 950ºC and 100ºC resulted large decrease in tensile strength after 50 cycles. However, it increased after 100 cycles. The ductility exhibited large decreased for both the treatments. The cycling between 875ºC and 100ºC in this region exhibited initial decrease in strength after 50 cycles which further increased after 100 cycles. 150 and 200 cycles treatment did not show much change in strength. There was no much reduction in ductility after 50 and 100 cycles treatment. However, after 150 and 200 cycle treatment, it reduced to large extent. The cycling from single phase β region to two phase (α+β) region between 1150ºC and 950ºC after 50 cycle did not affect the strength to large extent. However, the treatment exhibited reduction in ductility for both: 5 minute and 3 minute socking at 1150ºC. The extent of reduction being large for former compared to that for later. The hardness of all the samples including that for virgin sample exhibited very little variation. The microstructures of the alloy exhibited significant change in (α+β) phase morphologies. Similarly, the change in Young's modulus, thermal expansion coefficient, dislocation density etc has caused the degradation of the alloy.

1. INTRODUCTION

Two phase (α + β) Ti6Al4V alloy is well known for its high strength to weight ratio. It is recommended for structural applications in aerospace industries, power generation and marine engineering. It was originally developed for high-temperature applications in the compression section of jet engine and aircraft skin component in aerospace applications[1]. However, because of its pure ductility the applications are limited. It is reported that this alloy frequently undergoes thermal fluctuation when used in space satellite that moves around the earth in the orbit and caused failure[2]. Thermal fluctuations can result in the change of some of the important physical properties[3]. Thus, due to this change, the internal stresses are developed which influence the deformation behavior of the alloy to a large extent resulting its degradation. The literature survey provides very limited information on the thermal cycling which change the microstructure and mechanical properties. H.Geng *et al.* has reported the thermal cycling behavior of this alloy between 77 K and 623 K for 1000 cycles[3]. Similarly, Brindley *at al.* carried out experiments for 10,000 cycles[4]. No work is reported in the high temperature regions of this alloy where the transformation is accelerated due to faster atomic diffusion. Hence, the present work is focused on the thermal cycling of the alloy in (α + β) two phase region and single phase β to two phase (α + β) regions. The effects of this treatment on its microstructure, tensile strength, ductility and hardness are summarized.

2. EXPERIMENTAL

Forged Ti6Al4V alloy was obtained from Defense Metallurgical Research Laboratory (DMRL) Hyderabad, India, in a form of slab (15mm thick). Tensile sheet samples with 15 mm gauge length (L_0) and 10 mm^2 area of cross-section (A_0) were prepared. These were surface finished with 600 grit emery paper and vacuum sealed in a quartz tube under $1.3x10^{-7}$ MPa pressure. Thermal cycling programmes were based on Ti6Al-V equilibrium phase diagram[5]. Thus, the sealed samples were subjected to thermal cycling between 950ºC to 100ºC for 50 and 100 cycles, between 875ºC to 100ºC for 50, 100, 150 and 200 cycles in two phase (α+β) region. Similarly, between 1150ºC to 950ºC for 50 cycles with

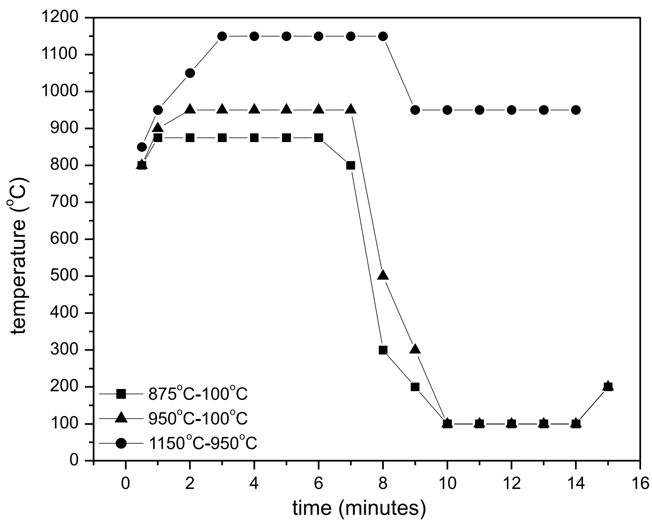

Fig. 1 : Thermal cycling programmes in two phase (α + β) region between 950ºC-100ºC, 875ºC - 100ºC and single phase β to two phase (α + β) regions between 1150ºC - 950ºC.

3 minutes and 5 minutes socking time at 1150^{o}C from single phase β to two phase (α+β) region. The cycling programmes (one cycle for each programme) are presented in Fig. 1. In this process the samples coupons were initially socked at higher temperatures (1150^{o}C, 950^{o}C) for longer time (30 minutes) to get them in equilibrium state. They were then moved from high temperature zone to low temperature zone and back again to high temperature zone. The treated samples were subjected to tensile test with a cross-head speed of 0.2 mm/min using "INSTRON 1195" tensile testing machine. For microstructure observations a small piece of each sample was polished using 600, 800 and 1000 grit emery papers. Final cloth polishing was performed on rotating wheel fitted with velvet cloth using 1 μm alumina slurry as polishing media. The sample were etched with Kroll Reagent (HF: 1 ml, HNO_3: 2 ml, H_2O:50 ml). Etched samples were observed in optical microscope (Axioscope MAT of Carl Zeiss, Germany) and micrographs were obtained with Carl Zeiss: "Axiolab 4.1" Image Analysis softwere The volume fraction of α or β phase was estimated by systematic point counting technique for selected samples. The hardness was estimated with "bareiss", Germany make micro/macro hardness tester with 100 gm load.

3. RESULTS AND DISCUSSION

The alloy sample in as received condition (virgin) exhibited ultimate tensile strength (UTS): 950 MPa and ductility:13 %. The stress-strain plot did not show a define transformation from elastic to plastic behavior. The microstructure exhibited an equiaxed grain structure of α and β phases (bright α and dark/grey β) with β phase exhibiting a feathery morphology shown in Fig. 2. The effects of thermal cycling in different phase regions on these properties of the alloy are presented below:

3.1 Cycling in two phase (α + β) region:

In this region two temperatures levels for thermal cycling were considered: one with lower ratio of equilibrium phases: α/β (at 950^{o}C) and other with higher ratio of equilibrium phases: α/β (at 875^{o}C).

3.1.1 Cycling between 950^{o}C to 100^{o}C

The sample coupons subjected to cycling treatment in this temperature region exhibited initial increase in UTS: 1150

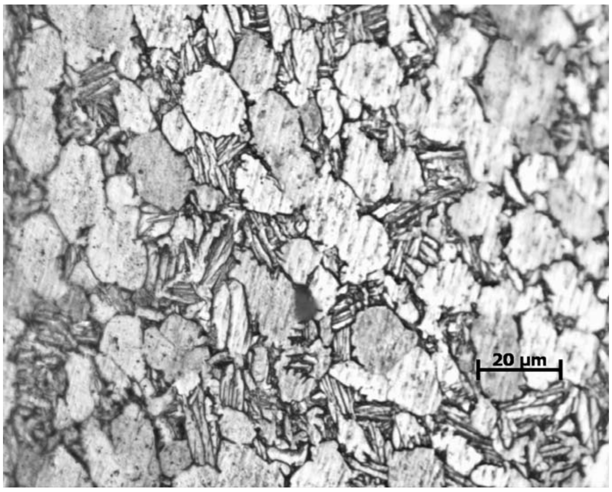

Fig. 2 : Optical micrograph of as received sample.

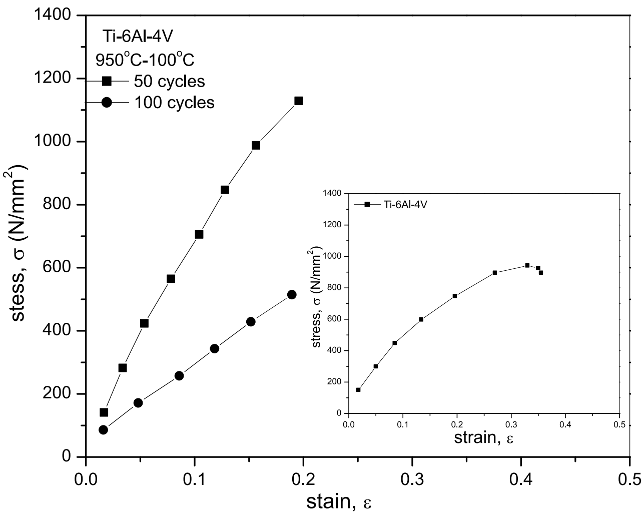

Fig. 3 : Stress-Strain curves of the samples thermal cycled between 950^{o}C -100^{o}C for 50 and 100 cycles.

MPa with large decrease in ductility: 7% after 50 cycles. When the number of cycles increased to 100, the strength largely decreased to 540 MPa with ductility remaining the same (7%). The stress-strain curves for 50 cycled sample exhibited a limited plastic behavior which further disappeared for 100 cycled sample. Both the samples failed without showing any necking after they reached to maximum load bearing capacity as shown in Fig. 3. The figure is also associated with the flaw curve of virgin sample for comparison. The microstructure morphologies showing the platelets of α and β phases is entirely different from that of the virgin sample. The exhibited volume fraction of β phase for 50 cycled sample was nearly 50% which further reduced to nearly 35 % for 100 cycled sample. Fine basket network of α, β phases can be seen in former as compared to that in the later. Ti6Al-V phase diagram exhibits more equilibrium fraction of β phase at 950^{o}C as compared to that at 875^{o}C[5]. Hence, the increased strength in the formal is due to the fine basket network as compared to that of later with coarse network of (α + β) phase morphologies. These microstructures are shown in Fig. 4: (a) for 50 cycled and (b) for 100 cycled samples.

3.1.2 Cycling between 875^{o}C to 100^{o}C:

The sample subjected to cycling in this temperature region exhibited large initial decrease in UTS to 500 MPa with marginal decrease in ductility to 11.7% after 50 cycles. When the number of cycles increased to 100, the strength largely increased to 1200 MPa with ductility coming to its original value:13%. When the number of cycles further increased to 150, the strength reached to its original value:960 MPa and ductility decreased to 10%. Further increase in the number of cycles to 200 did not affect the sample properties and they remained to the level of 150 cycled sample. Figure 5 shows the stress strain curves of these samples with the association of the virgin sample for comparision. All the four samples failed without showing any necking region after they reached to maximum load bearing capacity. The sample subjected 50 cycles did not show a define transformation from elastic to plastic behavior. However, further increase in number of cycles to 100, 150 and 200 exhibited a define elastic to plastic

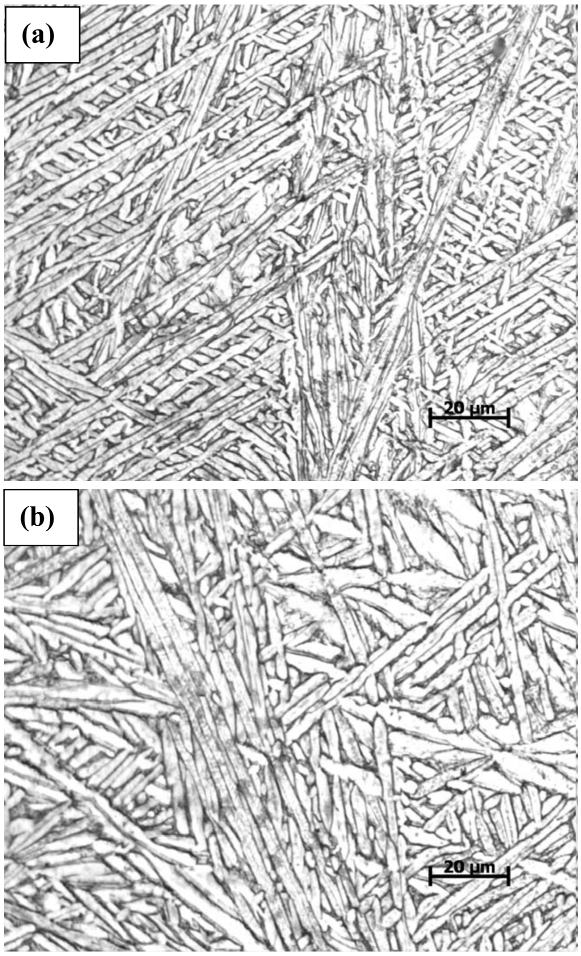

Fig. 4 : Optical micrograph of the samples thermal cycled between 950°C -100°C: (a) for 50 and (b) 100 cycles.

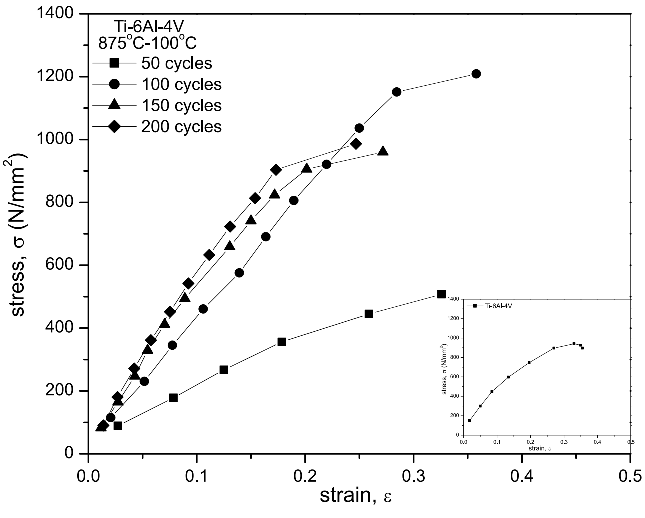

Fig. 5 : Stress-Strain curves of the samples thermal cycled between 875°C -100°C for 50, 100,150 and 200 cycles.

transformation with large elastic range as compared to that for virgin and the one after 50 cycle treatment. The microstructure morphologies exhibited fine needle like structure of α and β platelets after 50 cycles shown in Fig. 6 (a) where the estimated volume fraction of β phase was nearly 60 % (this is contrary to the amount estimated from the phase diagram by lever rule). With increased number of cycles to 100, the microstructure has shown a coarse morphology: Figure 6(b) with increased fraction of α. Here, the platelets are seen in a lamellar fashion. With further increase in number of cycles to 150, the phase morphology exhibited fine basket like sharp platelets. The microstructure is shown in Fig. 6 (c). Further increase in number of cycles to 200 slightly coarsen the microstructure keeping a similar fine basket like sharp platelets morphology exhibited in Fig. 6 (d). Here, a sharp decrease in the UTS to 500 MPa after 50 cycles and further increase it to 1200 MPa after 100 cycles could be due to a change in phase morphologies. Also, the reduction in UTS to its nearly original value (950 MPa) and reduction in ductility with increased number of cycles to 150 and 200 could also be due to the change in α, β phase morphologies.

3.2 Cycling between "β" to "(α + β") phase regions

In this process the samples were cycled between single "β" phase region at 1150°C to two phase (α + β) region at 950°C as shown in Fig. 1. The sample coupons were subjected to 50 number of cycles. The time of holding/socking the samples at 1150°C was 3 minutes and 5 minutes. The stress-strain curve exhibited small reduction in UTS to 850 MPa for 3 minutes and 900 MPa for 5 minutes treatments. However, the ductility reduced to larger extent i.e. 10 % for 3 minute treatment and 6% for 5 minutes treatment. Figure 7 shows these curves associated with that of a virgin sample for comparison. The micrographs of these samples presented in Fig. 8 : (a) for 3 minutes and (b) for 5 minutes treatment exhibited the morphology of α, β phases different than those shown above for cycling in (α + β) two phase region. Here, the sample treated for 3 minutes did not show any basket like structure which was prominent in sample coupons subjected to cycling in two phase (α + β) regions but α and β phase are aligned in a unidirectional manner. However, in 5 minutes treatment, fine α phase platelets are grown in crosswise manner showing few basket like regions. The α, β phase morphology is much finer as compared to those of cycling treatment carried out in (α + β) two phase region (Figs. 4 and 6).

The degradation of Ti6Al4V alloy on thermal cycling treatments described above could also be due to the additional feature of the phase diagram where the martensite (α') formation line in (α + β) two phase region appears (dotted line[5]). Therefore, during cycling treatments the nucleation and dissolution of the phases took place by the activated atomic diffusion. Since, there was continued variation in temperature of the sample coupons with time, sample could not achieve the equilibrium state. This has established a non-equilibrium state of sample at any instant. This would result in the variation of the physical properties like: Young's moduli, coefficients of thermal expansion, dislocation density in α, β and α' (which increased on cycling) and their pilling up against the grain boundaries and interface boundaries and caused degradation[3]. It is also reported that the different microstructure morphologies described above could be due to the precipitation and coalescence of one phase in/with other among α , β and α' and their simultaneous partial decomposition[3]. Similarly, the size, shape and spatial distribution of these phases/particles could influence the properties of the alloy. Further

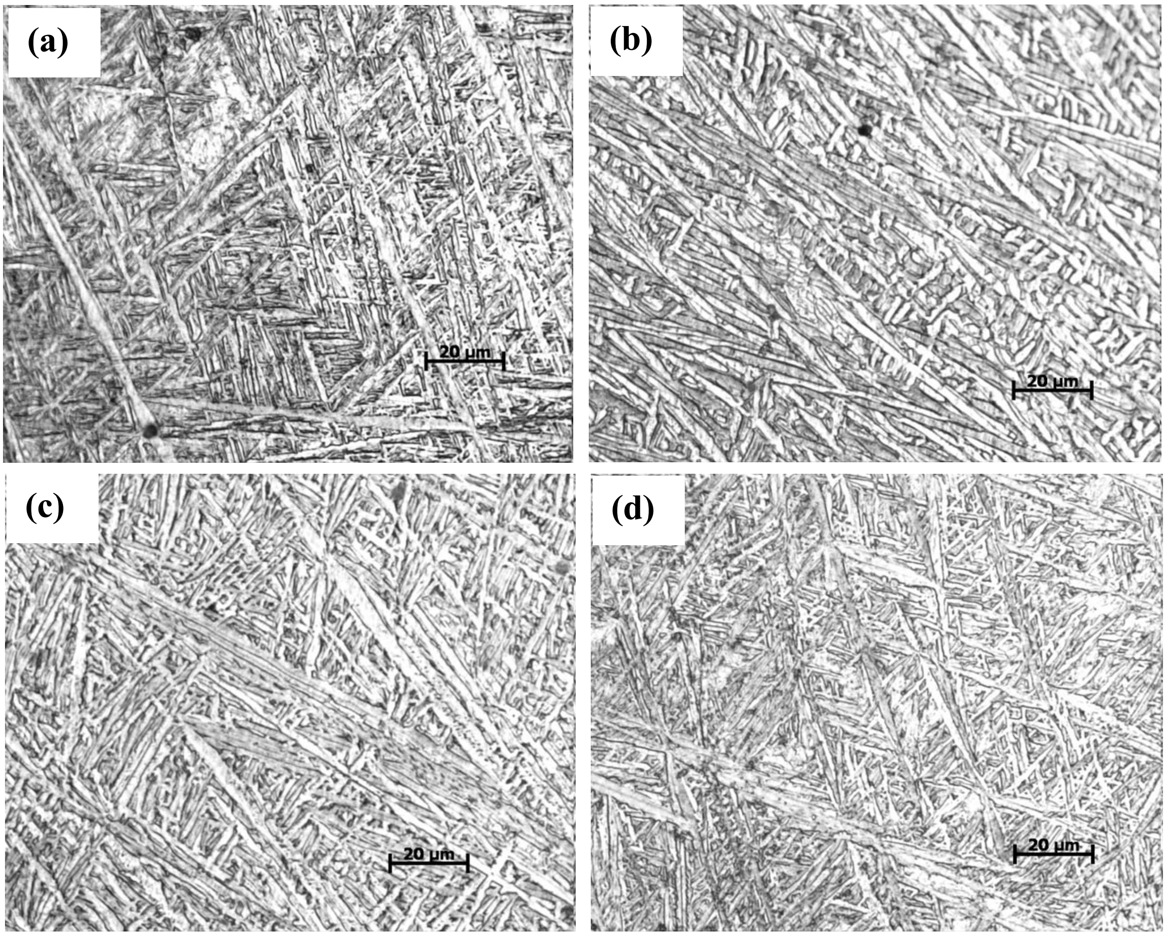

Fig. 6 : Optical micrograph of the samples thermal cycled between 875ºC -100ºC: (a) for 50, (b) for 100, (c) for 150 and (d) for 200 cycles.

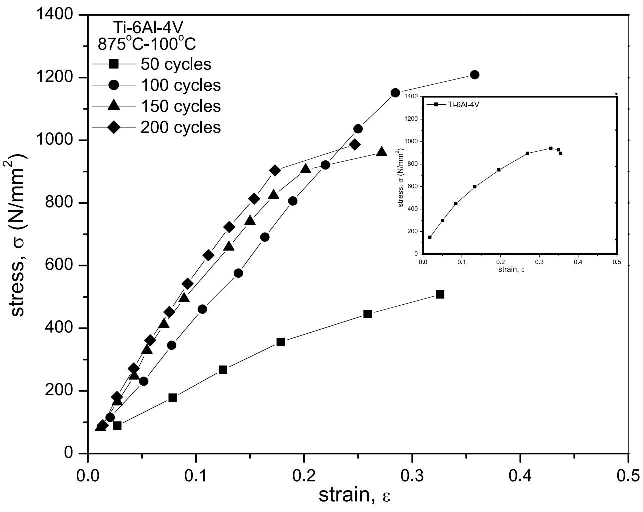

Fig.7 : Stress-Strain curves of the samples thermal cycled between 1150ºC -950ºC for 50 cycles for 3 minutes and 6 minutes soaking at 1150ºC.

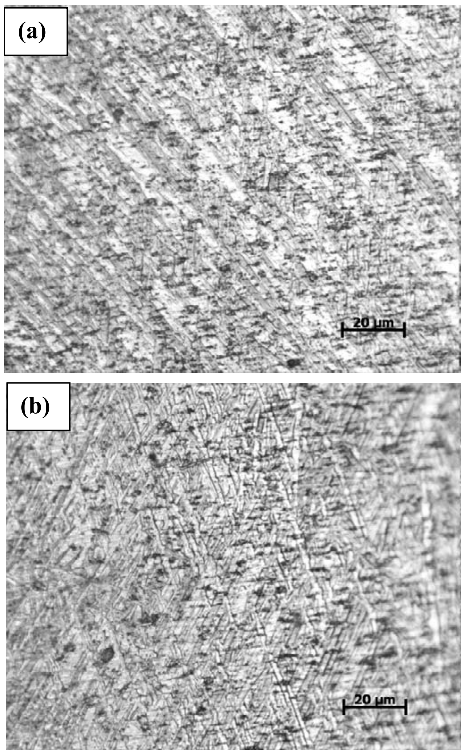

Fig. 8 : Optical micrograph of the samples thermal cycled between 1150ºC -950ºC for 50 cycles (a) for 3 minutes and (b) for 6 minutes soaking time at 1150ºC.

Table 1

Hardness of the samples thermal cycled in two phase (α + β) region between 950°C-100°C, 875°C -100°C and single phase β to two phase (α + β) regions between 1150°C-950°C.

Hardness, VHN				
Cycles	Temperature			
	950°C-100°C	875°C-100°C	1150°C-950°C	
50	431	441	419	443
100	414	430	-	-
150	-	414	-	-
200	-	442	-	-

Virgin sample-422

investigation on the quantitative basis is required to be carried out in terms of the parameters like: Young modulus, thermal expansion coefficients of α, β phases, dislocation density etc.

4. CONCLUSIONS

(i) Thermal cycling in Ti6Al4V alloy in two phase (α + β) region from 950°C to 100°C reduced the strength and ductility to 540 MPa and 7 % respectively after 50 cycles. After 100 cycles, the strength increased to 1150 MPa with ductility remaining the same. Similarly, from 857°C to 100°C in this region the strength decreased to 510 MPa after 50 cycles which then increased to 1200 MPa after 100 cycles. However, 150 and 200 cycle treatments did not show much change in the strength, but the ductility reduced to nearly 9 and 9.7 % respectively.

(ii) Thermal cycling from single phase β to two phase (α + β) region from 1150°C to 950°C after 3 minutes and 5 minutes socking at 1150 exhibited no significant change in the strength. However, the ductility reduced to 10 % and 6% respectively.

(iii) The thermal cycling treatment resulted significant change in (α + β) phase morphologies in microstructures.

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REFERENCES

1. Tobler R L, *Crack Fracture*, ASTM STP 601, ASTM, Philadelphia, PA, (1976) p 346.
2. Yunxue Wu: *Sinica J. Aerospace Mater. Technol*., **4** (1992) 62. Lei Sheng: *Sinica J. Aerospace Mater. Technol*., **4** (1992) 27.
3. Hongbin Geng, Shiyu He and Tingquan Lei, "Thermal Cycling Behavior of As-Quenched and Aged Ti-6Al-4V Alloy", *Metallurgical and Materials Trasactions A*, **28A** (1996) 1997.
4. Brindley R K, Mackay R A and Bartolotta P A, *HITEMP Review 1990*. NASA CP-10051, NASA, Washington DC, (1990) p 38-1-38-12.
5. Smith W F, *Structure and Properties of Engineering Alloys*, McGraw-Hill Int.N.Y., (1993).