

Dynamic globularization of α -phase in Ti6Al4V alloy during hot compression

K. Mutombo¹, C.Siyasiya², W.E. Stumpf³

¹*Council for Scientific and Industrial Research (CSIR), South Africa*

^{1,2,3}*University of Pretoria, South Africa*

KMutombo@csir.co.za,

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Abstract

Ti6Al4V samples were isothermally compressed using a Gleeble^(TM) 1500D thermo-mechanical simulator. Differential scanning calorimetry (DSC), microstructural analyses, and thermodynamic calculations were used to investigate the sequence of transformation of β into α or vice-versa and the presence of different phases in the compressed Ti6Al4V sample. Globular alpha phase was revealed in the isothermally compressed sample in addition to martensitic and lamellar α/β structures. The transition temperature range of β into α -phase was determined using the DSC thermograms and thermodynamic calculated diagrams. The fraction of α -phase globulized increased as the strain rate decreased from 0.01s^{-1} to 10^{-3}s^{-1} , and the spheroidization of the α -phase is only possible in a specific range of deformation temperatures.

Introduction

The final microstructure of the thermo-mechanical processed titanium alloy component is mostly controlled by the meta-stable β -phase transformation. Consequently, the mechanical properties, such as superplasticity of the Ti alloy, will be determined by the grain size of newly formed α -grains, and most importantly by the thermomechanical process variables. Therefore, the control and optimization of the microstructure of Titanium alloys is one of the most important parameters for achieving the desired mechanical and corrosion properties after hot forging, hot extrusion or hot rolling processes. Hot deformation or shape-making processes are mainly affected by the presence of the metastable phases such as beta or hexagonal and/or orthorhombic martensite at that specific moment of the thermo-mechanical process.

Much work on the chemical composition dependence of the martensite start temperature (M_s) has been done for Ti-Fe, Ti-Cr, Ti-Mo, Ti-V, Ti-Nb, Ti-Zr and Ti-Al alloys [1], [2]. The beneficial effect on the formation of hexagonal-structured martensite (α') of Al, Mn, Cr, Sn and Fe alloying elements, has been discussed by Lin et al [4]. However, the formation of the orthorhombic-structured martensite (α'') which is favoured by elements such as Nb, Mo, Zr, W and V (strong β stabilizers) or H (a strong β stabilizer), has been reported by Qazi et al, and Lin et al [3-4]. The simultaneous presence of orthorhombic and hexagonal martensite and their transition temperature in Ti6Al4V have been latterly reported by Kalenda et al [5]. Some thermodynamic and kinetic data of Ti alloys may be found in previous research work [6-14].

The occurrence of β into α or α into β transformations concurrently with isothermal and non-isothermal compression in the β or ($\alpha+\beta$) phase field, can impact on the microstructure evolution, and the final α -grain size.

Much effort has been invested in the understanding of the process mechanism and kinetics; and the effect of temperature, strain rate and strain on the dynamic globularization. Still, the impact of the β to α -phase transition during this process needs to be investigated. Therefore, this study is exploring the simultaneous occurrence of β to α -phase transformation and α -phase globularization during hot compression.

Experimental

Isothermal compression, to 60% reduction of cylindrical Ti6Al4V samples of 10 mm diameter and 15 mm length, was performed by means of a Gleeble^(TM) 1500D thermo-mechanical simulator, according to treatment condition A (Table 1). Samples, under strain rate of 10s^{-1} , 5s^{-1} , 1s^{-1} , 0.1s^{-1} , 0.01s^{-1} and 0.001s^{-1} , were compressed at temperatures varying from 650°C to 1100°C at intervals of 50°C . The WC anvils with a Silica barrier around them to approach near-isothermal conditions were used to minimise the temperature gradient along the length of the sample. The thermo-mechanical processing method is shown in Figure 1.

The thermal analysis was carried out in a simultaneous thermal analyzer NETZSCH DSC STA 449F3 (Rhodium furnace) using an Al_2O_3 crucible purged with 244.3 ml/min Argon. Ti6Al4V samples of 5 mm diameter and 2 mm thickness were heated from RT and cooled down to 30°C according to the treatment B (Table 1). The Ti6Al4V samples' chemical composition is shown in Table 2, and was previously isothermally compressed according to treatment A (Table 1).

Optical microscopy and scanning electron microscopy were performed on the as-received and isothermally compressed Ti6Al4V samples to investigate the mechanism of deformation in the β -field and ($\alpha+\beta$) field; and the globularization of the α -phase.

Table 1. Heat treatment conditions of the as received Ti6Al4V alloy

Treatment condition	Equipment	Heating rate, $^\circ\text{C/s}$	*Solution treatment Temperature, $^\circ\text{C}$	Cooling rate, $^\circ\text{C/s}$	Compression temperature, $^\circ\text{C}$	Cooling to RT, $^\circ\text{C/s}$
A	Gleeble	2	1200	150	T_D	150
B	DSC	5	1200	-	-	20

Note: * holding time of 5 min, T_D : 750°C , 800°C , 900°C , 1000°C or 1100°C

Table 2. The chemical composition of the as received Ti6Al4V alloy

Alloying elements	Ti	Al	V	O	Fe	C	N	Si	Zr	Ca	P
Wt %	Bal.	6.680	4.210	0.200	0.035	0.015	0.015	0.010	0.008	0.001	0.005

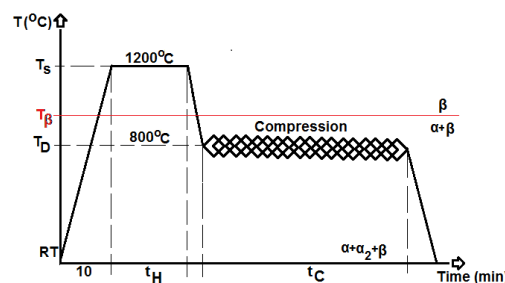


Figure 1. Schematic thermo-mechanical processing schedule used for compression of Ti6Al4V samples.

Results and discussion

The typical macrostructures of the isothermally compressed Ti6Al4V alloy in the respective temperature ranges of 1100°C to 950°C and 900°C to 650°C are shown in Figures 2a and 2b. Macroscopic observations revealed a homogenous deformation, with elongated grains in the deformation temperature range of 1100°C to 950°C (above the β -transus). However flow localization zones are observed in between 900°C to 650°C (in $[\alpha+\beta]$ field): little or no deformation zones (LDZ or NDZ), moderate deformation zones (MDZ) and intense shearing zone (ISZ).

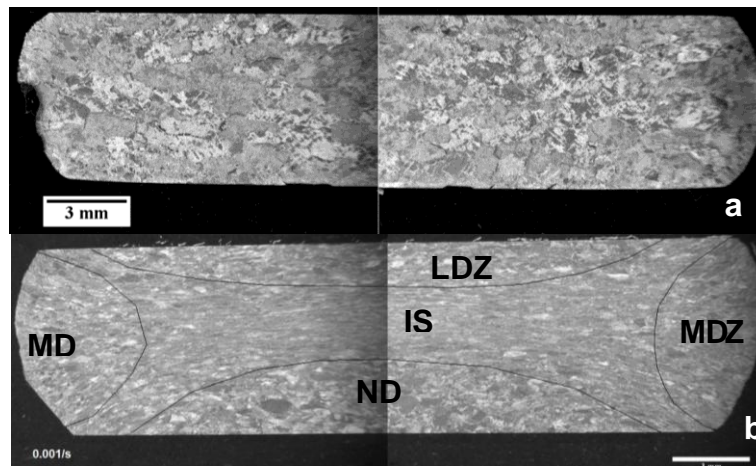


Figure 2. a) Homogenous deformation, and b) flow localization of the isothermally compressed Ti6Al4V alloy.

The typical microstructures of the isothermally compressed Ti6Al4V alloy at a strain rate of 0.001/s are shown in Figure 3. The Ti6Al4V compressed at the temperature range of 1100°C to 950°C (Figure 3a), revealed elongated and partially martensitic structured grains in the direction perpendicular to the compression stress. From 1100 to 950°C no dynamic globularization process occurred during compression (Figure 3a). However, compressing the Ti6Al4V alloy at the temperature range of 900°C to 650°C led typically to three differently structured zones. The first zone is NDZ or LDZ (Figure 3b) which has a partial martensitic structure with α -phase grain boundaries. The microstructure in this zone is similar to that obtained in Figure 3a. The second zone is MDZ (Figure 3c) which contains acicular and globular α -phase morphology. And the last zone is ISZ (Figure 3d) which has a relatively finer acicular and globular α -phase structure. At 900°C, 850°C, 800°C and 750°C, and at a strain rate of 0.001/s, dynamic globularization is predominantly observed in ISZ and MDZ (Figures 3c and 3d). Above 750°C the globularization of the α -phase disappeared.

Typical microstructures of Ti6Al4V isothermally compressed in the $(\alpha+\beta)$ field at a strain rate above 0.001/s, are represented in Figure 4. The microstructures of the MDZ (region dominated by tensile stress) and the ISZ (region dominated by shear stress), for the deformation range temperature from 900°C to 800°C, are respectively shown in Figure 4a. Partially distorted and segmented α/β platelets and breakup of the β -phase are clearly revealed in the MDZ. However, completely orientated α/β platelets, perpendicular to the compression direction and breakup of the β -phase are prominently visible in the ISZ. The microstructure of Ti6Al4V deformed at the temperature of 750°C and 650°C in the MDZ and ISZ are respectively shown in Figures 4b and 4d. Completely distorted thick α/β platelets were revealed in the MDZ and ISZ.

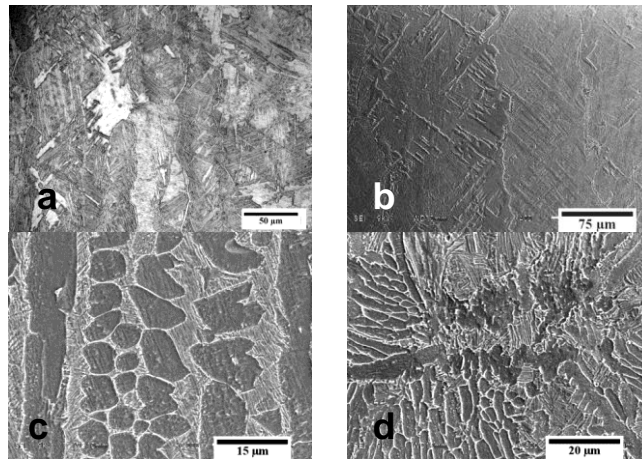


Figure 3. Typical microstructures of Ti6Al4V, a) compressed at a temperature from 1100°C to 950°C; and at temperature from 900°C to 750°C, a) in the LDZ or NDZ, b) in the MDZ and c) in the ISZ

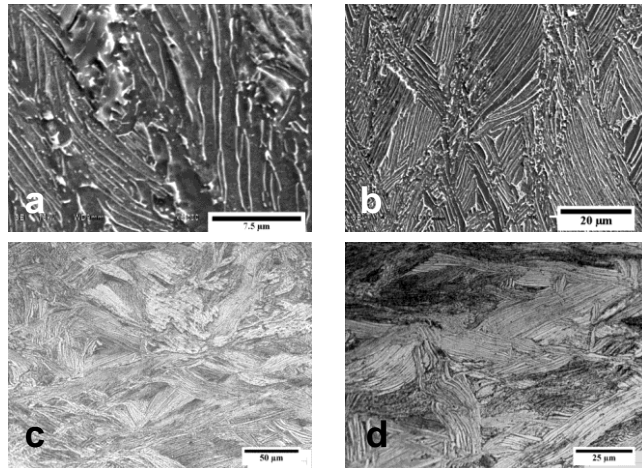


Figure 4. Typical microstructures of Ti6Al4V compressed at a strain rate above 0.001/s at 800°C, a) in the MDZ and b) in the ISZ; and at 750°C c) in the MDZ and d) in the ISZ.

The phase formation and phase stability diagrams of the Ti6Al4V alloy in the equilibrium condition are presented in Figure 5. The thermodynamic equilibrium phase calculation of Ti6Al4V alloy by the thermodynamic software, CompuTherm Pandat™ [5], revealed the presence of bcc or β -phase, Ti₃Al (hcp) or α_2 -phase and hcp or α -phase. These three phases coexist between RT and about 625°C. In the temperature range of 625°C and 960°C only α and β -phase are present. The α_2 -phase disappears completely when the temperature of 625°C is reached. Above 960°C the Ti6Al4V alloy is β -phase only. The α -phase has the lowest Gibbs free energy followed by α_2 -phase between RT and 960°C; however the β -phase becomes the most stable phase above 960°C.

The thermal analysis, according to schedule B, of the isothermally compressed Ti6Al4V is typically pictured by the DCS thermogram in Figure 6a. The sample contains α and β -phases as obviously revealed by the microstructural analysis, and the Ti₃Al as calculated (Figure 5). The α_2 -phase transforms to α -phase at about 650°C on heating. The transformed α and primary α -phase will then transform to β -phase at about 960°C (the transus temperature of

Ti6Al4V, with onset at 847°C and 1003°C which is the end of the reaction). The last peak appearing at 1080°C (starting at about 1020°C and ending at 1160°C), is the hexagonal martensite (α') transformation peak [5]. However the reverse reaction on cooling takes place at about 900°C (starting at 963°C and finishing at 878°C).

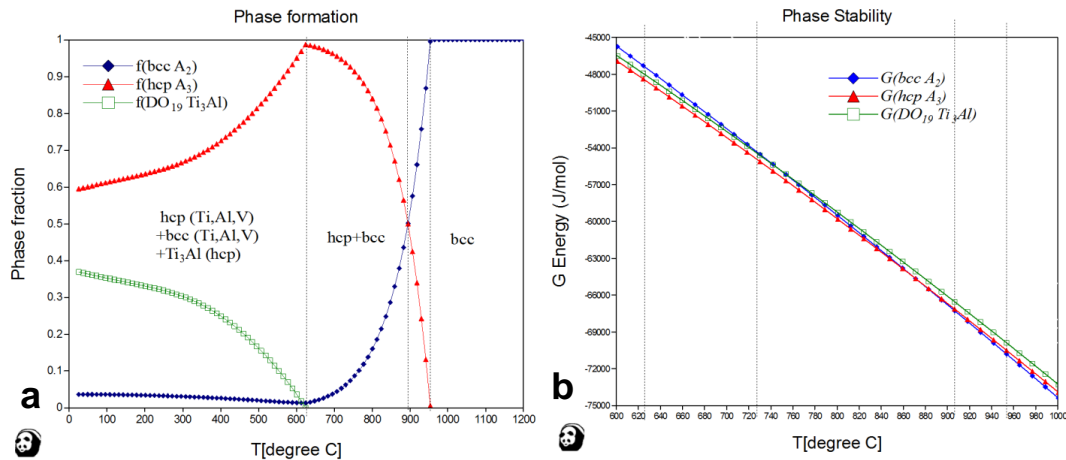


Figure 5. Phase stability and free energy of α_2 , α and β -phase in equilibrium condition from room temperature to 1200°C

The flow stress of the isothermally compressed Ti6Al4V at 800°C according to treatment A (Table 1) is shown in Figure 6b. The flow stress firstly exhibits strain hardening up to a strain of 0.2 followed by gradual softening before reaching a steady state stress. The transformation of β into α (the loose packed bcc structure of the β -phase is expected to be easier to deform than the α -phase which has an hcp structure that slips prismatically ($c/a < 1.62$) and not on its basal planes) and the distortion and reorientation of α/β platelets may contribute to this hardening effect. However, the subsequent flow softening is most likely attributed to dynamic recrystallization of deformed grains and deformation-induced dynamic globularization of α -phase.

The isothermally compressed Ti6Al4V contains α' , Ti_3Al , α , β and α'' (orthorhombic martensite) [5], as revealed by microstructural analysis, thermodynamic calculations and the DSC thermogram. Additionally, straight, kinked and reoriented α/β lamellae were revealed in the LDZ or the NDZ, the MDZ, and the ISZ respectively. The globularization of the α -phase dominated in the MDZ, however the fragmentation of the β -phase was more important in the ISZ. The microstructure evolution changing from the LDZ/NDZ to the ISZ was clearly visible. It was mostly affected by the stress characteristics (tensile stress in the MDZ, and shearing stress in the ISZ), strain rate and the deformation temperature. The the straight α/β lamella in the LDZ or NDZ revealed the non-deformed morphology of the prior α/β platelets. The kinking (in the MDZ) and complete reorientation (in the ISZ) of the α laths are due respectively to tension and shear stresses, as schematically shown in Figure 2b. The shear stress is the main cause of grain and phase boundary sliding. However the fragmentation or breakup of the β -phase is mainly attributed to the shear stresses in the ISZ and the partial transformation of the β -phase. The surface and free energy reduction are the driving forces for this concurrent deformation-transformation process.

The dynamic globularization of the α -phase is mostly controlled by the β into α transformation. Above the β -transus temperature (T_β), the isothermal compression concurrently occurred with an α into β transformation with β being the most stable phase, see Phase Formation and Stability diagram in Figure 5. Below T_β (between 900°C and 750°C) the β into α transformation, with α being the most stable phase above 850°C, occurred simultaneously with the isothermal compression. The optimum condition is obtained in the

temperature range of 900°C and 850°C where the α and β -phases have the same Gibbs free energy according to the thermodynamic calculation shown in Figure 5b. The tensile and shear stresses (leading to phase boundary sliding) are contributing significantly to the dynamic globularization of the α -phase. Therefore, the mechanism of dynamic globularization of the α -phase in the Ti6Al4V alloy is actively controlled by the β into α transformation and the flow stress characteristics. The relatively higher volume fraction of α -phase during the isothermal compression within the temperature range of 850°C and 950°C implies the improvement of the kinetics of β into α transformation which is due to stress-induced β into α transformation, as α and β -phase have the same Gibbs free energy.

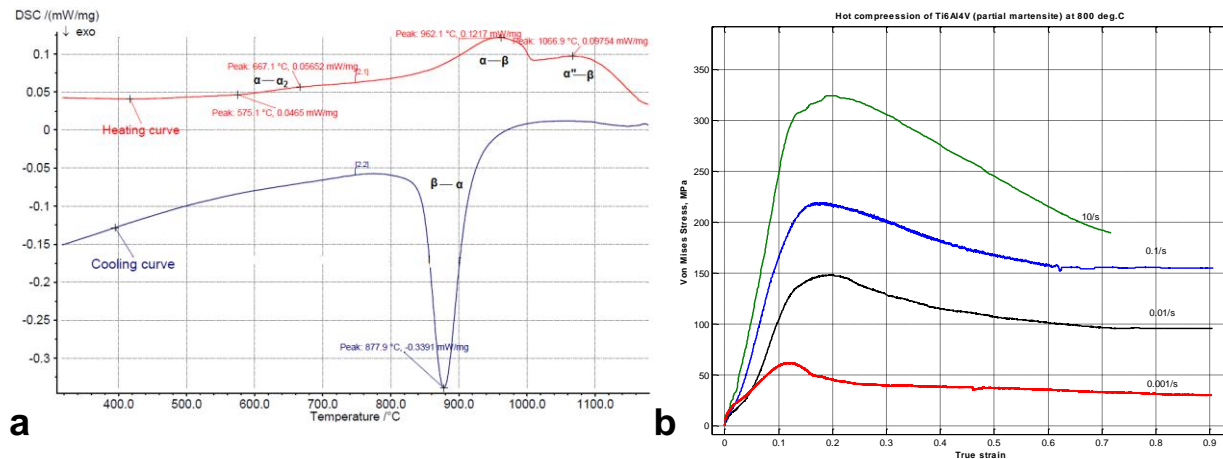


Figure 6. a) DSC thermogram of the isothermally compressed Ti6Al4V; and b) the flow stress of the isothermally compressed at 800°C

Conclusions

The dynamic globularization of α -phase in the Ti6Al4V alloy during isothermal compression was investigated using thermo-mechanical simulation. The conclusions are here below:

1. The isothermal compression above the β -transus temperature led to homogenous deformation, however compression in $(\alpha+\beta)$ field generated flow localization regions.
2. Compressing the Ti6Al4V alloy in the β field showed no dynamic globularization of the α -phase, however compression in the $(\alpha+\beta)$ field at temperature above 650°C produced α -phase globules.
3. Increasing the strain rate to above 0.01/s, suppressed the dynamic globularization of the α -phase.
4. The globular structure of the α -phase is mostly observed in the regions subject to tension and shear stresses.
5. Kinking and complete reorientation of α laths are due to tension and shear stresses respectively. However the breakup of the β -phase is mainly attributed to the shear stresses and partial transformation of β into α -phase.
6. The β into α -phase transformation mainly controlled the dynamic globularization of α -phase.

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