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The influence of initial plastic deformation on microstructure and hot plasticity of α+β titanium alloys

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ABSTRACT

Purpose: Hot deformation behaviour of two-phase titanium alloys is determined depending on microstructure developed in heat treatment and plastic deformation processes. In the paper stereological parameters of microstructure obtained in initial heat treatment and plastic working in the α+β↔β phase transformation range with various forging reduction ($\varepsilon \approx 20$ and 50%) were determined. Evaluation of the effect of thermomechanical process parameters on hot plasticity of Ti-6Al-4V and Ti-6Al-2Mo-2Cr titanium alloys was performed.

Design/methodology/approach: In the research, light and transmission electron microscopy were employed. Digital image analysis methods were used for determination of stereological parameters of microstructure obtained in particular stages of thermomechanical process of Ti-6Al-4V and Ti-6Al-2Mo-2Cr titanium alloys. Hot deformation of thermo mechanically processed titanium alloys was performed in vacuum at the temperature of 850 and 925ºC at the strain rates $\dot{\varepsilon} = 1\cdot10^{-2}$, $1\cdot10^{-1}$ and $5\cdot10^{-1}$ s^{-1}.

Findings: It was found that degree of initial plastic deformation in thermomechanical process considerably affects relative elongation in high temperature tensile test at the lowest strain rate applied ($\dot{\varepsilon} = 1\cdot10^{-2}$).

Research limitations/implications: Developed thermomechanical process enables controlling morphology of microstructural constituents and hot workability of two-phase α+β titanium alloys

Practical implications: Obtaining the demanded operational and technological properties of structural two-phase α+β titanium alloys is related to both the appropriate selection of hot working parameters and preceding thermomechanical process conditions.

Originality/value: The effect of heat treatment conditions in thermomechanical process on superplasticity of Ti-6Al-4V alloy was researched previously [1, 2]. In this paper two-phase Ti-6Al-2Mo-2Cr titanium alloy was examined too. Additionally, the influence of a degree of initial deformation in thermomechanical process was analyzed. Hot deformation test were conducted at conditions outside the superplastic range too.

Keywords: Titanium alloys; Thermomechanical process; Hot deformation; Heat treatment; β-solution

Reference to this paper should be given in the following way:

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PROPERTIES

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1. Introduction

Two phase titanium alloys most often are hot deformed, mainly by open die or die forging. Achievement of desired mechanical properties is related to development of proper microstructure in plastic working and heat treatment processes. Irreversible microstructural changes caused by deformation in α+β↔β phase transformation range quite often cannot be eliminated or decreased by heat treatment, and therefore, required properties of products cannot be achieved [3-5].

During hot working of titanium alloys several factors make obtaining products difficult or even preclude having adequate microstructure and properties i.e.: high chemical affinity to oxygen, low thermal conductivity and high heat capacity and significant dependence of plastic flow resistance on strain rate [6, 7]. Differences in temperature across the material volume, which result from various deformation conditions (local strain and strain rate) and physical properties of titanium lead to formation of zones having various phase composition (equilibrium α and β phases, martensitic phases α' (α")), morphology (equiaxial, lamellar, bi-modal) and dispersion (fine- or coarse-grained) and therefore various mechanical properties [8, 9].

Obtaining demanded microstructure of Ti-6Al-4V titanium alloy using plastic deformation in the α+β↔β phase transformation range is related to proper conditions selection taking into consideration plastic deformation, phase transformation, dynamic recovery and recrystallization effects [10-13]. Increase of plastic deformation effects (grain refinement) can be obtained by including preliminary heat treatment in thermomechanical process. The final heat treatment operations are usually used for stabilization of microstructure (they restrict grain growth) [14].

The effect of thermomechanical process conditions on superplasticity of Ti-6Al-4V alloy was previously investigated [1]. It was found that the proper selection of preliminary treatment parameters considerably enhances superplastic deformation of tested alloy which is related to initial microstructure and its changes during deformation [15].

In the paper the effect of conditions of heat treatment and degree of plastic deformation in thermomechanical process on development of microstructure and hot plasticity of Ti-6Al-4V and Ti-6Al-2Mo-2Cr titanium alloys was determined.

2. Experimental procedure

2.1. Material

Martensitic two-phase α+β Ti-6Al-4V and Ti-6Al-2Mo-2Cr titanium alloys bars (ϕ = 16 mm) were examined. Chemical composition of tested alloys is shown in Table 1.

Table 1.
Chemical composition of titanium alloys tested

Alloy	Al	V	Mo	Cr	Fe	Si	Ti
	wt. %						
Ti-6Al-4V	6.78	4.38	-	-	0.18	0.33	bal.
Ti-6Al-2Mo-2Cr	6.87	-	3.16	1.57	0.45	0.65	bal.

Ti-6Al-4V alloy is a popular structural material for aerospace applications while the Ti-6Al-2Mo-2Cr is used in Russia and known as WT3-1 alloy.

2.2. Techniques

Critical temperatures of α+β↔β phase transformation in tested titanium alloys were determined on BÄHR 805 A/D dilatometer using 10ºC/min heating and cooling rate. On the basis of dilatometric results and previous investigations conditions of heat treatment and plastic deformation were defined and two schemes of thermomechanical processing were worked out, called further in the paper as TMP-I and TMP-II (Fig. 1). Preliminary heat treatment – quenching – was carried out from the temperature T = 1050ºC – above the final temperature of α+β↔β phase transformation. Plastic deformation in the α+β↔β phase transformation range (T = 900ºC) was performed in WSK "PZL Rzeszów" S.A. using open die forging process with forging reduction by about 20 and 50% (Fig. 1).

a) b)

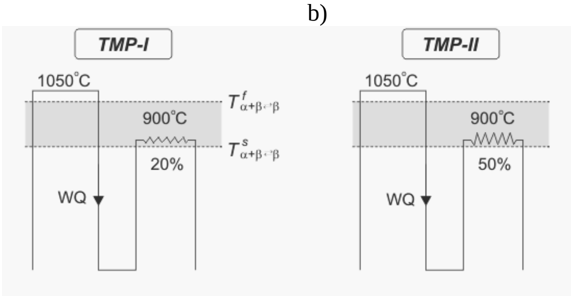


Fig. 1. Schemes of thermomechanical processing of Ti-6Al-4V alloy with forging reduction ε ≈ 20% (a) and ε ≈ 50% (b) (WQ - water quenching)

Light microscope (LM) Nikon Epiphot 300 equipped with digital camera Nikon DS-1U and transmission electron microscopes (TEM) Tesla BS540 and JEOL JEM-2100 were employed for microstructural observation. Metallographic specimens were edged using Kroll's reagent. Evaluation of stereological parameters of microstructural constituents was performed on longitudinal etched microsections using quantitative metallography methods and image analysis software Aphelion 3.2. Following parameters were determined:

- Ti-6Al-4V alloy with grained initial microstructure: grain size of α phase expressed by length of sides of rectangular circumscribed on grain section – $\overline{a}_\alpha$ and $\overline{b}_\alpha$, elongation factor of α phase grains – $\overline{f}_\alpha$ and volume fraction of α phase – $V_{V\alpha}$;
- Ti-6Al-2Mo-2Cr alloy with lamellar microstructure: grain size of primary β phase expressed by length of sides of rectangular circumscribed on grain section – $\overline{a}_{\beta\ \mathrm{prim}}$ and $\overline{b}_{\beta\ prim}$, elongation factor of primary β phase grains – $\overline{f}_{\beta\ \mathrm{prim}}$, size of the colony of parallel α lamellae – R, thickness of α-lamellae and volume fraction of α phase – $V_{V\alpha}$.

Hot deformation tests in vacuum (p = 0.005 Pa) were carried out on universal hydraulic testing machine Instron 8801 at the temperature T = 850 and 925ºC - below and within the temperature range of α+β↔β phase transformation, respectively.

The strain rates $\dot{\varepsilon} = 1\cdot10^{-2}$, $1\cdot10^{-1}$ and $5\cdot10^{-1}$ s^{-1} were applied. Round specimens having diameter d = 6 mm and gauge length l_0 = 8 mm were used. The maximum flow stress σ_{pm} and relative elongation A were determined.

3. Results and discussion

Microstructure of as-received Ti-6Al-4V alloy is composed of globular, fine α grains and β phase in the form of thin layers separating α grains (Fig. 2a). Quenching of Ti-6Al-4V alloy from the β phase temperature range leads to formation of microstructure composed solely of martensitic α'(α'') phase (Fig. 2b). Microstructure after following plastic deformation in the α+β↔β range with forging reduction of about 20% (TMP-I) and 50% (TMP-II) contains elongated and deformed grains of primary α phase in the matrix of β transformed phase containing fine globular grains of α secondary phase (Figs. 2c,d). Higher degree of initial deformation leads to obtaining finer microstructure containing more elongated α grains – $\bar{f}_\alpha$ = 16 for ε = 20% and 21.1 for ε = 50%. The larger volume fraction of α phase was also found (Table 2).

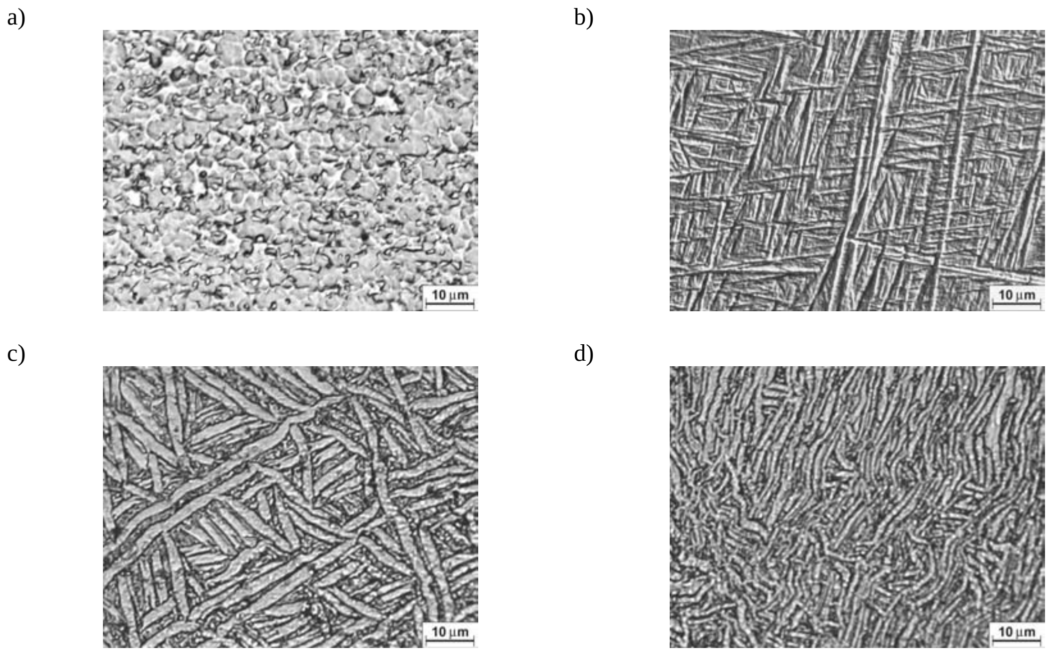


Fig. 2. Microstructure (DIC) of Ti-6Al-4V alloy before thermomechanical processing (a), after quenching from the β phase range (b) and after deformation in the α+β↔β range with forging reduction by 20 (c) and 50% (d)

Table 2.
Stereological parameters of microstructure of as-received and thermomechanically processed Ti-6Al-4V and Ti-6Al-2Mo-2Cr alloys

Condition of Ti-6Al-4V alloy	Stereological parameters					
	V_α	$\bar{a}_\alpha$	$\bar{b}_\alpha$	$\bar{f}_\alpha$		
	%	µm	µm			
As received	82	4.1	5.3	0.77		
TMP-I processed	59	51.3	3.2	16		
TMP-II processed	79	23.2	1.1	21.1		
Condition of Ti-6Al-2Mo-2Cr alloy	V_α	$\bar{a}_{\beta prim}$	$\bar{b}_{\beta prim}$	$\bar{f}_{\beta prim}$	R	g
	%	µm	µm		µm	µm
As received	76	137	42	3.26	12	1
TMP-I processed	34	-	-	-	-	4
TMP-II processed	40	-	-	-	-	1

a)

b)

c)

d)

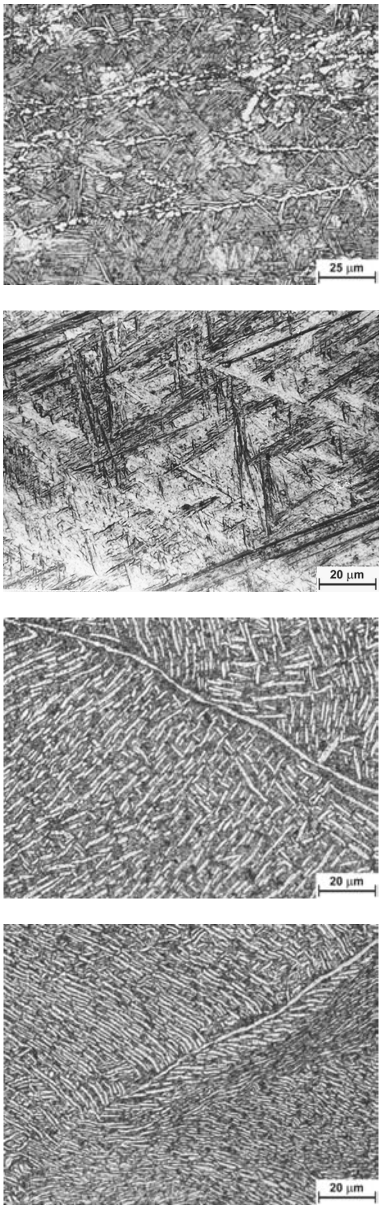


Fig. 3. Microstructure (DIC) of Ti-6Al-2Mo-2Cr alloy before thermomechanical processing (a), after quenching from the β phase range (b) and after deformation in the α+β↔β range with forging reduction by 20 (c) and 50% (d)

Microstructure of as-received Ti-6Al-2Mo-2Cr alloy is composed of colonies of parallel α-lamellae enclosed in primary β phase grains (Fig. 3a). Solution heat treatment leads to formation of microstructure composed of martensitic α'(α'') phase, similarly to Ti-6Al-4V alloy (Fig. 3b). Microstructure after thermomechanical processes (TMP-I and TMP-II) contains fine, elongated grains of α phase in the matrix of β transformed phase (Figs. 3c,d). In contrary to Ti-6Al-4V alloy primary β phase grain boundaries were observed. Higher degree of initial deformation in thermomechanical process leads to obtaining finer microstructure and larger volume fraction of α phase (Table 2).

TEM examination of Ti-6Al-4V alloy revealed fragmentation of elongated α phase (Fig. 4a) and presence of globular secondary α grains in the β transformed matrix (Fig. 4b) after TMP-I thermomechanical processing. Higher dislocation density in elongated α grains was observed after TMP-II processing (larger forging reduction) (Figs. 5a, b).

a)

b)

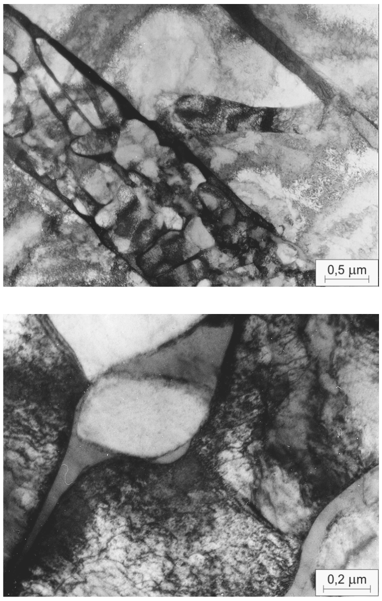


Fig. 4. Microstructure (TEM) of Ti-6Al-4V alloy after TMP-I process: fragmentation of α phase (a), globular secondary α phase grain (b)

a)

b)

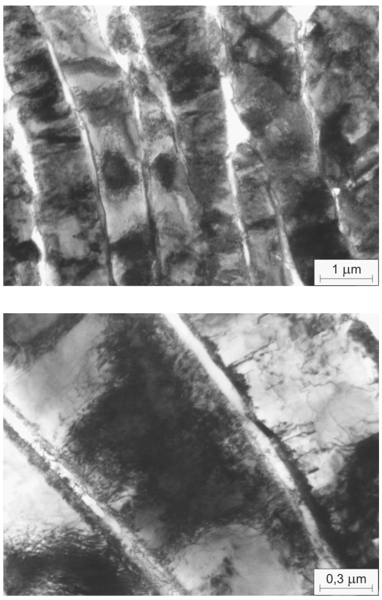


Fig. 5. Microstructure (TEM) of Ti-6Al-4V alloy after TMP II process: high dislocation density in α grains

In Ti-6Al-2Mo-2Cr alloy after TMP-I processing dislocations were observed mainly near grain boundaries (Fig. 6a). It was found that the secondary α phase in β transformed matrix occurs in lamellar form (Fig. 6b). Higher degree of deformation in TMP-II process led to higher dislocation density in α phase grains (Fig. 7a) and fragmentation of elongated α grains (Fig. 7b).

In Ti-6Al-2Mo-2Cr alloy higher volume fraction of β phase (Table 3) was found than in Ti-6Al-4V alloy which can be explained by higher value of coefficient of β phase stabilisation K_β [16].

Dilatometric examination revealed different critical temperatures of α+β↔β phase transformation in tested titanium alloys – the temperature range of phase transformation was considerably wider in Ti-6Al-2Mo-2Cr alloy (Table 3).

a)

b)

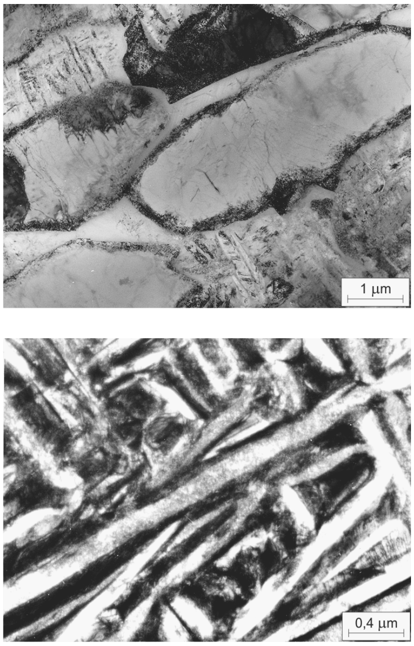


Fig. 6. Microstructure (TEM) of Ti-6Al-2Mo-2Cr alloy after TMP-II process: dislocations in α grains (a), subgrains in α phase (b)

a)

b)

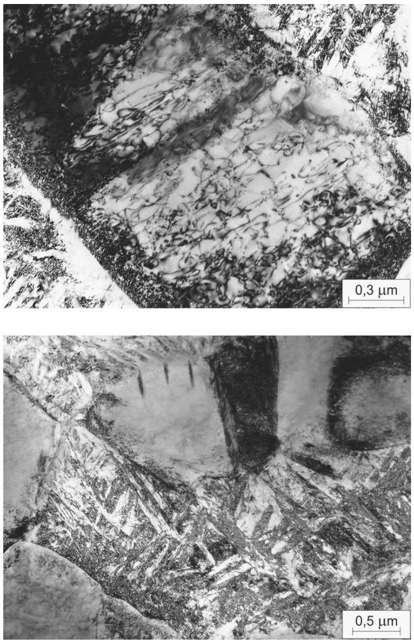


Fig. 7. Microstructure (TEM) of Ti-6Al-2Mo-2Cr alloy after TMP-II process: dislocations in α grains (a), subgrains in α phase (b)

Dilatometric examination revealed the influence of forging reduction on critical temperatures of α+β↔β phase transformation. The TMP-II thermomechanical processing with highest strain applied ($\varepsilon \approx 50\%$) causes significant increase of finish temperature of α+β↔β phase transformation in both examined titanium alloys (Tab. 3 and Figs. 8 and 9).

On the basis of tensile tests at 850°C and 925°C (below and within the temperature range of α+β↔β phase transformation, respectively) on thermo mechanically processed Ti-6Al-4V and Ti-6Al-2Mo-2Cr alloys it was found that the maximum flow stress σ_{pm} decrease with increase of hot deformation temperature and rise of strain rate (Fig. 10).

It was found that the maximum flow stress σ_{pm} determined in tensile test is higher at lower test temperature 850°C for the strain rate range applied (Fig. 10). There is no significant effect of a degree of initial deformation (forging) of two tested alloys on σ_{pm} value for both 850°C and 925°C test temperature (Fig. 10).

Table 3.
Critical temperatures of α+β↔β phase transformation of as received and thermomechanically processed Ti-6Al-4V alloy

Critical temperatures of α+β↔β phase transformation [ºC]	Condition of Ti-6Al-4V alloy		
	As-received	TMP-I processing	TMP-II processing
Start of α+β↔β	894	882	912
Finish of α+β↔β	979	976	1009
	Condition of Ti-6Al-2Mo-2Cr alloy		
	As-received	TMP-I processing	TMP-II processing
Start of α+β↔β	803	800	809
Finish of α+β↔β	991	992	1011

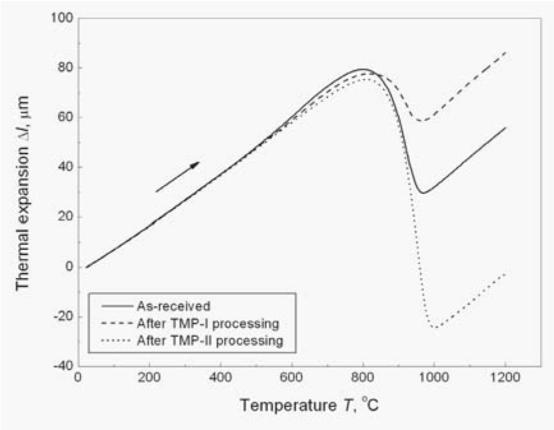


Fig. 8. Dilatometric curves of Ti-6Al-4V alloy in as-received state and after thermomechanical processing

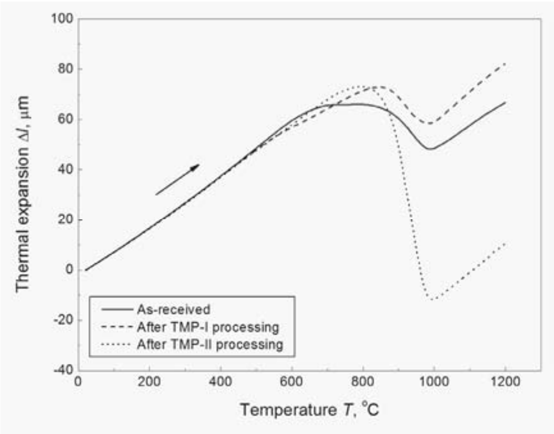
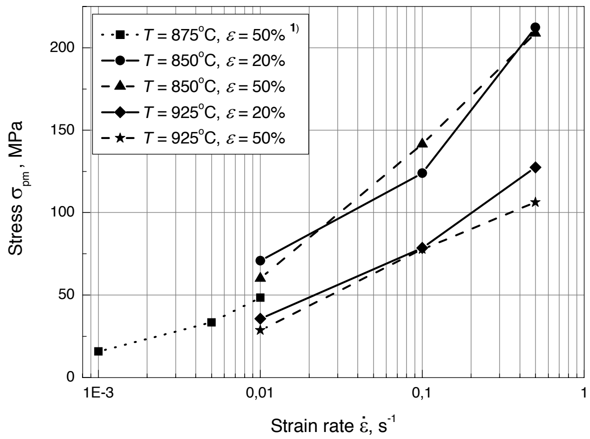


Fig. 9. Dilatometric curves of Ti-6Al-2Mo-2Cr alloy in as-received state and after thermomechanical processing

The relative elongation A of hot deformed Ti-6Al-4V and Ti-6Al-2Mo-2Cr titanium alloys decrease with the increasing strain rate $\dot{\varepsilon}$ in whole used range (Fig. 11). For higher $\dot{\varepsilon}$ the influence of forging reduction ε in thermomechanical processing and tensile test temperature is very slight. Considerable differences are visible for $\dot{\varepsilon} = 1 \cdot 10^{-2}\ s^{-1}$ where the maximum A value was achieved for both alloys deformed at 850°C. After thermomechanical processing TMP-II (ε ≈ 50%) alloys exhibit maximum elongations, typical for superplastic deformation (Fig. 11). It seems that higher grain refinement obtained in thermomechanical process enhanced hot plasticity of two-phase titanium alloys deformed with low strain rates. Similar behaviour was observed in previous researches on superplasticity of thermomechanically processed Ti-6Al-4V alloy [1, 15]. It was found that fragmentation and globularization of elongated α phase grains during initial stage of hot deformation restricted grain growth and resulted in higher values of strain.

Microstructural examination after thermomechanical processing and following hot deformation of Ti-6Al-4V and Ti-6Al-2Mo-2Cr titanium alloys was performed too (Figs. 12-15). It was found that microstructure of thermo mechanically processed Ti-6Al-4V alloy after tensile test at 850ºC is composed of elongated α grains mainly in the β transformed phase matrix with participations of α secondary phase (Fig. 12). Equiaxed microstructure was only observed for the lowest strain rate used ($10^{-2}\ s^{-1}$) in alloy previously processed using TMP-II method (Fig. 12d). It seems that fragmentation process of elongated α grains during hot deformation did not occur in Ti-6Al-4V alloy previously processed with lower initial plastic deformation (TMP-I).

a)



b)

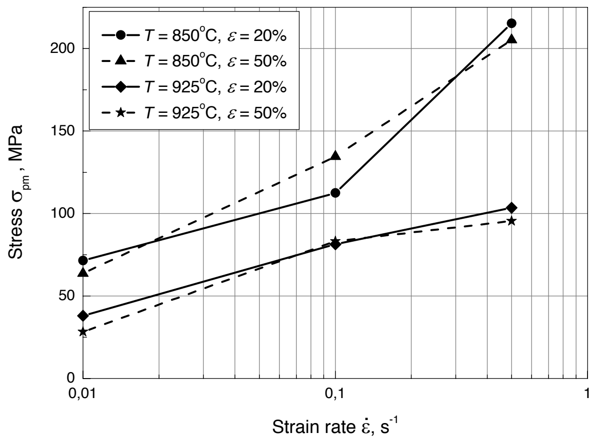
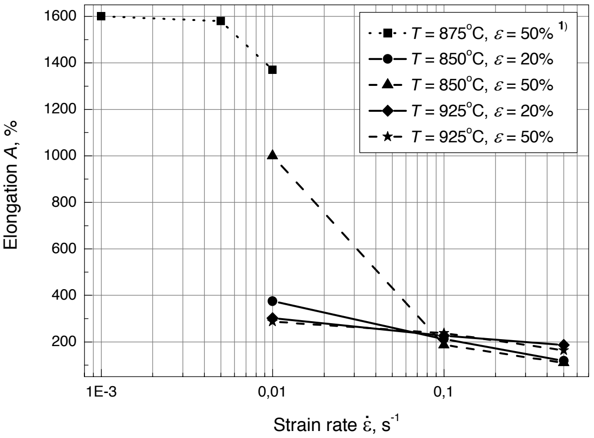


Fig. 10. The σ_{pm} - ε dependence (on the basis of tensile test) for Ti-6Al-4V (a) and Ti-6Al-2Mo-2Cr (b) alloys after processing TMP-I and TMP-II ([1) Results obtained in tensile tests in fine-grained superplasticity region for Ti-6Al-4V alloy after TMP-II processing [1])

Higher fragmentation effect was observed after tensile tests at 925ºC (within the temperature range of α+β↔β phase transformation) (Fig. 13). Similarly to previous tensile test conditions equiaxed microstructure was found in Ti-6Al-4V alloy for the lowest strain rate used but in this case both for TMP-I and TMP-II processes (Figs. 13a, d). It indicates a role for α+β↔β phase transformation in fragmentation and globularization processes of α grains during plastic deformation of two-phase titanium alloys at elevated temperature.

a)



b)

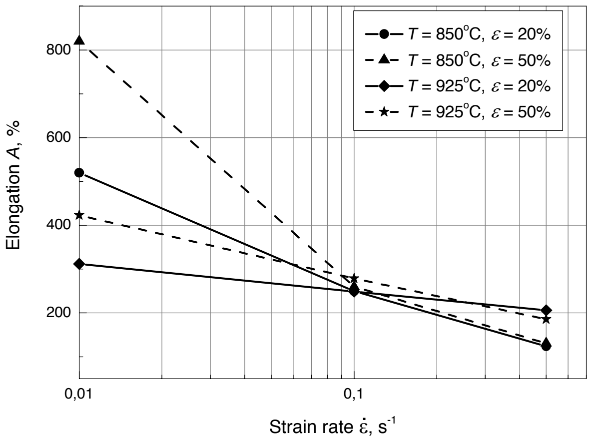


Fig. 11. The A - ε dependence (on the basis of tensile test) for Ti-6Al-4V (a) and Ti-6Al-2Mo-2Cr (b) alloys after processing TMP-I and TMP-II ([1] Results obtained in tensile tests in fine-grained superplasticity region for Ti-6Al-4V alloy after TMP-II processing [1])

Microstructure of thermo mechanically processed Ti-6Al-2Mo-2Cr alloy and hot deformed at 850ºC and 925°C contains primary and secondary α phase grains in the matrix of transformed β phase (Figs. 14 and 15).

Tensile test at 850°C caused microstructural changes similar to Ti-6Al-4V alloy deformed in the same conditions. After plastic deformation at higher temperature (925°C) α phase grains in the mixture of α and β lamellae were observed in microstructure (Fig. 15). Microstructural examination of Ti-6Al-4V and Ti-6Al-2Mo-2Cr titanium alloys deformed within the temperature range of α+β↔β transformation is difficult because of phase transformation occurred during the cooling.

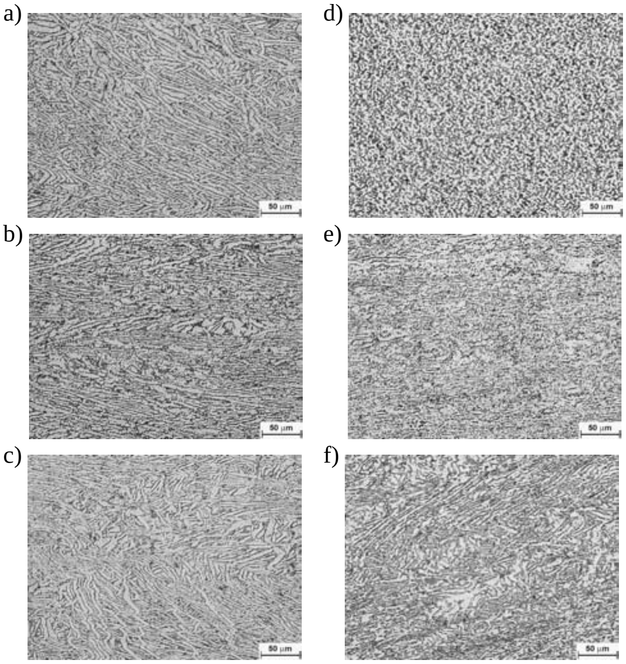


Fig. 12. Microstructure of Ti-6Al-4V alloy after TMP-I (a, b, c) and TMP-II (d, e, f) processing and plastic deformation at 850ºC with the strain rate of 10^{-2} (a, d), 10^{-1} (b, e) and $5\cdot10^{-1}$ s^{-1} (c, f)

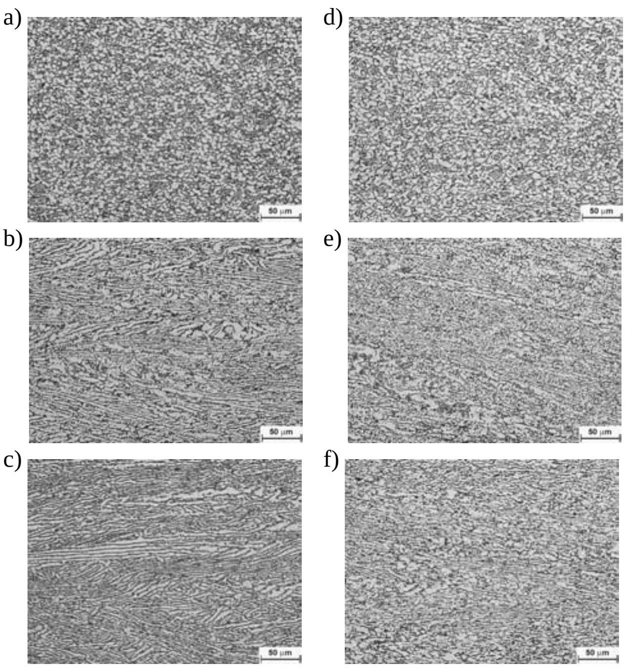


Fig. 13. Microstructure of Ti-6Al-4V alloy after TMP-I (a, b, c) and TMP-II (d, e, f) processing and plastic deformation at 925ºC with the strain rate of 10^{-2} (a, d), 10^{-1} (b, e) and $5\cdot10^{-1}$ s^{-1} (c, f)

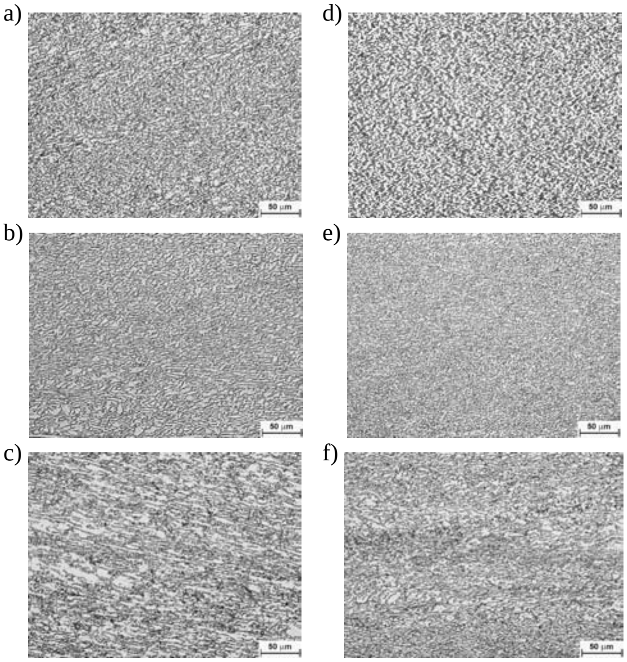


Fig. 14. Microstructure of Ti-6Al-2Mo-2Cr alloy after TMP-I (a, b, c) and TMP-II (d, e, f) processing and plastic deformation at 850ºC with the strain rate of 10^{-2} (a, d), 10^{-1} (b, e) and $5\cdot10^{-1}$ s^{-1} (c, f)

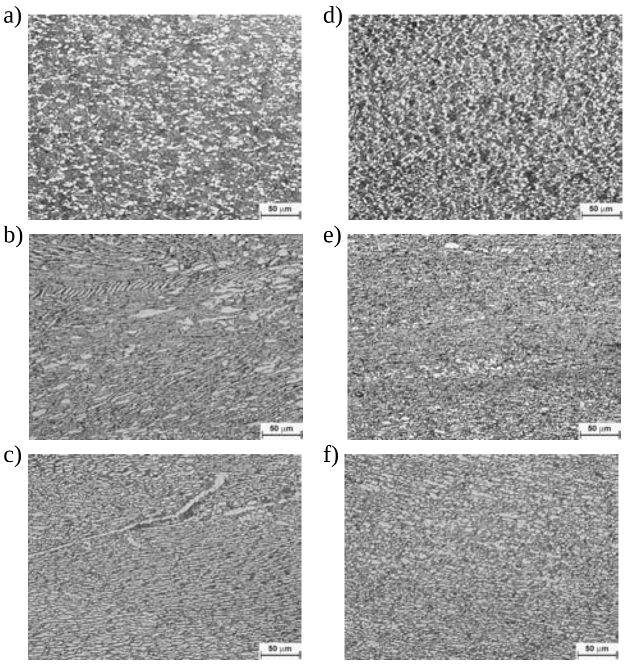


Fig. 15. Microstructure of Ti-6Al-2Mo-2Cr alloy after TMP-I (a, b, c) and TMP-II (d, e, f) processing and plastic deformation at 925ºC with the strain rate of 10^{-2} (a, d), 10^{-1} (b, e) and $5\cdot10^{-1}$ s^{-1} (c, f)

4. Conclusions

1. Proposed thermomechanical processing causes transformation of initial microstructure of Ti-6Al-4V and Ti-6Al-2Mo-2Cr alloys (globular and lamellar respectively) to highly deformed one containing distorted and elongated α grains.
2. Increase of a degree of initial deformation (forging) leads to formation of more elongated and refined α grains in both tested alloys.
3. Increase of strain rate during hot deformation of thermo mechanically processed two-phase titanium alloys causes rising of maximum flow stress σ_{pm} and decreasing of relative elongation A at both 850°C and 925°C deformation temperatures and strain rate range applied – independently on their microstructure.
4. Essential effect of degree of initial deformation in thermomechanical process is visible especially for the lowest strain rate $\dot{\varepsilon} = 1\cdot10^{-2}$ s^{-1} and lower tensile test temperature 850°C. Considerable rise of elongation A was observed in alloys with finer microstructure – after thermomechanical processing with a higher degree of initial deformation.
5. Hot deformation after thermomechanical processing of Ti-6Al-4V & Ti-6Al-2Mo-2Cr two-phase titanium alloys cause fragmentation of elongated α phase grains. Higher degree of initial deformation in thermomechanical process intensifies fragmentation process.

Acknowledgements

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