THE EFFECT OF INITIAL DEFORMATION ON HOT PLASTICITY OF Ti-6Al-4V ALLOY

Maciej Motyka

Summary

Hot deformation behaviour of two-phase titanium alloys is determined by type of microstructure developed in heat treatment and plastic deformation processes. Obtaining of demanded operational and technological properties is related to both the appropriate selection of hot working parameters and preceding thermomechanical process conditions. In the paper stereological parameters of microstructure obtained in initial heat treatment and plastic working in the $\alpha + \beta \leftrightarrow \beta$ phase transformation range with various forging reduction ($\varepsilon \approx$ 20 and 50%) were determined. Evaluation of the thermomechanical process parameters on hot plasticity of Ti-6Al-4V titanium alloy was performed. It was found that degree of initial plastic deformation considerably affects relative elongation in high temperature tensile test at the strain rate of $\dot{\varepsilon} = 1{\cdot}10^{-2}$ s^{-1}

Keywords: titanium alloys, thermomechanical process, microstructure, hot deformation

Wpływ wstępnego odkształcenia plastycznego na plastyczność na gorąco stopu Ti-6Al-4V

Streszczenie

Plastyczność na gorąco dwufazowych stopów tytanu jest determinowana rodzajem mikrostruktury kształtowanej w procesach obróbki cieplnej i odkształcania plastycznego. Uzyskanie wymaganych właściwości technologicznych i eksploatacyjnych zależy zarówno od prawidłowego doboru parametrów procesu przeróbki plastycznej na gorąco, jak i poprzedzającego go procesu cieplno-plastycznego. W pracy określono parametry stereologiczne mikrostruktury po wstępnej obróbce cieplnej i procesie odkształcania plastycznego w zakresie przemiany fazowej $\alpha + \beta \leftrightarrow \beta$ dla różnych wartości gniotu ($\varepsilon \approx$ 20 i 50%). Dokonano oceny wpływu parametrów procesu cieplno-plastycznego na plastyczność na gorąco stopu tytanu Ti-6Al-4V. Stwierdzono, że stopień wstępnego odkształcenia plastycznego ma istotny wpływ na wartość wydłużenia względnego w próbie rozciągania w podwyższonej temperaturze z prędkością odkształcania $\dot{\varepsilon} = 1{\cdot}10^{-2}$ s^{-1}.

Słowa kluczowe: stopy tytanu, proces cieplno-plastyczny, mikrostruktura, odkształcanie na gorąco

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

Address: Maciej MOTYKA, Ph.D. Eng., Rzeszow University of Technology, Faculty of Mechanical Engineering and Aeronautics, ul. W. Pola 2, 35-959 Rzeszów, phone: (+48, 17) 865-11-22, fax: (+48, 17) 854-48-32, e-mail: motyka@prz.edu.pl

processes. Irreversible microstructural changes caused by deformation in $\alpha + \beta \leftrightarrow \beta$ phase transformation range quite often can not be eliminated or decreased by heat treatment and therefore required properties of products can not be achieved [1-3].

During hot working of titanium alloys several factors make difficult or even preclude obtaining products 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 [4, 5]. 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 $\alpha'(\alpha'')$), morphology (equiaxial, lamellar, bi-modal) and dispersion (fine- or coarse-grained) and therefore various mechanical properties [6, 7].

Obtaining demanded microstructure of Ti-6Al-4V titanium alloy using plastic deformation in the $\alpha + \beta \rightleftarrows \beta$ phase transformation range is connected with proper conditions selection taking into consideration plastic deformation, phase transformation, dynamic recovery and recrystallization effects [8-10]. Increase of plastic deformation effects (grain refinement) can be obtained by including preliminary heat treatment in thermomechanical process. Final heat treatment operations are usually used for stabilization of microstructure (they restrict grain growth) [11].

The effect of thermomechanical process conditions on superplasticity of Ti-6Al-4V alloy was previously investigated [12]. It was found that the proper selection of preliminary treatment parameters considerably enhances super-plastic deformation of tested alloys which is related to initial microstructure and its changes during deformation [13].

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 titanium alloy was determined.

2. Material and experimental technique

Martensitic two-phase Ti-6Al-4V titanium alloy bars (ϕ = 16 mm) with chemical composition (wt %): Al – 6.78, V – 4.38, Fe – 0.18, Si – 0.33, Ni – 0.01, Ti – balance were used in the studies. Following critical temperatures of $\alpha + \beta \rightleftarrows \beta$ phase transformation were determined in dilatometric examinations: start – T^s = 887ºC and finish – T^f = 985ºC. On the basis of dilatometric results and previous investigations conditions of heat treatment and plastic deformation were defined and two schemes of thermomechanical process were worked out, called in the paper TMP-I and TMP-II (Fig. 1). Preliminary heat treatment – quenching – was carried out from the temperature T = 1050ºC – above the finish temperature of $\alpha + \beta \rightleftarrows \beta$ phase transformation. Plastic deformation in the $\alpha + \beta \rightleftarrows \beta$ phase transformation range were performed in WSK "PZL - Rzeszów" S.A. using open die forging process with forging reduction of about 20 and 50% (Fig. 1).

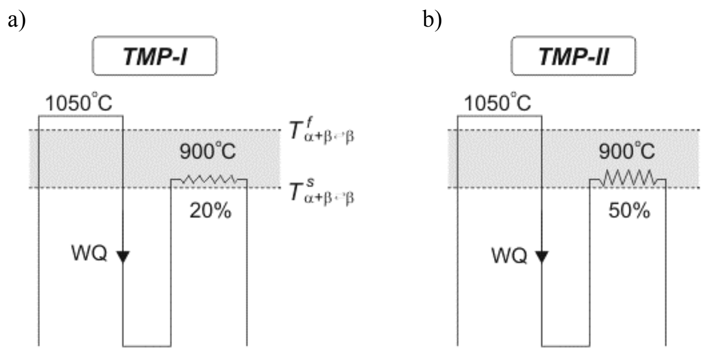

Fig. 1. Schemes of thermomechanical processes of Ti-6Al-4V alloy: forging reduction $\varepsilon \approx 20\%$ (a) and $\varepsilon \approx 50\%$ (b) (WQ – water quenching)

Light microscope (LM) Nikon Epiphot 300 equipped with digital camera Nikon DS-5 and transmission electron microscope (TEM) Jeol2010 were employed for microstructural observation. Evaluation of stereological parameters of microstructural components was performed on longitudinal etched microsections using quantitative metallography methods and image analysis software Aphelion 3.2. Following parameters were determined: 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 – $V_{V\alpha}$.

Hot deformation tests in vacuum conditions (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 $\alpha + \beta \rightleftarrows \beta$ phase transformation adequately. The strain rates $\dot{\varepsilon} = 1 \cdot 10^{-2}$, $1 \cdot 10^{-1}$ and $5 \cdot 10^{-1}$ 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 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'') (Fig. 2b). Microstructure after following plastic deformation in the $\alpha + \beta \rightleftarrows \beta$ range with forging reduction of about 20% (TMP-I) and 50% (TMP-II) contains elongated and deformed grains of primary α_P phase separated by β phase layers (Fig. 2c, d). Higher degree of initial deformation leads to obtaining finer microstructure containing more elongated α grains – $\overline{f_\alpha}$ = 16 for ε = 20% and $\overline{f_\alpha}$ = 21,1 for ε = 50%. The larger volume fraction of α phase was also found (Tab. 1.).

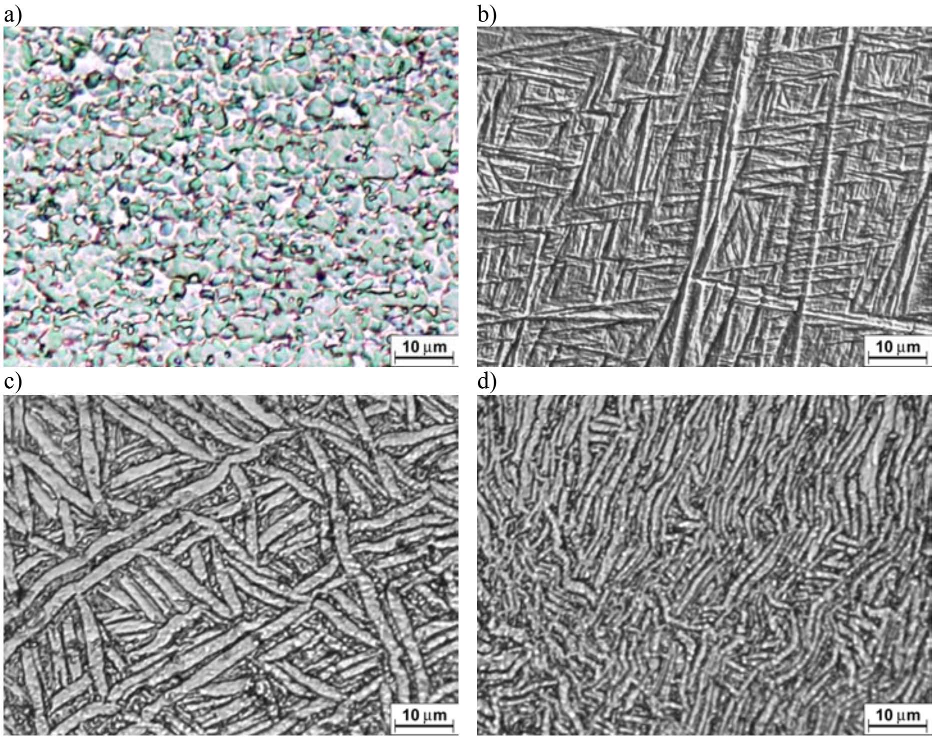

Fig. 2. Microstructure (DIC) of Ti-6Al-4V alloy before thermomechanical process (a), after quenching from the β phase range (b) and deformation in the $\alpha + \beta \rightleftarrows \beta$ range with forging reduction of 20 (c) and 50% (d)

TEM examination revealed presence of secondary α phase between primary α lathes in the alloy after TMP-I thermomechanical process (Fig. 3a) an higher dislocation density in elongated α grains in the alloys after TMP-II process (Fig. 3b).

Table 1. Stereological parameters of microstructure of as received and thermomechanically processed Ti-6Al-4V alloy

Condition of Ti-6Al-4V alloy	V_{α}, %	$\bar{a}_{\alpha}$, μm	$\bar{b}_{\alpha}$, μm	$\bar{f}_{\alpha}$
As received	82	4,1	5,3	0,77
Deformed with forging reduction of 20%	59,2	51,3	3,2	16
Deformed with forging reduction of 50%	78,5	23,2	1,1	21,1

a) b)

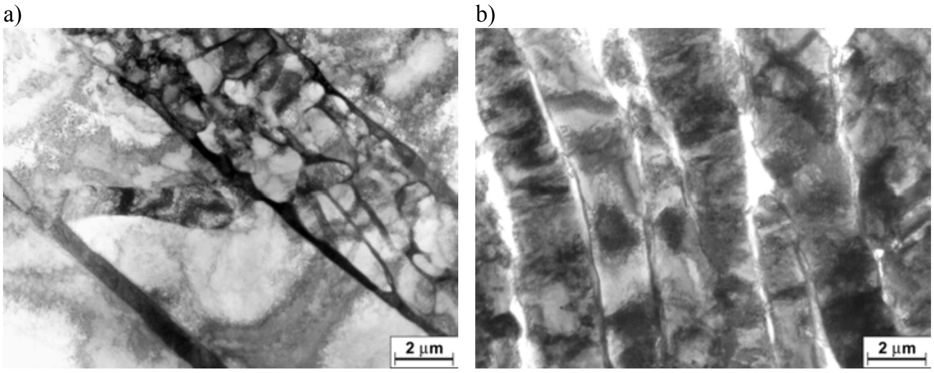

Fig. 3. Microstructure of Ti-6Al-4V alloy quenched from the β phase range and deformed in the $\alpha + \beta \rightleftarrows \beta$ range with forging reduction of 20 (a) and 50% (b)

Table 2. The average values of maximum flow stress σ_{pm} and relative elongation A determined in tensile test at the temperature T = 850 and 925°C with the strain rates of $\dot{\varepsilon}$ = $1\cdot10^{-2}$, $1\cdot10^{-1}$ and $5\cdot10^{-1}$ s^{-1}

Forging reduction in initial deformation of Ti-6Al-4V alloy, ε, %	**Deformation temperature**											
	T = 850°C						**T = 925°C**					
	Stress σ_{pm}, MPa			**Elongation A, %**			**Stress σ_{pm}, MPa**			**Elongation A, %**		
	Strain rate $\dot{\varepsilon}$, s^{-1}											
	10^{-2}	10^{-1}	$5x10^{-1}$	10^{-2}	10^{-1}	$5x10^{-1}$	10^{-2}	10^{-1}	$5x10^{-1}$	10^{-2}	10^{-1}	$5x10^{-1}$
20	70,8	123,9	212,3	375	212	118	35,7	78,6	127,4	302	226	187
50	60,2	141,5	208,8	1000	187	110	28,7	77,8	106,2	287	237	163

It was found that the maximum flow stress σ_{pm} in high temperature tensile test is higher for lower temperature $T = 850$ºC in the strain rate range of $\dot{\varepsilon} = 1\cdot10^{-2} \div 5\cdot10^{-1}$ s^{-1} (Fig. 4). There is no significant effect of degree of initial deformation (forging) on σ_{pm} value for both $T = 850$ºC and 925ºC deformation temperature (Table 2).

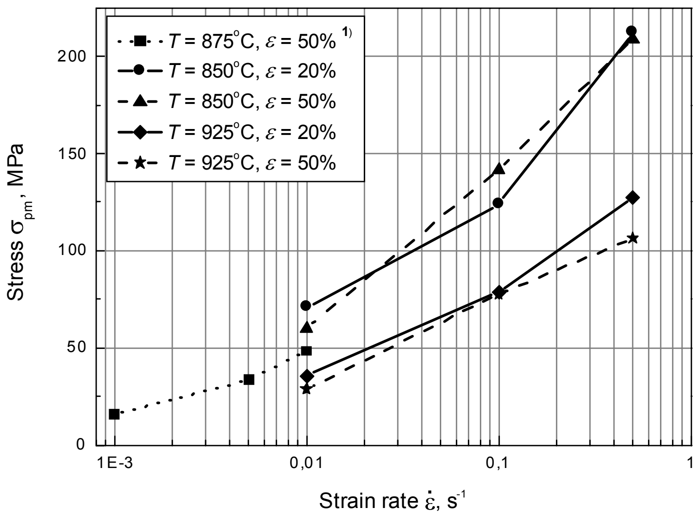

Fig. 4. The $\sigma_{pm} - \dot{\varepsilon}$ dependence (on the basis on tensile test) for Ti-6Al-4V alloy after processes TMP-I and TMP-II
[1)] Results obtained in typical superplasticity region for Ti-6Al-4V alloy after process TMP-II [12]

The relative elongation A of hot deformed Ti-6Al-4V alloy decrease with the increasing strain rate $\dot{\varepsilon}$ in whole used range (Fig. 5). For higher $\dot{\varepsilon}$ the influence of forging reduction ε in thermomechanical process and deformation temperature is very slight. Considerable differences are visible for $\dot{\varepsilon} = 1\cdot10^{-2}$ s^{-1} where the maximum A value was achieved for Ti-6Al-4V alloy deformed at $T = 850$ºC after thermomechanical process TMP-II (ε = 50%) – typical superplastic behaviour.

Light microscope investigation after hot deformation revealed that elongated primary α grains undergo fragmentation and globularization processes (Fig. 6a). The degree of microstructural changes is considerable for the lowest strain rate ($\dot{\varepsilon} = 1\cdot10^{-2}$ s^{-1}) which is related to the dynamic recovery processes (Fig. 6b, c). Microstructure of the sample where the maximum value of relative elongation A = 1000% was obtained (TMP-II, $T = 850$ºC, $\dot{\varepsilon} = 1\cdot10^{-2}$ s^{-1}) is equiaxed and fine-grained (grain size < 10 μm) (Fig. 6d). It is interesting that

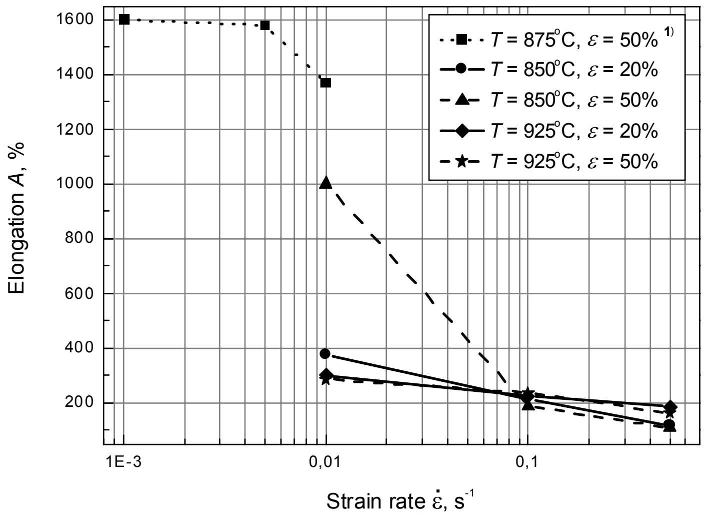

Fig. 5. The $A - \dot{\varepsilon}$ dependence (on the basis on tensile test) for Ti-6Al-4V alloy after processes TMP-I and TMP-II
[1)] Results obtained in typical superplasticity region for Ti-6Al-4V alloy after process TMP-II [12]

forging reduction ε = 20% (TMP-I) for the same hot deformation conditions does not lead to refining and spheroidization of α grains (Fig. 6e) so the elongation A is significantly smaller.

4. Conclusions

1. Proposed thermomechanical process causes transformation of microstructure of Ti-6Al-4V alloy from globular to highly deformed containing distorted and elongated α grains.
2. Increase of degree of initial deformation (forging) leads to formation of more elongated and refined α grains and reduces secondary α phase precipitation process.
3. Increase of strain rate during hot deformation of thermomechanically processed Ti-6Al-4V alloy causes rising of maximum flow stress σ_{pm} and decreasing of relative elongation A at both T = 850 and 925ºC deformation temperature and used strain rate range.
4. Essential effect of degree of initial deformation is visible especially for the lowest used strain rate $\dot{\varepsilon} = 1 \cdot 10^{-2}$ s^{-1} and lower temperature T = 850ºC where considerable rise of elongation A was observed (1000%).

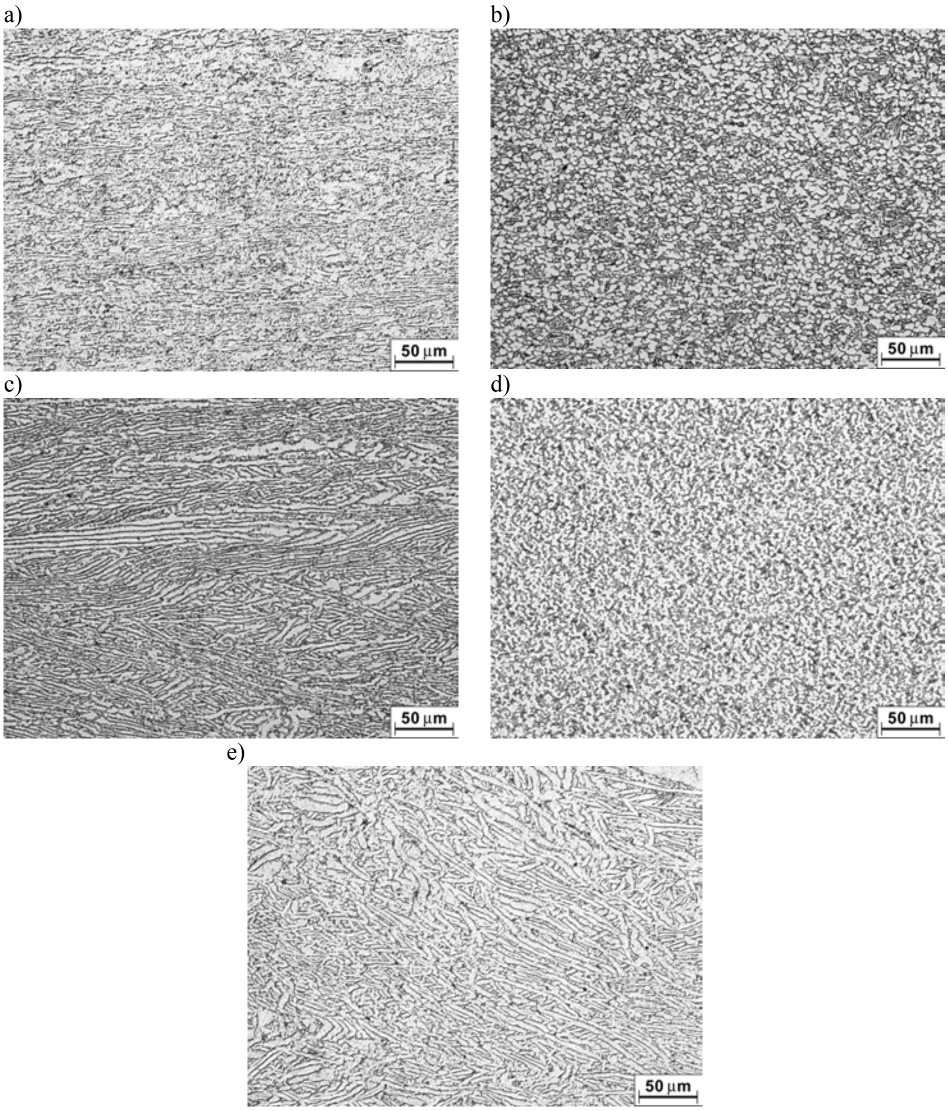

Fig. 6. Microstructure of Ti-6Al-4V alloy thermomechanically processed and hot deformed: TMP-II / $T = 850$ºC / $\dot{\varepsilon} = 1 \cdot 10^{-1}$ s^{-1} (a), TMP-I / $T = 925$ºC / $\dot{\varepsilon} = 1 \cdot 10^{-2}$ s^{-1} (b), TMP-I / $T = 925$ºC / $\dot{\varepsilon} = 5 \cdot 10^{-1}$ s^{-1} (c), TMP-II / $T = 850$ºC / $\dot{\varepsilon} = 1 \cdot 10^{-2}$ s^{-1} (d) and TMP-I / $T = 850$ºC / $\dot{\varepsilon} = 1 \cdot 10^{-2}$ s^{-1} (e) (thermomechanical process / deformation temperature / strain rate)

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References

[1] J. SIENIAWSKI: Przemiany fazowe i ocena możliwości kształtowania struktury w wieloskładnikowych stopach tytanu z zawartością Al, Mo, V i Cr. Zeszyty Naukowe Politechniki Rzeszowskiej, Mechanika, z. 10, Rzeszów 1985.

[2] A. BYLICA, J. SIENIAWSKI: Tytan i jego stopy. PWN, Warszawa 1985.

[3] J. SIENIAWSKI: Nickel and titanium alloys in aircraft turbine engines. *Advances in Manufacturing Science and Technology*, **27**(2003), 23-34.

[4] R.R. BOYER: An overview on the use of titanium in the aerospace industry. *Mater. Sci. Eng.*, **A213**(1996), 103-114.

[5] G. LÜTJERING: Influence of processing on microstructure and mechanical properties of $(\alpha + \beta)$ titanium alloys. *Mater. Sci. Eng.*, **A243**(1998), 32-45.

[6] K. KUBIAK, J. SIENIAWSKI: Development of the microstructure and fatigue strength of two phase titanium alloys in the processes of forging and heat treatment. *J. Mater. Process. Tech.*, **78**(1998), 117-121.

[7] A.W. BOWEN, D.S. McDARMAID, P.G. PARTRIDGE: Effect of high-temperature deformation on the texture of a two-phase titanium alloy. *J. Mater. Sci.*, **26**(1991), 3457-3462.

[8] R. DING, Z.X. GUO, A. WILSON: Microstructural evolution of a Ti-6Al-4V alloy during thermomechanical processing. *Mater. Sci. Eng.*, **A327**(2002), 233-245.

[9] T. SESHACHARYULU, B. DUTTA: Influence of prior deformation rate on the mechanism of $\beta \rightleftarrows \alpha + \beta$ transformation in Ti-6Al-4V. *Scripta Mater.*, **46**(2002), 673-678.

[10] K. KUBIAK: Technologiczna plastyczność dwufazowych stopów tytanu odkształcanych na gorąco. Oficyna Wyd. Politechniki Rzeszowskiej, Rzeszów 2004.

[11] C.H. JOHNSON, S.K. RICHTER, C.H. HAMILTON, J.J. HOYT: Static Grain Growth in a Microduplex Ti-6Al-4V Alloy. *Acta Mater.*, **47**(1999), 23-29.

[12] M. MOTYKA, J. SIENIAWSKI: The influence of thermomechanical process conditions on superplastic behaviour of Ti-6Al-4V titanium alloy. *Advances in Manufacturing Science and Technology*, **28**(2004)4, 31-44.

[13] M. MOTYKA: Evaluation of microstructural transformation during superplastic deformation of thermomechanically processed Ti-6Al-4V alloy. *Advances in Materials Science*, **7**(2007), 95-101.

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