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EFFECT OF DEFORMATION ON MICROSTRUCTURE AND MECHANICAL PROPERTIES PURE TITANIUM AND Ti6Al4V ALLOYS

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ABSTRACT
Exploitation of beneficial plastic properties of Ti_β structural phase is significantly limited at hot forming. Due to this, but also due to structural and mechanical properties, use of titanium alloys is prevalent. There are used particularly alloys with occurrence of (α+β) zone, which makes it possible to obtain very good resulting structures with high yield value and good plastic properties. Representative of the type of two-phase alloys at hot deformation is Ti6Al4V alloy, for which we investigated its resistance to deformation and formability. This paper describes manufacture of ultra-grain fine titanium, its structure and properties. Strength of ultra-grain fine titanium varies around 651 MPa, grain size around 300 nm.
Keywords: titanium, alloys, microstructure, mechanical properties, ECAP

1. INTRODUCTION
Pure titanium, as well as the majority of titanium alloys, crystallized at low temperatures in a modified ideally hexagonal close packed structure, called α titanium. At high temperatures, however, the body-centered cubic structure is stable and is referred to as β titanium. The β−transus temperature for pure titanium is 882 °C [1]. The atomic unit cells of the hexagonal close packed (hcp) α titanium and the body centered cubic (bcc) β titanium are schematically shown in Fig. 1 with their most densely packed planes and directions highlighted.

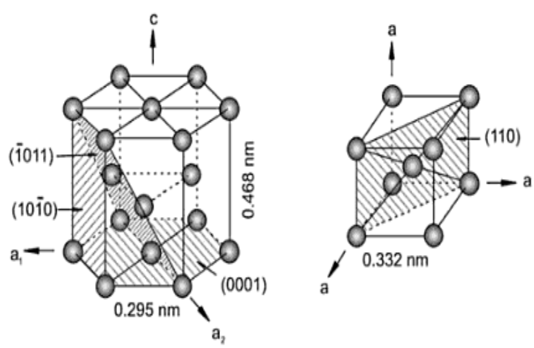


Figure 1. Crystal structure of (hcp) α and (bcc) β phase [1]

Structures with hexagonal lattice have at lower temperatures smaller number of slip planes and thus also lower plastic properties, which causes difficulties at cold forming. Number of slip planes in hexagonal lattice increases with increasing temperature and plastic properties also improves. Titanium alloys have substantially higher plastic properties at the interval of temperatures of β phase.
Titanium alloys are for these reasons characterised by limited formability at low temperatures, and by considerably higher formability at high temperatures. Forming of titanium alloys is therefore most frequently realised as hot forming in temperature interval from 900 ^{o}C to 1100 ^{o}C. Two-phase zone α+β, which in many alloys is comparatively narrow, can be extended by addition of other elements. Addition of approx. 0,3 % Fe extends this zone by more than 100°C. Only at flat forming, e.g. drawing of sheets, this is performed at temperatures of approx. 500 to 600 ^{o}C. Cold forming of titanium alloys can be used in case of comparatively small deformations.

2. MATERIALS AND EXPERIMENTAL METHODOLOGY

Experimental verification of deformation behaviour of titanium and its alloys has been performed with use of technically clean titanium and alloy of the type α and alloy (α+β), which have the largest use in industry: Ti 99,5 and alloys Ti6Al4V. Chemical composition of studied alloys is given in the Tab. 1.

Table 1. Chemical composition of titanium and titanium alloy Ti6Al4V

Alloy	Chemical composition [mass %]									
	Al	Sn	V	N	C	H	Fe	O	other	Ti
Ti 99,0	-	-	-	max. 0,05	max. 0,10	max. 0,015	max. 0,50	max. 0,40	-	rest
Ti6Al4V4	5,4	-	4,1	0,03	<0,08	<0,015	0,14	<0,15	0,05	rest

We have investigated effect of testing temperature in the temperature interval (320), 700 to 1200 ^{o}C on formability and resistance to deformation, at deformation rate 10^{1} to 10^{-2} s^{-1}, at magnitude of relative deformation ε = 5 to 80 %. Values of resistance to deformation are given in the Tab. 2.

Table 2. Resistance of titanium and Ti6Al4V alloys to deformation

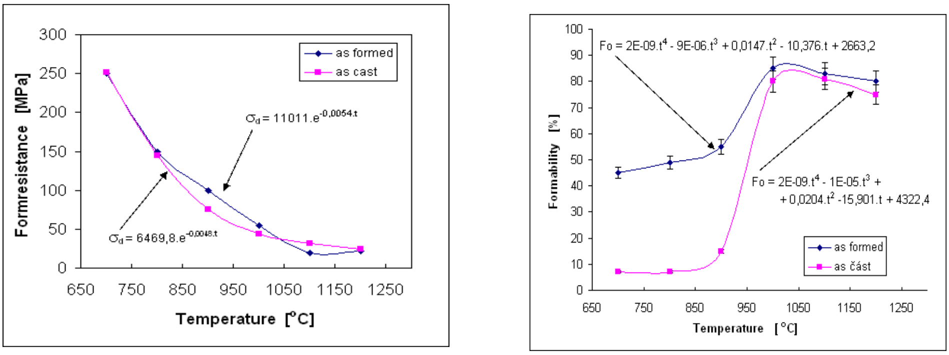
Grade	Structure	Temperature			
		900 ^{o}C		800 ^{o}C	
		$\dot{\varepsilon} = 10^{1}\ s^{-1}$	$\dot{\varepsilon} = 1 \cdot 10^{-2}\ s^{-1}$	$\dot{\varepsilon} = 10^{1}\ s^{-1}$	$\dot{\varepsilon} = 1 \cdot 10^{-2}\ s^{-1}$
		σ_d $[MPa]$	σ_d $[MPa]$	σ_d $[MPa]$	σ_d $[MPa]$
Ti (Grade 2)	α	50	29	96	54
Ti6Al4V (Ti Grade 5)	ααβ	171	87	396	205

The tests were made with use of mechanical upsetting of rolled samples. For upsetting test there were used the samples with dimensions: d_o = 13 mm and h_o = 15 mm. Contact surfaces on sample fronts were modified for application of lubricant. Lubrication of samples' fronts was effected by lubricants currently used for forming of titanium. The samples were re-heated in laboratory electric furnace in protective argon atmosphere. At least three samples have been tested for each temperature.
Deformation forces were measured by strain gauge, change of sample height was measured by electromagnetic sensor. Graphical representation of dependence of formability and resistance to deformation on temperature is for the alloy Ti6Al4V shown in Fig. 2.
At the specified rate of deformation there occurs a significant softening of titanium alloys, which is related to achievement of re-crystallisation temperature and polymorphous transformation. Optimal range of forming temperature for Ti6l64V alloy is between 975 up to 800 ^{o}C [2]. For forming into two phase structure α + β is initial structure state in dependence on used technological operation. At high deformations (e.g. degree of forging K= 2 up to 3) can be initial structure in acicular state.
Deformation resistance is affected by temperature and grain boundary, which are significant restriction in dislocation motion. With decreasing grain size is increasing share of grain boundary. At low temperatures will grain size cause increasing of strength, hardness and higher temperature will support

namely grain boundary sliding mechanism. For the dependence of strength, grain size can be used Hall-Petch relationship :

$$Rm = \sigma_o + k\,d^{\frac{-1}{2}} \qquad (1)$$

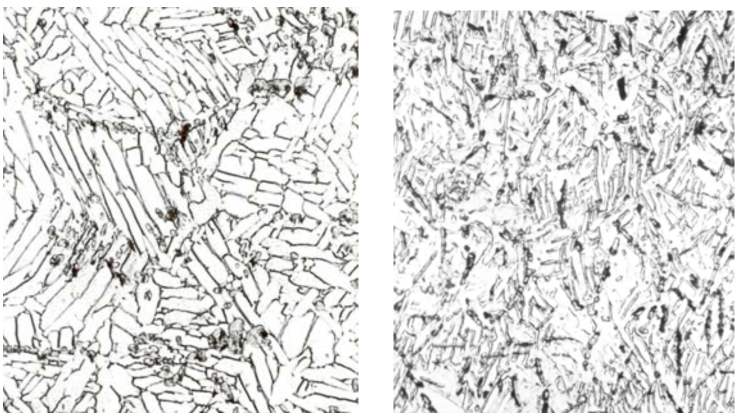
where σ_o and k are constants independent on grain size.



a) b)

Figure 2. Example of dependence of deformation resistance (a) and formability (b) on temperature for the alloy Ti6Al4V

Forming in range of $\alpha + \beta$ is accompanied by α needles browning, but these are not recrystallized. Transformation of original cast structure of the alloy Ti6Al4V (Fig. 3a) in dependence on deformation (Fig.3b)

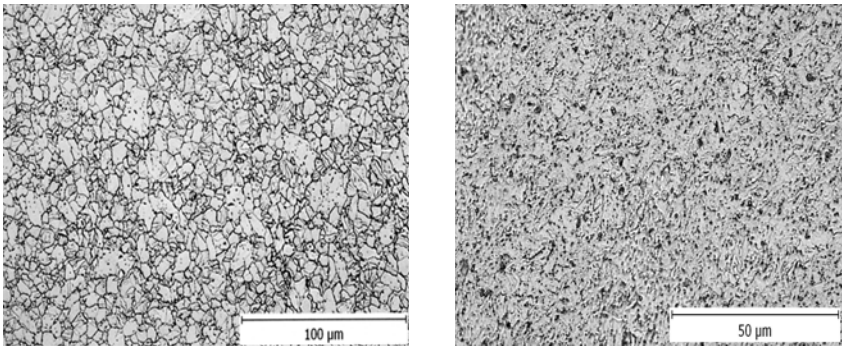


a) b)

Figure 3. Microstructure of TiAl6V4: a) in cast condition, b) after hot forming

3. ECAP OF COMMERCIAL PURE TITANIUM (GRADE 2)

ECAP is currently one of the most promising techniques that can produce ultra fine-grained materials. Commercial pure titanium with an average grain size of 30 μm was used as the starting material. The chemical composition shown in Table 1. An annealing treatment was carried out at 800 °C for 1 h to relieve the residual stress in the as-received state. For ECAP processing, cylindrical samples of ϕ 30 mm x 120 mm were machined from the annealed Ti. The ECAP die was designed to yield a shear strain of 1.83 by a single press: the inner contact angle and the arc of curvature at the outer point of contact between channels of the die were 105°. A single pass of ECAP was carried out on the samples at 400 °C. The specimens for tensile tests and for micro-structural analyses were prepared from individual variants of processing. On the basis of the results, particularly the obtained strength values, several variants were chosen for more detailed investigation of developments occurring in the structure at application of the ECAP and subsequent drawing after heat treatment. Structure of Ti after application of the ECAP process is shown in the Fig. 4. The structure was analysed apart from light microscopy also by the X-ray diffraction. Table 3 summarises the obtained basic mechanical properties. Mechanical properties were carried out using subsize specimens 3 mm in diameter developed in Material & Metallurgical research, Ltd.



a) b)

Figure 4. The typical microstructures of Ti the ECAP: a) 2 passes ECAP, b) 8 passes ECAP

Table 3. Mechanical properties pure Ti, Ti after ECAP and Ti6Al4V alloy

Forming processed	Tensile Strength [MPa]	0.2% Proof Stress [MPa]	Elongation Over 2 Inches [%]	Reduction in Area [%]	Elastic Modulus [GPa]	Grain Size d_z [μm]
Ti	365	212	51	71	100	30
Ti (2 passes ECAP)	579	523	15	68	80	4,3
Ti (8 passes ECAP)	651	560	14	57	103	0.3
Ti6Al4V	905	832	18	22	114	-

4. CONCLUSION

Basic factors influencing formability and resistance to deformation of titanium and its alloys are the following: chemical composition, microstructure and macrostructure, deformation temperature, rate of deformation and state of stress. At deformation with full re-crystallisation resistance to deformation remains at rates of deformation $\varepsilon' < 10^1\ s^{-1}$ almost constant. At forming below re-crystallisation temperatures resistance to deformation increases due to influence of deformation strengthening, and it therefore significantly depends on magnitude of deformation. In the present study, the analysis of microstructures was conducted on commercial pure titanium to understand the development of deformation structures during ECAP. Optical micrographs showed that the deformed structures after the single pass of ECAP were covered with multiple micro-twins. Strength of ultra-grain fine-titanium varies around 651 MPa, grain size around 300 nm.

Acknowledgement

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