On the activation energy for plastic flow during tension test at room temperature and the anisotropy behaviour of Ti-6Al-4V alloy

J D Muñoz-Andrade and M Aguilar-Sánchez

Departamento de Materiales, División de Ciencias Básicas e Ingeniería, Universidad Autónoma Metropolitana Unidad Azcapotzalco. Av. San Pablo No. 180, Col. Reynosa Tamaulipas, C.P. 02200 Ciudad de México, México

E-mail: jdma@azc.uam.mx

Abstract. The movement of dislocations inside of crystals during the tension test at constant crosshead velocity is related to activation energy for plastic flow in spatially extended polycrystalline systems. In this work, the main objectives are to establish the influence of the slip systems for \( \alpha \) hexagonal compact packaging (hcp) titanium phase on the activation energy for plastic flow and the anisotropy influence on the plastic flow behaviour of Ti-6Al-4V alloy in sheet form under tension test at constant crosshead velocity of 1 mm/min in three in-plane orientations, namely in the rolling 0º (RD), 45° (DD) and transverse (TD) directions, respectively. By applying the quantum mechanics and relativistic model (QM-RM) proposed by Muñoz-Andrade, it is shown that for a \(<c+a>\) pyramidal type slip with a Burgers vector \(b=0.553\) nm, the activation energy barrier for plastic flow at maximum stress in uniaxial tension in the sheet rolling direction, \(Q=115.115\) kJ/mol is lower in comparison with \(Q=116.629\) kJ/mol obtained by the \(<a>\) basal type slip with a Burgers vector \(b=0.295\) nm. These results are in accordance with the reduced cross-slip activation energy barrier for cross-slip onto pyramidal planes in an \(\alpha\) hexagonal crystalline structure with compact packaging (hcp) titanium phase. Additionally, it was shown that transverse direction (TD) of Ti-6Al-4V alloy in sheet form has developed the maximum stress in uniaxial tension test and ductility.

1. Introduction

Ti-6Al-4V alloy has a wide variety of industrial applications in the field of materials engineering, such as automotive, aerospace, biomedical, etc. It should be noted that \((\alpha+\beta)\) type Ti-6Al-4V alloy has a limited ductility in metal forming processes at room temperature, is attributed to it because the crystalline structure of the \(\alpha\) phase titanium is hexagonal with compact packaging (hcp) and due to its sliding systems related to the basal, prismatic and pyramidal plane, it tends to exhibit anisotropic behavior during metal forming processes at room temperature [1-3].

Some experimental research has recently been reported to evaluate the effect of anisotropy on the mechanical properties at room temperature of the Ti-6Al-4V alloy [4-6]. However, no research has been aimed at determining the activation energy for plastic flow during the uniaxial tension test at room temperature as a function of the sliding systems associated with the basal, prismatic and pyramidal planes of the \(\alpha\) phase of titanium with hcp crystalline structure. For this reason, the present investigation reports an analysis of the activation energy for the plastic flow of the Ti-6Al-4V alloy focused on sliding systems in the basal and pyramidal planes.

1 jdma@azc.uam.mx
Such determination is possible by applying the relativistic quantum model based on the cosmic connection and proposed by Muñoz-Andrade [7-12], which is summarized in the following equation:

\[ Q_{\perp} = -kT \ln \left( \frac{\rho_{\perp} v_{\perp} \lambda_{\perp}}{c} \right) = -kT \ln \left( \frac{\xi_{\perp}}{c} \right) \tag{1} \]

Where, \( \xi_{\perp} \) is the instantaneous strain rate for plastic deformation associated with the Orowan equation for plastic flow: \( \xi_{\perp} = \rho_{\perp} v_{\perp} \lambda_{\perp} \). Wherever, \( \rho_{\perp} \) is the density of dislocations, \( v_{\perp} \) is the average glide velocity, \( \lambda_{\perp} \) is the Burgers vector, \( T \) is the absolute temperature (K), \( k \) is the Boltzmann constant \( (k = 1.38 \times 10^{-23} \text{ J/K}) \) and \( c \) is the speed of light \( (c = 299792458 \text{ m/s}) \). Additionally, \( u_{\perp PV} = \xi_{\perp} \lambda_{\perp} \) is defined as dislocation phase velocity or wave velocity.

2. Experimental procedure

The material used for this investigation was Ti-6Al-4V alloy in a sheet form with a fine and equiaxed microstructure with \( \alpha \) grain size > 10\( \mu \)m. A set of three unidirectional tensile tests of this material at room temperature, in three in-plane orientations, namely in the rolling 0° (RD), 45° (DD) and transverse 90° (TD) directions, respectively, were carried out in a Universal Testing Machine SATEC System Inc., with a capacity of 2000kN, at the constant crosshead velocity: \( V = 1.0 \text{ mm/min} \). Where, the initial strain rate was \( \dot{\varepsilon} = 1.05 \times 10^{-3} \text{ s}^{-1} \). By the dislocation motion during plastic deformation as operative slip systems, in order to analyse the energetic possibility of their activation, the \(<c+a>\) slip and \(<a>\) slip are considered for the \( \alpha \) hcp titanium phase. The Burgers vector value is, \( b=0.553\text{nm} \), for a \(<c+a>\) type slip and \( b=0.295\text{nm} \), for a \(<a>\) type slip. The activation energy for plastic flow was calculated by using the mathematical model proposed by Muñoz-Andrade (1.1).

3. Results

The characteristic graphics of true stress versus true strain for the three tensile tests described away from the Ti-6Al-4V alloy in a sheet form are shown in figure 1. Ti-6Al-4V alloy under the same experimental conditions presented a non-the same answer during plastic flow and for different sample orientations. Here, it is remarkable to observe the influence of the sample orientation on reaching values of the yield stress, maximum stress and strain fracture. In contrast, samples oriented at 90°(TD) with respect to the rolling direction showed the biggest yield stress and the maximum UTS, while samples oriented at 90°(TD) and 45°(DD) revealed the strain fracture values. In consequence, the lowest mechanical properties were showed by sample oriented in the rolling direction 0°(RD).

![Figure 1](image-url)
4. Analysis of the experimental results

The variation of true stress with strain rate is exhibited in figure 2. Where, the range of the strain rate is increased as the strain fracture is increased, while the instantaneous strain rate is reduced period-by-period during the tension test of Ti-6Al-4V alloy with a constant crosshead velocity. The tensile samples oriented at 90°(TD) and 45°(DD) showed practically the same range of the strain rate.

![Figure 2. The variation of true stress with strain rate, during tension test at room temperature with a constant crosshead velocity of SEPCS Ti-6Al-4V alloy and their effect related with the rolling direction.](image)

The activation energy for plastic flow is increased from the beginning of the irreversible deformation process until the fracture of the tensile sample, such evolution processes are associated with the anisotropic effect related with the rolling direction of the tensile samples oriented at 0° (RD), 45° (DD) and transverse (TD) directions, in correlation with \(<a>\) and \(<c+a>\) slip dislocations as these revealed in figure 3 and figure 4, respectively.

![Figure 3. The variation of the activation energy with the true stress during tension test at room temperature with a constant crosshead velocity of Ti-6Al-4V alloy and their effect related with the rolling direction with \(<a>\) type slip.](image)
The difference of activation energy for plastic flow with strain rate during tension test at room temperature at constant crosshead velocity of Ti-6Al-4V alloy and their effect related with the rolling direction with $<$c+a$>$ slip dislocations are represented in figure 5. It must be noted that the Ti-6Al-4V alloy exhibits that activation energy is increased for plastic flow as the instantaneous strain rate is reduced during plastic flow at constant crosshead velocity of the tension test. In addition, the curves exhibit the same trend but with different levels of energy as a function of the type $<$a$>$ and $<$c+a$>$ slip dislocations activated mechanisms.

**Figure 4.** The variation of the activation energy with the true stress during tension test at room temperature with a constant crosshead velocity of Ti-6Al-4V alloy and their effect related with the rolling direction with $<$c+a$>$ type slip.

**Figure 5.** Variation of activation energy for plastic flow with strain rate during tension test at room temperature at constant crosshead velocity of Ti-6Al-4V alloy and their effect related with the rolling direction associated with $<$a$>$ and $<$c+a$>$ slip dislocations.
Figure 6. Variation of activation energy for plastic flow with dislocations phase velocity during tension test at room temperature at constant crosshead velocity of Ti-6Al-4V alloy and their effect related with the rolling direction associated with \(<a>\) and \(<c+a>\) slip dislocations.

The maximum dislocation phase velocity is reached with the minimum value of the activation energy for the plastic flow of Ti-6Al-4V alloy associated with the type \(<a>\) and \(<c+a>\) slip dislocations activated mechanisms, as it is shown in figure 6. The same effect is observed for the three samples oriented at 0° direction (RD), 45° direction (DD) and 90° direction (TD). Also, it must be observed that the Ti-6Al-4V alloy exhibits the increased activation energy for plastic flow as the dislocations phase velocity is reduced during plastic flow at constant crosshead velocity of the tension test.

5. Discussion

In this universe, nature operates in conditions of minimum energy and all processes require activation energy for it to manifest. Consequently, the nature of plastic deformation in crystalline and polycrystalline physical systems will take place from the mechanism that can be activated in conditions of minimum activation energy. Therefore, with the results reported in the present research for \(\alpha\) hcp titanium phase for plastic flow under uniaxial tension test of Ti-6Al-4V alloy at room temperature at constant crosshead velocity, the most favorable observed sliding system is \(<c+a>\) slip dislocations more than \(<a>\) slip dislocations. This result matches with the recent study reported by hcp metals related to the mechanism and energetic of \(<c+a>\) dislocation cross-slip in hcp metals [2].

The effect of anisotropy on the mechanical properties of Ti-6Al-4V alloy favors the best mechanical resistance and ductility response to the sample oriented at 90° direction (TD) rather than 0° direction (RD) and 45° direction (DD) during uniaxial tension test of Ti-6Al-4V alloy at room temperature at constant crosshead velocity. Similar behavior was observed in recent research relating to the experimental and numerical study of TA-6V mechanical behavior in different monotonic loading conditions at room temperature [4].

6. Conclusions

Based on the application of cosmic connection and quantum mechanics-relativistic model proposed by Muñoz-Andrade, it is possible to determine the activation energy for the plastic flow of the Ti-6Al-4V alloy in a sheet form under tension test at constant crosshead velocity for samples oriented in different directions with respect to the rolling direction, obtained the following relevant findings: The lowest activation energy for plastic flow is associated with the dislocations slip system \(<c+a>\) more than \(<a>\) slip dislocations for \(\alpha\) phase hcp titanium and the better mechanical behavior was obtained for the sample oriented at 90° direction (TD). Therefore, in this Ti-6Al-4V alloy, the phenomenon of anisotropy under unidirectional tension test is manifested both in the crystal structure dislocations slip systems and in the orientation of the sample.
Acknowledgements
The authors in this paper are grateful to the Autonomy Metropolitan University Campus Azcapotzalco for the authorization of the research project entitled: Study of Plastic Flow, Super Plastic and Dynamic Recrystallization in Spatially Extended Poly-Crystalline Systems.

References
[1] Matsumoto H, Yoshida K, Lee S-H, Ono Y and Chiba A 2013 Mater. Lett. 98 209
[2] Wu Z and Curtin W A 2016 PNAS 113-40 11137
[3] Dehghan-Manshadi A, Reid M H and Dippenaar R 2010 J. Phys.: Conf. Ser. 240 012022
[4] Gilles G, Cazacu O, Hammami W, Habraken A M and Duchêne L 2012 Procedia IUTAM 3 100
[5] Wang Q L, Novell M F, Ghiotti A and Bruschi S 2017 Procedia Eng. 207 21
[6] Wahed A, Gupta K, Singh K and Kotkunde N 2018 IOP Conf. Ser.: Mater. Sci. Eng. 346 012023
[7] Muñoz-Andrade J D 2007 Materials Science Forum Vols. 561-565 1927
[8] Muñoz-Andrade J D 2007 Key Eng. Mater. Vols. 345-346 577
[9] Muñoz-Andrade J D 2008 Int. J. Mater. Forum Suppl 1:8
[10] Muñoz-Andrade J D 2013 AIP Conf. Proc. 1576 796
[11] Muñoz-Andrade J D 2016 Mater. Sci. Forum Vols. 838-839 78
[12] Muñoz-Andrade J D 2018 Mater. Sci. Forum Vol. 941, 121