Advanced Materials Research *Online: 2012-06-14*
ISSN: 1662-8985, Vols. 535-537, pp 977-982
doi:10.4028/www.scientific.net/AMR.535-537.977

Thermal Flow Deformation Behavior and Mechanism of As-cast and As-extruded Burn Resistant Titanium Alloy

Huanying Sun[1, a], Jingxia Cao[1, b], Bao Wang[1, c], Xu Huang[1, d], Chunxiao Cao[2, e]

[1]Titanium Alloy Research Lab, Beijing Institute of Aeronautical Materials, Beijing 100095, China

[2]Beijing Institute of Aeronautical Materials, Beijing 100095, China

[a]huanying417@163.com, [b]caojingxia@sina.com, [c]wangrongjing@sogou.com, [d]xu.huang@biam.ac.cn, [e]chunxiao.cao@biam.ac.cn,

Keywords: Burn Resistant Titanium Alloy, Flow Behavior, Deformation Mechanism, Dynamic Reversion, Dynamic Recrystallization.

Abstract. Hot compressive deformation tests of burn resistant titanium alloy (Ti-35V-15Cr-Si-C) with initially as-cast and as-extruded microstructure were performed at deformation temperature between 900˚C to 1200˚C for as-cast and 900˚C to 1150˚C for as-extruded alloy, and strain rates between 10^{-3} s^{-1} to $1s^{-1}$. The compressive true stress vs. true strain curves were measured, the deformation activation energy was calculated and the microstructures after deformation were studied. The results show that dynamic reversion is the primary soften mechanism of the burn resistant titanium alloy during hot deformation. At the higher strain rate ($\dot{\varepsilon}=1s^{-1}$), the 'Necklace' Dynamic Recrystallization will occur for as-cast alloy, and a Continuous Recrystallization will occur for as-extruded alloy. At the lower strain rates, both as-cast and as-extruded burn resistant titanium alloy display the continuous recrystallization. The extruded alloy presents larger dynamic recrystallization regions than that of the as-cast alloy.

Introduction

Conventional titanium alloy may be ignited and burnt under high temperature, high pressure and high velocity gas flow condition, called titanium fire. In order to solve the problem of "titanium fire" which may occur in aeroengine under operating conditions, and meet the requirement for high-performance aeroplane materials, burn resistant titanium alloys have been studied during the recent years[1]. Alloy C (Ti-35V-15Cr) is a titanium base alloy that exhibits high elevated temperature strength properties and a markedly improved resistance to sustained combustion when ignited as compared to the more commonly used titanium alloys[2-4]. Researches indicate that burn resistant titanium alloys with C and Si additions have better creep properties. However, hot processing is difficult due to extensive surface and edge cracking, especially during the ingot breakdown. The purpose of this paper is to reveal the deformation mechanism of burn resistant titanium alloy (Ti-35V-15Cr-Si-C) at the elevated temperatures by studying of the flow behavior and microstructure evolution of differently hot compressed samples, based on compression testing data of as-cast and as-extruded burn resistant titanium alloy.

Experiment

The burn resistant titanium alloy with a nominal composition of Ti-35V-15Cr-Si-C was prepared by three times vacuum consuming arc melting. The microstructure of as-cast alloy is shown in Fig.1a, which consists of coarse β phase with some carbides in the matrix and the grain boundaries. As-extruded alloy is from extrusion bars with 25 mm in diameter. The microstructure of as-extruded alloy is shown in Fig.1b. It can be seen that a mass of fine recrystallized grain distributed around original grain boundaries and carbide branches. The cylindrical compressive specimens of 10 mm in diameter and 15 mm in height, were machined from the homogenized ingots and extrusion bars. The isothermal compressive tests were performed on the Gleeble-1500 simulator in the temperature range of 900～1200˚C for as-cast and 900～1150˚C for as-extruded alloy, over the range of strain rate from $10^{-3}s^{-1}$ to $1s^{-1}$. The height reduction is 50%. The microstructures were examined with an optical microscope (OM) and transmission electronic microscopy (TEM).

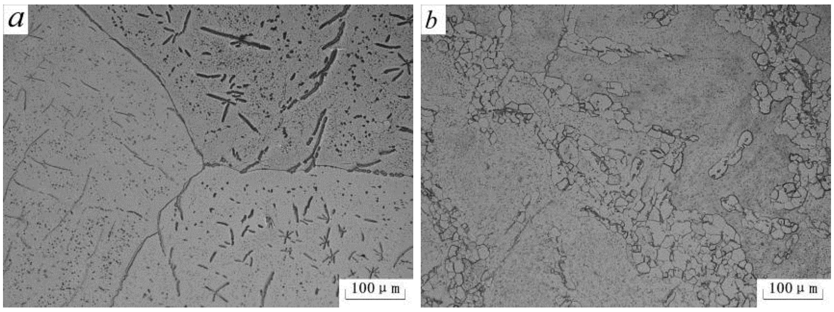

Fig.1 Initial microstructure of burn resistant titanium alloy:
(a) as-cast, (b) as- extruded

Thermal flow deformation and fracture behavior

The true stress-strain curves of the as-cast and as-extruded burn resistant titanium alloy (Ti-35V-15Cr-Si-C) obtained from compressive test at different temperature and strain rate were shown in Fig.2. The curves display that flow stress increases rapidly to a higher peak value, and then decreases sharply, i.e. discontinuous yielding phenomenon, and then decreases slowly with the increment of strain to a lower level. The tendency of stress drops with the increase of temperature at same strain rate. The low of flow behavior conform to common β titanium alloys.

The discontinuous yielding phenomenon of β titanium alloys has been related to the rapid generation of mobile dislocations from grain boundary sources, leading to hot deformation proceeding from the grain boundary region inward. Dislocation movement rate in the alloys varies with the stress is shown in Eq.(1) [5]:

$$v = (\sigma/\sigma_0)^n \tag{1}$$

Where σ is applied stress; σ_0 is reference stress; n is stress exponent. The strain rate during hot deformation is defined by Eq.(2):

$$\dot{\varepsilon} = \rho b v \tag{2}$$

Where ρ is mobile dislocation density; b is Burgers vector.
When strain rate is invariable, Eq.(2) reveals that dislocation movement rate v is higher with lower dislocation density ρ in early stage of deformation, and higher stress, were shown in Eq.(1), leading to the rapid generation of dislocations, and then flow stress decreases with the increment of dislocation density. For β phase burn resistant titanium alloy, pile-up of dislocation forms easily from grain boundary, and the mobile dislocations generate rapidly with smaller deformation degree, as a result the discontinuous yielding phenomenon is seen in Fig.2.

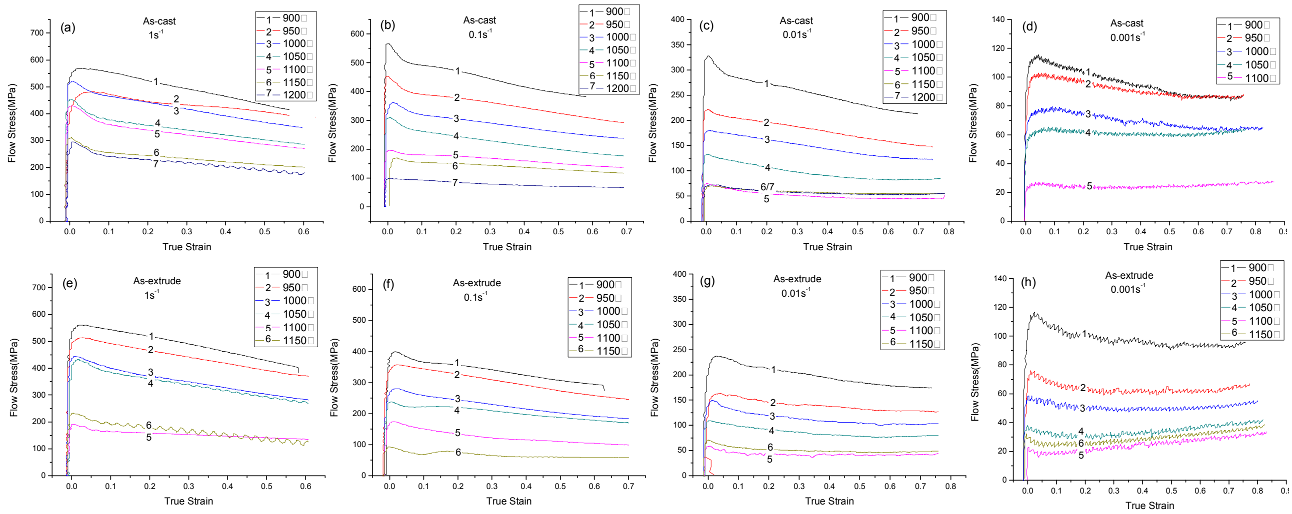

Fig.2 True stress-strain curves of burn resistant titanium alloy: (a), (b), (c), (d) as-cast; (e), (f), (g), (h) as- extruded

The as-extruded burn resistant titanium alloy has a mass of fine recrystallized grains as shown in Fig.1b. Compared to the as-cast burn titanium alloy, the extrusion alloy has less pile-up of dislocation as a result of more grain boundary for dislocation generation, which leading to smaller peak flow stress as shown in Fig.2. As-extruded burn resistant titanium alloy exhibits the markedly improved processing plasticity as compared to as-cast alloy, because extrusion alloy has less stress on grain boundaries during hot deformation, as well as good deformation compatibility from the fine grains. The isothermal compressive tests display that the hot deformation of burn resistant titanium alloy has a very strong dependence on strain rate, and have crack tendency at higher strain rate. For as-cast state alloy, surface cracks can be found at all deformation stain rate of $1s^{-1}$, $0.1s^{-1}$ and $0.01s^{-1}$, as shown in Fig.3. For as-extrude state alloy, none cracks can be found but when deformed at strain rate of $1s^{-1}$, as shown in Fig.4.

Fig.3 Cracking in as-cast state alloy, occurring at $1s^{-1}$ and $0.01s^{-1}$, 50% reduction

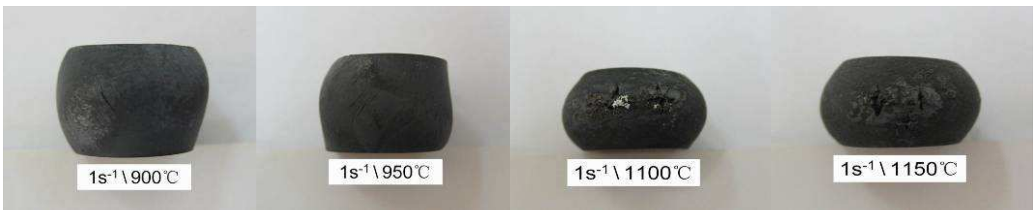

Fig.4 Cracking in as-extrude state alloy, occurring at $1s^{-1}$, 50% reduction

Hot deformation activation energy

The work-hardening and softening of alloys occur at the same time and compete between contenting aspects during hot deformation. The work-hardening is a phenomenon that flow stress increases with increment of the upset reduction, because of pile-up of dislocation forms around original grain boundaries and carbide branches. For burn resistant titanium alloy, the dynamic reversion by climb and cross-slip of dislocation are the primary hot soften mechanism, which leading to flow stress decreases due to pile-up of dislocation are relaxed. The climb and cross-slip of dislocation is nonconservative diffusion process that is carried through to need a period of time. The dynamic reversion is easier to progress at higher temperature and lower strain rate, because of the atom is easier to diffuse at such technological conditions.

For further understanding of deformation behavior and mechanism of burn resistant titanium alloy (Ti-35V-15Cr-Si-C) at elevated temperatures, the deformation activation energy (Q) was calculated. We assume that constitutive relationships between flow stress and deformation temperature and strain rate for burn resistant alloy are defined by Arrhenius equations[6]:

$$\dot{\varepsilon}\exp(Q/RT) = A_1\exp(\beta\sigma) \tag{3}$$

$$\dot{\varepsilon}\exp(Q/RT) = A_2\sigma^n \tag{4}$$

$$\dot{\varepsilon}\exp(Q/RT) = A_3[\sinh(\alpha\sigma)]^{n_1} \tag{5}$$

Where A_1, A_2 and A_3 are material parameters; n is the stress exponent; Q is the deformation activation energy; R is gas constant; T is absolute temperature. The Arrhenius hyperbolic sine equation can be written in the form:

$$\ln\dot{\varepsilon} = \ln A_3 + (-Q/RT) + n_1\ln[\sinh(\alpha\sigma)] \tag{6}$$

The solution formula of the deformation activation energy can be obtained from Eq.(6)

$$Q = R\frac{\partial\ln[\sinh(\alpha\sigma)]}{\partial(1/T)}\Big|_{\dot{\varepsilon}}\frac{\partial\ln\dot{\varepsilon}}{\partial\ln[\sinh(\alpha\sigma)]}\Big|_T = Rkn_1 \tag{7}$$

Since the peak flow stress σp and strain rate $\dot{\varepsilon}$ and deformation temperature T are known based on hot compression testing data, using Eq.(3) and Eq.(4) and Eq.(6), the parameter of k and n_1 can be obtained by linear fitting, and deformation activation energies can be calculated. The average deformation activation energy for as-cast burn resistant titanium alloy is 231.5kJ/mol, and that of as-extruded alloy is 258.3kJ/mol. The deformation activation energies at different temperatures and strain rates are shown in Fig.5.

The calculated values of the average deformation activation energy close to the self-diffusion activation energy of 153 kJ/mol for pure β titanium, which shows that hot deformation of the burn resistant titanium alloy is lattice diffusion controlled, and dynamic reversion is the primary soften mechanism. However, the calculated values of 231.5 kJ/mol and 258.3kJ/mol are higher the self-diffusion activation energy of 153 kJ/mol, which suggests that dynamic recrystallization may occur during hot deformation of burn resistant titanium alloy. Moreover, flow stress passed through peak and decreases with the increment of strain at higher strain rate, as shown in Fig.3, and the phenomenon was generated by dynamic recrystallization.

Fig.5 showed the as-cast burn resistant titanium alloy and the as-extruded alloy have the similar deformation activation energy at strain rate of $0.001s^{-1}$ and $0.01s^{-1}$ and $0.1s^{-1}$, but the deformation activation energy for as-cast alloy is much smaller than that of the as-extruded alloy at strain rate of $1s^{-1}$. For understanding of the phenomenon we need to observe the microstructures of hot compressed samples.

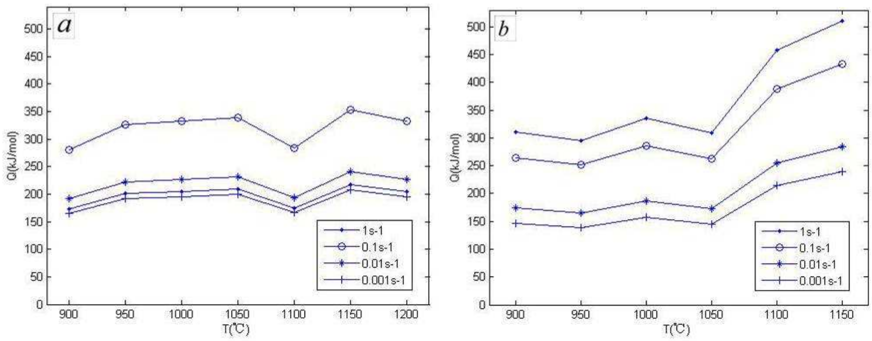

Fig.5 The deformation activation energies of burn resistant alloy at different conditions: (a) as-cast, (b) as-extruded

Microstructure evolution

The microstructures of burn resistant titanium alloy evolved at different temperatures and strain rates are shown in Fig.6. Fig.6a and Fig.6b show typical “necklace” dynamic recrystallization grains in as-cast alloy deformed at 900˚C and 1000˚C with a strain rate of $1s^{-1}$. Fig.6d and fig.6e show continuous recrystallization features in as-extruded alloy deformed at 900˚C and 1000˚C with a strain rate of $1s^{-1}$. The grain boundaries become straight and grain sizes increase at 1000˚C. The deformation activation energy of as-extruded alloy is higher than that of the as-cast alloy, because of the region of recrystallization is larger.

When strain rate is higher, there is not enough time to relax the dislocation block formed by deformation through dynamic recovery. The dislocation blocks are more and more severe with the increment of strain degree, and distortion energy accumulates to a high degree to promote the recrystallized nucleation. When the as-cast alloy deforms at strain rate of $1s^{-1}$ the recrystallization by dislocation block generated around grain boundaries and carbide branches, as shown in Fig.7a. When the as-extruded alloy deforms at strain rate of $1s^{-1}$ the ‘necklace’ dynamic recrystallization does not generated, because the degree of the dislocation block for as-extruded alloy with higher grain density is lower than that of as-cast alloy, which leading to the distortion energy can not achieved to limit degree of recrystallized nucleation. However, the subgrain for as-extruded alloy can form by dislocation polygonization, so the continuous recrystallization generates by merge of the subgrain, as shown in Fig.7b. When strain rate is lower, for as-cast alloy the continuous recrystallization was

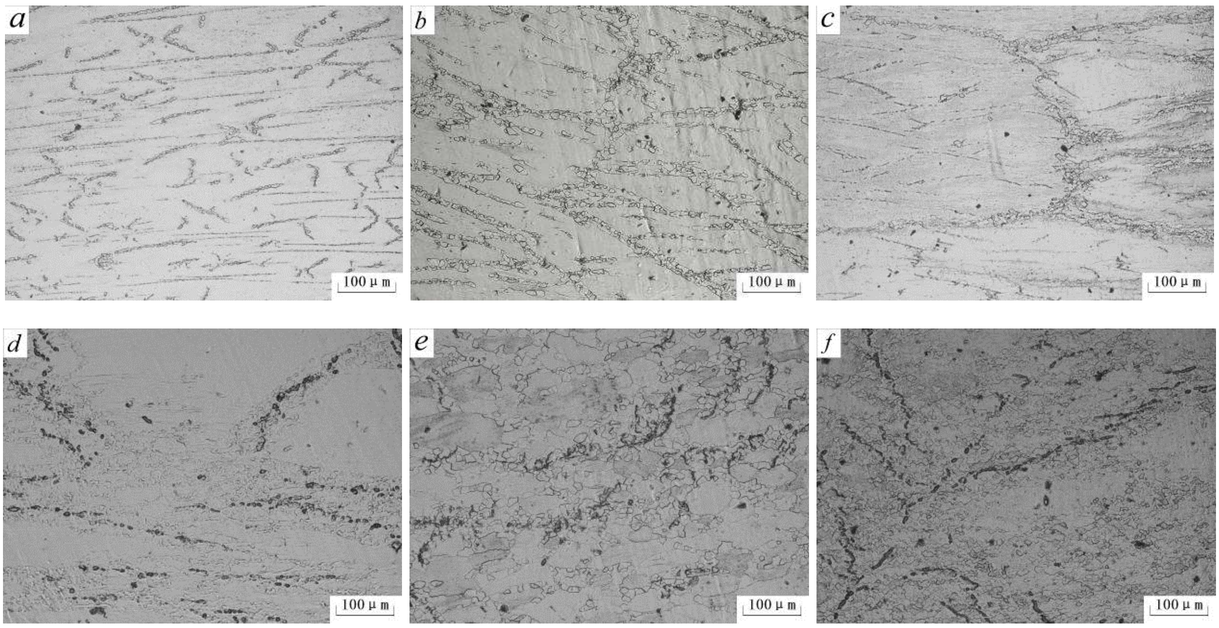

Fig.6 The Microstructure of burn resistant titanium alloy at different conditions: (a), (b), (c) as-cast; (d), (e), (f) as-extruded

generated too, but the region of recrystallization was smaller, which along grain was shown in Fig.6c (at temperature of 950˚C and strain rate of $1s^{-1}$). Fig.6f showed when the as-extruded alloy deformed at same condition the region of recrystallization is much larger than that of the as-cast alloy.

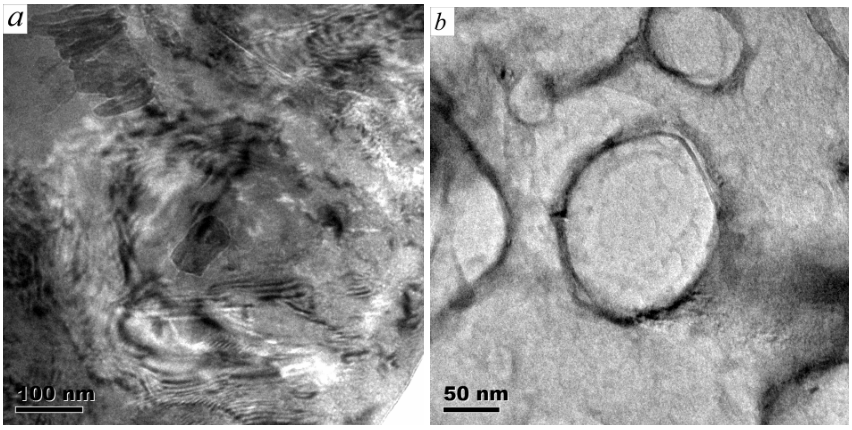

Fig.7 TEM micrographs of recrystallized nucleation

Conclusions

1) Flow behaviors of the as-cast and as-extruded burn resistant titanium (Ti-35V-15Cr-Si-C) alloy are studied. Based on the mobile dislocations rapidly generation during hot deformation, the paper indicates that the dislocation block around grain boundaries creates the discontinuous yielding phenomenon. The reason of good processing plasticity of as-extruded alloy compared to as-cast alloy is a mass of fine recrystallized grain.

2) The average deformation activation energy for as-cast burn resistant titanium alloy is 231.5kJ/mol and that of as-extruded alloy is 258.3kJ/mol, compared to the self-diffusion activation energy of 153 kJ/mol for pure β titanium, which shows that dynamic reversion and the local dynamic recrystallization are the primary soften mechanism of the burn resistant titanium alloy during hot deformation.

3) When as-cast alloy deformed at higher strain rate ($\dot{\varepsilon}=1s^{-1}$) the 'necklace' dynamic recrystallization was generated, and when as-extruded alloy deformed at same conditions the continuous recrystallization was generated. When strain rate is lower ($\dot{\varepsilon}\leq 0.1s^{-1}$), whether as-cast or as-extruded alloy the continuous recrystallization was generated, but the region of recrystallization for as-extruded alloy is much larger than that of the as-cast alloy.

Reference

[1] Huang Xu, Cao Chunxiao, Wang Bao et al. Alloy C burn resistant titanium alloy [J]. Aviation Engineering & Maintenance, 1997(6): 24－26. (in Chinese)

[2] Hansen J O，Sound H，Novotnak D，et al. Heat treatment to reduce embrittlement of titanium alloys [P]. US Paten：5397404，1995-03-14.

[3] Seagle S R. The state of the USA titanium industry in 1995 [J]. Materials Science and Engineering A，1996，213：1－7.

[4] Boyer R R. An overview on the use of titanium in the aerospace industry [J]. Materials Science and Engineering A，1996, 213: 103－114.

[5] Zhao Yongqing. Deformation Mechanism and Burn Resistant Mechanism of Ti40 Burn Resistant Titanium Alloy [D]. Shen Yang: Northeastern University, 1998：26－27. (in Chinese)

[6] Zhao Weigang, Li Xin, Li Zhenxi et al. Study on Constitutive Relationship of TC11 Titanium Alloy during High *Temperature* Deformation [J]. Journal of Plasticity Engineering, 2008, 15(3)：123－127. (in Chinese)