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ARTICLE

Stress Induced Martensitic Transformation of As-cast TB6 Titanium Alloy During Hot Process

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Abstract: Hot compression tests of as-cast TB6 titanium alloy were performed at the temperature of 800~1150 °C and the strain rate of 0.001~10 s^{-1} to examine microstructure evolution associated with stress induced martensite (SIM). The results reveal the occurrence of the SIM with the dendritic morphology in the present alloy during hot compression process. The orthorhombic structure of SIM was confirmed for the alloy. It is found that the SIM nucleates both in the β grain interior and at grain boundary. The alloy composition uniformity and internal stress are strongly dominated by strain rate and deformation temperature, which are responsible for the amounts of SIM. The content of SIM at different strain rates is related to the temperature ranges. More SIM appear at the strain rate of 0.1 s^{-1} for the temperature of 800~900 °C, at 0.01 and 1 s^{-1} for the temperature of 900~1000 °C, at the strain rate of 1 s^{-1} for the temperature of above 1000 °C. 50% martensite can be obtained at an optimal combination of the temperature of 925 °C and the strain rate of 1 s^{-1}.

Key words: as-cast TB6 titanium alloy; martensite; hot process

Due to its good combination of strength, toughness, hardenability, and crack growth resistance, TB6 (Ti-10V-2Fe-3Al, wt%) titanium alloy represents an ideal material as a forging alloy that is suitable for aircraft structural applications [1-3]. As a kind of near-β titanium alloy, one of the most important transformations in the alloy is the stress induced martensitic transformation (SIMT) of β to orthorhombic. Ma et al.[4] and Pan et al.[5] found that the formation of SIMT dividing β grain into smaller domains responded to the improvement of mechanical properties. Bai et al.[6] and Bhattacharjee et al.[7] suggested that metastable β phase of TB6 titanium alloy could be obtained by water quenching from above the β transus temperature because of its β stable elements of V and Fe. It is reported that the stability of metastable β phase was insufficient to prevent it from martensititally decomposing when a sufficient external stress was applied [8, 9]. This allows the retained metastable β phase of the alloy to transform to martensite when subjected to an external stress, generally designated as stress or strain induced martensite (SIM). Duerig et al.[10] and Srinivasu et al.[11] suggested that the SIM of Ti-10V-2Fe-3Al alloy was generally orthorhombic phase, designated α'', and the orientation relationship between the original β and orthorhombic α'' follows approximately : $(111)_{\alpha''}//(110)_{\beta},[110]_{\alpha''}//[111]_{\beta}$. It is well known that a critical stress is required to trigger the SIM transformation of near-β titanium alloy, which is dominated to the stability of metastable β phase. Pan et al.[5] showed that the martensitic transformation from β to α'' was induced when the critical strain reached to 10% in metastable β Ti-10V-2Fe-3Al alloy. If there existed composition segregation, such as in as-cast state, martensite would be induced for the metastable β phase with lower β stable elements, while no martensite could be induced even with larger stress for the metastable phase with larger β stable elements[12, 13]. It means that hot deformation parameters (temperature, strain rate and strain) have a significant influence on the internal stress and composition redistribution of as-cast TB6 titanium alloy, which affects the amounts of SIM. By now, the influence of composition segregation (e.g.

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in as-cast) as well as deformation processes on the SIM transformation of the alloy during hot process remains poorly understood.

Compared to previous works, the focus of the present study is to examine the SIM transformation taking into consideration of the effect component segregation in as-cast TB6 titanium alloy during the hot working process. In addition, the influence of deformation parameters including strain rate and temperature on the SIM transformation was examined.

1 Experiment

The as-received titanium alloy used in the current study was as-cast TB6 titanium alloy, which consisted of a lamellar structure (Fig.1). The chemical composition (wt%) of the alloy is 10.2V, 1.8Fe, 3.1Al, and the balance Ti. The β-transus temperature of the Ti-alloy was metallographically determined as (802±3) °C. The cylindrical specimens with the diameter of 8 mm and the height of 12 mm were machined from the ingot with flat bottomed grooves on both the end surfaces for holding lubricant in such a way to reduce the friction in-between the die and workpiece. Hot compression tests were conducted on a Thermecmastor-Z hot simulation machine at the temperature of 800~1150 °C, and the strain rate of 0.001~10 s^{-1}. The samples were quenched after compression immediately with helium gas. The specimens for metallographic examination were taken from the cross section of the deformed workpieces. The microstructure examination and estimation of martensite content of the alloy were employed by XJP-6H optical microscope with a built-in quantitative analysis system. The measurement of area fraction by lattice method instead of volume fraction of martensite was used. Microstructural evaluations were conducted by X-ray diffraction (XRD, BRUKER D8). The chemical composition of the martensite was determined by the SEM-energy dispersive spectroscopy (EDS) analysis.

2 Results and Discussion

2.1 Stress-induced martensitic transformation

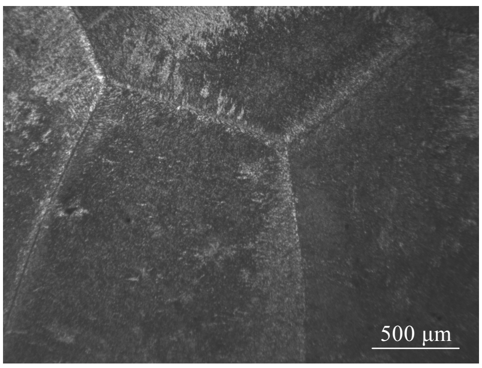

Fig.1 Original microstructure of as-cast TB6 titanium alloy in the as-received condition

The SIM of as-cast TB6 titanium alloy was observed when the alloy was deformed at the temperature of 800~1150 °C, and the strain rate of 0.001~10 s^{-1}. Fig.2 shows typical SIM morphology of the alloy deformed at the temperature of 825 °C and strain rate of 0.1 s^{-1} with the strain of 0.92. Preferentially cluster morphologies with microstructural characteristic of a needle-like martensite laths in the SIM are observed from Fig.2a. The interior morphology in martensite cluster, as shown in Fig.2b, presents a characteristic of approximate parallel martensite dendrites and well defined. A supplementary analysis obtained from the X-ray diffraction patterns (Fig.3) provides the evidence of the existence of α'' martensite.

Two main factors of the β stable coefficient K_β and an external stress applied contribute to martensite transformation[14, 15]. The K_β of Ti-alloy represents the start transformation temperature of martensite, and the value of K_β can be calculated by Eq.(1):

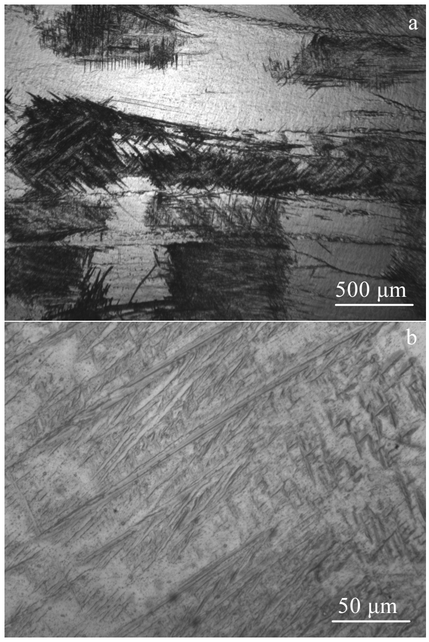

Fig.2 Typical morphologies of transition structure (a) and local magnification in Fig.2a (b)

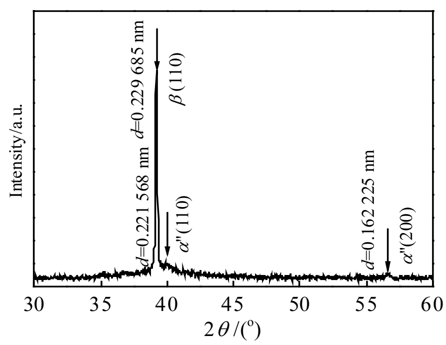

Fig.3 X-ray diffraction pattern of transition structure

$$K_\beta = \frac{C_1}{C_{k1}} + \frac{C_2}{C_{k2}} + \frac{C_3}{C_{k3}} + \cdots + \frac{C_n}{C_{kn}} \tag{1}$$

where C_n is the concentration of β stable elements in the alloy (wt%), C_k is the critical concentration of the β stable elements (wt%). A larger value of K_β means that there is a lower start transformation temperature of martensite. When the K_β is larger than 1.0, the martensite transformation temperature dropping to below room temperature will be expected. Since the elements of V with the critical concentration of 15% and Fe with the critical concentrations of 5% are the β stable elements of TB6 (Ti-10V-2Fe-3Al) titanium alloy, nominal β stable coefficient of about 1.06 for TB6 titanium alloy was calculated according to Eq.(1). It indicates the start transformation temperature of martensite of the Ti-alloy is below room temperature, and no martensite appears in the process of solution treatment [16, 17]. However, owing to the segregation for as-cast TB6 titanium alloy, the difference of K_β exists in various region. Since the average value K_β is of 1.06, there must be K_β of lower than 1.06 in some region and larger than 1.06 in other regions. Martensite can be induced in the region with lower K_β. When the stress maintains a constant value, the lower K_β is, or when the K_β maintains a constant value, the larger the stress is, the higher the content of martensite can be obtained. Evidence is provided by the EDS analysis for the difference of chemical composition and K_β between in the region of martensite and in the region of β phase, as shown in Fig.4, in which K_β of 1.011 for martensite and 1.068 for β phase can be calculated. It is slightly implied that, assuming the stress is the same in various regions, the difference of K_β is responsible for martensite transformation in some regions while no martensite transformation in other regions of as-cast TB6 titanium alloy, which are the same as that of Ti-*x*Nb-(0.5~1.5)at% Si metastable β-titanium alloy reported by Kim et al.[15]

2.2 Effect of hot compressive deformation on martensite transformation

2.2.1 At the temperature of 800~900 °C

Fig.5 shows the optical microstructures of martensite of as-cast TB6 titanium alloy deformed at the temperature of 825 °C and strain of 0.92 with various different strain rates. A remarkable variety of martensite transformation of the Ti-alloy deformed at different strain rates is observed. Nearly no martensite transformation occurs at the strain rate of 0.001 s^{-1}(see Fig.5a). As the strain rate is increased to 0.01 s^{-1}, 13.5% martensite distributed in the original β grain is observed (see Fig.5b). As the strain rate is further increased to 0.1 s^{-1}, the microstructure shows apparent martensite transformation with the content of about 40%. Martensites appear either near the initial β grain boundaries or in the β grain interior. With the increase of the strain rate to 1 and 10 s^{-1}, the lower amount of martensite of about 10% and 8% is observed.

The influence of strain rate on the martensite transformation of as-cast TB6 titanium alloy deformed at the temperatures of 800~900 °C is highlighted in Fig.6. The relationship between the amount of martensite and strain rate was found to present a characteristic that martensite transformation initially increases, and then decreases with strain rate. Maximum content of martensite can be obtained at the strain rate of 0.1 s^{-1}, and the small amount of martensite transformation appears at the strain rate of lower than 0.01 s^{-1} or higher than 1 s^{-1}. Owing to the departure of the K_β in the local region from the nominal β stable coefficient of the alloy, martensite transformation may be induced in the region with lower K_β, while no martensite can be induced even with larger stress in the region with larger K_β. In addition, the internal stress raised by deformation is also responsible for the differences of martensite transformation for the present alloy at different strain rates.

It is expected to display more uniform composition at low strain rate. Increasing uniformity of composition could lead to the increasing K_β of pre-existing region with K_β of lower than 1.06, and much larger stress is necessary to induce martensite transformation. On the other hand, in general, when other conditions are equal, the decrease of strain rate will promote dynamic recrystallization, while the internal stress in the alloy is decreased. Thus, there is not enough larger stress to induce martensite transformation, resulting in that less amount of martensite transformation ap-

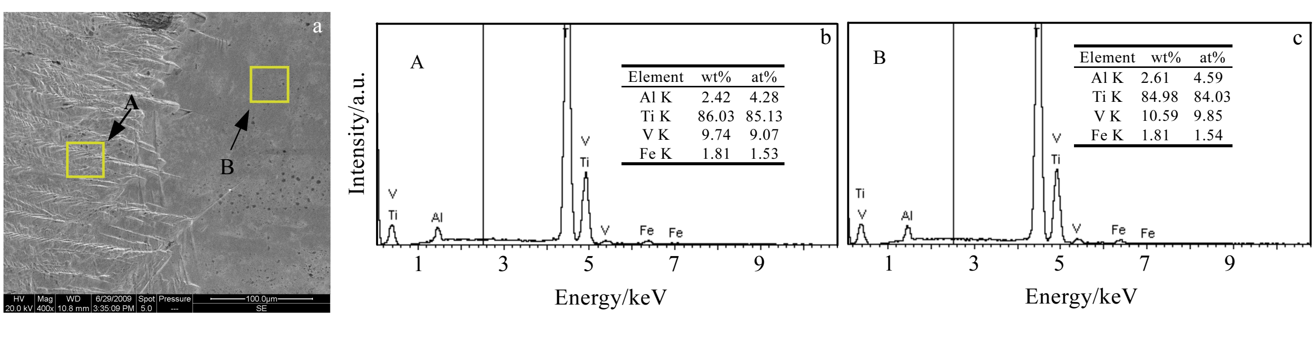

Fig.4 SEM image (a) and EDS analysis of the SIM marked as A zone (b) and the β phase marked as B zone (c)

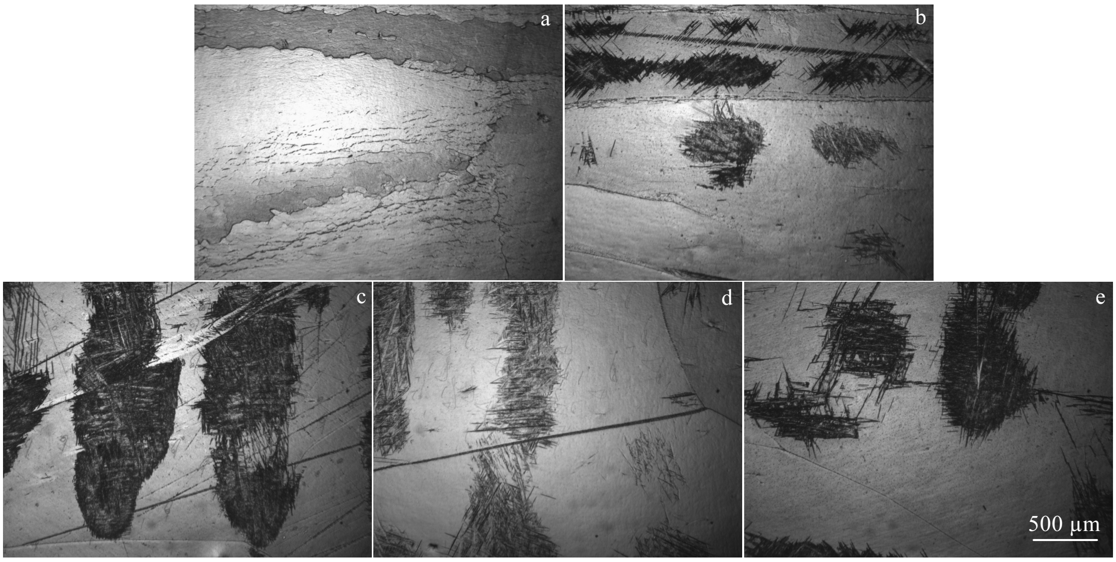

Fig.5 Optical micrographs of martensite of as-cast TB6 titanium alloy deformed at the temperature of 825 °C and strain of 0.92 with different strain rates: (a) 0.001 s^{-1}, (b) 0.01 s^{-1}, (c) 0.1 s^{-1}, (d) 1 s^{-1}, and (e) 10 s^{-1}

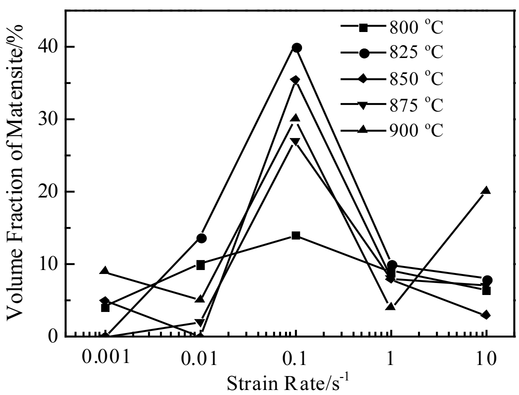

Fig.6 Dependence of the volume fraction of martensite on strain rate at the temperature of 800~900 °C

pears at the strain rate of lower than 0.01 s^{-1}. At high strain rate, the alloy remains inhomogeneous composition, and larger internal stress exists. Although martensite transformation may be induced in the region with the K_β of lower than 1.06, no martensite transformation appears in the region with larger K_β. Therefore, a small amount of martensite transformation can be obtained even if there is larger internal stress at the strain rate of higher than 1 s^{-1}. At medium strain rate, an optimal combination of composition uniformity and internal stress for martensite transformation reaches at the strain rate of 0.1 s^{-1}, and maximum precipitation of martensite can be obtained.

2.2.2 At the temperature of 925~1000 °C

Fig.7 shows the optical microstructures of martensite in as-cast TB6 titanium alloy deformed at the temperature of 925 °C and strain of 0.92 with different strain rates. As can be seen in Fig.7, few martensite transformation is observed at the strain rate of 0.001 s^{-1}. When the strain rate is 0.01 s^{-1}, the content of martensite is increased to 35%. With the strain rate is increased to 0.1 s^{-1}, the content of martensite decreases slightly to 15%. When the strain rate continues to increase to 1 s^{-1}, martensite transformation becomes more prevalent, resulting in about 50% martensite. The decrease of martensite transformation is observed when the strain rate is increased to 10 s^{-1}, and the content of martensite is about 11.2%.

The influence of strain rate on the martensite transformation of as-cast TB6 titanium alloy deformed at the temperatures of 925~1000 °C is highlighted in Fig.8. It is worth mentioning that compared with at the temperature of 800~900 °C, the uniformity of the alloy increases and the internal stress decreases when the alloy is deformed at 925~1000 °C. As can be seen from Fig.8, the curves exhibit two peaks of martensite transformation at strain rate of 0.01 and 1 s^{-1}. This means that an optimal combination of composition uniformity and internal stress for martensite transformation can be obtained at the strain rate of 0.01and 1 s^{-1}. At low strain rate of 0.001 s^{-1}, the internal stress is less and not enough to induce martensite transformation, and thus less amount of martensite can be obtained. At the strain rate of 0.1 and 10 s^{-1}, despite of the occurrence of a certain amount martensite transformation, the optimal combination of composition uniform and internal stress of martensite transformation is still not achieved.

2.2.3 At the temperature of above 1000 °C

Fig.9 shows the optical microstructures of martensite in

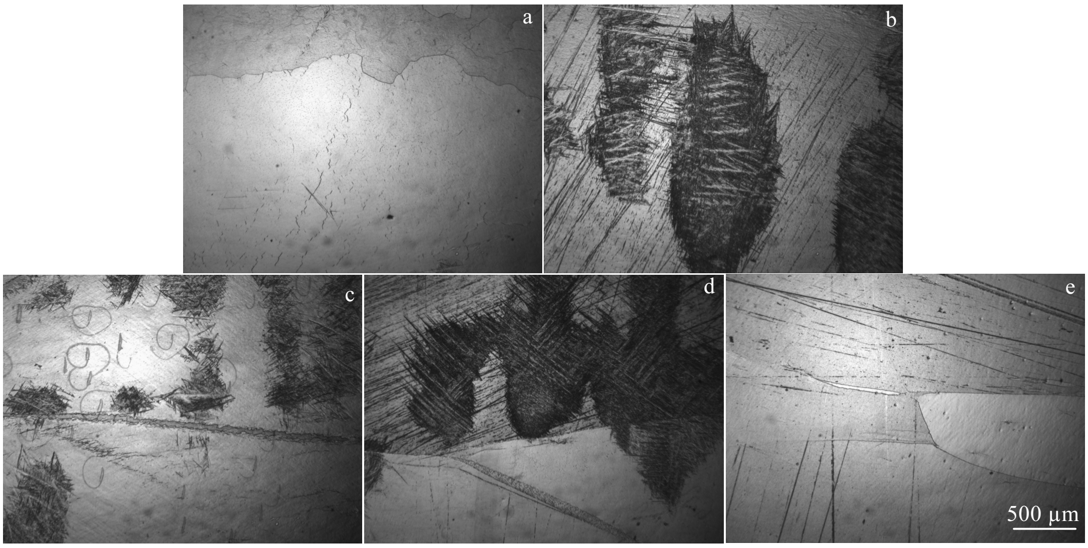

Fig.7 Optical micrographs of martensite of as-cast TB6 titanium alloy deformed at the temperature of 925 °C and strain of 0.92 with different strain rates: (a) 0.001s^{-1}, (b) 0.01 s^{-1}, (c) 0.1 s^{-1}, (d) 1 s^{-1}, and (e) 10 s^{-1}

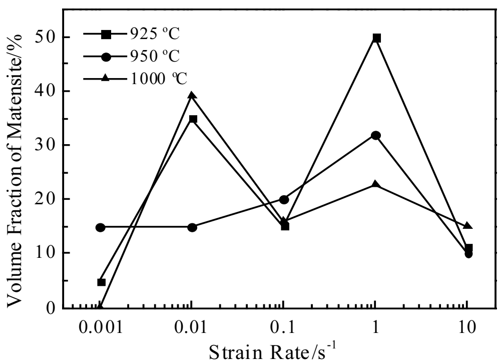

Fig.8 Dependence of the volume fraction of martensite on strain rate at the temperature of 925~1000 °C

as-cast TB6 titanium alloy deformed at the temperature of 1100 °C and strain of 0.92 with different strain rates. As can be seen in Fig.9, few martensite transformation is observed at the strain rate of 0.001 and 1 s^{-1}, and maximum content of martensite about 30% can be obtained at the strain rate of 0.1 s^{-1}. Fig.10 shows the relationship between the content of martensite transformation and strain rate. The relationship curves reveal that the optimal strain rate of 0.01~0.1 s^{-1} for martensite transformation is evident. It is worth mentioning that maximum content of martensite is lower at the temperature of above 1000 °C as compared to at the temperature of blow 1000 °C.

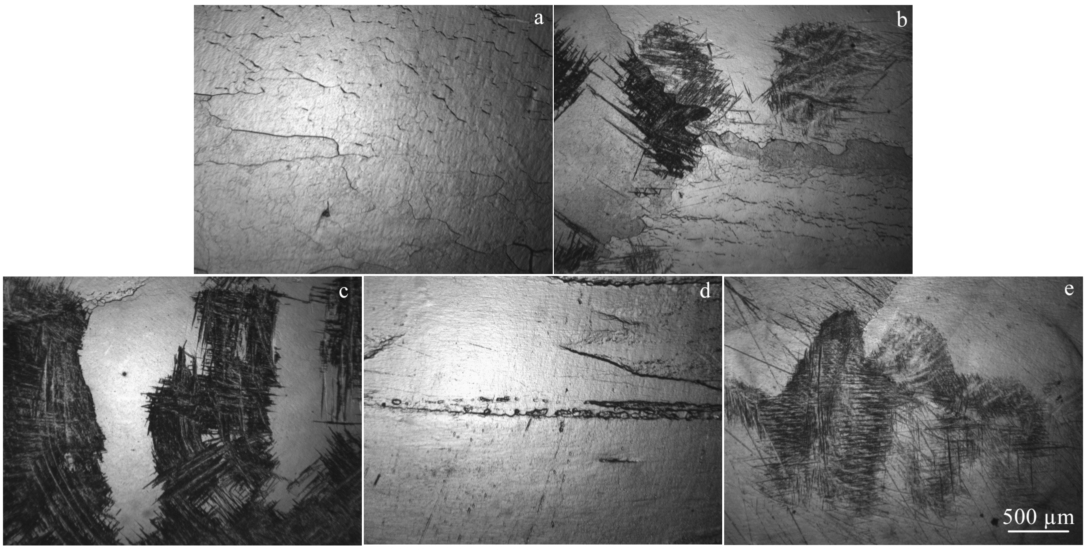

Fig.9 Optical micrographs of martensite of as-cast TB6 titanium alloy deformed at the temperature of 1100 °C and strain of 0.92 with different strain rates: (a) 0.001 s^{-1}, (b) 0.01 s^{-1}, (c) 0.1 s^{-1}, (d) 1 s^{-1}, and (e) 10 s^{-1}

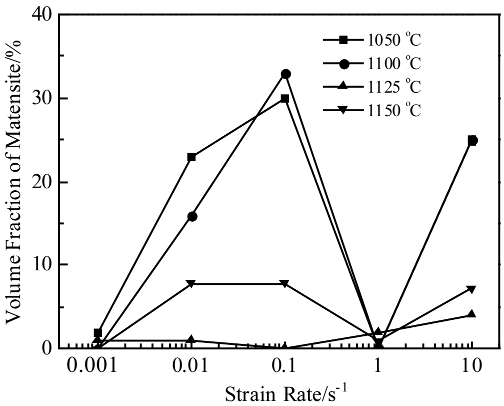

Fig.10 Dependence of the volume fraction of martensite on strain rate at the temperature of 1050~1150 °C

3 Conclusions

1) The nominal β stable coefficient is calculated to be 1.06, which is responsible for the mechanical instability of β phase in TB6 titanium alloy.

2) The SIM transformation with the dendritic morphology and the orthorhombic crystal structure of martensite is operative during the hot deformation of as-cast TB6 titanium alloy.

3) The alloy composition uniformity and internal stress are dependent on the deformation conditions, which are responsible for the content of SIM transformation. 50% martensite can be obtained at an optimal combination of the temperature of 925 °C and the strain rate range of 1 s^{-1}.

4) The effect of strain rate on SIM transformation is dependent on the temperature ranges. More SIM transformation appears at the strain rate of 0.1 s^{-1} when the temperature is 800~900 °C, at 0.01 and 1 s^{-1} when the temperature is 900~1000 °C, and at the strain rate of 1 s^{-1} when the temperature is above 1000 °C.

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铸态 TB6 钛合金热变形过程中应力诱发马氏体相变

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摘　要：对铸态TB6钛合金进行了恒应变速率热模拟压缩试验（变形温度为800~1150 ℃、应变速率为0.001~10 s^{-1}），研究了合金微观组织演变和应力诱导马氏体（SIM）相变。结果表明，该合金在热变形过程中出现了具有枝晶形态的正交结构SIM。SIM在β晶内和晶界形核。应变速率和变形温度控制合金成分均匀性和内应力，是SIM析出量的主要影响因素。不同应变速率的SIM析出量与变形温度范围有关。SIM析出量较高变形条件为：在800~900 ℃时应变速率为0.1 s^{-1}，900~1000 ℃时应变速率为0.01和1 s^{-1}，在1000 ℃以上时应变速率为1 s^{-1}。在变形温度925 ℃、应变速率1 s^{-1}时SIM析出量达最大化为50%。

关键词：铸态TB6钛合金；马氏体；热变形

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