Rare Metal Materials and Engineering
Volume 44, Issue 9, September 2015
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2015, 44(9): 2105-2108

ARTICLE

Macro-Micro Fracture Mechanism of TA3 Alloy under High-Velocity Deformation

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Abstract: The formability and the forming accuracy of materials will be greatly improved in high-velocity forming process. However, the fracture mechanism of materials in macro-micro scale keeps unknown or unclear yet. Herein, TA3 titanium alloy was adopted to investigate the fracture mechanism by Hopkinson bar test and analysis approaches of OM, SEM and stress-strain response. The results show that adiabatic shear bands (ASBs) induce the formation and the propagation of macroscale fracture, as well as softening in stress response; the fracture mechanism of TA3 titanium alloy during dynamic deformation in microscale is that spindle-shaped voids nucleate separately and then grow up to impenetrate each other, and finally micro cracks occur; the aggregation of the second-phase particles serves as the source for crack generation.

Key words: titanium alloy; dynamic deformation; fracture mechanism; adiabatic shear band

Recent interests in lightweight and high-strength components in aeronautic and astronautic applications have led to a favor of lightweight materials like titanium alloys and mass-reducing integral structure [1]. However, bad ambient ductility, large springback after forming, and parameter-sensitive damage of titanium alloys always result in hard forming and unsatisfied forming accuracy. In the light of previous investigations on high velocity deformation, materials will gain a noticeable increase in formability and forming accuracy under the interactions of inertia stabilization, tool/material impact and changes in constitutive behavior [2]. Therefore, high-velocity forming technology, such as electro-magnetic forming and explosive welding, is widely used. Researches have been done on dynamic deformation behavior [3], constitutive modeling [4], microstructure evolution [5], and the formation of adiabatic shear band (ASB) [6] of commercial pure titanium.

However, some defects such as adiabatic shear band and fracture will easily happen in the high velocity deformation [5]. They are of the characters which are quite different from that in quasi-static deformation. The characters have crucial influences on the improvement of forming limit. So, the fracture mechanism in high velocity deformation is needed for investigation.

1 Experiment

The material used was a TA3 alloy, as hot-rolled and annealed rods. The measured composition is listed in Table 1. Fig.1 shows the microstructure of the as-received material, which is composed of equiaxed α-grains with ~80 μm in size.

Small specimens (Φ6 mm × 9 mm) were prepared for the test (impact deformation) by Hopkinson bar. Fig.2 shows the profile of a specimen before and after test. The stress, strain and strain rate presented in the work were obtained via the post-treatment of the intensity of incident, reflected and transmitted waves in the test.

Moreover, optical microscopy (OM), and SEM observations were conducted on specimens after test. Specimens were mechanically polished and then electro-polished in a solution

Table 1 Chemical components of the TA3 alloy

Element	wt%	at%
Al	0.97	1.71
Ti	99.03	98.29

Received date: October 25, 2014
Foundation item: National Basic Research Program of China (2012CB012802)
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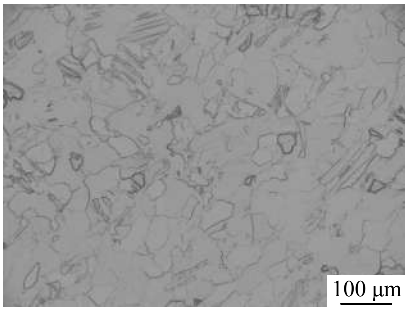

Fig.1 OM photograph of the microstructure of the as-received TA3 alloy

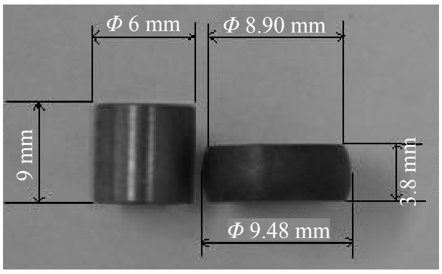

Fig.2 Profiles of the specimen before (left) and after (right) test

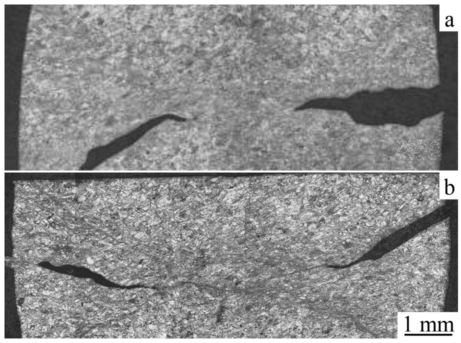

Fig.3 Fracture and adiabatic shear band in the middle section of the specimens deformed at 4000 s^{-1} and 423 K (a) and 573 K (b)

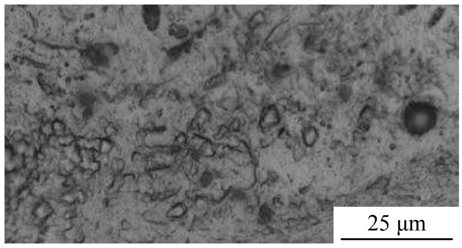

Fig.4 Equiaxed grains with nanometer size within the adiabatic shear band

consisting of perchloric acid, methyl alcohol and normal butanol with volume fraction of 1:6:3 using a voltage of 30 V for 15 s at –40 °C. Subsequently, the specimens were etched with Kroll reagent solution (HF:HNO_3:H_2O was 2:4:94).

2 Results and Discussion

2.1 Macroscale fracture and adiabatic shear band

Fig.3 shows the macroscale fracture of the specimens deformed at a strain rate of 4000 s^{-1} and temperatures of 423 and 573 K. Adiabatic shear band (ASB) can be easily observed, and macroscale fractures occur along the ASBs. By comparing the two images in Fig.3, it is clear that ASBs are thinner and stronger when the specimen is deformed at higher temperature. This can be attributed to the contribution of deformation temperature to the adiabatic temperature rise in ASBs. In addition, affected by the ASBs, fractures occur and propagate not along the 45° to the load axis as that in quasi-static deformation, but along the direction of ASBs. Moreover, fractures appear at interior section when the specimen is deformed at 573 K, while at the margin when the specimen is deformed at 423 K. It indicates that material damage is sensitive to the adiabatic temperature rise. A high adiabatic temperature rise leads to the separated nucleation of cracks inside the specimen.

Fig.4 is the enlarged view of the ASB in Fig.3b. Small equiaxed grains with the size of 2~3 μm are observed, which are believed as recrystallized grains [7]. It indicates a large temperature rise in the ASB which exceeds the recrystallization temperature. Some researchers reported that the calculated temperature rise was up to 970 K [8], while the recrystallization temperature of TA3 alloy was about 780 K [9].

2.2 Ductile fracture in microscale

In order to make clear the mechanism of macroscale fracture, scanning electronic microscope (SEM) was adopted to investigate microstructure in microscale. Fig.5a shows the fracture near the crack tip in Fig.3b. Beadlike dimples can be observed. They nucleate separately. When they grow up, they may impenetrate each other, resulting in a microscale crack, following as coming to a macroscale fracture. When the enlarged view of one of the dimples is focused on, as shown in Fig.5b, the right characters of ductile dimple are clearly illustrated. In addition, some white particles are embedded in the dimple and cracks propagate along the margin of the particles. They are the second-phase particle, e.g. alumina particle. So, the second-phase particle may contribute to the nucleation and the growth of the ductile dimples in the high-velocity deformation. It can also be verified from the almost peeled particles from the dimple in Fig.5b. Some researchers reported that high strain rate can lead to aggregation of the second-phase particles[9]. The aggregation of the second-phase particles serves as the source for crack generation.

2.3 Stress-strain response during damage

Stress-strain response illustrates the macroscale characters caused by ASBs, the nucleation of ductile dimples, the propagation of microscale cracks and fracture. Fig.6 shows stress-strain response of TA3 alloy deformed at 573 K and 4000 s^{-1}.

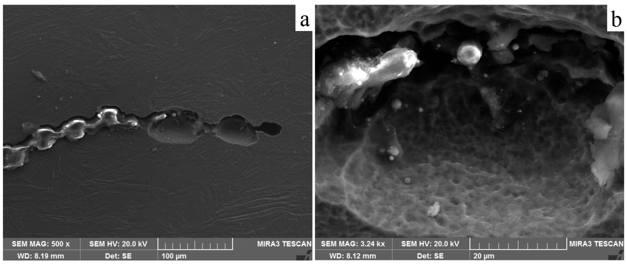

Fig.5 SEM image of the microscale void (a) and the enlarged view (b) of the specimen deformed at 4000 s^{-1} and 573 K

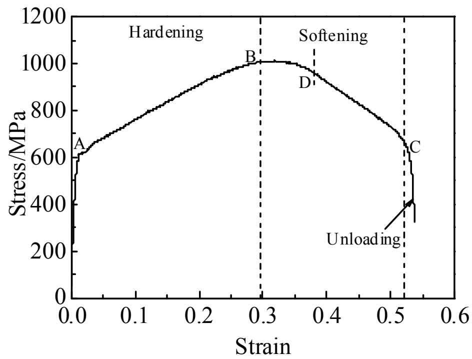

Fig.6 Stress-strain response of TA3 alloy deformed at 573 K and 4000 s^{-1}

Remarkable hardening happens with increasing strain up to about 0.3 (point B) accompanied by a clear yield (point A). Then the material shows notable softening till unloading (point C). The stress drops more and more rapidly with increasing of strain within the stage of softening. It is well known that titanium alloy is very sensitive to strain and strain rate (will be discussed later) [10]. However, the material will soften once ASBs occur since they cause a distinct local temperature rise and a large local strain. In addition, the nucleation of ductile dimples, the propagation of cracks and fracture (may initiate from point D) intensify the softening, which leads to a rapider stress drop.

2.4 Effects of strain rate and temperature

Strain rate and deformation temperature affect not only the hardening, but also the occurrence of ASB, the ductile dimple, the crack and fracture of the material in high-velocity deformation. Fig.7 shows the effect of strain rate on stress-strain response of TA3 alloy deformed at 573 K, and Fig.8 shows the effect of deformation temperature at a constant strain rate of 4000 s^{-1}.

It can be easily found from these two figures that there exist the strain rate hardening and temperature softening. No softening can be observed at strain rates of 1000 and 2000 s^{-1}. It indicates there is no ASB in these cases. Slight softening can be observed at strain rate of 3000 s^{-1}, which indicates the occurrence of ASB. However, it can not be easily found in the OM photograph (Fig.9c). Remarkable softening happens in all

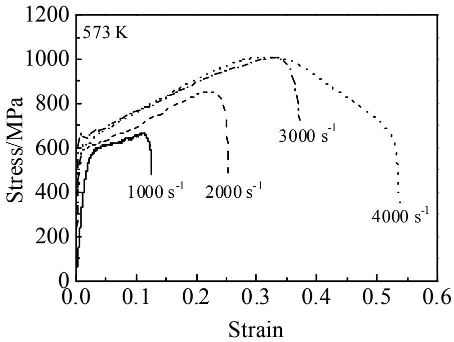

Fig.7 Stress-strain responses of TA3 alloy deformed at 573 K and different strain rates

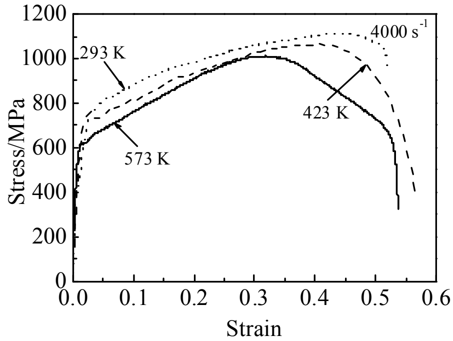

Fig.8 Stress-strain responses of TA3 alloy deformed at strain rate of 4000 s^{-1} and different temperatures

of the cases at 4000 s^{-1} in spite of deformation temperatures (Fig.8). Nevertheless, softening weakens with decreasing of temperature. That is to say, deformation temperature makes significant contribution on the formation of ASBs and cracks. It is believed that no fracture (or cracks) happens when the specimen is deformed at 293 and 423 K.

2.5 Microstructure evolution

Fig.9 shows the microstructures evolution of TA3 alloy

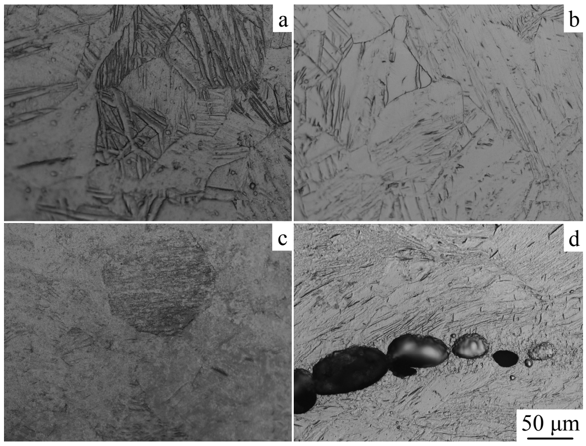

Fig.9 Microstructures of TA3 alloy deformed at 573 K and different strain rates: (a) 1000 s^{-1}, (b) 2000 s^{-1}, (c) 3000 s^{-1}, and (d) 4000 s^{-1}

deformed at 573 K. Clear grain boundaries can be observed at the strain rate of 1000 s^{-1}, and grain deformation is not noticeable except for some twins (Fig.9a). Twins are also observed, but grain boundary becomes vague at 2000 s^{-1} (Fig.9b). However, most of grain boundaries become impossible to distinguish at 3000 s^{-1} (Fig.9c), while ASBs occur in fact (according to Fig.7), but are not easy to be observed. Evidently ASBs can be clearly observed and spindle-shaped voids nucleate separately along the ASB (Fig.9d). It may be attributed to the stress wave propagation and inertial effect in the high-velocity deformation. Both of them can relax strain localization, which results in almost the same nucleation probability for voids along the ASB. That is to say, this is the special fracture mechanism of TA3 alloy in high-velocity deformation.

3 Conclusions

1) ASB is the nature of flow softening and for the propagation of macroscale fracture. Large adiabatic temperature rise in ASB caused by deformation temperature makes fracture occur at interior section of the specimen and thus a long range softening appears in stress-strain response.

2) Spindle-shaped voids nucleate separately in microscale and then grow up to impenetrate each other, resulting in a crack.

3) The aggregation of the second-phase particles caused by dynamic deformation serves as the source for crack generation.

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TA3 钛合金高速变形的断裂机制

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摘　要：材料在高速成形过程中其成形性能和成形精度更能够得到显著的提高。但是，材料在高速成形过程中的断裂机制尚不清楚或未知。因此，采用 TA3 钛合金材料利用 Hopkinson 压杆实验并结合显微镜、扫描电镜和应力响应分析手段研究了该材料在动态变形过程中的断裂机制。结果表明，绝热剪切带是导致宏观裂纹的形成和扩展以及流动软化的根源；TA3 钛合金动态变形微观断裂机制为纺锤状孔洞在绝热剪切带内各自独立形核，然后各自长大从而相互贯通，形成微观裂纹；第二相粒子的偏聚是微观裂纹发生的源泉。

关键词：钛合金；动态变形；断裂机制；绝热剪切带

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