Shock-induced Martensite phase transformation and its effects of metastable near β Ti-5553 titanium alloy

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Abstract. In this paper, microstructure evolution and mechanic properties of metastable near β Ti-5553 alloy were investigated. SHPB, SHTB and light gas gun were employed to carry out the dynamic loadings. Microstructure evolution were characterized by OM, quantitative metallography and XRD. The experimental results demonstrated that stress-induced martensite transformation occur in metastable Ti-5553 alloy through SHPB, SHTB and plate impact loadings. In SHPB loading test, stress-induced martensite transformation is one of the methods that dissipate energy besides of adiabatic shear band, and also occur before ASB. In SHTB and SHPB+SHTB loading tests, the transformation amount of stress-induced martensite exhibit similar trend. In plate impact experiment, the content of martensite phase transformation increased with the impact velocity.

1 Introduction

Titanium alloys have many excellent physical and mechanical properties, such as low density, high strength-to-weight ratio and good corrosion resistance. These properties have resulted in the use of titanium alloys in motor vehicle, aerospace, bio-medical and industrial applications [1-4]. When a titanium alloy is used in dynamic loading conditions, adiabatic shear band usually occur due to its relatively low heating capacity [5-6]. Meanwhile, under some dynamic loadings, another microstructure evolution, i.e. shock-induced phase transformation, or stress-induced martensite (SIM) happened [7-8]. The adiabatic shear behaviour of titanium alloys has been extensively studied. Shock induced phase transformation in metastable β titanium alloys under high strain rate loading still need further more research [9-10]. The relationship between adiabatic shear band and shock induced phase transformation and their effects on the properties are not clear. In this paper, microstructure evolution and mechanical response of metastable near β Ti-5553 alloy under both Split Hopkinson Pressure Bar (SHPB) and Split Hopkinson Tension Bar (SHTB) dynamic loading, under light gas gun were studied.

2 Experimental procedures

Ti-5553(Ti-5Al-5Mo-5V-3Cr-1Fe) alloy was chosen as the experimental material. The β-transus temperature T_β is 814 °C. The alloy was solid solution treated at 870 °C for 2 h and then water cooled. Dynamic compression tests were carried out with two size of SHPB with ϕ 14.5 mm and ϕ 37 mm respectively, while dynamic tension test was carried out with SHTB. ϕ 4 × 4 mm cylinders were used for ϕ 14.5 mm SHPB experiment and ϕ 10 × 25 mm cylinders for ϕ 37 mm SHPB. For SHTB experiment, ϕ 6 mm × 23 mm cylinders with screws were machined from the original Ti bar and from the recovered ϕ 10 × 25 mm cylinders respectively.

Standard metallurgical samples were prepared and etched in 4%HF + 6%HNO_3 + 90%H_2O solution for OM observation. The amounts of phase transformation were measured and calculated by the combination of more than thirty OM images in one sample and quantitative metallographic analysis method, which was used to analyse the effect of impact velocity or strain rate on the amount of new phase. The calculation formula is shown in (1).

$$L_A=L/S \tag{1}$$

L_A: the length of α″ phase strip in unit area (mm)
L: the total length of α″ phase strip in each picture (mm)
S: the actual area of each picture (mm^2)

3 Experimental results and discussions

3.1 Microstructural evolution and stress-strain relationship of Ti-5553 alloy under SHPB dynamic compression

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Microstructural characteristics of Ti-5553 alloy undergoing SHPB dynamic compression were shown in Fig.1. Original grains with β single phase are solution treated and unloaded. The amount of stress-induced martensite increases with the increasing of strain rate from 1500 s^{-1} to 3000 s^{-1}. When the strain rate is 1500 s^{-1}, the lamellar martensite can be observed. When the strain rate increase to 2000 s^{-1}, the martensite strip exhibit a bending deformation, while the strip bend severely at 2500 s^{-1}. With further high strain rate of 3000 s^{-1}, adiabatic shear band form along the bending area.

Therefore, under dynamic compression loading, the microstructure evolution of β single phase Ti-5553 alloy includes shock induced martensite phase transformation and ASB. Under strain rate of 1500 s^{-1}, the energy absorption are mainly consumed in stress-induced phase transformation. With the increasing strain rate of 3000 s^{-1}, energy consumption can not only be through phase transformation, ASB, as another way of energy consumption, occur together, which finally develop into crack and failure of the material.

The stress-strain curves demonstrate that with the increasing of strain rate (Fig.2), the yield stress increase from about 1400 MPa to 1500 MPa, meanwhile the maximum stress also increase. However, β single phase Ti-5553 alloy does not exhibit obvious strain rate hardening effect. The plastic strain at which the stress collapse or at the end of the loading time, decreases with the increasing of strain rate.

3.2 Microstructural evolution and stress-strain relationship of Ti-5553 alloy under SHPB+SHTB dynamic loadings

The Ti-5553 alloy cylinders were undergoing dynamic compression by use of ϕ37mm SHPB at first, the recovered large cylinders were machined into smaller dynamic tension cylinders. The microstructure evolution under SHPB, SHTB, SHTB+SHPB dynamic loadings are compared in Fig. 3.

It can be seen that under both SHPB and SHTB loadings, shock-induced martensite occur in some grains. In the circle area, we can clearly see that there are several bunch of martensite with different growth direction in one grain, while in some grains, there are the martensite in one growth direction. In SHTB tests, most martensite grows in one direction. Under combined loadings of SHPB+SHTB, the density of martensite increase and the grain number which contains martensite also increases.

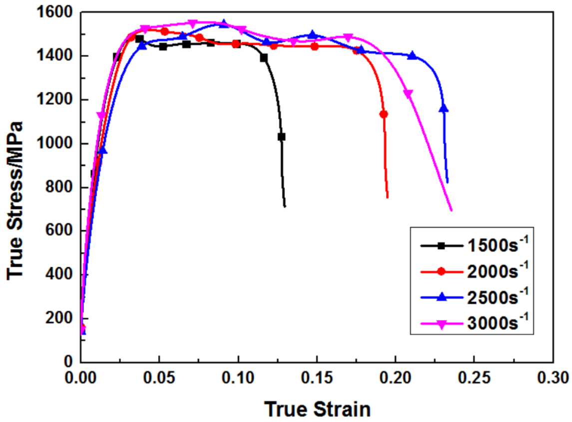

Fig. 2. True stress-strain curves of Ti-5553 alloy under SHPB dynamic loading.

Combined with the quantitative metallographic method, as shown in Table 1, it is clearly demonstrate that under SHPB loading, the amount of β→α″ transformation is more than that under SHTB loading. While under SHPB and SHTB combined loadings, the martensite amount per area is the most in these three kinds of loadings.

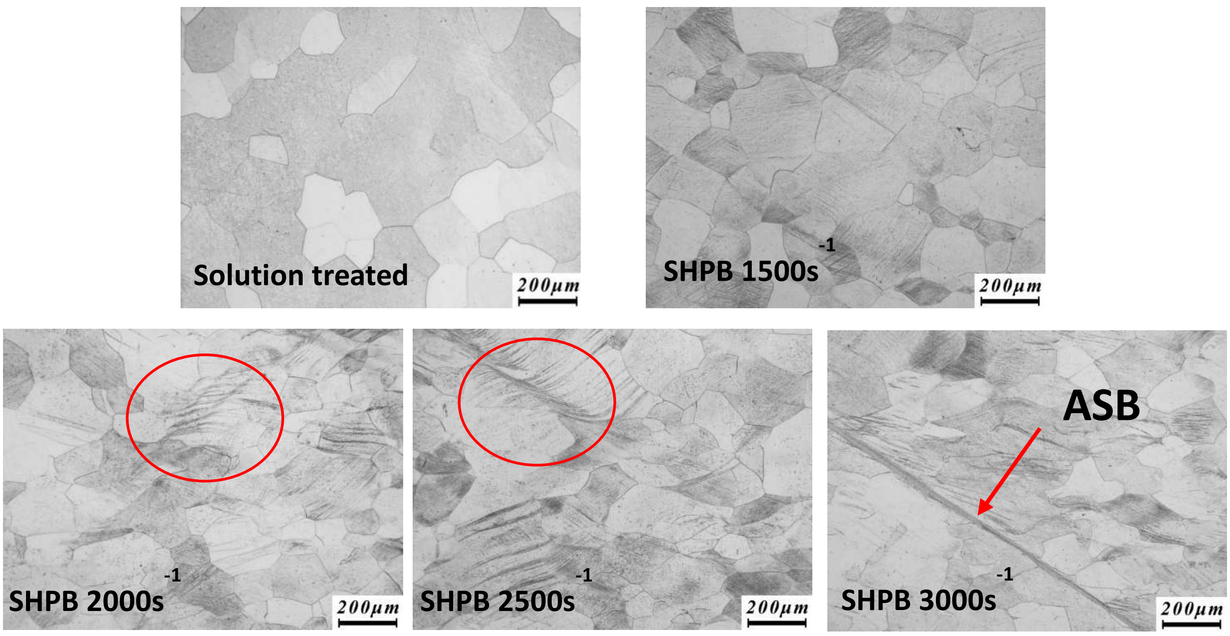

Fig. 1. Microstructure evolution of Ti-5553 alloy with the strain rates.

However, the transformation amount under combined loading is not linear combining result of the two separate loadings, which indicates that in SHPB+SHTB loading test, the further transformation of stress-induced martensite is suppressed, in the case of pre-occurrence of martensite after SHPB testing.

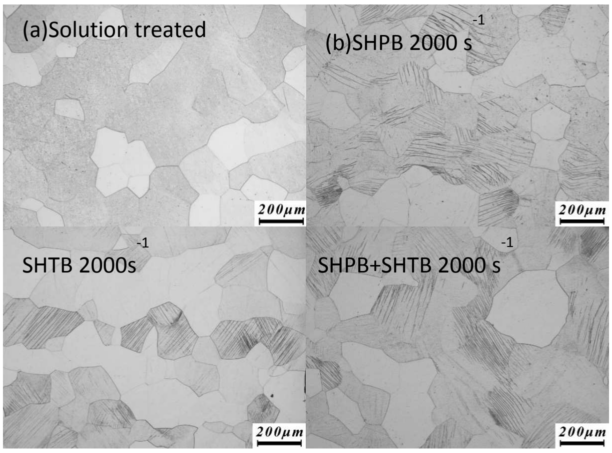

Fig. 3. Microstructure evolution of Ti-5553 alloy go through unloading, under SHPB, SHTB and SHPB+SHTB dynamic loadings.

Table 1. β→α″ phase transformation amount of Ti-5553 alloy under different loadings.

Loading conditions	L(mm)	L_A(mm.mm^{-2})
SHPB 2000 s^{-1}	10.53	8.26
SHTB 2000 s^{-1}	8.72	6.84
SHPB2000 s^{-1} +SHTB2000 s^{-1}	20	11.14

3.3 Microstructural evolution of Ti-5553 alloy under light gas gun

Plate impact experiments were carried out with the velocity range of 380 m/s to 560 m/s. Thickness of flyer plate is 6 mm. Fig. 4 demonstrate that with the increasing of impact velocity, the amount of α″phase increase obviously.

Table 2 shows the quantitative metallographic results. The total length and the average length per area clearly demonstrate the increasing transformation amount of martensite with the impact velocity.

In order to verify the exact phase structure of the phases, XRD characterization result indicate that the original solution treated R4 is single β phase (Fig. 5). When the impact velocities are 380m/s and 560m/s, α″phase can be measured, which is a verification of β→α″ phase transformation occur under dynamic loading.

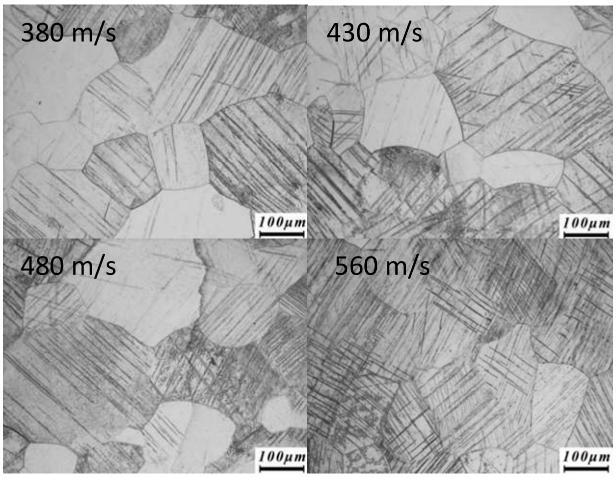

Fig. 4. Microstructures evolution of Ti-5553 alloy impacted by flyer plates under different velocities.

Table 2. α″ phase transformation amount of Ti-5553 alloy under light gas gun.

Impact velocity	L(mm)	L_A(mm.mm^{-2})
380	13.62	39.18
430	15.01	43.19
480	15.33	52.65
560	18.31	54.65

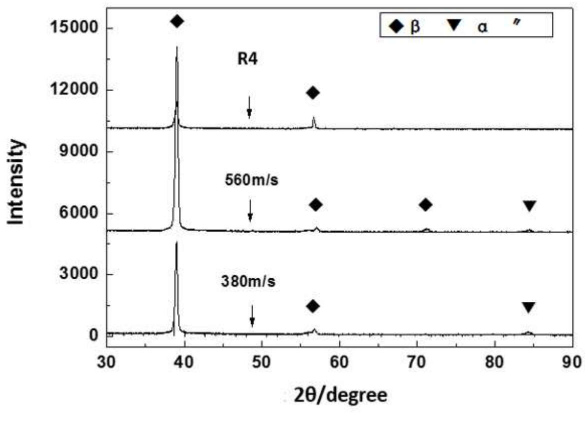

Fig. 5. XRD characterization of original Ti-5553 alloy, under 380m/s and 560m/s impact velocities.

4 Conclusions

In this paper, microstructure evolution and mechanical properties of β single phase Ti-5553 alloy were investigated. The experimental results demonstrated that Stress-Induced Martensite (SIM) phase transformation (namely β→α″phase) occurs in β single-phase metastable titanium alloy, under various dynamic loadings. The SHPB, SHTB and plate impact result in the stress-induced martensite transformation in metastable Ti-5553 alloy. In SHPB loading test, stress-induced martensite transformation is one of the methods that dissipate energy. With the increase of strain rate, the adiabatic shear band occurs after martensite phase transformation. In SHPB+SHTB loading test, the transformation of stress-induced martensite is suppressed. In plate impact experiment, the content of martensite phase transformation increased with the impact velocity.

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