Adiabatic Shearing Behavior of Shock-Prestrained Ti-2Al-9.2Mo-2Fe Alloy at Different Reloading Strain Rates

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Abstract. The effect of shock-prestrain on the adiabatic shearing behavior of a metastable β titanium alloy, Ti-2Al-9.2Mo-2Fe (2A2F), is systematically investigated. 2A2F alloy blocks with average grain size of 67 μm were first shock-prestrained at 6 and 12 GPa, and then reloaded at strain rates of 3000 and 4000 s⁻¹. The results show that, the dynamic strength of 2A2F hardly increases after the shock prestrain. Adiabatic shear bands (ASBs) are more likely to bifurcate and interact, and the density of micro-damages and micro cracks in ASBs increases in the shock-prestrained materials. This trend becomes more significant with the increased preshock stress amplitude. However, in general, the amount of ASBs is low regardless of shock stress amplitude. The dynamic ductility is also hardly affected by shock-prestrain. These suggest that 2A2F alloy has good resistance to multiple impacts.

1. Introduction
Near- and metastable-β titanium alloys have excellent fracture toughness and cold working performance compared with α titanium alloys. And they can be hardened after solution and aging treatment[1]. Although some β titanium alloys, such as Ti-13V-11Cr-3Al and Ti-5Al-5V-5Mo-3Cr, have been industrialized, the difficulties in smelting and high cost of β titanium alloys have always limited their wider applications[2-3]. The addition of Fe in titanium alloys will produce strong solid solution strengthening. The addition of Mo can significantly reduce the elastic modulus of the materials while Mo is commonly used β phase stable element in titanium alloys. Because Fe and Mo are so common in steel industry that they are relatively cheap. For the above reasons, Ti-Al-Mo-Fe
alloys have become the general choice for the design of low cost β titanium alloys with low modulus and high strength[4].

Ti-2Al-9.2Mo-2Fe alloy (2A2F) is a low-cost β titmetastableanium alloy with low modulus and high strength designed according to the molecular orbital calculation method of electronic structure[5]. After solution and aging treatment, its strength can exceed 1500 MPa with acceptable ductility[6]. The effect of shock prestrain on the mechanical properties of 2A2F, especially dynamic mechanical properties, has been rarely studied. In this research, 2A2F rolled sheets were solution treated to obtain equiaxial microstructure with grain size of 67 μm. 2A2F alloy blocks were first shock prestrained at 6 GPa and 12 GPa. Then the split Hopkinson pressure bar (SHPB) were used to evaluate the reloading dynamic mechanical properties of the shock-prestrained alloys at different strain rates. The features of adiabatic shear bands (ASBs) formed during the reloading processes were also studied.

2. Experiment

2.1. Materials
The material used in this research was 2A2F hot-rolled sheet, whose βT (β transition temperature) is 820°C. Equiaxial microstructure with grain size of 67 μm was obtained by heating at 850°C for 30 minutes followed by water quenching. Figure 1 shows the metallographic photograph and TEM image of 2A2F alloy. Metallographic photograph shows that 2A2F is composed of equiaxial β grains. A few α” phase induced by thermal stress was found in β grains by TEM image. In addition, the dislocation density of the solution-treated 2A2F alloy is very low and no other phase except α” was formed during this process.

![Metallographic photograph and TEM image of the solution-treated 2A2F alloy with β grain size of 67 μm.](image)

Figure 1. Metallographic photograph and TEM image of the solution-treated 2A2F alloy with β grain size of 67 μm.

2.2. Shock prestrain
One-dimensional shock waves with stress amplitude of 6 GPa and 12 GPa were yielded in 2A2F alloy blocks through the plate impact tests using a single-stage gas gun. The experiments adopted symmetrical impact, and the impact velocities corresponding to 6 GPa and 12 GPa were 474 m/s and 906 m/s, respectively. In this process, a specially designed so-called “soft-recovery” shock wave
loading device was used to ensure that the residual strain is less than 2% after shock loading. The detailed device diagram can be referred to Reference [7].

2.3. Reloading and microstructure analysis
Dynamic reloading compression to the shock-prestrain alloys was performed using a SHPB apparatus at the ambient temperature. The average strain rate set for the dynamic compression tests was 3000 and 4000 s\(^{-1}\). Metallographic samples of the shock-prestrained 2A2F alloy were polished by water-lubricated silicon carbide sandpaper and corroded after mechanical polishing, then metallographic photos were taken by Olympus BX51M.

3. Results

3.1. Mechanical properties during reloading
The reloading stress-strain curves of 2A2F alloy under different strain rates during dynamic compression are shown in Figure 2. Under the strain rate of 3000 s\(^{-1}\), the flow stress of 2A2F decreases slightly after shock-prestrained at 6 GPa compared to the shock-free 2A2F. When the preshock stress amplitude increases to 12 GPa, the reloading flow stress is equivalent to that of shock-free 2A2F. As the strain rate is up to 4000 s\(^{-1}\), the flow stress of 2A2F preshocked at 6 GPa is almost same to that of shock-free 2A2F. While the reloading flow stress of 2A2F preshocked at 12 GPa has tiny increment. This indicates that the shock prestrain process hardly has influence on the dynamic strength (flow stress) of 2A2F alloy.

![Figure 2. The dynamic reloading true stress-strain curve of 2A2F: (a)3000s\(^{-1}\);(2)4000s\(^{-1}\).](image)

3.2. Adiabatic shear behavior
Figure 3 shows the adiabatic shear bands formed inside 2A2F during dynamic reloading at the strain rate of 3000 s\(^{-1}\). The results enlighten us that the width of ASBs formed in 2A2F increases after shock prestrain. In addition, the ASBs are more likely to bifurcate and interact, and the density of micro-damages and micro cracks in ASBs increases in the shock-prestrained alloys. This trend becomes more significant with the increased preshock stress amplitude. However, the total amount of ASBs is small and all the ASBs are self-organized.
Figure 3. The ASBs formed inside 2A2F at the strain rate of 3000 s$^{-1}$: (a) 0 GPa; (b) 6 GPa; (c) 12 GPa.

The ASBs formed inside 2A2F at the strain rate of 4000 s$^{-1}$ are exhibited in Figure 4. It can be seen that the width of ASBs, the possibility of ASBs interaction and the amount of microvoids in the ASBs augment slightly when the reloading strain rate increases to 4000 s$^{-1}$. However, the increase of reloading strain rate has no essential effect on the adiabatic shear behavior of 2A2F.
4. Discussion

For 2A2F, the dynamic compression stress-strain curve does not show obvious strain hardening due to the thermal softening caused by the adiabatic temperature rise in high strain-rate loading, regardless of whether the alloy was pretrained by shock wave. However, with the increased reloading strain rate, a slightly obvious change in flow stress of 2A2F with the prestrain stress amplitude was observed. Similar performance mentioned by Le Chang et al.\[8\] was proved to be mainly due to dislocation hardening. It indicates that the higher the reloading strain rate, the more sensitive the dynamic reloading strength to prestrain stress amplitude.

When the reloading strain rate is 3000 s\(^{-1}\), the amount of ASBs in the shock-free 2A2F is small, whose width is about 1~2 μm. There is no bifurcation, and these ASBs are parallel arranged and self-organized. As the strain rate is up to 4000 s\(^{-1}\), the width of ASBs is slightly increased and bifurcation occurs, but the distribution characteristic is still "self-organization", which has been observed in other metals such as ZK60 Magnesium alloy\[9\] and 1Cr18Ni9Ti austenitic stainless steel\[10\]. Compared with the shock-free 2A2F, the width of ASBs in 2A2F pretrained at 6 GPa is

**Figure 4.** The ASBs formed inside 2A2F at the strain rate of 4000 s\(^{-1}\):
(a) 0 GPa; (b) 6 GPa; (c) 12 GPa.
increased at the same strain rate. In this case, ASBs with more microvoids, microcracks and other micro-damages are more prone to bifurcate. When the shock stress amplitude increases to 12 GPa, compared to the 6 GPa shocked alloy, the morphology of ASBs changes little at the same strain rate. “Self-organization” and occasional bifurcation are still. The ASBs not only bifurcate, but also converge when the strain rate rises to 4000 s⁻¹. That is to say, after the bifurcations, the bifurcated ASBs expanded for a distance and then merged into the main ASBs again, forming a ring-like structure. The ring-like structure is distinctly different from plug of ASBs reported by Y Ren et al[11]. In contrast, the ASB interaction in the ring structure is not drastic due to the low density of ASBs in 2A2F.

With the increased preshock stress amplitude, the amount of micro-defects such as dislocations and twins in the material increases significantly. Even new phases may be formed in shock wave propagation. Changes in microstructure cause local stress concentration and increased internal aberration energy, which are the driving forces of ASBs nucleation. So that ASBs nucleate and interact more easily. Therefore, the higher the preshock stress amplitude, the larger the width of ASBs. At the same time, there is a significant increase in the number of bifurcations, microvoids and microcracks in ASBs. In general, the amount of ASBs formed in 2A2F during dynamic reloading is small, and the ASBs are self-organized. However, from the perspective of reloading mechanical properties, the extent of this increase does not have a great degradation on the material properties, and 2A2F alloy shows good resistance to multiple impact failure.

5. Conclusion
The dynamic mechanical behavior of 2A2F alloy with an average grain size of 67 μm in this research shows a low sensitivity to preshock stress amplitude. The adiabatic shear behavior of 2A2F alloy is also hardly significantly changed even if the alloy was subjected to 6 GPa and 12 GPa shock prestrain. The low density of ASBs and its self-organized characteristic remain well. In general, 2A2F alloy shows good resistance to multiple impact failure.

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