Dynamic mechanical behavior and microstructure evolution of 7A52-T6 alloy at elevated temperatures

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Abstract: Dynamic mechanical behavior and microstructural evolution of 7A52-T6 aluminum alloy were investigated at elevated temperatures ranging from 150 to 350℃ and strain rates ranging from 2000s⁻¹ to 5000s⁻¹ using a compressive hospitalization pressure bar (SHPB) system. The results show that 7A52 aluminum alloy has obvious temperature sensitivity, but the sensitivity to strain rate is weak. The effects of temperature on the microstructure of 7A52 aluminum alloy are significant, and the dislocation density decreases with the increase of temperature. With the increase of impact temperature, some of the η’ phases are dissolved, and some of them are transformed into η phases. This study in general provides a significant understanding on the relationship between microstructure evolution and mechanical behavior of 7A52-T6 aluminum alloy under dynamic loading and at elevated temperature.

1. Introduction

7A52 aluminum alloy belongs to Al-Zn-Mg series heat treatable high strength aluminum alloy, which has a wide range of applications, especially in the field of weapons industry, including tank armor and gun frame. The composition and properties of the alloy are similar to those of 7039 aluminum alloy for the second generation of armor in the United States [1]. Many previous investigations into 7A52 aluminum alloy were carried out primarily on welding property [2-4]. A considerable amount of work has been carried out on the plastic flow of this material under low strain rates and various temperatures [5-8]. However, up to now, work concerning the systematic effects of strain rate and temperature on the plastic flow response has been done, as well as the evolution of the microstructure, during dynamic impact deformation. So far, less research has been given to the microstructure evolution process during high temperature deformation [9]. From the deformability viewpoint and for structural design purposes, it is necessary to characterize the mechanical properties of 7A52-T6 Al alloy over a wide range of temperatures and strain rates up to impact loading. Given the service conditions of the material, examining its dynamic shock performance is particularly important [10]. Meanwhile, it is well known that the tests based on the split Hopkinson bar have been used successfully not only to determine the mechanical properties of materials at the strain rates from $10^2$ to $10^4$s⁻¹ [11-13], but also to perform the dynamic impact deformation responses for many kinds of aluminum alloys [14-16].
2. Materials and experimental procedure

The material tested was a commercially produced 7A52-T6 aluminum alloy with the following chemical composition: Zn 4.4, Mg 2.35, Mn 0.47, Cr 0.21, Cu 0.18, Zr 0.08, Fe 0.19, Si≤0.25, and a balance of Al (wt.%). Cylindrical specimens with a length of 4 mm in thickness and 6 mm in diameter were cut from 7A52-T6 aluminum alloy plate, which was supplied as hot-rolled plates of 10mm thickness, and subsequently heat treated to the T6 temper (120℃ for 24 h) for dynamic impact tests. Dynamic compression tests were conducted in the nominal strain-rate range of from 2000s⁻¹ to 5000s⁻¹ and at temperatures of 150 to 350℃ utilizing a split Hopkinson method. The sample was heated by 1000W split plastic hot air gun, and for each keeping warm 3min. Also for each strain rate, three specimens were tested to obtain reliable results. The impact direction was parallel to the rolling direction of the plate. Elevated temperature separated Hopkinson pressure bar devices are shown in Fig. 1.

Specimens for optical metallography were sectioned perpendicular to the loading axis from the deformed samples, polished conventionally and etched using an acidic solution (1mLHF, 2.5mL HNO₃, 1.5mLHCl, 95mL H₂O). Following the impact tests, thin foils for TEM observation were prepared by cutting slices with a thickness of 0.7 mm in a direction perpendicular to the compression axis. The slices were ground to a final thickness of 0.2 mm using 1200 grit size soft paper and discs with a diameter of 3 mm were then trepanned from each slice using an electron discharge machining system. Finally, the discs were polished in a circulating electrolyte solution comprising 50% HNO₃ and 50% C₂H₅OH at -15℃ using a twin-jet polishing machine with an agitation voltage of 15V DC. The TEM observations were performed using a Talos F200X transmission electron microscope with an operating voltage of 300 kV.

Fig. 1. Setup for the high strain rate tests at elevated temperatures

3. Experimental results and discussion

3.1 Stress-strain curves

Figs. 2. (a-d) show the stress-strain curves of the 7A52-T6 specimens deformed at strain rates of 2000s⁻¹~5000s⁻¹ and temperature of 150℃~350℃, respectively. It is seen that the flow response of the 7A52-T6 specimens is sensitive to both the temperature and the strain rate. For a given temperature, the flow stress increases with increasing strain rate. However, for a constant strain rate, the flow stress decreases with increasing temperature. Comparing these curves with one another, it is found that, for a specific strain rate, the flow stress decreases markedly with temperature. Further, changes in temperature have a significant effect on the work-hardening rate: the degree of work hardening is
considerably smaller during deformation at the higher temperature of 350°C, at this temperature a nearly horizontal line being obtained, suggesting that the rate of work-hardening is being balanced by the rate of thermal softening. In contrast, at 150°C, the flow stress generally increases as the strain rate increases due to an increase of dislocation density and the dislocation multiplication rate\cite{17}. When the flow stress relative to the temperature is compared to the flow stress relative to the strain rate, there is no doubt that the effect of temperature on the flow stress is more pronounced than that of the strain rate on flow stress. Flow softening appears more clearly as the temperature increases, even when the specimen is loaded at a high strain rate.

Fluctuation of the stress to strain in the way similar to a sinusoidal wave is observed in the strain-stress curves especially at 150°C. The flow stress drops beyond the yield point at first, and with further increase in strain, the flow stress starts to increase, reaches a maximum value and then decreases rapidly. The details are shown by the inset in Fig.2.(b). It should be the sign of the alternating softening and hardening phenomenon, and finally thermal softening counteracted the stability resulted from hardening. However, When the competition between work hardening and thermal softening effect reaches equilibrium, the flow stress tends to steady state.

![Fluctuation of stress to strain](image)

Fig. 2. True stress-strain curves of 7A52-T6 aluminum alloy impacted at strain rates of 2000s\(^{-1}\)~5000s\(^{-1}\).

3.2 Strain rate and temperature effects

Fig. 3 shows the variation of the flow stress with the logarithmic strain rate as a function of the temperature at true strains of 0.05 and 0.2, respectively. It is seen that the true stress has not changed much as the strain rate is increased from 3000s\(^{-1}\) to 5000s\(^{-1}\), respectively. This observation demonstrates clearly that the temperature sensitivity of the tested material is dependent of strain rate\cite{18}.
However, it can be seen that with increasing temperature at all values of the strain the flow stress decreases linearly. Thus, it is obvious visually that the deformation resistance of 7A52 Al alloy at the high temperature range is dominated by the temperature effect. It is therefore inferred that a greater degree of dislocation annihilation and mobility occurs at higher deformation temperatures. (as evidenced by the TEM observations presented later in Fig. 7) The temperature sensitivity of the deformed specimens can be quantified as follows[19]:

\[ n_a = \frac{\sigma_2 - \sigma_1}{(T_2 - T_1)} , \]

where the compressive stresses \( \sigma_2 \) and \( \sigma_1 \) are obtained in tests conducted at temperatures of \( T_2 \) and \( T_1 \), respectively. Fig. 4 shows the variation of the temperature sensitivity with the true strain rate as a function of the true strain and temperature, respectively.

As can be seen, When the temperature range is 150°C-250°C, the temperature sensitivity coefficient increases at first and then decreases with the increase of strain rate. At the temperature range of 250°C to 350°C, the temperature sensitivity increases with increasing strain rate. This different laws of change is sufficiently large as to imply that different temperature sensitivity and microstructural evolution appear in the material at these two temperature ranges. It can be inferred that the strain rate-induced strengthening effect is restrained by the thermal softening effect.

3.3 Macroscopic features of the impact specimen

Macroscopic features of the 7A52-T6 specimens after impact testing under different strain rates were compared, as shown by Fig. 5. When the specimen was compressed at different strain rate and
different temperature, the degree and shape of specimens change turn different. When the nominal strain rate was increased to 4000s⁻¹, the height of the specimens reduced to 1.79%, 2.02%, 2.34%, and the shape of the specimens changes from forty-five degrees to a round table and then to a drum at impact temperatures of 150, 250 and 350℃, respectively. Fig. 5 shows that when the impact temperature is 150℃, the deformation of the specimens increase with the increase of strain rate. When the nominal strain rate is 4000s⁻¹, 45°shear occurs along the impact direction, and when the nominal strain rate is 5000s⁻¹, The 45°shear is more obvious, and the specimen is not broken but has obvious cracks. When the temperature increases above 250℃, no macroscopic damage could be found, which indicates a more homogenous deformation.

It is noted that none of the specimens fail; even under a large true strain rate of 5000s⁻¹ at 350℃. In other words, 7A52-T6 alloy has good deformability at high temperatures.

3.4 Evolution of the microstructure during impact deformation

3.4.1. Optical micrographs
Fig. 6 (a-d) shows optical micrographs of the specimens after impact deformation at elavated temperature. When materials are subjected to compact loading, such as explosive, penetration, high speed machining, the deformation is prone to be localized and produces shear bands⁵. Fig. 6. (b)-(d) shows the microstructure after impact under the nominal strain rate of 5000s⁻¹ at 150℃. As the microstructure shows in Fig. 6.(b), the width of the adiabatic shear band is larger, and the average width is about 155 μm, and accompanied by a small number of microcracks. The adiabatic shear band is symmetrically distributed, as shown in Fig. 6.(d), there are obvious cracks in the shear band of the symmetrical part of the specimens.

However, at 250℃ and 350℃, the microstructure of the sample is distorted and almost no adiabatic shear band and cracks is formed, as shown in Fig. 6.(c) and Fig. 6.(d). At this time, the soften effect of the specimen is larger, and the interaction with dislocation is less under the action of impact load. The microstructure deformation is mainly compose of deformation band, and the grain is elongated along the impact direction.
Fig. 6. Optical micrographs of 7A52-T6 aluminum alloy specimen before impact and impacted at different temperatures of the strain rate at 5000 s\(^{-1}\) (RD: rolling direction, ND: normal direction, ID: impact direction)

### 3.4.2. TEM examination results

Fig. 7(a) - (d) shows the bright field images of 7A52-T6 aluminum alloy samples at different impact temperatures when the strain rate 5000 s\(^{-1}\). After impact deformation at 150°C, a large number of dislocations were introduced, see Fig. 7(a), and it is not easy to see (sub) grain boundaries clearly. The strength of Al-Zn-Mg-Cu alloy is mainly dependent on precipitations. Among many factors\(^{[20, 21]}\), \(\eta'(\text{MgZn2})\) phases play a dominant role in the strengthening of AA7xxx series aluminum alloys in T6 due to their existence in significant amount and also due to strong pinning effect. However, \(\eta'\) phases are metastable and thus with an increase in temperature, they are prone to coarsening and transform to stable phases and dissolve in Al matrix. It is obviously observed in Fig. 7(b)-(d) that with the increase of deformation temperature, \(\eta'\) coarsens and dissolves gradually, which is the reason why the flow stress of 7A52 aluminum alloy decreases obviously at 250°C. In addition, at temperatures above 350°C, the dislocation density is lower in the grain interior and grain boundaries (Fig. 7(d)). This could be attributed to the loss of precipitation strengthening and dynamic recovery.
4. Conclusions
(1) The experimental results have shown that the flow stress increase with increasing strain rate, but decrease with increasing temperature. At 350°C, the temperature sensitivity increases with both increasing strain rate and increasing temperature.

(2) The microstructure deformation is mainly composed of deformation, and the grain is elongated along the impact direction.

(3) TEM microstructure observation shows that both strain rate and temperature have significant effects on the dislocation microstructure of 7A52-T6 aluminum alloy. The dislocation density increases with the increase of strain rate and decreases with the increase of temperature.

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