Under shock loading, the plastic flow of polycrystalline material tends to localise into shear bands. As shear bands form, most materials dramatically lose their strain hardening property and quickly fail. Here, we present the experimental and microstructural evidence of a new shear banding mode—ductile shear band, in magnesium alloy at high temperature under shock loading. The results show that magnesium alloy could exhibit high strength and good plasticity even after ductile shear bands occurred and contributes to improve understanding of the strain rate-dependent of failure modes in magnesium alloy.

1 | INTRODUCTION

Adiabatic shear band of polycrystalline materials has generally been attributed to the extreme localisation of shear plastic deformation [1]. When adiabatic shear bands occur, most materials lose their strength and is always followed by catastrophic failure [2]. Although many reported results have shown the micromechanisms and physics behind adiabatic shear bands by using experimental and theoretical methods [3–8], the full understanding of adiabatic shear band is still a hard work [9], as it is very difficult to get panoramic information and well-defined data during transient shock process [10].

In the physical view, shear bands are always coupled with thermomechanical instability of plastic deformation [11]. Local temperature rise is important for the onset and evolution of the shear bands [12, 13]. Direct temperature measurements estimate that the temperature rise could be as high as thousands of degrees over nanoseconds within the shear bands [14]. Hence, many investigations concern the temperature effects on the physical mechanisms of shear bands, so-called thermal softening [15]. The physics behind thermal softening during shear banding still remain unclear. In this work, we present new experimental evidence of strain rate and temperature effects on shear bands and discover the underlying micromechanisms in magnesium alloy under shock loading.

2 | EXPERIMENTAL SECTION

The AZ31 magnesium alloy (mass: Al 3.0%, Zn 1.0%, Mn 0.4%, Mg balance) was selected as the experimental material in this study. Magnesium alloys are a class of important light-weight structural material. Earlier works suggest that extensive shear bands occur when magnesium alloy is subjected to shock loading [16]. In order to get an ultra-high strain rate, the dynamic shock tests were performed by using a mini-split Hopkinson pressing bar, which is a widely used device for dynamic tests at different temperature circumstance [17]. The shear bands and fracture surfaces were systematically examined by using optical microscopy (OM) and scanning electron microscopy (SEM).

3 | RESULTS AND DISCUSSION

Figure 1(a) shows that AZ31 magnesium alloy exhibits intense strain-rate sensitivity, and enhancement of strength and plasticity could be simultaneously achieved at high strain rates at room temperature. Under quasi-static compression (black curve in Figure 1(a)), AZ31 magnesium alloy exhibits poor plasticity (15% compress strain) owing to its hexagonal close-packed crystal structure, which lacks sufficient slip systems at room temperature [18]. At all strain rate, after an initial yield, the flow
stress continuously rises before the end of peak stress. This strong strain hardening is caused by intense dislocation multiplications and interactions along limited basal \(<a>\) slip plane. In the dynamic regime, a distinct feature is observed with respect to the rate dependence of mechanical behaviours of AZ31. After peak stress is reached, the plasticity of AZ31 samples increases monotonically with increasing strain rate. At the highest strain rate (red curve in Figure 1(a)), a marked enhancement in compress plasticity (58% compress strain), which is almost four times larger than its counterpart at quasi-static condition, has been found concurrent with the occurrence of ideal plastic flow (without strain hardening or softening). In this distinct state, AZ31 flows like a viscous fluid while retaining its strength (dot-dash line in red curve in Figure 1(a)).

The dynamic fracture strains as the function of strain rate at various temperatures are summarised in Figure 1(b). The results show two distinct regions: In region 1 (strain rate below \(1.2 \times 10^4 \text{ s}^{-1}\)), the fracture strains exhibit a linear relationship with strain rates at various temperatures. This means that the AZ31 failed in the same mode–adiabatic shear bands, which are very sensitive to the strain rate. In region 2 (strain rate beyond \(1.2 \times 10^4 \text{ s}^{-1}\)), although the fracture strains also increase with increasing strain rate, the fracture strains show strong temperature dependence at a fixed strain rate. This difference indicates that a certain failure mode transition happened.

OM observations on the section of deformed specimens are given in Figure 2(a). Figure 2(a) shows obvious local plastic localisation in the deformed specimen at 573 K and a strain rate of \(3 \times 10^4 \text{ s}^{-1}\). The elongated grains are found within shear bands. As samples are subject to high strain rate compression, the large plastic deformation generates a lot of heat, which cannot release during that transient loading time (about 30 \(\mu\text{s}\)). As a result, the temperature quickly increases under dynamic loading and is localised in shear bands. In order to investigate the temperature effect, we calculate the temperature rise and find the largest temperature rise is about 300 K (Figure 2(b)).

Figure 2(c) shows the fracture surface of AZ31, which deformed at quasi-static loading and room temperature. The fracture surface is relatively rough with clear fracture edges, which mean the crack propagated at low velocity and there is no melting evidence. However, at high strain rate and high-temperature conditions, as in Figure 2(d), SEM observation on the fracture surfaces shows obvious melting evidence. Many hemispherical beads could be observed on the fracture surface, which is formed from huge deformation heat and large plastic deformation.

The correlation of failure modes with strain rate and temperature can be represented in the schematic diagram in Figure 3. At quasi-static and room temperature loading condition, the AZ31 yields and flows exclusively through dislocation motion and multiplication of the initial dislocations, forming dense dislocation tangle inside the relative ‘softer’ grains and pile up near the grain boundaries. During quasi-static plastic flow, the strain hardening properties are majorly governed by the dislocation multiplication and interaction in a limited basal \(<a>\) slip plane [19]. As the local dislocation density and shear stress increase, the microcracks appear in the stress concentration areas, and then the overall flow stress gradually decreases as microcracks propagate and finally forming obvious brittle intergranular fracture mode.

At a high strain rate and moderate temperature, we observe the obvious localisation of plastic stain along the shear direction, which finally formed adiabatic shear bands. At any higher strain rate, the AZ31 starts to exhibit large plasticity at room temperature with insufficient slip planes (see Figure 1(a)). On the other aspect, such contrasting differences are not surprising, and it has long been known that when magnesium alloys deform at a high strain rate, deformation twinning will take place in a major deformation mode. In addition, at a high strain rate and high-temperature loading conditions, the AZ31 exhibits very large plastic strain even during shear banding. This unusual plasticity enhancement comes from the large local plastic deformation in ductile shear bands (Figure 2(a)). In this stage, the AZ31 shows large plasticity and keep its strength. Our works suggest that the formation of ductile shear bands can improve the plasticity without losing strength. Finally, as localised shear deformation dramatically increasing in shear bands, the material fails in melting, which have been proved by using SEM characterisation (see in Figure 2(d)).
FIGURE 2  (a) Optical microscopy image of local deformation region at high strain rate and high temperature, (b) temperature rises under shock loading. Scanning electron microscopy characterisations of fracture surfaces, (c) quasi-static loading, and (d) dynamic loading.

FIGURE 3  Schematic diagram of the failure modes under different loading conditions of magnesium alloy

4 CONCLUSION

In summary, the experiments and microstructural characterisations provide a new shear banding mode (ductile shear bands) in AZ31 magnesium alloy under shock and high-temperature conditions as shown in Figure 3. The ductile shear bands strongly depend on deformation temperature and strain rate. This ductile shear bands in magnesium alloy have not been reported before because this mode only occurred at high temperature and high strain rate. We also find that the failure modes are strongly rate and temperature dependence and indicate that the magnesium alloys could exhibit large plasticity as ductile shear bands formation.

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