Deformed Microstructure of AZ91 Magnesium Alloy Impacted by Projectiles with Velocities of 2 – 3 km/s*


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Abstract
AZ91 magnesium alloy in different heat treatment conditions was impacted by GCr15 steel projectile (2 km/s, power gun) and 2017 Al alloy projectile (3 km/s, two-stage light gas gun). Deformed bands, plastic flow and a wealth of cracks were observed near the crater in as-cast magnesium alloy impacted by GCr15 steel projectile, while for the solution treated alloy, both deformed and transformed bands were observed accompanied by fewer cracks near the crater. Upon higher velocity impact using two-stage light gas gun, many cracks and severe deformed areas containing a number of elongated grains were observed near the crater for both hot-forged and solution-treated targets, while fewer adiabatic shear bands could be found. Most of these shear bands were located at the end of cracks. The strain hardening at different zones under the crater was also investigated.

Key words: Hypervelocity Impact, Adiabatic Shear, Magnesium Alloy

1. Introduction
The deformation and damage behaviors of materials under dynamic or shock loadings are essential for the selection and proper use of materials under different extreme situations. Macro- and microscopical observation of various phenomena related to dynamic or shock loadings, such as cracks, adiabatic shear bands (ASBs), deformation twins, grain refinement, is the foundation for understanding the deformation and damage mechanism. During the past few decades, lots of efforts have been paid on the high velocity impact study of various metal and alloys, such as steel, copper, aluminum alloys, titanium alloys and etc [1-4]. For example, the crater formation process and microstructure changes near the crater in steel targets under high velocity impact have been investigated [5-8], and ASBs and phase tranformation induced by dynamic deformation were found. Meanwhile, the impact cratering and crater-related microstructures in copper targets have been studied, and microbands and linear microstructure are the dominant feature [9-11]. ASBs in Al alloy and its composite induced by high velocity impact have been studied [12, 13], and the deformation localization and dynamic recrystallization in Ti alloys targets have been investigated [4, 14].

Magnesium alloy, as one of the most important light alloys with characteristic of low density, high specific strength and high specific stiffness, is suggested to be an attractive candidate structure material in both aeronautics and astronautics fields. Understanding the deformation and damage behaviors of the alloy under dynamic loadings is the predetermination of the applications of Mg alloy in these fields. Recently, we have studied the deformed microstructure of AM60B magnesium alloy under hypervelocity impact at
velocities of 4 and 5 km/s. The deformation twins, ultrafine recrystallined grains as well as dislocations were comprehensively characterized [15, 16]. In the present work, a zinc-containing AZ91 magnesium alloy was selected as the target material, and different heat treatment process were performed with the alloy in order to investigate the influence of initial microstructure and mechanical properties on the deformation and damage behaviors of magnesium alloy under high velocity impact. Preliminary experimental observation of the deformation microstructures in the alloy impacted by two types of projectiles with different velocities was conducted.

2. Experimental

AZ91 magnesium alloy was chosen as target material. The chemical compositions of the alloy are as follow: 8.5~9.5 Al, 0.45~0.90 Zn, 0.15~0.30 Mn, 0.20 Si, 0.01 Ni and the balance of Mg (wt.%). The target type is semi-infinite, with thickness of 30 mm for as-cast alloy and 35 mm for hot-forged one, as calculated from the physical and mechanical properties of target and projectiles shown in Table 1. Solid solution treatment at 400 ºC for 24 h was performed for both the as-cast and as-forged targets. The optical micrographs of the alloy in different heat treatment conditions were shown in Figure 1. Impact experiments were conducted with power gun and two-stage light gas gun using GCr15 steel ball at a velocity of 2 km/s and 2017Al ball at a velocity of 3 km/s, respectively. The diameters of the two types of balls are the same of 4 mm. The impacted targets were sectioned along longitudinal direction, polished and finally etched by 5.0 g picric acid + 5.0 g acetic acid + 10 ml H2O + 100 ml ethanol, and examined by a Zeiss HAL 100 optical microscope and a Hitachi S-570 scanning electron microscope (SEM). Vickers microhardness was obtained using MMT-3 microhardness tester. The load of 50 g and a dwell time of 10 s were employed during microhardness measurement.

<table>
<thead>
<tr>
<th>Target (wt.%)</th>
<th>HB (MPa)</th>
<th>ρ (g/cm³)</th>
<th>Cv (J/Kg·ºC)</th>
<th>Tm (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ91</td>
<td>650</td>
<td>1.81</td>
<td>1900</td>
<td>650</td>
</tr>
<tr>
<td>GCr15</td>
<td>1900</td>
<td>7.85</td>
<td>473</td>
<td>1535</td>
</tr>
<tr>
<td>2017Al</td>
<td>450</td>
<td>2.79</td>
<td>921</td>
<td>640</td>
</tr>
</tbody>
</table>

Figure 1 Optical micrographs of AZ91 magnesium alloy in different heat treatment conditions. (a) As-cast; (b) as-cast and solution treated; (c) as-forged; (d) as-forged and solution treated.
3. Results and discussion

Cylinder-like craters were formed in both as-cast and solution treated Mg alloy targets impacted by GCr15 ball with a velocity of 2 km/s, as shown in Figure 2. The strength and density of GCr15 projectile is higher than that of the magnesium alloy target, and thus the craters are with cylinder-like shape. The crater diameters are almost the same (about 5.0 mm), while the crater depth of solution treated target is lower than that of as-cast target due to higher strength after solution treatment.

Figure 2 Cross section views of the craters in AZ91 magnesium alloy targets impacted by GCr15 projectile at 2 km/s. (a) As-cast alloy target; (b) Solution treated alloy target.

Figure 3a shows the deformation microstructures under the crater in the as-cast Mg alloy target impacted at a velocity of 2 km/s. Severe plastic deformation occurred near the crater, resulting in the elongation of grains. ASBs as well as cracks were observed in both the side and bottom areas near the crater. The typical SEM image of ASBs was shown in Figure 3b. ASBs were initiated from the crater fringe and about 45 ° angled to the impact direction. Further SEM observations showed that there is the trace of plastic flow lines near the crater, as shown in Figure 3c. The ASBs are mostly extending across the flow lines. Only the deformed bands were observed with absence of transformed bands. As for the solution treated targets, the density of ASBs near the crater is apparently higher than that in as-cast target, while fewer cracks were observed near the crater, indicating that the impact toughness was significantly improved upon solution treatment. The distribution of ASBs under the crater in solution treated target was shown in Figure 4a, and a high magnification SEM image of ASBs was given in Figure 4b, depicting the existence of both deformed and transformed bands in the solution treated target. The density of the ASBs distributed around the crater is non-uniform, as shown in Figure 4a, and ASBs at 45 ° angled to the impact direction present the highest density than other directions, which is associated with different stress state. The direction of maxium shearing stree is 45 ° angled to the impact direction, which is accounting for the extending direction of ASBs. The cracks formed in ASBs are observed, as shown in Figure 4b, indicating that the harder ASBs can be acted as preferential sites for cracks formation and propagation. When the ASBs propagate from the crater to the matrix, the bifurcation of the ASBs is observed, as shown in Figure 4b. The bands width is supposed to maintain unchanged during propagation, and thus new bands were formed.

Table 2 show the variation of microhardness of AZ91 magnesium alloy target before and after impact at a velocity of 2 km/s. The microhardness measured in the zone adjacent to the crater was much higher than that of the original sample due to severe plastic deformation. With the increase of distance from the crater, the microhardness decreased. The microhardness measured inside the ASBs was rather higher, which was about one times higher than that of as-cast sample.
Figure 3 (a) Optical microscopy photograph showing the deformation microstructure under the crater in as-cast AZ91 Mg alloy target impacted at a velocity of 2 km/s. (b) Typical SEM image of ASBs. (c) Plastic deformation flow lines near the crater.

Figure 4 (a) Optical microscopy photograph showing the distribution of ASBs under the crater in solution treated AZ91 Mg alloy target impacted at a velocity of 2 km/s. (b) SEM image showing the co-existence of deformation and transformation bands.
Table 2 Microhardness of AZ91 Mg alloy target before and after impacted at a velocity of 2 km/s.

<table>
<thead>
<tr>
<th>Heat treatment</th>
<th>Original target</th>
<th>Very near to the crater bottom</th>
<th>Far away from the crater bottom</th>
<th>ASBs</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-cast</td>
<td>665 MPa</td>
<td>1078 MPa</td>
<td>866 MPa</td>
<td>1297 MPa</td>
</tr>
<tr>
<td>Solution treated</td>
<td>732 MPa</td>
<td>1057 MPa</td>
<td>940 MPa</td>
<td>1269 MPa</td>
</tr>
</tbody>
</table>

The deformation behavior of as-forged and solution treated Mg alloy impacted by Al projectile at higher velocity of 3 km/s was also investigated. The results showed that by using Al projectile with lower strength, hemispherical craters were formed, and the crater in solution treated target looked more regular, as shown in Figure 5. The diameters of craters are 6.0 and 6.5 mm for as-forged and solution treated targets, respectively, which are evidently larger than that of the target impacted by GCr15 projectile.

![Figure 5 Cross section views of the craters in AZ91 Mg alloy targets impacted by 2017Al projectile at 3 km/s. (a) As-forged alloy target; (b) Solution treated alloy target.](image)

Table 3 show the variance of microhardness of AZ91 magnesium alloy target before and after impact at higher velocity of 3 km/s. The microhardness measured in the zone under the crater was much higher than that of the original sample due to severe plastic deformation. The microhardness decreased with the increase of distance from the crater.

<table>
<thead>
<tr>
<th>Heat treatment</th>
<th>Original target</th>
<th>Very near to the crater bottom</th>
<th>2–3 mm away from the crater</th>
<th>4–5 mm away from the crater</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-forged</td>
<td>-</td>
<td>1169 MPa</td>
<td>1082 MPa</td>
<td>798 MPa</td>
</tr>
<tr>
<td>Solution treated</td>
<td>858 MPa</td>
<td>1275 MPa</td>
<td>1170 MPa</td>
<td>1065 MPa</td>
</tr>
</tbody>
</table>

4. Conclusions

In summary, the macro- and micro-damage behaviors of AZ91 magnesium alloy in different heat treatment conditions under high velocity impaction were studied. Phenomenal observation of cracks, ASBs, flow lines near the cracks and their microscopical details characterization were performed. Microharness of the impacted target near the crater was recorded. The deformation and damage behavior of Mg alloy was significantly affected by the impact conditions as well as the heat treatment conditions of the target.
Figure 6 (a) Optical micrograph showing the deformation microstructure at side of the crater in as-forged AZ91 Mg alloy target impacted at a velocity of 3 km/s; (b) Optical micrograph showing the deformation microstructure under the crater in solution treated AZ91 Mg alloy target impacted at a velocity of 3 km/s.

References