Energy absorption within elastic range for AZ31 magnesium alloy

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Abstract
Energy absorption for AZ31 magnesium Alloy was investigated with Split Hopkinson Pressure Bar using single stress wave so as to avoid multiple stress wave loading. The stress wave amplitude, which was in elastic stress range and propagated along the AZ31 magnesium bar, was reduced with increasing propagating distance, and with increasing stress wave amplitude, the stress wave amplitude reduction along the magnesium bar was increased losing more energy as compared with that of the stress wave with lower amplitude. The drastically decreased stress wave amplitude could be explained based on dislocations movements, which was similar to the established theory of damping for the explanation of the energy loss during cyclic loading. However, it was not the case for LY12 aluminum alloy: the stress wave amplitude changed slightly without drastic energy loss regardless of the variation of stress wave amplitude.

1. Introduction
Magnesium alloys are ideal candidates for reducing fuel consumption due to their low density in comparison to aluminum and steel alloys when designing work pieces with lower weight [1, 2]. Because of their high strength-to-weight ratios, magnesium alloys in particular have the potential to replace steel or aluminum components currently in use.

The advantages of magnesium alloys have promoted the wide application of magnesium alloys in many fields, including rail transit, wheel and missiles, all of which will be subjected to impact [3, 4]. Therefore, the understandings of the impact behaviors of magnesium alloys are of great importance, thus extensive investigations have been carried out under impact (high strain rate) loading mode.

Bin Li investigated the Rate-dependent hardening due to twinning in an ultrafine-grained magnesium alloy. The results showed that the flow stresses exhibited the characteristic sigmoidal profile, and that both twinning and high density non-basal dislocations were activated [5]. H Asgari carried out research of texture evolution and dynamic mechanical behaviors of cast AZ magnesium alloys under high strain rate compressive loading, and proved the fact that the initial weak texture of the cast samples transformed to a relatively strong basal texture after shock loading,which can be ascribed to deformation by twinning [6]. Mao Ping-li published paper concerning with microstructure evolution of extruded Mg–Gd–Y magnesium alloy under dynamic compression. They found out the three stages evolution of microstructure: twining, discontinuous adiabatic shear band and continuous adiabatic shear band [7]. Neha Dixit studied the microstructural evolution of pure magnesium under high strain rate loading. The results indicated that both twinning and dislocation were required to accommodate plastic deformation [8]. Matthew T Tucker investigated the anisotropic effects on the strain rate dependence of a wrought magnesium alloy. The findings revealed strong strain rate dependence on the compressive yield strength, hardening rate and ductility in the normal direction, while the rolling and transverse directions exhibited no strain rate dependence [9]. Zhi Wang investigated the high strain rate behavior of Mg-6Zn-1Cu-0.6Zr (ZC61) alloy fabricated by a novel extrusion-shaping process that combined traditional hot extrusion with equal-channel angular pressing (ECAP). They disclosed that extension twinning was the main deformation mechanism at room temperature, and that secondary order pyramidal slip and
double twins coordinated the dynamic deformation at elevated temperature [10]. The role of extension twinning of highly textured magnesium alloy under high strain rate deformation were carried out using both Split Hopkinson Tension and Pressure Bar. The results demonstrated that the six variants of tension twinning had the same opportunity to activate under tensile loading, while only two variants had the opportunity of operating for compression loading resulting in asymmetric dynamic behaviour [11]. The effects of different stress states were simulated and tested with regard to twinning in AZ31 under impact loading, and it has been verified that extension twinning in the magnesium alloy tend to occur for the studied alloy when loading was applied perpendicular to the crystallographic c-axis, regardless of the stress states [12].

However, all of the investigations were carried out using plastic stress wave as the loading mode. Seldom investigations were performed concerning with stress wave in elastic stress range for magnesium alloy, because it has been considered almost unanimously that one dimensional stress stress wave propagating in elastic stress range did not decay sharply for slender metal bar, a typical example of which is the stress wave propagating in the incident and transmission bar used by Split Hopkinson Pressure Bar (SHPB) test system [13]. The main aim of the present paper is to investigate the propagation of stress wave within elastic stress range for the commercially available AZ31 magnesium alloy so as to enlighten a potentially new research field that has been ignored for a long time.

2. Experimental

The materials used were commercially available homogenized Mg-3Al-1Zn (AZ31) magnesium alloy. Figure 1 shows the schematic illustration of the Split Hopkinson Pressure Bar (SHPB) for studying stress wave propagation. The striker bar, incident bar and transmission bar were AZ31 magnesium alloy bars with 20 mm in diameter. The laser detector device system was used for testing the velocity of the striker bar. The strain gauges mounted on the incident bar were connected with the super dynamic strain indicator linking with data processing system; therefore the magnitude of the stress wave propagating at different positions \((X_1, X_2)\) of the incident bar could be recorded. The striker bar was launched by gas and collided with incident bar, resulting in a compressive stress wave propagating to the right direction along the incident bar, and then the transmission bar. Once the compressive stress wave reached the free surface of the transmission bar, the tensile wave would be generated and propagated to the left direction along the transmission bar. Upon the tensile wave reaching the contact surface, the contact surface of the incident bar and the transmission bar would be separated. When the tensile wave reached the contact surface of the striker bar and incident bar, the striker bar would be separated from the incident bar due to the same reasons as mentioned above. Therefore, the incident bar would only be affected by a single pulse compressive stress wave. The damper could be used to slow down the speed of the transmission bar and prevent it from being damaged. For comparison, similar tests were also carried out using Al-4Cu-1Mg (LY12) aluminum alloy as the material for the striker bar, incident bar and transmission bar.

The loaded AZ31 magnesium incident bar was sectioned along the compression axis, then mechanically polished using a series of sandpapers from 1000 down to 5000 grit. Disks of 3 mm diameter were mechanically punched out of the polished samples, then ion milled for 1 h using a low incident angle and a low voltage. The electron-transparent samples were examined using a JEOL2010 microscopy at an accelerating voltage of 120 keV.
3. Results and discussion

3.1. Stress wave propagation

The stress wave propagation experiment along LY12 aluminum bar was carried out using the SHPB system with striker bar, the velocity of which can be detected by the laser detector device, as shown in figure 1. The striker bar velocity can be controlled by adjusting the pressure of the gas system, which is not shown in this paper. The distance between the two strain gauges ($x_1$, $x_2$) on the incident bar, indicating stress wave propagating distance, was 90 cm, and the stress wave amplitude along the incident bar is showed in figure 2(a) with strike bar velocity of 3 m s$^{-1}$. The strain gauge could measure the strain caused by the propagating stress wave, and the corresponding stress wave amplitude could be calculated by multiplying the strain with the elastic modulus (70 GPa) of the aluminum bar. The stress wave amplitude is characterized by using the average peak values of the stress wave, and the stress wave amplitude at location $X_1$ and $X_2$, where the strain gauges were glued to the bar, were characterized by solid and dotted lines and indicated by arrows, respectively, as shown in figure 2(a). The stress wave amplitude at location ($x_1$) was 22.8 MPa, far below the yield strength of this aluminum alloy (350 MPa), when the velocity of the striker bar was 3 m s$^{-1}$, as shown in figure 2(a) for solid line. The stress wave amplitude was reduced slightly from 21.8 MPa ($x_1$) after propagating (0.9 m) to 20.2 MPa ($x_2$), and an amplitude reduction of 1.7 MPa m$^{-1}$ along the bar could be obtained by using the value of stress wave amplitude reduction (21.8–20.2 MPa) divided by the distance between the two gauges (0.9 m). The amplitude reduction equaled to 2.1 MPa m$^{-1}$ when the velocity of the strike bar reached 3.7 m s$^{-1}$ (figure 2(b)). The amplitude reduction increased slightly with increasing stress wave amplitude for the LY12 aluminum alloy.

The stress wave propagation along AZ31 magnesium bar was measured by the same method. The distance between the two strain gauges was 10 cm, and the transmission bar was also used to ensure the single pulse compressive stress wave loading mode. The velocity of the striker bar was the same as before (3 m s$^{-1}$) or

![Figure 2. Amplitude-time curve of with different strike bar velocity: (a) LY12, 3 m s$^{-1}$; (b) LY12, 3.7 m s$^{-1}$; (c) AZ31B, 3 m s$^{-1}$; (d) AZ31B, 3.7 m s$^{-1}$.

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3.7 m s$^{-1}$), and the stress wave amplitude on the AZ31 bar is shown in figures 2(c) and (d), respectively. It could be seen that the stress wave amplitude was also in elastic range with the yield strength of AZ31 magnesium alloy being 100 MPa approximately. When the velocity of the striker bar reached 3 m s$^{-1}$ or 3.7 m s$^{-1}$ respectively, the amplitude reduction equaled to 13 MPa m$^{-1}$ and 25 MPa m$^{-1}$ respectively, assuming the elastic modulus of the AZ31 magnesium alloy equaled to 40 GPa, (figures 2(c)–(d)). The amplitude reduction was almost doubled with increasing initial stress amplitude for the AZ31 magnesium alloy. Furthermore, the stress wave amplitude reduction of the AZ31 magnesium alloy (13 MPa m$^{-1}$ or 25 MPa m$^{-1}$) were obviously much higher as compared with that of the amplitude reduction LY12 aluminum alloy (1.7 MPa m$^{-1}$ or 2.1 MPa m$^{-1}$).

Based upon the experiments carried out with aluminum alloy bar and magnesium bar, it can be confirmed that the capacity of energy absorption for magnesium alloy is higher than that of the aluminum bar for impact loading conditions when the stress wave amplitude is in elastic range. The SHPB has been used for many years for the testing of high strain rates behaviour of various materials, and the stress wave propagating along the incident bar and transmission steel bar was always considered to be same, which is also the basis of the theory for calculating the stress for the material subjected to impact loading. However, this is not the case for magnesium alloy, which could be contributed to the dislocations movements that is unique to the studied AZ31 magnesium alloy.

3.2. Microstructure
The stress wave in the range of elastic stress amplitude in slender metals bar were considered to have slight change by many researchers, and it is the case for the steel bar and LY12 aluminum alloy bar our group investigated in this article, both of which are widely used for SHPB testing system. However, previous researchers did not take the energy absorption capacities in elastic stress range of different metals into consideration. Magnesium alloy has high damping properties, therefore there will be energy loss caused by dislocation movement below yield strength [14]. It is reasonable to consider that whether the amplitude reduction could be omitted for certain metals should be closely related to its dislocation movement upon dynamic loading. The strain caused by the stress wave is in the range of (15–20) MPa/40 GPa = (3.8–5)×10$^{-4}$ assuming the stress wave is in the range of 15–20 MPa and the elastic modulus of the magnesium bar is 40 GPa. This is enough to trigger the dislocation movement according to the investigation of the damping properties of AZ31 magnesium alloy, because the dislocation movements even occurred in the elastic range of 10$^{-5}$ for the test of damping for AZ31 magnesium alloy [15, 16]. Therefore dislocation activities upon dynamic loading were expected.

The postmortem microstructure of the AZ31 bar impacted at a velocity of 3.7 m s$^{-1}$ was characterized using TEM, as shown in figure 3 (a). Dislocations bowing out and dislocations breaking away could be seen as indicated by the arrows. The decreasing of stress wave amplitude for the AZ31 magnesium alloy could be explain based on the theory of Granato and Lucke for damping, as shown in figure 3(b) [17]. Dislocation bowing out could consume energy, which normally requires low stress level, and contributed to the amplitude reduction (13 MPa m$^{-1}$) for AZ31 loaded at a velocity of 3 m s$^{-1}$. The breaking away of dislocations could drastically increase the energy loss due to higher stress level, thus contributed to the increased amplitude reduction (25 MPa m$^{-1}$) for AZ31 impacted at a speed of 3.7 m s$^{-1}$. It might be that the dislocations were not easy to bow out or break away from the pinning point for the LY12 aluminum alloy, so the stress wave amplitude decreased slightly compared with that of the AZ31 magnesium alloy.

Generally speaking, most researchers tend to think that there are no plastic deformation within elastic range for metals undergoing loading. However, due to the inhomogeneity of the metal from the perspective of scales down to the size of dislocation, irreversible dislocations activities prone to happen inevitably even at elastic loading range due to stress concentration leading to plastic deformation at places where stress concentration surpass the yield stress. The dislocations movements loaded within elastic range is the very reason for the explanation of damping, fatigue and micro yielding of metals, all of which tests are loaded below the yielding strengthen and within elastic range [18–20]. An interesting example even showed that dislocations movements were closely related both with micro yielding and damping: both the micro yielding under uniaxial deformation and the occurrence of strain-dependent damping capacity pertain to the same physical event- the breaking away of basal dislocations from weak pinning points and the subsequent sweeping motion of dislocations between strong pinning points [21].

This methods could be used for the testing of the energy absorption capacity of metals of various kinds, serving as a new method to test the dislocations movements of metals upon being impact in elastic range. The advantage of this method is that a single stress wave was used, so that it can be confirmed that the dislocation movements were not caused by multiple loading induced by the reflection of stress wave, which tend to trigger cyclic compressive and tensile stress wave. It is likely that this method could initiate a new field for the studying
impact properties of metals within elastic range, just like the way researcher have investigated the damping, fatigue and micro yielding properties of metals.

4. Conclusions

The Stress wave amplitude propagating along the LY12 aluminum alloy did not change obviously. The stress wave amplitude decreased drastically with increasing propagating distance for the AZ31 magnesium alloy, and the amplitude reduction increased with increasing initial stress wave amplitude, both of which could be explained based on dislocation movement. The new methods could be used for the testing of the energy absorption for metals subjected to elastic range impact loading.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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