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Energy Absorption at High Strain Rate of Magnesium Alloy AZ31B

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Abstract: This paper presents the efficient energy absorption of magnesium alloy AZ31B with reinforcement carbon nanotubes (CNT) and lead (Pb). The high specific energy absorption demonstrated by CNT compared to metals is one of the criteria to improve the AZ31B performance against ballistic penetration. More ductility by adding Pb in the alloy also plays a vital role to increase the energy absorption capability. Four-cylinder shape AZ31B-based specimens are tested dynamically by using compression Split Hopkinson Pressure Bar (SHPB). The diameter and thickness of the specimen is 18 mm and 12.5 mm respectively. The striking velocity used in this work is 20 m/s. By equation of 1D wave propagation, stress-strain curve is plotted and the area under the curve is equivalent to energy absorption. The highest energy absorption is about 270 kJ with the increment of 47% compared to original AZ31B. This increment is consistent with the higher strain rate experienced by the specimen during the test. The strain rate determined from the study is 1300 per second compared to original AZ31B of 850 per second. The finding of this paper is the presence of CNT and lead could improve the energy absorption performance as the strain rate of the specimen also increased.

Keywords: AZ31B, energy absorption, SHPB, CNT, high strain rate

1. Introduction

The applications of magnesium alloys in automotive especially defence industry have been increasing due to low density and high strength [1]. The density at room temperature of 1740 kg/m3 is the key parameters in contributing vehicle manoeuvrability [2]. However, structural parts in defence industry are prone to ballistic penetration. Considering the behavior of the material under dynamic loading are totally different compared to quasi static, it is necessary to understand the dynamic response. The properties of dynamic loading can be seen from stress-strain graph and the area under the curve is equal to the energy that can be absorbed by the material. Characterization of dynamic properties of material with strain rate ranging between 102 and 104 per second is typically accomplished via compression Split Hopkinson Pressure Bar (SHPB) or Kolsky bar [3,4].

A work done by Abdullah et al. (2015) showed that the optimum percentage of Pb addition can increase the capability of absorbing the energy by almost 5% [5]. Pb addition increased the ductility of magnesium alloy since ductility is the main parameter to enhance energy absorption. Leng et al in their work revealed that the specific energy absorption of single walled carbon nanotubes is significantly higher than metals [6]. According to Ahmad and Shu (2018), increasing the strain rate could increase the energy absorbed by the material [7]. Adding CNT alone without optimal value may decreased the energy absorption capability as the introduction of insufficient CNT will make the material prone to molecule sliding [8]. As mention from the previous studies, the presence of CNT and Pb had proven to affect the material

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behavior in term of ballistic impact [9,10], thus energy absorption performance. Mention that their several to enhance magnesium alloy such heat treatment such as annealing, quenching, normalizing and so on [11,12].

With low density and good impact performance, AZ31B can be an alternative to Rolled Homogeneous Armour (RHA) which is typically used for energy absorbed material. From previous studies, energy absorption of AZ31B can be improved with nanotechnologies and Pb. For this reason, the objective of this paper is to investigate the effect of both CNT and Pb presences in AZ31B in term of energy absorption capability.

1.1 Split Hopkinson Pressure Bar (SHPB) theory

SHPB is a common device to characterize dynamic properties of material with strain rate value between 102 s-1 and 104 s-1. SHPB setup typically consists of incidence bar, transmitted bar and striker bar [13]. Specimen will be sandwiched between incidence and transmitted bar. Strain gauges will be placed in incidence bar and transmitted bar. Gas gun has been used to propel striker bar towards incidence bar. Once the striker bar hit the incidence bar, an incidence strain pulse will be generated and propagate along incidence bar. Due to impedance mismatch between incidence bar and specimen, some part of the incidence strain pulse will be reflected back into incidence bar namely reflected strain pulse and the rest will continue to travel towards transmitted bar namely transmitted strain pulse. All these 3 strain pulses will be recorded using strain gauges. Assuming that stress equilibrium and uniform deformation during the event, the transmitted strain pulse is equal to summation of incidence strain pulse and reflected strain pulse [13]. The strain rate, strain and stress of the specimen can be determined by those equations.

$$\dot{\varepsilon}(t) = -C\_bar / L\_s(\varepsilon\_r) \tag{1}$$

$$\varepsilon(t) = -\int [C\_bar / L\_s(\varepsilon\_r)dt] \tag{2}$$

$$\sigma(t) = A\_bar / A\_s E\varepsilon\_t \tag{3}$$

where *c_bar* is longitudinal wave speed of bar, *L_s* is length of the specimen, *ε_r* is reflected strain pulse, A bar is cross-sectional area of bar, As is cross-sectional of the specimen, E is Young Modulus of the bar and *ε_t* is transmitted strain pulse [10]. Longitudinal wave speed of the bar can be determined by $\sqrt{(E/\rho)}$ with ρ is the density of the bar. The incidence strain pulse plateau is associated with striking velocity, *v_st* and can be determined by

$$a = x0 < x1 < x2 < \text{L} < xn = b. \tag{4}$$

Numerical methods were applied by using Trapezoidal rule to determine the area under stress strain curve. Under this rule, the area under a curve is evaluated by dividing the total area into little trapezoids rather than rectangles. Let *f(x)*be continuous on *(a,b)*. We partition the interval *(a,b)* into n equal subintervals as in the following equations:

$$\int_a^b f(x)dx \approx T_n = \frac{\Delta x}{2}[f(x_0)+2f(x_1)+2f(x_2)+\ldots+2f(x_{n-1})+f(x_n)] \tag{5}$$

Where,

$$\Delta x = \frac{b-a}{n} \tag{6}$$

and

$$x_i = a + i\Delta x. \tag{7}$$

As n → ∞, the right-hand side of the expression approaches the definite integral ∫f(x)dx. From obtaining the area under the line from stress strain data enable to abstract the amount of energy absorbed by specimen [5,10].

2. Methodology

2.1 Sample Preparation

In this research, each sample has been machined into cylinder shape with length and diameter of 12.5 mm and 18 mm respectively. This cylinder shape is suitable for Split Hopkinson Pressure Bar test. In order to enhance the strength and ductility of the magnesium alloys, it have been added with CNT and Pb, as shown in Table 1. This process of adding foreign substances into the AZ31B is known as the Disintegrated Melt Deposition (DMD) method. In this case, the

AZ31B ingot was heated in an induction furnace until it melted. This heating was conducted in a chamber where the air had been sucked out to create a partial vacuum before argon gas was piped through the combustion chamber at a speed of 25 mm/min.

Table 1 - Tested material with composition

Specimens	Material	Added elements
1	AZ31B	No
2	AZ31B	CNT
3	AZ31B	Pb
4	AZ31B	CNT + Pb

2.2 SHPB Test

Dynamic test has been implemented by SHPB available in UPNM as shown in Fig 1. The material and dimension of SHPB are shown in Table 2. The diameter of each part of SHPB is 20 mm. The velocity of the striker bar is 20 m/s. The strain pulse has been recorded by using strain gauges located in incidence and transmitted bar. Strain pulses have been filtered at 1.0 kHz.

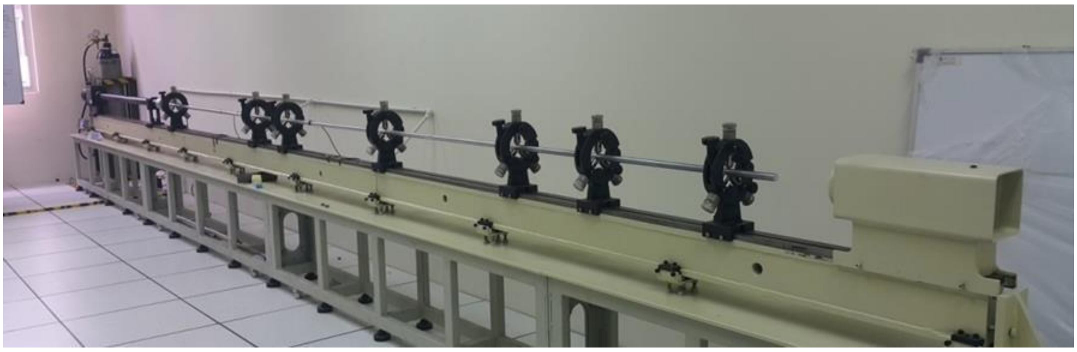

Fig. 1 - SHPB in UPNM's laboratory

Table 2 - SHPB dimension in UPNM's laboratory

Part	Materials	Length (*mm*)
Incidence Bar	Aluminium	2000
Transmitted Bar	Aluminium	2500
Striker Bar	Aluminium	200

3. Result and Discussion

3.1 Strain Pulse

Generated strain pulse during SHPB testing is very important to get better and accurate result. The recorded strain pulses of incidence bar and transmitted by using SHPB are shown in Fig. 2 and Fig. 3 respectively. By using Eq. (4), the plateau of each strain pulse can be determined. From Fig. 2, strain pulse plateau is quite differ compared to theoretical value and the differences are shown in Table 3. These differences might be induced during the test due to friction and impedance mismatch between striker bar and incidence bar. Fig. 3 depicts the highest transmitted strain pulse belongs to AZ31B with addition of CNT and Pb. This strain pulse is associating directly to the stress in the specimens.

Table 3 - Comparison of strain pulse plateau for each specimen

Material	Strain Plateau ($\mu\varepsilon$)	Difference (%)
AZ31B	-1664.11	15.27
AZ31B + CNT	-1759.31	10.42
AZ31B + Pb	-1773.46	9.70
AZ31B + CNT + Pb	-1841.10	6.26

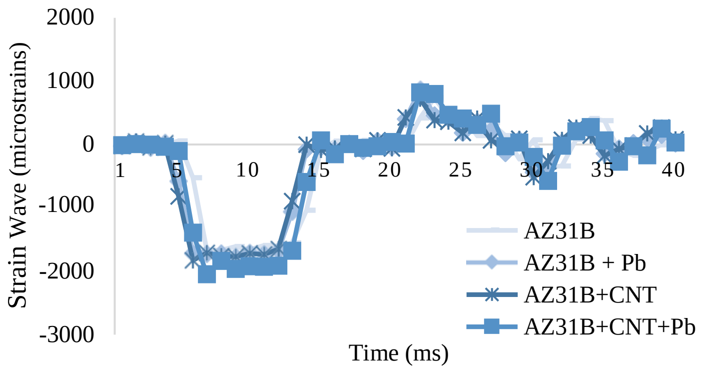

Fig. 2 - Strain waves of incidence bar

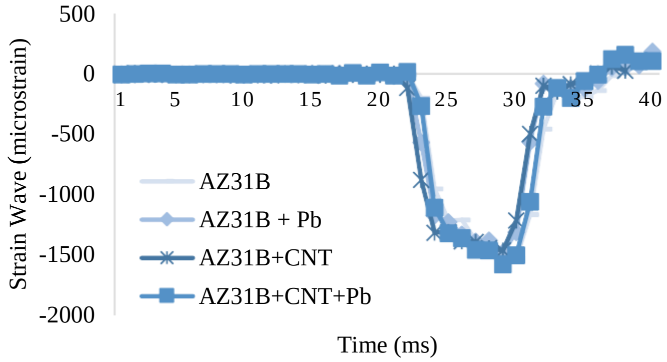

Fig. 3 - Strain wave recorded in transmitted bar

3.2 Strain Rate

Strain rate of the specimen developed during the test is associated with the reflected strain pulse. Higher reflected strain pulse will result in higher strain rate. Based on Eq. (1), the strain rate developed in the specimen with striking velocity of 20 m/s is shown in Fig. 4. The highest strain rate recorded is about 1300 per second, developed in AZ31B with added CNT and Pb. The improvement in term of strain rate is 52.9%. Reflected strain pulse of this material is higher compared to others.

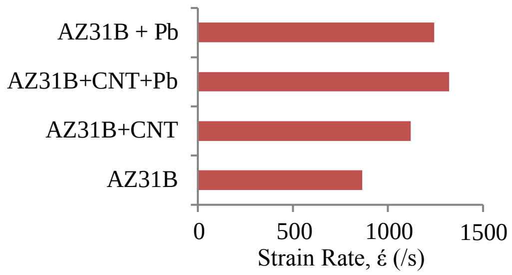

Fig. 4 - Strain rate experienced by the specimens by velocity of 20 m/s

3.3 Energy Absorption

The energy absorption capability of each specimen is determined by the area under the stress strain curve [14]. Strain and stress of the specimens are evaluated by using Eq. (2) and Eq. (3) respectively. Stress-strain curves for each specimen is shown in Fig. 5. Fig. 6 reveals that with addition elements to AZ31B, the energy absorption is higher compared to original magnesium alloy. Applying this method in Fig.5 was to obtained the amount of energy absorbed by the specimen. Addition of CNT and Pb increased the energy capability by 47%. This higher energy absorption is correlates with the higher strain rate developed in the specimen [15].

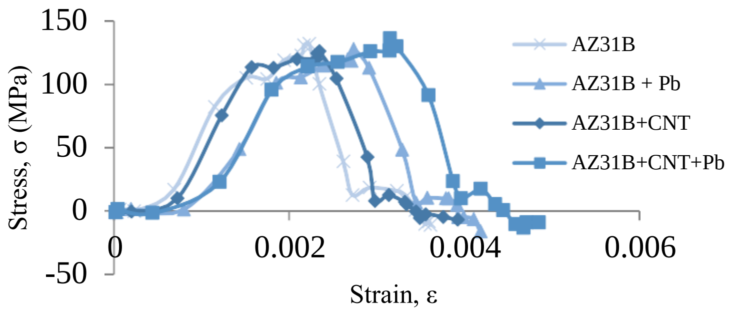

Fig. 5 - Trend of stress-strain curve for high velocity impact

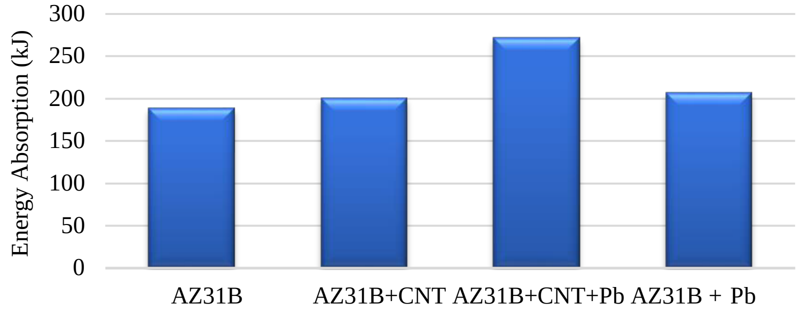

Fig. 6 - Energy absorption capability of AZ31B with added elements.

4. Conclusion

Impact performance of magnesium alloy AZ31B can be enhanced by adding Pb and CNT. This is due to the advantages provided by Pb and CNT. The former extends the ductility of magnesium alloy while the latter increased performance in term of specific absorption energy. The presence of Pb and CNT improved AZ31B's performance against ballistic penetration by 47% in term of energy absorption. This significant improvement is supported by the increasing strain rate value of 52.9%. The lightweight AZ31B with better energy absorption capability can be lined up as an alternative to replace RHA so that the maneuverability of defence vehicle can be enhanced. Besides, the fuel consumption also can be reduced.

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