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Tensile Properties of die-cast magnesium alloy AZ91D at high strain rates in the range between 300 s^{-1} and 1500 s^{-1}

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Abstract. Magnesium alloys have been increasingly used in the automobile, aerospace and communication industries due to their low density, high strength to weight ratio, good impact resistance and castability. Magnesium alloys, previously not used in load bearing components and structural parts are strongly being considered for use in such applications. Impact events in vehicles and airplanes as well as developments in weaponry and high speed metal working are all characterized by high rates of loading. Understanding of the dynamic behaviour of materials is critical for proper design and use in different applications. In the current study, a cast magnesium alloy AZ91D has been investigated at quasi-static and higher strain rates in the range between 300 s^{-1} and 1500 s^{-1}. The INSTRON machine was used to perform the quasi-static tests. High strain rate tests have been performed using the Split Hopkinson Tensile Bar (SHTB), a very useful and widely used tool to study the dynamic behaviour of variety of engineering materials. The results of a tensile testing indicate that the tensile properties including yield strength (YS), ultimate tensile strength (UTS) and the elongation at fracture (E_f) are affected by the strain rate variation. Higher stresses are associated with higher strain rates. The alloy AZ91D displays approximately 45% higher tensile stresses at an average strain rate of approximately 1215/s than at quasi-static strain rate. The dependence of the yield stress and tensile strength on the strain rate in the range of high strain rate above 1000 s^{-1} is larger than that at lower strain rates. The alloy AZ91D is observed to be more strain rate sensitive for strain rate higher than 1000 s^{-1}. A decrease in the strain rate sensitivity is also observed with the increasing strain in the specimen. It is observed that the hardening behaviour of the alloy is affected with increasing the strain rate. At high strain rates, the fracture of magnesium alloy AZ91D tends to transit from ductile to brittle.

INTRODUCTION

Light weight magnesium alloys due to their excellent strength to weight ratio and good impact strength are being investigated for use in the automotive, aerospace and electronics industries. AZ91D is being used extensively for manufacturing of gearboxes, steering column holders and brackets, cam covers, transmission housings, drive brackets, 4-wheel drive transfer cases, clutch and brake pedals and many other components. In recent years, AZ91D due to its suitable properties is also being used for information and communication technology (ICT) appliances such as mobile phones, cameras, laptops and compact and mini disc cases as well [1].

Magnesium alloys, which are rapidly becoming popular for fabricating structural and load bearing parts in the automobile, aerospace and electronic industries due to light weightiness, high specific strength and good impact resistance, have not been tested adequately at impact rates of loading. Lack of sufficient and conclusive data about their dynamic behaviour has steered the research to investigate these alloys at high strain rates. Aune et al [2] investigated the effects of strain rate on the dynamic properties of the die cast AZ91D, AM60B and AM50A. They found that the stress increases and percentage elongation is not affected by strain rates from 15 s^{-1} to 130 s^{-1}. No significant strain rate sensitivity variations were found for strain rate change from 15 s^{-1} to 130 s^{-1}. Ishikawa, Watanabe and Mukai [3] examined the compressive properties in the solution treated AZ91 at a strain rate of 10^3 s^{-1} and in the temperature range from 296 K to 723 K. At room temperature the maximum flow stress at a strain rate of 10^3 s^{-1} is about 15% higher than the stress at 10^{-3} s^{-1}. The dynamic stress-strain behavior of the AZ91 alloy at strain rates between 10^2 s^{-1} and 10^3 s^{-1} was investigated by Han, Xu and Liu [4]. The flow stress increased at first and then decreased with the strain rate increasing from 10^2 s^{-1} to 10^3 s^{-1}. The alloy exhibited both strain rate hardening and strain rate softening effects within the selected strain rate range. Shu, Zhou and Ma [5] found an increase in the tensile strength of magnesium alloys AM50 with increasing strain rate from 600 s^{-1} to 1350 s^{-1}. Abbott, Easton and Song [6] investigated the tensile properties of AZ91D in a strain rate range between 0.01 s^{-1} and 1 s^{-1} and found no significant effect of strain rate on AZ91D.

From the existing literature, it is observed that the micro-structural characteristics and tensile properties of magnesium alloys at quasi-static loading have been investigated by most of the authors but little is known about its mechanical properties at low to high strain rates between 10^2 s^{-1} and 10^3 s^{-1}. In the current study, AZ91D has been investigated under tensile loading using Split Hopkinson Tensile Bar (SHTB) in the range of strain rates between 300 s^{-1} and 1250 s^{-1}. The strain rate dependence of stress has been evaluated for the alloy.

EXPERIMENTAL SETUP AND DATA ANALYSIS

The Split Hopkinson Pressure Bar (SHPB) technique is a widely used technique for testing materials at high strain rates. As long as the equipment is calibrated accurately with proper preparations, this technique will offer a relatively high level of accuracy. The tensile Hopkinson bar apparatus consists of one input bar, one output bar, a striker tube, an anvil bar and an absorber bar at the end. Both the input and the output bars are fitted with a pair of strain gauges, each pair mounted 500 mm away from the specimen end. The strain gauges in a pair are fixed 180° apart on the bar to record the strain when impacted. The schematic diagram of the tensile Hopkinson bar is shown in Fig. 1

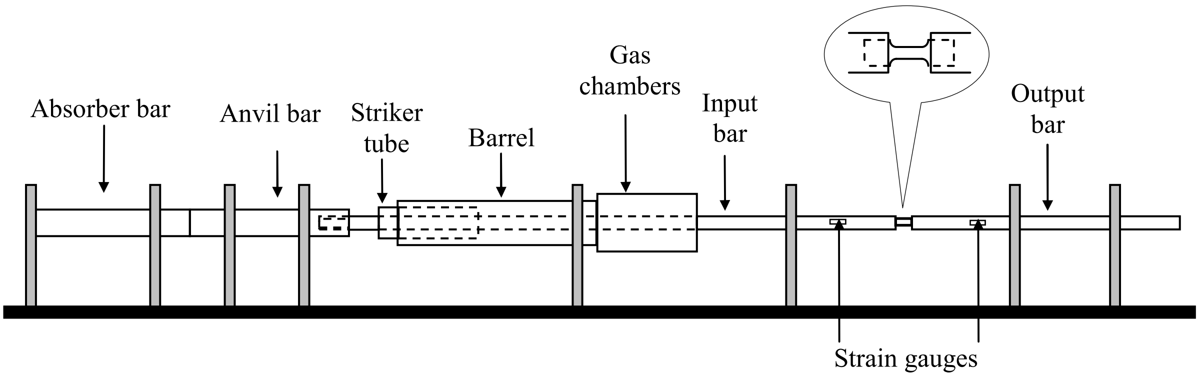


Fig. 1. A schematic diagram of Split Hopkinson Tensile Bar

The dog bone shaped specimen with threaded flanges is screwed between the input bar and the output bar. A gas gun drives the striking tube that is propelled from the barrel. The striking tube hits the anvil bar to initiate a compressive stress wave that propagates with speed c_o where $c_o = (E/\rho)^{1/2}$, being E the elastic modulus and ρ the bar material density, along the anvil bar into the absorbing bar until it reaches the free end of the absorbing bar where it reflects back as a tensile pulse. The tensile pulse will not be able to propagate back into the anvil bar and is absorbed in the absorber bar. A tensile wave also known as the incident wave propagates along the input bar towards the specimen/bar interface where it is measured by the strain gauges on the input bar. At this interface, the incident wave is partially reflected and partially transmitted through the specimen to the output bar as a transmitted wave. The reflected wave is again captured by the strain gauges on the input bar and the transmitted wave is measured by the strain gauges on the output bar. Measuring the amplitude of the incident, reflected and the transmitted pulses, ε_I , ε_R and ε_T respectively, shown in Fig. 2, it is possible to determine the stress-strain relationship of the specimen.

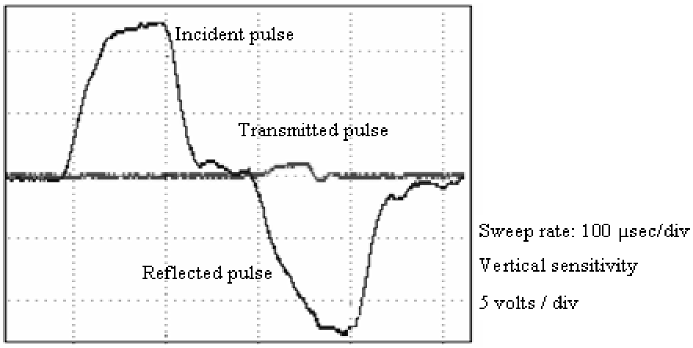


Fig. 2. Oscilloscope traces obtained from tensile Hopkinson bar on AZ91D alloy

When the specimen is deforming uniformly, the strain rate within the specimen is directly proportional to the amplitude of the reflected pulse. Likewise, the stress within the specimen is directly proportional to the amplitude of the transmitted pulse. The strain rate $\dot{\varepsilon} = {d\varepsilon}/{dt}$ in the specimen is calculated as

$$\frac{d\varepsilon_s}{dt} = -\frac{2c_o}{l_s}\varepsilon_R \,. \tag{1}$$

where l_s is the length of the specimen before impact. The strain is determined by integrating the strain rate from 0 to t, the total duration of the test.

$$\varepsilon_s(t) = -\frac{2c_o}{l_s}\int_0^t \varepsilon_R(t)dt \,. \tag{2}$$

Stress in the specimen can be calculated by using the following equation;

$$\sigma_{ave}(t) = E\frac{A_o}{A_s}\varepsilon_T(t) \,. \tag{3}$$

Where A_o and A_s are the cross sectional areas of the incident bar and the specimen.

Specimen

Fig. 3 shows the geometry of the specimens used in the present tests. The specimens were prepared from the same batches of AZ91D alloy to avoid any metallurgical effects.

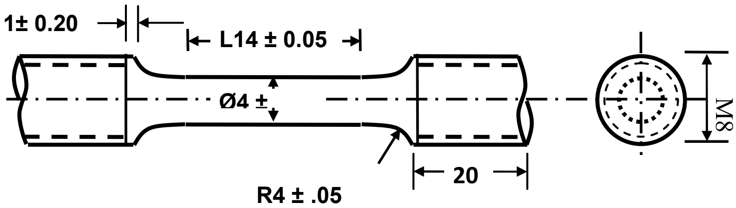


Fig. 3 Dimensions of the tensile specimen used

Test Results and Discussions

In order to study the tensile behavior of the magnesium alloy AZ91D, a series of impact tests were performed at various strain rates between 300 s^{-1} and 1250 s^{-1}. The strain rate variation with time is plotted in Fig. 4 for various tested strain rates. The values of strain rates shown in figure 4 are the average values. It is observed that the strain rate is relatively uniform at lower strain rates as compare to high strain rates.

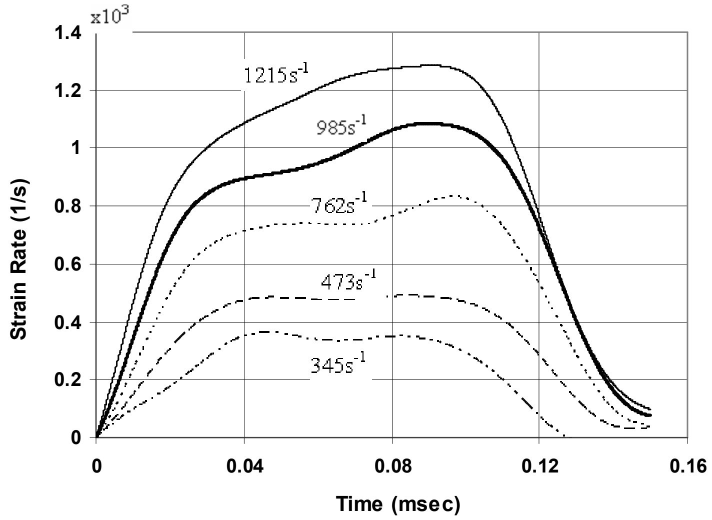


Fig. 4. Strain rate variation with time at different strain rate loadings

Effect of strain rate on dynamic properties of the alloy

Figure 5 depicts the resulting impact tensile stress-strain relations for the AZ91D alloy at various rates of strain. The alloy exhibit distinct yield points at high strain rates and the stress increases with increasing the strain rate monotonically. At a strain rate of 1215 s^{-1}, approximately 15 % and 45% high stresses are observed as compare to what is experienced at a strain rate of 345 s^{-1} at 1.5% strain and quasi-static test at 2% strain respectively. A similar trend is seen for other higher strain rates. The elongation to fracture of the specimen increases with increasing strain rate except the specimen tested at 473 s^{-1}. A slight work hardening during plastic deformation is also observed.

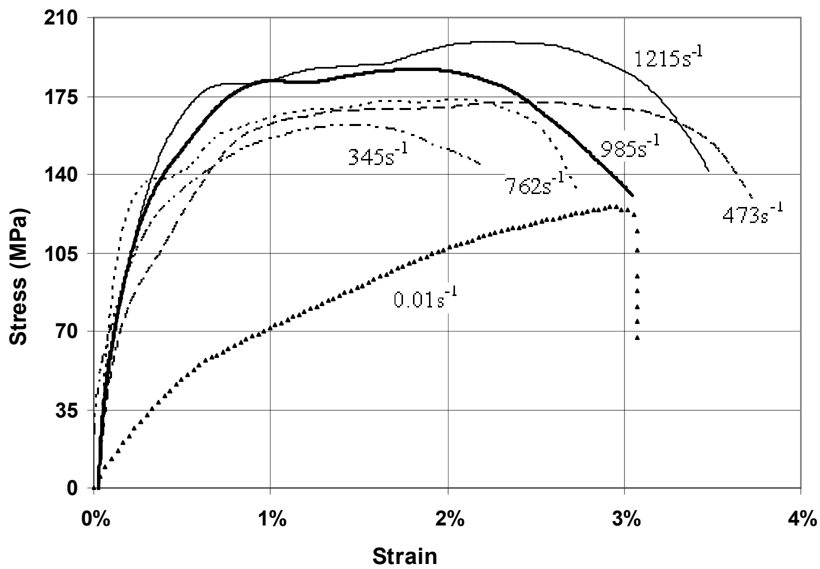


Fig. 5. Stress-strain relation for magnesium alloy AZ91D at different strain rates

Strain-hardening and strain rate sensitivity

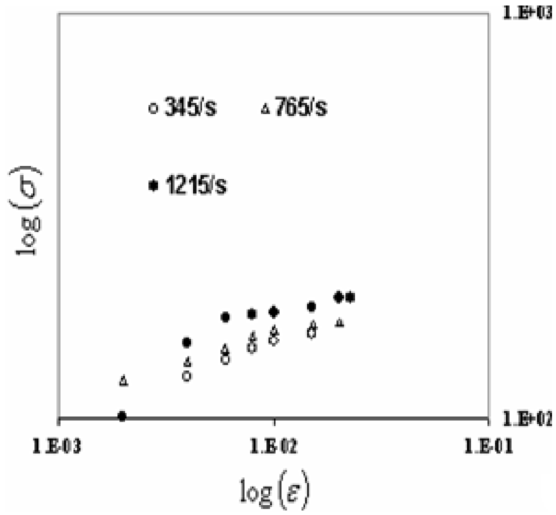
The material deformation becomes increasingly difficult during plastic deformation due to increasing dislocation density. This process is called strain hardening and is depicted by the well known Hollomon equation;

$$\sigma = K\varepsilon^n \, . \tag{4}$$

K and *n* are the strength coefficient and the strain hardening exponent respectively. The hardening exponent can be found by determining the slope of a plot of *log (σ)-vs-log (ε).* Figure 6, shows such a plot for the current study at various strain rate levels. The value of *n* calculated from this plot for three different strain rates 345, 762 and 1215 s^{-1} are 0.23, 0.196 and 0.185 indicating a slight decrease in the hardening exponent with increasing strain rate. In order to examine the effect of the strain rate on the tensile stress, the respective values of stress at different percentage strains are plotted in Fig.7 as a function of log of average strain rate. In order to evaluate the rate sensitivity of the stress the strain rate sensitivity *m*, is introduced in the following equation;

$$m = \left(\frac{\partial \sigma}{\partial \log \dot{\varepsilon}} \right)_{\varepsilon, T} . \quad (5)$$

Where T is the test temperature, which is room temperature in the present study



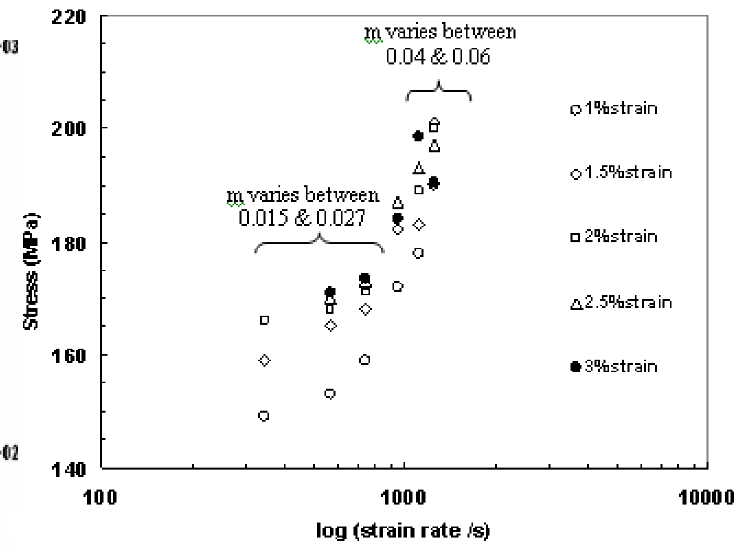


Fig. 6. log (σ)-vs-log (ε) Fig. 7. Stress as a function of log strain rate.

The stress σ corresponds to different strain rates at some constant strain $\varepsilon = \varepsilon_{\circ}$. The value of m is plotted for different values of specimen strain. It is clear that the alloy AZ91D is a rate sensitive material. It is noted that the strain rate sensitivity of the AZ91D alloy varies between 0.015 and 0.027 for strain rate lower than 1000 s^{-1} and it is between 0.04 and 0.06 when the deformation rate is higher than 1000 s^{-1} indicating high rate sensitivity of the alloy at higher strain rates. The values of strain rate sensitivity calculated for the AZ91D alloy for strain rates up to 1000 s^{-1} are plotted as a function of the specimen strain in Fig. 8. As the strain increases, the strain rate sensitivity decreases monotonically. However, the decrease in strain rate sensitivity is minute for larger strains (> 2%) as compare to what is observed at lower strains. Similar behavior is observed for strain rate higher than 1000 s^{-1}.

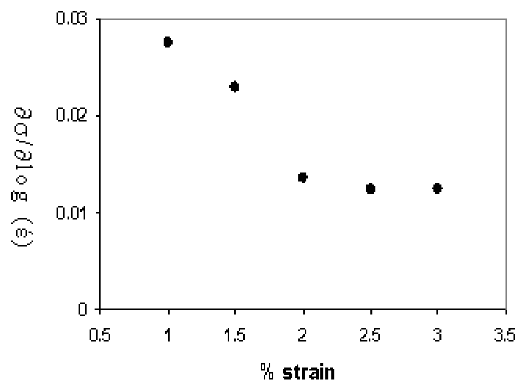


Fig. 8. Strain rate sensitivity *m* vs. specimen strain

CONCLUSION

A die cast magnesium alloy AZ91D has been investigated for its tensile properties at high strain rates. It is observed that the strain rate variation with time is relatively uniform when the specimen is deforming at lower strain rates as compare to high strain rates. A monotonic increase in the stress is observed with increasing strain rate from 345 s^{-1} to 1215 s^{-1}. At a strain rate of 1215 s^{-1}, approximately 15 % and 45% high stresses are observed as compare to what is experienced at a strain rate of 345 s^{-1} at 1.5% strain and quasi-static test at 2% strain respectively. The hardening exponent decreases with the increasing the strain rate. It is noted that the strain rate sensitivity for AZ91D alloy is lower for strain rate up to 10^3 s^{-1} and it increases sharply at strain rates higher than 10^3 s^{-1}. A decrease in the strain rate sensitivity is observed with increasing %strain in the specimen.

Future Recommendations

More tests with an extended range of strain rates up to 2000 and higher followed by numerical simulation using the Johnson-Cook materials mode, needed for better understanding of the dynamic behaviour of the alloys, are in progress.

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