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Effect of Temperature on the Dynamic Compressive Properties of Magnesium Alloy and its Nanocomposite

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ABSTRACT

Magnesium alloys are very attractive in applications such as automotive, railway and aerospace industries due to their low density in comparison with aluminum and steel alloys. Magnesium-based composites exhibit high specific properties compared to unreinforced magnesium alloys and they are found to be promising for mechanical applications under impact and high temperature conditions beyond those possible with magnesium alloys. In the present study, the effect of temperature variation has been investigated for both magnesium alloy AZ31B and the same alloy reinforced with silicon carbide nano-particles at high strain rates. The temperature is varied in the range from -30 °C to 200 °C at a high strain rate of 3300 s⁻¹. Lower stresses and larger strains to peak compressive stresses are observed with increasing temperature. An analytic comparison between AZ31B alloy and AZ31B nanocomposite was also examined and results reveal that AZ31B nanocomposite displays superior strength properties with slightly weaker ductility than AZ31B alloy at all three temperature variations. The result of this is an improved energy absorption capability possessed by AZ31B nanocomposite.

Keywords: AZ31B alloy; Magnesium nanocomposite; Split Hopkinson Pressure Bar; Temperature effects

1. INTRODUCTION

In recent years, the use of magnesium alloys as automotive and aerospace parts has increased dramatically. Magnesium alloys are an ideal candidate for designing a vehicle with lower weight and therefore, reduced fuel consumption, due to their low density in comparison to aluminum and steel alloys. However, compared to other structural metals, magnesium alloys have a relatively low absolute strength, especially at elevated temperatures. Currently, the most widely used magnesium alloys are based on the Mg-Al system. Their applications are usually limited to temperatures of up to 120 °C. Further improvement in the high-temperature mechanical properties of magnesium alloys will greatly expand their industrial applications. During the past decades, efforts to develop high temperature magnesium materials have led to the development of several new alloys. However, this progress has not generated extensive applications of these magnesium alloys in the automotive industry, either because of insufficient high temperature strength or high cost¹. The need for high-performance and lightweight materials for some demanding applications has led to extensive R&D efforts in the development of magnesium matrix composites (MMCs). In many engineering applications, the materials are subjected to severe impact strains. The values defining the basic properties of an MMC are usually lower as the strain rate increases. The mechanical behavior of the MMCs at high temperature is often the critical parameter for the choice of these materials for a given industrial application². In general, a higher temperature gives rise to a reduction of the elastic module, the elastic limit and the maximum strength of the material³.

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The unreinforced magnesium alloy AZ31B and its nanocomposite have been considered in this investigation because of their growing importance in the automobile and aviation industries as well as the scarcity of studies on their performance at high strain rates. The objective of the present paper is to obtain some mechanical characteristics of both materials at high strain rates and elevated temperatures. The effect of the ceramic particle reinforcement on the base alloy will also be discussed.

2. EXPERIMENTAL METHOD AND SPECIMEN PREPARATION

High strain rate compressive tests were carried out using Kolsky's bar (SHPB) ⁴. The Kolsky's bar used in present study constitutes a striker bar, an input bar, an output bar and an absorbing bar as shown in Figure 1. The incident and transmitted bars were made of spring steel 65Si2MnWa with 12.7 mm diameter and 1.0 m in length. Spring steel bars were used in order to minimize the impedance difference between the bars and specimen and also to increase the signal/noise ratio. The cylindrical specimen is placed between the input and the output bar. Strain gauges positioned on the center of incident and transmitted bars respectively in a Wheatstone-bridge configuration were used to measure the time-dependent incident strain $\epsilon_I(t)$, reflected strain $\epsilon_R(t)$, and transmitted strain $\epsilon_T(t)$. A digital oscilloscope is utilized to record the signal from the strain gauges.

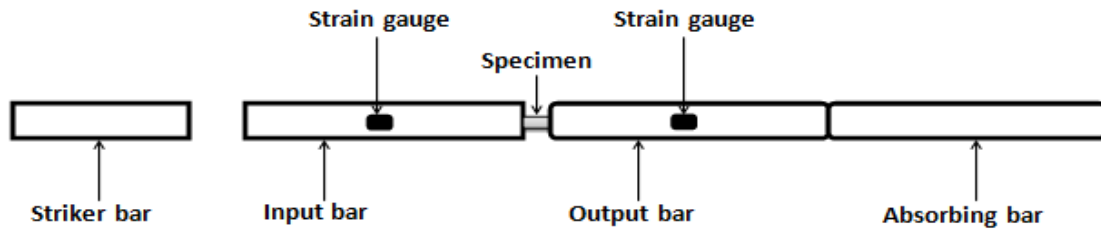


Figure 1: Simplified schematic drawing of the Split Hopkinson Pressure bar

The strain rate, strain and average stress in the specimen are calculated by the following well known Hopkinson equations:

$$\dot{\epsilon} = \frac{d\epsilon_s}{dt} = -\frac{2c_o}{l_s} \epsilon_R \quad (1)$$

$$\epsilon_s(t) = -\frac{2c_o}{l_s} \int_0^t \epsilon_R(t) dt \quad (2)$$

$$\sigma_{ave}(t) = E \frac{A_o}{A_s} \epsilon_T(t) \quad (3)$$

where c_o is the wave velocity in the bars and E is the Young's modulus of the bars, l_s = length of the specimen before impact, A_o and A_s = cross-sectional areas of the incident bar and the specimen.

Dry ice was used to achieve $-30\text{ }^\circ\text{C}$ and C-146 HotSat Induction heater was used to obtain elevated temperature as shown in Figure 2. All temperatures in the compressive SHPB experiment are measured using Tokyo Sokki Portable Data Logger TDS-303-thermocouple.

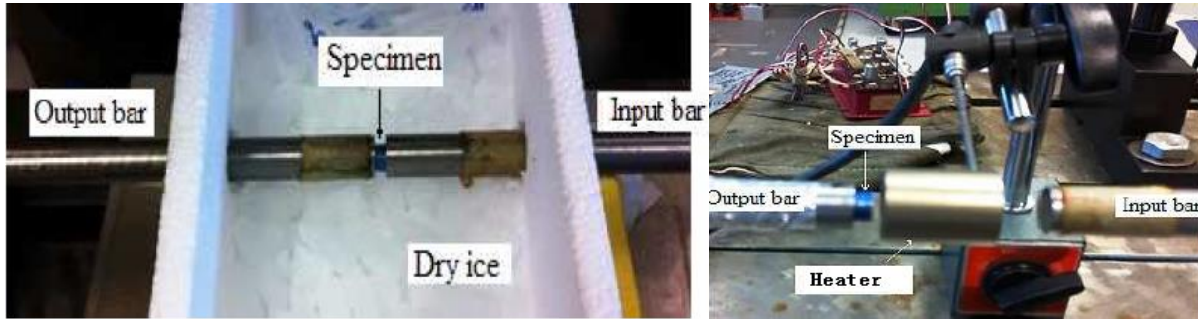


Figure 2: Arrangement for below zero and elevated temperature high strain rate testing

The materials in this work were magnesium alloy AZ31B and the same alloy reinforced. The reinforcement was SiC particles in a 1.0vol.% with a mean particle size of 60nm. Cylindrical Specimens were prepared with dimension of diameter $8 \pm 0.05\text{mm}$ and height $4 \pm 0.05\text{mm}$ using wire cutting method for smooth impact surface.

3. RESULTS AND DISCUSSION

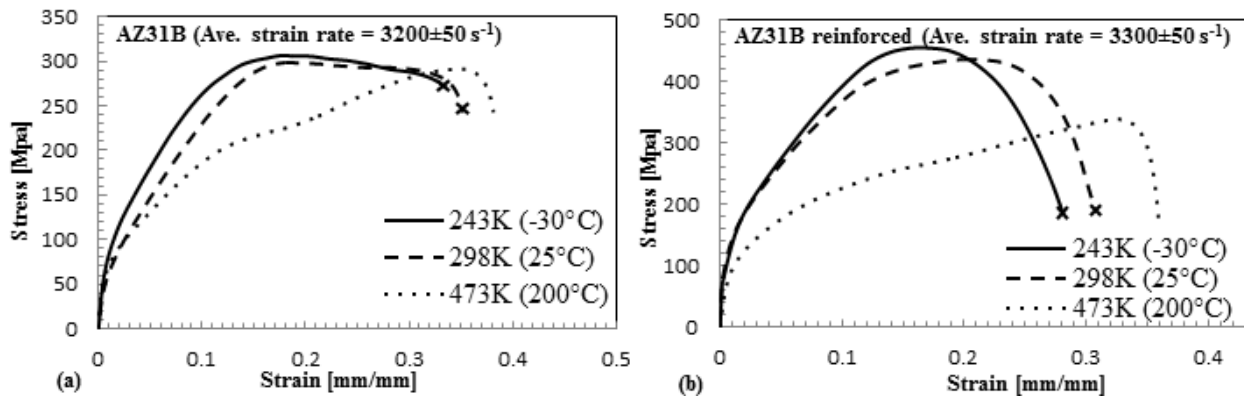


Figure 3: Effect of temperature on stress-strain relationship of (a) the base alloy and (b) the reinforced material

Figure 3(a) and Figure 3(b) show experimental stress-strain curves of magnesium alloy and reinforced material at various temperatures ranging between $-30\text{ }^{\circ}\text{C}$ (243K), $25\text{ }^{\circ}\text{C}$ (298K) and $200\text{ }^{\circ}\text{C}$ (473K) at high strain rates. At least 3 tests were conducted for each condition so as to insure the reproducibility of the results. Stress decreases and strain to failure increases with increasing temperature from $-30\text{ }^{\circ}\text{C}$ to $200\text{ }^{\circ}\text{C}$. For AZ31B alloy, there is a 4.90% decrease in peak stress and 15.2% increase in strain to failure from $-30\text{ }^{\circ}\text{C}$ to $200\text{ }^{\circ}\text{C}$ at 3200 s^{-1} . With regard to AZ31B nanocomposite, the decrease of peak stress is 25.7% and increase of strain to failure is 28.6% from $-30\text{ }^{\circ}\text{C}$ to $200\text{ }^{\circ}\text{C}$ at 3300 s^{-1} strain rate. It is thus observed that as temperature increases, the decrease in peak stress and the increase in strain to failure of AZ31B are more than those of AZ31B nanocomposite.

From Figure 4, it is seen that the stress levels of reinforced AZ31B is comparatively higher than AZ31B alloy under all temperature variations. At $-30\text{ }^{\circ}\text{C}$, the peak stress of AZ31B nanocomposite is 48.7% higher than AZ31B. At $25\text{ }^{\circ}\text{C}$, peak stress of AZ31B nanocomposite is 46.0% higher than AZ31B and at $200\text{ }^{\circ}\text{C}$, peak stress of AZ31B nanocomposite is 16.2% higher than AZ31B. The higher peak stress value of AZ31B nanocomposite indicates superior compressive strength performance than AZ31B. The increase in compressive strength of AZ31B composite can be attributed to the integration of hard, nano-ceramic-particulates in the magnesium matrix. Presence of these nano-particulates presumably serves as obstacle to and reduces the free path for dislocation motion. In addition, elastic modulus and coefficient of thermal expansion mismatch between the matrix and the reinforcement result in dislocation generation, enhancing both

the compressive and yield strength properties ⁵. The price for this enhancement in hardness and strength is a slight decrease in the ductility of AZ31B nanocomposite which is shown in Figure 5.

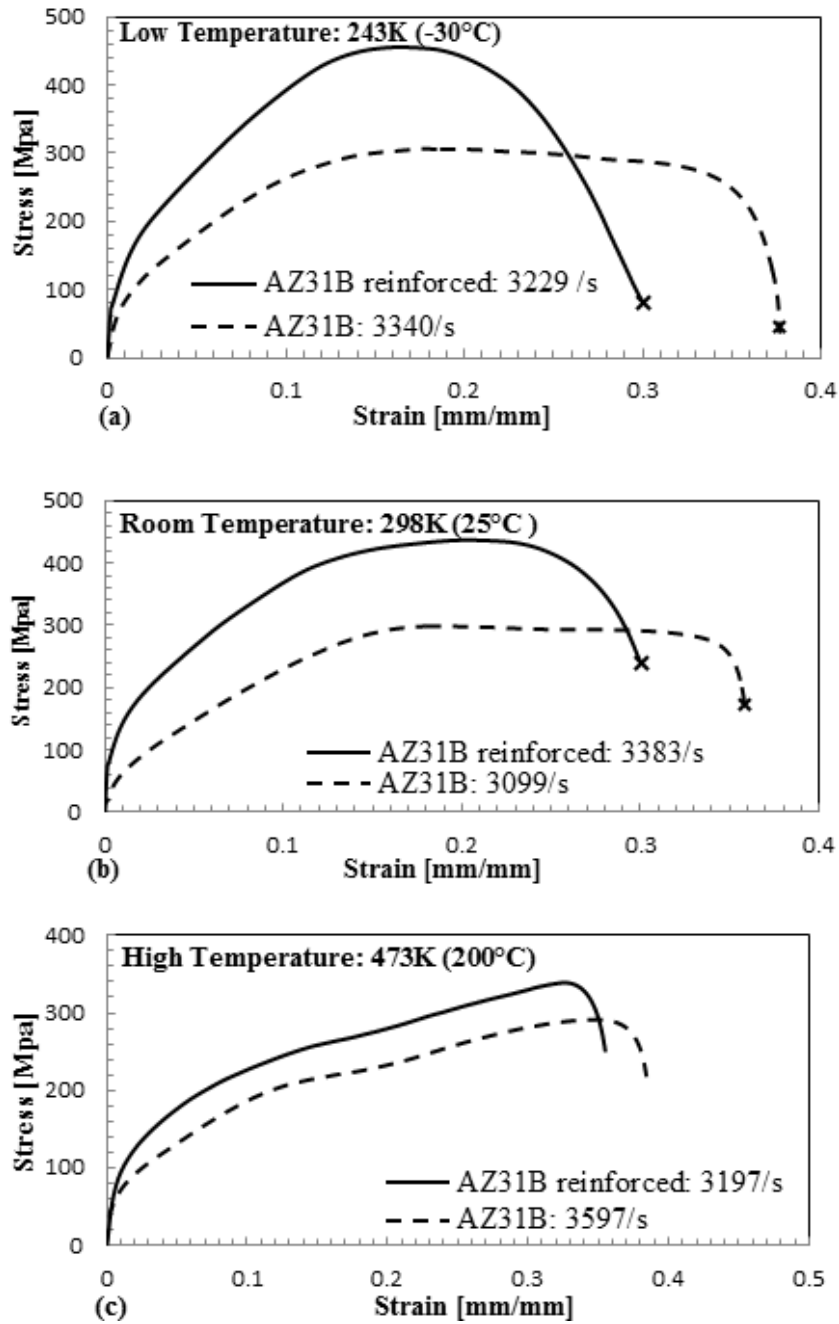


Figure 4: Stress-strain curves of AZ31B and AZ31B reinforced composite at (a) -30 °C (b) 25 °C (c) 200 °C

Figure 5 shows the effect of the temperature on the strain to failure at high strain rates. The homologous temperature is defined by Equation (4), where T_0 (-273K) is the absolute zero and T_m (873K) is the melting temperature in Kelvin.

$$T^* = \frac{T - T_0}{T_m - T_0} \tag{4}$$

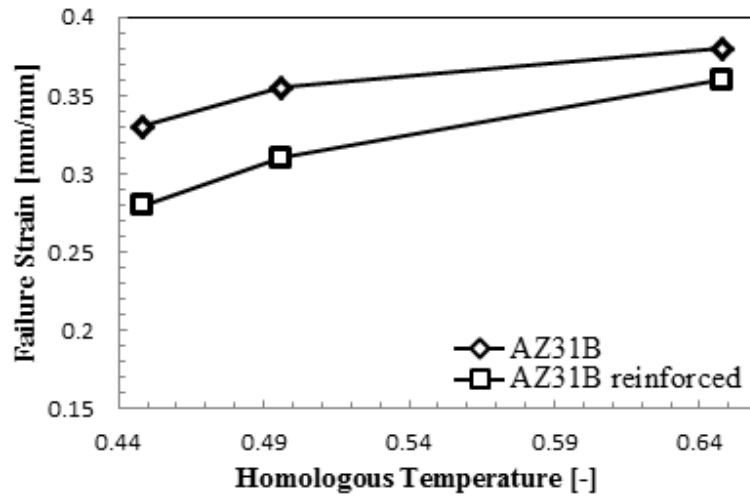


Figure 5: Strain to failure as a function of temperature

From Figure 5, it can be seen that the failure strain-homologous temperature line of AZ31B composite is lower than that of AZ31B. The smaller strain to failure of AZ31B nanocomposite at each temperature indicates a slightly lower ductility compared to its matrix alloy. Notably, ductility difference between both specimens at 200 °C is most nominal. Like AZ31B alloy at 200 °C, AZ31B nanocomposite was deformed but there was no fracture or breakage to the composite structure.

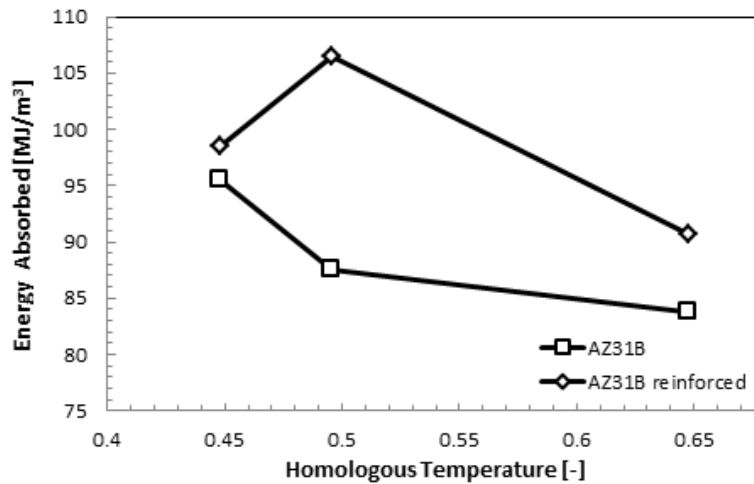


Figure 6: Effect of temperature on the Energy absorption capability of AZ31B and AZ31B reinforced composite

The effect of temperature on the energy absorption of the base alloy and the reinforced material are plotted in Figure 6. The energy per unit volume absorbed by the material during compression was calculated using Equation (5) where $\int_0^\epsilon (\sigma \times \epsilon)$ is the area under the stress-strain curve up to failure strain. However, the specimens tested at 200 °C were not broken so the energy absorption at 200 °C is calculated by taking the area under the stress-strain curve up to 0.37 strain. It is observed that at each temperature, AZ31B reinforced composite has better energy absorption capability than its matrix alloy.

$$E = \int_0^{\epsilon} \sigma d\epsilon \quad (5)$$

4. CONCLUSION

The effect of temperature on the mechanical behavior of magnesium alloy AZ31B and its nanocomposite is investigated at high strain rates. Stress decreases and strain to failure increases with increasing temperature from -30 °C to 200 °C for both materials. The presence of the reinforcement improves the strength of the material in relation with the base alloy but somewhat reduces its ductility. The improvement of strength is less evident when the material is subjected at high temperature. Although the ductility of the AZ31B decreases after the addition of ceramic nano-particulates, AZ31B nanocomposite still has better energy absorption capability than its matrix alloy at all three temperature variations.

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REFERENCE

1. Ye, H. Z., and Liu, X. Y., "Review of recent studies in magnesium matrix composites," *Journal of Materials Science*, 39(20), 6153-6171 (2004).
2. Taya, M., "Mechanical behaviour of metal matrix composites at high temperatures," *Mechanical Properties of Metallic Composites*, 553-611 (1994).
3. El-Saeid Essa, Y., and Pérez-Castellanos, J. L., "Effect of the strain rate and temperature on the mechanical behaviour of a Mg-5%Zn alloy reinforced with SiC particles," *Journal of Materials Processing Technology*, 143-144(1), 856-859 (2003).
4. Kolsky, H., "An Investigation of the Mechanical Properties of Materials at very High Rates of Loading," *Proceedings of the Physical Society Section B*, 62(11), 676 (1949).
5. Nguyen, Q. B., and Gupta, M., "Enhancing compressive response of AZ31B magnesium alloy using alumina nanoparticulates," *Composites Science and Technology*, 68(10-11), 2185-2192 (2008).