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Promising Magnesium Alloys for Mobility and Portability

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Abstract. Magnesium alloys being the lightest of all metals offer great potential to achieve weight reduction by replacing the most commonly used materials, i.e. steel, aluminium and plastics. Limited data available for high strain rate deformation of magnesium alloys combined with an insufficient understanding of the underlying deformation mechanisms adds to the reservations for their use as structural materials. Limited data is available for high strain rate deformation of magnesium alloy and its nanocomposites, which makes it difficult for widespread usage of these lightweight materials. For widespread usage of magnesium alloys, their dynamic behaviour must be determined to assess their performance during a crash event. In the present work, an experimental and numerical study followed by the microstructural analysis has been carried out to investigate the dynamic behaviour of as-cast AZ91D and wrought AZ31B magnesium alloys. These alloys have been tested at strain rates in the range between $10^{-4}s^{-1}$ and $4x10^{3}s^{-1}$ and at temperatures between -30ºC and 200ºC under compression and under tension between $10^{-4}s^{-1}$ and $1500s^{-1}$ strain rates and at 25ºC and at 250ºC temperatures. Increasing stresses, larger strains and higher energy absorption are observed with increasing strain rate in both alloys under compression as well as in tension. Temperature has little effect on the mechanical behaviour of these alloys at dynamic strain rates. It has been found that the addition of stiffer and stronger second-phase reinforcements can enhance strength and ductility of magnesium alloys. Micro-sized reinforcements are effective in enhancing stiffness and strength but accompanied by an obvious decrease in ductility. In the present work, the compressive mechanical response of magnesium alloy AZ31B, AZ31B/0.5%SiC and AZ31B/1.0%SiC to quasi-static and dynamic loading over a wide range of temperature is investigated. The addition of silicon carbide nanoparticles can enhance the strength of the base alloy, while it slightly decreases the ductility of the material. It doesn't apply to all strain-rate and temperature conditions that higher volume fraction of nanoparticles results in higher strength.

1. Introduction

As a result of environmental considerations, a key challenge for the automobile and aerospace industries is to reduce greenhouse gas emissions and to enhance fuel efficiency. This motivates the development of new lightweight alloys as replacement for steel and aluminium alloys. Magnesium and its alloys with low specific weight, high specific strength, vast resources, easy recyclability and biodegradation have attracted extensive interest in recent years. However, the low absolute strength and low ductility limit their usage.

There are many applications where materials are subjected to high strain rate loading. High strain rate deformation encounters in crash of automobiles or airplanes, where the structural material deforms under various strain rates. In defence and security sector, designing the bomb-proof shields and human protection against bullets and other penetrators need to consider high strain rate deformation of materials. In addition, high strain rate loading also arise in many aspects of everyday life. The dynamic response of a material is quite different from its static response. Limited data is available for high strain rate deformation of magnesium alloy and its nanocomposites, which makes it difficult for widespread usage of these lightweight materials.

The dynamic response of a material is quite different from its static response. Limited data is available for high strain rate deformation of magnesium alloy and its nanocomposites, which makes it difficult for widespread usage of these lightweight materials. For widespread usage of magnesium alloys, their dynamic behaviour must be determined to assess their performance during a crash event. In the present work, an experimental and numerical study followed by the microstructural analysis has been carried out to investigate the dynamic behaviour of as-cast AZ91D and wrought AZ31B magnesium alloys. These alloys have been tested at strain rates in the range between 10-4s-1 and 4x103s-1 and at temperatures between -30oC and 200oC under compression and under tension between 10-4s-1 and 1500s-1 strain rates and at 25oC and at 250oC temperatures. Quasi-static tests were performed using universal testing machine and high strain tests were carried out with Hopkinson Bar apparatus. Dry ice was used to achieve below zero temperature while the elevated temperatures were obtained by using coil heater. Increasing stresses, larger strains and higher energy absorption are observed with increasing strain rate in both alloys under compression as well as in tension. Temperature has little effect on the mechanical behaviour of these alloys at dynamic strain rates. The alloys deform by dislocation glide and twining at room temperature. Number of twins decreases as the strain rate increases. Twins, voids, shear bands, grains refinement and elongation have key role in alloys response such as strength, ductility, hardenability and energy absorption. AZ31B alloy is strongly anisotropic and shows a considerable tensile-compressive yield asymmetry. The experimental data was fit to Johnson-Cook model and the results are in reasonable agreement except in the beginning portion of the flow curves, where the fitted curves deviate from the experimental data.

It has been found that the addition of stiffer and stronger second-phase reinforcements can enhance strength and ductility of magnesium alloys. Micro-sized reinforcements are effective in enhancing stiffness and strength but accompanied by an obvious decrease in ductility. Recent studies show that it is possible to obtain simultaneous enhancement in strength and ductility when ceramic nanoparticles are employed as reinforcements. The resulting nanocomposites have great potential to replace the existing metals and alloys for various automobile, aerospace and other applications. In the present work, the compressive mechanical response of magnesium alloy AZ31B, AZ31B/0.5%SiC and AZ31B/1.0%SiC to quasi-static and dynamic loading over a wide range of temperature is investigated. The split Hopkinson pressure bar (SHPB) is used to study high strain rate behaviour of the materials in this work. The experimental investigation on the effect of specimen size and pulse shapers has been carried out to decide the optimal specimen dimension and the most suitable pulse shapers used in SHPB tests. The addition of silicon carbide nanoparticles can enhance the strength of the base alloy, while it slightly decreases the ductility of the material. It doesn’t apply to all strain-rate and temperature conditions that higher volume fraction of nanoparticles results in higher strength, but the strengthening appears more at higher strain rate.

2. Experiments, Investigation, and Discussions of AZ91D and AZ31B

2.1 Materials, specimen, and test plan

Two types of magnesium alloys, as cast AZ91D and rolled AZ31B were characterized as a part of the current study. The densities of about 7 to 8 specimens of each alloy were measured using displacement method (Archimedes Principal) and the following densities were AZ91D (1.79-1.81) and AZ31B (1.70-1.80). The chemical compositions of the two alloys are given below in Table 1.

Table 1: Chemical composition of tested magnesium alloys

Alloy	Al [%]	Mn [%]	Zn [%]	Si [%]	Cu [%]	Ni [%]	Fe [%]	Mg [%]
AZ91D	8.5-9.5	0.17-0.3	0.35 -1	0.05	0.025	0.002	0.004	balance
AZ31B	2.5-3	0.3-1	0.7-1.3	-	-	-		balance

In the present study the specimen geometries for static compression tests were manufactured according to the ASTM standards E9-89a. The dimensions of the cylindrical specimen for quasi-static compression tests for AZ91D and AZ31B are shown in Table 2.

Table 2: Specimen dimensions for quasi-static compression test

Alloy	Height L(mm)	Diameter D (mm)	Length to diameter ratio
AZ91D	25.00 ± 1.0	12.50 ± 0.20	2.0
AZ31B	20.00 ± 1.0	10.00 ± 0.20	2.0

Optimum specimen geometries for compression and tensile tests were chosen to minimize the size effects on the behaviour of material. The diameter and height of the cylindrical specimens used for high strain rate compression tests are 8.0 ± 0.10and 4.0 ± 0.05 respectively for both AZ91D and AZ31B alloys. All compression specimens were machined using Wire Electrical Discharge Machining (EDM) followed by the fine grinding of the specimen ends to make them flat and parallel for perfect contact with the bar ends. The specimen geometry for high rate tensile tests was chosen with a minimum length to diameter ratio of 2.5 and detailed dimensions are shown in Fig. 1. The tensile specimen geometry used was modified (a small portion of 1.5 mm was kept without threads starting from the edge of transition zone) in order to get a better tight fit of specimen into the bars, a loose fit will introduce some noise in the data.

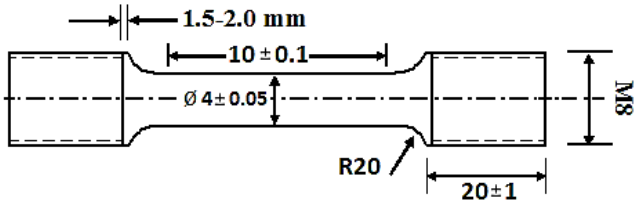

Figure 1: High strain rate tensile specimen used in present study

The various experiments are carried out as the plans below.

Table 3: Matrix of experiments performed under compression at room temperature

Material	Average tested strain rate [s^{-1}]							
	10^{-4}	500	1000	1500	2000	2500	3000	3500
AZ91D	x	x	x	x	x	x	x	
AZ31B (45^o)	x	x	x	x		x		x
AZ31B (N)	x	x	x	x		x		x
AZ31B (R)	x	x	x	x		x		x
AZ31B (T)	x	x	x	x		x		x

(x) shows that the tests were performed under this strain rate or temperature

Table 4 Matrix of experiments performed under tension at room temperature

Material	Average tested strain rate [s^{-1}]						
	10^{-4}	350	500	750	1000	1400	1500
AZ91D	x	x		x			x
AZ31B (R)	x		x		x	x	
AZ31B (T)	x		x		x	x	

Table 5 Matrix of experiments performed under compression at various temperatures

Material	Average tested strain rate [s^{-1}]							
	10^{-4}		1000		2250		2500	
	-30°C	200-250°C	-30°C	200-250°C	-30°C	200-250°C	-30°C	200°C
AZ91D	x	x	x	x			x	x
AZ31B	x	x	x	x	x	x		
AZ31B	x	x	x	x	x	x		
AZ31B	x	x	x	x	x	x		
AZ31B	x	x	x	x	x	x		

Table 6: Tensile tests at elevated temperature

Material	Average tested strain rate [s^{-1}]	
	10^{-4}	1500
	250°C	250°C
AZ91D	x	x
AZ31B	x	x
AZ31B (T)	x	x

2.2 AZ91D and AZ31B

The strain rate effect on the compressive behaviour of AZ91D at room temperature is shown in Fig.2. The stress level increases with increasing strain rate. For a fixed strain of 0.1, an increase of about 53% and 25% in stress is noticed as the strain rate is increased from 10^{-4} s^{-1} to 1500s^{-1} and from 1500s^{-1} to 3000s^{-1} respectively. Over the whole range of dynamic strain rate considered, yield strength (YS, stress at 0.2% offset), peak compressive strength (*PCS, the maximum stress*) and the strain to failure all show a monotonic increasing behaviour. It is also noted that at a strain rate of 1500s^{-1} and above, the stress-strain curves become flat after a certain strain, indicating a mitigating effect of hardening and softening of the alloy during deformation.

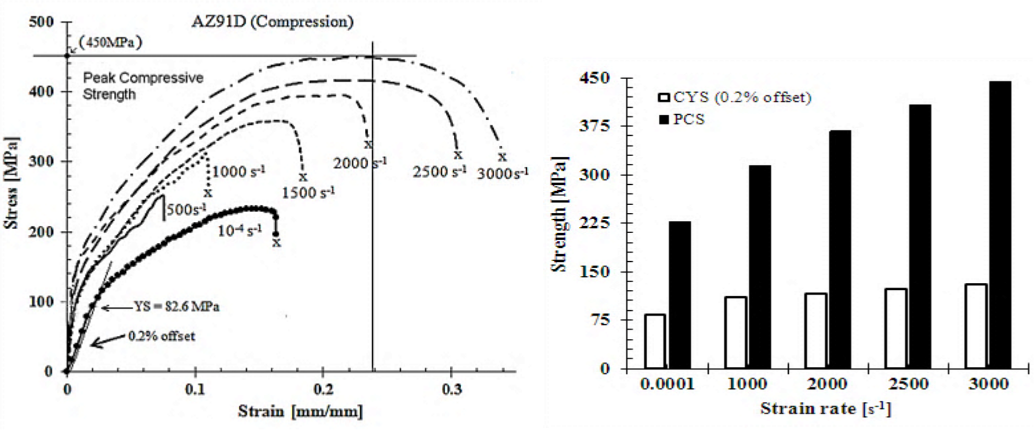

Figure 2: Stress-strain relationship for AZ91D at room temperature

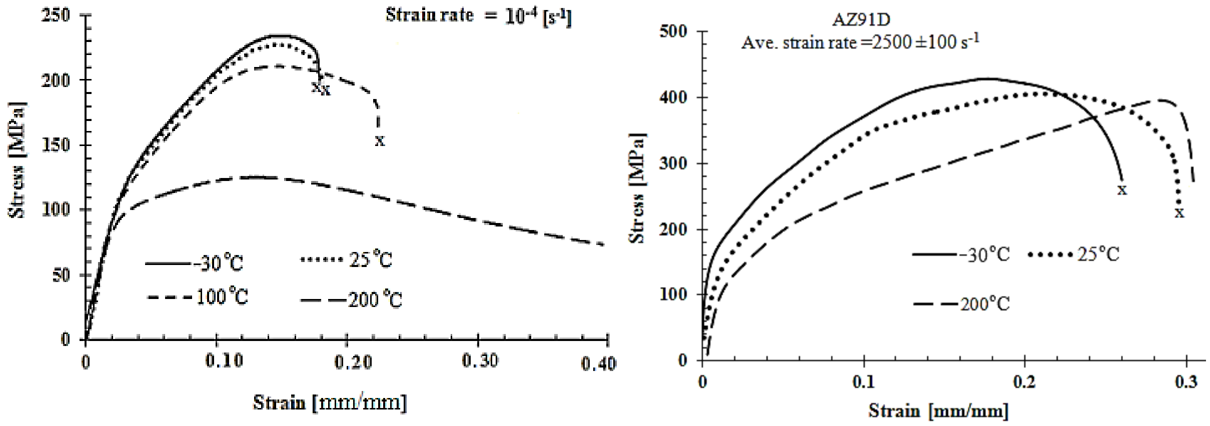

Fig 3 Temperature effect on the mechanical behaviour of AZ91D at $10^{-4}s^{-1}$ and $2500S^{-1}$.

2.3 AZ91D and AZ31B with SiC reinforcement

In this present study the specimen dimension for quasi-static compressive tests were processed according to ASTM standard E9-89a. The dimensions of specimens in solid cylindrical form for quasi-static compressive tests on AZ31B and its nanocomposites are shown in Table .

Table 7: Solid cylindrical specimen dimensions for quasi-static compressive test

Material	Length(mm)	Diameter(mm)	Approx L/D Ratio
AZ31B	16.00±0.1	8.00±0.1	2.0
AZ31B/0.5 vol.%SiC	16.00±0.1	8.00±0.1	2.0
AZ31B/1.0 vol.%SiC	16.00±0.1	8.00±0.1	2.0

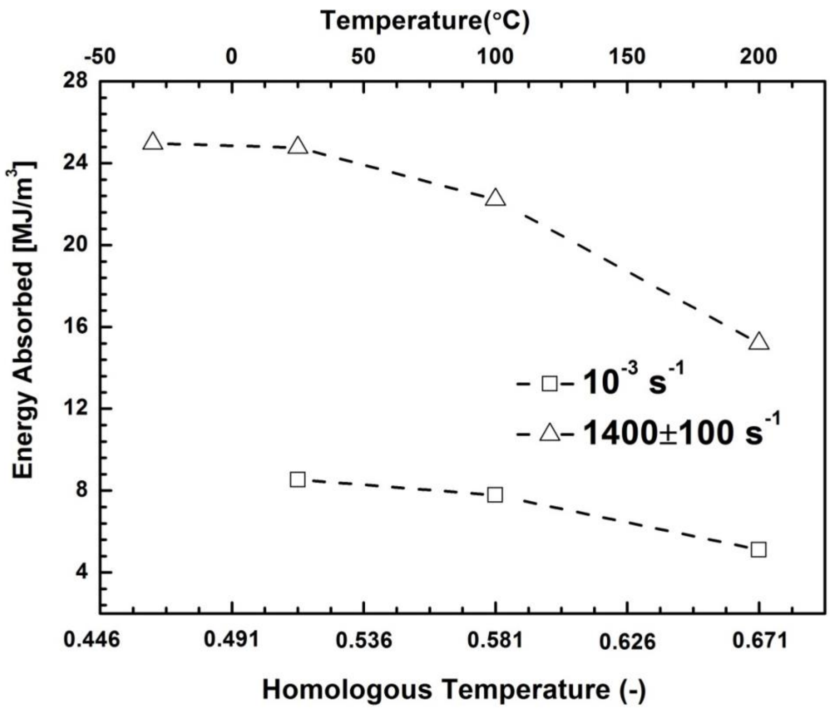

Figure 4: Energy absorption capability of 0.5vol% SiC_p/AZ31B

3. Conclusion

Temperature has little effect on the mechanical behaviour of AZ91D and AZ31B (between -25C and 200C) at dynamic strain rates. AZ31B alloy is strongly anisotropic and shows a considerable tensile-compressive yield asymmetry. The experimental data was fit to Johnson-Cook model and the results are in reasonable agreement except in the beginning portion of the flow curves, where the fitted curves deviate from the experimental data. It has been found that the addition of stiffer and stronger second-phase reinforcements can enhance strength and ductility of magnesium alloys. Micro-sized reinforcements are effective in enhancing stiffness and strength but accompanied by an drop in ductility. The addition of silicon carbide nanoparticles can enhance the strength of the base alloy, while it slightly reduces the ductility of the material. It doesn't apply to all strain-rate and temperature conditions that higher volume fraction of nanoparticles results in higher strength, but it strengthens more at higher strain rate.

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