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COMPRESSION AND FLEXURE BEHAVIOURS OF MAGNESIUM ALLOY AZ41 AT DIFFERENT STRAIN RATES

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An experimental investigation on the compression and flexure behaviours of the magnesium alloy AZ41 is done at different strain rates under room temperature 25°C. Quasi-static compressive tests are performed on electromechanical universal testing machine (Zwick/Roell Z250) at strain rates 0.0001s^{-1}, 0.001s^{-1}, 0.01s^{-1} and 0.1s^{-1} whereas, 3-point bending tests/flexural tests are conducted on the same machine at various cross-head speeds (1, 10 and 100mm/min) for different span lengths (80, 120 and 160mm) and orientations (flat and transverse) of flexural specimens. High strain rates (2400, 2500 and 2900s^{-1}) compression experiments are carried out on split Hopkinson pressure bar (SHPB) apparatus.

Keywords: Mg-alloy, split Hopkinson pressure bar, strain rate sensitivity, compression and flexure behaviours.

1. Introduction

The increasing use of magnesium alloys in engineering structures is due to its low density. It is the need for structural engineer to understand the behaviour of materials used in various structures under different kinds of service loads. There are several researchers and scientists who have taken interests in determining the mechanical properties of the magnesium alloys at different strain rates and temperatures. The compressive behaviour of AZ41M magnesium alloy was studied by Cai *et al.* [1] at different strain rates (0.005-1s^{-1}) and temperatures (523K to 723K). It was found that the flow stresses of the alloy increase with increasing strain rates and decreasing temperatures. The dynamic compressive behaviour of Mg-Gd-Y magnesium alloy was realized by Yu *et al.* [2] at high strain rates (949-3344s^{-1}) and temperatures (300K to 573K). Ishikawa *et al.* [3] reported the effects of temperatures (296K to 723K) on dynamic compressive behaviour of AZ91 magnesium alloy and observed that the strain hardening in the alloy decreases with increasing temperature. Asgari *et al.* [4] studied the dynamic compressive behaviours of AZ31, AZ61 and AZ91 magnesium alloys in the strain range from 1000s^{-1} to 1400s^{-1} at room temperature and found that flow stresses

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and ductility of the alloys increase with increasing strain rate. It was detected that the strain hardening and tensile strength increase while the ductility decreases with increasing aluminium contents in the magnesium alloys. Prakash *et al.* [5] studied the tensile behaviours of AZ41 magnesium alloy at different strain rates (0.0001-1150s^{-1}) and temperatures (25-200℃). Wan *et al.* [6] conducted high loading rates compressive experiments on split Hopkinson pressure bar (SHPB) to investigate the effects of strain rate and loading direction on the AZ31 magnesium alloy. Luo *et al.* [7] analyzed the mechanical behaviour of AZ81 magnesium alloy under compressive loads at different strain rates (0.001-5s^{-1}) and temperatures (200-400℃), and observed that flow stresses increase with increasing strain rates and decreasing temperatures. Wang *et al.* [8] conducted some hot (350-480℃) compression tests at different strain rates (0.001-10s^{-1}) on Gleeble 1500D thermo-mechanical simulator to study the mechanical behaviour of AE21 magnesium alloy and obtained that flow stress is sensitive to strain rates and temperatures. Compressive tests at elevated temperatures (250℃ to 450℃) were conducted by Changizian *et al.* [9] to investigate the flow behaviour of AZ81 magnesium alloy on Gotech AI-7000 LA 30 servo controlled electronic universal testing machine at different strain rates (0.003-0.3s^{-1}). The flow stresses were found to be positive sensitive to strain rates and obvious the flow stresses decreased with increasing temperatures. At lower strain rates, strain hardening appeared at lower temperatures while at higher strain rates, significant strain hardening observed at all temperatures. Sabokpa *et al.* [10] conducted hot compression tests on INSTRON 4208 to study the mechanical behaviour of AZ81 at strain rates from 0.0001s^{-1} to 0.01s^{-1} and temperatures from 250℃ to 400℃. Flow stresses predicted by ANN model were found in good agreement with the experimental results. Guo *et al.* [11] investigated the deformation behaviour of cast AM80 magnesium alloy under compressive loads in the wide range of strain rates ($3\times10^{-5}s^{-1}$ to $2.3\times10^{3}s^{-1}$) at room temperature. The flow stresses were found to be negative strain rate sensitive in the quasi-static strain rates from $3\times10^{-5}s^{-1}$ to $4\times10^{-1}s^{-1}$ while positive strain rate sensitive at higher strain rates from $4.5\times10^{2}s^{-1}$ to $2.3\times10^{3}s^{-1}$. Sani *et al.* [12] performed compressive tests on Zwick/Roell Z250 testing machine to study the flow behaviour of cast magnesium alloy (Al-Mg-Ca) in strain rate range from 0.001s^{-1} to 1s^{-1} and temperature range from 250℃ to 450℃. Flow behaviour of ZK60 magnesium alloy under compressive loads was investigated by Wu *et al.* [13] at different strain rates (0.1-50s^{-1}) and temperatures (25 - 400℃).

Bending behavior of ZEK100 magnesium alloy was studied by Aslam *et al.* [14] at different deformation rates (1, 5, 10, 20 and 50mm/min) along and perpendicular to the rolling direction. Flexural behaviours of AM20, AM50, AM60 and AZ31 (magnesium alloys), Al6061-T6 (aluminium alloy) and HA300 (1006), (mild steel) were investigated by Easton *et al.* [15]. It was reported that magnesium alloys have better energy absorption capacity and strength than other two materials. Hilditch *et al.* [16] studied the flexural behaviours of wrought magnesium alloy (AZ31) and aluminium alloys (Al6063-T6 and Al7075-T6) tubes in 3-point bending. It was observed that the peak load and energy absorption capacity for AZ31 is significantly larger than Al6063-T6 and smaller than Al7075-T6 on equal mass basis of specimens. The peak load and energy absorption capacity increase with increasing thickness of tubes and diameter of indenter. The peak load also increases with decreasing span length. This paper describes the compression and flexure behaviours of AZ41 magnesium alloy at different strain rates under room temperature 25℃.

2. Experiments

Commercially available AZ41 magnesium alloy sheets of thickness 4mm are used to prepare the specimens for compression and 3-point bending tests. The chemical composition (wt.%) of the alloy is, Mg: 94.81, Al: 3.991, Zn: 0.79, Mn: 0.32, Si: 0.012, Cu: 0.011 and Fe: 0.001. The cylindrical specimens of diameter 4mm and length 4mm are used for compression tests at different strain rates (0.0001-2900s^{-1}) whereas, 4mm thick, 10mm wide and 250mm long flat specimens are prepared for 3-point bending tests/flexure tests.

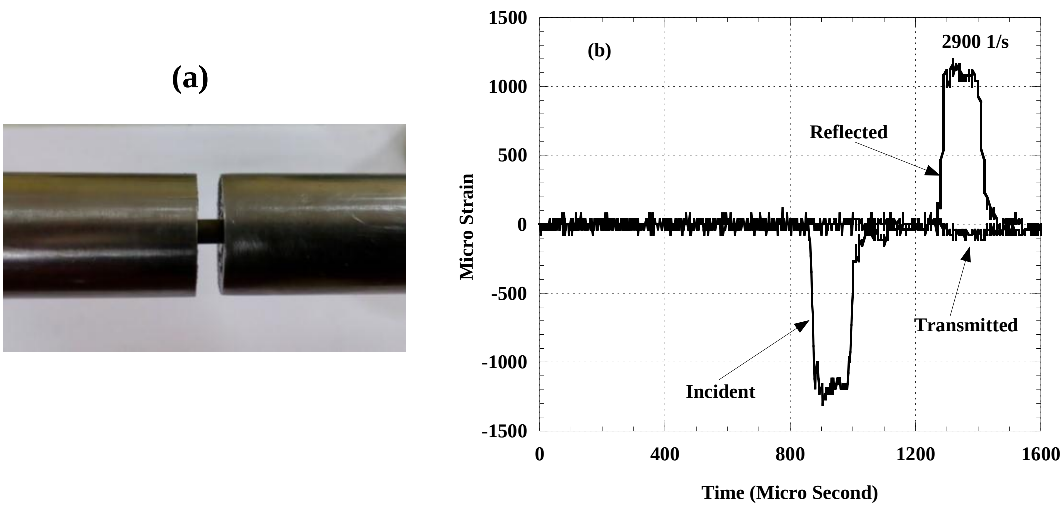

Fig. 1. Compression tests (a) specimen between the input and output bars and (b) signals obtained during compression tests at 2900s^{-1}.

The diameter of indenter and lower supports used in 3-point bending tests are 20mm and 50mm respectively. Quasi-static compression tests are performed on electromechanical universal testing machine (Zwick/Roell Z250) and high strain rate compression tests are conducted on split Hopkinson pressure bar (SHPB) at room temperature 25℃. The striker, incident and transmitter bars are of 20mm diameter while their lengths are 400mm, 2000mm and 1000mm respectively. Strain gauges are mounted on input and output bars at a distance of 500mm from their approaching ends. The cylindrical specimen is placed between the Hopkinson bars (input and output pressure bars) as shown in Fig. 1a. The signal obtained from SHPB during testing of a specimen at strain rate 2900s^{-1} under compressive loads is shown in Fig. 1b. For flexure loads, the true stress (σ_T) and true strain (ε_T) are calculated by using equation (1) from engineering stress (σ_s) and engineering strain (ε_s) whereas, for compressive loads, the true stress and true strain are calculated by using equation (2) (Hosford 17; Meyers and Chawla 18; Samantaray 19).

$$\sigma_T = \sigma_s(1+\varepsilon_s) \text{ and } \varepsilon_T = \ln(1+\varepsilon_s) \quad (1)$$

$$\sigma_T = \sigma_s(1-\varepsilon_s) \text{ and } \varepsilon_T = -\ln(1-\varepsilon_s) \quad (2)$$

3. Results and discussion

The experimental data of compression and 3-point bending tests obtained from different setups using suitable fixtures are analyzed and the results obtained are discussed. Three different specimens are tested at a particular loading rate and the mean value is presented. Yield stress is determined at 0.2% offset strain.

3.1 Compression behaviour

The engineering and true stress-strain curves [17-19] are compared at different strain rates (0.0001-2900s^{-1}) under compression in Fig.2a and Fig.2b respectively. The experimental results obtained under room temperature 25℃ are presented in Table 1 and can be compared with the available results (approx.) of existing literatures given in Table 2. Some deviations in obtained results as compared with the existing results are due to changed strain rates, temperatures, chemical compositions and heat treatment of specimens. It is observed that on increasing strain rate (0.0001-2500s^{-1}), the flow stress of AZ41 alloy increases i.e, the yield strength and compressive strength increase. At 2900s^{-1}, the flow stress is slightly decreased due to thermal softening which is caused by adiabatic heat transfer at high strain rate as obtained by Malik *et al.* [20] for ZK61 magnesium alloy. On increasing strain rate from 0.0001s^{-1} to 2500s^{-1}, the true yield strength increases by 136% while the true compressive strength of the alloy increases by

85%. With reference to $2500 s^{-1}$, the true yield strength and maximum compressive strength decreased by approx. 13% and 15% respectively at $2900 s^{-1}$. Thus, the alloy is found strain rate sensitive in the strain rate range from $0.0001 s^{-1}$ to $2500 s^{-1}$. In Table 2, Malik *et al.* [20] found that true yield stress and true maximum stress of ZK61 alloy increased by 42% and 30% respectively in the strain rate range $1000\text{-}3000 s^{-1}$ whereas decreased by 2% and 7% respectively in the strain rate range $3000\text{-}4000 s^{-1}$.

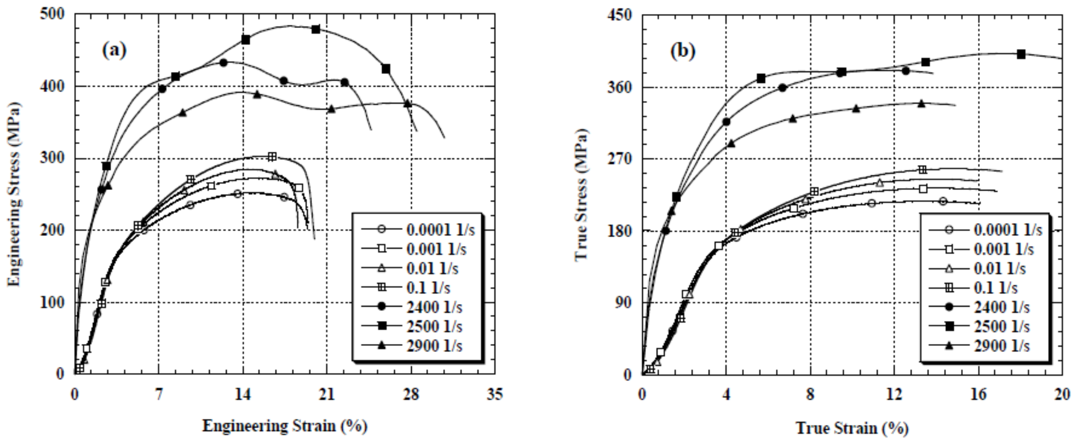

Fig. 2. Comparison of stress-strain curves under compressive loads (a) engineering stress-strain curves and (b) true stress-strain curves.

Table 1

Experimental results of compression tests at room temperature.

Strain Rate (s^{-1})	Engineering Stress-Strain Curves		Compression (%)	True Stress-Strain Curves	
	Yield Stress (MPa)	Maximum Compressive Strength (MPa)		Yield Stress (MPa)	Maximum Compressive Strength (MPa)
0.0001	151 ± 2	251 ± 3	19.5 ± 0.15	147 ± 2	214 ± 2
0.001	155 ± 2	270 ± 3	19.25 ± 0.25	150 ± 2	228 ± 3
0.01	158 ± 2	283 ± 3	18.5 ± 0.25	153 ± 2	241 ± 3
0.1	159 ± 2	300 ± 3	20 ± 0.3	155 ± 2	253 ± 3
2400	329 ± 3	433 ± 4	24.5 ± 0.3	316 ± 3	377 ± 4
2500	362 ± 2	483 ± 4	28.5 ± 0.3	347 ± 4	396 ± 5
2900	316 ± 3	391 ± 3	31 ± 0.4	301 ± 3	337 ± 3

The stress-strain curves in Fig. 2 look like as tensile curves as the test specimens fractured during compression tests [6, 10]. The compression in specimen increases with increasing high strain rate (2400-2900s^{-1}) while at low strain rates (0.0001-0.1s^{-1}), it remains almost constant [4, 10]. The engineering stress and strain rate versus time curves are presented in Fig. 3 which indicates that the strain rate during the plastic deformation of the alloy AZ41 is almost constant [21].

Table 2

Experimental results of compression tests available in existing literatures.

References	Materials	Strain-Rate (s^{-1})	Temperature (ºC)	True Yield Stress (MPa)	True Maximum Compressive Strength (MPa)
Cai *et al.* [1]	AZ41M	0.005-1	300	65-85	85-195
Ishikawa *et al.* [3]	AZ91	0.001-1000	Room Temperature	120-130	300-360
Sabokpa *et al.* [9]	AZ81	0.0001-0.01	250	80-110	110-195
Luo *et al.* [6]	AZ81	0.001-1	200	80-110	160-200
Wan *et al.* [5]	AZ31 (Annealed)	883-1686	Room Temperature	200-280	380-480
Asgari *et al.* [4]	AZ31	1000-1400	Room Temperature	50-80	240-380
	AZ61			60-90	250-390
	AZ91			70-110	300-400
Malik *et al.* [19]	ZK61	1000-3000	Room Temperature	190-270	310-404
		3000-4000		270-265	404-374

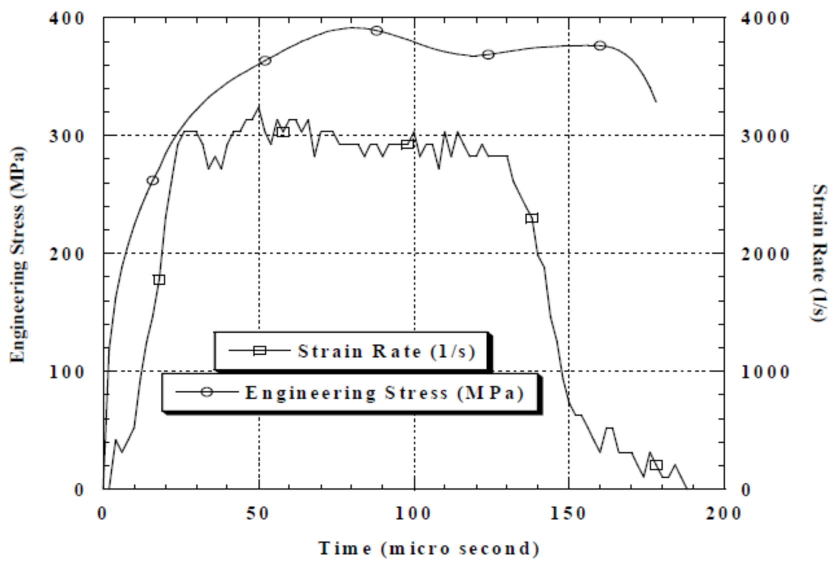

Fig. 3. Engineering stress and strain rate versus time curves.

3.2 Flexural behaviour

The engineering and true stress-strain curves are compared under flexural loads in Fig. 4a and Fig. 4b respectively at three different cross-head speeds (1, 10 and 100mm/min) for span length 120mm. The obtained flexural properties at room temperature 25°C are presented in Table 3 and can be compared with the available results (approx.) of existing literatures given in Table 4. Some deviations in obtained results as compared with the available results of existing literatures are due to changed dimensions of specimens, cross-head velocity, chemical compositions and heat treatment of specimens. It is found that the yield stress is slightly changed and almost insensitive whereas the maximum flexural strength is positive sensitive to cross-head speeds. When the speed increases from 1mm/min to 100mm/min, the engineering flexural strength increases by approx. 11% and the true flexural strength increases by approx. 12% as given in Table 3. Maier *et al.* [22] also observed that on increasing speed (1-10mm/min) in 3-point bending tests, the flexure yield strengths of Mg4Gd and Mg6Ag wires increased by approx. 5% and 4% whereas, their maximum flexural strength increased by approx. 11% and 3.5% respectively. There is no yielding instability in the alloy under flexural loads and the curve is convex upward.

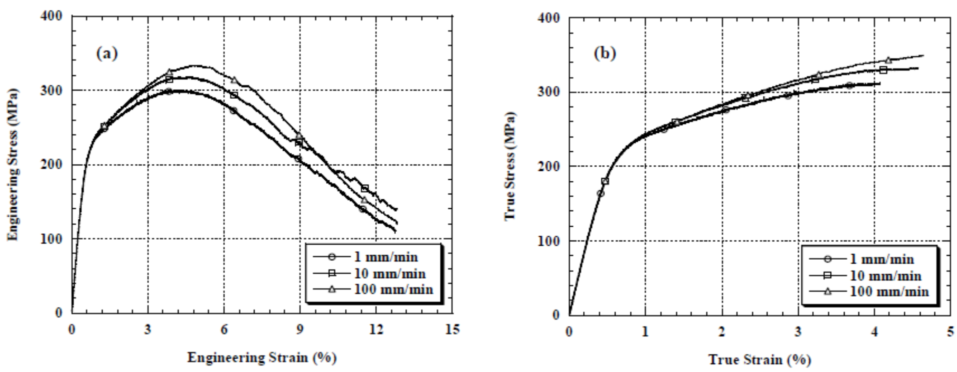

Fig. 4. Comparison of flexural stress-strain curves at different cross-head speeds for 120mm span length (a) engineering stress-strain curves and (b) true stress-strain curves.

The total elongation in each stress-strain curve corresponds to the 80 mm vertical displacement at mid span during 3-point bending. The engineering stress-strain curves for different span lengths (80, 120 and 160mm) and orientations (flat and transverse) at cross-head speed 1mm/min are compared respectively in Fig. 5a and Fig. 5b with deformed specimens. The flow stress under flexural loads decreases with increasing span length as obtained by Hilditch *et al.* [16] for AZ31 magnesium alloy tubes. In case of flat orientation of specimen, the alloy has slightly more yield strength and significantly less flexural strength compared to that for specimen in transverse orientation. The specimen of 120mm span length in transverse orientation fractured in approx. 36mm (corresponding to 15.22% elongation) vertical displacement due to flexural loads at mid span.

Table 3

Experimental results of flexure tests at different velocities, span lengths and orientations at room temperature.

Orientations	Velocity (mm/min)	Span Length (mm)	Engineering Stress-Strain Curves		Elongation (corresponding to 80mm vertical displacement) (%)	True Stress-Strain Curves	
			Yield Stress (MPa)	Maximum Flexural Strength (MPa)		Yield Stress (MPa)	Maximum Flexural Strength (MPa)
Flat (Loading along thickness)	1	120	217 ± 1	298 ± 3	12.8	218 ± 1	310 ± 2
	10		219 ± 2	317 ± 2	12.8	221 ± 2	331 ± 3
	100		220 ± 2	332 ± 3	12.8	222 ± 2	348 ± 3
	1	80	218 ± 2	554 ± 7	28.8	220 ± 2	616 ± 8
		160	209 ± 1	256 ± 2	7.2	210 ± 1	262 ± 2
Transverse (Loading along width)	1	120	205 ± 1	391 ± 2	15.22 (crack generated corresponding to 36mm)	206 ± 1	433 ± 3

Table 4

Experimental results of flexure tests available in existing literatures.

Reference	Materials	Span Length (mm)	Velocity (mm/min)	Temperature	Flexural Yield Stress (MPa)	Maximum Flexural Strength (MPa)
Aslam *et al.* [13]	ZEK 100	15	1-20	Room Temperature	296-306	550-590
Easton *et al.* [14]	AM20	90	5	Room Temperature	180	270
	AM50				220	320
	AM60				240	360
	AZ31				200	330
Maier *et al.* [21]	Mg4Gd (Annealed)	25	1-10	Room Temperature	400-420	720-800
	Mg6Ag (Annealed)				480-500	890-920

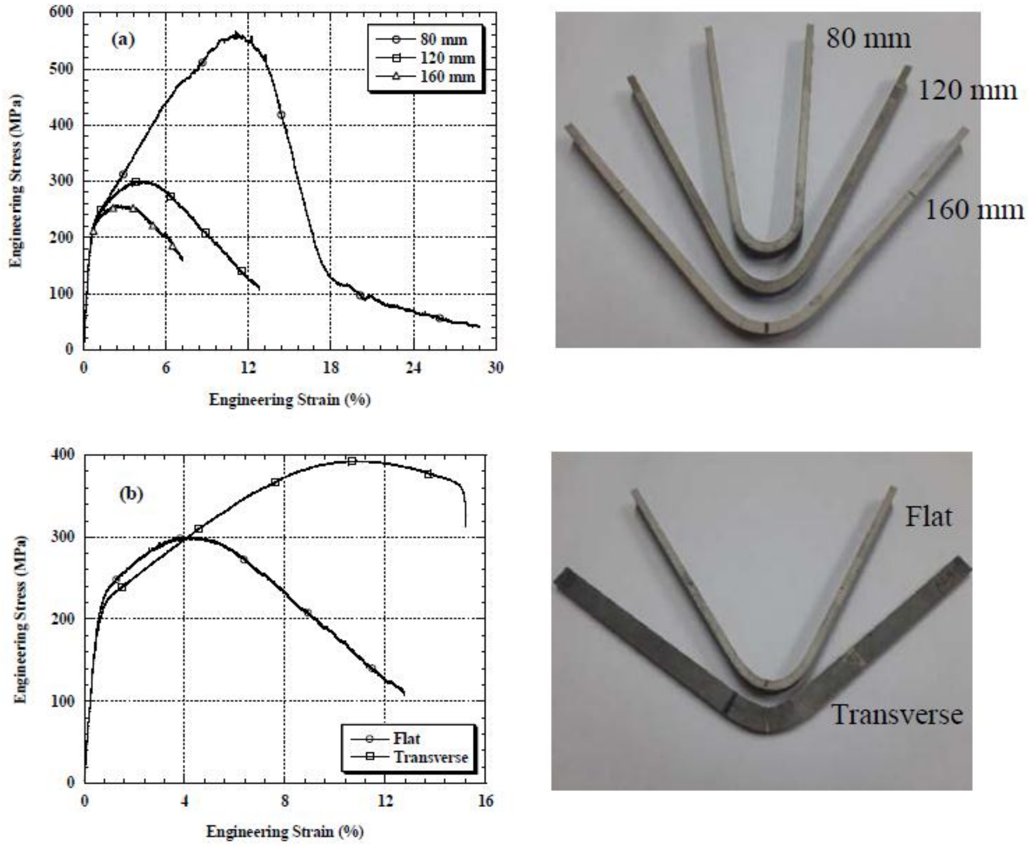

Fig. 5. Comparison of engineering stress-strain curves under 1mm/min cross-head speed with deformed specimens at different (a) span lengths and (b) orientations.

The engineering stress and vertical displacement at mid span versus flexural angle curves are shown in Fig. 6 for span length 120mm. It is found that the variation of vertical displacement and flexural angle is almost linear in low bending ($\leq 70^{\circ}$) of the specimen whereas in its high bending ($\geq 70^{\circ}$), the deformation becomes non-linear. The flexural stress for span length 120mm is maximum at flexural angle nearly 50.5°. For span lengths 80mm and 160mm, the flexural stresses are maximum at angles about 90.1° and 39.3° respectively. Therefore, the flexure strength increases on increasing the flexure angle as observed by Prakash *et al.* [23] for Al5052-H32 aluminium alloy.

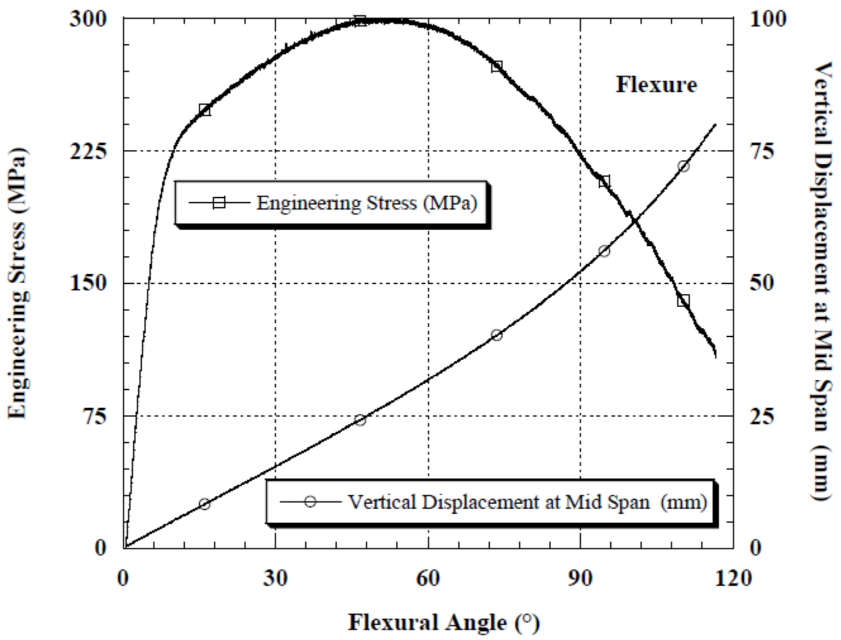

Fig. 6. Engineering stress and vertical displacement at mid span versus flexural angle curves.

4. Conclusions

The compressive behaviour of AZ41 magnesium alloy at strain rates from $0.0001s^{-1}$ to $2900s^{-1}$ and the flexural behaviour of the alloy at velocities from 1mm/min to 100mm/min for different span lengths and orientations are investigated. Following outcomes are obtained from the general observations.

1. The magnesium alloy AZ41 exhibits positive strain rate sensitivity in the range, $0.0001\text{-}2500s^{-1}$ under compressive loads. Dynamic softening appeared at strain rate $2900s^{-1}$.
2. True yield strength increases by 136% while true compressive strength of the alloy increases by 85% on increasing strain rate from $0.0001s^{-1}$ to $2500s^{-1}$. On increasing strain rate from $2500s^{-1}$ to $2900s^{-1}$, the true yield strength and compressive strength decreased by 13% and 15% respectively due to thermal softening.
3. The deformation (% compression) in the alloy increases with increasing strain rate ($2400\text{-}2900s^{-1}$) under dynamic compressive loads.

4. In 3-point bending tests/flexural tests, the flow stress increases with increasing cross-head speeds (1-100mm/min).
5. The flow stress of the alloy under flexural loads significantly increases with decreasing span length (80-160mm). The yield stress for flat orientation is higher while the ultimate (maximum) flexural stress is higher for transverse orientation of the specimen during 3-point bending.
6. In flat orientation no cracks found upto 80mm vertical displacement at mid span whereas the specimen got fractured at almost 36mm vertical displacement at mid span in transverse orientation under flexural loads.
7. Maximum flexural strengths for span lengths 80mm, 120mm and 160mm are obtained at flexural angles nearly 90.1°, 50.5° and 39.3° respectively.

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