

## EFFECT OF LOADING RATE ON FRACTURE BEHAVIOUR OF Mg-Al-Zn ALLOYS

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### Abstract

In recent years, magnesium alloys are widely used for automotive applications as structural components due to its lightweight property and high specific strength. In this regards, magnesium alloys are subjected to high velocity and impact loads during accident. Hence, understanding the impact and dynamic behaviours of magnesium alloys are essential. In this study, the effect of loading rates on the fracture behaviour of Mg-Al-Zn alloys was investigated using pre-cracked single-edge notched bending (SENB) specimens. Three-point bending tests were conducted at different loading rates of 5, 50 and 500 mm/min. The Mg-Al-Zn alloys that used in the present study were extruded AZ31 and AZ61 magnesium alloys. From the load-load line displacement results, both alloys exhibited nonlinear fracture behaviour. The maximum load ( $P_{max}$ ) of these two alloys increased with increasing loading rate. Comparing both alloys, AZ61 exhibited higher  $P_{max}$  than that of AZ31 due to the higher volume of  $\beta$ -phase and smaller grain size in AZ61. Fracture surface observation revealed that both alloys fractured in ductile manner with large scale yielding and high shear lips ratio at all loading rates.

Keywords: Loading rate, three-point bending, ductile, elastic-plastic fracture, Mg-Al-Zn alloys.

### Abstrak

Dalam tahun-tahun kebelakangan ini, aloi magnesium digunakan secara meluas untuk aplikasi automotif seperti komponen struktur kerana sifatnya yang ringan dan kekuatan tentu yang tinggi. Dengan ini, aloi magnesium akan dikenakan halaju dan hentaman beban yang tinggi semasa kemalangan. Oleh itu, memahami kesan hentaman dan sifat-sifat dinamik pada aloi magnesium adalah penting. Dalam kajian ini, kesan kadar pembebanan pada sifat patah aloi Mg-Al-Zn telah dikaji dengan menggunakan spesimen lentur satu takuk (SENB) dengan pra-retak. Ujian lenturan tiga-titik telah dijalankan pada kadar pembebanan yang berbeza iaitu 5, 50 dan 500 mm/min. Aloi Mg-Al-Zn yang digunakan dalam kajian ini adalah aloi magnesium AZ31 dan AZ61 tersemerit. Daripada keputusan beban-anjakan garis beban, kedua-dua aloi telah mempamerkan kelakuan patah tak linear. Beban maksimum ( $P_{max}$ ) kedua-dua aloi meningkat dengan peningkatan kadar pembebanan. Dengan membandingkan kedua-dua aloi, AZ61 mempamerkan  $P_{max}$  lebih tinggi daripada AZ31 disebabkan oleh jumlah fasa- $\beta$  yang lebih tinggi dan saiz ira yang lebih kecil pada AZ61. Pemerhatian permukaan patah mendedahkan bahawa kedua-dua aloi patah secara mulur dengan pengalihan berskala besar dan nisbah bibir ricih yang tinggi pada semua kadar pembebanan.

*Kata kunci:* Kadar pembebanan, lenturan tiga-titik, mulur, kegagalan elastik-plastik, aloi Mg-Al-Zn.

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## 1.0 INTRODUCTION

Magnesium alloys have been used as structural components in automotive application due to its low density and high specific strength. Besides that, machinability, castability, excellent damping capacity and recyclability are advantages of these alloys. These good properties significantly attracted automobile manufacturer to utilise magnesium alloys for replacing the conventional materials such as steel and aluminium. Generally, most popular magnesium alloys used for automotive application are AZ (Mg-Al-Zn) and AM (Mg-Al-Mn) series alloys. The reason was that these magnesium alloys provide the best combination of alloying element contents for better mechanical properties. Aluminium (Al) is one of common alloying element used in magnesium alloys [1,2]. Addition of aluminium with sufficient composition in magnesium corresponds to the formation of  $\beta$ -phase and reduce grain size for improving the strength and hardness of magnesium alloys [3,4]. Manufacturing processes are also very important parameters to be considered in selecting magnesium alloys for production of components in automobile. In previous studies, Sajuri reported the tensile strength of extruded and as-cast billet AZ91D were higher compared to the tensile strength of extruded and as-cast billet AZ61 [5]. Subsequently, Chamos *et al.* reported that tensile strength of rolled AZ61 was higher compared to the tensile strength of rolled AZ31 [6].

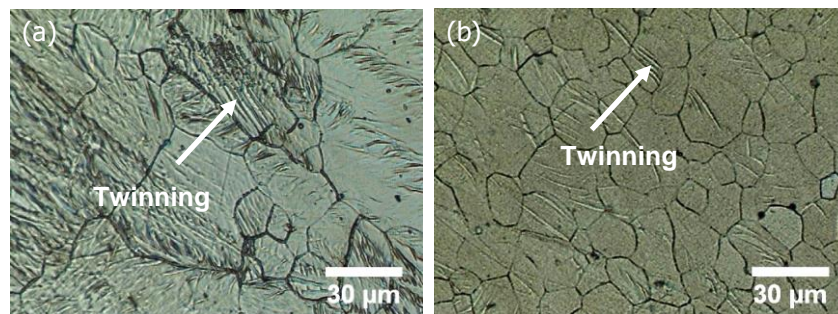
In automotive application, magnesium alloys are commonly subjected to high loading and impact responses during vehicle accident. At the same time, structures for automotive application are also subjected to fluctuating loads in real service. Under these circumstances, fatigue crack could be initiated and grow after continuously experiencing fluctuation of high loads on structures. However, the effect of high loading rate on fracture behaviour of AZ31 and AZ61 magnesium alloys is still unknown. Therefore, in this study the effect of loading rate on fracture behaviour of AZ31 and AZ61 magnesium alloys was investigated.

## 2.0 MATERIALS AND EXPERIMENTAL PROCEDURES

Extruded Mg-Al-Zn alloys of AZ31 and AZ61 were used in the present study. For both alloys, the chemical compositions are listed in Table 1 and the microstructures are shown in Figure 1. The average grain sizes of AZ31 and AZ61 were 24  $\mu\text{m}$  and 15  $\mu\text{m}$ , respectively. It is found that the grain size of AZ61 was significantly smaller than that of AZ31. Smaller grain size of AZ61 is believed due to the high aluminium content in the alloy. Consequently, twinning was also found in AZ31 and AZ61 magnesium alloys. Twinning formation is commonly resulted from extrusion process as mention by Barnett (2007).

**Table 1** Chemical compositions of extruded AZ31 and AZ61 magnesium alloys

	Al	Zn	Mn	Fe	Si	Cu	Ni	Mg
AZ31	3.35	0.88	0.33	0.003	0.01	<0.002	<0.002	Balance
AZ61	5.84	0.65	0.29	0.002	0.01	0.001	0.0003	Balance



**Figure 1** Microstructures of extruded (a) AZ31 and (b) AZ61 magnesium alloys

Tensile test was conducted at standard strain rate of  $1 \times 10^{-3} \text{ s}^{-1}$  for AZ31 and AZ61 magnesium alloys. Prior to conduct the three-point bending test, fatigue pre-crack was introduced to a single edge notch bending (SENB) specimen using a servo hydraulic fatigue testing machine. The SENB specimen was machined to  $10 \times 10 \times 50 \text{ mm}^3$  with a  $45^\circ$  V-notch of 1.75 mm in depth. The pre-cracking procedure was conducted under a three-point bending fatigue test configuration using a sinusoidal waveform of loading with the stress ratio (load ratio),  $R = P_{min}/P_{max}$  equal to 0.1 and frequency of 10 Hz. Travelling microscope was used to measure the length of crack growth. The fatigue pre-cracking was performed until the crack length ( $a$ ) reached 0.45 ~ 0.55 of specimen width ( $W$ ). The plastic zone size and stress intensity factor range ( $\Delta K$ ) were controlled to satisfy the requirements of the ASTM E399. The values of  $\Delta K$  was measured from the  $K_{max} - K_{min}$  in which the stress intensity factor  $K$  was calculated according to Equations (1) and (2).

$$K = \frac{3PS}{2BW^{\frac{3}{2}}} f(\alpha) \quad (1)$$

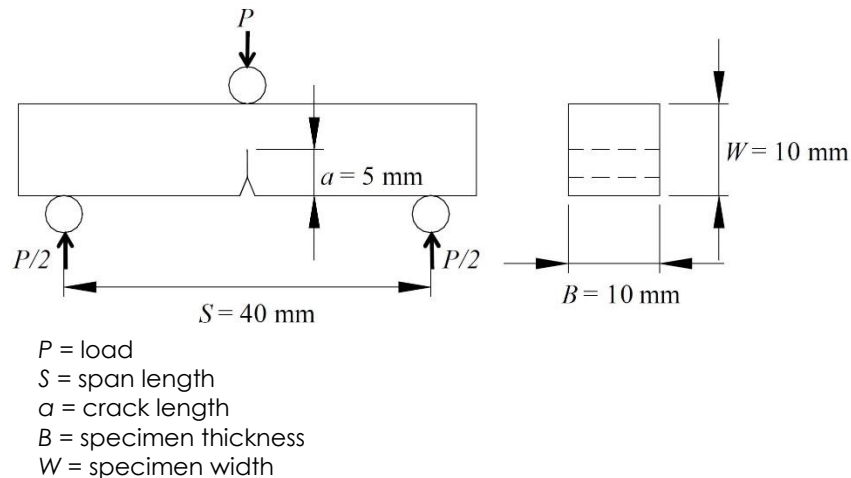


Figure 2 Three-point bending test

### 3.0 RESULTS AND DISCUSSION

Tensile properties of AZ31 and AZ61 magnesium alloys are listed in Table 2. Elongation of both alloys were more than 15% which indicating ductile behaviour of the alloys. The load-load line displacement curves of AZ31 and AZ61 magnesium alloys are shown in Figure 3. From these curves, both alloys exhibited nonlinear fracture behaviour at lower loading rate. However, the fracture behaviours of both alloys changed to almost linear elastic fracture behaviour up to the maximum load point at increasing loading rates. The maximum loads ( $P_{max}$ ) of these two alloys were also measured from the curves and listed in Table 3. It was found that the  $P_{max}$  of AZ61 and AZ31 magnesium

alloys were increased at increasing loading rate, while displacement at  $P_{max}$  of both alloys were decreased with increasing loading rate. Similar result was reported by Joyce where,  $P_{max}$  at high loading rate was higher than that of  $P_{max}$  at static loading rate for A106 steel [9]. In other report, Li *et al.* mentioned that twinning was increased at high loading rate [10]. Low plasticity behaviour was found for both alloys at higher loading rate due to shortest time to plastic deformation. Similar finding was reported by Feng *et al.* for AZ31B magnesium alloy [11]. In this case, fracture behaviour of Mg-Al-Zn alloys was loading rate dependent which believed due to the high twinning density and limited time of plastic deformation at high loading rate. Comparing both alloys, AZ61 exhibited

$$f(\alpha) = 1.93\alpha^2 - 3.07\alpha^2 + 14.53\alpha^2 - 25.11\alpha^2 + 25.8\alpha^2 \quad (2)$$

Here,  $P$  is the load,  $S$  the span length,  $B$  the specimen thickness,  $W$  the specimen width,  $a$  the crack length and  $\alpha = a/W$ . The geometrical factor  $f(\alpha)$  is defined as:

The  $\Delta K$  was constantly controlled at 3.5 to 4  $\text{MPa}\cdot\text{m}^{1/2}$  while, fatigue cracks growth were maintained at a rate of  $1 \times 10^{-8} \text{ m/cycle}$ . Consequently, three-point bending test as seen in Figure 2 was carried out in the lab air condition. Three different loading rates of 5, 50 and 500 mm/min were subjected to each specimen for this test. The three-point bending test was conducted using the universal testing machine (UTM) with load capacity of 20 kN.

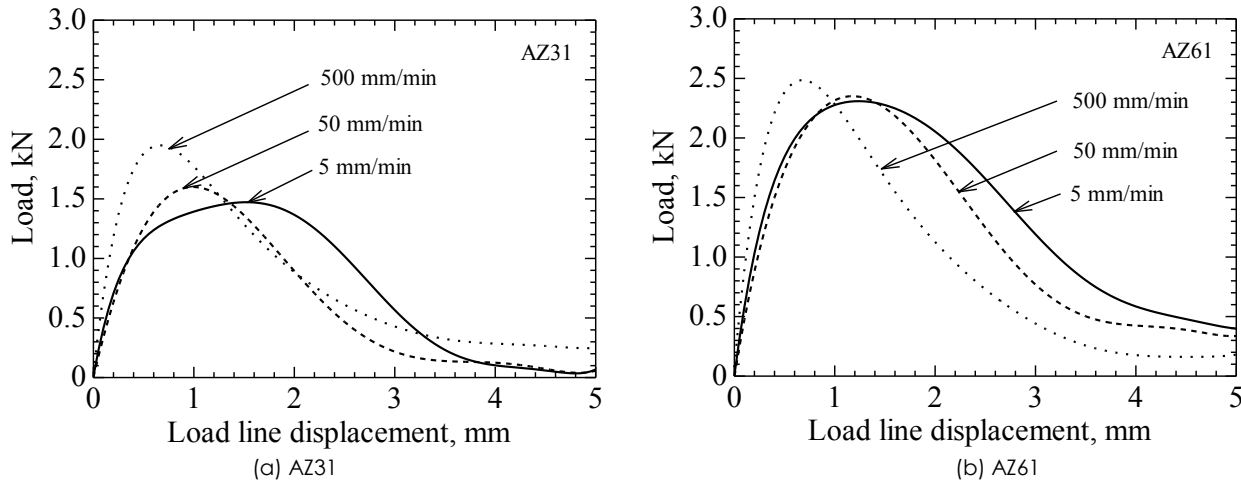
Fracture surface was captured using a stereo microscope to measure the shear lips ratio. Shear lips ratio was measured by dividing the average area of both sides shear lip by its specimen thickness. Detail fracture surface in secondary electron image was observed by scanning electron microscope (SEM) to identify the effect of loading rate on fracture behaviour.

higher  $P_{max}$  than that of AZ31 at all loading rates due to the higher aluminium content in AZ61 which corresponds to high volume of  $\beta$ -phase and smaller grain size in microstructure [3,4]. In general, material's resistance to fracture is significantly influenced by

dislocation pile-up and block at  $\beta$ -phase and large grain boundaries of smaller grain size. Further, twinning also provides high dislocation density by producing more barriers into grains [12,13].

**Table 2** Tensile properties of AZ31 and AZ61 magnesium alloys

	$\sigma_y$ [MPa]	$\sigma_{UTS}$ [MPa]	$\epsilon$ [%]
AZ31	191	240	16.2
AZ61	219	327	16.6



**Figure 3** Load-load line displacement curves of extruded Mg-Al-Zn alloys

**Table 3** Effect of loading rate on fracture properties for extruded Mg-Al-Zn alloys

	Loading rate [mm/min]	$P_{max}$ [kN]	Displacement at $P_{max}$ [mm]	Shear lips ratio [%]
AZ31	5	1.47	1.52	25
	50	1.60	1.02	22
	500	1.92	0.67	20
AZ61	5	2.31	1.23	30
	50	2.33	1.18	29
	500	2.50	0.67	29

### 3.1 Fracture Surface

Overview fracture surfaces of extruded Mg-Al-Zn alloys were shown in Figure 4. Regions of fatigue pre-crack and crack growth were significantly observed on fracture surface. Apart of that, formation of shear lips on fracture surface was also appeared. In this case, non-flat fracture was observed at the crack growth region. Determination of shear lips ratio is to characterise the extruded Mg-Al-Zn alloys either fractures in ductile or brittle behaviour. Small shear lip area with less than 10% corresponds to the brittle fracture [14] and fast crack growth [15]. Hence, the shear lips ratios of extruded Mg-Al-Zn alloys were summarized in Table 3. It found that the extruded Mg-Al-Zn alloys were significantly ductile materials where, shear lips ratio is more than 19%. Therefore, these alloys

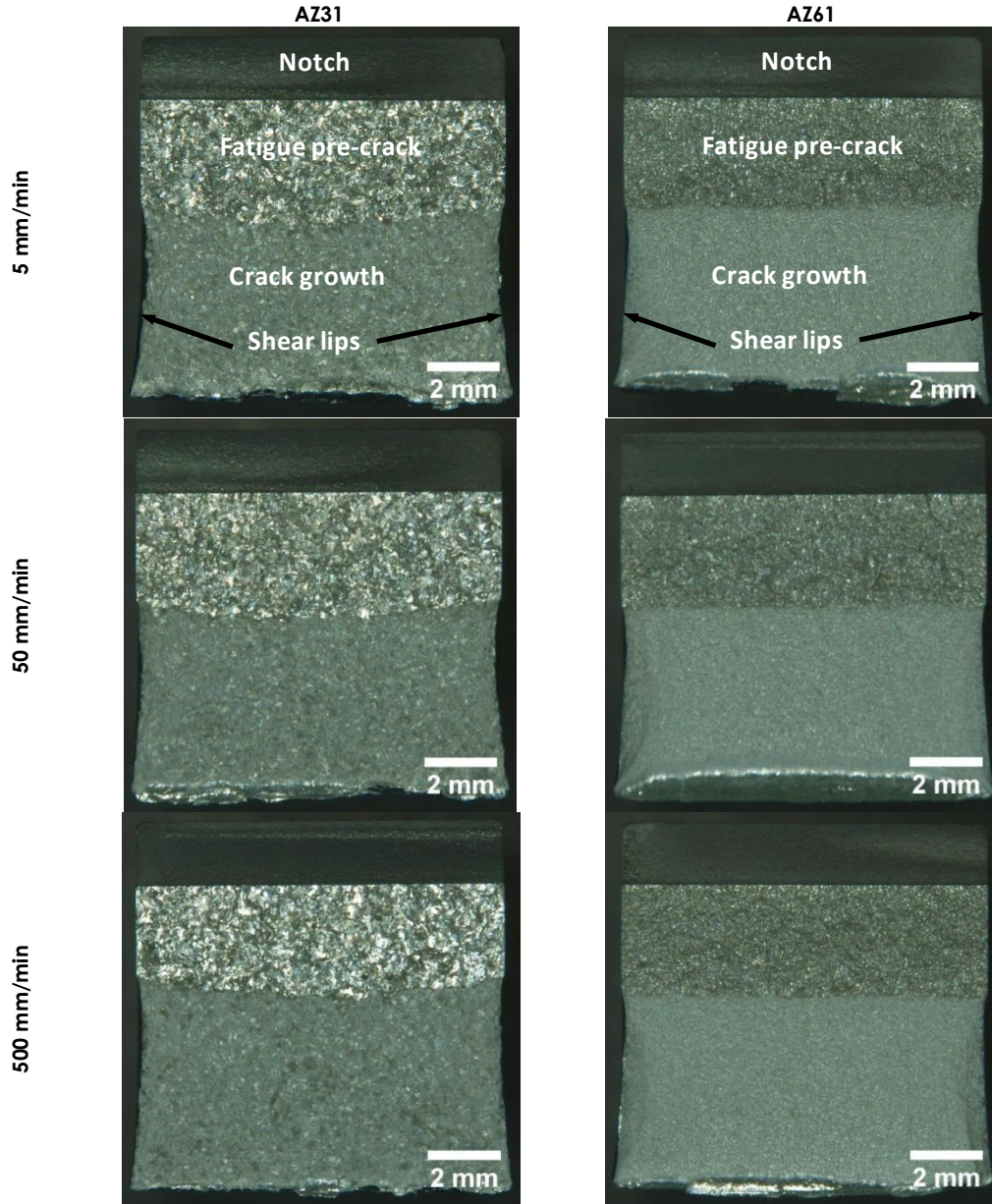
are corresponded to elastic-plastic fracture behaviour with large scale yielding even at high loading rates. Additionally, the specimen size that machined for Mg-Al-Zn alloys is relatively small specimen size which tends to fracture in plane stress condition with large formation of shear lips.

Figure 5 shows the fracture surface of AZ31 and AZ61 magnesium alloys that taken at magnification of 300 $\times$ . Region I indicates the fracture surface of fatigue pre-cracked, while Region II presents the fracture surface of crack growth. Meanwhile, 800 $\times$  magnifications of crack growth at three different loading rates for both alloys are shown in Figure 6.

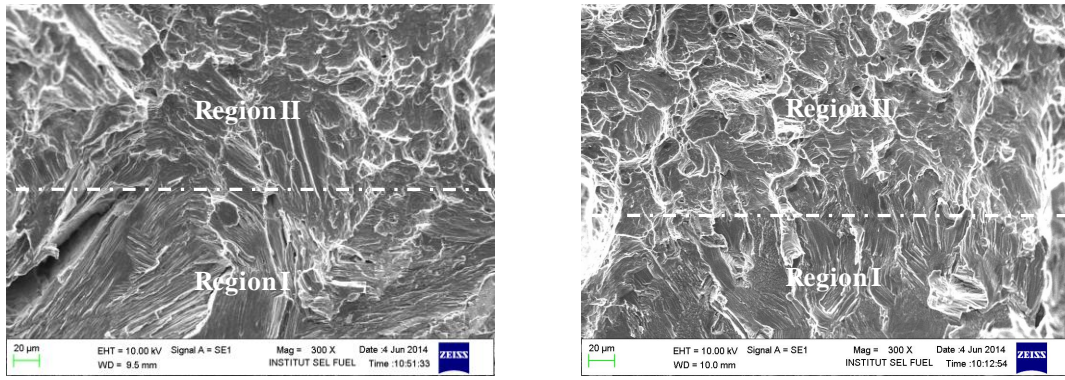
A marginally different of fracture pattern was found in both fracture surfaces. The AZ61 indicated slightly high ductile fracture behaviour than that of the AZ31 at low loading rates. It was indicated by the

evidence of dimples in the fracture surface of AZ61. AZ31 is also categorised as a ductile material based on the ductile fracture pattern observed. The fibrous fractures of these two alloys involved void nucleation and void coalescence before crack initiation and growth. However, ductile fracture pattern was clearly seen at low loading rates compared to the high

loading rate of both alloys. At high loading rates, quasi cleavage and tearing fractures were observed. It was found that ductility of AZ31 and AZ61 magnesium alloys were slightly decreased with increasing loading rates. However, these fracture surfaces still indicate ductile fracture pattern.



**Figure 4** Overview fracture surface of extruded Mg-Al-Zn alloys



(a) AZ31

(b) AZ61

Figure 5 Fracture surface of Mg-Al-Zn alloys

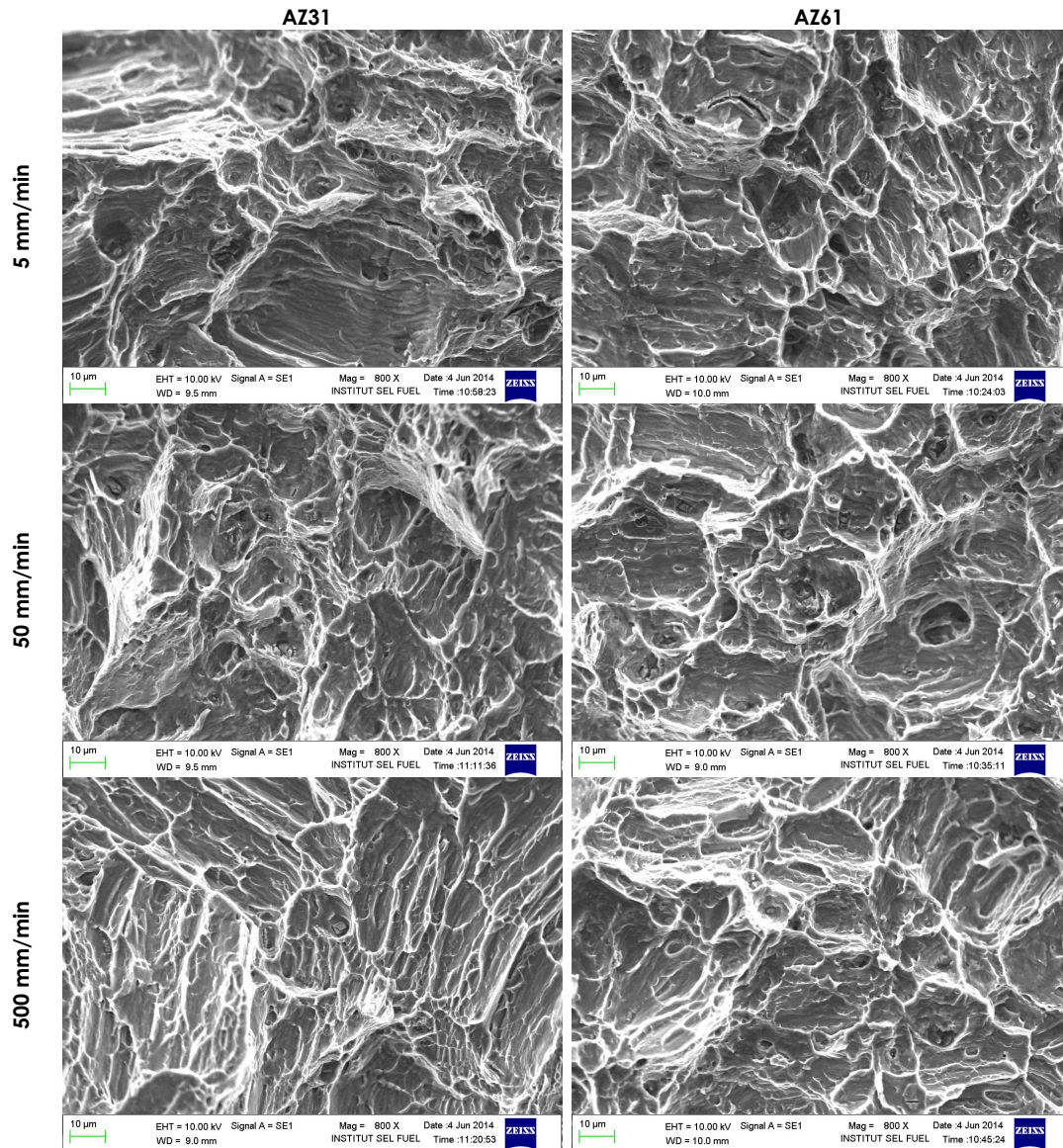


Figure 6 Fracture surfaces of crack growths at three different loading rates for Mg-Al-Zn alloys

## 4.0 CONCLUSION

Three-point bending test was conducted on pre-cracked SENB specimen at different loading rates for extruded Mg-Al-Zn alloys. It was found that both AZ31 and AZ61 magnesium alloys exhibited elastic-plastic fracture behaviour at low loading rate. However, fracture behaviours of both alloys changed to almost linear elastic fracture behaviour at increasing loading rates. The change was believed due to high dislocation density and shortest time of plastic deformation at high loading rate. Consequently,  $P_{max}$  of AZ61 was higher than that of AZ31 which attributed to high aluminium content in AZ61. The shear lips ratios of all specimens were larger than 19%. This result indicated that extruded Mg-Al-Zn alloys were ductile materials, and exhibited large scale yielding at the crack tip.

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