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EFFECT OF WIRE-EDM CUTTING ON FATIGUE STRENGTH OF AZ61 MAGNESIUM ALLOY

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ABSTRACT

Effect of wire electrical discharge machining (wire-EDM) cutting on fatigue strength of an extruded AZ61 magnesium alloy at room temperature was investigated. The surface condition of the samples after the wire-EDM cutting process is compared to the samples which have undergone careful polishing on their surfaces. A series of high cycle fatigue tests are performed on both the wire-EDM as-cut and polished samples with constant amplitude stress at the frequency of 10 Hz. Fractographic analyses were conducted on the tested samples to identify the mechanism of fatigue fracture. The finding show that the fatigue limit of wire-EDM as-cut specimen is 20 MPa lower as compared to smoothly polished specimens. Fatigue cracks are found to initiate and propagate to final failure from a cutting pit on the wire-EDM as-cut specimens.

Keywords: *Wire-EDM, cutting pit, stress intensity factor, fatigue, magnesium alloy*

1.0 INTRODUCTION

The use of magnesium alloys is being promoted in the automotive industry due to the demand of weight reduction of automobiles with the purpose of increasing efficiency and reducing fuel consumption. Comparatively the density of magnesium is found to be only two-third of aluminium and one-fourth of iron. Magnesium alloy is known to have the lowest density (about 1.74 g cm^{-3}) as compared to known alloys like other aluminium and titaniums alloys. It is a known fact that the magnesium alloys have been widely used in the aircraft as well as in the European automobile industry for some time started few decade ago [1,2]. However, at present the majority of engineering structural components for aerospace and automobile applications demand high fatigue properties. In general, fatigue cracks initiate at or close to the surfaces of the specimens. The occurrence

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of surface cracks in the duration of service may result in the failure of the structural components. Therefore, there is a huge interest in estimating the fatigue behaviour of the structural components made of magnesium alloys. Umehara et al. [3] and Yerokhin et al. [4] show that the various research works have been conducted on fatigue behaviour of magnesium alloys over the past decade. From these studies, it is has been established that surface roughness and stress concentration significantly influence the tensile strength and fatigue properties of magnesium alloys.

Cole and Sherman [5] stated that the magnesium alloys, normally exhibit relatively low mechanical properties as that compared to aluminium or other steel alloys because of their hexagonal closed pack structure (h.c.p.) that results in a limited deformation mechanism at room temperature. Based on these factors, there is still a necessity to improve mechanical properties, which can be carried out through designing new alloys, improving the heat treatment process and their conditions, etc. Therefore, the drive for several recent investigations has risen due to the necessity of having a better understanding of the behavior and properties of magnesium alloys. Russel et al. [6] and Srivatsan et al. [7] found that the mechanical properties of the magnesium alloys decrease with the presence of surface defects after the machining process.

Besides traditional machining such as turning, milling, grinding, etc., there are many advanced machining processes for non-traditional machining such as laser-beam machining, abrasive-jet machining, electrical discharge machining (EDM), etc. For the non-traditional processes, the advantages of EDM process are: firstly, it produces a stress and burr-free cutting, secondly it has efficient production capabilities and thirdly a reduction in cost with an excellent finishing [8].

The use of wire electrical discharge machining (wire-EDM) cutting in the production of forming tools and precision components for industries has been firmly established in recent years. Wire-EDM cutting is commonly used when low residual stresses are desired. Wire-EDM process introduces significantly low residual stress on the workpiece less than those that may be left if the same workpiece was obtained by conventional machining. The cutting mechanism in wire-EDM process is by bombarding the work piece with short but intense sparks of electricity. Each discharged spark leaves a tiny crater or pit in the workpiece.

Several studies on effects of machining defects of materials mechanical performance using a variety of machining processes have been reported. Arola and William [9] have examined the influence of machined surface profiles on fatigue life in terms of stress concentration for AISI 4130 steel. Jeelani and Collin [10] highlighted that the EDM cutting left surface defects cause slight reduction in fatigue life of an Inconel 718 alloy. Ramulu and Paul [11] confirm that the EDM spark dramatically increases the surface roughness and reduces the fatigue strength of the SiC/Al metal matrix composite. Even though there have been many studies conducted on the effects of wire-EDM cutting process on surface roughness and fatigue strength of structural materials, so far researchers have not used magnesium alloys as test material in any of their studies. However, due to the promising advantages of wire-EDM cutting process for production, the information and knowledge from studies on wire-EDM cutting effects on properties of magnesium alloys is very useful for engineers in producing structural components. In addition, since magnesium has h.c.p. crystal structure, its notch sensitivity is high compared to steel and aluminium alloys [12]. The formation of tiny creater or pit on the cutting surface of wire-EDM may act as a stress raiser and influence the mechanical performance of magnesium alloy. Therefore, the objective of this study is to investigate the effects of wire-EDM cutting process on surface finishing quality and fatigue strength of AZ61 magnesium alloy.

2.0 EXPERIMENTAL PROCEDURES

The material used in this study was an extruded AZ61 magnesium alloy. The chemical composition of the material is shown in Table 1. The AZ61 magnesium alloy is composed of 6% aluminium and 1% zinc as its major alloying element. Figure 1 shows the microstructure of the as-received material used. The average grain size was about 15 μm.

Two types of sample specimens i.e. the wire-EDM as-cut specimens and smooth specimens for comparison were prepared in order to investigate the effects of wire-EDM cutting on the fatigue performance of the AZ61 magnesium alloy. The wire-EDM as-cut samples were prepared by using a HITACHI H-CUT 203M20 EDM machine. The wire used was a 0.25 mm diameter copper wire. The cutting speed was 1.2 mm/min with cutting voltage of 3 V.

The wire-EDM as-cut specimens were then slightly polished using #1000 emery paper to de-burr and clean off the cutting debris without removing the wire-EDM cutting pits from the surface. Specimens for comparison were prepared by carefully polishing the specimens up to #1500 emery paper to obtain a smooth finished surface. The surface roughness of both specimens was measured and the parameters for roughness obtained are shown in Table 2.

Fatigue tests were conducted on a pneumatic fatigue testing machine with a maximum capacity of 14 kN. All fatigue tests were performed under a load control of sinusoidal waveform with a stress ratio R = 0.1 at a frequency of 10 Hz. The test was interrupted when the specimen does not fail up to 10^7 cycles. The fracture and specimen surfaces are studied under a scanning electron microscope (SEM). The tests were conducted in a laboratory environment at temperature of 25°C.

Table 1: The chemical compositions of AZ61 magnesium alloy (wt.%).

Al	Zn	Fe	Ni	Cu	Si	Mn	Mg
6.53	0.96	0.002	0.001	0.001	0.024	0.164	Bal.

Table 2: Surface roughness of AZ61 magnesium alloy.

Specimen	Average surface roughness R_a (μm)	Maximum surface roughness R_{max} (μm)
EDM as-cut specimen	0.158	2.09
Smooth specimen	0.121	1.57

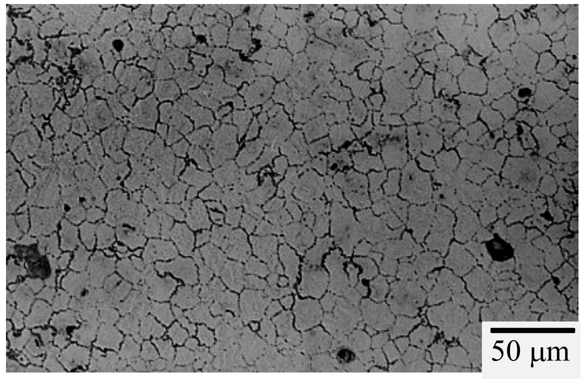
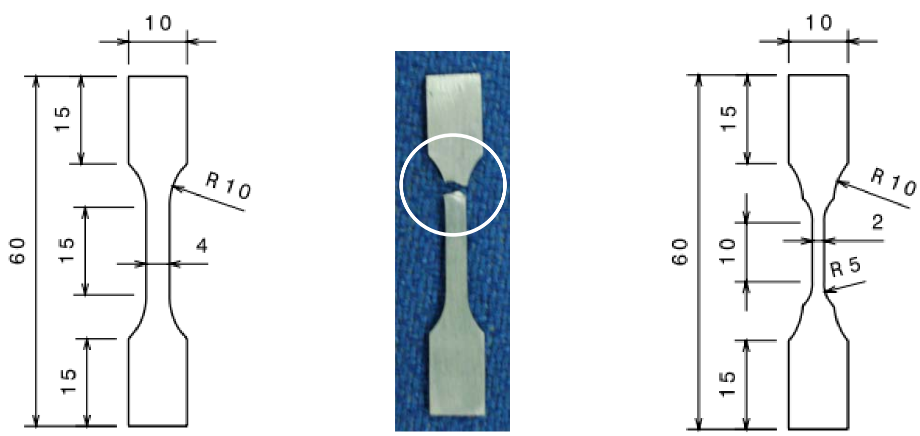


Figure 1 : Microstructure of used AZ61 magnesium alloy

Prior to the fatigue test, tensile test was conducted on the specimen to obtain yielding stress and ultimate tensile strength of the AZ61 magnesium alloy. The tensile test was performed at a fixed displacement rate of 1.2 mm/min.

Table 3: Mechanical properties of AZ61 magnesium alloy

Yield Stress σ_y (MPa)	**Ultimate Tensile Strength σ_{uts} (MPa)**	**Young Modulus, E (Gpa)**
249	**323**	**43**



(a) Original shape of specimen (b) Specimen failed at fillet (c) New shape of specimen

Figure 2 : Specimen for tensile and fatigue test

3.0 RESULTS AND DISCUSSION

Table 2 shows the surface roughness measurement results for wire-EDM as-cut and smooth samples. The average surface roughness R_a and maximum surface roughness R_{max} for wire-EDM sample were higher compared to the carefully polished specimen. The maximum surface roughness value for wire-EDM was 2.09 µm. However, after careful polishing the maximum surface roughness value reduced to 1.57 µm.

In the initial stage of fatigue test, a specimen shape with a thickness of 2 mm as shown in Figure 2(a) was used. The specimen gauge length was 15 mm and the smallest cross-sectional area of the specimen was 8 mm^2. During the test it is observed that fatigue crack initiates at the fillet part which is in contact with the test jig of the specimen. The stress at the contact point rises sharply and eventually it becomes the initiation point of the fatigue crack and the specimen fractures at the fillet position as shown in Figure 2(b).

In order to make sure that the fatigue test data obtained is valid, the fatigue specimen must fail from the smallest cross-sectional area. Therefore, new specimen shape was designed and fabricated to reduce the stress concentration at the fillet contact area, as shown in Figure 2(c). The new cross-sectional area is 4 mm^2. On using these new specimen specifications, all fatigued specimens were found to fail in the middle of the gauge area and therefore the tests are considered to be successfully conducted.

Table 3 shows the mechanical properties for the AZ61 magnesium alloy. The yield stress and the ultimate tensile strength obtained are 249 and 323 MPa, respectively. From the tensile properties obtained, 240 MPa (slightly lower than the yield stress) is chosen as the highest stress level to be used in the fatigue test.

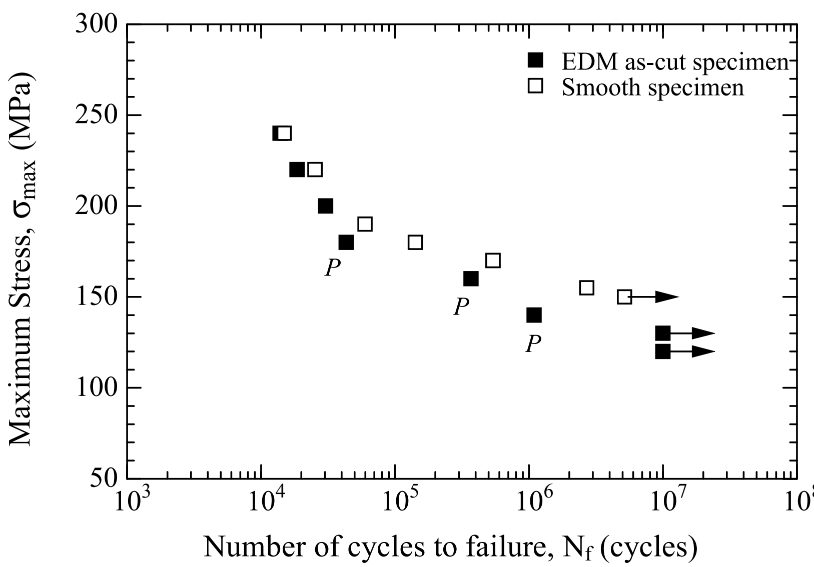


Figure 3: S-N curves of EDM as-cut and smooth samples

Figure 3 shows the relationship between the maximum applied stress and number of cycles to failure (S-N curve). The mark *P* represents the initiation of fatigue fracture from a cutting pit formed during the EDM wire cutting process. Arrow indicates the fatigue limit for EDM as-cut and smooth specimens. The S-N curve shows that when a higher or maximum stress is applied, the stress level bears no significant difference in fatigue strength for both specimens. However, at a maximum level that is lower than 160 MPa, fatigue strength of the EDM as-cut samples further decreases as compared to that of the smooth samples. The fatigue limit for the smooth samples is found to be 150 MPa. In comparison, the fatigue limit for EDM as-cut samples is higher at 130 MPa.

SEM fracture surface observation findings show that, there is a cutting pit at the crack nucleation site for EDM as-cut specimens which are fatigued at maximum stress levels lower than 160 MPa. However, there is no cutting pit observed on the fracture surface of the smooth specimens and the fatigue fracture origin are rather relatively flat as shown in Figure 4. It is speculated that a fatigue crack nucleated from the pit and propagated to final failure.

The size of the pit observed was around 20 μm. The size of the cutting pit is largely dependent on several cutting parameters such as electrical pulse on-off time and the peak current and voltage. The more the "On Time" of the electrical pulse, the larger the craters or pits, and result in the faster the cut and the rougher the cutting surface. Khan et al. [13] and Singh et al. [14] observed that the higher the peak current and voltage, the rougher the cutting surface. Therefore, to reduce the effect of cutting pit, it is important to control the cutting parameters of wire-EDM process.

Figure 5 shows an example of cutting pit observed on the fracture surface of EDM as-cut specimen. The dimension of the pit observed at the origin of fatigue crack site is then measured. The pit depth is about 25 μm. The pit size is assumed to be a semi-elliptical crack and with a stress intensity factor range ΔK-value which is estimated by the equation proposed by Newman and Raju [15];

$$(\Delta K)_{pit} = 1.12\Delta\sigma\sqrt{\pi D/Q} \tag{1}$$

$$Q = 1 + 1.464\left(\frac{D}{c}\right)^{1.65} \tag{2}$$

where $\Delta\sigma$ is the stress range, Q (=1.53) is the shape factor, c is the pit length and D is the cutting pit depth. For instance, the specimen fatigued at the maximum stress level of 140 MPa, the stress range value $\Delta\sigma$ = 126 MPa, and the pit size c and D are 46 and 25 μm, respectively. Therefore based on the above equations, the calculated ΔK value is 1.01 MPa$\sqrt{m}$. This value is slightly higher as compared to the threshold stress intensity factor value for AZ61 (ΔK_{th} = 0.87 MPa$\sqrt{m}$) that is defined by Sajuri et al. [16]. This indicated that existing cutting pit size on the specimen surface is large enough to become the fatigue crack initiation site for AZ61 magnesium alloy. Figure 6 shows some example of crack emanating in between two cutting pits. To avoid the cutting pit to be the crack initiator, the wire-EDM cutting parameters need to be improved to produce smoother surface.

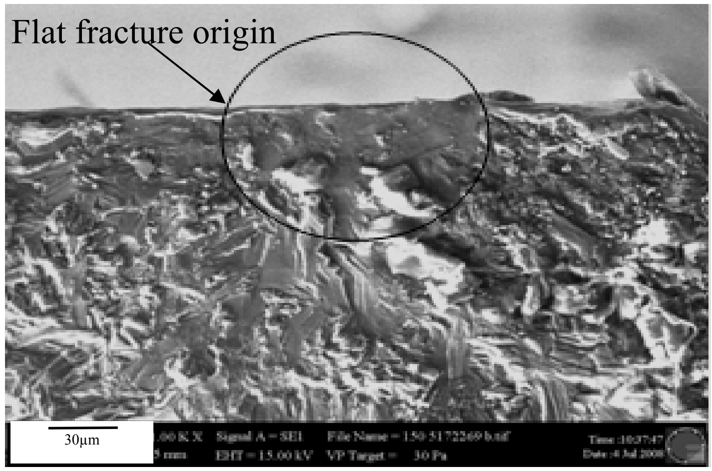


Figure 4 : Surface flat fracture originating for a smooth specimen (σ_{max}=150 MPa)

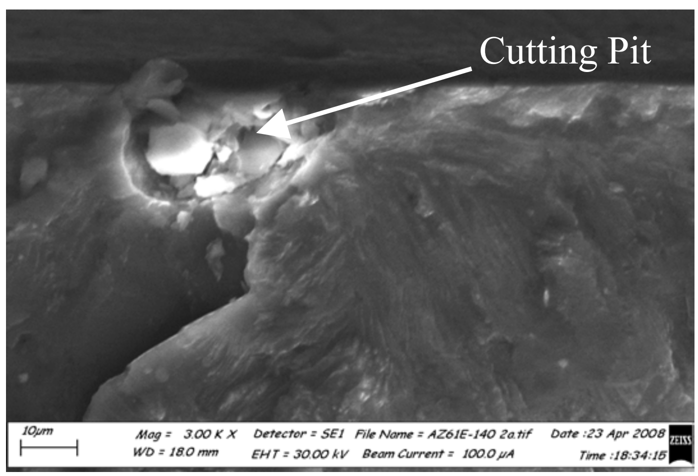


Figure 5 : Surface fracture of specimen machined by EDM as-cut (σ_{max}=140 Mpa)

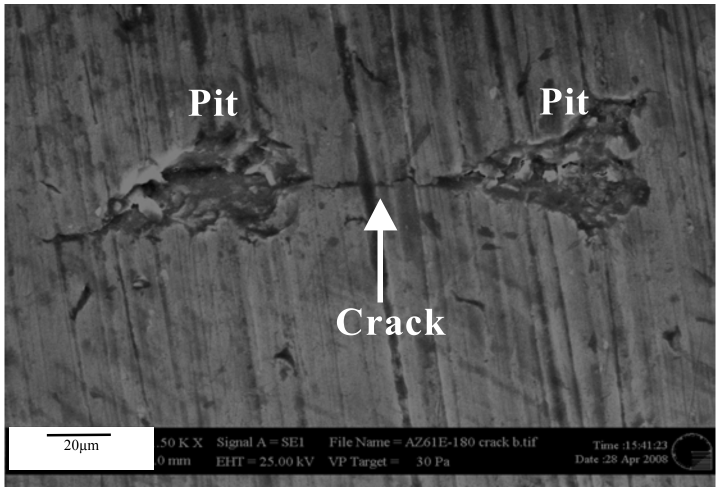


Figure 6 : Crack emanating from cutting pits observed on specimen surface of EDM as-cut sample (σ_{max}=180 MPa)

4.0 CONCLUSION

Experimental investigation on the effect of wire-EDM cutting to the fatigue properties of AZ61 magnesium alloy is carried out. Based on the finding the following conclusions are made:

i. The fatigue limit of wire-EDM cutting specimen is 20 MPa lower as compared to the fatigue limit of the smooth specimens.
ii. Fatigue crack initiates from a cutting pit for the wire-EDM cutting specimen and propagates to final failure.
iii. The stress intensity factor value of the cutting pit for fatigue crack initiation was slightly higher than the threshold value stress intensity factor of AZ61 magnesium alloy.
iv. Wire-EDM cutting parameters significantly affect the surface quality of AZ61 magnesium alloy.

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