Effect of Wire EDM on Microstructure and Fracture Toughness of 7075-T6511 Aluminum Alloy

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Abstract - **This paper reports on an investigation conducted to establish the influence of Wire Electrical Discharge Machining (WEDM) on the fracture toughness of aluminum 7075-T6511. The main objective was to determine if WEDM can be used to introduce a pre-crack into a compact tension specimen instead of the ASTM E-1820-11 specified fatigue pre-crack method. Fracture tests were conducted on four specimens which were pre-cracked using the WEDM technique. The rest of the fracture toughness evaluation followed the ASTM E-1820-11 guidelines. Results obtained from the experimental data were found to be inconsistent with the theoretical expectations. The fracture toughness was found to be significantly dependent on the effect of the WEDM on the material. The WEDM introduced a Heat Affected Zone (HAZ) on the surface of the pre-crack which modifies the fracture behavior of the material. It was concluded that WEDM is not a viable alternative to create a pre-crack in a compact tension specimen to perform fracture toughness testing of aluminum 7075-T6511.**

Key words: EDM, Compact tension specimen, Fracture toughness, 7075-T6511 aluminum alloy, microstructure, Wire EDM

I. INTRODUCTION

Aluminum alloys offer attractive strength-to-weight ratios especially when compared to other structural materials such as steels. Aluminum is manufactured in many different alloys and heat treatments such as 2014-T6, 7075-T6, and 7079-T6 [1]. They have therefore found extensive use in many applications ranging from automotive to aerospace. In addition, aluminum alloys have good corrosion resistance, formability and machinability. They can therefore be made into many components of different sizes ranging from screws to aircraft wing sections.

7075 T6511 aluminum alloy is a special heat temper grade of the 7075 alloy. It is the workhorse alloy for high performance applications. Its main alloying element is zinc. It has good fatigue resistance and was first introduced in automotive applications in 1943 [2]. Since then, it has become a key material in the manufacture of aerospace components including fuselages, wing spurs, landing gear components and many others. Its strength and light weight has also attracted application in such areas as rock climbing equipment and bicycle components.

As a high performance material, new ways are always being developed to produce 7075-T6511 components more cost effectively. This includes power metallurgy and special castings [3] to name just a few. As a result fatigue and fracture [4] tests are always required to assess the mechanical performance of materials and components in service. One way of reducing the time and cost of conducting fracture toughness tests is to use wire electrical discharge machining (WEDM) to induce a crack into the compact tension (CT) specimen. The recommended pre-cracking method according to ASTM E-1820-11 guidelines is to use fatigue cycling [5]. Fatigue cycling is a time consuming and expensive procedure. The aim of this work is therefore to investigate the feasibility of using WEDM to pre-crack CT specimen during fracture toughness testing of 7075-T6511 aluminium alloy.

WEDM is a variation of the electrical discharge machining (EDM) process [6], [7], [8]. It uses an electrical discharge between an electrode and an anode in the presence of a dielectric (typically deionised water) to erode a material. Fig. 1 shows a schematic of the process.

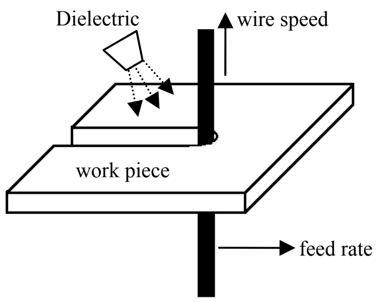

Fig. 1: Schematic of the Wire EDM process

The high temperatures involved in EDM and WEDM may alter the surface and sub-surface integrity of the material and hence affect the fracture performance of the material.

II. EXPERIMENTAL DESCRIPTION

A. *Aim of the Experiments*

The aim for the experiment was to determine the fracture toughness of 7075-T6511 aluminium alloy which had been pre-cracked using WEDM. In addition, the effect of the WEDM process on the microstructure of the material is also evaluated.

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B. Materials

Aluminium 7075-T6511 alloy in round bar form was supplied by DEM Manufacturing (Pvt) Ltd. [9], Pretoria, South Africa. The chemical composition of the material as presented in the manufacturer's certificate is shown in Table I.

TABLE I
COMPOSITION OF 7075 T6511 AS SUPPLIED [9]

Elem.	Wt. %	Elem.	Wt. %	Elem.	Wt. %
Al	87.1 - 91.4	Mg	2.1 - 2.9	Si	Max 0.4
Cr	0.18 - 0.28	Mn	Max 0.3	Ti	Max 0.2
Cu	1.2 - 2	Other, each	Max 0.05	Zn	5.1 - 6.1
Fe	Max 0.5	Other, each	Max 0.15	-	-

The mechanical properties of the same material as supplied by the manufacturer are given in Table II.

TABLE II
MECHANICAL PROPERTIES OF 7075 T6511 AS SUPPLIED [9]

Property	Value	Comment
Ultimate Tensile Strength	572 MPa	AA; Typical
Tensile Yield Strength	503 MPa	AA; Typical
Fatigue Strength	159 MPa	AA; 500,000,000 cycles completely reversed stress; RR Moore machine / specimen
Fracture Toughness	20 MPa-m½	K(IC) in S-L Direction
Fracture Toughness	25 MPa-m½	K(IC) in T-L Direction
Fracture Toughness	29 MPa-m½	K(IC) in L-T Direction

C. Specimen Design and Manufacture

The specimen geometry was designed in accordance to ASTM E-1820-11 standard [5]. The critical thickness was calculated to be 10 mm, therefore any thickness above this can be used to measure plane strain fracture toughness. A thickness of 20 mm was selected based on the clevis opening available on the testing machine. The width and other dimensions of the specimen are given in Fig. 2.

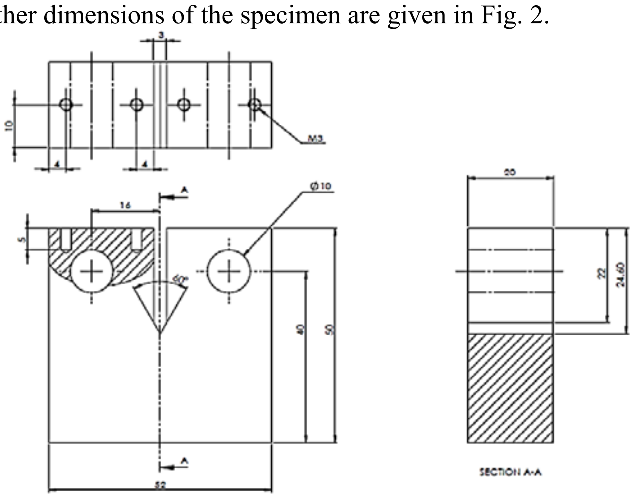
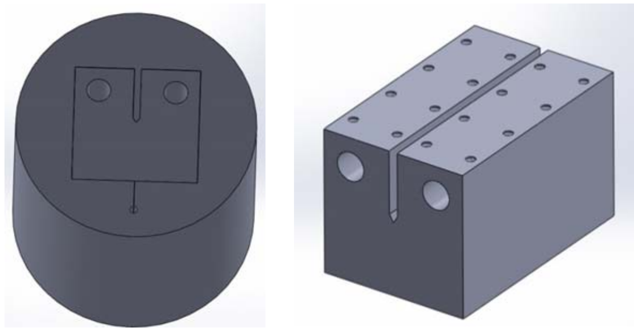


Fig. 2: Compact tension specimen geometry [5]

The specimen were manufactured by GEM Manufacturing (Pvt) Ltd. using a Xenon Actspark WEDM machine (see Fig. 3). Deionized water was used as the dielectric. The specimen outline was cut using a 250 µm tungsten coated brass wire while the pre-crack was cut using a 100 µm tungsten coated brass wire.

(a) (b)
Fig. 3: (a) Xenon Actspark WEDM (b) Clamping table

The outline of the compact tension specimen produced after the WEDM using a 250 µm wire is shown in Fig. 4. The block is then WEDM pre-cracked using a 100 µm wire followed by slicing into CT specimen size.



(a) (b)
Fig. 4: (a) Outline of brass wire cut, (b) Specimen after outline cut

D. Equipment

Fracture tests were conducted using a 100 kN Instron 1195 tensile testing machine that was controlled using Bluehill 2 software. Fig. 5 shows the Instron machine and the clevis used to mount the specimen.

(a) (b)
Fig. 5: (a) Instron 1195 tensile testing machine (b) specimen mounting clevis

Fracture surface and microstructure examination was conducted using an optical microscope.

E. Testing Procedure

Prior to mounting onto the testing machine clevis, extension brackets are mounted to each specimen to provide extensometer grips. The specimens are then mounted onto the machine and an extensometer attached. The specimen is then loaded under displacement control at a rate of 0.4 mm/min until the maximum load is reached or when pop-in

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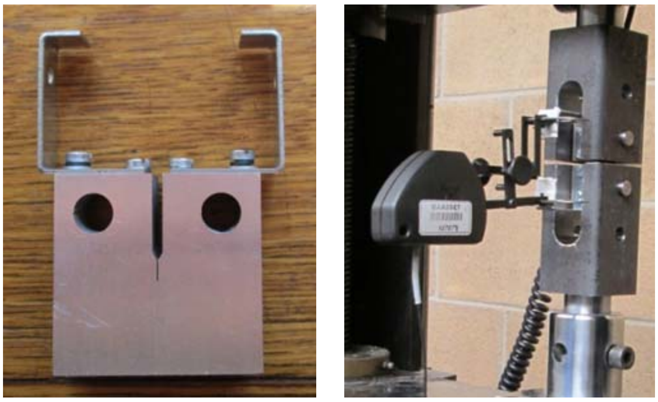
is heard. During loading, the displacement and load are monitored and recorded. The specimen is then un-mounted, heat tinted if possible, soaked in liquid nitrogen and remounted on the machine and loaded to complete fracture. The final configuration of the specimen showing the extension brackets is shown in Fig. 6(a). Fig. 6(b) shows the specimen mounted in the machine clevis together with the extensometer.



(a) (b)

Fig. 6: (a) Prepared CT specimen (b) Mounted in clevis with extensometer

III. RESULTS

A. Load Displacement Response

The load displacement response for three of the specimens is shown in Fig. 7. One of the specimens underwent premature failure and hence is not included in the presented results. The specimen load displacement responses follow similar behavior albeit with significantly different maximum loads. This behavior was unexpected.

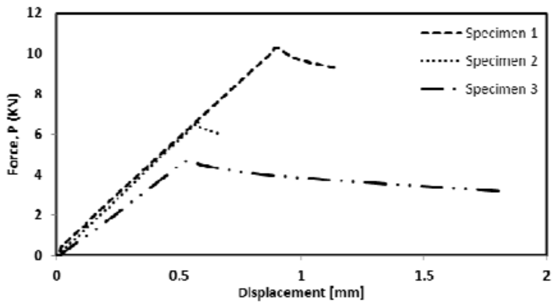


Fig. 7. Load-displacement responses for the tested CT specimens

The actual fracture loads experienced by each specimen are then extracted for computing the fracture toughness in accordance to the ASTM E-1820-11 procedure. These forces are shown in Table II together with the average and theoretically expected value.

TABLE III
MAXIMUM FRACTURE LOADS

Test Specimen	Fracture Load, P_{MAX} [kN]
Specimen 1	10.27
Specimen 2	6.61
Specimen 3	4.67
Average	**7.19**
Theoretical	**21.52**

For closer analysis of the response behavior, the conditional plane strain fracture load is determined by drawing a 95% secant line on the force versus displacement graph, this is illustrated in Fig. 8 for specimen 1. The point where the two lines intersect is determined and expressed as P5. A conditional fracture load P_Q is determined from the force versus displacement graph. P_Q depends on which principal type the response satisfies. In this case type III is satisfied, hence P_Q is equal to P_{MAX}, the maximum fracture load recorded. This conditional fracture load is used to calculate the plane strain fracture toughness. The details of this procedure are discussed in ASTM E-1820-11 [5].

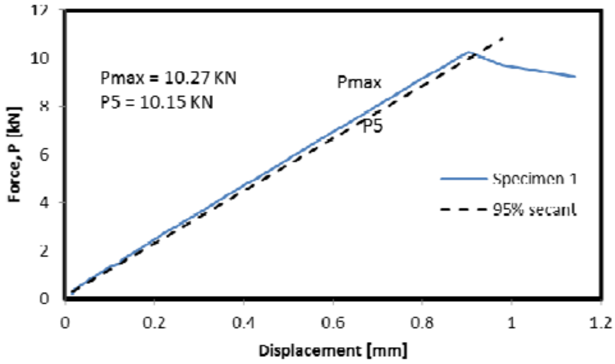


Fig. 8: Determination of the conditional fracture load for specimen 1

B. Fracture Toughness Results

The resulting fracture toughness values are compared in Fig. 9. Also shown in Fig. 9 are the average fracture toughness value of 15.99 MPa-m$^{0.5}$ and the expected theoretical value (according to literature) of 24.5 MPa-m$^{0.5}$. There is therefore a significant discrepancy (35%) between the value reported in literature and that obtained in this work.

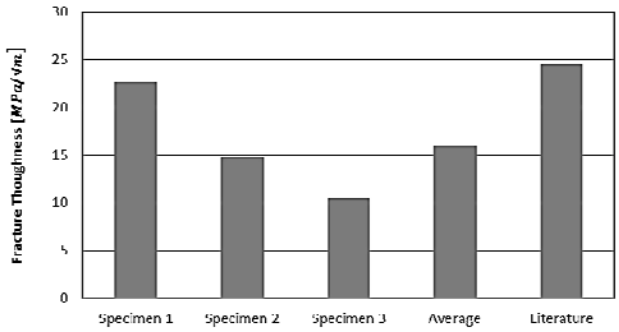


Fig. 9: Fracture toughness results for the tested specimens

C. Crack Tip Opening Displacement (CTOD)

A comparison is also made between the physically computed crack tip opening displacement (CTOD) (by similar triangles from measured displacements) and that obtained through the computed J-integral. CTOD is an indicator of the level of plastic activity in the crack tip region. Low CTOP reflects predominant elastic behavior while large CTOD is accompanied by significant plastic deformation in the crack tip zone. The procedure for determining the J-integral and crack tip opening displacement is also detailed in ASTM E-1820-11. The results are presented in Fig. 10.

The close relationship between the physical CTOD and that obtained from J-integral for specimen 1 may be an indication of the predominance of plastic deformation. This might explain the high toughness value recorded for specimen 1 when compared with the other specimens. This

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was also in closer agreement with the CTOD determined from the J-integral reported in literature. The rest of the specimens exhibit CTOD values of almost 50% of the theoretical values.

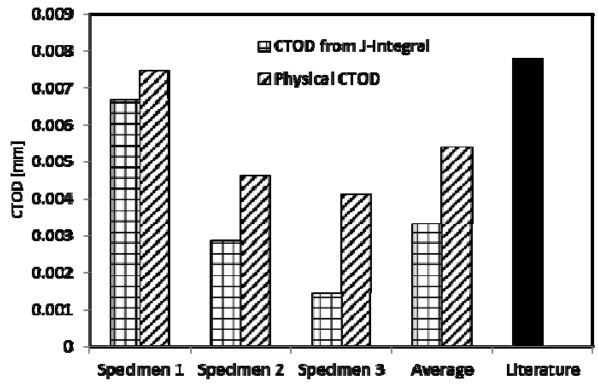
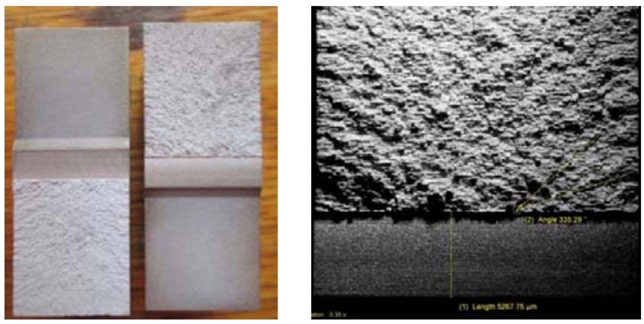


Fig. 10: Comparison of physical CTOD and CTOD from J-integral

D. Fracture Surface and Microstructure

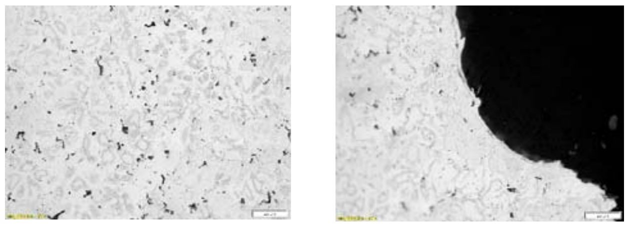
The fracture surfaces of all specimens displayed brittle fracture as shown on Fig. 11. The pictures show the global brittle fracture exhibited by the largely flat fracture surface (Fig. 11(a)). The lack of significant shear lips proves that the fracture was largely plane strain with insignificant plane stress. This confirms the validity of the obtained fracture toughness. The chevron marks showing the crack initiation zones and the fast fracture directions are clearly seen in Fig. 11(b).



(a) (b)

Fig. 11: Fractured surfaces for specimen 1(a) global (b) close up

An examination of the microstructure shows that the WEDM process had an effect on the microstructure of the 7075 T6511 as shown in Figure 12.



(a) (b)

Fig. 12: Specimen 1 microstructure (a) Parent material (b) WEDM edge

The WEDM surface has a thin layer of oxide that can serve as a source of crack initiation. In addition, grains on the WEDM surface appear smaller than the parent material. This is evidence of the existence of a heat affected zone (HAZ). This would suggest a significant change of material properties that may affect the fracture behavior of the material.

IV. Conclusions

The fracture toughness of aluminum 7075-T6511 was experimentally determined using CT specimen manufactured using WEDM. WEDM was also used to create the pre-crack of the specimens. This was a deviation from the ASTM E-1820-11 guidelines. The recommended pre-cracking procedure is to use fatigue pre-cracking. Based on the results obtained, the following conclusions can be made:

1. The average K_{IC} value obtained during the experiment was 15.99 MPa /√m, which is 35% lower than that reported in literature.
2. The WEDM pre-cracking had an effect on the fracture behavior of 7075-T6511 aluminum alloy. This differs from the findings of Madyira and Akinlabi [10] who found no effect of WEDM on the fracture behavior of Ti6Al4V.
3. WEDM with wire size of 100 μm cannot be used to pre-crack CT specimen in fracture toughness testing of 7075-T6511.
4. The average J-Integral/ strain energy release rate obtained was 3186.96 J/m^2. This value is more than half of the critical J-Integral value. Thus a much lower strain energy release rate was needed to propagate the pre-crack.
5. The average CTOD obtained during the experiment was 0.00540 mm, at a CTOA of 40.63°.
6. The macroscopic analysis of the fractured surfaces indicated plane strain and brittle fracture failure modes. This was in line with the thickness of the specimen that was twice the computed critical thickness.
7. WEDM introduced a HAZ on the surface of the material which was more pronounced in the crack tip region.

It is therefore recommended that future work be conducted using smaller wire diameter during the pre-cracking of the specimen using WEDM. More investigations are also required to understand the effect of the WEDM process parameters such as current and wire feed rate on the surface condition of the WEDM'ed surface.

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