Effects Of Wire Electrical Discharge Machining On Fracture Toughness Of Grade 5 Titanium Alloy

Daniel M. Madyira and Esther T. Akinlabi, *Member, IAENG*

Abstract— **Grade 5 titanium (Ti6Al4V) is considered as the workhorse material when it comes to automotive and aerospace applications. It is widely referred to as an aerospace alloy and is relatively a new engineering material. The main attraction of this material is its high strength to weight ratio when compared to such common engineering materials such as steel and aluminum alloys. One of the major challenges in the use of this aerospace material is its machinability. Its high strength which is maintained at elevated temperatures, low thermal conductivity, low elastic modulus and high reactivity with oxygen is a perfect recipe for machining challenges. This leads to high tool wear and long production times. Such challenges are sometimes overcome by electrical discharge machining (EDM). Given that titanium is usually applied to mission critical components (gears, shafts, wing sections), it is important to understand the possible effect of wire EDM on their structural performance. One of the structural integrity indicators in such applications is fracture toughness. Fracture toughness is widely used for damage tolerance analysis of aerospace components in which critical crack sizes are computed for given loading conditions to arrive at safe inspection and maintenance intervals. It is therefore the purpose of this paper to conduct a study on the effect of wire EDM on the fracture toughness of this aerospace material. Standard test procedure using compact tension (CT) specimen is used to measure the fracture toughness. Four specimens are produced using wire EDM. This includes the pre-crack which is usually produced by fatigue cycling. Obtained results indicate a slight decrease in fracture toughness compared to that reported in literature. In addition, it can also be concluded that wire EDM can be used as an alternative to fatigue pre-cracking in fracture toughness testing of titanium alloys.**

Key words: EDM, Compact tension specimen, Fracture toughness Grade 5 titanium, Ti6Al4V, Wire EDM

I. INTRODUCTION

Titanium as an element is the ninth most abundant on Earth and makes up about 1% of the Earth's crust [1]. Titanium alloys have unique mechanical properties that make them eminently suited to challenging engineering applications. The density of titanium alloy is about 4500 kg/m^3 compared to 7800 kg/m^3 for steel and 2800 kg/m^3 for aluminum. The tensile strength of titanium alloy is about 1000 MPa, steel 600 MPa and aluminum 450 MPa. Therefore titanium exhibits superior strength-to-weight ratio when compared to its main competitors. This is in addition to its excellent corrosion resistance. Furthermore these properties are maintained at relatively high temperatures making titanium alloys good candidates for use in high temperature applications such as burners and compressor and turbine blades and discs [2]. The workhorse alloy of the titanium family of alloys is grade 5 (Ti6Al4V) whose nominal composition is 6 percent aluminum and 4 percent vanadium and the remainder being largely titanium. It constitutes about 60% of titanium alloy usage. This is a two phase material with both alpha (hexagonal close packed (hcp)) and beta (body centered cubic (bcc)) phases. The alloying element aluminum is the alpha phase stabilizer while vanadium stabilizes the beta phase.

Despite these major advantages, engineering use of titanium alloys is mainly limited to specialized applications such as aerospace and biomedical fields. This is mainly a result of high primary and secondary processing costs which make these alloys too expensive for common engineering applications. Primary processing is complicated largely by the high reactivity of titanium with other elements including oxygen. Hence nothing much can be done, using current technology, to reduce primary processing costs. However, secondary processing costs such as machining can be reduced by using such techniques as high speed machining (HSM) which increase the material removal rate (MRR). HSM has been highly successful in the production of aerospace aluminum components such as wing sections. In addition, HSM produces better surface finish leading to better quality products when compared to conventional machining. A lot of research work is currently being conducted to understand the effect of HSM on the structural integrity of grade 5 titanium alloys [3], [4], [5]. Recently wire EDM has also become a viable option for economically processing difficult-to-machine materials including grade 5 titanium alloy (Ti6Al4V).

Although EDM is a non-traditional material removal technique it has been traditionally used in specialised applications to produce complex shapes such as dies and moulds [6]. In this technique, material removal is achieved by repeated electrical discharges between an electrode and a work piece in the presence of a dielectric fluid. Most applications use copper electrodes and deionised water as the dielectric fluid but hydrocarbon dielectrics are also viable alternatives. EDM is therefore a thermoelectric

Mr D. M. Madyira is a Lecturer in the Department of Mechanical Engineering Science, University of Johannesburg, Auckland Park, Johannesburg, South Africa, 2006. Phone: +2711-559-4030; e-mail: dmadyira@uj.ac.za).

Dr E. T. Akinlabi is a Senior Lecturer in the Department of Mechanical Engineering Science, University of Johannesburg, Auckland Park, Johannesburg, South Africa, 2006. Phone: +2711-559-2137; e-mail: etakinlabi@uj.ac.za).

process hence the need for both the work piece and the electrode to be good electrical and thermal conductors. Li et al suggest that the maximum temperature attained in the process zone during EDM can be as high as 40000 K [7]. Such temperatures inevitably lead to localised melting of the material which is quenched and washed away by the dielectric fluid. Vaporisation of the dielectric fluid also occurs hence the need to use environment neutral dielectrics such as water when compared to hydrocarbons. Since the electrodes do not make contact with the work piece, no mechanical stresses are induced in the work piece. In the same vein, absence of contact eliminates vibrations and tool chatter which are the major causes of poor surface integrity in such processes as milling and turning. The performance of the EDM process depends on such factors as the discharge power density, pulse duration, electrical and thermal conductivity of the materials being processed, motion of the tool, tool work piece gap and rate of tool wear. Over the almost half a century of EDM use, a number of improvements have been introduced aimed at better productivity and quality. The most prominent enhancements have been the introduction of tool and wire vibration [8], [9], work piece vibration [10] and dry EDM [11].

WEDM is a variation of EDM among other variations that include EDM milling, Ultrasonic EDM (UEDM) and conventional EDM. Mohd Abbas et al suggest that WEDM makes up about 24% of EDM activities therefore it is becoming a key enabling manufacturing technique [6]. Fig. 1 presents a schematic representation of the WEDM process.

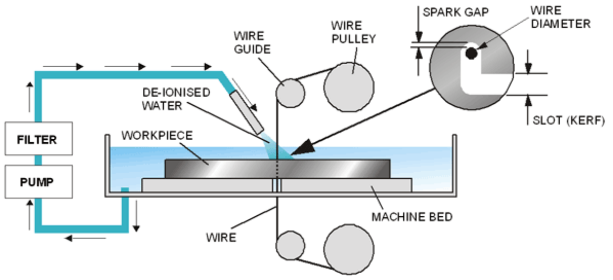

Fig. 1: Wire electrical discharge machining (WEDM) [12]

Some of the advantages of wire EDM include low work holding forces, low cutting forces, high accuracy process, capability to produce complex shapes, ability to produce small holes of the order of 50 µm diameter, minimal too wear, ability to machine materials with high hardness (i.e. difficult to machine) and can handle small corners and narrow slots and no burrs generated during machining. The negative side of wire EDM is that the machines are very expensive compared to other similar sized tools, high skilled operators are required to run the machines, the process can only be applied to electrical conductors, the material removal rate (MRR) is low compared to turning and milling and the process requires de-ionised water. Furthermore, the high localised temperatures produce a heat affected zone (HAZ) which can negatively affect the surface and hence structural integrity of the component.

Li et al have shown that varying discharge energy density during WEDM has a direct effect on the resultant surface integrity of Inconel 718 [7]. Deionised water dielectric and an uncoated brass wired were used in the process. The surface microstructure changed from coral reef topography at high discharge energy density to one with random micro voids at low energy density. A largely isotropic surface topology was reported in which average surface roughness decreased from 3.75 µm to 1.25 µm for corresponding energy density values. The white layer was found to be discontinuous in the thickness range of 13.3 µm to 3.3 µm. Micro hardness was found to be very low at the surface due to the white layer and increased to parent material hardness within 20 µm from the surface. No surface micro cracks were reported for the range of discharge energies investigated.

The poor thermal conductivity of titanium alloys makes it important to understand the effect of WEDM on surface integrity. Recently, Nourbakhsh et al have reported on the effect of varying WEDM parameters on surface integrity of titanium components [13]. WEDM was applied to Ti6Al4V using deionised water as a dielectric and three different wires. Standard uncoated high-speed brass wire was used as baseline study and compared to zinc coated brass wire. Using Taguchi design of experiments they concluded that the cutting speed is a function of the pulse width and the peak current. Surface roughness was reported to increase with pulse width and peak current while decreasing with wire tension. Increase in wire tension leads to a reduction in wire vibration and hence lower surface roughness. In general, it was also found that uncoated wire produced the worst surface finish. Furthermore the uncoated brass wire produced surfaces with more cracks, craters and melted drops.

Similar work by Antar et al reported similar performance of coated and uncoated wire on WEDM of Ti6Al$_2$Sn$_4$Zr$_6$Mo titanium alloy [14]. Using a five axis machine with deionised water as a dielectric two coated copper core wires, they found very interesting results when compared to the standard brass wire. Roughness decreased from about 3.8 µm for rough cut to about 0.6 µm for finishing cuts. There was no major difference in roughness between coated and uncoated wires. However, the uncoated wire produced almost twice the size of the white layer thickness. This is significant as most micro cracks are found in this layer. In terms of residual stresses, all wires produced tensile residual stresses of about 150 MPa during rough cutting. This decreased to about 50 MPa for finishing cuts. It was interesting that the uncoated wire produced compressive residual stresses for the finishing cut. This is significant as compressive residual stresses are associated with favourable fatigue performance attributed to crack closure. Finally, almost 70% improvement in productivity was reported for coated wires compared to uncoated wires during rough cutting. The authors suggested that this was due to increased sparking gap due to rapid melting and vaporisation of zinc coating. The zinc particles also led to the improvement in dielectric ionisation. Parameters with the greatest import on structural integrity are surface roughness, heat affected zone and residual stresses. Surface roughness determines the level of stress concentrations on the surface of loaded components. The heat affected zone means that the surface and subsurface layers of the components see modified mechanical properties of the component material while residual stresses affect the load carrying capacity and fatigue performance of the components in service.

It is clear that previous research has proven the significant effect of the WEDM process on surface integrity of the produced components. This is amplified during WEDM of titanium alloys because of poor thermal conductivity of these materials. However, very little work has been published on the effect of WEDM or EDM on structural integrity of produced components. One of the most important structural integrity indicators is fracture toughness. The objective of this investigation was therefore to determine the effect of wire EDM on the fracture toughness of grade 5 titanium alloy (Ti6Al4V).

II. THEORETICAL BACKGROUND

Fracture toughness is a material property that can be characterised by a number of different parameters ranging from Charpy Impact Energy (CIE), Energy Release Rate (ERR) and Stress Intensity Factor (SIF) [15]. These parameters represent the change in energy that occurs at the point of fracture. In this investigation, the stress intensity concept is used to determine the fracture toughness of Ti6Al4V after WEDM. Fracture toughness measurement is conducted in accordance with ASTM E1820-11 [16]. In this method the mode I (opening mode) critical stress intensity factor (K_{IC}) is measured using the compact tension specimen. The size of the specimen depends on the material being tested. Fig. 2 shows the variation of stress intensity with specimen thickness. The critical SIF is therefore obtained under plane strain conditions.

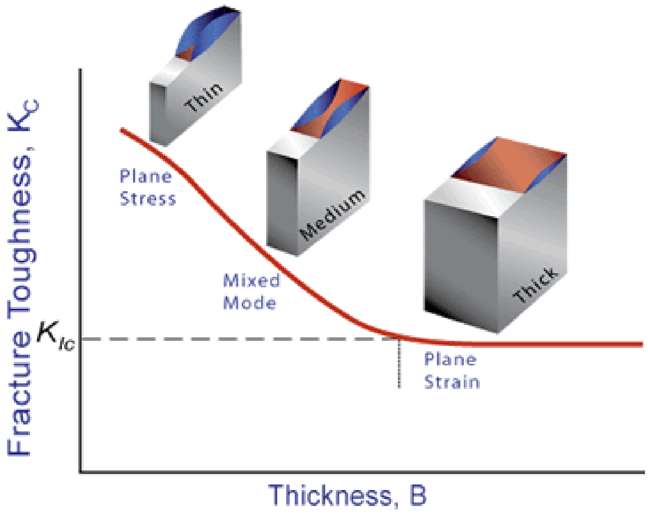

Fig. 2. Variation of stress intensity with specimen width **[17]**

The critical specimen size according to ASTM E1820-11 is [16]:

$$B, a, W \geq 2.5\left(\frac{K_{Ic}}{\sigma_Y}\right)^2 \qquad (1)$$

where B is the specimen thickness, α is the crack size and W is the width. The full specimen specification is shown in Fig. 3.

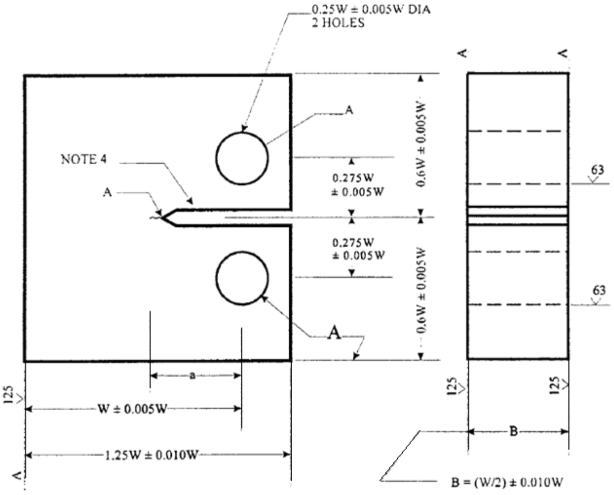

Fig. 3: Compact tension specimen specifications [16]

The critical stress intensity factor is then computed from [16]:

$$K_{IC} = \frac{P_{max}}{(B\,B_N W)^{0.5}} f\left(\frac{a}{W}\right) \qquad (2)$$

where

$$f\left(\frac{a}{W}\right) = \frac{\left(\left(2+\frac{a}{W}\right)\left[0.886 + \frac{4.64a}{W} - 13.32\left(\frac{a}{W}\right)^2 = 14.72\left(\frac{a}{W}\right)^3 - 5.6\left(\frac{a}{W}\right)^4\right]\right)}{\left(1-\frac{a}{W}\right)^{\frac{3}{2}}} \qquad (3)$$

and B_N is equal to B in the absence of side groves. The pre crack size is limited to 0.05B.

III. EXPERIMENTAL DESCRIPTION

A. *Aim*

The purpose of this investigation was to determine the effect of wire electrical discharge machining on the fracture toughness of grade 5 titanium alloys. In the process it is also required to establish if the use of wire EDM to introduce pre-cracks in compact tension specimens that are used to measure fracture toughness is a viable substitute to the more time consuming fatigue pre-cracking.

B. *Materials*

The grade 5 titanium alloy used for this investigation was supplied in round bar form (65 mm diameter) by a Pretoria based company GEM Manufacturing (Pvt) Ltd. The chemical composition of the material as per supplier material certificate is given in Table 1.

TABLE I
CHEMICAL COMPOSITION OF GRADE 5 TITANIUM ALLOY AS SUPPLIED

	Al	**V**	**Fe**	**C**	**N**	**O**	**H**	**Ti**
Content (%)	6.4	4.2	0.03	0.01	0.01	0.18	0.003	Remainder

The corresponding mechanical properties for this material are given in Table 2.

TABLE II
MECHANICAL PROPERTIES OF TI6AL4V ALLOY USED IN THIS INVESTIGATION

Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Reduction of Area (%)
885-910	980-1010	14-18	43-45

C. Specimen Preparation

Fracture toughness testing was conducted according to ASTM E1820-11 [16]. Computed size of the specimen according to Fig. 3 was W = 40 mm and B = 20 mm. Four specimens were machined from a 65 mm diameter round bar using a Xenon WEDM machine (see Fig. 4). The machine is controlled by Actspark software. Deionised water was used as the dielectric using a 250 µm diameter uncoated brass wire for profile cutting followed by pre crack cutting using100 µm diameter wire.

Fig. 4. (a) WEDM machine (b) wire reel (c) Actspark control console

The preparation was done in three phases. The first stage involved WEDM of the profile of the specimen using a 250 µm. This was then followed by the introduction of the pre crack using a 100 µm diameter wire. Finally the specimens were then separated from the main bar. Fig. 5 shows the WEDM of fatigue pre-crack.

Fig. 5: WEDM of fatigue pre-crack

The complete specimens with extensometer mounting bracket holes are shown in Fig. 6.

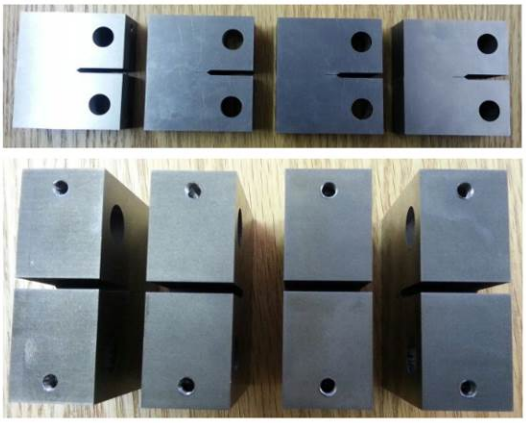

Fig. 6. Completed Ti6Al4V compact tension specimens

D. Equipment

Tensile loading of the specimens was conducted using Instron 1195 testing rig driven by Bluehill 2 software. This is a screw type machine with a 100 kN load cell. The specimen mounting arrangement with extensometer mounted is shown in Fig. 7.

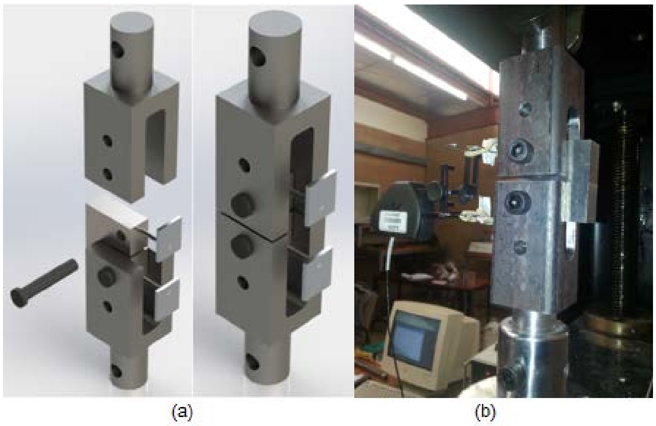

Fig. 7. (a) Specimen mounting arrangement 3D model (b) Actual machine

E. Experimental Protocol

All specimens were tested under displacement control at a rate of 1.6 mm/min in line with ASTM E1820-11. The load versus displacement response was recorded during the test. Displacement was measured using the extensometer shown in Fig. 7. In cases where fast fracture did not lead to complete separation of the specimen, the specimen was un-mounted, cooled in liquid nitrogen and quickly mounted in the machined for fast brittle fracture to complete specimen separation.

IV. RESULTS

A. Load – displacement response

The load displacement response for all the four specimens is given in Fig. 8. The summary of the maximum loads obtained during the experiments is given in Table 3.

TABLE III
MAXIMUM FRACTURE FORCES

Specimen	Maximum Force (kN)	Test Time (sec)
1	62.5	154.44
2	63.4	165.078
3	57.9	120.252
4	58.8	149.592

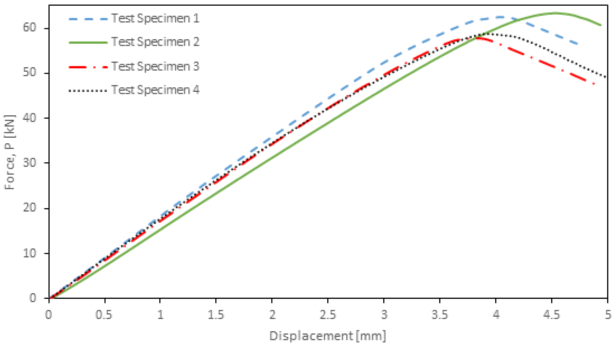

Fig. 8. Force-displacement response for the four specimens

B. *Fracture Toughness*

Fracture toughness values were then computed based on the maximum fracture load i.e. the load at which fast fracture of the specimen occurred. The obtained values are given in Fig. 9 and compared to the average toughness value for the material as reported in literature. The average value obtained experimentally was 111.82 MPa.m$^{0.5}$ with a standard deviation of 6.38 MPa.m$^{0.5}$. This compares to 117 MPa.m$^{0.5}$ reported in literature.

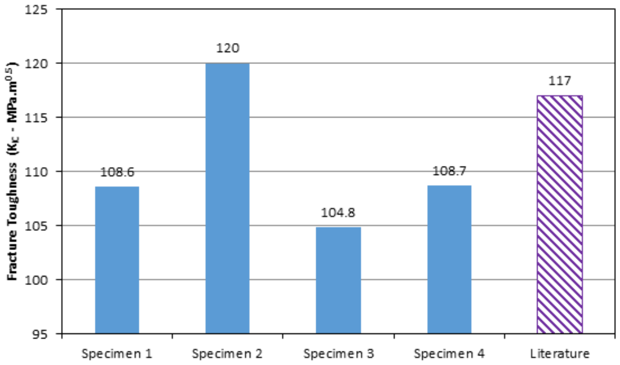

Fig. 9. Comparison of the fracture toughness values

Confirmation of plane strain fracture was done by observing fracture surfaces using optical microscope. Fig. 10 shows typical fracture topography of all the specimens. A large portion of the fracture surface underwent plane strain fracture as evidenced by the flat fracture surface. The edges displayed shear lips associated with plane stress failure. The size of the shear lips was found to be about 1 mm on each side of the plane strain zone. Hence the total plane stress zone was 10% of the plane strain region. This is within acceptable limits of the standard. The crack tip radius was measured to be 200 µm which is twice the size of the wire used to generate the pre-crack. In addition it can be observed from Fig. 10 that the fast fracture originated in the plane strain zone as displayed by the radiation points of the Chevron marks.

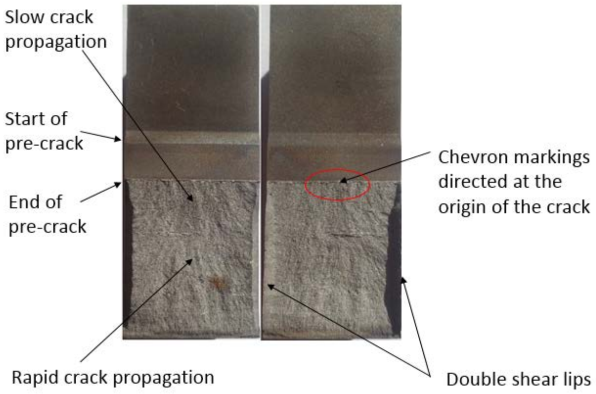

Fig. 10. Typical fracture surface after test

V. DISCUSSION

Compact tension specimens produced for this investigation were made using WEDM in a fraction of the time that it would take using the standard recommended procedure. Given that these specimens were made using difficult to machine materials, it is also expected that the cost of producing the specimens using WEDM would be much lower as well. The average fracture toughness measured using SIF was 111.82 MPa.m$^{0.5}$ which was lower than the value of 117 MPa.m$^{0.5}$ reported in literature.

The specimens used in the tests satisfied the requirements of ASTM E1820-11 [16] with the exception of fatigue pre-crack which was produced by WEDM instead of the recommended fatigue cycling. The obtained disparity (4.4% lower) between the measured values and the average reported in literature is close enough for all practical engineering purposes more so given a standard deviation of 6 MPa.m$^{0.5}$ for the sample used. Such a difference would have little consequence in service conditions considering the conservative safety factors applied in most applications. However this variation could also be considered to be a result of the WEDM process used. Key parameters of concern are the crack tip radius.

The order of magnitude of the crack tip expected using fatigue pre-cracking is 20 µm which is about the average grain sizes for these materials. This compares to 200 µm achieved using WEDM with a 100 µm diameter wire. The result of this would be a reduction in stress concentration and hence stress intensity in the crack tip region. The expected effect of this is to increase the fracture toughness. However, the modified properties of the materials as a result of the HAZ would lead to a reduction in maximum fracture load. Although no detailed analysis was conducted on the effect of WEDM on the microstructure or hardness of the material, the results indicate a definite reduction of mechanical properties. The combined effect of these key factors was the slightly reduced average critical stress intensity factor compared to the expected values as reported in literature. Finally the fracture surfaces confirmed the attainment of plane strain conditions as stipulated by the standard.

VI. CONCLUSIONS

Fracture toughness tests were conducted on Ti6Al4V compact tension specimens made using WEDM. The pre-crack was introduced by WEDM using a 100 µm diameter uncoated brass wire. The measurements satisfied the requirements of ASTM E1820-11 [16]. The obtained average toughness value using four specimens was 111.82 MPa.m$^{0.5}$ which was 4.4% lower than that reported in the literature. Fracture surfaces showed conformance with plane strain requirements. It can therefore be concluded that WEDM can be safely used to pre-crack compact tension specimens for the purpose of measuring fracture toughness of grade five titanium alloys. In addition, it is concluded that the WEDM process did not significantly affect the material properties.

REFERENCES

[1] "Titanium Alloy Guide," RMI Titanium Company, [Online]. Available: http://RMITitanium.com. [Accessed 15 August 2013].

[2] V. N. Moiseyev, Titanium: Russian aircraft and aerospace applications, CRC Press, 2005.

[3] P. Mawanga, An investigation on the effects of high speed machining on the surface integrity of grade 4 titanium alloy, University of Johannesburg, M. Ing. Thesis, 2012.

[4] D. M. Madyira, R. L. Laubscher, N. Janse van Rensburg and P. F. J. Henning, "High speed machining induced residual stresses in Grade 5 titanium alloy," Proceedings of IMechE Part L: Journal of Materials: Design and Applications, vol. 227, no. 3, pp. 208-215, 2013.

[5] N. Janse van Rensburg, R. F. Laubscher, D. M. Madyira and T. Oosthuisen, "Residual stress depth profiling of titanium alloys subjected to high speed machining by energy dispersive diffraction," in COMA Conference, Stellenbosch, 2013.

[6] N. Mohd Abbas, D. G. Solomon and M. F. Bahari, "A review on current research trends in electrical discharge machining (EDM)," International Journal of Machine Tools & Manufacture, vol. 47, pp. 1214-1228, 2007.

[7] L. Li, Y. B. Guo, X. T. Wei and W. Li, "Surface integrity characteristics in wire-EDM of inconel 718 at different discharge energy," Proceedings of CIRP 6, pp. 220-225, 2013.

[8] J. Zhixin, Z. Jianhua and A. Xing, "Ultrasonic vibration pulsevelectro discharge machining of holes in engineering ceramics," Journal of Materials Processing Technology, vol. 53, pp. 881-816, 1995.

[9] Z. N. Guo, T. C. Lee, T. M. Yue and W. S. Lau, "Study on the machining mechanism of WEDM with ultrasonic vibration of wire," Journal of Materials Processing Technology, vol. 69, pp. 212-221, 1997.

[10] K. Egashira and T. Masuzawa, "Microultrasonic machining by the application of work piece vibration," CIRP Annals - Manufacturing Technology, vol. 48, pp. 131-134, 1999.

[11] Z. B. Yu, T. Jun and K. Masanori, "Dry eletrical discharge machining of cemented carbide," Journal of Materials Processing and Technology, vol. 149, pp. 353-357, 2004.

[12] Mechanical Design Forum, "Electro-discharge wire cutting (EDWC)," Mechanical Design Forum, 25 October 2011. [Online]. Available: http://www.mechanicaldesignforum.com/content.php?16-Electro-discharge-wire-cutting-(EDWC). [Accessed 2013 August 15].

[13] F. Nourbakhsh, K. P. Rajurkar, A. P. Malshe and J. Cao, "Wire Eletro-discharge machining of titanium alloy," in The first CIRP Conference on Biomanufacturing, Proceedings of CIRP 5, 2013, pp. 13-18.

[14] M. T. Antar, S. L. Soo, D. K. Aspinwall, D. Jones and .. Perez, "Productivity and workpiece surface integrity when WEDM aerospace alloys using coated wires," 1st Conference on Surface Integrity (CSI), Proceedings of Engineeering, vol. 19, pp. 3-8, 2011.

[15] M. F. Kanninen and C. H. Popelar, Advanced Fracture Mechanics, New York: Oxford University Press, 1985.

[16] Standard Test Method for Measurement of Fracture Toughness, ASTM, ASTM E1820-11: ASTM International, 2011.

[17] "Fracture Toughness," NDT Resource Center, [Online]. Available: http://www.ndt-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/FractureToughness.htm. [Accessed 15 August 2013].