# Effect of Machining Induced Microstructure Changes on the Edge Formability of Titanium Alloys at Room Temperature

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**Abstract**
The challenges in forming titanium alloys at room temperature is well researched and is linked both to the limitations imposed by the basic crystal structure and their ability to form texture during plastic deformation. One major issue of concern for the sheet forming of titanium alloys are their high sensitivity to surface inhomogeneity. Various machining processes are utilised in preparing sheet hole edges for edge flanging applications. However, the response of edge forming tendencies of titanium to different edge surface finishes is not well investigated. The hole expansion test is used in this project to elucidate the impact of Abrasive Water Jet (AWJ) and Electro-discharge machining (EDM) cutting techniques on the edge formability of CP-Ti (Grade 2) and Ti-3Al-2.5V alloys at room temperature. The results show that the quality of the edge surface finish has major effect on the edge formability of the materials. The work also found that the variations in the edge forming performance are mainly the result of the influence of machining induced edge surface defects.

Keywords: Titanium alloys, Hole expansion test, Edge formability, Non-conventional machining

## 1 Introduction
Titanium and its alloys have been widely used in the aerospace industry mainly due to their excellent properties such as high temperature strength compared to aluminium, their good strength to weight ratio compared to steels and their good corrosion resistance [1]. However, various issues have been identified to have limited their use. One such is their low formability at room temperature due to limited slip systems caused by their crystallographic structure and their tendency to develop strong textures with concomitant planar anisotropy [2]. Another limiting factor is their high sensitivity to surface inhomogeneity resulting in reduced fatigue life [3]. These surface inhomogeneities are sometimes introduced during machining processes. Considering the poor machinability of titanium [4], issues relating to the extent of edge defects produced during machining becomes a major area of research interest. Low heat conductivity coupled with chemical reactivity of titanium are some of the reasons contributing to their poor machinability [5]. Depending on the method used to machine titanium, certain levels of edge surface defects may be introduced onto the part surface. The common edge surface defects produced during machining of titanium includes carbide cracking induced cracks, microstructure alteration, white layer formation and residual stress [6]. Normally, conventional and non-conventional machining methods are adopted in cutting titanium and other metals. Non-conventional machining methods are non-contact techniques widely adopted in industry

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since they eliminate tool-part contact related issues [7]. Abrasive water jet (AWJ) cutting and Electro discharge machining (EDM) are used in this work. A standard hole expansion test (HET) is used in this research to examine the hole edge formability of the materials. The extent of edge formability is defined by the hole expansion ratio (HER). The higher the HER value, the higher the edge forming performance of the material. The HER is enumerated by finding the percentage of the ratio of the difference between the final and initial hole diameter to the initial hole diameter [8];

$$HER = \frac{d_f - d_0}{d_0} \times 100\% \quad (1)$$

*Where* $d_f$ *- final hole diameter,* $d_0$ *– initial hole diameter*

Since areas around the hole edge are regions of high stress concentration, the integrity of the fabricated edge becomes a significant factor during HET. However, the impact on forming performance of edge surface micro features and defects introduced into titanium alloys during machining has not been extensively researched. This work is directed at ascertaining the impact of EDM and AWJ induced edge microstructure alterations on the edge formability of titanium alloys deformed at room temperature. The work seeks to understand how the cutting techniques examined alter the edge related failure modes and failure nucleation process in titanium alloys.

## 2 Experimental procedure

### 2.1 The materials

The materials studied in this work are commercially pure titanium (CP-Ti) Grade 2 and Ti-3Al-2.5V alloys. Ti-3Al-2.5V alloys have intermediate strength and good cold workability. This alloy is mainly utilised in aerospace applications such as hydraulic tubing and light weight honeycomb structures. CP-Ti (Grade 2) possesses a good strength to weight ratio and also has the ability to maintain its strength appreciably during deformation. They are also largely employed in airframe skin applications [9].

### 2.2 Material preparation

The edge surface roughness values and micrographs were characterised using an Alicona 3D microscope. The edge surface topography and crack surface fractographs were also examined using a Quanta FEG 250 microscope. AWJ cut edges were prepared with a Calypso water jet machine, operated at 70HP and at a feed rate of 400g/min. The transverse cutting speed was varied to attain two different edge surface finishes for both materials (250mm/min: finished edge surface and 600mm/min: unfinished edge surface). Both materials showed higher edge surface micro-ridge distribution for the unfinished AWJ edges compared to the finished parts. The ratio of the edge surface micro-grooves to micro-ridges was also fairly even for the finished AWJ cut edges compared to the unfinished parts for both materials; Figure 1 *a,b,e,f*. The EDM cut edges were machined using a GF FI 440 CCS machine fitted with a 0.25mm diameter brass cutting wire. The EDM cutting parameters were varied to attain two distinct edge surface finishes (1. wire tension~$2\times10^1$N, pulse on time~ 0.05ms, pulse off time~ 20ms: for finished edges and 2. wire tension~$1.3\times10^1$N, pulse on time~0.7ms pulse off time~12ms: for unfinished edges). Both materials showed a finer distribution of surface micro-grooves for the finished

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EDM edges compared to the unfinished edges; Figure 1 *c,d,g,h*. The attained surface micro-groove size and distribution for the finished EDM edges for CP-Ti are finer compared to those observed for Ti-3Al-2.5V; Figure 1 *d, h*.

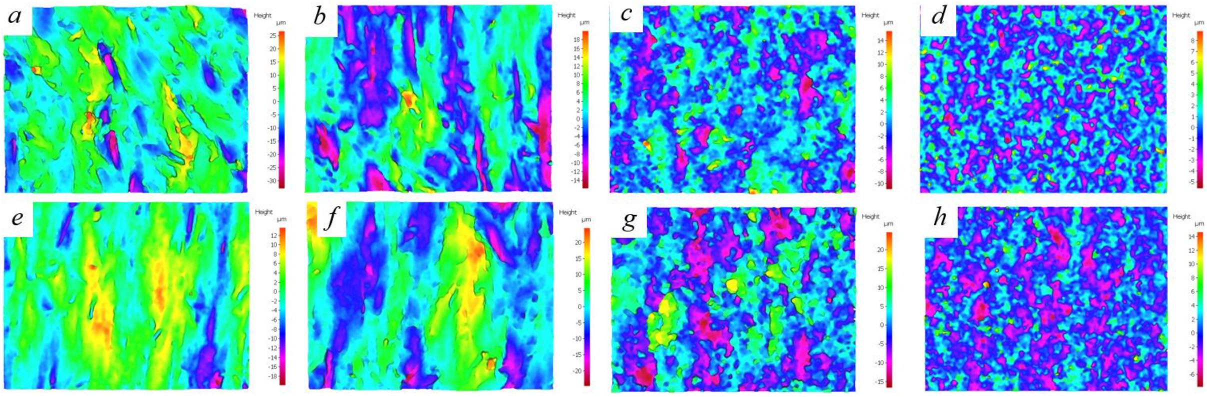


Figure 1. Alicona micrograph of surface topography and roughness after EDM and AWJ cutting
(*a*)Unfinished (Ra~5.2µm) and (*b)* Finished (Ra~3.2µm) AWJ for CP-Ti; (*c*) Unfinished (Ra~2.7µm) and (*d*) Finished (Ra ~0.8µm) EDM for CP-Ti; (*e*) Unfinished (Ra ~5.7µm) and (*f*) Finished (Ra ~3.8) AWJ for Ti-3Al-2.5V; (*g*) Unfinished (Ra ~2.9µm) and (*h*) Finished (Ra ~1µm) EDM for Ti-3Al-2.5V

### 2.3 Hole expansion test

Hole expansion testing was performed on a Zwick/ Roell BUP 1000 testing machine controlled by testXpert II software. A $60^0$ head conical punch with a die set design consistent with ISO 16630:2017, was used to deform a 10mm diameter hole produced with either AWJ or EDM cutting methods. The test trials were done for the two cutting methods as well as their two distinct edge surface finish qualities. A blankholder force of 150kN was used to prevent the material from drawing-in during the test. The punch was driven at a speed of 1mm/s through the fabricated hole until an edge crack occurred.

### 2.4 Mechanical properties

A Zwick/ Roell Z150 tensile testing machine was used to perform a standard room temperature uniaxial tensile test consistent with ISO 6892-1:2016. The tests were conducted at a constant strain rate of 0.001/s. Both materials exhibited anisotropic behaviour when examined in three sheet processing directions, Table 1.

Table 1. Room temperature tensile properties

| Material | Type | Yield strength ($0^0$,$45^0$,$90^0$), MPa | Tensile strength ($0^0$,$45^0$,$90^0$), MPa |
|---|---|---|---|
| CP-Ti (Grade 2) | α | 197.99, 218.19, 250.05 | 550.31, 489.43, 513.25 |
| Ti-3Al-2.5V | α/near α | 165.97, 188.75, 168.99 | 605.44, 504.38, 529.42 |

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## 3 Results and Discussion

### 3.1 Machined edge surface topography and defects

The edge surfaces after AWJ machining were characterised by surface mechanical erosion features, produced by the tracks travelled by the abrasive particles during the cutting process. The surface draglines, micro-grooves and dents observed are also due to the areas occupied and/or vacated by the abrasive particles during the cutting process, Figure 2*a*.

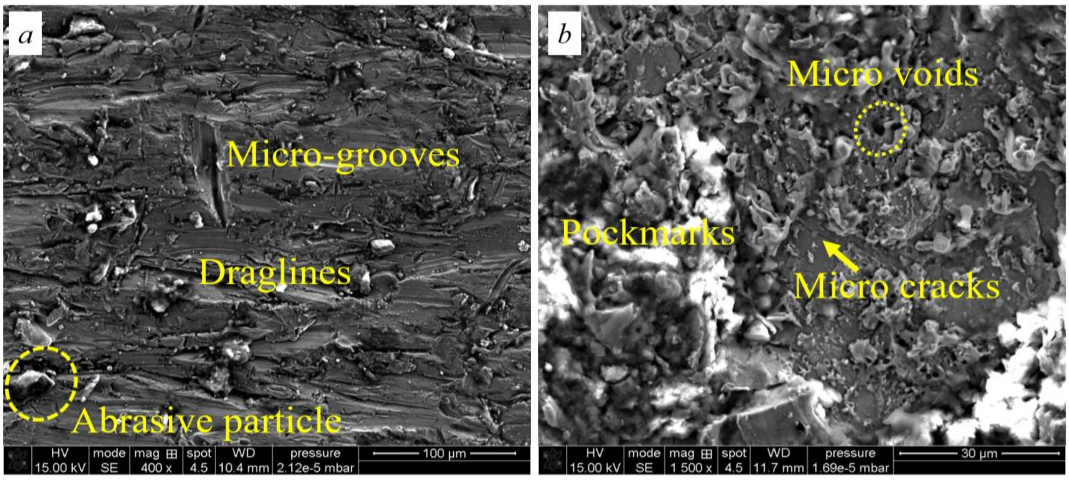


Figure 2. Surface topography of machined edges
(*a*)AWJ cut edge surface, (*b*) EDM cut edge surface

The surface after EDM cutting showed features consistent with its heat erosion attributes. The surface featured micro voids, micro cracks, craters, ridges and pockmarks as the main edge defects, Figure 2*b*. The extent of surface pockmarks produced is a function of the ability of the dielectric fluid to wash away debris during the cutting process in the quest to minimise melt solidification.

### 3.2 Hole edge formability

Figure 3 shows the hole edge forming performance of both materials tested for two different edge cutting methods and edge surface finish qualities.

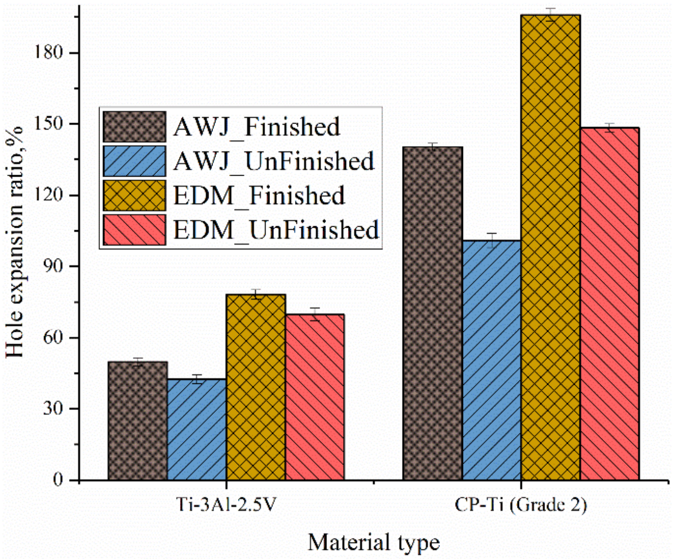


Figure 3. Edge formability of CP-Ti and Ti-3Al-2.5V alloys

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The EDM cut edges showed highest edge formability (CP-Ti: ~195.86% and Ti-3Al-2.5V: ~78.16%) compared to AWJ cut edges (CP-Ti: ~140.38% and Ti-3Al-2.5V: ~49.84%). Both materials showed better edge formability for the finished cut edges (CP-Ti: EDM ~195.86%, AWJ ~140.38% and Ti-3Al-2.5V: EDM ~78.16%, AWJ ~49.84%) compared to the unfinished edges (CP-Ti: EDM ~148.4%, AWJ ~100.9% and Ti-3Al-2.5V: EDM ~69.73%, AWJ ~42.48%) for both cutting techniques. Overall, CP-Ti showed better edge formability compared to Ti-3Al-2.5V alloy. This trend could be attributed to the nature of the edge microstructures produced after machining of both materials. Generally, the edge micro features attained for both materials are varied after EDM and AWJ machining. CP-Ti after AWJ cutting showed lower levels of edge surface micro-grooves and defects compared to Ti-3Al-2.5V, Figure *4a,b*. The EDM microstructure also showed a high volume fraction of machining induced micro-cracks in CP-Ti compared to Ti-3Al-2.5V, Figure 4*c,d.* Pure titanium are predominantly alpha phased alloys and are relatively soft and easier to machine compared to alloyed titanium [10]. Heat conductivity also plays a massive role in titanium machinability in terms material and heat removal rate. Pure titanium generally exhibits stable heat conductivity with rising temperature during machining compared to its alloyed counterparts [11]. The severity of defects produced during machining is a function of the ease of machinability of the components.

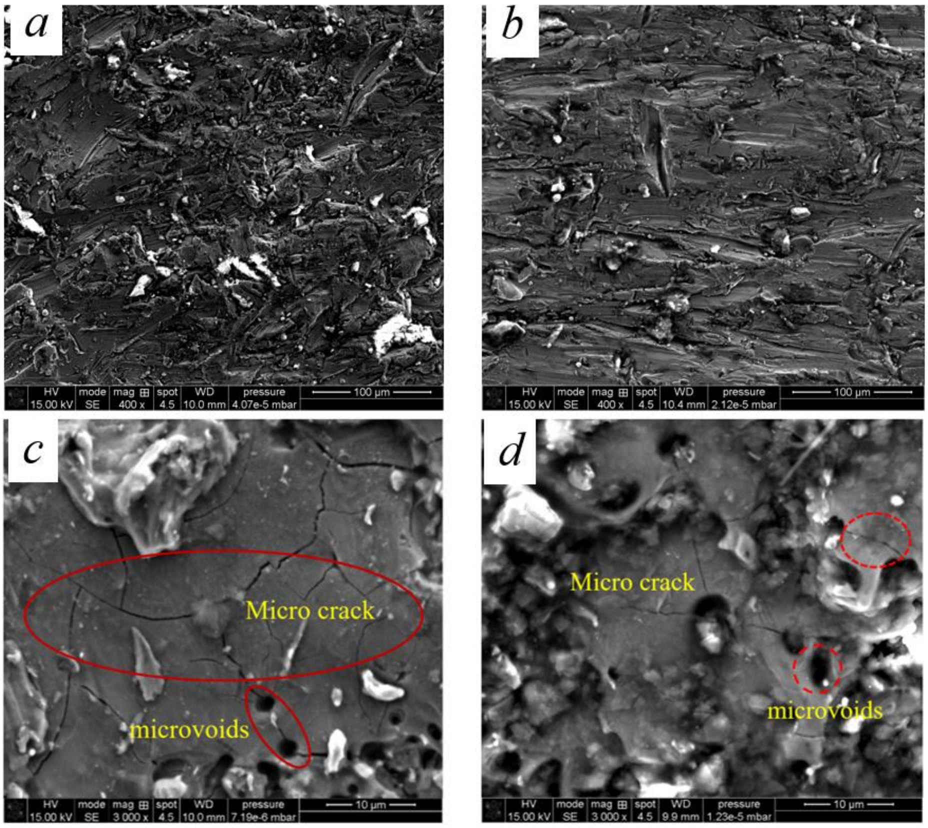


Figure 4. Machining induced surface microstructure changes
(*a*)CP-Ti AWJ cut edge, (*b*) Ti-3Al-2.5V AWJ cut edge, (*c*) CP-Ti EDM cut edge, (*d*) Ti-3Al-2.5V EDM cut edge

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### 3.3 Failure nucleation

The edge surface defects observed after AWJ machining are mainly due to the action of the abrasive particles. The severity of the edge defects is a function of the machining parameters and the material's machinability. The surface defects produced on the material surface after AWJ machining act as stress concentration sites (yellow arrow) during HET, Figure *5 a*. These defects sites serve as areas of high energy concentration where the cracks begin to grow. The rate of the crack growth is dependent on the defect depth, distribution and size.

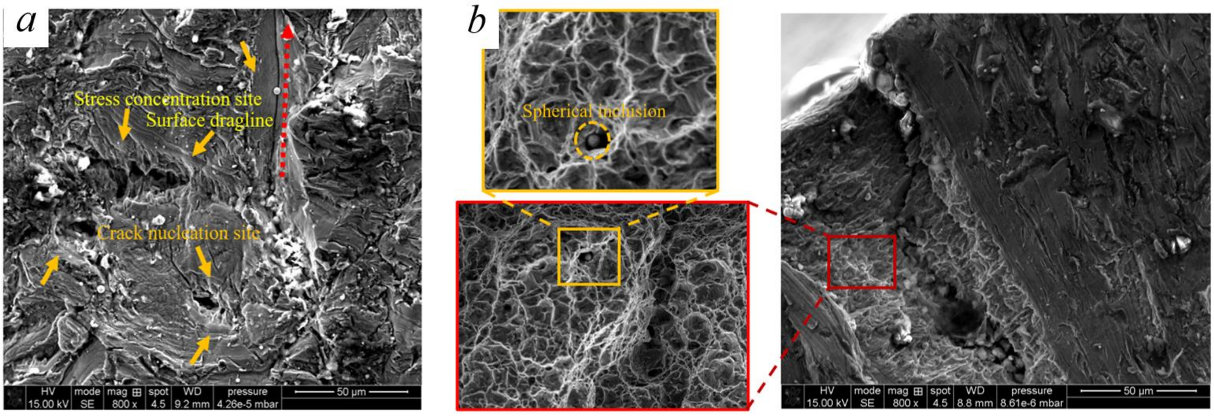


Figure 5. Failure mode during HET of AWJ cut edge
(*a*)Crack nucleation site at defect zones, (*b*) dimpled crack surface of AWJ cut edge

The AWJ fracture surface is characterised by microvoid nucleation sites with dimpled surface at spherical inclusions, Figure *5b*. The growth of these microvoids around the spherical inclusions (by virtue of interface decohesion) are mainly due to the action of plastic strain and hydrostatic stress which results in major flaws and subsequent failure upon coalescence. Generally, the trajectory of the crack is a function of the stress state at the hole edge. The stress state around the hole edge during HET is pure uniaxial tension [12].

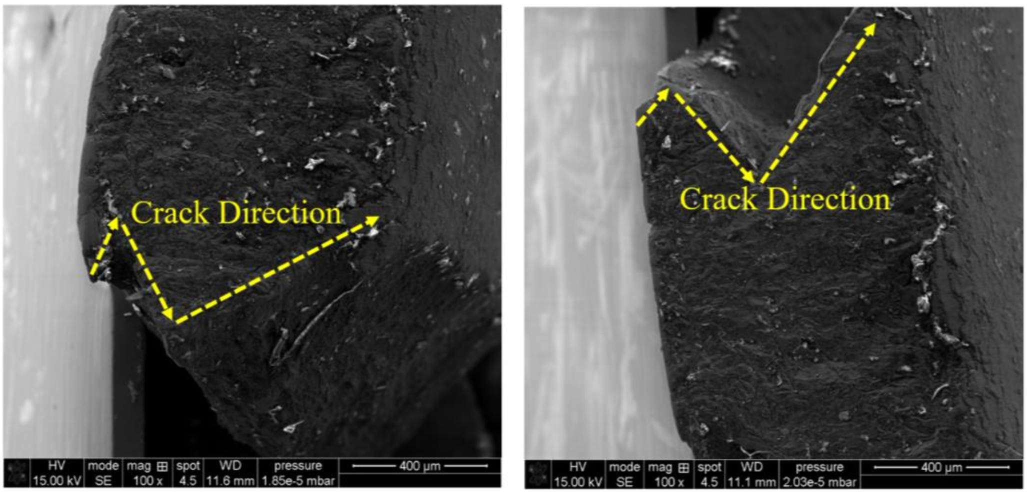


Figure 6. AWJ edge crack orientation

Since the hole edge is subjected to plane strain mode I loading, the optimum plastic strain is obtained at an angle of $45^0$ to the crack axis. From a localised point of view, this angle becomes

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the favoured trajectory for microvoid growth and coalescence. However, global constraints like edge defects (surface draglines and grooves) have the tendency of redirecting the crack plane path. The zigzag patterns seen at the AWJ cut edge fracture tip is as a result of the corrections made to the deviation by global constraints, reverting back to the optimum plastic strain angle, Figure *6*.

On the other hand, the thermal stresses produced during EDM machining due to plastic deformation or during the cooling process are manifested on the machined surface as micro-cracks. These surface micro-cracks are responsible for distributing the imposed stresses homogenously around the hole edge during HET. This phenomenon delays early failure of the material by preventing the cracks from developing towards the thickness direction of the sheet, Figure 7*a*. CP-Ti exhibited higher volume fraction of EDM machining induced surface micro-cracks compared to Ti-3Al-2.5V cut edge, Figure 4*c, d*, hence the higher edge performance. The higher the EDM induced surface micro-cracks, the higher the edge formability of the material. Hasegawa, et al. [13] in their research also reported the influence of stress induced surface micro-cracks produced after punching of martensite single phase steels and their role in the restriction of crack extension towards the sheet thickness direction with an accompanying increase in the material's HER performance.

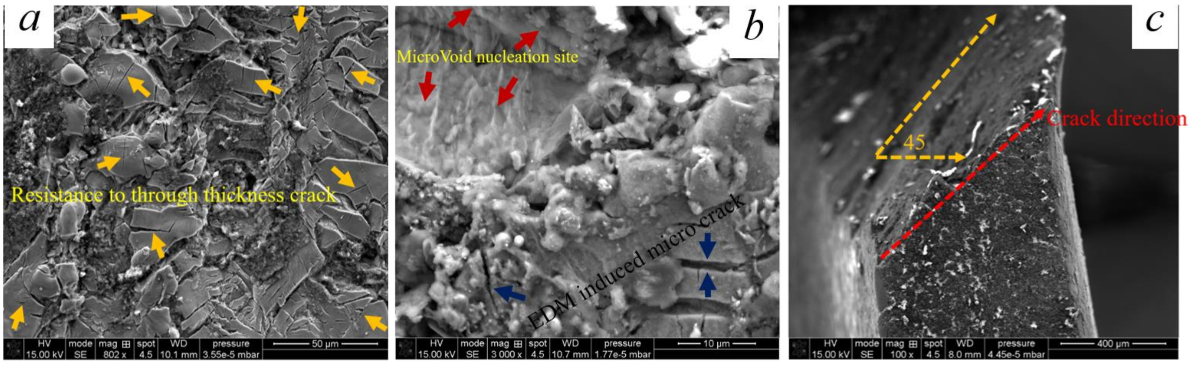


Figure 7. EDM cut edge failure initiation process during HET
(*a*) Resistance to through-thickness cracking by EDM induced surface micro cracks (yellow arrows), (*b*) free surface formation (red arrow), (*c*) edge crack orientation

The differences in the attained EDM edge performance observed for CP-Ti and Ti-3Al-2.5V alloys could also be attributed to the variation in EDM induced residual stress. Normally, metallurgical alterations and thermal gradients produced during EDM machining induces residual stresses [14]. As a consequence, the attained strains results in the inception of tensile residual stresses, which are deleterious in terms of shortened fatigue life and enhanced fatigue crack growth. Fatigue generally emanates from the surface, hence the integrity of component surface is of significant essence. The residual stress values attained after EDM cutting are linked to the attained surface topography and the material yield strength [15].
The crack tip of the EDM samples after HET showed localised necking with ductile shear failure, Figure 7*c*. The crack occurred just after the formation of micro-voids on the free surface, Figure 7*b*. The shear stresses acting during plastic deformation become highest for a plane of maximum plastic shear strain at $45^0$. Through-thickness disparity in triaxiality could

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also be responsible for the shear deformation governed by fracture trajectory at the crack tip orienting at $45^0$ to the optimum principal stress. In such cases, the triaxiality at the crack tip offers an adequate upgrade for micro-void nucleation reminiscent of ductile fracture [16].

## Conclusions

Varied machining methods are used to cut titanium alloys and these introduce edge surface defects and microstructure alteration into the material. This project sought to examine the impact of AWJ and EDM induced microstructure changes on the edge formability of CP-Ti (Grade 2) and Ti-3Al-2.5V alloys. The research also examined the nature of the edge surface related failure modes and failure nucleation processes linked to these cutting methods. It was found that;

- EDM machined test samples showed higher edge forming performance compared to AWJ cut edges for both materials
- The high edge formability of the EDM machined edges for CP-Ti was due to the high volume fraction of cutting induced surface micro cracks compared to those observed in Ti-3Al-2.5V. CP-Ti also showed a lower volume fraction of edge surface micro-grooves after AWJ cutting compared to Ti-3Al-2.5V.
- The quality of the edge surface finish has a significant impact on the edge formability of the materials (1. CP-Ti: AWJ finished~140.38%, unfinished~100.9%; EDM finished~195.86%, unfinished~148.4%, and 2. Ti-3Al-2.5V: AWJ finished~49.84%, unfinished~42.48%; EDM finished~78.16%, unfinished~69.73%
- The nature of defects introduced onto the edge surface by virtue of the machining process governs the crack nucleation, growth rate and orientation in the material
- The failure mechanism in both materials is ductile fracture with the associated growth of microvoids around spherical inclusions upon increase in plastic strain and hydrostatic stress

## Acknowledgement

The authors acknowledge the support of the Advanced Forming Research Centre (AFRC) and the Department of Design, Manufacturing and Engineering Management of the University of Strathclyde, UK. The authors would also like to acknowledge TIMET for material supply.

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