Investigation of The Effect of Notch Tip Radius on Fracture Energy of Charpy in 7075 Aluminium Alloy

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Abstract: In the present study Charpy impact tests on a 7075-T651 aluminium alloy with full size (55×10×10 mm) with different notch tip radius (range of 0.19 to 0.40 mm) were conducted and the fracture energy was measured. The experimental results showed that the relationship between the fracture energy (E) and the notch tip radius of the Charpy samples (r) for the tested Aluminium is E=18.052r+1.741. Using this relationship, the Charpy energy can be determined for this Aluminium for any notch tip radius. Fracture surfaces revealed an intergranular failure for base metal in longitudinal direction, that a predominately brittle failure (cleavage) with some insights of ductile characteristics was observed. Moreover, with increasing notch tip radius, cracked particles were observed and some microvoids were nucleated, i.e., ductile fracture. Changes in the primary crack notch cause a change in the stress intensity factor adjacent to the crack tip, where the fracture energy in the Charpy Impact Test is subjected to the primary crack notch.

Keywords: Aluminum Alloy 7075, Charpy Impact Test, Notch Tip Radius Effect, V-Notch,

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1 INTRODUCTION

The presence of geometrical discontinuities, such as notch or holes in an object, leads to uneven distribution of stress around it or concentration of stress, which is the main cause of why applied fracture stress is less than theoretical fracture stress; Therefore, the harmful effect of crack is the increase in local stress and three-dimensional stress state adjacent to the crack tip [1]. Notch causes concentration of the force lines in the notch tip and increases the stress and thus increases the applied stress at the crack tip [2].

In recent years, the U and V notches have received much attention, since these notches are a good example of the large radius of plastic zone around the notch. It is important to determine the dynamic fracture energy in the Charpy impact test and its relation to the dynamic fracture toughness through semi-experimental relationships.

The present study analyses the effect of V-shaped tip radius variation on Charpy fracture energy and microstructure changes of fracture in 7075-T651 Aluminium with different notch tip radius.

2 LITERATURE REVIEW

In 1987, Druce et al. [3] using a Charpy impact test studied the effect of notch geometry at different temperatures on SA351 CF3 steel. In this study, samples of U and V notches in geometries were used. At low temperatures, it receives the least amount of energy and exhibits brittle material behaviour, and at high temperatures, receives the highest amount of energy and exhibits ductilr material behaviour.

In 1989, Lukas et al. [4] numerically examined the notch size and its effect on copper-steel material fracture. In this study, a linear relationship between the radius of the semicircular notch and the fracture energy is proved.

In 2005, Gomez et al. [5] used two types of U and V notch by varying the notch depth, notch angle and notch radius in the three-point bending experiments with PMMA polymer material. In this study, more force is needed by increasing the notch angle of the specimen.

In 2009, Barati et al. [6] investigated the effect of depth and radius of the U-shaped notch (0 to 30 mm and 0 to 3 mm, respectively) in the Charpy impact test on the average strain density of the sample. The average strain energy density value was reported for a 1 mm radius of 1 kPa.

In 2014, Salavati et al. [7] experimentally and numerically investigated the effect of notch depth as well as radius on the force applied in a three-point bending experiment. In this study, they compared the simulation and experimental test of three-point bending with changing the notch tip radius and notch depth.

In 2015, Ramkumar et al. [8] studied the experimental investigation on mechanical and turning behaviour of Aluminium 7075. In this research, work involves the study of AA 7075-TiB2-Gr in situ composite through stir casting route. In situ method, it involves formation of reinforcements within the matrix by the chemical reaction of two or more compounds which also produces some changes in the matrix material within the vicinity.

In 2015, Ambriz et al. [9] investigated the fracture energy evaluation on 7075-T651 aluminium alloy weld determined by instrumented impact pendulum. In this study, fracture surfaces revealed an intergranular failure for base metal in longitudinal direction, whereas a predominately brittle failure (cleavage) with some insights of ductile characteristics was observed for the transverse direction. In contrast, a ductile failure was observed for weld metal and HAZ.

In 2015, Cova et al. [10] studied the influence of geometric size on the fracture resistance of the GJ400 iron.

In 2018, Hosseinzadeh and Hashemi [11] experimentally investigated the notch depth effect on Charpy fracture energy in API X65 steel. In this study, a linear relationship between the notch depth and the fracture energy is proved.

In 2019, Hosseinzadeh et al. [12] experimentally investigated the notch depth effect on Charpy fracture energy in Aluminum 7075. In this study, an exponential relationship between the notch depth and the fracture energy is proved.

In 2019, Emamverdi et al. [13] experimentally investigated the notch tip radius effect on Charpy fracture energy in Aluminium 7075. In this study, a linear relationship between the notch tip radius and the fracture energy is proved.

In 2019, Maraki et al. [14] experimentally investigated the notch angle effect on Charpy fracture energy in Aluminium 7075. In this study, a power relationship between the notch angle and the fracture energy is proved.

In 2019, Patil et al. [15] studied about microstructure, Tensile Properties and Hardness Behaviour of Aluminium 7075. In this research, an effort is made to familiarize and best potentials of the reinforcing agent in aluminium 7075 matrices with naturally occurring Beryl and Graphene to develop a new hybrid composite material are suggested. Microstructure study through scanning electron microscope demonstrated the homogeneous distribution reinforcement Beryl and GNPs into the Al7075 matrix.

In 2020, Prema et al. [16] investigated the characterization, corrosion and failure strength analysis of Aluminium 7075. In this research, the casted samples have been characterized by x-ray Diffraction (XRD),

Thermo Gravimetric Analysis (TGA/DSC), Energy Dispersive Spectrum (EDS), and Scanning Electron Microscope (SEM). In case of hybrid composite, the hardness and the tensile strength decrease when the content of Al_2O_3 increases.
In 2020, Hosseinzadeh and Hashemi [17] experimentally and numerically investigated the notch depth effect on Charpy fracture energy in API X65 steel. In this study, the experimental results were compared using the Abqus simulation of the Gurson model.
Importance and novelty of this research is experimental results showing that the relationship between the fracture energy (E) and the notch tip radius of the Charpy samples (r) for the tested Aluminium is E=18.052r+1.741. Using this relationship, the Charpy energy can be determined for this Aluminium for any notch tip radius. Moreover, Investigating the microstructure at the fracture surface of the specimens that have altered the radius of the notch is part of the significance of this study.

3 MATERIALS AND EXPERIMENTAL PROCEDURES

3.1. Material

The material selected in this study is an aluminum alloy 7075-T651 with a thickness of 10 mm in a plate with a dimension of 2000×1000 mm. Aluminum alloy 7075 is a thermal alloy and is commonly used in the manufacture of components such as body panels and aircraft wings in the aerospace industry. Details of the chemical composition and mechanical properties of aluminum 7075-T651 are shown in “Table 1 and Table 2”, respectively [18].

Table 1 Chemical composition of aluminum 7075-T651 [18]

No.	Elements	Percent(%)
1	Zn	5.5
2	Cu	1.3
3	Mg	2.4
4	Fe	0.5
5	Si	0.4
6	Mn	0.4
7	Ti	0.2
8	Cr	0.2

To prepare the samples from the primary material, the parts are subjected to a machining process. Size, tolerance, and notch characteristics are significant features in the fabrication of the specimens as illustrated in “Fig. 1” for the ASTM E23 standard Charpy impact test.

Table 2 Mechanical properties of aluminum 7075-T651 [18]

Mechanical Properties	Value
Modulus of elasticity (GPa)	72
Yield strength (MPa)	435.7
Ultimate strength (MPa)	462.3
Poison ratio	0.33
Elongation%	13.2

After final heat treatment, all machining and grooving steps should be performed. Unless it is proven that the impact characteristics of the specimens before and after heat treatment are exactly the same. The notch must be perfectly flat and since the variation in notch sizes is very influential in the test results, the standard specimen is a V-notch specimen as shown in “Fig. 1”. It has been proven that high surface smoothness is not necessary, but a polishing of 2 μm for the notched surface and the opposite surface and 4 μm for other surfaces is required. The notch can be created in any way but it must be carefully avoided to damage the surface of the hole (the zone of failure of the sample) [19].

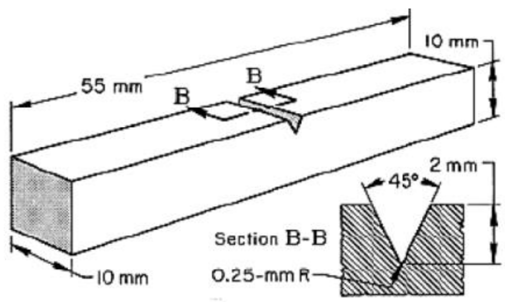

Fig. 1 Standard Sample Dimensions of Charpy Impact Test [19].

3.2. Experimental

First, the aluminum sheet 7075 is 1000×2000 mm. The sheet was cut to 60×500 mm. The sheet was cut to 55 mm (sample length) using a milling machine. Specimen notches can be pressed or machined (Chevron V-notch) according to the API 5L3 standard, which is created by a wirecut machine. The press notch created in the laboratory specimen by pressing the chisel is sharp enough and there are no residual stresses in the notch tip zone and also the type of notch can affect the fracture start energy [20].

In this study, notches were created using wirecut machine with 0.17 mm wire diameter. Specimens with standard dimensions of 10 x 10 x 55 mm and notch with 45 degree angle and 2 mm notch depth and notch radius from 0.19 to 0.40 mm (8 specimens with 0.03 mm difference) with sufficient accuracy And the standard requirements were made. The image of a group of five samples in standard dimensions before failure is shown in “Fig. 2”.

Fig. 2 A group of 5 Charpy samples before failure.

In order to achieve the objectives of the study, 40 Charpy samples were divided into 8 groups of 5 each. The impact test was performed using a Charpy Gunt impact machine with capacity of 25J (C-shaped hammer with an 8 mm radius) at 23°C. The schematic of the forces applied to the Charpy impact test is shown in “Fig. 3”.

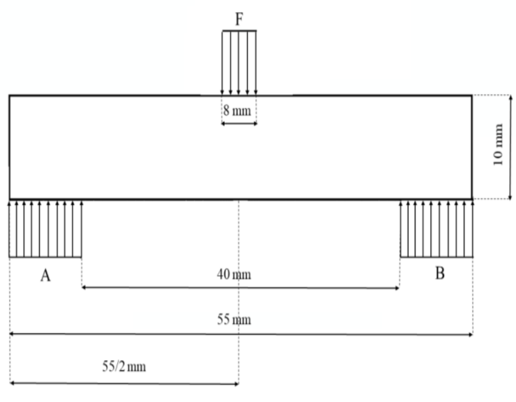

Fig. 3 Schematic of the forces applied to the Charpy impact test.

The Charpy impact test was repeated 5 times for each sample and the mean fracture energy was obtained. This Charpy machine is extrude by an energy display system and can be read digitally from the monitor screen on the sample fracture energy. Charpy impact samples in a standard group dimensions after failure are shown in “Fig. 4”. Complete failure of the specimens and separation into two parts indicate the accuracy of the test.

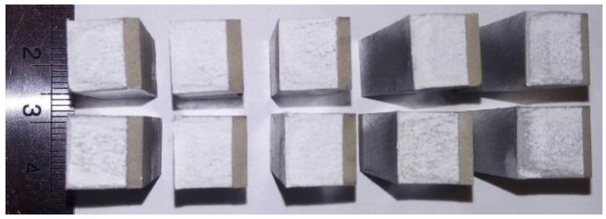

Fig. 4 A standard Charpy sample group after failure.

4 RESULTS AND DISCUSSION

By performing Charpy impact tests on laboratory specimens by changing the notch tip radius (the notch tip radius sizes is 0.19, 0.22, 0.25, 0.28, 0.31, 0.34, 0.37 and 0.40, respectively), the fracture energy of the specimens was measured. Then the average fracture energy of 5 samples from each notch tip radius was obtained which is shown in “Table 3”.

Table 3 Charpy impact test results for different notch tip radius

No.	Notch tip radius (mm)	Fracture Energy (J)	Description
1	0.19	7.43	
2	0.22	7.66	
3	0.25	8.78	Standard Sample
4	0.28	8.52	
5	0.31	8.52	
6	0.34	9.35	
7	0.37	10.90	
8	0.40	11.37	

Figure 5 shows the Charpy fracture energy diagram in terms of the notch tip radius of the specimens, which is considered a linear relationship.

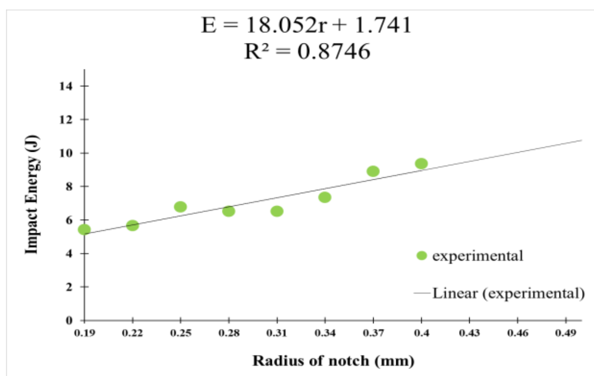

Fig. 5 Fracture energy diagram by norch tip radius with standard sample.

Two methods are employed to ensure the linear relationship obtained:

1- Remove the standard sample from the experimental data and paste the standard sample data into the obtained relation and determine the linear relationship error percentage.

2- It is based on the Irwin relation according to the Neuber results and expresses the relationship between the notch tip radius and the stress intensity factor [21].

$$\left.\begin{array}{l} K=\dfrac{\sqrt{\pi}}{2}\lim\limits_{\rho\to 0}\sigma_{Max}\sqrt{r} \\ \\ E=\dfrac{K^2}{2}(1-\nu^2) \end{array}\right\} \Rightarrow E\approx r \qquad (1)$$

In this relation, K is the stress intensity factor, r is the notch tip radius, σ is the maximum stress, E is the fracture energy and Poisson's coefficient. From the "Eq. (1)", the relation between the fracture energy and the notch tip radius is linear.

Figure 6 shows the Charpy fracture energy diagram in terms of notch tip radius regardless of the fracture energy with the standard notch tip radius.

According to "Fig. 5", the Charpy energy can be obtained from the following "Eq. (2)":

$$E = 18.052r + 1.741 \qquad (2)$$

In this relation, E is the impact energy in terms of joules and r is the notch tip radius in terms of millimeters. Using Equation (2) and by setting the standard value of the notch tip radius (0.25 mm), the Charpy fracture energy value of 8.25 j is obtained, which is in agreement with the experimental results (8.78 j, Less than 7% error). One of the benefits of the linear relationship is that, by knowing the notch tip radius (arbitrary), one can determine the fracture energy of the sample for this aluminum.

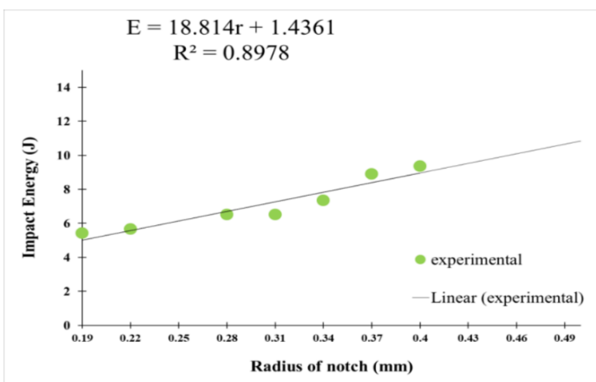

Fig. 6 Fracture energy diagram by norch tip radius without standard sample.

5 FRACTURE CHARACTERISTICS

Figure 7 shows the fractured Charpy specimens for the base metal .The crack propagation for the tested samples in longitudinal direction ("Fig. 7") was aligned to the normal impact force.

In transverse direction, the crack propagation describes a zigzag pattern. These characteristics were ascribed to the granular structure morphology [9].

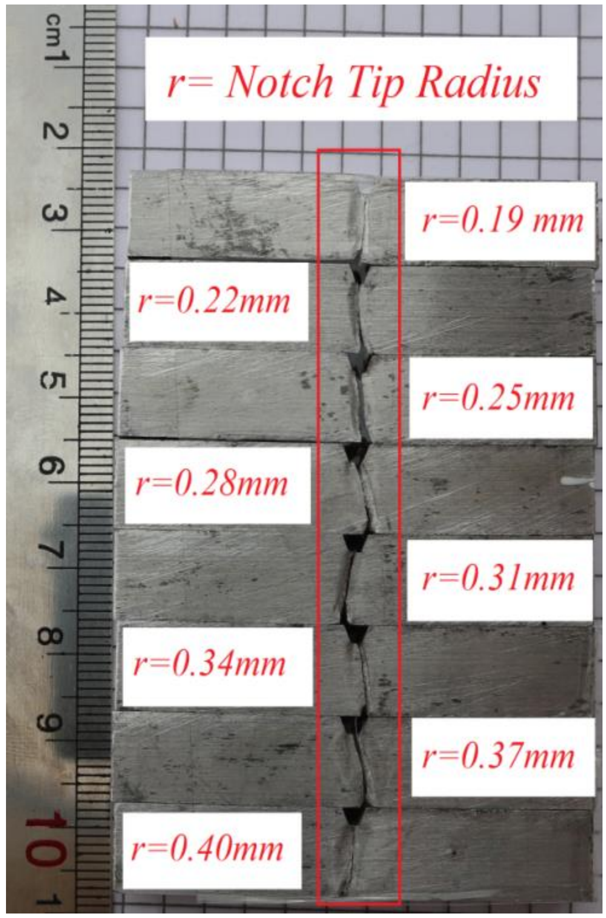

Fig. 7 Crack propagation in Charpy V-notch specimens.

The elongated grains produced by the high deformation of the material in longitudinal direction ("Fig. 8(b)") increase the strength but decrease its ductility [22]. This aspect promulgates the propagation of the crack along grain boundaries following a straight path (brittle fracture). On the other hand, in transverse direction, the granular structure tends to be less elongated ("Fig. 8(c)"), i.e., there are more barriers to propagate the crack. This structure produces a propagation of the crack as a function of the grain morphology (intergranular propagation), and a certain quantity of the impact energy is consumed during the plastic deformation [9].

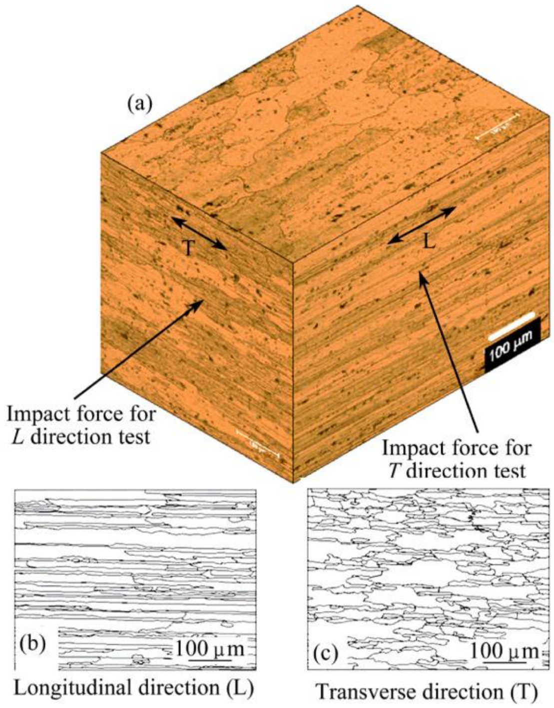

Fig. 8 (a): Granular structures of AA7075, (b): longitudinal and (c): transverse, to rolling direction planes, respectively [22].

Figure 9 shows a general view of the fracture appearance of the Charpy specimen for the tasted metal. A brittle fracture was observed for the tasted metal, where characterized by a flat surface without lateral expansion.

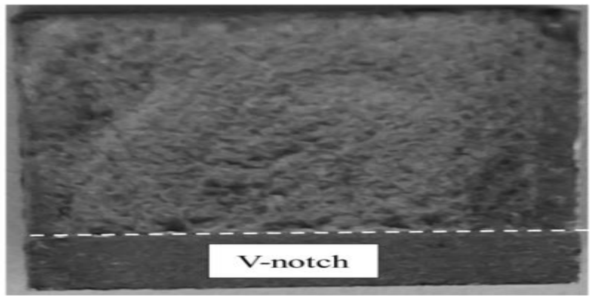

Fig. 9 General characteristics of fracture surfaces for standard sample.

Figures 10 and 11 show the SEM microgragh of the Charpy fracture surfaces for the specimens showing different notch tip radus (ranging from 0.19 to 0.40 mm) at different magnifications (500X, 1000X, 2500X, 5000X). Several crack initiation sites were observed. These cracks were propagated along grain boundaries practically with no dimple formation, i.e., quasi-brittle fracture. However, with increasing notch tip radius, brittle fracture characteristics prevail with some ductile evidences reflected by fibrous zones, as well as the presence of some dimples. These features tend to slightly increase the ductility of the material, i.e., fracture impact energy increment.

Further details of the fracture surfaces are presented in higher magnifications (On the right of Fig. 10 and Fig. 11). An intergranular fracture was observed for the tasted metal. In metals, this fracture mechanism is typically related to intergranular corrosion. with increasing noch tip radius, cracked particles were observed and some microvoids were nucleated, i.e., ductile fracture.

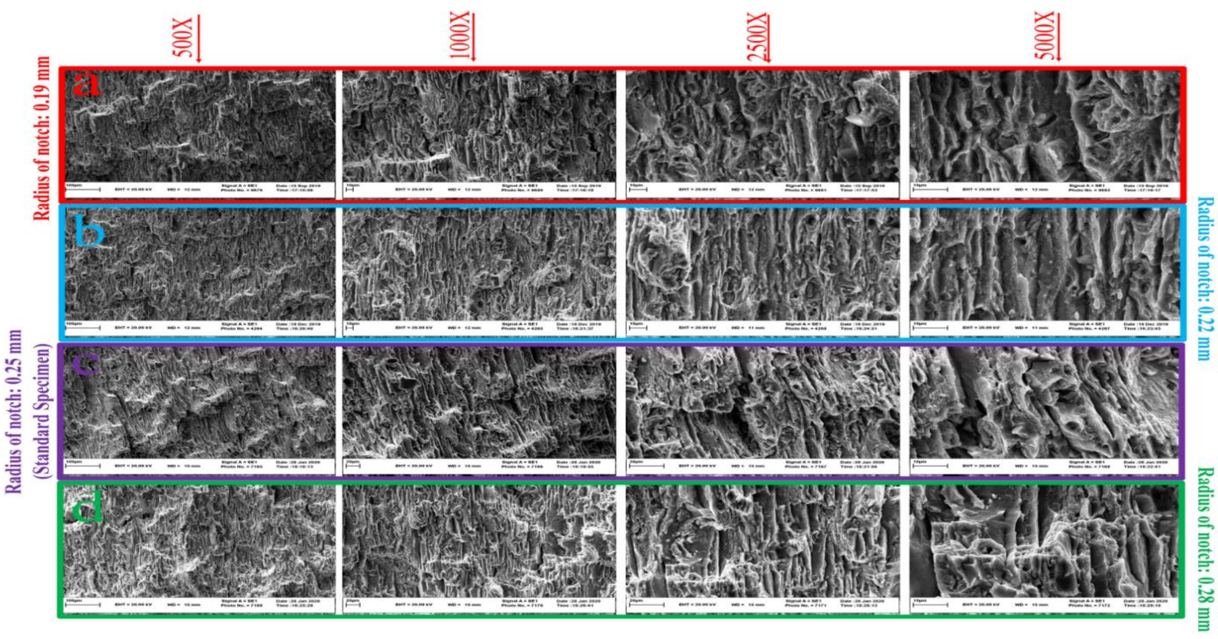

Fig. 10 Fracture surfaces for tasted samples (range from 0.19 to 0.28 mm).

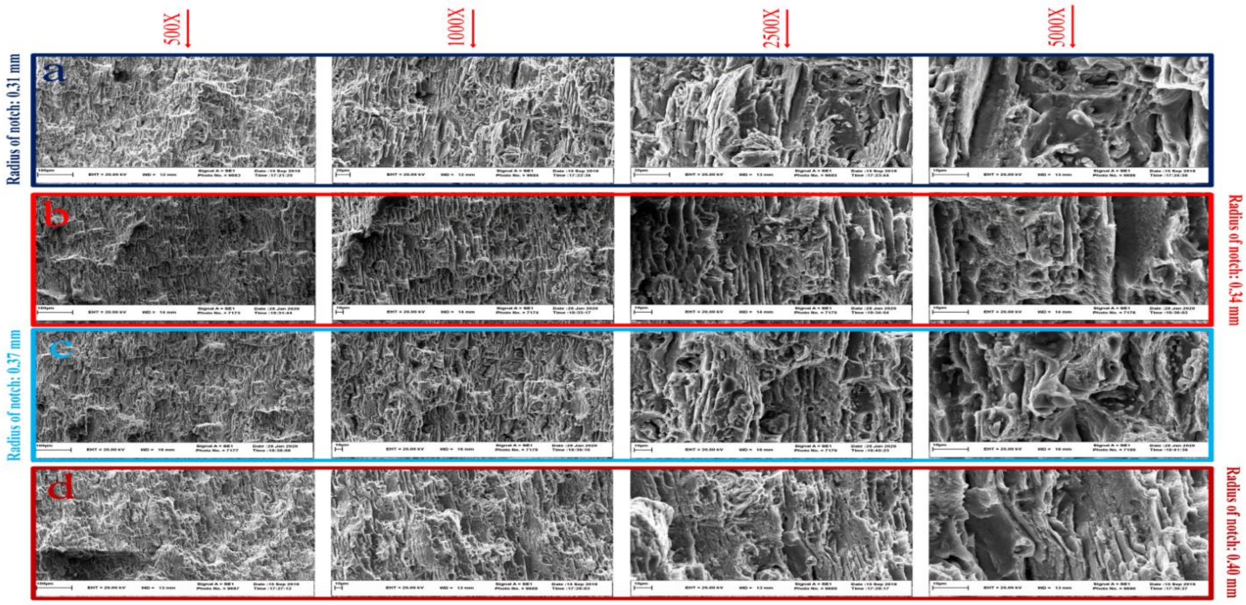

Fig. 11 Fracture surfaces for tasted samples (range from 0.31 to 0.40 mm).

7 CONCLUSION

In the present study, the effect of notch tip radius on Charpy fracture energy in Aluminium 7075-T651 was investigated. 40 samples were tested in seven sample series (each sample 5 times) with a non-standard notch tip radius as well as a standard series (5 samples). The Charpy impact machine used in this experiment had the capacity of 45 joules, which is selected according to ASTM E23.Using SEM imaging of the fractography of 8 different samples, the results are summarized as follows:

By increasing the notch tip radius, the energy of the Charpy fracture increases linearly according to knowing this relationship, the exact amount of Charpy fracture energy for each desired notch tip radius in the tested aluminium can be calculated.

The value of impact energy obtained from the experimental relationship for the standard sample with a notch depth of 2 mm is 8.25 J, which is in good agreement to the value of the experimental test (8.78 J). The interpolation error of the empirical relation for calculating the standard sample fracture energy is 6%.

By increasing notch tip radius, cracked particles were observed and some microvoids were nucleated, i.e., ductile fracture.

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