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Effect of V-shaped Side Groove on Shear Lips Formation of Aluminium Alloy 6061 by Charpy Impact Test

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ABSTRACT

This study investigates the effect of V-shaped side grooves on shear lip formation in aluminium alloy 6061 through Charpy impact testing. Aluminium is used in machines and industry as a structural component due to its mechanical properties, lightweight characteristics, easy fabrication, and high specific strength. The presence of a V-shaped side groove alters the stress distribution during impact, potentially influencing the deformation behaviour and fracture characteristics of the material. In this work, the impact tests were conducted on specimens with and without a V-shaped side groove, and the resulting shear lips formation was analysed. The findings reveal that the V-shaped side groove minimises shear lip formation compared to specimens without side grooves. This can be attributed to the surface morphology, which shows a lesser shear lip area with an increasing side groove depth ratio. A smaller shear lips area in Charpy impact tests signifies reduced plastic deformation near the groove or notch region. It indicates the material's fracture characteristic has lower ductility and limited ability to deform plastically before a fracture occurs. This implies decreased energy absorption capacity, equated to impact energy, and an increased likelihood of brittle fracture behaviour as the side groove depth ratio increases. The micrograph of the fracture surface shows dimples, shear, and cleavage patterns.

1. Introduction

The use of aluminium alloy 6061 (AA6061) in the automobile sector can reduce vehicle weight and increase fuel efficiency, which aligns with environmental objectives [1]. AA6061 has advantages such as corrosion resistance, machinability, and heat treatability, making it a popular choice for extrusion and structural purposes. It exhibits excellent bearing and wear qualities, and when a crack occurs in AA6061, the breadth of the cracked body determines the extent of plastic deformation at the crack tip, known as shear lips, which affects the fractured body's malleability [2,3].

The execution of standard fracture toughness experiments is costly and complex, leading to the successful utilisation of the Charpy impact test to assess the ability of aluminium alloys to resist

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dynamic cracks [4]. Some studies have used side grooves in Charpy impact test samples to mimic plane strain conditions and analyse high-toughness steels on smaller scales [5]. However, including side grooves in Charpy impact tests has been found to increase the ductile-to-brittle transition temperature and decrease the upper shelf energy, attributed to the rise in stress triaxiality caused by lateral restraint [6].

Previous research by Asry and Harimon [7] explores the effect of side grooves on shear lip formation in AA6061 using Finite Element Analysis (FEA). The study aims to understand how the presence of rectangular-shaped side grooves' depth ratios of 0, 0.1, 0.2, and 0.25 influence the fracture behaviour of the alloy. The findings have implications for improving the design and performance of structures utilising AA6061. Meanwhile, research done by Suresh and Harimon [8] emphasised the shape of the side groove, which is V-shaped, with ratios of 0.1, 0.3 and 0.5 and its impact on the shear lips formation using the same software and impact testing. The study focuses on understanding the alloy's fracture behaviour and impact energy with and without side grooves. The findings provide valuable insights into the role of V-shaped side grooves in shear lip formation and fracture behaviour, aiding in optimising the alloy's performance for different applications.

This study focuses on examining the failure and cracking behaviour of AA6061 in transportation, equipment, and daily applications. The fracture behaviour of AA6061 was investigated by using the Charpy impact test. Experimental comparisons were made with benchmark samples, considering factors such as impact energy, shear lips, and fracture morphology. The study's objectives include determining the impact energy and evaluating the shear lips ratio of the AA6061 with and without V-shaped side grooves, investigating the effect of side groove depths on impact energy and shear lips ratio, and studying the fracture surface morphology of the specimens. The findings will contribute valuable insights into the fracture behaviour of AA6061 and the potential benefits of incorporating V-shaped side grooves.

2. Methodology

The AA6061 is widely used in various applications, especially in the automotive sector. The specific characteristics and values of this alloy in the experiment are listed in Tables 1 and 2.

Table 1
Composition of the AA6061 [9]

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	
								Each	Total
0.04 – 0.08	0.70	0.15 – 0.04	0.15	0.8 – 1.2	0.04 – 0.35	0.25	0.15	0.05	0.15

Table 2
Mechanical properties of the AA6061 [9]

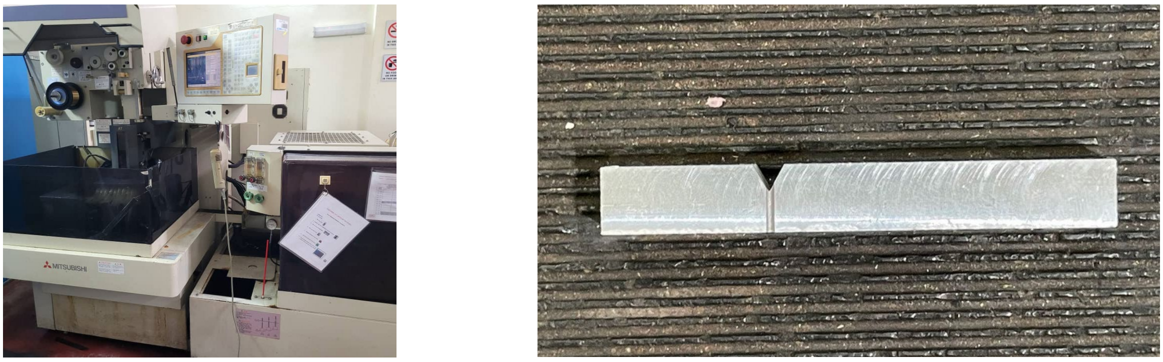
Ultimate Tensile Strength (MPa)	Tensile Yield Strength (MPa)	Brinell Hardness (500kg load/ 10 mm ball, HB)	Elongation at break (1.6 mm, %)
289.58	241.317	95	10

To ensure accurate fracture results, the specimen for the designated Charpy impact test machine must be accurately done. Therefore, the size of the specimen was established before initiating the experiment. The study considered the presence of a notch when constructing the specimen for fracture analysis. There are 4 types of specimens were used, with side groove depth ratios of 0, 0.2, 0.4 and 0.6. The specimen was rectangular with a single V-shaped notch. The dimensions of the specimen were determined to be 75 mm in length, 10 mm in width, and 10 mm in depth, conforming to ASTM A370 standards. The V-notch angle of the specimen was calculated to be 60°. The specifications of the AA6061 sample used in this study are listed in Table 3.

Table 3
The size configuration of the Charpy impact test specimens

Type (Specimen Model)	Unit (*mm*)
Depth	10.0
Length	75.0
Width	10.0
V-notch angle	60°

Wired electrical discharge machining (EDM), which is shown in Figure 1(a), was used to create precise notches and side grooves (see Figure 1(b)) by cutting and removing material. This involved passing an electrically charged wire through the workpiece, causing electric discharges that shaped it horizontally. The Mastercam app was used to draw the notch and side grooves, and G-code programming was established based on their dimensions. AA6061 samples with notches and V-shaped side grooves were obtained with everything set up.

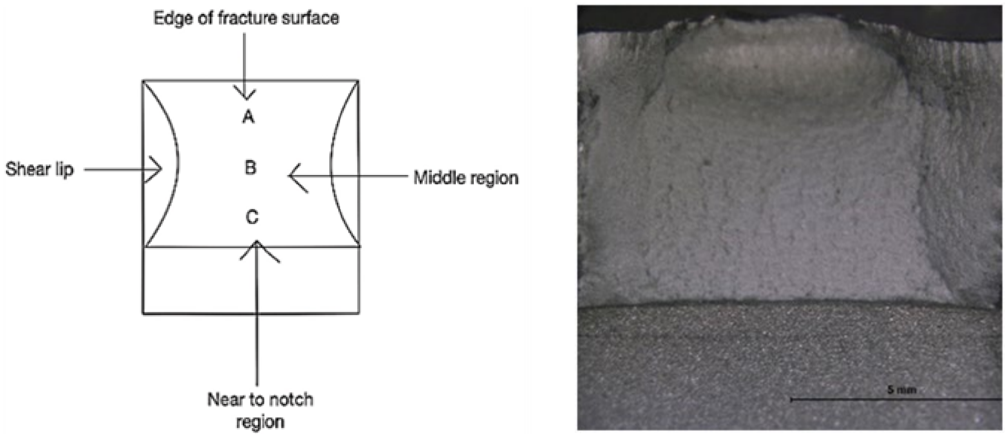


(a) (b)

Fig. 1. (a) EDM wire cut machine and (b) AA6061 specimen with side grooves

The Charpy impact test was done using the Charpy impact equipment of Wolpert with a maximum capacity of 50 Joule, located in the Metallurgy Laboratory, Faculty of Mechanical Engineering and Manufacturing, Universiti Tun Hussein Onn Malaysia (UTHM). The energy value displayed on the testing machine is recorded, representing the impact energy absorbed by the specimen. The process is repeated for multiple specimens to ensure statistical validity.

Shear lips formation is further analysed where the scanning electron microscope (SEM) was utilised to observe the near notch, middle region, final cracked, and side groove portions of the fracture surface, as shown in Figure 2. Depending on the specimen breaking time, each surface has a distinct form of structure, such as a dimple or cleavage. All the surfaces were reviewed and analysed after the specimen was split into two sections. Optical microscopy was done first to see the overall fracture surface as shown in Figure 2.



(a) (b)

Fig. 2. The formation of shear lips (a) schematic diagram (b) Actual sample

3. Results

3.1 The Effect of Side Groove Depth Ratio on Impact Energy and Shear Lips Ratio

Data was collected in this study using a Charpy impact test machine at room temperature for samples with varying side groove depth ratios (see Table 4). The data shows a pattern where the side groove depth ratio increases from 0.0 to 0.6 mm/mm, and the impact energy decreases. As the ratio of side groove depth to groove length increases, the material or structure becomes less resistant to impact forces. Additionally, as the side groove depth increases from 0 to 3 mm, the impact energy also decreases. This implies that deeper side grooves reduce impact resistance [10]. Therefore, the table suggests that increasing the side groove depth or the depth ratio weakens the material or structure's ability to absorb energy during impact, resulting in lower impact energy [11]. As we know, the lower a metal absorbs the energy to fracture, the closer it is to brittle behaviour [12]. Figure 3 shows the impact energy gradually decreased as the side groove depth ratio increased, indicating a decrease in the specimen's ability to absorb impact energy.

Table 5 summarises the shear lips ratio of different side-grooved aluminium 6061 samples at room temperature. A significant decrease is observed between side groove depth ratios of 0 and 0.2, while minimal changes occur between 0.4 and 0.6. This indicates that the total thickness reduction of the specimen should not exceed 0.25B, with a recommended decrease of 0.20B [13]. The side groove depth and the total fracture surface area influence fluctuations in the shear lips ratio. Figure 4 reveals that all ratios exceed 10%, indicating ductile fracture behaviour in the specimens rather than brittle fracture behaviour [14].

Table 4
Impact energy for different side groove depth ratio specimen

Side Groove Depth Ratio (mm/mm)	Side Groove Depth (mm)	Impact Energy (J)
0	0	26
0.2	1	21
0.4	2	18
0.6	3	16

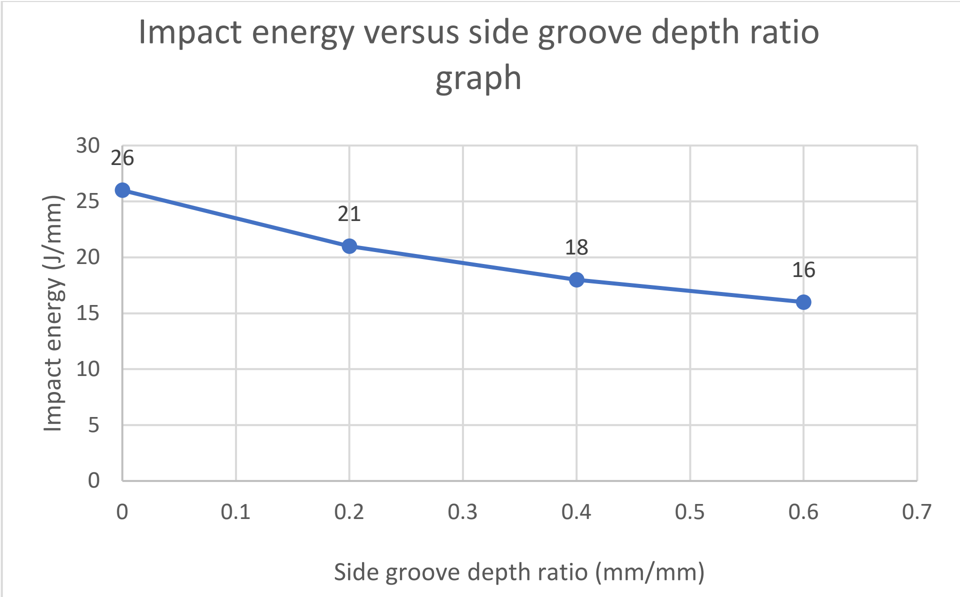


Fig. 3. Graph of impact energy versus side groove depth ratio

Table 5
Shear lips ratio of AA6061 with different side groove depth ratios at room temperature

Side groove depth ratio	Right			Left			Total fracture surface area (mm²)	Shear lips ratio (%)
	a (mm)	b (mm)	Shear lips area (mm²) ($A = \pi ab$)	a (mm)	b (mm)	Shear lips area (mm²) ($A = \pi ab$)		
0	6.1	1.1	21.08	6.1	0.95	18.2	58.6	67
0.2	6.0	0.16	3.0	6.0	0.16	3.0	53.5	11
0.4	6.1	0.095	1.8	6.1	0.08	1.5	39.0	8
0.6	6.1	0.095	1.8	6.1	0.095	1.8	25.6	14

However, the steep graph shown in Figure 4 indicates that plastic deformation is greatly affected and can be reduced by inducing a slight depth of side groove. The graph also illustrates a decreasing trend in the shear lips ratio as the side groove depth ratio increases, suggesting a transition from ductile to brittle fracture as the depth increases. Smaller shear lips ratios indicate a higher likelihood of approaching brittle fracture. Energy absorption is a key factor in Charpy impact testing and provides insight into specimen fracture, assessed after the specimen was fractured into two pieces. A smaller shear lips area in Charpy impact tests signifies reduced plastic deformation near the groove or notch region. It indicates the material has lower ductility and limited ability to deform plastically before a fracture occurs [15]. This implies decreased energy absorption capacity and an increased likelihood of brittle fracture behaviour as the side groove depth ratio increases [16].

In summary, the relationships observed in the previous data—decreasing total fracture surface area, decreasing shear lips ratio, and decreasing shear lips area with increasing side groove depth ratio—suggest a trend towards more brittle fracture behaviour, reduced material toughness, and limited energy absorption capacity in Charpy impact tests.

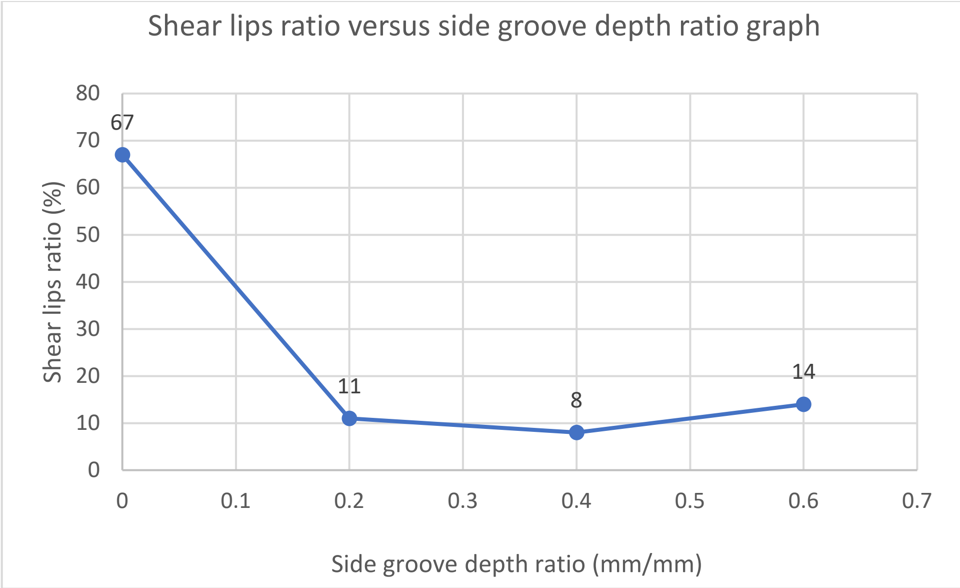


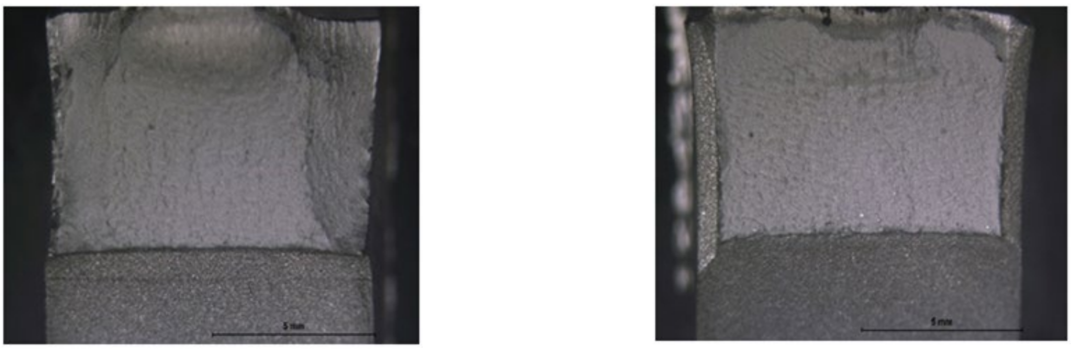
Fig. 4. Graph of shear lips ratio versus side groove depth ratio

3.2 The Effect of Side Groove Depth Ratio on Fracture Morphology

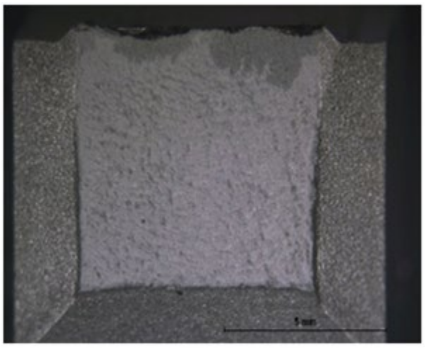
Figure 5 illustrates the shear lips formation after the impact test which resulted in its fracture into two separate pieces that were conducted under room temperature with a constant load rate applied to four types of specimens with different side groove depth ratios, which is 0.0, 0.2, 0.4 and 0.6. Based on naked eye observation, the formation of the shear lips area is most common on non-existent side groove samples and decreases as the side groove depth ratio increases. An increase in the shear lips ratio generally indicates increased plastic deformation in a material. It quantifies the extent to which the material has undergone plastic deformation and flow during fracture, which happened most on aluminium 6061 with no side groove [17].

As AA6061 undergoes plastic deformation, it means that it has undergone permanent changes in shape and volume due to the redistribution of stress. Plastic deformation occurs near the crack tip and is often associated with the formation of shear bands and material upward folding or protrusion, known as shear lips [18]. However, the formation of shear lips has been constant as the side groove depth ratio exceeds 0.2.

An increase in the shear lips ratio indicates a larger material deformation during fracture. It suggests that AA6061 of 0.0 side groove depth ratio has undergone greater plastic flow and displacement, absorbing more energy before fracturing. In other words, a higher shear lips ratio signifies a greater degree of plastic deformation and ductility exhibited by the AA6061. The facial crack for each sample was photographed using an optical microscope as shown in Figure 5 below.



(a) (b)


(c)

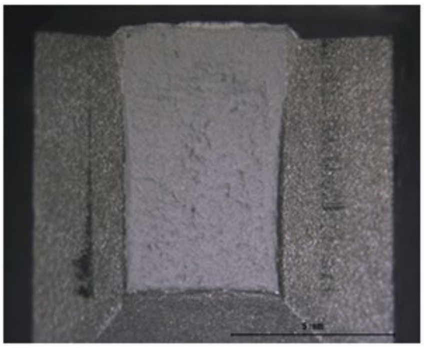

(d)

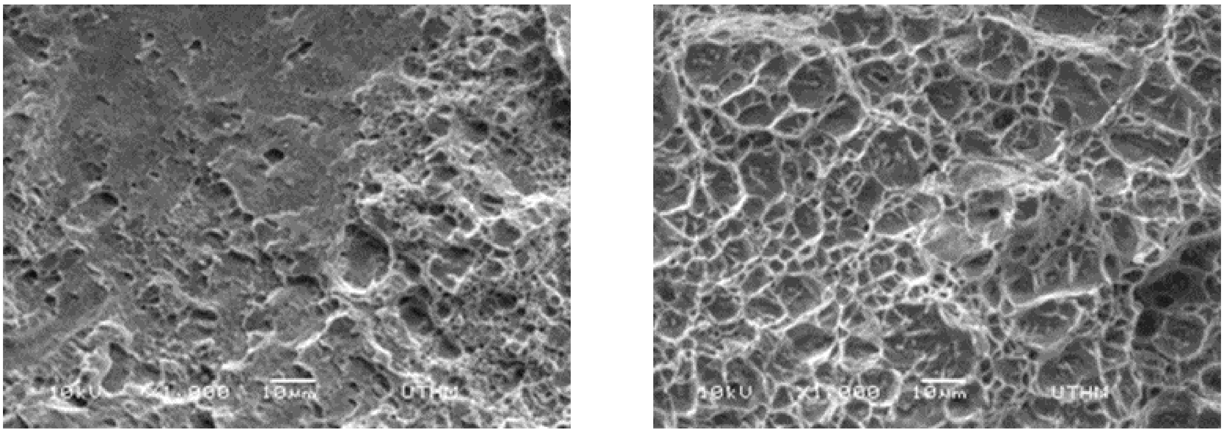
Fig. 5. Optical microscopy of AA6061 with different side groove depth ratios (a) 0.0 (b) 0.2 (c) 0.4 (d) 0.6

Fracture is a complex and successive phenomenon that involves various interconnected processes, such as plastic deformation, crack nucleation, and crack growth. These processes follow a generalised energy failure criterion, indicating the critical conditions under which a material fails. Figure 6 supports these insights, showing that cleavage occurs in the shear lips region due to the formation of plastic slips. Cleavage is observed when the material slides along a plane experiencing maximum shear stress, resulting in specific failure patterns. Additionally, the presence of dimples in the figure, formed by micro-voids at grain boundaries or inclusions, provides crucial information about the material's fracture behaviour, aiding the understanding of fracture mechanics and deformation processes [19].

Figure 6 also reveals important observations concerning dimple formation in samples with a side groove ratio greater than 0.0. This observation suggests the propagation of cracks in that region, significantly inhibiting larger plastic deformation. This inhibiting effect implies that certain configurations or conditions can influence the fracture behaviour of the material, leading to altered deformation and crack propagation patterns. Moreover, Figure 7 indicates that the initial phase of the fracture process is critical, as a considerable number of small dimples are observed in the vicinity of the notch region, signifying that most of the impact energy is consumed during the crack initiation stage [20].

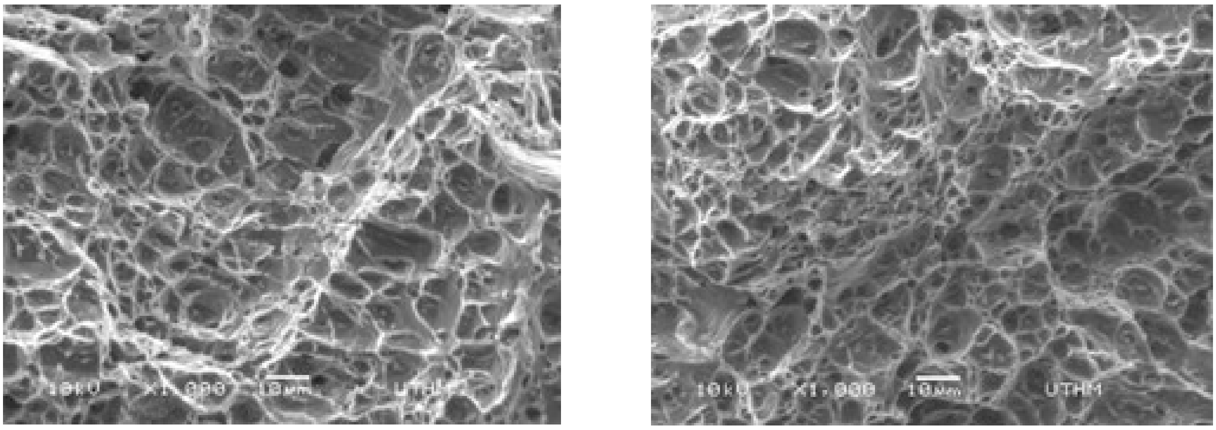
In the middle region, as depicted in Figure 8, the fracture mechanism of the AA6061 matrix alloy is predominantly characterised by dimple rupture. The fractography shows numerous cup-like dimples or depressions formed due to the presence of micro-voids, secondary solute-rich particles, dislocation of grain boundaries, vacancies, and similar defects at localised strain zones [21,22]. These localised strain zones act as nucleation sites, forming micro-voids that eventually coalesce, resulting in the observed dimple patterns.

Further insights from Figure 9 reveal the formation of shear bands during shock or impact events at the edges of the fracture surface. These shear bands play a critical role in the material's response to crack propagation, exhibiting higher resistance to this process [23]. Numerous shear bands on the otherwise smooth fracture surface of aluminium 6061 are crucial in determining the material's behaviour under impact or shock stimuli. These mesoscopic band-like deformation inhomogeneities contribute to the localised plastic deformation response when subjected to external forces, making them essential to understanding for engineers and researchers, especially in high-stress situations. Additionally, despite the prevalence of shear bands, observing dimples in samples with specific side groove configurations suggests that multiple factors, including the groove depth ratio and specific conditions, influence the material's response to fracture.



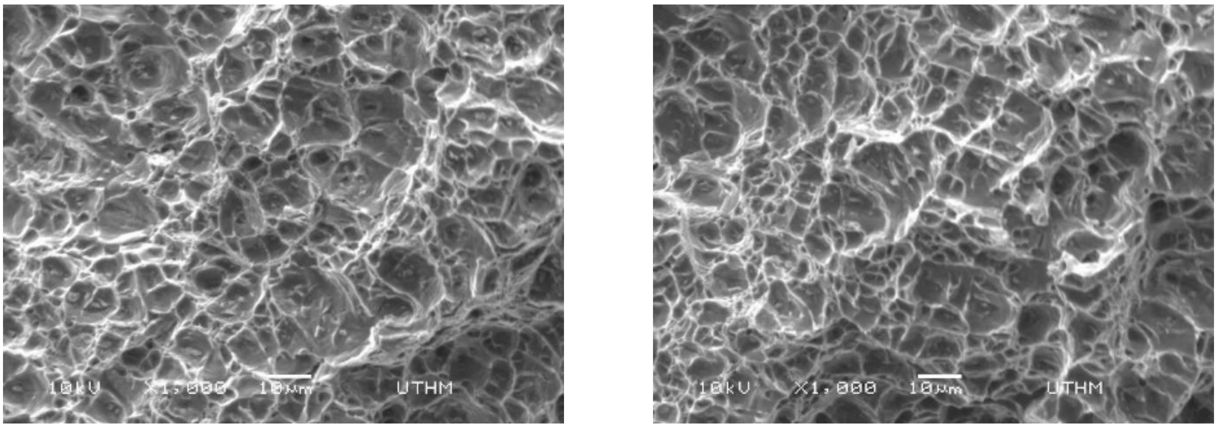
(a) (b)

Fig. 6. SEM micrograph of the fractured surface at shear lips region with side groove depth ratio of (a) 0.0 (b) 0.2



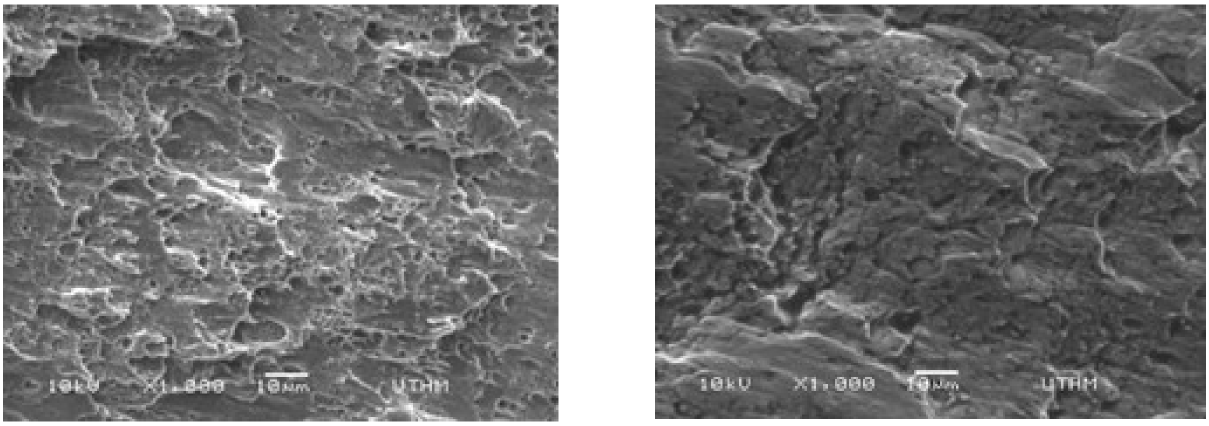
(a) (b)

Fig. 7. SEM micrograph of the fractured surface near the notch region with side groove depth ratio of (a) 0.0 (b) 0.2



(a) (b)

Fig. 8. SEM micrograph of the fractured surface at the middle region with side groove depth ratio of (a) 0.0 (b) 0.2



(a) (b)

Fig. 9. SEM micrograph of edge fractured surface region with side groove depth ratio of (a) 0.0 (b) 0.2

4. Conclusions

This study effectively achieved its objectives, providing valuable insights into the fracture behaviour of AA6061 under varying side groove depth ratios. A clear correlation between the depth ratio of the side grooves and the impact energy absorbed during fracture was demonstrated. The study found that the impact energy decreases as the side groove depth ratio increases. However, AA6061 with side groove depth ratios beyond a certain extent exhibited resistance to the criterion, such as a side groove depth ratio of 0.6, rendering it invalid for testing. Moreover, inducing side grooves led to a significant reduction in shear lips ratio. The fracture surface morphology was successfully examined revealing dimples, shear, and cleavage patterns with noticeable differences across the samples. These findings provide crucial evidence of how the side groove depth ratio influences the material's fracture behaviour, aiding researchers and engineers in material design and applications.

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