University of Baghdad
College of Engineering
JE
JOURNAL OF ENGINEERING

Journal of Engineering
journal homepage: www.jcoeng.edu.iq
Volume 32 Number 4 April 2026

Experimental Investigation of the Influence of Notch Geometry on Impact Resistance of Al/Cu Bimetallic Sheets

Shadi B. Ahmed*, **Paiman S. Salih**, **Hameed D. Lafta**

Mechanical and Manufacturing Engineering Department, Technical College of Engineering, Sulaimani Polytechnic University, Sulaymaniyah, Kurdistan, Iraq

ABSTRACT

The impact resistance of bimetallic materials is a critical aspect of engineering, particularly in the aerospace and automotive industries. Notched geometries are often encountered in real-world scenarios due to manufacturing defects or intentional design features. The present work investigates the impact resistance and fracture behavior of Al/Cu bimetallic sheets, focusing on the influence of notches on fracture energy, the fracture process zone, and overall failure mechanisms. For interpretation and analyses purposes, the impact test results were integrated with SEM fractographic analysis and the Essential Work of Fracture (EWF) framework. Four notch dimensions of U and V geometries were tested. Experimental results indicated that U-notches yielded higher fracture toughness and lower stress concentration factors. Conversely, V-notch specimens experienced a 32.5% reduction in toughness and a 25.5% increase in stress concentration as notch depth increased. Also, the Analytical EWF predictions showed good agreement with experimental data provide that Al/Cu obey the fracture ductile behavior. The SEM images emphasized on the ductile fracture nature of the Al/Cu sheet, and U-notches reveal a wider and rougher fracture area shows larger FPZ. As well, as the Al layer exhibited ductile plastic deformation, while the Cu layer showed brittle cleavage and acted as a structural hinge to arrest cracks. These findings provide critical insight into enhancing the use of bimetallic metals under dynamic loading, establishing a basis for future investigations into the relationship between bimetallic parameters and fracture behavior.

Keywords: Charpy test, Al/Cu bimetallic sheet, Notch geometry, Impact resistance, Essential work of fracture (EWF).

1. INTRODUCTION

In recent years, Al/Cu bimetals have been widely used due to their combined mechanical, physical, and functional properties, such as lightweight characteristics, high impact resistance, high tensile strength, wear resistance, corrosion resistance, and appropriate electrical and thermal conductivity **(Avcı and Erdoğdu, 2021; Alaie et al., 2021;**

---

*Corresponding author

Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2026.04.11

Article received: 04/01/2026
Article revised: 26/03/2026
Article accepted: 27/03/2026
Article published: 01/04/2026

Motamedi et al., 2024; Yousefi Mehr and Toroghinejad, 2024). Laminated metals are applied in various fields, including electrical components such as wires and tapes, as well as in aerospace applications such as landing gear, control surfaces, actuator bushings and bearings, wing flap bearings, wheel bearings, brakes, door hardware, hydraulic actuators, valves, and steering joints **(Kaya, 2018; Trzepieciński et al., 2021; El Etri et al., 2022; Wang et al., 2025).**

Notched geometries are frequently encountered in real-world components due to manufacturing defects or intentional design features. Notches are important sources of stress concentration in engineering structures and therefore play a critical role in safety design **(Hertzberg, 1995; Rösler et al., 2007).**

Several experimental studies have investigated the influence of notch geometry on the impact behavior of metallic materials. **(Omiya et al., 2022)** examined the effect of notch shape and material strength on crack initiation and propagation in advanced high-strength steel sheets. Their digital image correlation results demonstrated that notch radius strongly affects stress triaxiality and equivalent strain distribution near the notch root. Similarly, **(Xu et al., 2025)** studied the low-speed impact behavior of marine aluminum alloy sheets using experimental and finite element approaches. They showed that impact velocity plays a dominant role in determining critical failure energy, whereas the influence of impact mass is relatively minor when the impact energy remains constant. Similarly, **(Hosseinzadeh et al., 2022)**, experimentally investigated the influence of tip radius notch and notch depth on the Charpy fracture energy of 7075-T651 aluminum alloy. From the results showed that decreasing the notch root radius significantly increases stress concentration and reduces absorbed impact energy, highlighting the sensitivity of impact toughness to notch geometry. The effect of notch geometry on fracture toughness has also been examined by **(Lee et al., 2025)**, who evaluated crack tip opening displacement (CTOD) for different notch shapes. Their results indicated that increasing the notch radius reduces stress concentration and enhances fracture toughness. In bimetallic and laminated composites, the roles of interfacial bonding and notch geometry have been widely studied. **(Li et al., 2018)** demonstrated that in Al/Cu laminated composites subjected to tensile loading, cracks tend to initiate at the interface due to mismatched mechanical properties. Brittle cleavage was observed in weakly bonded regions, while ductile tearing occurred in areas with stronger bonding. Similarly, **(Rahmatabadi, 2018)** investigated Al1050/Cu/MgAZ31ZB multilayered composites produced by accumulative roll bonding and reported that strong interfacial bonding enabled the material to behave monolithically under loading, thereby enhancing fracture toughness and energy absorption capacity.

These findings are consistent with more recent studies on welded and roll-bonded Al/Cu systems, which confirm that notch geometry and interfacial quality govern crack initiation and fracture mechanisms. **(Torabi et al., 2023)** analyzed the fracture behavior of friction-stir-welded AA7075–AA6061 and AA7075–Cu joints containing V-notches under opening-mode loading. Their results revealed that notch geometry significantly influences elastic–plastic fracture regimes and crack initiation behavior. More recently **(Motamedi et al., 2024)** experimentally investigated the notch strength of roll-bonded Al/Cu bimetal sheets under pure tensile and pure in-plane shear loading using U-notched specimens. The results confirmed strong interfacial bonding and showed that crack initiation occurred at the notch root across the entire specimen thickness, allowing the bimetal sheet to be treated as a monolithic material in fracture analysis.

For impact-related applications**(Kaya, 2018)** studied the impact toughness of explosively welded Al/Cu composites and reported that increased deformation hardening and higher explosive ratios reduced impact toughness. In addition, **(Yousefi Mehr and Toroghinejad, 2024)** numerically investigated the fracture behavior of Al/Cu composites under Mode I loading using finite element analysis. Their results showed that plastic deformation is more pronounced in the aluminum layer, whereas the copper layer exhibits more localized deformation ahead of the crack tip.

In addition to the above experimental investigations, several fracture mechanics-based studies have provided fundamental insight into the role of notch geometry and bi-material interfaces on crack initiation and propagation. These studies demonstrate that variations in notch radius significantly alter stress intensity factors, constraint conditions, and plastic zone development at the crack tip, thereby affecting fracture toughness and energy absorption capacity. Furthermore, fracture analyses of layered and bi-material systems have shown that elastic mismatch across interfaces leads to stress redistribution and possible crack deflection or interfacial separation under mixed-mode loading conditions **(Krishnan and Xu, 2013; Jiang et al., 2021**; **Lei et al., 2023)**. In this context, the Essential Work of Fracture (EWF) methodology has been increasingly optimized to accurately characterize fracture resistance in thin metallic sheets, providing improved reliability in separating essential and non-essential plastic work contributions **(Hilhorst et al., 2022)**. Incorporating these fracture mechanics principles is therefore essential for interpreting the impact response of roll-bonded Al/Cu bimetal composites. Despite these efforts, the literature reveals a lack of systematic experimental studies addressing the combined effects of notch geometry and notch dimensions on the impact resistance and fracture toughness and characterizing how the asymmetric interface of Al/Cu bimetallic dictates the transition between ductile and brittle failure under varying notch geometries of Al/Cu bimetallic sheets.

Therefore, the present study aims to experimentally evaluate the impact resistance and predict the analytical estimations of the total fracture energy of Al/Cu bimetallic sheets with different notch geometries and dimensions. The SEM fractography of the fractured surfaces is integrated with estimations of fracture energy to identify and explore the fracture characterization of failed specimens under dynamic impact loading conditions.

2. MATERIALS AND METHODS

2.1 Selection of Materials

The material of the bimetallic sheet used in the present study consists of Aluminum (Al 1060) and Copper (Cu C1100) metal, which were joined together by a bonding rolling process. According to the manufacturer's fact sheet, the sheet is subjected to heat treatment after the production process. The bimetallic sheets were produced with a fixed percentage thickness ratio of 80/20 for each millimeter of Al/Cu bimetal sheet thickness. The bimetallic sheet mechanical properties and thickness of Al-Cu are shown in **Table 1.**

Table 1. Bimetallic sheet mechanical properties and thickness ratio.

Sheet metal	Tensile Strength N/mm^2	Elongation %	Hardness (HV 0.3)	Thickness (mm)
Al	70	25	27	1.2
Cu	235	20	95	0.3
Al/Cu	70	30	-	1.5

2.2 Preparation of Samples

To meet the required dimensions, the specimens are prepared before the notching process. Accordingly, all (24) sample specimens were cut in a rectangular shape, in the rolling direction, with dimensions of (10) mm width, (55) mm length and (1.5) mm thickness according to the standard of **(ASTM E23-02a, 2002; ISO 148-1, 2016).** Specimen preparation and impact testing were performed according to these guidelines to ensure reproducibility and comparability of results, as shown in **Fig. 1**. To provide precise dimensions in accordance with standard specimen preparation procedures and to ensure uniform cross-sectional areas before impact testing **(Romanowski et al., 2021; Harrigan et al., 2022)**, the cutting process was carried out by using a CNC machine fiber laser.

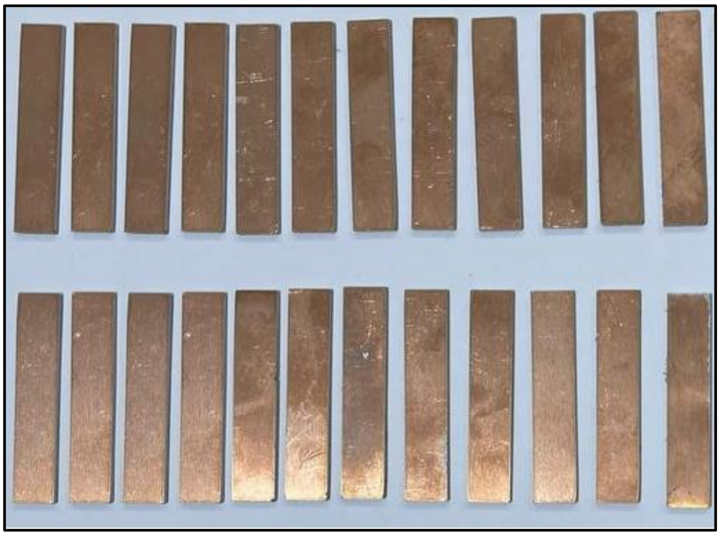


Figure 1. The rectangular shape of blank specimens.

2.3 Notched Specimens Preparation

The notched specimens were prepared from the blank samples with 12 samples of V-notched geometry and 12 samples of U-notched geometry according to **(ASTM E23-02a, 2002)** standard, as shown in **Table 2.** In the present study, the Al/Cu bimetallic sheets U and V notches of (1–4) mm depth were machined across the specimen width perpendicular to both layers of Al and Cu sheets, while the total thickness kept constant at 1.5 mm. The notches produced by the electric notching (JJANM) series machine as shown on **Fig. 2a**. Also, it is for mentioning that all the notched specimen dimensions were checked and measured by using JC- 10 readout 40X Brinell microscopic portable, shown in **Fig. 2b**. In additions, the Cu and Al layers were cut through the thickness direction, insuring that the crack propagation occurred through the thickness direction across both Cu and Al layers **(Wallin, 2022; Wong and Walters, 2025)**, as explained in **Figs. 3 and 4**. After the preparation of all specimens, the specimens were labeled according to their notches depth as shown in **Fig. 5**, to carry out the design of the experiments of the present work.

Table 2. Dimensions of Charpy Impact Specimens.

Notches type	Length (mm)	Width (mm)	Thickness (mm)	Notch depth (mm)	Notch angle (°)	Root radius (mm)
V shape	55	10	1.5	1, 2, 3, 4	45	0.25
U shape	55	10	1.5	1, 2, 3, 4	U-notch	0.35

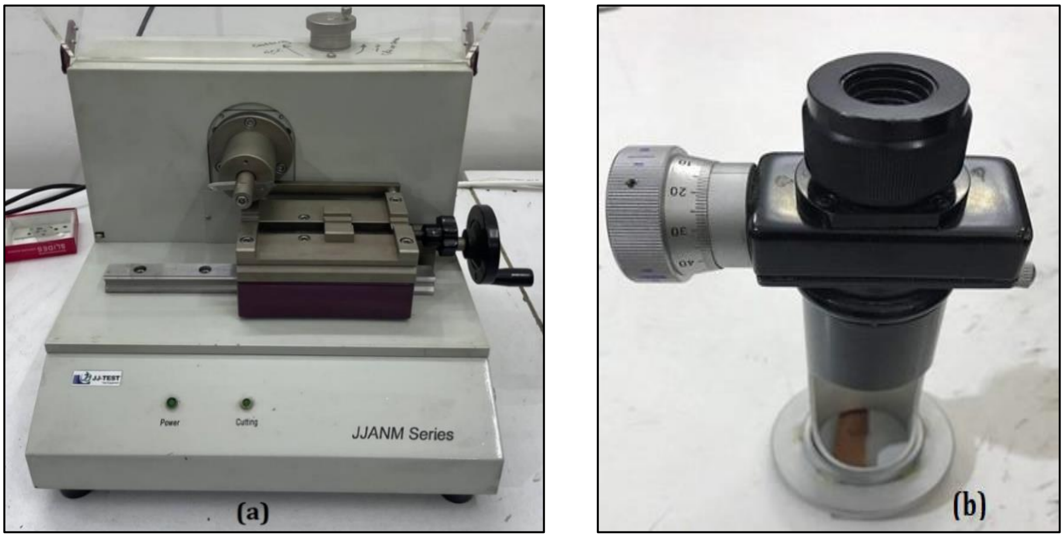


Figure 2. a) electric notching (JJANM) series machine, b) JC- 10 readout 40X Brinell microscopic portable

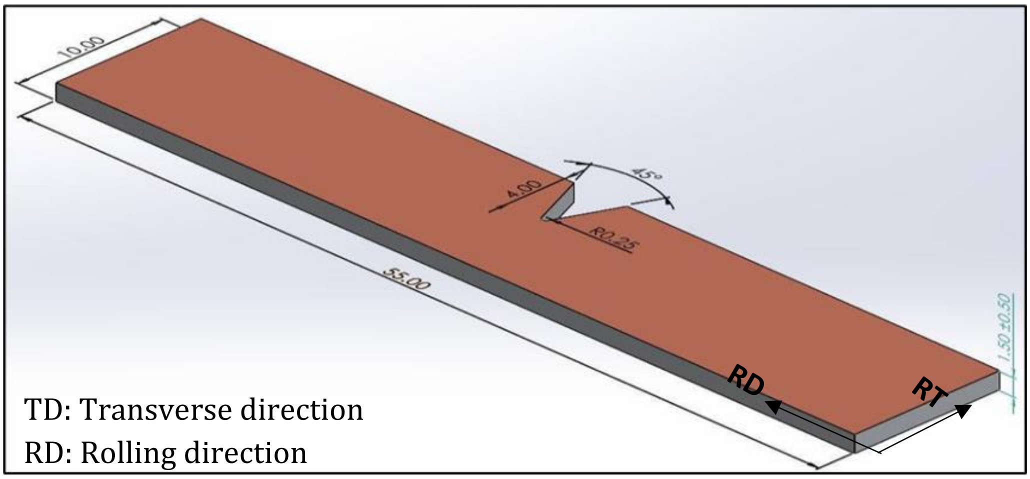


Figure 3. The standard shape and dimensions of the V- notch impact test specimens

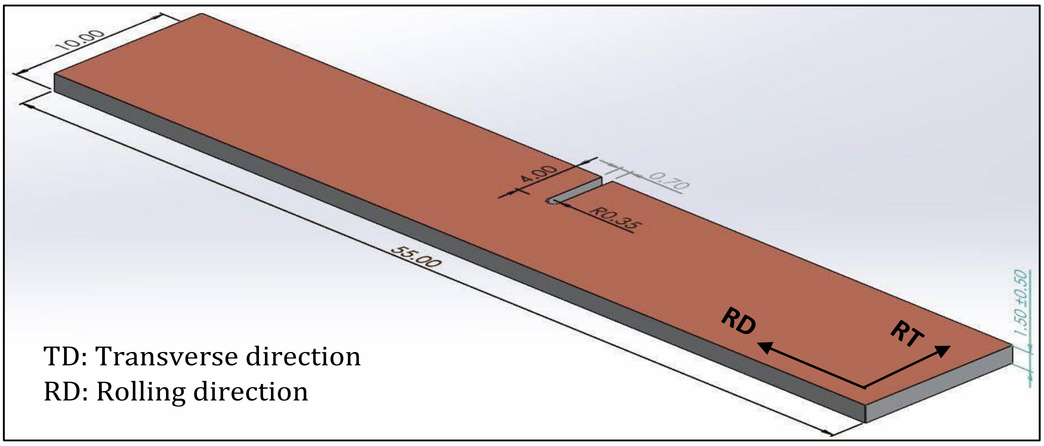


Figure 4. The standard shape and dimensions of the U- notch impact test specimens.

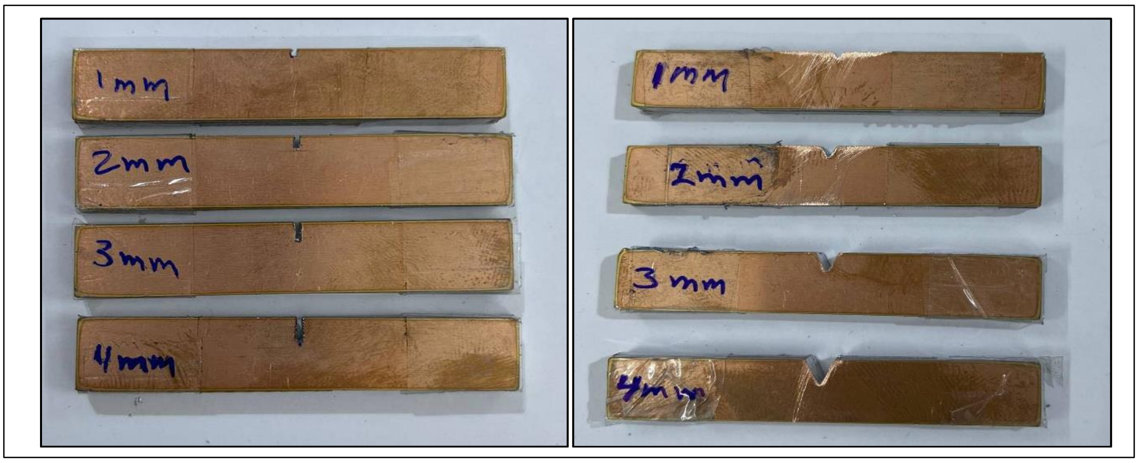
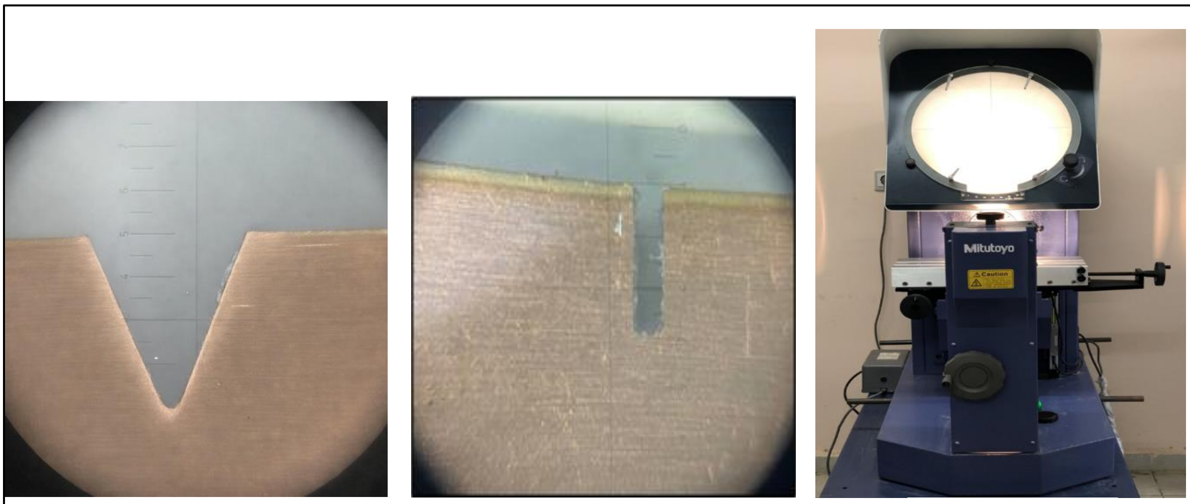


Figure 5. Specimen labelling for both U and V notches.

Before carrying out the tests, the samples were visually inspected for any surface flaws that may have resulted from the preparation process, and the U and V notches sizes were checked and measured by using JC-10 with readout of portable 40X Brinell microscopic and Optical comparator – profile projector (angle measurement), as shown in **Fig. 6.**



V-notch U-notch Notch angle

Figure 6. Measuring dimensions of U and V notches.

2.4 The Impact Test

All impact tests were performed using an XJJD-50 Pendulum Impact Tester configured in a Charpy (simply supported) configuration, in accordance with **(ASTM E23-02a, 2002).** The machine has a load of 1.27 kg (corresponding to 7 J of potential energy) and an impact velocity of 3.8 m/s. Each test specimen, either V-notched or U-notched, was positioned horizontally on two anvils of the tester, as illustrated in **Fig. 7**. The configuration of the Al/Cu specimen was installed during test, such that the Al layer face up and the Cu layer face down and the hammer was then released from its original height to strike the specimen through the thickness section. All tests were performed at room temperature. The absorbed impact energy was obtained directly from the machine digital readout, calculated as the difference between the initial potential energy and the residual energy after fracture. No additional correction factors were applied. This procedure was repeated for all specimens to ensure consistency in the experimental results.

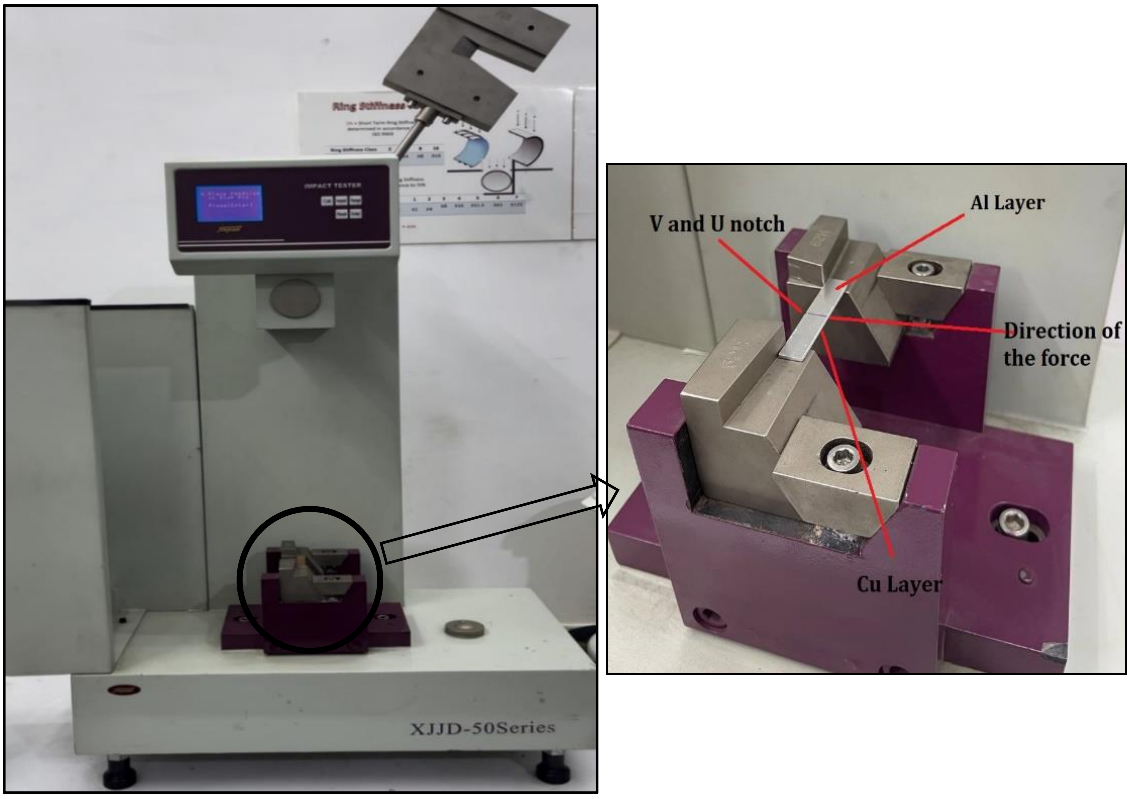


Figure 7. The impact test machine with Al/Cu specimen support setup.

3. ANALYTICAL CORRELATION WITH EXPERIMENTAL MEASUREMENTS

3.1 Correlation between Charpy Impact Energy and Fracture Toughness

The impact energy results, obtained by the Charpy impact test, can be further processed to correlate the relationship between the ruptured energy and fracture toughness of the bimetallic sheet of AL/Cu in terms of notch geometry and depth. Furthermore, the results can be extended to interpret the fracture nature and mode of fracture in such a composite material. Many researchers contributed to the prediction and formulation of accepted and reliable formulas to correlate between experimental energy measurements and the empirical or analytical trusted equations. Among these researchers **(Yousefi Mehr and Toroghinejad, 2024)**, cited that Rolfe-Novak-Barsom (RNB) formula may be the appropriate formula for predication of fracture toughness behavior based on the impact energy of the bimetallic sheet. This formula was adopted because the two base metals of the Al/Cu sheet are ductile. As well as, the bimetallic sheet produced by the roll bonding process, minimizes brittle intermetallic growth, the sheet will experience a high energy absorption as a typical behavior **(Lei et al., 2023)**. The RNB Rolfe-Novak-Barsom (RNB) formula is generally used to relate the upper-shelf Charpy impact energy impact energy to the fracture toughness for steels **(Yousefi Mehr and Toroghinejad, 2024)**. For ductile materials like aluminum and copper, the standard formula in (S.I. Unit) is presented in Eq. (1) by:

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 = 0.647\left(\frac{CVN}{\sigma_y} - 0.0098\right) \quad (1)$$

where:
K_{Ic}: Fracture Toughness (MPa√m).
CVN: Impact energy (J).
σ_y: Yield strength (MPa)

As well as the stress concentration factor can also be further applied to interrupt the nature of the bimetallic sheets under loading conditions for different notch geometries and sizes. The stress concentration factor is typically estimated using the relationship presented in Eq. (2) **(Yousefi Mehr and Toroghinejad, 2024)**:

$$K_t = 1 + 2\sqrt{\frac{d}{r}} \quad (2)$$

Where: d: notch depth and r: notch root radius.
Eqs. (1) and (2) are utilized in the subsequent sections to correlate analytically the experimental impact energy measurements with the fracture behavior of the bimetallic sheet. This approach enhances the analysis and interpretation of the effects of notches type and dimensions on the impact energy of the Al/Cu bimetallic sheet.

3.2 Prediction of Total Fracture Energy and Fracture Mechanism

The prediction of total fracture energy is essential for interpreting material failure under impact loading. By integrating these predictions with SEM fractographic analysis, the energy distribution during crack initiation, propagation, and final plastic deformation can be characterized. SEM was performed on four specimens representing the extremes of V and U notches at 1 mm and 4 mm depths under identical conditions to ensure a valid morphological comparison. This approach is assessed on explore the fracture behavior with the experimental measured energy levels. Consequently, the total specific fracture energy can be predicted using the Essential Work of Fracture (EWF) **(Hilhorst et al., 2022)**, presented by Eq. (3):

$$w_{f,p} = G_f + \beta w_p l \quad (3)$$

Where $W_{f,p}$: specific partial of work, G_f: specific fracture energy, β: the actual volume of the plastic zone, W_p: plastic work, and l: ligament length.

Based on experimental measurements of partial fracture energy, the specific total fracture energy can be predicted by applying the Essential Work of Fracture (EWF) analysis for partial ligament separation. For these purposes, linear regression is performed by plotting the partial fracture energy against the ligament length (l). By extrapolating this line to a zero-ligament length (l=0), the intercept on the energy axis (y-axis) provides the essential specific fracture energy (Gf) of total fracture. This approach was really followed in the present work to correlate between the experimental energy measurement and the SEM test results to identify the fracture behavior and morphology of fractured surface, which in turn help in finalizing the material failure in impact analysis of bimetallic sheets.

4 RESULTS AND DISCUSSION

4.1 Statistical Assessment of Notch Dimensions

Measurements of different dimensions of specimens, and notch dimensions require high level of accuracy of measurement and the statistical analysis of measurements must be carried out to verify the accuracy of produced geometries and enhancement of their validity with the standard test requirements. The overall measurements process of different dimensions of specimens and notches as shown in **Table 3.** are based on the following tolerances of instruments used in measurements process such as: Notch angle: ± 2 ^{o}, Notch depth: ±0.05 mm, and Notch root radius: ±0.02 mm. The statistical analysis caried out for one set of specimens, and the formula utilized to calculate the mean standard deviation is given by Eq. (4) below:

$$SD = \sqrt{\frac{\sum(x_i - \tilde{x})^2}{n-1}} \tag{4}$$

Where: x_i is the individual measurement and $\tilde{x}$ is the average of n specimens.

Table 3. The summarization of data analysis

Notch type	Notch depth (mm)	thickness (mm)	Width (mm)	Notch root radius (mm)	Notch angle (deg.)	Ligament area (mm^2)
V	1.05	1.55	10.05	0.23	43	13.950
V	1.95	1.45	10.05	0.23	43	11.745
V	3.05	1.55	9.95	0.27	47	10.695
V	4.05	1.55	9.95	0.23	43	9.145
U	0.95	1.45	10.05	0.37	-	13.195
U	1.95	1.55	10.05	0.37	-	12.555
U	3.05	1.55	10.05	0.37	-	10.850
U	3.95	1.45	9.95	0.33	-	8.700
Standard Deviation (s=1)	**1.2083**	**0.0518**	**0.0518**	**0.0668**	**-**	**1.8645**

The results gathered by statistical analysis for standard deviation of the different measurements of notch dimensions focused on that the accuracy measurements are acceptable and consistent from point of view of the notch geometry type and notch dimensions. Thus, the energy experimental results may be focused on exploring the actual effect of notch geometry and dimensions on metal fracture behavior and failure type rather than the effect of change in material bulk size. In general, these results provide sufficient statistical impact to verify the correlation between notch geometry, energy level, and failure mode of fracture **(Montgomery, 2019).**

4.2 The Impact of Notch Geometries on Fracture Toughness and stress Concentration

The experimental test results of the impact energy of the V-notch and U-Notch are shown in **Table 4.** respectively**.** The tests conducted for 8 specimens with three repetitions for each test, as appeared from the table, to ensure accurate measurements of the impact energy.

Table 4. Energy test results of V-and U notch specimens.

Test No.	Notch type and depth	Absorbed energy (J)			Average absorbed energy (J)
		Repetition 1	Repetition 2	Repetition 3	
1	V- Notch - 1 mm	3.825	3.975	4.010	3.936
2	V- Notch -2 mm	3.188	3.288	3.213	3.229
3	V- Notch -3 mm	2.570	2.620	2.562	2.584
4	V- Notch -4 mm	2.128	2.196	2.166	2.163
5	U- Notch -1 mm	4.080	4.160	4.020	4.086
6	U- Notch -2 mm	3.457	3.188	3.924	3.523
7	U- Notch -3 mm	2.762	2.814	2.957	2.844
8	U- Notch -4 mm	2.666	2.730	2.626	2.674

Based on the above experimental data and utilizing the fracture toughness expression and stress concentration factor given by Eqs. (1) and (2) respectively, the variation of fracture toughness and stress concentration factor with the notch depth for both types of notch geometries are depicted in **Figs. 8 and 9,** respectively.

The analytical estimations of the fracture toughness results reflect an inverse correlation between the notch depth and the fracture toughness for both U- and V-notch geometries, especially, for the V-notch geometry, and show a higher sensitivity to depth. Accordingly, for the V-notch type, the fracture toughness lowering from 12.13 MPa√m to 8.18 MPa√m, showing a 32.5% decrease, while 23.4 % decreases depicted in the fracture toughness of the U-notch type at the corresponding notch depth. This observation leads to the sensitivity of fracture toughness to notch depth, and geometry is particularly critical when applied to Al/Cu bimetallic sheets.

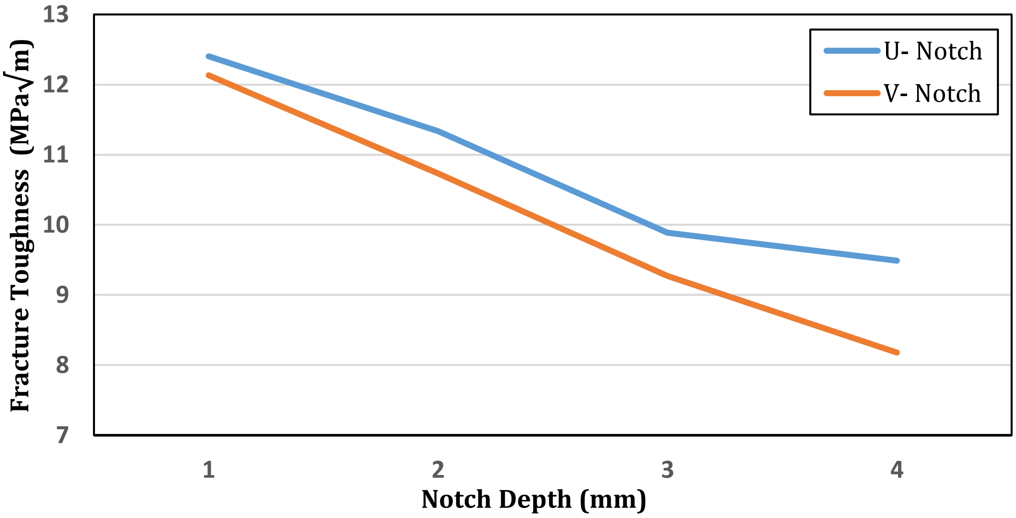


Figure 8. Variations of the fracture toughness with V and U notch depth.

This trend is confirmed by the results of the stress concentration factor given in **Fig. 9**, which indicates that the increase in the notch depth significantly increases the stress concentration factor. These differences at the same depths can be attributed to the effect of the notch root radius, whereas the U-notch, characterized by a blunter tip, depicts lower stress concentration values (ranging from 4.2 to 7.92), which assist a larger plastic zone at the notch root. For Al/Cu bimetallic sheet, this high geometric severity is critical, because it accumulates the strain at the Al-Cu interface, resulting in delamination of the layer interface before shifting the sheet toward dissipation of energy by the ductile Aluminum matrix and leading to a transition toward brittle interfacial failure **(Yousefi Mehr and Toroghinejad, 2024)**. Consequently, these findings are vital for the assessment of Al/Cu bimetallic sheet usage in the engineering industry.

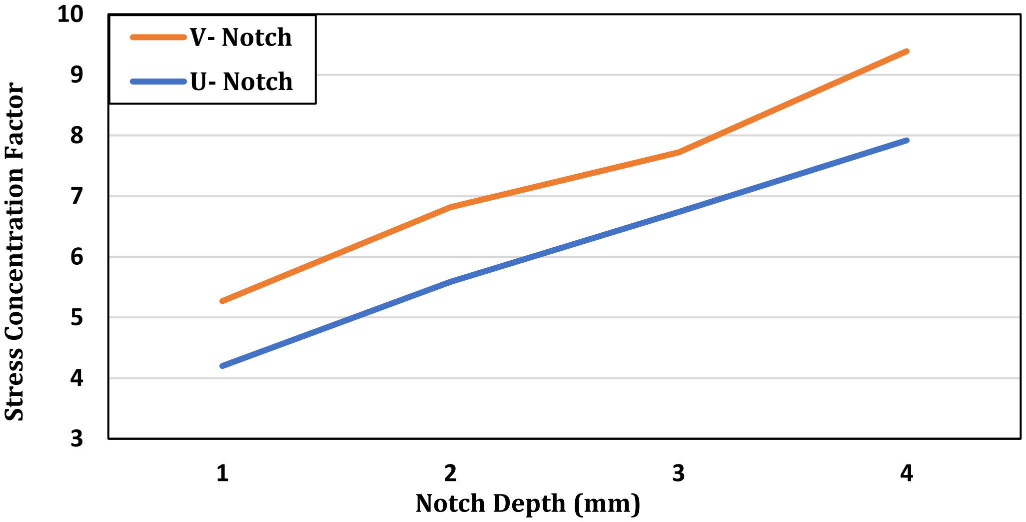


Figure 9. Variations of the stress concentration factor with V and U notch depth.

4.3 The Impact of Notch Geometries on Fracture Process Zone

The results of fracture toughness and the stress concentration factor were integrated with SEM fractographic analysis to verify the relationship between notch geometry (type and dimensions) and the fracture process zone of the Al/Cu bimetallic thin sheets. For this purpose, SEM testing was conducted on U- and V-notches with depths of 1 mm and 4 mm. To ensure the SEM results effectively correlate with analytical estimations of fracture toughness and stress concentration, all four tests were performed under similar conditions **Fig. 10**. The established testing parameters included a working distance (WD) maintained between 8.49 mm and 9.34 mm and a constant high voltage (HV) of 20.0 kV for all 500x magnifications, this ensures that visual comparisons are valid for interpreting the SEM results **(Schroeder et al., 2024).** In general, both U-notch SEM images reveal a wider and rougher fracture area. This surface morphology is consistent with a larger FPZ, where more extensive microcracking and widespread plastic deformation (likely microvoid coalescence leading to the visible dimples in the Al layer) occurred over a greater volume of material before the final fracture event. The wider zone suggests the material absorbed more energy before failure compared to the V-notch configuration, this morphology supports the higher toughness values you measured at 1 mm depths (12.40 MPa√m and 12.13 MPa√m). In contrast, the 4 mm V-notch image shows a smoother fracture surface in both layers, with less pronounced dimpling and some cleavage near the interface. This visual transition to a more brittle morphology directly explains the sharp decrease in measured toughness (8.18 MPa√m), as less energy was dissipated during crack propagation **(Lei et al., 2023)**. While, in point of view of the stress concentration results, the morphology of the U-notches fracture surface shows larger dimples in the Al layer with less concentrated fracture zone over the yielding of material before fully of crack propagation.

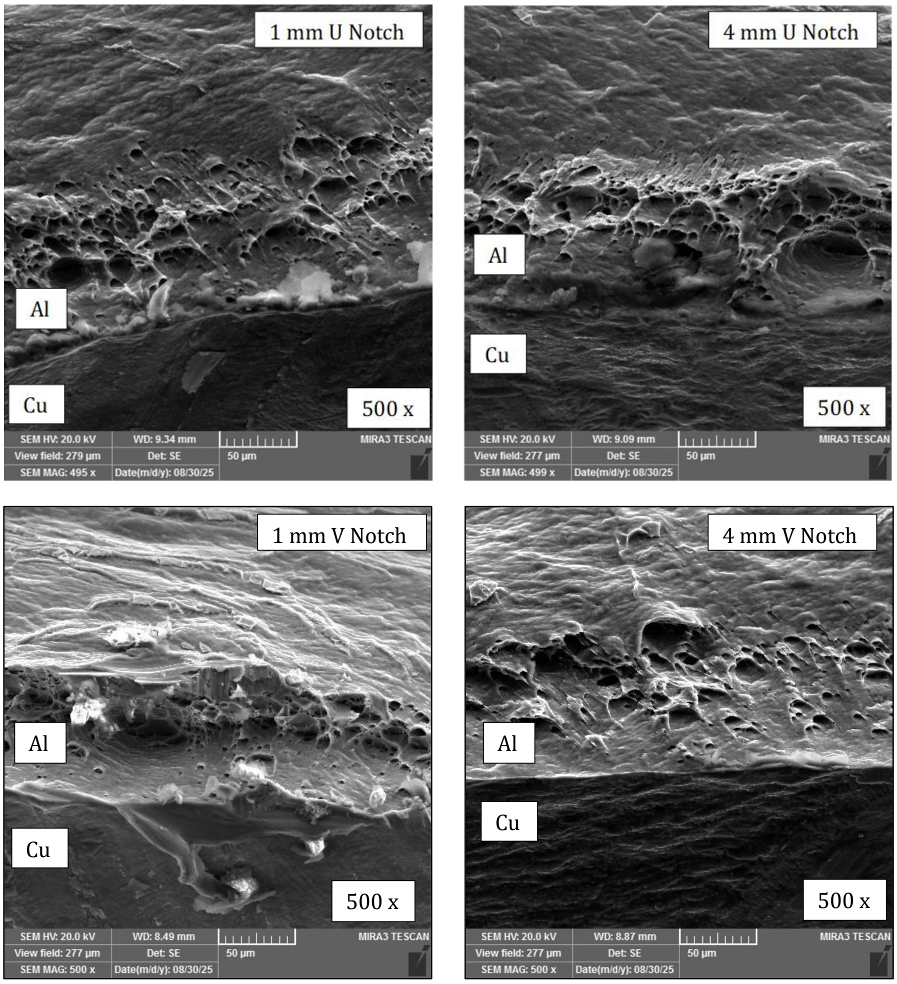


Figure 10. Impact fracture surface of V and U notches specimens (All SEM micrographs were captured at an intermediate cross-section of the fracture surface width).

This is attributed to the U-notches having a larger root radius (1 to 4 mm), which induces a lower stress concentration value permitting the induced stress to be distributed over a wider region. While, the V-notches have a smaller root radius (0.25 mm) this results in a higher values of stress concentration factor, thus the surface morphology show a ductile dimpling (micro-voids) in Al layer results in localization of plastic deformation and accelerate transition to brittle failure in Cu Layer **(Yousefi Mehr and Toroghinejad, 2024)**. Finally, these results introduce a critical understanding of how notch geometry and size dictate fracture behavior and lead to the reliability maximization in Al/Cu bimetallic sheets. These findings assist engineers to predict the failure in components of systems including geometric discontinuities or defects, providing more safety in engineering applications.

4.4 The Impact of Notch Geometry and Dimensions on Fracture Energy

The impact resistance energy measured in the present experimental represents the partial energy of fracture for all test specimens as appear clearly for the shapes of the fractured specimens after the impact test depicted in **Fig. 11**.

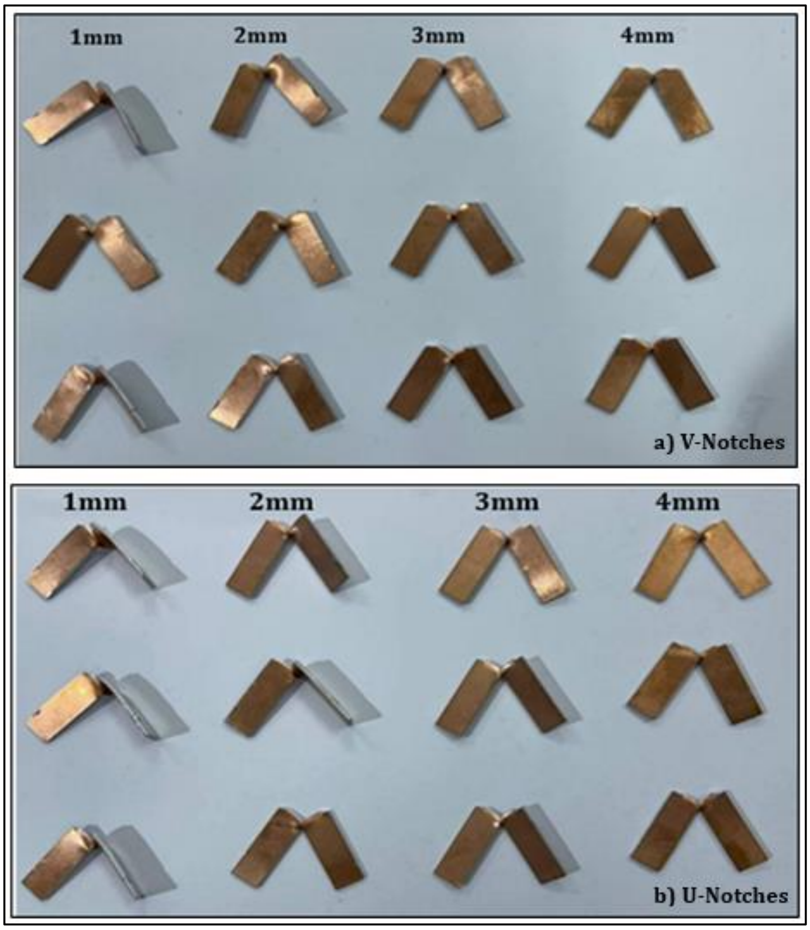


Figure 11. Fracture shape of the specimens after the impact test:
a) V-notches, b) U-notches.

For precise determination of the Al/Cu fracture mechanisms and total absorbed energy, the linear regression analysis based on the essential work fracture energy presented in Eq. (3) was carried out. The analysis yielding that the essential work of fracture (G_f) at zero ligament values, are (0.129 J/mm^2) and (0.2616 J/mm^2) for both V and U respectively, while, the plastic work component (βw_p) are (0.0177 J/mm^2) and (0.0039 J/mm^2) for both V and U respectively. The graphical presentation of the total fracture energy analytical predictions and the measured partial impact energy of both types of V and U notch geometries is depicted in **Fig. 12**. Consequently, these results demonstrate that the total specific work is partitioned into the essential work (G_f), representing the energy required for creation the plastic deformation surface, and the non-essential plastic work (βw_p), representing volume-dependent energy dissipation **(Pardoen et al., 2002)**. Also, the good agreement between the experimental data with the analytical predictions of fracture energy, revealed an accepted prediction of the required energy until full fracture of tested specimens irrespective of the non-separation of specimen's appearance, and, this appearance may reveal that the impact energy applied by the test machine absorbed by plastic deformation without the completion the specimens fracture **(Deng et al., 2022; Shajari et al., 2022)**, and the experimental test needs to be achieved on large scale impact test machines. Consequently, this evidence emphasized on the fact that the fracture behavior of the Al/Cu thin sheet obey the fracture theory for metallic sheets, thus, more experimental investigations can be carried out to explore the fracture performance under impact loading conditions for different bimetallic sheets process parameters.

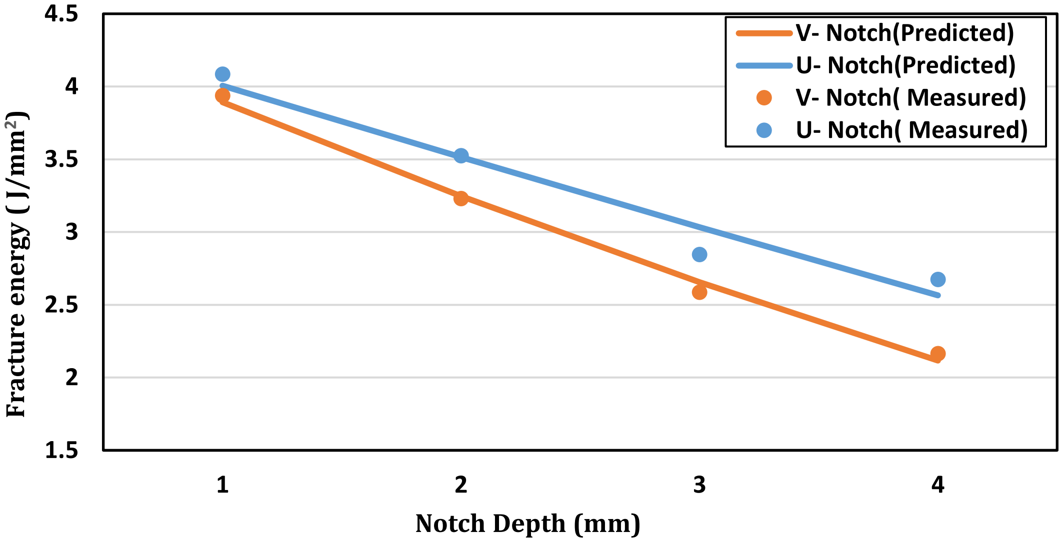


Figure 12. Correlation between measured experimental fracture energy and analytical estimations of total fracture energy.

Based on fracture energy and SEM fractography analyses, the fracture behavior of the Al/Cu bimetallic sheet under impact loading demonstrates an interactive relationship between notch geometry, energy partitioning, and microstructural morphology. The visual appearance of the fractured surfaces of 1 mm and 4 mm, of both V and U notches, revealing a ductile dimple rupture morphology characterized by a dimple distribution, **(Chen and Cao, 2015; Anderson, 2017)**. Whereas, the Al layer exhibits large, deep, equiaxed dimples, indicating extensive micro void coalescence, while the Cu layer shows fine dimples that act as a constrained structural hinge to resist crack propagation. Also, the intermetallic compound layer shows that the Al layer absorbs the most plastic deformation, but, the tougher Cu interface preventing more crack propagation throughout the deformation process, **(Chen et al., 2006; Wang et al., 2019; Xu et al., 2020).** In other words and from point of view of engineering perspective, these findings emphasized on the fact that the Al/Cu bimetallic sheets are an appropriate selection in engineering components ensuring that the material may withstand significant dynamic loads without catastrophic failure.

5. CONCLUSIONS

The impact resistance of Al/Cu bimetallic sheets was explored to determine the impact of notch geometry and dimensions. Experimental measured impact energy was validated against analytical total energy predictions, providing the following conclusions:

1- Comparison between experimental data and theoretical predictions confirms that the analytical EWF framework is valid for characterizing the impact performance of Al/Cu bimetallic sheets.
2- V-notches are more critical than U-notches, showing higher percentage reduction in fracture toughness (32.5% versus 23.4%), and greater stress concentration (25.5% versus 18.7%).

3- Increased notch depth (V-notches), localize strain, and increase stress concentration, leading to ductile dimpling in the Al layer, and brittle cleavage in the Cu interface.
4- Fracture behavior of Al/Cu bimetals makes it suitable for engineering applications requiring high impact toughness and resistance to catastrophic failure.
5- Selection of notch geometry is vital for the structural integrity of Al/Cu bimetallic components and impacts its dynamic resistance performance.

Credit Authorship Contribution Statement

Shadi Ahmed: Writing – review & editing, Methodology, Formal Analysis, Paiman Salih: writing original draft preparation, resources, Hameed Lafta: writing—review and editing; All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Alaie, A., Hashemi, R. and Kazemi, F., 2021. Investigation of forming limit diagram and mechanical properties of the bimetallic Al/Cu composite sheet at different temperatures fabricated by explosive welding. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 235(1–2), pp. 1–12. https://doi.org/10.1177/0954405420949227

Anderson, T.L., 2017. *Fracture Mechanics: Fundamentals and Applications. 4th ed*. Boca Raton: CRC Press.

ASTM E23-02a, 2002. Standard test methods for notched bar impact testing of metallic materials. ASTM International.

Avcı, U. and Erdoğdu, Y.E., 2021. Microstructure and mechanical properties of a semi-centrifugal compression processed Al6013 and Cu bimetal. *Materials Testing*, 63(5), pp. 471–478.

Chen, C.Y., Chen, H.L. and Hwang, W.S., 2006. Influence of interfacial structure development on the fracture mechanism and bond strength of aluminium/copper bimetal plate. *Materials Transactions*, 47(4), pp. 1232–1239. https://doi.org/10.2320/matertrans.47.1232

Chen, J. and Cao, R., 2014. Micromechanism of cleavage fracture of metals: a comprehensive microphysical model for cleavage cracking in metals. *Butterworth-Heinemann*. https://doi.org/10.1016/B978-0-08-100499-1.00001-7

Deng, Y., Zhang, C., Shao, J. and Li, W., 2022. Modeling the effect of temperature and notch root radius on fracture toughness. *Frontiers in Materials*, 9, 990314. https://doi.org/10.3389/fmats.2022.990314

El Etri, H., Korkmaz, M.E., Gupta, M.K., Gunay, M. and Xu, J., 2022. A state-of-the-art review on mechanical characteristics of different fiber metal laminates for aerospace and structural applications. *International Journal of Advanced Manufacturing Technology*, 123, pp. 2965–2991. https://doi.org/10.1007/s00170-022-10277-1

Harrigan, J., McClure, P., McNulty, R., McCabe, R. and Reddy, V., 2022. Towards standardizing the preparation of test specimens made with material extrusion: review of current techniques for tensile testing. *Additive Manufacturing*, 58, 103050. https://doi.org/10.1016/j.addma.2022.103050

Hertzberg, R.W., 1995. *Deformation and fracture mechanics of engineering materials. 4th ed.* Hoboken: John Wiley & Sons.

Hilhorst, A., Pardoen, T., and Jacques, P. J., 2022. Optimization of the essential work of fracture method for characterization of the fracture resistance of metallic sheets. *Engineering Fracture Mechanics*, 268, 108442. https://doi.org/10.1016/j.engfracmech.2022.108442

Hosseinzadeh, A., Farhangdoost, K., Maraki, M.R. and Sadidi, M., 2022. Investigation of the effect of notch tip radius and notch depth on Charpy fracture energy in 7075-T651 aluminium alloy. *International Journal of Advanced Design and Manufacturing Technology,* 13(2), pp. 65–72. https://doi.org/10.1080/00084433.2022.2066241

ISO 148-1, 2016. Charpy impact test on metals—Determination of impact strength using U-notch and V-notch specimens. International Organization for Standardization

Jiang, S., Zhang, H., Li, X., and Wang, J., 2021. Fracture mechanics analysis of bimaterial interface cracks using the generalized finite difference method. *Theoretical and Applied Fracture Mechanics*, 113, 102942. https://doi.org/10.1016/j.tafmec.2021.102942

Kaya, Y., 2018. Investigation of copper–aluminium composite materials produced by explosive welding. *Metals*, 8(10), P. 780. https://doi.org/10.3390/met8100780

Krishnan, A., and Xu, L. R. 2013. An experimental study on the crack initiation from notches connected to interfaces of bonded bi-materials. *Engineering Fracture Mechanics*, 111, pp. 65–76. https://doi.org/10.1016/j.engfracmech.2013.08.010

Lee, J., Jo, W., Seo, J. and An, G., 2025. Effect of notch shape on the fracture toughness behavior. *Journal of the Society of Naval Architects of Korea*, pp. 2092–6782. https://doi.org/10.1016/j.ijnaoe.2025.100646

Lei Z., Zhang B., Liu G., Zhao T., Zhang Z., Gao H., Cai J., and Wang, K., 2023. Study on microstructure evolution and fracture behavior of Al/Al/Cu multilayer composites. *Journal of Materials Research and Technology*, 25, pp. 5307–5317. https://doi.org/10.1016/j.jmrt.2023.07.014

Li, X.B., Yang, Y., Xu, Y.S. and Zu, G.Y., 2018. Deformation behavior and crack propagation on interface of Al/Cu laminated composites in uniaxial tensile test. *Rare Metals*, 39(2), pp. 296–303. https://doi.org/10.1016/S1003-6326(19)65069-7

Montgomery, D. C., 2019. *Design and analysis of experiments.* 10th ed. John Wiley & Sons.

Motamedi, M.A., Torabi, A.R. and Hashemi, R., 2024. Notch strength evaluation for highly ductile Al/Cu bi-metal fabricated by the roll-bonding technique under pure mode I and pure mode II loading conditions. *Theoretical and Applied Fracture Mechanics,* 129. https://doi.org/10.1016/j.tafmec.2024.104435

Omiya, M., Arakawa, S., Yao, Z., Muramatsu, M., Nishi, S., Takada, K., Murata, M., Okato, K., Ogawa, K., Oide, K., Kobayashi, T., Han, J. and Terada, K., 2022. Influence of strength and notch shape on crack initiation and propagation behavior of advanced high strength steel sheets. *Engineering Fracture Mechanics*, 271, 108573. https://doi.org/10.1016/j.engfracmech.2022.108573

Pardoen, T., Marchal, Y., and Delannay, F., 2002. *Essential work of fracture compared to fracture mechanics—Towards a thickness independent plane stress toughness. Engineering Fracture Mechanics, 69*(5), pp. 617–631. https://doi.org/10.1016/S0013-7944(01)00099-6

Rösler, J., Harders, H. and Bäker, M., 2007. Mechanical behaviour of engineering materials. *Berlin Heidelberg*: Springer.

Rahmatabadi, D., 2018. Fracture toughness investigation of Al1050/Cu/MgAZ31ZB multi-layered composite produced by accumulative roll bonding process. *Materials Science and Engineering* A, 734, pp. 427–437. https://doi.org/10.1016/j.msea.2018.08.017

Romanowski, M., Łukianowicz, C., Sutowska, M., Zawadka, W., Pimenov, D.Y. and Nadolny, K., 2021. Assessment of the technological quality of X5CrNi18 10 steel parts after laser and abrasive water jet cutting using a synthetic index of technological quality. *Materials*, 14(17), P. 4801. https://doi.org/10.3390/ma14174801

Schroeder C. J., Parrington R. J., Maciejewski J. O., and Lane, J. F., 2024. *Revised ASM handbook: Vol. 12: Fractography*. ASM International.

Shajari, Y., Ghasemi, R., Zarei-Hanzaki, A. and Abedi, H., 2022. Formation of intermetallic compounds in Al–Cu interface via cold roll bonding: A review. *Surface Engineering and Applied Electrochemistry*, 58(1), pp. 41–50. https://doi.org/10.3103/S1068375522010112

Torabi, A.R., Mirzavand, M., Saboori, B. and Cicero, S., 2023. Fracture behavior of AA7075–AA6061 and AA7075–Cu friction-stir welded joints containing blunt V-notches under opening-mode loading. *Materials*, 16. https://doi.org/10.3390/ma16030789

Trzepieciński, T., Najm, S.M., Sbayti, M., Belhadjsalah, H., Szpunar, M. and Lemu, H.G., 2021. New advances and future possibilities in forming technology of hybrid metal–polymer composites used in aerospace applications. *Journal of Composites Science*, 5(8), 217. https://doi.org/10.3390/jcs5080217

Wang, R., Zhao, Q. and Li, M., 2025. Interface microstructure and corrosion resistance of T2 Cu/6061 aluminum composites produced by explosion welding. *Journal of Materials Research and Technology*, 39, pp. 4745–4757. https://doi.org/10.1016/j.jmrt.2025.10.168

Wang, X., Li, F., Chen, S. and Cao, L., 2019. SEM analysis of microvoid coalescence and dimple morphology in ductile fracture of steels under dynamic loading. *International Journal of Impact Engineering*, 130, pp. 537–548. https://doi.org/10.1016/j.ijimpeng.2019.05.001.

Wong, W.J. and Walters, C.L., 2025. Damage mechanics model for correlating notch toughness in Charpy impact tests with fracture toughness in cracked static fracture tests. *Engineering Fracture Mechanics*, 320, 111043. https://doi.org/10.1016/j.engfracmech.2025.111043

Xu, S., Zhang, H., Shen, W., Luo, W. and Zhang, Y., 2025. Mechanical behavior of marine aluminum alloy sheet under low-speed impact resistance. *Chinese Journal of Ship Research*, 20, p.148. https://doi.org/10.19693/j.issn.1673-3185.03648

Yousefi Mehr, V. and Toroghinejad, M.R., 2024. Mode I fracture analysis of aluminum-copper bimetal composite using finite element method. *Heliyon*, 10(4), e26329. https://doi.org/10.1016/j.heliyon.2024.e26329

دراسة تجريبية لتأثير الشكل الهندسي للشق على مقاومة الصدمات لصفائح الألومنيوم/النحاس ثنائية المعدن

شادي بكر أحمد*، بيمان صديق صالح، حميد دويج لفته

قسم الهندسة الميكانيكية والتصنيعية، كلية الهندسة التقنية، جامعة السليمانية التقنية، السليمانية، كردستان، العراق.

الخلاصة

تُعدّ مقاومة الصدمات للمواد ثنائية المعدن جانبًا بالغ الأهمية في التطبيقات الهندسة، لا سيما في صناعات الطيران والفضاء والسيارات. غالبًا نصادف أشكالًا هندسية محززة في تطبيقات واقعية بسبب عيوب التصنيع أو سمات التصميم المعقدة. تبحث هذه الدراسة مقاومة الصدمات وسلوك الكسر في صفائح ثنائية المعدن من الألومنيوم/النحاس، مع التركيز على تأثير الشقوق على طاقة الكسر، ومنطقة عملية الكسر، والأداء الميكانيكي العام. لغرض تحليل النتائج وتعليلها، دُمجت نتائج اختبار الصدمات مع تحليل الماسح الإلكتروني (SEM) لسطح الكسر نظرية العمل الضروري للكسر (EWF). تم اختبار أربعة أبعاد للشقوق على شكل حرفي U وV. أشارت النتائج التجريبية إلى أن الشقوق على شكل حرف U تُنتج صلابة كسر أعلى ومعاملات تركيز إجهاد أقل. في المقابل، بينت عينات الشقوق على شكل حرف V انخفاضًا بنسبة 32.5% في الصلابة وزيادة بنسبة 25.5% في تركيز الإجهاد مع زيادة عمق الشق. كما أظهرت تنبؤات EWF التحليلية توافقًا جيدًا مع البيانات التجريبية، مما يُشير إلى أن الألومنيوم/النحاس يتبع سلوك الكسر المطيلي. أظهرت صور الماسح الإلكتروني طبيعة الكسر المطيلي لصفائح الألومنيومa/النحاس، وكشفت الشقوق على شكل حرف U عن منطقة كسر أوسع وأكثر خشونة، مما يدل على تولد منطقة كسر أكبر. كما أظهرت طبقة الألومنيوم تشوهًا لدنًا مطيليا، بينما أظهرت طبقة النحاس انشقاقًا هشًا وعملت كمفصل هيكلي لوقف انتشار الشقوق. توفر هذه النتائج رؤى بالغة الأهمية لتحسين استخدام المعادن ثنائية المعدن تحت التحميل الديناميكي، مما يرسخ أساسًا لدراسات مستقبلية حول العلاقة بين خصائص المعادن ثنائية المعدن وسلوك الكسر.

الكلمات المفتاحية: اختبار جاربي، صفائح الألومنيوم/النحاس، صفائح ثنائية المعدن، الشكل الهندسي للشق، مقاومة الصدمات، نظرية الشغل الضروري للكسر