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ORIGINAL ARTICLE

Wire cutting as a viable substitute for machining standardized V-notches for Charpy specimens

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Abstract
In engineering, selecting the right material is crucial, with toughness being a key property. The Charpy impact test is essential for assessing a material's ability to absorb energy during sudden loads, aiding in material selection, temperature behavior analysis, and heat treatment effects. Modern manufacturing technologies address materials with poor machinability, such as those in metalworking. Fabricating standardized Charpy specimens requires machining notches. While traditional milling methods are standard, there is growing interest in alternative processes like electro-discharge machining, which can replace milling without significantly affecting mechanical properties. This study evaluates the feasibility of wire electrical discharge machining with a conventional wire as an alternative to the standardized machining method for creating notches in Charpy specimens. The results show that for brass and AISI 1045 steel, no significant differences in resilience were observed between processes. However, the resilience of the aluminum specimens tested by Charpy with the WEDM notch was 28% lower than that of the machined specimens. This work demonstrates the potential of wire electrical discharge machining for manufacturing V-notches in Charpy specimens across a broad range of materials while preserving the sensitivity of the standard test. These findings highlight valuable insights for its application in various industries where impact toughness assessment is critical.

Keywords Charpy test · Resilience · Fracture surface · V-notch · Milling · Wire EDM

1 Introduction

In engineering, selecting the appropriate material for a specific application is critical. Among the key properties considered, toughness plays a pivotal role, with the Charpy impact test serving as an invaluable tool. This test measures the impact toughness of a material, indicating its ability to absorb energy under sudden loading conditions. The energy absorbed is particularly useful for (a) material selection, aiding in the choice of materials for applications requiring impact resistance, such as structural components in vehicles, machinery, or structures subject to dynamic loads; (b) evaluating temperature-dependent behavior, as toughness typically decreases at lower temperatures, crucial for components operating in cold environments, such as cryogenic pipelines or structures in frigid climates; and (c) analyzing heat treatments, since microstructural changes caused by such treatments can significantly affect toughness [1, 2].

Meanwhile, advances in manufacturing technologies have enabled rapid and precise fabrication of metal components, even from materials with poor machinability, as required by modern metalworking industries [3]. Among the diverse parts produced, test specimens used to characterize the mechanical behavior of metallic materials are noteworthy. Examples include cylindrical or flat specimens for tensile

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testing and Charpy specimens to determine absorbed energy during impact bending tests [4]. Although standardized test protocols for tensile [5] and impact testing [6] specify that reduced sections (in tensile specimens) and notches (in Charpy specimens) must be created through smooth machining methods (e.g., turning, milling, or broaching), alternative fabrication methods may offer practical advantages for industries with specific production constraints. For instance, Martínez Krahmer et al. [7], investigating tensile specimens of low-carbon steel and Inconel 718 across three thicknesses, compared conventional milling to four alternative methods: laser cutting, abrasive water jet (AWJ), wire electrical discharge machining (WEDM), and computer numerical control (CNC) punching. They concluded that AWJ was a viable alternative to milling, as it preserved mechanical properties equivalent to those obtained from milled specimens. Similar results were confirmed in a broader recent study [8], demonstrating consistent trends in tensile properties across various materials and thicknesses, namely, as ultimate tensile strength increases, percent elongation decreases when comparing milled specimens with respect to specimens cut with abrasive water jet.

In addition to exploring alternative manufacturing methods, researchers have also pursued cost-effective surrogate tests for industry and laboratories. Lucon [9] investigated alternatives to conventional Charpy tests for modern steels exhibiting high toughness and ductility (absorbed energy > 400 J). Promising results were achieved using notches cut with WEDM employing a 0.1-mm diameter wire, though this wire size is unconventional. Similarly, Martínez Krahmer et al. [10] studied a shorter-duration pin-on-disk test as an economical replacement for traditional machinability tests by turning, commonly used in steel mills [11, 12]. Here, WEDM is proposed, using a conventional 0.2-mm wire diameter, as an alternative method for machining V-notches in Charpy specimens. While WEDM has been previously applied to hard metals [13], miniature specimens (KLST type) [14], or materials requiring special notch modifications for fracture assurance [9], its application to standard Charpy specimens across a variety of materials remains unexplored. This work compares the geometry and surface integrity of notches produced by the standardized milling method and WEDM to ensure reliable Charpy test results. Such analyses are crucial to maintaining the test's sensitivity, which can differentiate energy absorption capacities of materials under various conditions, including temperature changes [15], aging treatments on AISI 316 LN stainless steel [16], specimen size variations [17], and different nickel contents in powder metallurgy steels [18]. Factors like notch radius, depth, angle, type, specimen size, and surface integrity significantly influence the Charpy test results [19]. For instance, Shahsavani and Hashemi [19] found that notch radii in the 0.25 ± 0.12 mm range resulted in less than ± 2% variation in impact energy for API X65 steel. In contrast, Hosseinzadeh et al. [20] reported a ± 24% variation in AA 7075 aluminum alloy. Similarly, notch depth variations of 2.0 ± 0.5 mm produced ± 24% differences in API X65 steel [21]. However, these effects can be mitigated by considering resilience as the absorbed energy divided by the area below the notch [22]. Notch angle studies, performed by Maraki et al. [23], indicate minimal differences near the standardized 45° angle (30–90° range). Lastly, the surface integrity of notches is critical, as surface defects can alter ductility and test results [24]. Lucon [14] found that EDM-produced Charpy notches showed a recast layer of up to 16 μm and hardness increases of 34–84%, depending on steel carbon content, with no observed microcracks. Following this research topic, this study comprehensively evaluates the capability of wire electrical discharge machining (WEDM) to cut V-notches in Charpy specimens made from five different materials. The analysis includes a comparison of geometric accuracy and Charpy impact test results at room temperature between WEDM and standard milled specimens. Additionally, chemical and mechanical characterizations, such as microhardness measurements and tensile tests, are conducted to assess the material properties after machining. The study further investigates surface integrity effects, including hardness variations and the depth of the affected layer. The novelty of this work lies in extending WEDM applications to standard Charpy specimens while identifying its limitations and advantages. This research aims to ensure that the sensitivity of Charpy testing is maintained while achieving suitable notch geometries and minimizing potential adverse effects on material properties and surface integrity.

2 Materials and method

The experimental work followed the UNE-EN ISO 148–1 standard as a reference for constructing the specimens. This analysis focuses on the impact of different cutting processes on the resilience of five common materials: low- and medium-carbon steels, austenitic stainless steel, and two non-ferrous metals. Initially, 40 specimens were made using these materials, two cutting methods (milling and WEDM), and four repetitions for each combination. Then, the focus was on ductile materials—aluminum, AISI 1010 steel, and AISI 304 stainless steel. For these materials, 42 specimens were tested with the same two cutting methods and six repetitions per material and method. Additionally, six AISI 304 stainless steel specimens were made using a fine WEDM. The second batch of tests was performed to avoid the influence of the notch radius on resilience, ensuring that the radii of the milled notches matched those of the eroded notches. The goal was to see how different cutting techniques impact material properties and resilience, with special attention to ductile materials and how they respond to the thermal impact from WEDM. Figure 1 shows the geometric and dimensional characteristics of a Charpy specimen, as specified in this standard. The specimens were prepared from square-drawn bars with a 10 mm side length to ensure microstructural homogeneity. All the Charpy tests were performed at room temperature. Table 1 shows the nominal chemical composition of ASTM and the Vickers hardness of each tested material.

The peripheral down milling was used to accomplish the standard and to have a gentle chip removal machining process. In this regard, peripheral down milling results in less surface impact, meaning less hardening and a thinner plastically deformed layer [25]. The milled notches were machined using a Promecor CNC milling machine equipped with a 12-mm diameter high-speed steel end mill, operating at a feed rate of 0.035 mm/tooth and a cutting speed of 15 m/min [26]. The notches created by WEDM were fabricated using a Novick AR 35 MA machine with a 0.2-mm molybdenum wire under roughing conditions—pulse on-time (ton) of 50 µs, pulse off-time (toff) of 180 µs, and open voltage (V) of 6 V—and finishing conditions—ton = 5 µs, toff = 34 µs, and V = 4 V [27]. Initially, the rough cutting method (more energy-intensive) was selected to provide greater generality to the study's conclusions, as this condition would result in the most significant impact on surface integrity [28]. Microhardness measurements at the core were performed using a Digimess Vickers microhardness tester (1 N and 2 N, 10 s). A LEICA MDI8 optical microscope with LAS 4.9 software measured the notch radius (see Table 2). Additionally, the cross-sectional areas beneath the notches were measured using a Starrett EC 799A-8/200 digital caliper. Impact bending tests were carried out on a Tinius Olsen pendulum with a capacity of 360.7 J (serial number 136055). The tensile tests were carried out on an Instron 3400 series machine with a 3-t capacity at a speed of 10 mm/min, using ASTM E8 subsize specimens with a 6 mm diameter in the reduced section. To analyze the impact of the notch radius deviation, the geometric factor that most affects resilience was considered [20]. Finally, Fig. 2 shows the flow diagram of the experimental work to summarize the methodology in the two batches.

3 Results and discussion

The results of this study are presented in the following subsections: impact bending tests and surface properties.

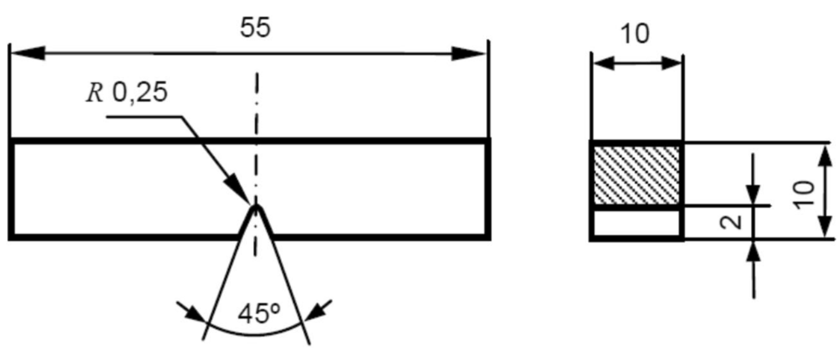

Fig. 1 Geometry and dimensions of a Charpy specimen [6]

Table 1 Chemical composition (%wt) and Vickers hardness of the evaluated materials

Material	C	Si	Fe	Cu	Mn	Cr	Zn	Pb	Ni	Al	HV2/10
Aluminum	–	0.44	0.25	0.08	0.04	0.005	0.07	–	–	Bal	61.6 ± 5.1
AISI 1010	0.10	–	Bal	–	0.45	–	–	–	–	–	242.0 ± 8.1
AISI 1045	0.45	–	Bal	–	0.75	–	–	–	–	–	283.6 ± 7.1
AISI 304	0.07	1	Bal	–	2	19	–	–	9	–	275.1 ± 16.7
Brass	–	–	–	57	–	–	40	3	–	–	179.4 ± 9.6

The steels presented P and S contents lower than 0.05

Table 2 Dimensions of the mean notch radius obtained via milling and WEDM processes

Parameter	UNE-EN ISO 148–1	Materials	Milling	WEDM
Notch radius (mm)	0.250 ± 0.025	Ductile & Brittle (1st batch)	0.303 ± 0.015	0.258 ± 0.008
		Ductile (2nd batch)	0.230 ± 0.011	0.258 ± 0.010

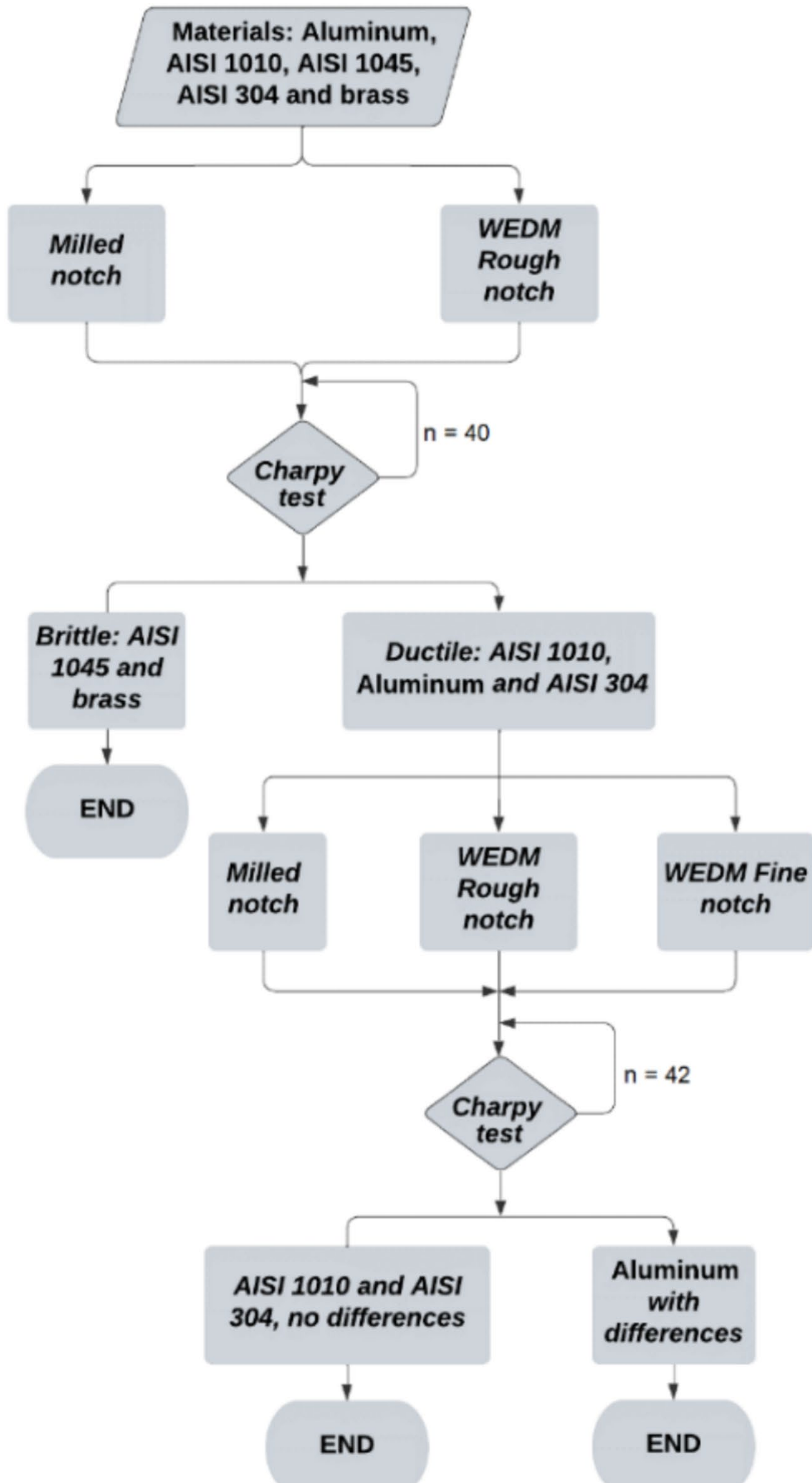

Fig. 2 Flowchart of the experimental procedure undertaken

3.1 Impact bending tests

The resilience (ratio between absorbed energy and resistant section of each specimen below the notch) was studied to mitigate the impact of minor dimensional variations in the sections beneath the notches across the different specimens. Table 3 presents the resilience values and their % deviations after four repetitions, segmented by material and the cutting process used for the notch.

Table 3 Resilience (J/cm^2) and % deviation, segmented by material and process

Material	Milling (J/cm^2)	Rough WEDM (J/cm^2)
Brass	15.4 ± 11.3%	16.1 ± 0.3%
AISI 1045 steel*	16.2 ± 36.9%	17.8 ± 33.8%
AISI 1010 steel	61.3 ± 23.7%	70.8 ± 11.1%
Aluminum	83.3 ± 13.2%	101.9 ± 17.9%
AISI 304 stainless steel*	207.0 ± 3.3%	214.8 ± 0.6%

*Similar values to Calik et al. [29] and Anoop et al. [30]

Table 3 presents the resilience values and percentage deviations measured for five materials with notches produced by milling and WEDM in rough conditions. Similar resilience results were observed for brass and AISI 1045 steel, indicating no significant differences between the two cutting methods. In contrast, for ductile materials (AISI 1010 steel, aluminum, and AISI 304 stainless steel), specimens with WEDM-cut notches exhibited slightly higher resilience values, with the difference becoming more pronounced as the material absorbed more energy. Figure 3 further illustrates this trend, particularly for AISI 304 stainless steel, where the increase in resilience was statistically significant. Additionally, lower value dispersion was observed across all materials when using WEDM, suggesting greater consistency in resilience measurements compared to milling.

In terms of fracture surface analysis, based on UNE-EN ISO 148–1 standards, brass and AISI 1045 specimens showed near 100% brittle fracture, as illustrated in Fig. 4. For these materials, the cutting process did not influence the resilience values. It is also noted that WEDM apparently allows for lower values of the deviations, despite the lower number of repetitions. The materials in the previous figure are arranged in increasing resilience, from the lowest (brass) to the highest (AISI 304 stainless steel). From the analysis of Fig. 4, it can be observed that as the material absorbs more energy, the lateral expansion of the fracture section increases. The lateral expansion is evident on the side opposite the edge with the notch and becomes more remarkable as its length increases. It is absent in the case of brass and AISI 1045 steel and reaches its maximum in AISI 304 stainless steel among the materials studied.

Table 4 presents the resilience values and their percentage deviation after six repetitions. Comparing the resilience values obtained in the same materials provides an initial insight. A reversal in the resilience values is observed between specimens with eroded notches and those with milled notches, highlighting the influence of the notch radius on the absorbed energy, as observed by Hosseinzadeh et al. [20]. In the first batch of tests, which included both ductile and brittle materials, the average notch radius was approximately 0.303 mm for the milled specimens, reaching the upper limit of the tolerance range. To ensure consistency, the second batch

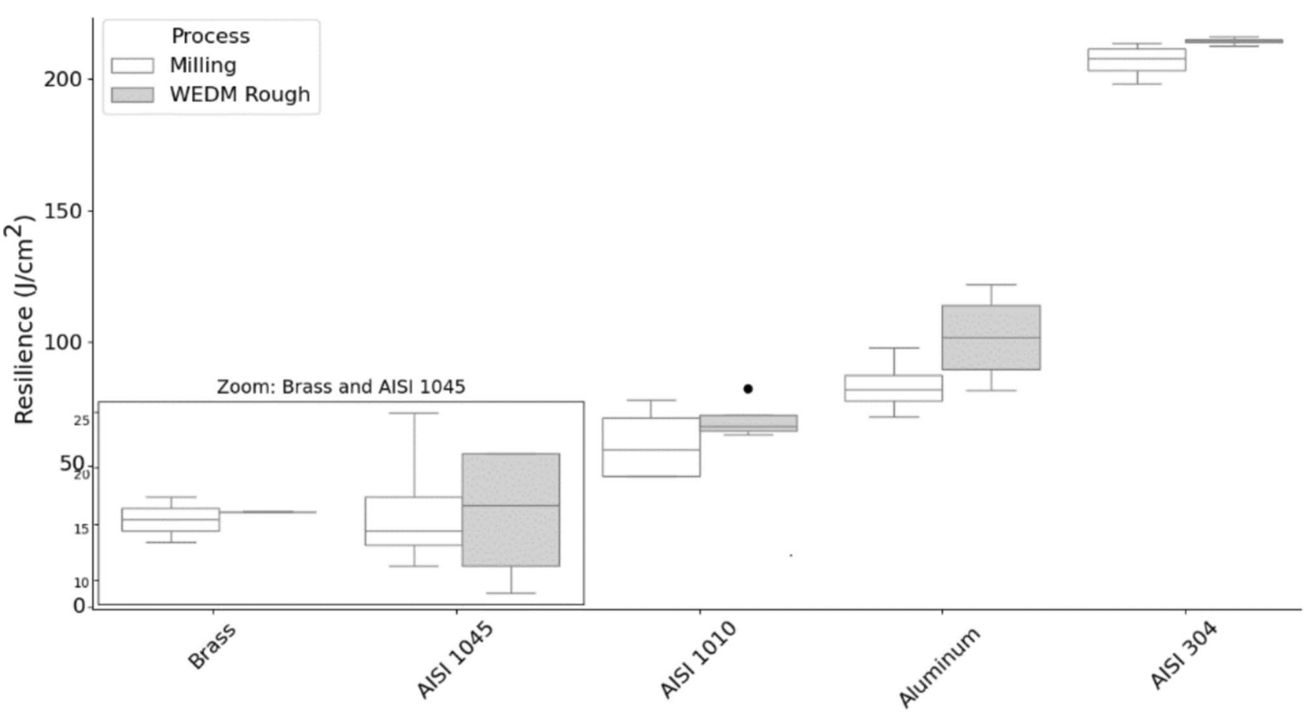

Fig. 3 Material resilience in Charpy tests

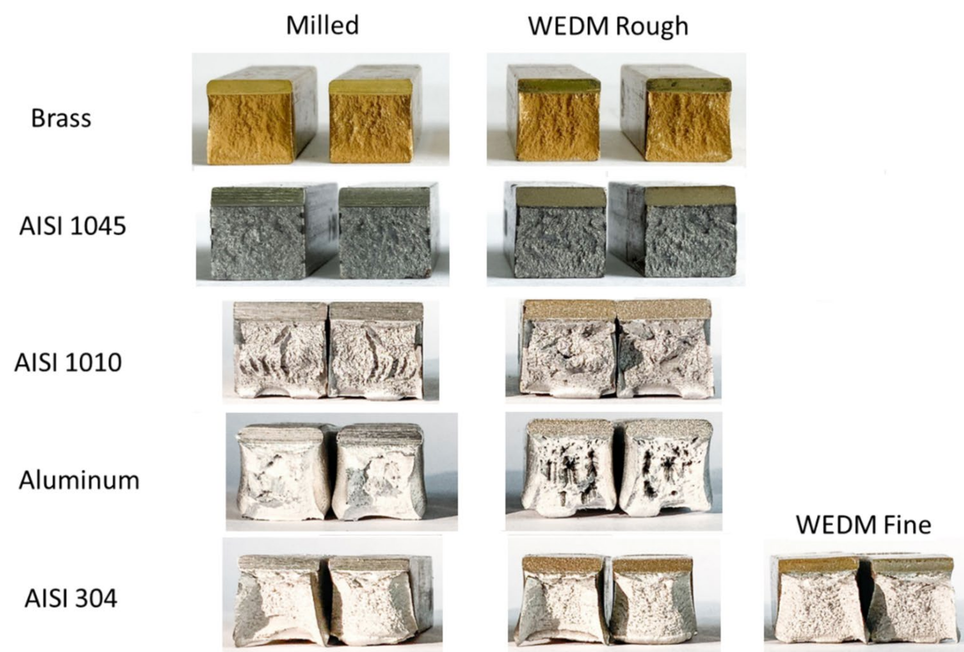

Fig. 4 Fracture analysis of specimens made from different materials with notches created by milling and WEDM, tested in Charpy impact tests; transverse section view

Table 4 Resilience (J/cm^2) and % deviation segmented by ductile material and process

Material	Milling (J/cm^2)	Rough WEDM (J/cm^2)	Fine WEDM (J/cm^2)
AISI 1010 steel	50.0 ± 14.4%	45.1 ± 23.4%	–
Aluminum	81.5 ± 20.0%	58.6 ± 6.1%	
AISI 304 stainless steel	186.5 ± 7.2%	192.6 ± 6.1%	192.7 ± 4.9%

was designed to align the radii of the milled notches with those of the eroded notches, thereby mitigating potential discrepancies in the results due to variations in notch geometry. In the second batch of tests, conducted exclusively on ductile materials, the notch radii were adjusted to match the nominal standard value of 0.25 mm to minimize the influence of notch radius on resilience measurements. As shown in Table 2, the average notch radius for milled specimens was 0.230 mm with a tolerance of 0.011 mm. In contrast, specimens produced by WEDM had an average notch radius of 0.258 mm with a tolerance of 0.010 mm, showing that both materials closely aligned with the nominal value of the standard UNE-EN ISO 148–1. Thus, Fig. 5 exhibits the resilience values from the second phase, which are presented graphically using box plots. Again, lower value dispersion was observed across all materials when using WEDM. There were no significant differences in the behavior of AISI 1010 steel and AISI 304 stainless steel. Similarly, no differences were observed in the behavior of eroded specimens under rough and fine conditions for the more ductile material (AISI 304). In the case of aluminum, a particular behavior was noted, which will require further in-depth study.

3.2 Notch mechanical properties

After analyzing the resilience, the materials can be categorized into two groups: (a) those where no significant differences in resilience were observed between specimens with milled and eroded V-notches (AISI 1010 and AISI 304) and (b) those where significant differences were noted (aluminum). Tensile tests were conducted on these materials to delve deeper into the mechanical properties of AISI 304 stainless steel and aluminum. Table 5 presents the average values of six repetitions for the yield strength ($\sigma_{0 \cdot 2}$%), ultimate tensile strength (UTS), percentage elongation at fracture (A%), and strain hardening coefficient (n).

The following profiles of Vickers microhardness (HV1/10) are presented for AISI 304 and aluminum, measured from the surface notch to the core, in specimens with milled and WEDM notches, as shown in Fig. 6. Table 6 presents the values of surface properties and the thickness of the affected layer for each process, broken down by material and cutting method, following the guidelines of Laamouri et al. [25]. Note that the HVs/HVo represents the ratio between the surface hardness with respect to the hardness at the nuclei.

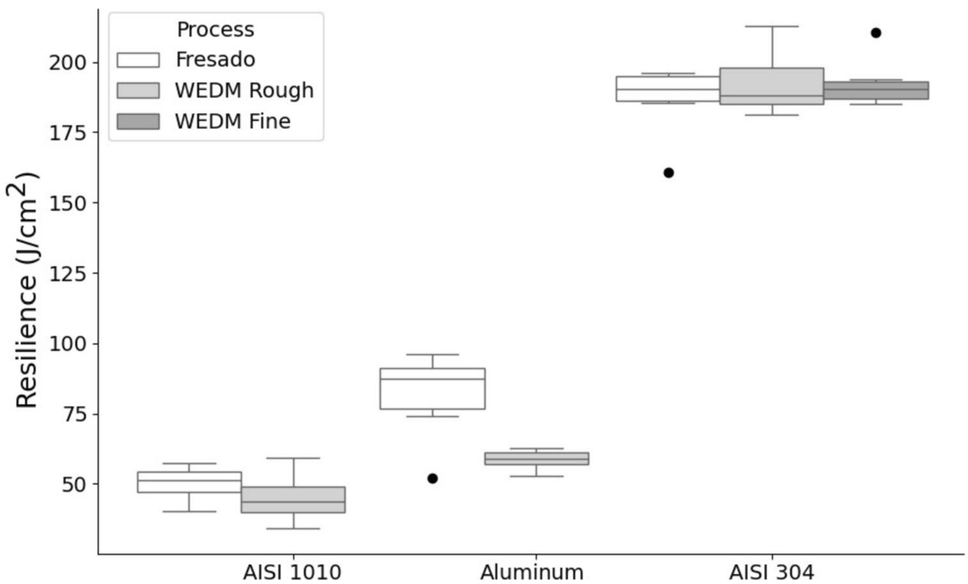

Fig. 5 Resilience in Charpy tests for ductile materials

Table 5 Mechanical properties of AISI 304 and aluminum

Material	$\sigma_{0.2\%}$ (MPa)	UTS (MPa)	*A* (%)	*n**
AISI 304	186.3 ± 7.4%	750.2 ± 1.8%	55.9 ± 11.6%	3.03
Aluminum	391.5 ± 1.4%	438.2 ± 1.0%	19.1 ± 2.0%	0.12

*Estimated according to [31]

It is necessary to differentiate between milled and WEDM notches to perform an initial analysis based on the microhardness profiles shown in Fig. 6 and Table 6. Milling is a plastic deformation process that, depending on the material's strain hardening coefficient, either increases the hardness in the deformed layer (as in AISI 304) or maintains approximately constant hardness (as in aluminum). In the particular case of aluminum, it behaves almost as a perfectly plastic material with no strain hardening [32]. In contrast, the surface effect of WEDM depends on the material's thermal conductivity. The effect is highly localized for a material with low thermal conductivity (like AISI 304). However, in a material with high thermal conductivity (like aluminum), the heat generated by the cutting process is rapidly conducted away from the cutting zone [33]. For AISI 304, both cutting processes (WEDM and milling) resulted in a similar increase in microhardness, with an average increase of around 22% compared to the core, consistent with those obtained by Das et al. [34]. The affected zone by both cutting processes was similar, approximately 400 µm. Similar values were obtained by Klocke et al. [35].

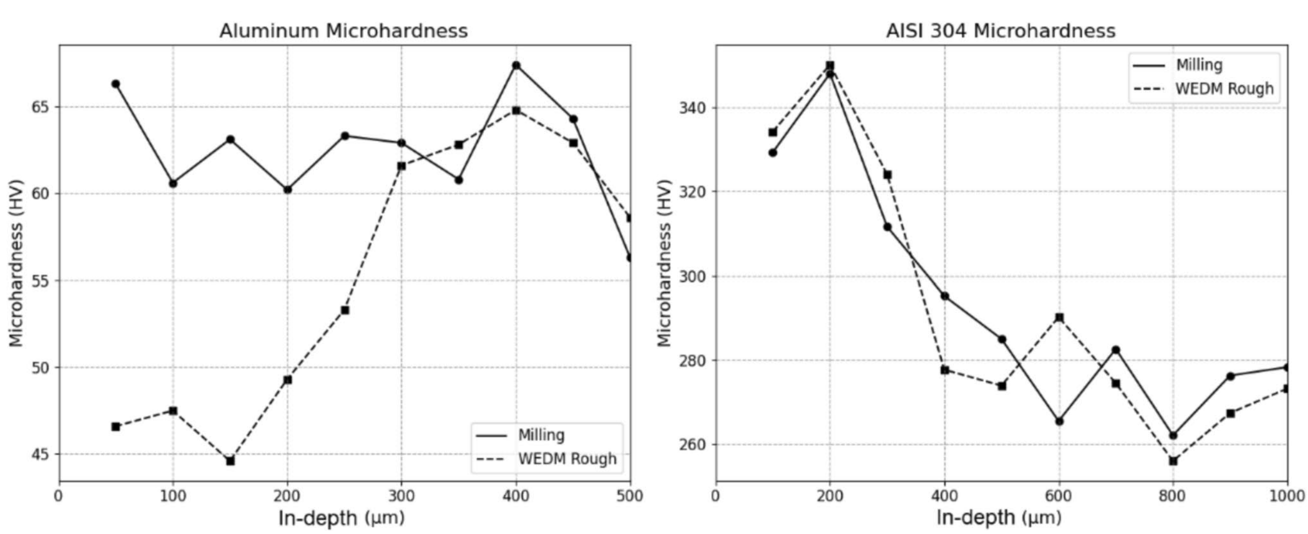

Fig. 6 Microhardness profiles in-depth in aluminum (right) and stainless steel (left) for V-shaped notches obtained by WEDM and milling

Table 6 Surface properties in milled and WEDM notches in aluminum and AISI 304

	AISI 304 stainless steel		Aluminum	
	Milling	WEDM	Milling	WEDM
Surface hardening, HVs/HVo (%)	122	122	0	76
Layer thickness (µm)	400	400	< 50	300

In contrast, for aluminum, electroerosion caused an average decrease in Vickers microhardness of about 24% near the surface of the notch (300 µm). No significant changes were observed in the milled specimens. These findings align with those reported by Akkurt [36]. A more comprehensive study by Sidorov et al. [37] involving similar materials found similar hardness trends. For a titanium alloy (similar to AISI 304) and two aluminum alloys (AlMg and AlCuMg), plasma-cut specimens showed hardness profiles with an increase at the surface for both titanium and a decrease for the aluminum alloys, in agreement with the results observed in this study. Additionally, the cold working process used in producing the Charpy specimens, through bar drawing, introduces significant work hardening, which increases microhardness, given that the small cross-section of the bar (10 × 10 mm), penetrates to its center. As a result, the drawn aluminum is initially unstable due to the high energy stored during deformation. At low temperatures, aluminum remains stable; however, a subsequent annealing treatment allows the release of this stored energy, with the material returning to a more equiaxed grain structure, reducing hardness [38, 39]. This process is similar to the effects induced by WEDM, which generates a heat-affected zone where the hardness due to thermal exposure is reduced [40]. Therefore, the observed reduction in hardness in the aluminum specimens, particularly at the stress concentrator near the notch, helps explain the decrease in resilience for the aluminum specimens with eroded notches compared to those with milled notches.

4 Conclusions

This study evaluates the feasibility of using WEDM for cutting V-notches in Charpy specimens and its impact on resilience sensitivity to notch radius. Resilience values from five common engineering materials are compared to those from specimens with standardized milled notches. The key conclusions, limitations, and future research directions are as follows:

- For brittle materials that absorb low energy, no differences were observed in resilience values between specimens with notches produced by milling and WEDM, despite differences in notch radii. Therefore, WEDM is suitable for cutting V-notches in brittle materials and can also reduce deviation, leading to more consistent and precise Charpy test results.
- When testing ductile materials (1010 steel, aluminum, and 304 stainless steel) and their notch geometries in impact bending tests, the resilience results showed no significant differences for 1010 steel and 304 stainless steel. However, a notable difference was observed for aluminum, indicating the need for further study.
- WEDM is a reliable method for cutting V-notches in Charpy specimens, even in rough conditions. It provides consistent resilience measurements with low variability. This study confirms its effectiveness not only for hard-to-mill materials but also for standard engineering materials.

A limitation of this study is that WEDM altered the surface hardness of aluminum, leading to reduced resilience values. However, WEDM presents the advantage of reducing variability compared to milled specimens. The effect of the cutting method on notch geometry can significantly influence resilience, particularly for ductile materials. These variations point to further research to optimize WEDM for consistent results and to understand its impact on different materials for specific applications to be used as a standardized method.

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Author contribution All authors contributed to the study's conception and design. Florencia, Mariano, and Diego collected material preparation data and performed experimental tests. Hernán analyzed and carried out fracture observation and material microhardness. Daniel and Antonio wrote the manuscript and edited and formatted the text and figures. All authors commented on previous versions and read and approved the final version of the manuscript.

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Declarations

Ethics approval There are no ethical conflicts.

Consent to participate The study did not include data from humans or animals.

Consent for publication Included in submission.

Competing interests The authors declare no competing interests.

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