

Effect of Specimen Extraction Method on Surface Condition and Mechanical Performance of 2024-T3 Aluminum Alloy



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ABSTRACT

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Certain mechanical properties, such as tensile strength, depend on the surface finish, which is itself influenced by the material removal process used. In sheet metal manufacturing, tensile test specimens can be cut by abrasive water jet (AWJ), wire electrical discharge machining (WEDM), laser, or plasma machining, rather than by conventional milling. This work aims to evaluate the effect of the test piece extraction method on surface condition, dimensional accuracy, and mechanical performance through tensile tests performed on 2024-T3 aluminum alloy plates. The test pieces were prepared using different techniques: AWJ, WEDM, and conventional milling. The surface roughness was measured using a roughness tester, and tensile tests were then carried out to determine the mechanical properties. The results revealed that the total roughness (Rz) varied significantly depending on the extraction method: milling produced the smoothest surfaces (Rz: 12.4-14.7 μm), followed by WEDM (Rz: 27.3-33.3 μm), and abrasive waterjet (Rz: 37.3-46.3 μm). Despite these differences, the impact on tensile properties remained within 5%, with the largest deviation recorded for elongation at break (-4.87% for AWJ) and the smallest for yield strength ($\pm 1.9\%$). These findings suggest that WEDM and AWJ can serve as viable alternatives to milling for specimen extraction when deviations up to 5% are acceptable.

1. INTRODUCTION

Tensile testing is one of the most widely used mechanical characterization methods for evaluating the behavior of structural materials under uniaxial loading [1, 2]. The quality and representativeness of the results obtained depend not only on the testing conditions but also, and critically, on the method used to extract the specimens from the base material. To date, milling remains the only internationally standardized method for producing flat tensile specimens from sheet metal, as prescribed by ASTM E8/E8M [3, 4], and ISO 6892-1, and it is widely used in industry

However, recent advances have introduced a variety of material removal processes, such as electrical discharge machining (EDM) [5], beam-based machining techniques (laser beam machining [6], plasma beam machining, etc.), as well as abrasive jet machining [7], water jet machining, and abrasive water jet (AWJ) machining [8]. These techniques represent potential alternatives to milling for specimen extraction, offering advantages in productivity, time efficiency, cost reduction, and cutting precision [9].

While milling ensures high dimensional accuracy and surface quality, it presents several practical limitations, including the need for a dedicated clamping system for each specimen geometry, the requirement to use cutting tools whose diameter does not exceed the specimen fillet radius, and an inherently low material removal rate [3]. These constraints translate into increased production time and cost, particularly when large batches of specimens are required.

Recent advances in non-conventional machining have introduced a variety of alternative material removal processes that may overcome these limitations. Wire electrical discharge machining (WEDM) enables the cutting of electrically conductive materials with high dimensional accuracy and without mechanical contact, making it particularly well-suited for stacking and batch cutting of sheet metal [3]. Laser beam machining (LBM) is a well-established industrial process widely used in sheet metal fabrication since the early 1980s [10-12]; it offers high cutting speed and flexibility, though it generates a heat-affected zone (HAZ) that may alter the surface and subsurface properties of the material [13]. Plasma beam cutting is another thermally intensive process applicable

to a broad range of metallic materials regardless of their hardness or refractory nature, and is extensively used in heavy industry [14]. Abrasive water jet (AWJ) machining, first applied industrially in 1983 [3], has grown steadily and enables the cutting of hard and tough materials, including steels, titanium alloys, and aluminum alloys, up to 200 mm in thickness, at relatively high feed rates and without thermal effects [15].

Several studies have examined the influence of cutting parameters associated with these alternative processes on surface integrity and mechanical properties. For fiber laser cutting of AA2B06-T4 aluminum alloy, the effects of laser parameters on cut-edge microfeatures and tensile performance were systematically studied [13]. The optimization of AWJ machining parameters for Al 7071 was investigated [16], while the effect of AWJ on the properties of aluminum-matrix nanocomposites was explored [17]. Regarding WEDM, its influence on the surface finish of aluminum alloys and on the mechanical performance of Inconel 939 was examined in the studies [18, 19], respectively. The effect of cutting methods on surface microstructure and hardness was also reported for Al-6061 alloy [20]. At a broader level, Kraemer et al. [3] evaluated the suitability of WEDM, laser cutting, and AWJ as alternatives to milling for extracting flat tensile specimens from low-carbon steel sheets and Inconel 718, concluding that the deviation in mechanical properties was acceptable for most industrial applications. Similarly, the laser cutting process was assessed for the preparation of standard flat tensile specimens from thin galvanized steel sheets, with attention to dimensional accuracy, TAZ characteristics, and mechanical properties (tensile strength, yield strength, and elongation) [11].

At present, several researchers employ WEDM for the extraction of tensile test specimens [21, 22]. In contrast, AWJ is used to prepare specimens for mechanical testing other than tensile loading [23].

Despite this body of work, the literature addressing the specific case of 2024-T3 aluminum alloy, a material widely used in aeronautical structures, high-strength non-welded assemblies, and armament applications, with ultimate tensile strength reaching up to 485 MPa, remains limited.

In particular, no study has yet simultaneously and systematically compared milling, WEDM, and AWJ as extraction methods for flat tensile specimens from this alloy, considering both surface integrity (roughness, microstructure, hardness) and mechanical performance (tensile strength, yield strength, elongation at break). This gap is the primary motivation for the present work.

The objective of this study is therefore to evaluate the effect of three specimen extraction techniques: conventional milling, WEDM, and AWJ, on the surface condition, microstructural characteristics, Vickers microhardness, and tensile properties of 6 mm-thick 2024-T3 aluminum alloy sheets. The results are intended to provide practical guidelines for production and quality control engineers regarding the admissibility of non-standard extraction methods in industrial and research contexts.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1 MATERIAL

The material investigated in this study is a 2024-T3 aluminum alloy sheet, 6 mm in thickness. This alloy belongs to the 2xxx series (Al-Cu-Mg system) and is supplied in the T3 temper condition, which corresponds to solution heat treatment, cold working, and natural aging. Its nominal chemical composition and mechanical properties, as specified by the manufacturer and consistent with ASTM B209, are summarized in Tables 1 and 2.

Table 1. Chemical composition (in wt. %) of the studied alloy

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
AA2024-T3	0.5	0.5	4.09	0.43	1.44	0.25	0.15	0.1	Bal

Table 2. Mechanical properties of the studied alloy

	Tensile Strength, MPa	Yield Strength, MPa	Elongation, %
AA2024-T3	435	290	15

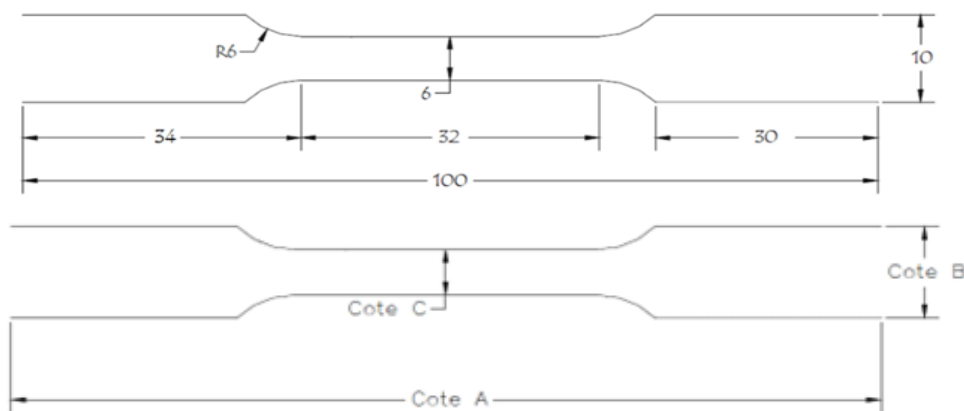


Figure 1. Dimensions of tensile test specimens, mm

2.2 Specimen geometry and preparation

Flat tensile test specimens were extracted from the 2024-T3 aluminum alloy sheets in accordance with ASTM E8/E8M-25 [4]. All specimens were oriented parallel to the rolling direction in order to minimize anisotropy effects on the measured mechanical properties. The nominal gauge dimensions were: gauge length $L_0 = 50$ mm, width $w = 12.5$ mm, and thickness $t = 6$ mm. A schematic of the specimen geometry is provided in Figure 1.

Three specimen extraction techniques were evaluated, described in detail in the following subsections.

2.3 Cutting techniques and process parameter

2.3.1 Conventional milling (reference process)

Milling was used as the reference process, in accordance with the standard requirement of ASTM E8/E8M [4]. Specimens were machined using a four-flute carbide end mill ($\varnothing 8$ mm, $Z = 4$) under the following cutting conditions: cutting speed $V_c = 75.4$ m/min and feed per tooth $f_z = 0.067$ mm/tooth/rev. Cutting was performed under dry conditions. Milling was selected as the baseline because it is the sole internationally accepted method for producing flat tensile specimens from sheet metal.

2.3.2 Abrasive waterjet machining

AWJ specimens were cut using a high-pressure waterjet system operating at a water pressure of 3200 bar. Garnet abrasive particles (mesh size 80 -100) were used as the cutting medium, delivered through a nozzle of 0.8 mm diameter, 2 mm standoff and 350 g/min mass flow rate. The traverse speed was set to 600 mm/min, which was determined based on preliminary trials to ensure complete penetration of the 6 mm sheet without excessive taper deviation.

2.3.3 Wire electrical discharge machining

WEDM specimens were produced using a 0.25 mm diameter copper wire electrode. The machine was operated with a discharge voltage in the range $V_d = 80$ V and a wire feed rate of 3.988 mm/min. No flushing fluid other than the standard deionized water dielectric was used. A single cutting pass was applied for all WEDM specimens.

2.4 Dimensional verification

The dimensional conformity of the extracted specimens was verified using a digital caliper with a resolution of 0.01 mm. Width and length measurements were performed at three positions along the gauge section of each specimen, and the mean value was retained. Dimensional tolerances were assessed against the requirements of ASTM E8/E8M (width: 12.5 ± 0.1 mm).

2.5 Surface roughness measurement

Surface roughness was characterized using a contact-type roughness tester (TR-100) with a stylus tip radius of 5 μ m. The total height of the roughness profile (R_z) was chosen as the evaluation parameter, as it is sensitive to extreme peaks and valleys introduced by the cutting process and is therefore more discriminating than the arithmetic mean roughness R_a for comparing machining processes. Measurements were performed on the cut lateral faces of the specimens, over an

evaluation length of 6 mm with a cut-off length $\lambda_c = 0.8$ mm, in accordance with ISO 4288. A minimum of five measurements were taken per specimen face, and mean values with standard deviations are reported.

2.6 Metallographic analysis

To assess the influence of each cutting technique on the near-surface microstructure, cross-sectional metallographic specimens were prepared from each cutting method. Samples were sectioned perpendicular to the cutting direction, hot-mounted in epoxy resin, and mechanically polished through successive grades of SiC abrasive papers (120, 320, 600, 1200, and 2500 grit), followed by final polishing with 1 μ m diamond paste. Microstructural features were revealed by chemical etching using Keller's reagent (2.5 ml HNO_3 , 1.5 ml HCl , 1.0 ml HF , 95 ml H_2O) for 15-30 seconds at room temperature. Observations were carried out using an optical microscope at magnifications of $\times 20$.

2.7 Microhardness measurements

Vickers microhardness (HV) was measured on the polished cross-sections using a microhardness tester with an applied load of 100 gf (HV0.1) and a dwell time of 15 seconds, in accordance with ASTM E384. Measurements were performed along a line perpendicular to the cut surface. A minimum of five indentations were made at each measure point, and mean values are reported.

2.8 Tensile testing

Uniaxial tensile tests were performed on a servo-hydraulic universal testing machine, at a constant crosshead displacement rate of 1 mm/min, in accordance with ASTM E8/E8M [4]. For each cutting condition, a minimum of three specimens were tested to ensure statistical repeatability. The following mechanical properties were determined from the engineering stress-strain curves: ultimate tensile strength (R_m , MPa), 0.2% offset yield strength (R_e , MPa), and elongation after fracture (A , %).

3. RESULTS AND DISCUSSION

3.1 Dimensional accuracy

The dimensional conformity of the extracted specimens was assessed by measuring the gauge width at three positions along the gauge section using a digital caliper (resolution: 0.01 mm). The target width, as specified by ASTM E8/E8M, is 12.5 ± 0.1 mm. The results are summarized as follows:

Milling produced specimens with the highest dimensional accuracy, with a maximum deviation of ≤ 0.07 mm, well within the prescribed tolerance of ± 0.1 mm. WEDM yielded the most precise results among the three techniques, with a maximum deviation of ≤ 0.05 mm, confirming the known capability of this process for tight-tolerance cutting. Abrasive waterjet cutting exhibited the largest dimensional deviation, reaching up to 0.3 mm, which exceeds the ASTM E8/E8M tolerance of ± 0.1 mm. This deviation is primarily attributed to the jet taper effect, which results from the loss of kinetic energy of the abrasive particles as they traverse the full thickness of the material [3]. As reported in the literature, the

taper error in AWJ machining is strongly dependent on the traverse speed and the standoff distance [16]; optimizing these parameters could bring the dimensional deviation within acceptable limits, as demonstrated by Kraemer et al. [3] for steel sheets.

It should be noted that, while the AWJ specimens did not strictly comply with the dimensional tolerance of ASTM E8/E8M in the present configuration, this deviation can be systematically reduced through process parameter optimization and does not, per se, invalidate the comparative analysis of surface condition and mechanical properties presented in the following sections.

3.2 Surface morphology and macroscopic appearance

The macroscopic surface appearance of specimens produced by the three cutting techniques is shown in Figure 2. Clear visual differences in surface texture can be observed, consistent with the distinct material removal mechanisms involved.



Figure 2. The macroscopic surface appearance of tensile test specimens

The milled specimen exhibits a regular, striated surface topography characteristic of chip-based machining, with well-defined and uniformly spaced tool marks aligned in the cutting direction. This regularity reflects the deterministic nature of the milling process and is associated with the lowest surface roughness among the three methods. The WEDM specimen displays the isotropic, cratered surface texture that is

characteristic of electro-erosive material removal [3], resulting from the superposition of successive discharge craters of relatively uniform size. No preferential directionality is observed on the EDM surface, which is consistent with the spark discharge mechanism. The AWJ specimen presents the most irregular surface, with clearly visible abrasive particle trajectories and lateral striations resulting from the deflection of the jet as it penetrates the material thickness. Taper-induced geometric imperfections are also visible along the specimen perimeter, as previously noted in the dimensional analysis.

These macroscopic observations are in qualitative agreement with the surface roughness measurements reported in Section 3.3 and with the findings of Kraemer et al. [3] for steel and Inconel specimens.

3.3 Surface roughness

The total surface roughness parameter R_z was measured on the cut lateral faces of each specimen using a TR-100 contact profilometer, over an evaluation length of 6 mm and a cut-off wavelength $\lambda_c = 0.8$ mm, in accordance with ISO 4288. The R_z parameter was selected in preference to R_a because it captures the extreme peak-to-valley height within each sampling length and is therefore more sensitive to the localized damage introduced by non-conventional cutting processes. The minimum and maximum R_z values recorded for each process are presented in Table 3.

Milling produced the smoothest and most consistent surfaces, with R_z values ranging from 12.4 to 14.7 μm and a narrow dispersion indicative of a stable and repeatable process. Wire EDM generated intermediate roughness values (R_z : 27.3-33.3 μm), approximately 2.2 times higher than milling on average. Abrasive waterjet cutting yielded the highest roughness (R_z : 37.3-46.3 μm), approximately 3.1 times higher than milling, with greater dispersion reflecting the inherent stochasticity of the particle-based material removal mechanism.

These results are consistent with the general trend reported in the literature for comparative cutting studies on metallic alloys [3, 18, 20]. The roughness hierarchy, milling < WEDM < AWJ, is directly attributable to the respective material removal mechanisms. In milling, the tool geometry imposes a well-defined and periodic surface texture. In WEDM, the superposition of thermal discharge craters generates a more irregular, though still relatively fine, surface. In AWJ, the combination of micro-cutting, micro-ploughing, and micro-cracking induced by the impacting abrasive particles generates a highly irregular surface with both macro-scale striations and micro-scale pitting [15].

Table 3. Total roughness range

Methods	R_z min (μm)	R_z max (μm)	Mean R_z (μm)
Milling	12.4	14.7	13.6
WEDM	27.3	33.3	30.3
AWJ	37.3	46.3	41.8

3.4 Microstructural analysis

Optical micrographs of the cross-sections obtained for the three cutting methods are presented in Figure 3. The 2024-T3 alloy exhibits a characteristic elongated grain morphology in the rolling direction, with visible intermetallic precipitates (primarily Al_2Cu Mg, S-phase) dispersed within the aluminum matrix.

Importantly, based on observation under an optical microscope at 20 \times magnification, for all three cutting processes- milling, WEDM, and AWJ -the grain morphology in the near-surface region is preserved and shows no evidence of plastic deformation, recrystallization, or thermally induced microstructural alteration. No heat-affected zone (HAZ) is detectable at the optical microscopy level for any of the three

methods, which is consistent with the relatively moderate thermal conditions generated during these processes.

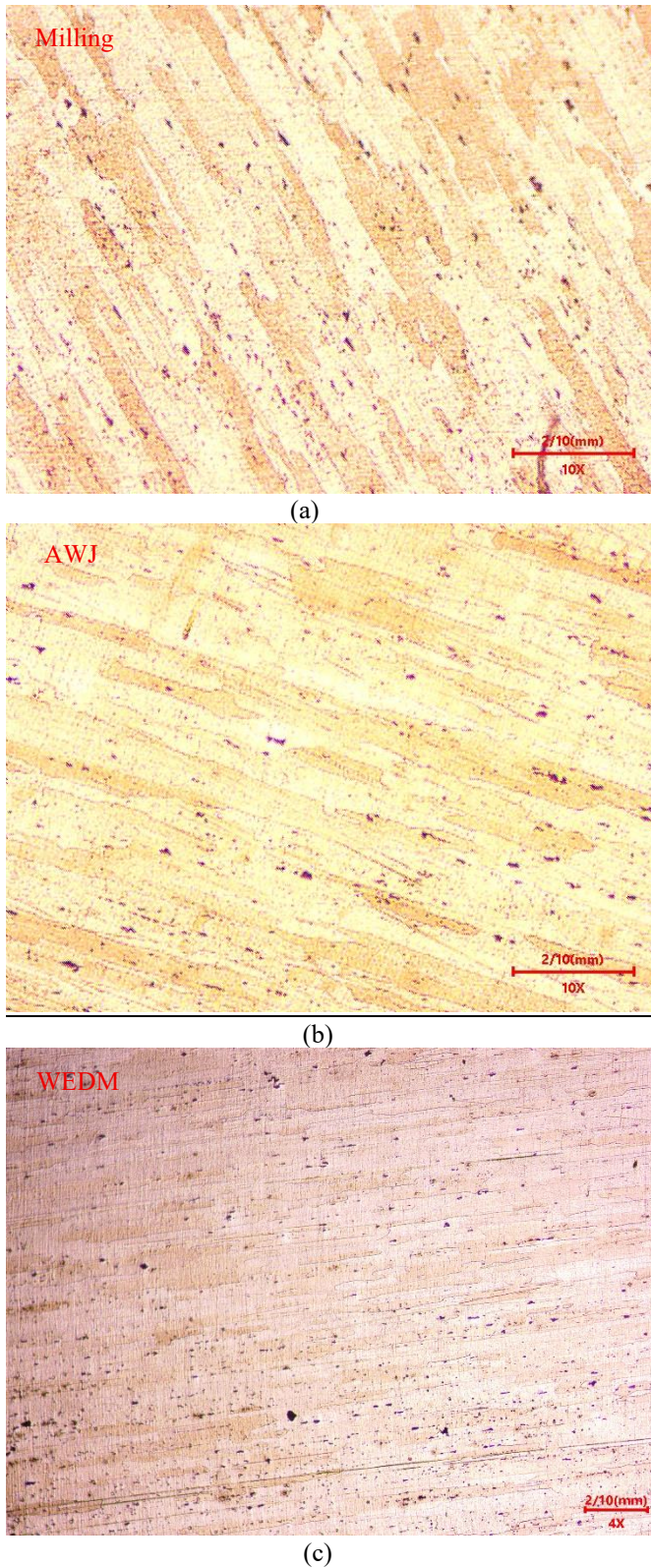


Figure 3. The grain morphology of the 2024-T3 aluminum alloy after specimen extraction: (a) milling, (b) AWJ, (c) WEDM

This observation deserves further discussion in light of the thermomechanical conditions associated with each process. During milling of AA2024-T351, cutting temperatures at the tool-chip interface can reach approximately 225 °C at feed rates comparable to those used in the present study [24]. In

WEDM, the temperature of the copper wire has been reported to reach approximately 240 °C [25]. Both values remain well below the solution heat treatment temperature of the 2024 alloy (~493 °C), which explains the absence of microstructural alteration. AWJ machining is essentially a non-thermal process, as the waterjet provides continuous cooling of the cutting zone, further ruling out thermally induced microstructural changes. These findings are in agreement with those of Krahmer et al. [3] for low-carbon steel and Inconel 718 specimens, and with the observations of Akkurt [20] for Al-6061 alloy.

It should be noted that a more in-depth microstructural analysis with precision equipment and greater magnification may reveal microstructural modifications.

3.5 Vickers microhardness

The Vickers microhardness values measured on the polished cross-sections of specimens produced by the three cutting methods are summarized in Table 4.

Table 4. Percentage deviation of mechanical properties relative to milling (reference process)

Methods	$\delta A\%$ (%)	δR_m (%)	δR_e (%)
WEDM	+3.38	-0.45	+1.87
AWJ	-4.87	-2.52	-1.33

The microhardness values are virtually identical across the three processes, with a maximum difference of less than 1 HV (< 0.7%). These results confirm that none of the cutting techniques introduced significant work hardening or thermal softening in the near-surface material. This observation is consistent with the microstructural analysis presented in Section 3.4, and further supports the conclusion that the thermal and mechanical effects of all three cutting processes are too limited to alter the bulk properties of the 2024-T3 alloy.

This finding contrasts with results reported for higher-energy processes such as laser cutting or plasma cutting, which are known to induce significant hardness gradients in the near-surface region of aluminum alloys due to the formation of a heat-affected zone [13, 14]. The thermal stability of milling, WEDM, and AWJ surfaces thus constitutes a key advantage of these processes for specimen preparation applications.

3.6 Tensile properties

The engineering stress–strain curves for specimens produced by milling, WEDM, and AWJ are shown in Figure 4. All three curves exhibit the characteristic elastic-plastic behavior of the 2024-T3 alloy, with a well-defined elastic slope, a progressive transition to plastic deformation, and a strain-hardening plateau prior to fracture. No anomalous features (premature fracture, irregular serrations) are observed in the curves for WEDM or AWJ specimens, suggesting that the surface condition introduced by these processes did not act as a critical stress concentration site under the loading rates applied.

The percentage deviations of the mechanical properties, ultimate tensile strength (R_m), yield strength (R_e), and elongation after fracture ($A\%$), relative to the milling reference are summarized in Table 5.

The results demonstrate that the influence of the cutting technique on the tensile properties of the 2024-T3 alloy is

modest. The maximum deviation is recorded for elongation at break (-4.87% for AWJ), followed by tensile strength (-2.52% for AWJ) and yield strength (-1.33% for AWJ). WEDM induces even smaller deviations, with a maximum of +3.38% for elongation at break.

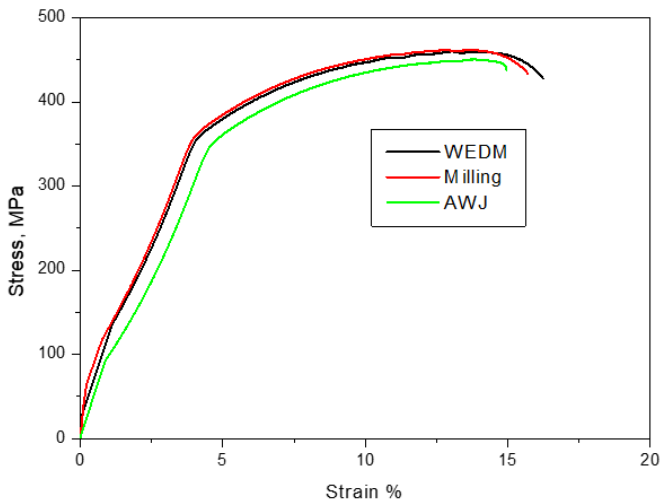


Figure 4. The Stress–strain curves of specimens cut by milling, WEDM, and AWJ from 2024-T3 aluminum alloy

Table 5. Vickers hardness values for surfaces cut by milling, WEDM and AWJ

Methods	Hv
Milling	147
WEDM	148
AWJ	147.5

The slight reduction in elongation and tensile strength observed for AWJ specimens can be plausibly attributed to the higher surface roughness generated by this process (Rz up to 46.3 μm), which introduces more severe stress concentration sites at the specimen edges compared to milled or WEDM specimens. This interpretation is consistent with the well-established relationship between surface roughness and fatigue or ductility in aluminum alloys [3, 20]. However, the magnitude of the effect (< 5%) suggests that the influence of roughness on quasi-static tensile properties remains limited for the present material and specimen geometry.

The slightly positive deviation in elongation observed for WEDM (+3.38%) may appear counterintuitive given the higher roughness of WEDM surfaces compared to milling. This could reflect specimen-to-specimen variability in the absence of full statistical analysis ($n \geq 5$ per condition), and warrants further investigation with a larger sample size.

These findings are in broad agreement with those of Kraemer et al. [3], who reported deviations of less than 5% in the tensile properties of low-carbon steel and Inconel 718 specimens extracted by non-standard methods, and support the conclusion that WEDM and AWJ are viable alternatives to milling for non-critical tensile specimen preparation.

4. CONCLUSION

This study investigated the influence of three specimen extraction techniques - conventional milling, WEDM, and abrasive waterjet machining (AWJ) - on the surface condition,

microstructural integrity, Vickers microhardness, and tensile properties of 6 mm-thick 2024-T3 aluminum alloy sheets. Based on the experimental results presented and discussed in the preceding sections, the following conclusions can be drawn:

- Dimensional accuracy: Milling and WEDM both satisfied the dimensional tolerance requirements of ASTM E8/E8M (± 0.1 mm), with maximum deviations of 0.07 mm and 0.05 mm, respectively. AWJ cutting exceeded this tolerance (deviation up to 0.3 mm) due to the jet taper effect; however, this deviation can be reduced through optimization of the traverse speed and standoff distance, and does not preclude the use of AWJ in applications where moderate dimensional tolerances are acceptable.

- Surface roughness: The three processes produced significantly different surface finishes, following the hierarchy: milling (Rz: 12.4 -14.7 μm) < WEDM (Rz: 27.3 - 33.3 μm) < AWJ (Rz: 37.3 - 46.3 μm). The roughness generated by WEDM and AWJ is approximately 2.2 and 3.1 times higher than that of milling, respectively. These differences are directly attributable to the distinct material removal mechanisms of each process.

- Microstructural integrity: Optical microscopy revealed that none of the three cutting processes induced detectable microstructural alterations (including grain deformation, recrystallization, or heat-affected zones) in the near-surface region of the 2024-T3 alloy. This result is consistent with the moderate thermal conditions associated with milling (≈ 225 $^{\circ}\text{C}$) and WEDM (≈ 240 $^{\circ}\text{C}$), both of which remain well below the solution heat treatment temperature of the alloy (≈ 493 $^{\circ}\text{C}$), and with the essentially a thermal nature of AWJ machining.

- Microhardness: Vickers microhardness measurements confirmed the absence of near-surface work hardening or thermal softening for all three cutting techniques, with values remaining stable at approximately 147–148 HV regardless of the process used. This further validates the microstructural observations and indicates that the mechanical integrity of the material is preserved during specimen extraction by any of the three methods.

- Tensile properties: The deviations in ultimate tensile strength (R_m), yield strength (R_e), and elongation after fracture (A%) relative to the milling reference remained within $\pm 5\%$ for both WEDM and AWJ. The largest deviation was observed for elongation at break (-4.87% for AWJ), followed by tensile strength (-2.52% for AWJ). Yield strength was the least affected property (maximum deviation: $\pm 1.87\%$). The small reduction in ductility observed for AWJ specimens is consistent with the higher surface roughness generated by this process, which introduces more pronounced stress concentration sites at the specimen edges.

On the basis of these results, WEDM and AWJ can be considered viable alternatives to milling for the extraction of flat tensile specimens from 2024-T3 aluminum alloy sheets in contexts where a deviation of up to 5% in tensile parameters is acceptable. These processes offer notable practical advantages over milling, including the elimination of dedicated clamping fixtures, the ability to cut complex geometries and stacked sheets in unattended mode, and reduced preparation time and cost. However, for critical structural or certification applications where strict compliance with ASTM E8/E8M dimensional and property requirements is mandatory, milling remains the recommended method.

These findings provide actionable guidelines for production

engineers, quality control specialists, and researchers working with 2024-T3 aluminum alloy and related high-strength aluminum sheet materials.

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NOMENCLATURE

HV	vickers microhardness, Hv
Rz	total roughness, μm
R_m	ultimate tensile strength, Mpa
R_e	0.2% offset yield strength, MPa
A	elongation after fracture, %
Vc	cutting speed, mm/min
fz	feed per tooth, mm/tooth/rev
Vd	discharge voltage in the range, V
λ_c	cut-off wavelength, mm

Subscripts

HAZ	heat-affected zone
LBM	laser beam machining
AWJ	abrasive water jet
EDM	electrical discharge machining
WEDM	wire electrical discharge machining