



Multi-Criteria Evaluation of Cryogenic Holding Time Effects on AA7075-T6 Milling Performance

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Abstract

Machining of AA7075-T6 is challenged by high cutting temperature, process instability, and multiple interacting performance responses. This study investigates the effect of deep cryogenic holding time (CHT) on the milling performance of AA7075-T6 through a combined experimental and multi-criteria optimization approach. The material was cryogenically treated at -146°C for 12, 24, and 36 h, while untreated specimens were used as the reference condition. Milling experiments were carried out using a full factorial design with cutting speed (200, 250, and 300 m/min), feed per tooth (0.08, 0.10, and 0.12 mm/tooth), and CHT as control factors. Machining performance was evaluated based on the resultant cutting force, vibration, cutting temperature, power consumption, and surface roughness. In addition, microstructural and mechanical changes were examined by X-ray diffraction, SEM/EDS observations, and hardness measurements. The results showed that increasing CHT led to a measurable increase in hardness and induced lattice modifications, which influenced the thermo-mechanical behavior during machining without forming new phases. Among the machining responses, CHT had the strongest effect on cutting temperature and also contributed to a reduction in cutting force, whereas vibration, surface roughness, and power consumption were primarily affected by cutting parameters. Entropy-weighted grey relational analysis identified the optimal condition as 36 h CHT, a cutting speed of 250 m/min, and a feed per tooth of 0.08 mm. Under this condition, cutting force, temperature, and vibration were reduced by 23.7%, 35.0%, and 52.1%, respectively, relative to the reference condition. These findings demonstrate that cryogenic pre-treatment, combined with cutting parameters, can improve milling performance and process stability in AA7075-T6.

Keywords AA7075-T6 · Deep cryogenic treatment · Milling · Cryogenic holding time · Machinability · Grey relational analysis

1 Introduction

Aluminum 7075 (AA7075) is a high-strength alloy widely used in aerospace, defense, and automotive industries due to its high mechanical performance (yield strength $\approx 410\text{--}470$ MPa,

ultimate tensile strength $\approx 485\text{--}530$ MPa, $T_m \approx 635^{\circ}\text{C}$ [1] and Vickers hardness (HV 0.05) ≈ 160 [2, 3]), ductility, good corrosion resistance, and thermal conductivity capable of rapid heat dissipation [4–6]. Despite these advantages, its machining remains challenging, particularly at high speeds,

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where rapid temperature rise and high strain rates can alter material flow behavior and promote thermomechanical instabilities that adversely affect process stability and surface integrity [7]. In milling chip formation is governed by severe plastic deformation under high strain rates and elevated temperatures, where the coupled evolution of stress and temperature controls the flow response [8, 9].

The temperature rise generated during metal cutting governs the magnitude and stability of plastic deformation, and therefore directly influences chip formation, surface integrity, and tool performance [10]. Although higher temperatures facilitate dislocation movement and expand the elastoplastic zone [11], under high-speed cutting, they may destabilize plastic flow, alter chip morphology, and deteriorate surface quality [12]. A substantial fraction of the cutting energy is converted into heat through plastic deformation and friction, which accelerates local deformation rates and directly affects tool life [13–15]. Elevated temperatures can further undermine thermo-mechanical stability by promoting energy accumulation within the primary shear zone and inducing microstructural changes [16, 17], implying that both material response and machining parameters control deformation stability [11, 18]. Using numerical and experimental approaches, several studies have investigated chip formation mechanisms in AA7075 under high-speed machining conditions. For instance, Jomaa et al. [1] reported that increasing cutting speed (V_c) promotes chip segmentation and reduces cutting forces. Similarly, Ma and Shuang [12] demonstrated that transitions between continuous and serrated chip formation depend on both cutting parameters and material behavior. These findings indicate that chip morphology and energy consumption are strongly governed by the interplay between machining conditions and material response. In addition, higher cutting speeds have been associated with reduced plastic deformation and improved process efficiency [19]. Overall, achieving robust control over plastic deformation in milling requires considering not only cutting parameters but also tool material and geometry, as well as the workpiece microstructure [20].

Cryogenic treatment has attracted increasing attention as a pre-treatment to improve machinability by modifying the microstructural state and thermo-mechanical response of metallic materials. Typically performed at temperatures near liquid-nitrogen conditions (approximately -140 to -196 °C) [21], this process does not introduce new phases in precipitation-hardened aluminum alloys; instead, thermal contraction mismatch between the matrix and second-phase constituents can generate persistent micro-stress fields within the microstructure [22]. These micro-stresses cause the reorientation of existing dislocations, particularly at phase interfaces, leading to the development of dislocation clusters and cell-like substructures [23]. In 7xxx series

alloys, the mismatch between η/η' precipitates and the α -Al matrix triggers partial fragmentation or interfacial debonding of coarse MgZn_2 (η) precipitates, contributing to the refinement of precipitate morphology and a more refined distribution [24]. These micro-stress regions also create energetically favorable zones for the short-range rearrangement of solute atoms, enabling the denser formation of GP zones and a finer, more homogeneous distribution of η' phases during the subsequent aging heat treatment [23–25]. Accordingly, cryogenic treatment has been reported to accelerate precipitation kinetics and, together with increased dislocation density, yield modest yet measurable improvements in microhardness and wear resistance [26].

Additionally, low-temperature-induced contraction and micro-stress redistribution have been reported to reduce tensile residual stresses and promote locally compressive stress states in certain alloys, which can benefit surface integrity and machinability [27]. Consistent with these microstructural changes, machining of cryogenically treated materials has been associated with lower cutting forces, improved chip morphology, and enhanced surface integrity [28, 29]. However, since increased hardness after cryogenic treatment can generate higher contact pressure on the cutting tool, the optimization of cutting parameters is of critical importance [30]. Importantly, the response to cryogenic treatment is sensitive to the holding duration, which has been reported to modulate key microstructural features, including defect-structure evolution and residual-stress redistribution, as well as, in some studies, changes in precipitate characteristics and indications of grain refinement [22, 27, 31–34]. Therefore, a systematic investigation of the persistent effects of cryogenic holding time (CHT) on precipitate homogeneity, internal stress balance, and phase distribution is critical for the mechanical and machinability performance of AA7075 alloy [24, 35, 36].

Most studies on cryogenic treatment of AA7075 have primarily focused on mechanical properties or reported machinability using a limited set of outputs [37, 38]. For instance, Shen et al. [39] demonstrated that cryogenic treatment applied prior to milling significantly reduced machining-induced residual stresses and part deformation in aluminum alloys, and further ensured a more homogeneous distribution of stresses by lowering strain energy. In another study [40], cryogenic treatment was applied to the cutting tool during the milling of AA6061-T651 alloy, and its effects on surface roughness and tool wear were examined. Cryogenic technology is also widely investigated in the literature as an active cooling strategy to promote sustainable and eco-friendly manufacturing. In this context, Park et al. [41] demonstrated that cryogenic cooling serves as a viable green alternative by reducing cutting forces and tool wear compared to conventional flood cooling, highlighting its

potential for energy consumption and sustainability. Similarly, Jain et al. [42] emphasized the use of liquid nitrogen as a sustainable ‘green coolant’ to overcome the health and environmental hazards of traditional metalworking fluids, noting significant improvements in chip morphology and thermal stability. However, studies that specifically evaluate the machinability of cryogenically pre-treated AA7075 remain scarce, and existing literature typically considers restricted performance indicators [43]. Consequently, a significant research gap exists regarding the systematic quantification of the persistent effects of CHT and its interaction with cutting parameters across coupled responses (force, temperature, vibration, power, and roughness), which this study aims to address.

To address these gaps, the present study systematically investigates the coupled influence of deep CHT and key milling parameters (cutting speed, V_c , and feed per tooth, f_z) on the dry-milling machinability of AA7075-T6 using a full factorial experimental design. Machining performance is quantified through multiple responses, including cutting force, vibration, cutting temperature, power consumption, and surface roughness. At the same time, microstructural changes induced by cryogenic holding are assessed using XRD and BSE/EDS observations together with hardness measurements. The relative contributions of CHT and cutting parameters, as well as their interactions, are evaluated via ANOVA. To enable robust multi-response comparison and optimization, an Entropy-weighted grey relational analysis (Entropy–GRA) is employed to objectively weight the criteria and integrate them into a unified performance index. Overall, the proposed experimental–analytical framework provides actionable guidance for dry-milling process planning of AA7075-T6 by jointly improving thermo-mechanical loads and dynamic stability, while explicitly accounting for performance trade-offs.

2 Materials and Experimental Procedure

2.1 Material and Cryogenic Treatment Procedure

Rolled AA7075-T6 aluminum alloy (supplied by SEYKOÇ Aluminum, Turkey) was used in this study. The nominal chemical composition is given in Table 1.

Prior to the milling experiments, four workpieces (80 mm × 100 mm × 20 mm) were prepared. Three workpieces were subjected to deep cryogenic treatment (DCT) at $-146\text{ }^{\circ}\text{C}$ with holding times of 12, 24, and 36 h, respectively, while

the remaining workpiece was kept in the as-received condition and used as the reference.

For microstructural characterization, both treated and untreated specimens were prepared by sequential grinding using SiC papers (P400, P800, P1200, and P2400), followed by polishing with 1 μm and 0.25 μm diamond suspensions. Final polishing was carried out using a 0.2 μm fumed silica suspension. The specimens were then ultrasonically cleaned in ethanol and air-dried prior to microscopy.

2.2 Experimental Setup

The experimental setup, including the CNC machine tool, cutting tool, dynamometer, accelerometer, infrared camera, and data acquisition systems, is schematically shown in Fig. 1. Milling tests were performed on a HAAS VF-2 SS CNC vertical machining center. The workpiece material was AA7075, and all experiments were conducted under dry cutting conditions. An uncoated carbide end mill (WIDIN) with a 45° helix angle and three flutes was used as the cutting tool.

Cutting forces were measured using a Kistler 9272 three-component piezoelectric dynamometer, and the signals were recorded via a Kistler 5070 A multi-channel charge amplifier. Measurements were acquired in three orthogonal directions: the feed direction (F_x), the normal direction (F_y), and the axial direction (F_z). Using the obtained force components, the resultant cutting force (F_R) was calculated for each experimental condition.

Vibration was monitored using a YMC 141A10 IEPE tri-axial accelerometer, rigidly mounted on the dynamometer near the workpiece. Acceleration signals were sampled at 50 kHz using a YMC 9004 data-acquisition system and analyzed in the frequency domain, with the measurement axes aligned with the force-coordinate system.

Cutting temperature measurements were carried out using a FLIR T440 infrared (IR) thermal camera. During the measurements, the emissivity value specified in the manufacturer’s documentation was used, set to 0.04 [44]. All experiments were conducted under identical optical conditions. Thus, the measurements were intended to reflect relative temperature variations between different experimental conditions rather than absolute temperature values. Aluminum alloys are known to have low emissivity values that may vary depending on surface condition. To reduce measurement uncertainty associated with low emissivity and environmental reflections, the thermal camera was positioned approximately 650 mm (see Fig. 1a,

Table 1 Nominal chemical composition of AA7075-T6 alloy (wt%)

Element	% Al	% Zn	% Cu	% Cr	% Ti	% Fe	% Mn	% Zr	% Ni	% Other
Al7075-T6	92.432	5.481	1.534	0.169	0.144	0.112	0.037	0.035	0.016	0.04

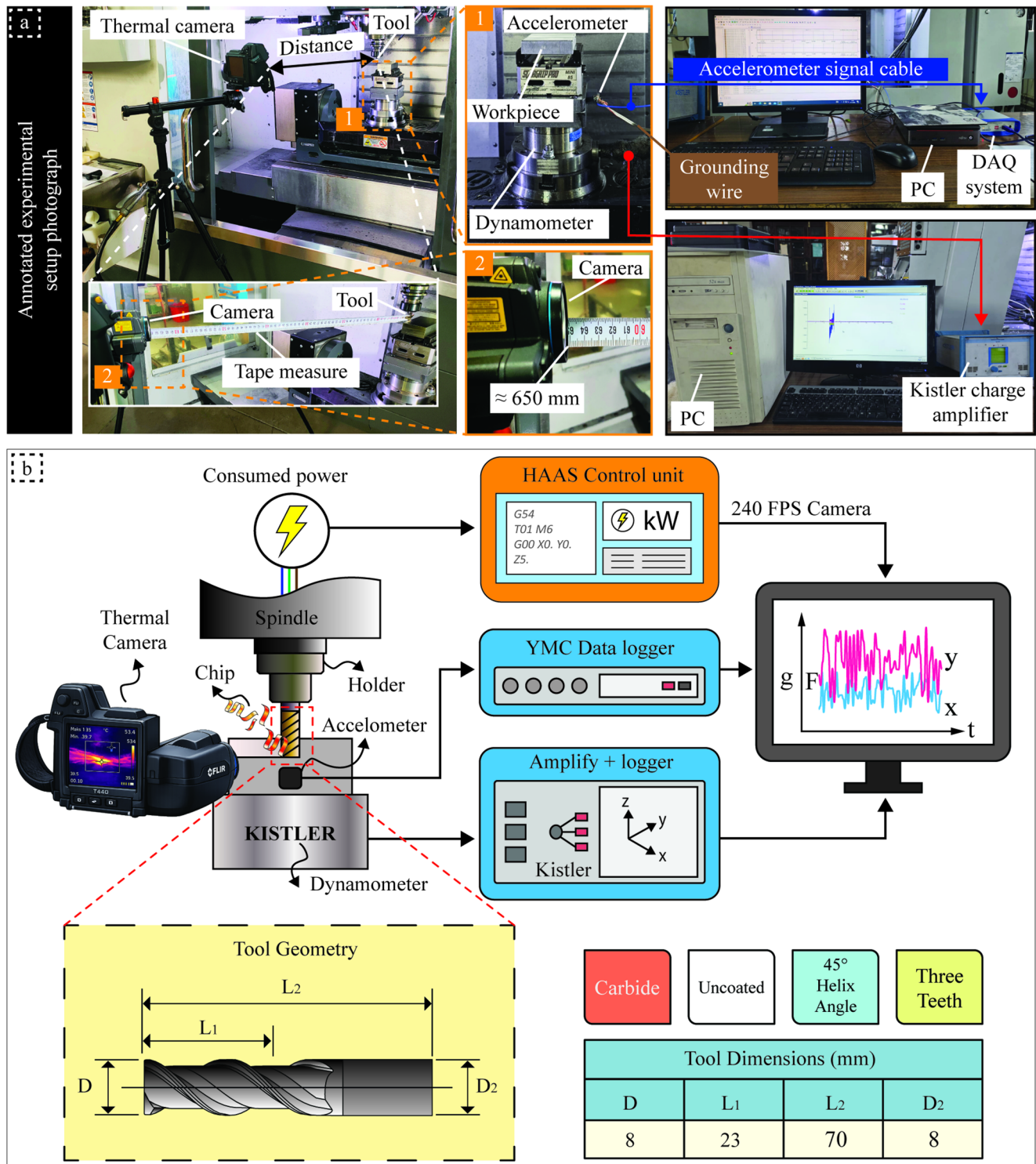


Fig. 1 **a** Annotated photograph of the experimental setup: (1) dynamometer, workpiece, accelerometer, and grounding connection; (2) measured distance between the thermal camera and the cutting tool; **b** schematic illustration of the experimental setup

region 2) from the tool–workpiece contact zone with a direct view of the cutting region, without any protective machine enclosure in front of the camera. Maximum temperature values in the cutting zone were determined from

the thermal images for each experiment and used in the comparative evaluations.

In addition, instantaneous power consumption was recorded from the CNC controller (spindle power/load

output) during machining. Power data were evaluated together with force, vibration, and temperature to assess the energy response under different cutting conditions.

To ensure high experimental repeatability and consistency, all tests were conducted under identical conditions using the same tool geometry and cutting strategy. The workpiece dimensions and fixturing positions were kept constant throughout the experiments, and a new cutting tool was used for each run to avoid variability associated with tool wear. Data acquisition was performed using certified shielded cables routed away from power lines to minimize electromagnetic interference (EMI). In addition, a grounding protection scheme was applied to the vibration measurement system to reduce the influence of leakage currents (see Fig. 1a, region 1). Pre-test noise analyses indicated that the signal-to-noise ratio was sufficient to ensure reliable signal interpretation, with only minor interference originating from unavoidable grid frequencies and inherent system dynamics. Importantly, these noise characteristics remained consistent across all 108 experimental runs (comprising 36 unique parameter combinations with three replicates each), preserving the validity of comparative analyses. Therefore, the acquired force and vibration signals were evaluated in their raw form without additional filtering, ensuring that the results accurately reflect the physical behavior of the process.

2.3 Control Factors and Design of Experiments

A full factorial design was employed to quantify the effects of CHT and principal cutting parameters on the machinability of AA7075 aluminum alloy. Milling tests were conducted under a constant axial depth of cut ($a_p = 2 \text{ mm}$), using three cutting speeds ($V_c = 200, 250$, and 300 m/min) and three feeds per tooth ($f_z = 0.08, 0.10$, and 0.12 mm/tooth). The selected parameter ranges were based on the tool manufacturer's recommendations (Table 2).

In total, 36 unique parameter combinations ($3 \times 3 \times 4$) were tested. To ensure repeatability, all trials were conducted under the same tool, fixturing, and dry-cutting conditions, following an identical toolpath strategy. Measurements of cutting force, vibration, temperature, and surface roughness were taken according to a predefined and consistent measurement protocol. Each condition was repeated three times, and the mean values were used for subsequent analysis.

Table 2 Control factors and levels used in the experimental design

Parameters	Symbol	Level	Level	Level	Level
		1	2	3	4
Cryogenic Holding Time (h)	CHT	0	12	24	36
Cutting speed (m/min)	V_c	200	250	300	
Feed rate (mm/tooth)	f_z	0.08	0.1	0.12	

2.4 Mechanical and Microstructural Characterization

Hardness was evaluated for both cryogenically treated and untreated specimens using Brinell macrohardness testing (HBW 2.5/62.5) in accordance with ASTM E10. A 2.5 mm hardened steel ball and a load of 62.5 kgf were applied, and at least five indents were made at different locations on each specimen; the arithmetic mean and standard deviation were reported.

The microstructural properties and surface morphologies of the specimens were examined using a field emission scanning electron microscope (FE-SEM) (Hitachi SU8700). Analyses were performed under an accelerating voltage of 10 kV and a working distance of 12.3 mm. The surfaces of the treated and untreated specimens were evaluated comparatively. Additionally, Energy-Dispersive X-Ray Spectroscopy (EDS) was performed to determine the surface elemental composition.

The phase composition, crystal structure, and changes in lattice parameters of the specimens were investigated using X-ray diffraction (XRD). XRD analyses were carried out using a Bruker D8 Advance diffractometer. Measurements employed Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) with a scanning range of 20° – 80° (2θ). The scans were performed in the Bragg–Brentano (θ – 2θ) geometry with a step size of 0.02° . The obtained diffractograms were compared to assess variations in phase and crystal structure as a function of CHT.

To quantitatively assess surface quality, surface roughness was measured using a Mitutoyo 178-560-11D surface roughness tester, in accordance with ISO 4287 and ISO 4288. Measurements were taken from three distinct locations on the machined surfaces after each experiment, and the average of these values was utilized for analysis. The arithmetic average roughness (R_a) was selected as the primary evaluation parameter. Furthermore, the surface topography of the specimens exhibiting the best and worst surface conditions was examined using an optical profilometer, and the roughness values were verified against these measurements.

2.5 Entropy-based Grey Relational Analysis for Multi-objective Optimization

The Entropy-weighted GRA method was employed to comprehensively evaluate multiple performance criteria, specifically cutting force, vibration, temperature, power consumption, and surface roughness, that possess distinct units and scales. GRA is a widely utilized and effective technique in multi-criteria decision-making (MCDM) problems for determining the proximity of alternatives to the ideal solution.

2.5.1 Data Normalization

In multi-criteria problems, data normalization is a prerequisite to render criteria comparable. Since all criteria evaluated in this study exhibit a “smaller-is-better” characteristic, the “smaller-is-better” normalization approach was applied:

$$x_{ij}^* = \frac{x_j^{max} - x_{ij}}{x_j^{max} - x_j^{min}} \quad (1)$$

Where x_{ij} denotes the actual experimental value of the i -th alternative for the j -th criterion, x_j^{max} and x_j^{min} represent the maximum and minimum values of the j -th criterion, respectively, and x_{ij}^* indicates the normalized value.

2.5.2 Calculation of Entropy Weights

Conventional GRA typically assumes equal weights for all criteria. However, in practice, the information contributed by each criterion varies significantly. In this study, the Entropy method was utilized to calculate weights based on the information content of each criterion, which were subsequently integrated into the GRA framework. Entropy weighting assigns higher importance to criteria with greater variability, reflecting their higher information content.

Entropy weights are computed from normalized data using the following probability matrix:

$$P_{ij} = \frac{x_{ij}^*}{\sum_{i=1}^m x_{ij}^*} \quad (2)$$

Where m is the total number of alternatives, and P_{ij} represents the contribution of the i -th alternative under the j -th criterion. Entropy is calculated as follows:

$$E_j = -k \sum_{i=1}^m P_{ij} \times \ln(P_{ij}) \quad (3)$$

Where $k = \frac{1}{\ln(m)}$. To avoid undefined values in $\ln(0)$, a small constant (e.g., 10^{-10}) is added:

$$E_j = -k \sum_{i=1}^m P_{ij} \times \ln(P_{ij} + \epsilon) \quad (4)$$

Lower entropy values indicate higher information content and greater contribution to the decision-making process. Consequently, the degree of divergence (d_j), representing the information utility, is calculated as follows:

$$d_j = 1 - E_j \quad (5)$$

Subsequently, the weights are calculated as follows:

$$\omega_j = \frac{d_j}{\sum_{j=1}^n d_j} \quad (6)$$

Where n denotes the total number of criteria, and the sum of the weights equals 1 ($\sum \omega_j = 1$).

Grey relational coefficient and grade The subsequent step involves the calculation of the Grey Relational Coefficients (GRC). In GRC calculation, the reference sequence (ideal solution) is assumed to be 1. Consequently, the deviation sequence (Δ_{ij}), which represents the absolute difference between the reference sequence and the normalized sequence, is calculated using Eq. (7):

$$\Delta_{ij} = |1 - x_{ij}^*| \quad (7)$$

The GRC (ξ_{ij}) is then calculated as follows:

$$\xi_{ij} = \frac{\Delta_{min} + \rho \times \Delta_{max}}{\Delta_{ij} + \rho \times \Delta_{max}} \quad (8)$$

Where $\Delta_{min} = \min_{i,j} \Delta_{ij}$ and $\Delta_{max} = \max_{i,j} \Delta_{ij}$ denote the minimum and maximum deviations, respectively. The term ρ represents the distinguishing coefficient, which is typically set to 0.5.

Subsequently, the Entropy-weighted Grey Relational Grade (GRG) is computed by aggregating the weighted GRCs, as shown in Eq. (9):

$$GRG_i = \sum_{j=1}^n \omega_j \times \xi_{ij} \quad (9)$$

Finally, all calculated GRG_i values are ranked; the alternative with the highest GRG_i value is considered the optimal condition. The flowchart illustrating the calculation steps is presented in Fig. 2.

3 Results

3.1 Microstructural and Phase Analysis Results

The BSE image of the AA7075-T6 specimen subjected to cryogenic treatment (36 h) reveals secondary phase regions aligned along the extrusion direction, distinguished by their bright contrast within the matrix (Fig. 3a). These bright regions correspond to clusters of intermetallic phases containing elements with higher atomic numbers. Point EDS analyses obtained from the locations marked as Spectrum 1 (Speck 1) and Spectrum 2 (Speck 2) in Fig. 3a support the compositional character of these phases.

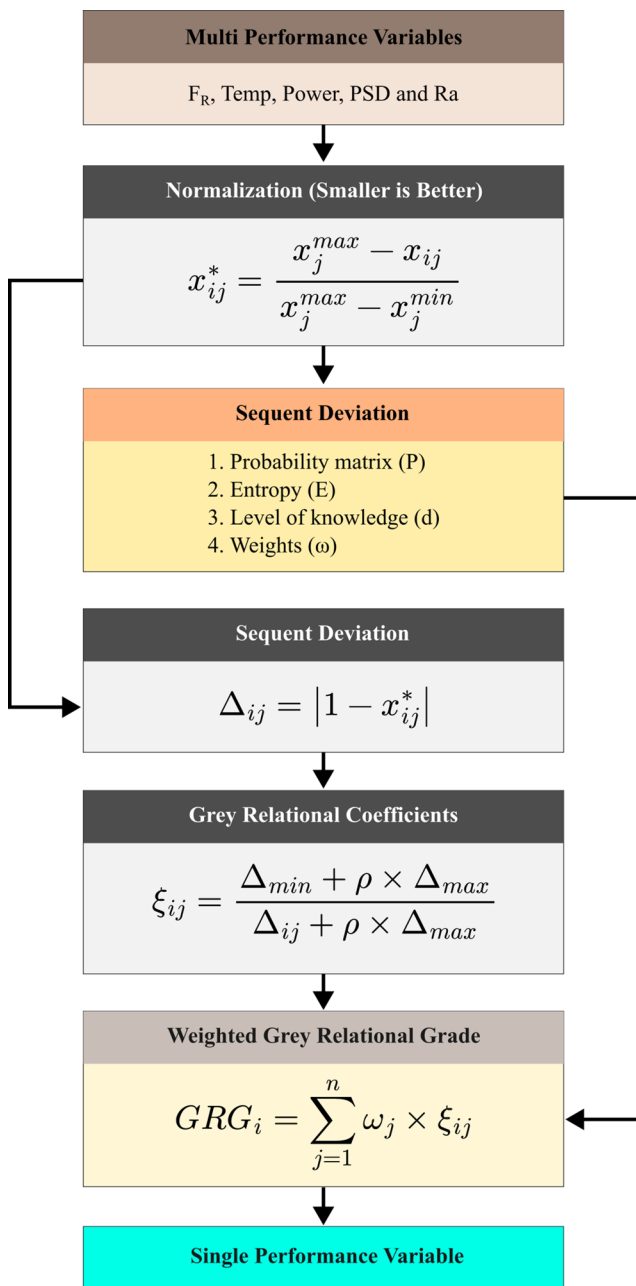


Fig. 2 Flowchart of the Entropy-weighted GRA calculation steps

The EDS elemental mapping images in Fig. 4b confirm the presence of both Cu-rich and Mg/Zn-rich secondary phases in areas where Mg–Zn–Cu elements are co-enriched. Speck 1 exhibits a high Al content (≈ 87.9 wt%) and low alloying element ratios, indicating that this region represents the α -Al matrix. In contrast, Speck 2 shows an increase in Fe content together with a decrease in the Al ratio, suggesting that this region corresponds to an Fe-containing complex intermetallic phase. At Speck 3, the high Cu content

(≈ 45.2 wt%), lower Al ratio (≈ 26.2 wt%), and co-enriched Zn–Mg elements indicate the presence of Cu-rich intermetallic phases (e.g., Al_2Cu and/or Al_2CuMg) (Fig. 3c).

The XRD patterns of the AA7075 alloy before cryogenic treatment and after 36 h of cryogenic holding are shown separately in Fig. 4a to avoid graphical overlap. The diffraction patterns of both specimens contain characteristic reflections corresponding to the face-centered cubic (FCC) aluminum phase, with main peaks located at approximately 38° , 45° , 65° , and 78° corresponding to the (111), (200), (220), and (311) planes, respectively. Prior to cryogenic treatment, no distinct second-phase peak structure was observed; however, trace reflections attributed to the MgZn_2 (η) phase could be very weakly distinguished in the spectrum [45]. After cryogenic treatment, these low-intensity reflections corresponding to the MgZn_2 phase appeared slightly more pronounced.

Gradual shifts towards higher 2θ values were determined in the main diffraction peaks with increasing CHT (12, 24, and 36 h). However, to avoid graphical clutter, only the diffraction patterns of the untreated sample and the sample subjected to 36 h of cryogenic holding are presented together in Fig. 4. For instance, the reflections corresponding to the (111), (200), and (220) planes were located at 38.39° , 44.67° , and 64.97° , respectively, prior to treatment; however, these shifted to 38.63° , 44.84° , and 65.17° after 36 h of cryogenic holding. The interplanar spacings (d) corresponding to these shifts decreased from 2.35 Å, 2.03 Å, and 1.43 Å to 2.34 Å, 2.02 Å, and 1.42 Å, respectively. Furthermore, an increase in peak intensities was observed for all main reflections; the intensity of (111) reflections rose from 56.827 to 91.315, (200) intensity from 3.104 to 5.002, and (220) intensity from 3.508 to 5.282 [46].

3.2 Hardness Variation with CHT

Brinell hardness measurements were performed on untreated specimens and those subjected to cryogenic treatment for 12, 24, and 36 h, respectively. For each specimen, five distinct measurements were taken from different regions, and the mean hardness value is presented in Fig. 4b along with its standard deviation.

The results indicate a gradual increase in Brinell hardness with increasing CHT. The mean hardness was 173.6 HB for the untreated specimen and increased to 175.4 HB, 177.2 HB, and 179.6 HB after 12, 24, and 36 h of cryogenic treatment, respectively. A one-way ANOVA ($n=5$) showed that the effect of CHT on hardness was statistically significant ($F(3,16)=9.31$, $p<0.01$), although the magnitude of the increase was limited.

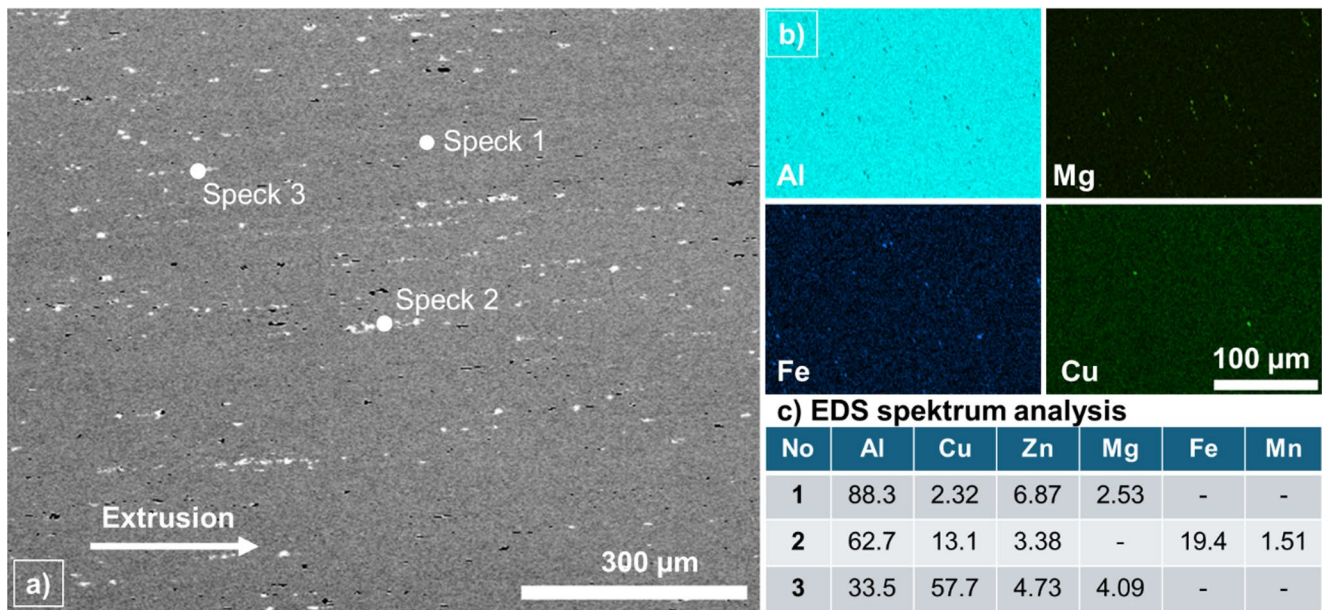


Fig. 3 **a** BSE (Backscattered Electron) image of the cryogenically treated (36 h) AA7075-T6 alloy. Intermetallic particles appearing in white/grey tones within the matrix and extending parallel to the extrusion direction are evident. The regions where EDS point analyses were conducted are marked as Spectrum 1, Spectrum 2, and Spectrum 3. **b** EDS distribution (mapping) maps of Al, Mg, Fe, and Cu elements belonging to the region indicated by the white box in **(a)**. The maps

show intermetallic phase clusters in regions where Mg and Cu elements are locally enriched. **(c)** Normalized EDS point analyses (wt%) obtained from points Spectrum 1, Spectrum 2, and Spectrum 3 numbered in **(a)**. While Spectrum 1 stands out with high Al content characteristic of the matrix, Spectrum 2 corresponds to an Fe-containing complex intermetallic structure, and Spectrum 3 corresponds to a distinctly Cu-rich intermetallic phase

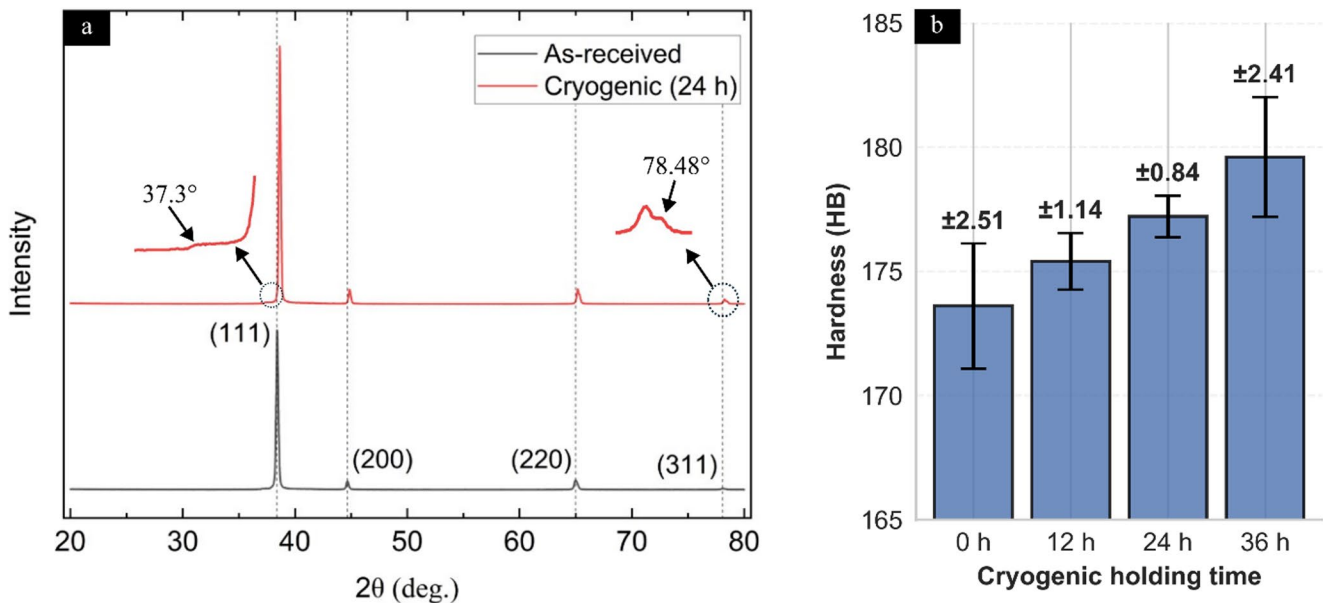


Fig. 4 **a** XRD patterns of the AA7075 alloy in the as-received condition and after cryogenic treatment. Both patterns exhibit the characteristic FCC Al reflections at approximately 38° (111), 45° (200), 65° (220), and 78° (311). Weak η -MgZn₂ reflections (e.g., near 37.3° and

78.48°) become slightly more distinguishable after cryogenic treatment, while no new phases are detected. **b** Variation of hardness as a function of CHT, showing a progressive increase in hardness with increasing holding duration; error bars represent the standard deviation

3.3 Statistical Analysis Results (ANOVA and Factor Contributions)

The ANOVA-based percentage contribution analysis (Table 6, Fig. 5) revealed the relative effects of control factors on each performance response. For the resultant cutting force (F_R), the most dominant factor was f_z (33%), while V_c (25%) and CHT (15%) provided lower yet statistically significant contributions ($p < 0.01$). The cutting temperature (T_c) was predominantly controlled by CHT (54%; $p = 2.02 \times 10^{-10}$), followed by V_c (27%; $p < 10^{-6}$) and f_z (7%; $p < 0.01$). Regarding power consumption (P_c), the effect of V_c was dominant (57%; $p = 3.67 \times 10^{-7}$), whereas the contributions of CHT (5%; $p = 0.207$) and f_z (7%; $p = 0.0568$) remained statistically limited. In terms of the vibration response (PSD), V_c (40%; $p < 0.001$) and f_z (30%; $p < 0.001$) were found to be significant, while the contribution of CHT was low and statistically insignificant (4%; $p = 0.256$). Regarding surface roughness (R_a), the most determining parameter was f_z (67%; $p = 4.28 \times 10^{-9}$); the effect of V_c was marginal (5%; $p = 0.0519$), and the effect of CHT was insignificant (5%; $p = 0.143$).

3.4 Machining Performance Responses under Full Factorial Design

The mean values of the responses obtained from the three repeated experiments for each condition are presented in Table 3. Within the experimental design space, the values for resultant cutting force (F_R), cutting temperature (T_c), power consumption (P_c), vibration metric (PSD), and surface roughness (R_a) varied in the ranges of 166.3–274.7 N,

48.3–88.7 °C, 1.8–3.9 kW, 2.927–16.587 g²/Hz, and 0.543–1.860 μm, respectively. In the subsequent subsections, each response is evaluated under a dedicated heading.

3.4.1 Resultant Cutting Force

The variation of resultant cutting force is presented in Fig. 6. The resultant cutting force (F_R) was calculated from the measured force components in the x, y, and z directions using the standard vector summation approach:

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (10)$$

where F_x , F_y , and F_z represent the cutting force components along the respective axes. The minimum F_R value (166.3 N) was recorded under the conditions of CHT=36 h, $V_c = 250$ m/min, and $f_z = 0.08$ mm/tooth, whereas the maximum F_R value (274.7 N) was obtained at CHT = 0 h, $V_c = 300$ m/min, and $f_z = 0.12$ mm/tooth. These values correspond to a reduction of approximately 39.5% in F_R from the maximum to the minimum.

The effect of increasing f_z on F_R exhibited an increasing trend across most experimental conditions. For instance, at CHT=0 h and $V_c = 200$ m/min, F_R increased to 218.0, 229.8, and 264.9 N as f_z increased to 0.08, 0.10, and 0.12 mm/tooth, respectively. Similarly, under the condition of CHT = 24 h and $V_c = 250$ m/min, F_R rose to 168.5, 205.0, and 227.0 N.

Conversely, an increase in CHT was associated with a reduction in F_R values under constant cutting conditions. For example, when $V_c = 250$ m/min and $f_z = 0.08$ mm/tooth were held constant, F_R decreased to 217.4, 181.2, 168.5, and 166.3 N for CHTs of 0, 12, 24, and 36 h, respectively. A similar trend was observed for $V_c = 200$ m/min and $f_z = 0.08$ mm/tooth, with values decreasing to 218.0, 204.3, 198.5, and 193.6 N.

At constant CHT and f_z levels, the effect of V_c on F_R did not exhibit a monotonic trend; instead, indicating a marked interaction effect. Under many conditions, lower F_R values were obtained at the level of $V_c = 250$ m/min. For instance, for CHT = 0 h and $f_z = 0.12$ mm/tooth, F_R was measured as 264.9, 228.1, and 274.7 N at V_c levels of 200, 250, and 300 m/min, respectively, with the minimum value observed at $V_c = 250$ m/min. Similarly, under the condition of CHT = 36 h and $f_z = 0.08$ mm/tooth, F_R values were 193.6, 166.3, and 203.7 N for $V_c = 200$, 250, and 300 m/min, respectively, with the lowest value again obtained at $V_c = 250$ m/min. Conversely, in certain combinations, an increase in V_c demonstrated a tendency to reduce F_R (e.g., 241.7, 205.0, and 195.9 N for CHT = 24 h and $f_z = 0.10$ mm/tooth).

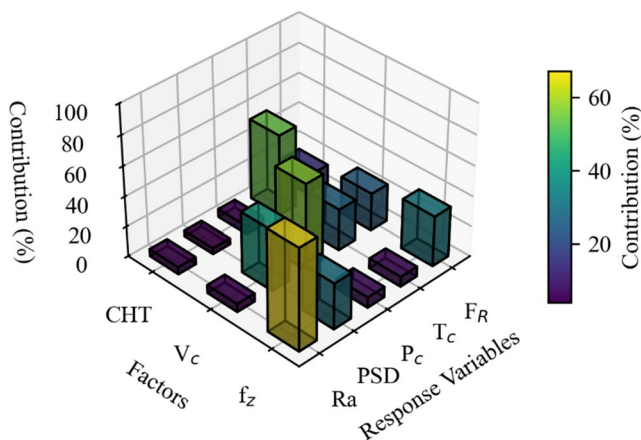


Fig. 5 Three-dimensional bar plot illustrating the contribution percentages of control factors (CHT, V_c , f_z) on each performance response based on ANOVA results

Table 3 Experimental measurements according to full factorial experimental design

Runs	CHT (h)	V_c (m/min)	f_z (mm/tooth)	F_R (N)	T_c (°C)	P_c (kW)	PSD (g ² /Hz)	R_a (μm)
1	0	200	0.08	218.0	81.5	2	7.036	0.929
2	0	200	0.1	229.8	85.2	2.2	7.716	1.687
3	0	200	0.12	264.9	88.7	2.5	9.085	1.549
4	0	250	0.08	217.4	79.8	2.2	4.587	0.903
5	0	250	0.1	198.0	84.7	2.4	5.345	1.000
6	0	250	0.12	228.1	84.2	2.1	6.729	1.529
7	0	300	0.08	210.4	66.8	3	2.927	0.858
8	0	300	0.1	234.3	71.3	3.7	4.292	1.047
9	0	300	0.12	274.7	80.7	3.5	6.814	1.373
10	12	200	0.08	204.3	60.7	1.8	6.747	0.759
11	12	200	0.1	236.9	59.2	2	8.116	1.099
12	12	200	0.12	257.0	59.5	2.2	11.359	1.196
13	12	250	0.08	181.2	69.3	2.2	3.766	0.730
14	12	250	0.1	207.0	71.9	2.3	6.95	0.964
15	12	250	0.12	197.0	80.3	2.3	6.602	1.375
16	12	300	0.08	190.7	49.6	2.7	3.421	0.713
17	12	300	0.1	200.0	55.4	3.1	3.695	0.757
18	12	300	0.12	257.1	56.1	3.9	6.274	1.842
19	24	200	0.08	198.5	73.1	2	5.836	0.790
20	24	200	0.1	241.7	77.1	2.2	9.295	1.149
21	24	200	0.12	232.7	84.8	2.5	10.911	1.490
22	24	250	0.08	168.5	70.3	3.1	5.377	0.777
23	24	250	0.1	205.0	79.2	2.9	9.646	1.108
24	24	250	0.12	227.0	85.3	2.7	9.071	1.450
25	24	300	0.08	223.5	55.6	3.4	3.499	0.543
26	24	300	0.1	195.9	60.2	3.1	5.238	1.032
27	24	300	0.12	229.4	58.3	2.9	8.651	1.276
28	36	200	0.08	193.6	60.7	2.2	8.309	0.833
29	36	200	0.1	218.1	56	2.6	7.362	1.438
30	36	200	0.12	242.2	62	3	16.587	1.860
31	36	250	0.08	166.3	53	2.1	3.37	0.829
32	36	250	0.1	187.4	63	3.4	8.233	1.386
33	36	250	0.12	194.5	64.3	2.6	6.35	1.308
34	36	300	0.08	203.7	48.3	3	3.185	0.814
35	36	300	0.1	218.9	53.7	3.2	3.155	1.072
36	36	300	0.12	199.8	54.8	3.3	5.185	1.225

3.4.2 Cutting Temperature

Although a general trend of decreasing temperature values was observed with increasing CHT, the temperature variation exhibited non-monotonic behavior depending on the cutting parameter combinations (Fig. 7). Under untreated (CHT = 0 h) conditions, cutting temperature (T_c) and cutting force values reached their maximum levels in certain combinations, whereas the highest value in terms of vibration response (PSD) was observed under a different condition. At cutting speeds of $V_c = 200$ and 250 m/min, a decrease in temperatures was recorded after 12 h of treatment in some parameter combinations; however, distinct increases in temperature values were subsequently

observed at the 24-hour level. Conversely, lower temperature values were consistently observed for the 36-hour cryogenic treatment duration across all conditions.

Representative thermal camera images belonging to the conducted experiments are depicted in Fig. 7. Figure 7a–c illustrate the temperature variations occurring in the cutting zone depending on different cutting parameters and cryogenic treatment durations. Regarding specific cases, the minimum temperature value obtained at $V_c = 200$ m/min is visualized in Fig. 7d, the optimum cutting conditions determined in terms of all response variables are shown in Fig. 7e, and the thermal distribution formed under the most unfavorable cutting conditions is displayed in Fig. 7f.

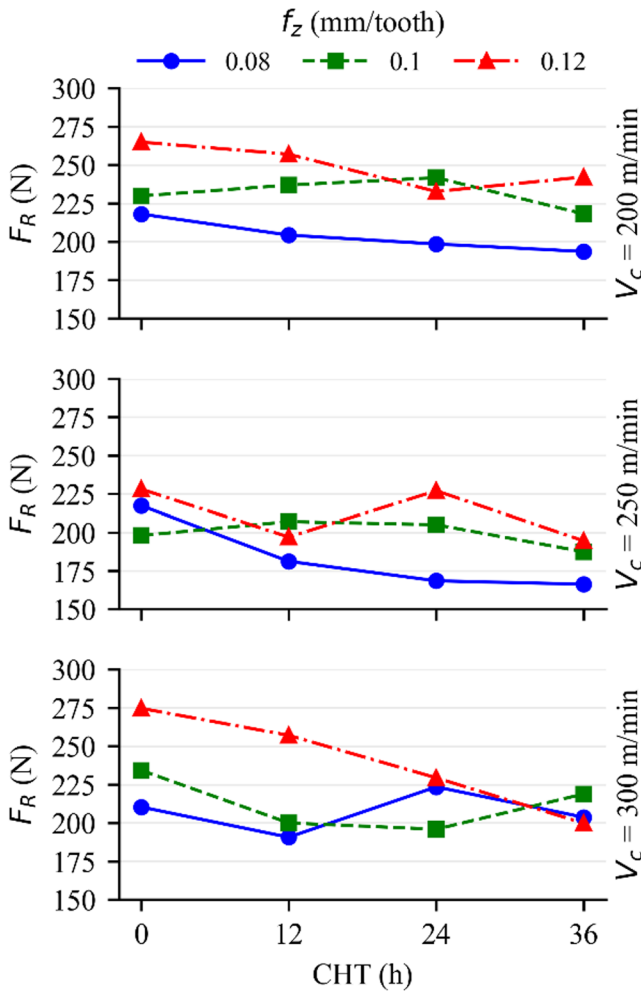


Fig. 6 Variation of resultant cutting force

3.4.3 Power Consumption

The ANOVA results regarding the power consumption data obtained during the milling of AA7075 alloy subjected to various CHT are presented in Table A1. Upon examining the analysis conducted at a 95% confidence level, V_c was identified as the most statistically influential parameter on power consumption, exhibiting a low p -value ($p < 0.05$) and a dominant percentage contribution of 57%.

In contrast, the p -values for f_z and CHT exceeded the 0.05 threshold, indicating that these variables did not exert a statistically significant influence on power consumption. Notably, the low contribution rate of approximately 5% for CHT, a primary variable in this study, suggests that variations in the duration of cryogenic treatment did not significantly alter power requirements during chip removal within the investigated range.

3.4.4 Surface Roughness and Surface Topography

According to the ANOVA results regarding surface roughness (R_a) data (Table 6), f_z was identified as the primary control parameter determining surface quality, characterized by a high contribution rate of 67% and a high level of statistical significance ($p < 0.001$, $F = 41.45$). Conversely, the fact that the p -values for V_c and CHT exceeded the confidence interval threshold ($p > 0.05$) indicates that these variables did not exert a statistically significant influence on R_a . In particular, the limited impact of CHT on surface roughness (5% contribution rate) suggests that the duration of the applied cryogenic holding did not significantly alter the surface texture.

Figure 8a represents the surface morphology associated with the parameter combination yielding the worst performance, where deep valleys and peaks attributed to feed marks are clearly observed. On the other hand, an examination of Fig. 8b, obtained using optimal machining parameters, reveals a much more homogeneous surface profile where machining marks are minimized, resulting in a substantially lower roughness level.

3.4.5 Vibration Response (PSD-Based Metrics)

During milling operations, acceleration signals in the X, Y, and Z directions were recorded for each experimental condition using a triaxial accelerometer, and the total Power Spectral Density (PSD) was calculated from these acceleration data. The obtained vibration accelerations and total PSD results are presented in Table 7. The highest total PSD value was recorded in Experiment 30. Additionally, the X-axis emerged as the dominant vibration component in the majority of the experiments. However, under certain conditions, elevated vibration components were observed in different axes (e.g., $4.503 \text{ g}^2/\text{Hz}$ in the Z-axis for Experiment 27, and $3.157 \text{ g}^2/\text{Hz}$ in the Y-axis for Experiment 23). Conversely, total PSD values remained lower in Experiments 7, 34, 35, and 31.

A comparison of PSD distributions and frequency intensities for all experiments is provided in Fig. 9. In the PSD plot for the X-axis (Fig. 9a), a high-energy region was identified in the 0–3 kHz range. While energy levels decreased in the 3–8 kHz band, regions sensitive to experimental parameters were evident around 6–7 kHz and in the 14–16 kHz range. Energy concentration was detected across all axes at approximately 24 kHz. In the Y-axis plot, lower energy levels were observed compared to other axes, particularly around 15–16 kHz. The Z-axis exhibited a general behavior similar to that of the X-axis.

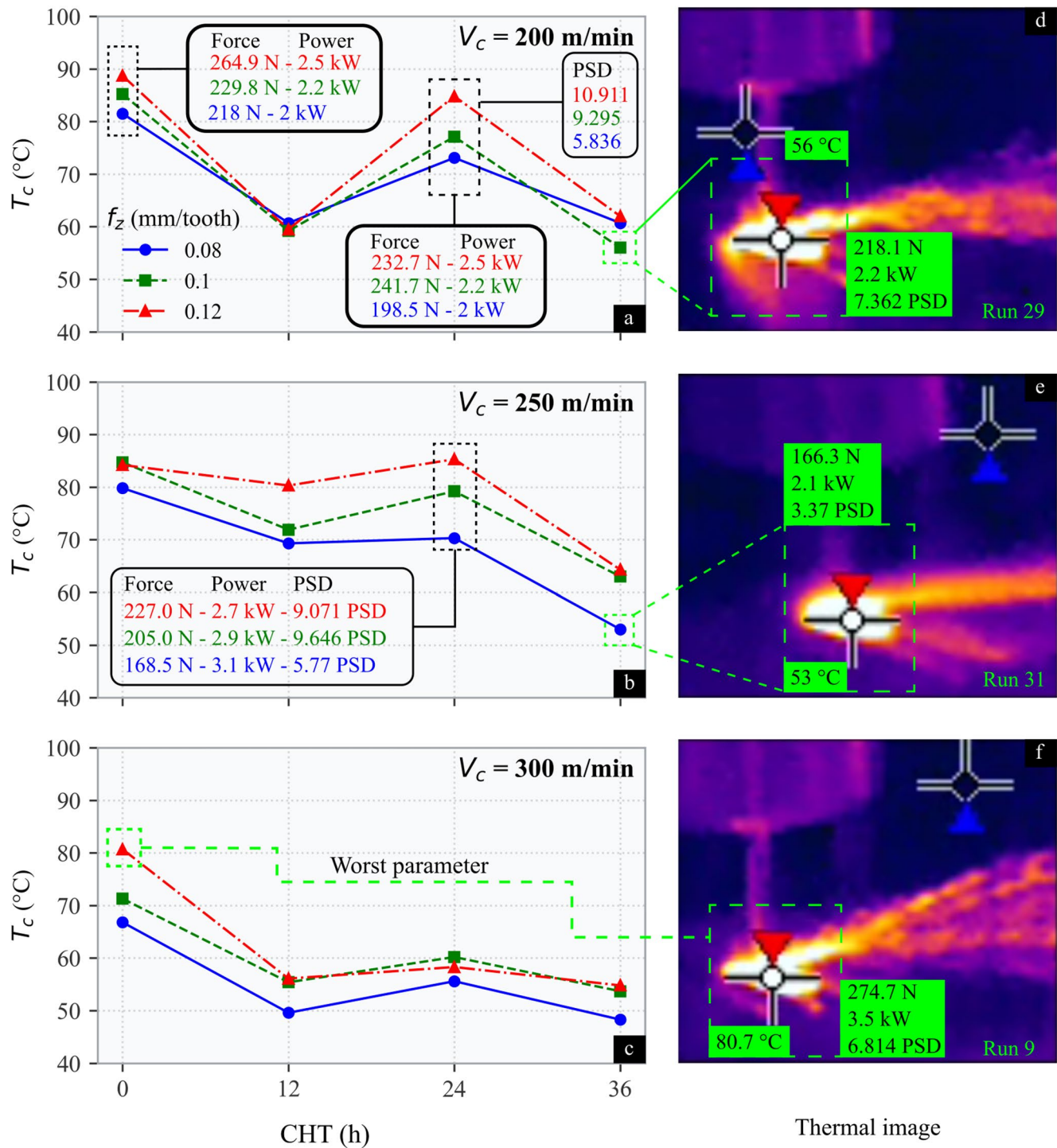


Fig. 7 Effect of CHT on temperature: Thermal camera images for (a) $V_c = 200$, (b) $V_c = 250$, and (c) $V_c = 300$ m/min; d Experiment 29, (e) Experiment 31, and (f) Experiment 9. Red and blue arrows in d–e–f indicate the maximum and minimum temperature points, respectively

In Fig. 10, the vibration responses of the tool under cutting load and no-load conditions are compared based on the Power Spectral Density (PSD) of triaxial (X, Y, Z) acceleration data from Experiment 31. In the low-frequency band (approximately 0–4 kHz) indicated by 1, 2, and 3 in the figure, harmonics with significantly increased amplitudes

under load are observed. This increase is particularly higher for the X-axis (Fig. 10a) compared to the other axes. However, when the amplitude variation in this region is compared with that in Fig. 9, it is evident that it exhibits a similar trend across all experiments and is independent of the cutting parameters.

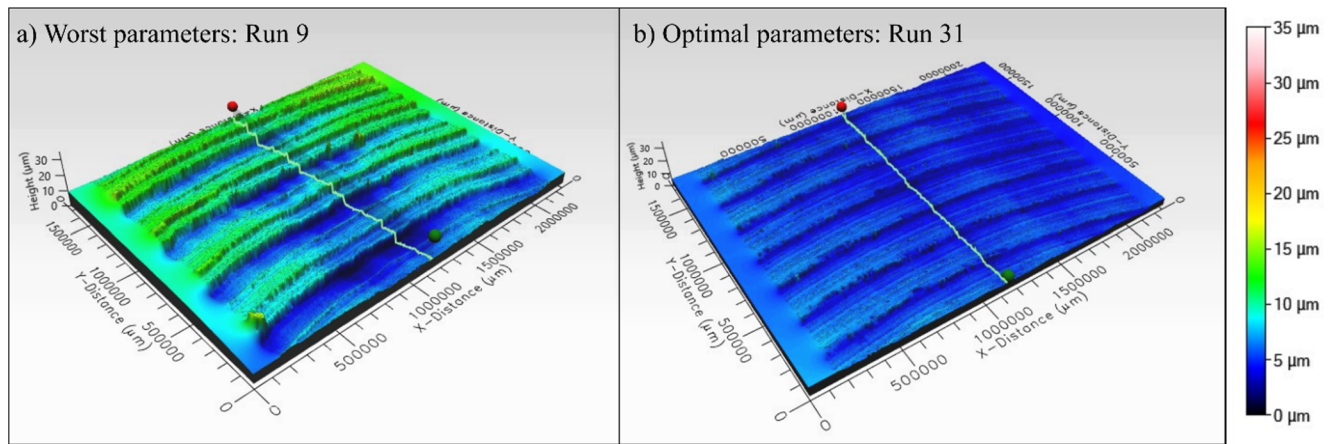


Fig. 8 3D surface topographies obtained from experimental studies: (a) Surface profile exhibiting high surface roughness, (b) Surface profile exhibiting low surface roughness (optimal)

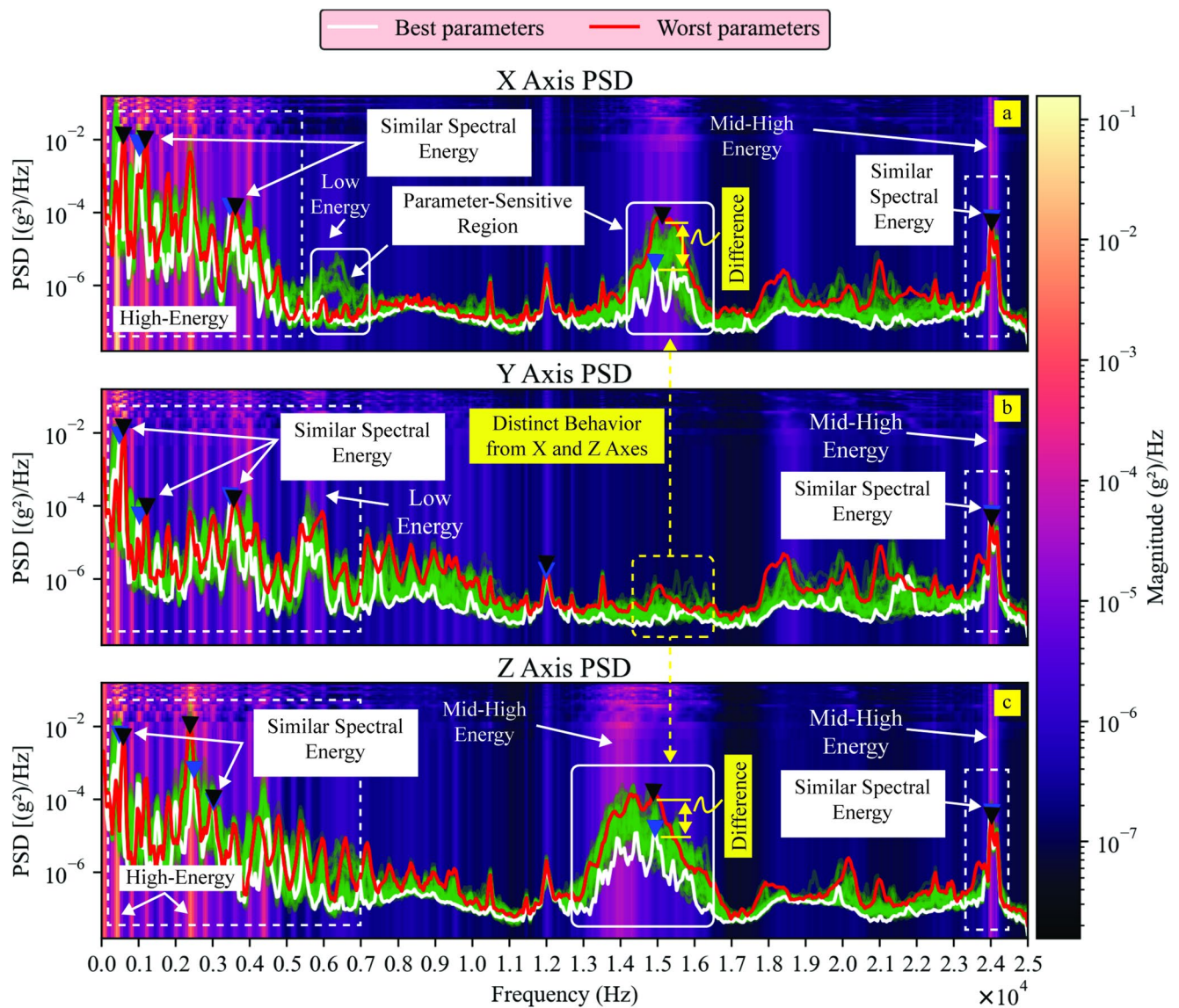


Fig. 9 PSD plots for all experiments: (a) for X-axis, (b) for Y-axis, and (c) for Z-axis

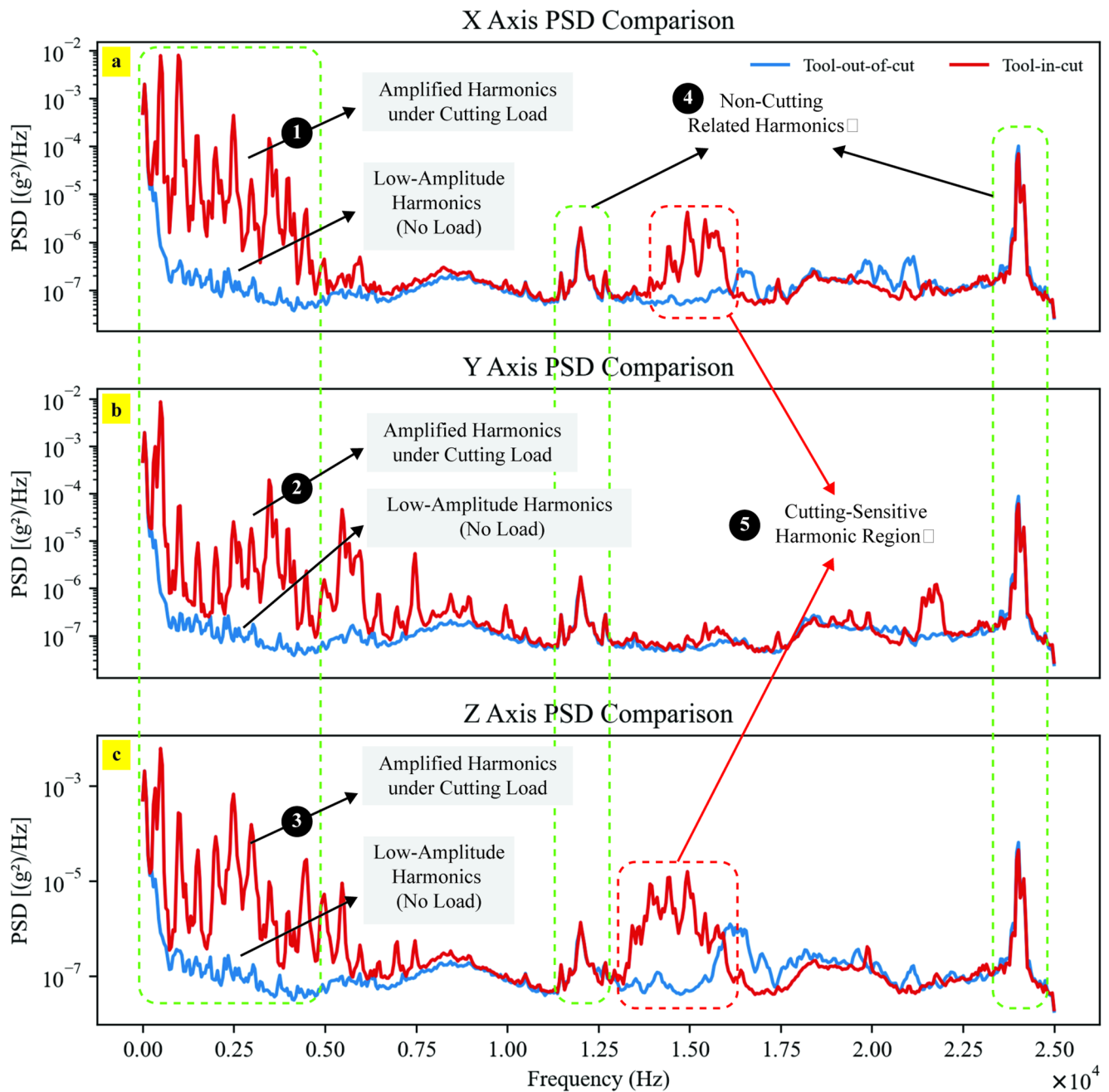


Fig. 10 PSD plots of vibrations measured while the tool is under chip load and under no-load conditions: (a) for X-axis, (b) for Y-axis, and (c) for Z-axis

In contrast, it was determined that the harmonics around 12 kHz and 24 kHz, marked with number 4, appeared with similar amplitudes under both load and no-load conditions and were unaffected by cutting forces. The frequency range of approximately 14–16 kHz, indicated by 5 in Fig. 10a and c, contains harmonics whose amplitudes increase significantly during cutting and, compared with Fig. 9, demonstrate sensitivity to cutting parameters. No variation was observed in this frequency band for the Y-axis (Fig. 10b).

3.5 Multi-Response Optimization Results and Confirmation Experiments

To effectively perform multi-objective optimization, the Entropy-based GRA method was employed in this study, enabling the reduction of multiple performance outputs into a single integrated index. The values of this integrated index, calculated as the GRG, are presented in Table 8. The

Table 4 ANOVA of control factors according to the results of entropy-weighted GRA analysis

Source	DF	SS	MS	F-value	P-value	Contr. (%)
CHT	1	0.00015	0.00015	0.0371	0.84877	0.0178
V_c	1	0.04788	0.04788	11.88738	0.00194	5.70489
f_z	1	0.37041	0.37041	91.95759	0	44.13149
CHT^2	1	0.05444	0.05444	13.51641	0.00108	6.48668
f_z^2	1	0.22364	0.22364	55.52133	0	26.64531
$V_c \times f_z$	1	0.01212	0.01212	3.01009	0.09459	1.44458
$CHT^2 \times f_z$	1	0.00329	0.00329	0.81611	0.37461	0.39166
$CHT \times V_c \times f_z$	1	0.003	0.003	0.74381	0.39633	0.35696
$CHT \times f_z^2$	1	0.01966	0.01966	4.88202	0.03615	2.34294
Residual (Error)	26	0.10473	0.00403	-	-	12.47769
Total	35	0.83933				100.00%

R-squared: 87.52%
Adj. R-squared: 83.20%
Predictive R-squared: 73.08%

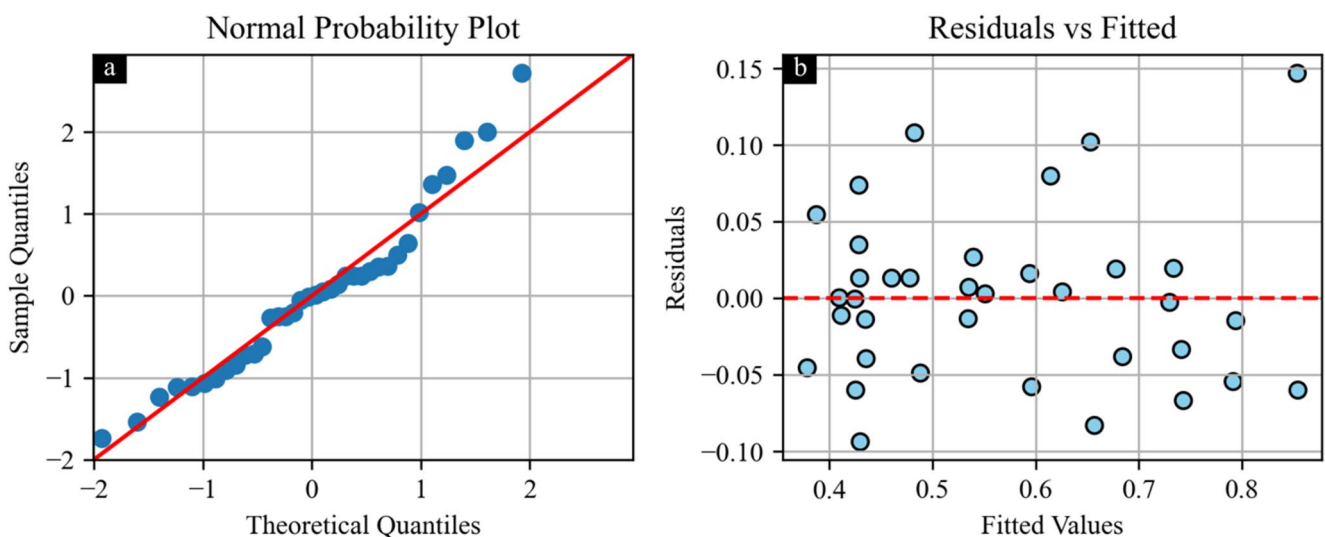
experimental condition with the highest GRG value was identified as the condition providing the best overall performance under multiple criteria. In this context, the optimal machining parameters were determined as 36 h for CHT, 250 m/min for V_c , and 0.08 mm/tooth for f_z .

According to the results of the ANOVA conducted on GRG values (Table 4), f_z emerged as the most influential control parameter with a contribution rate of 44.13% and a statistically significant p -value ($p < 0.001$). While the quadratic effect of feed rate (f_z^2) reinforced this influence with a 26.65% contribution, the linear effect of CHT was not found to be statistically significant. However, the quadratic effect of CHT (CHT^2 , 6.49%) and its interaction with the square of f_z ($CHT \times f_z^2$, 2.34%) were found to be significant. These results indicate that variations in GRG are

significantly affected not only by main factors but also by higher-order non-linear effects. V_c was identified as another significant factor with a 5.70% contribution rate and a significant p -value ($p = 0.0019$). Conversely, the main CHT effect and multiple interaction terms were not found to be statistically significant.

Analyses regarding the distribution of model residuals are presented in Fig. 11. In Fig. 11a, the residuals largely exhibit a normal distribution. In Fig. 11b, although minor deviations exist, no systematic bias is observed, and the assumption of homogeneous variance is largely satisfied. These results demonstrate the validity and reliability of the measurements performed.

The mathematical model developed to explain the effects of control factors on GRG is provided in Eq. (11):

**Fig. 11** Residual analysis plots for the GRG model: (a) Normal probability plot, (b) Residuals vs. fitted values

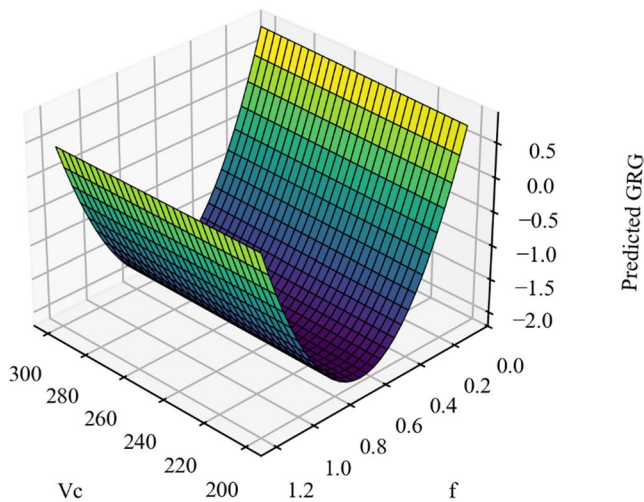


Fig. 12 3D surface plot of all predicted GRG values under constant CHT

$$GRG = \beta_0 + \beta_1 CHT + \beta_2 V_c + \beta_3 f_z + \beta_4 CHT^2 + \beta_5 f_z^2 + \beta_6 (V_c f_z) + \beta_7 (CHT^2 f_z) + \beta_8 (CHT V_c f_z) + \beta_9 (CHT f_z^2) + \epsilon \quad (11)$$

Where the coefficients are calculated as $\beta_0 = 1.242313$, $\beta_1 = 0.013172$, $\beta_2 = 0.001288$, $\beta_3 = -11.352013$, $\beta_4 = -0.000412$, $\beta_5 = 8.966051$, $\beta_6 = -0.001473$, $\beta_7 = 0.000308$, $\beta_8 = 0.000034$, and $\beta_9 = -0.014874$.

To elucidate the effects of statistically significant parameters, a three-dimensional surface plot generated under constant CHT is presented in Fig. 12. This plot visually demonstrates the variation in predicted GRG values depending on changes in V_c and f_z . The graph clearly indicates that the f_z has a distinct and curvilinear effect on GRG. Notably, GRG values reach a minimum in the medium-to-high feed range, pointing to an unfavorable machining region in terms of multi-performance criteria. The increase in GRG at both low and high feed rates suggests that the f_z should be selected depending on other parameter effects. V_c , on the other hand, exhibited a more limited and linear effect on GRG. These findings indicate that f_z plays a dominant role in outputs such as surface quality, cutting force, and vibration, which is further supported by the significant high contribution rates of f_z and f_z^2 terms in the ANOVA analysis.

3.6 Performance Results under Optimal Machining Conditions

Experimental results obtained under optimal machining parameters demonstrate distinct variations in performance indicators when compared to the initial conditions (CHT=0 h, $V_c=200$ m/min, and $f_z=0.08$ mm/tooth). The

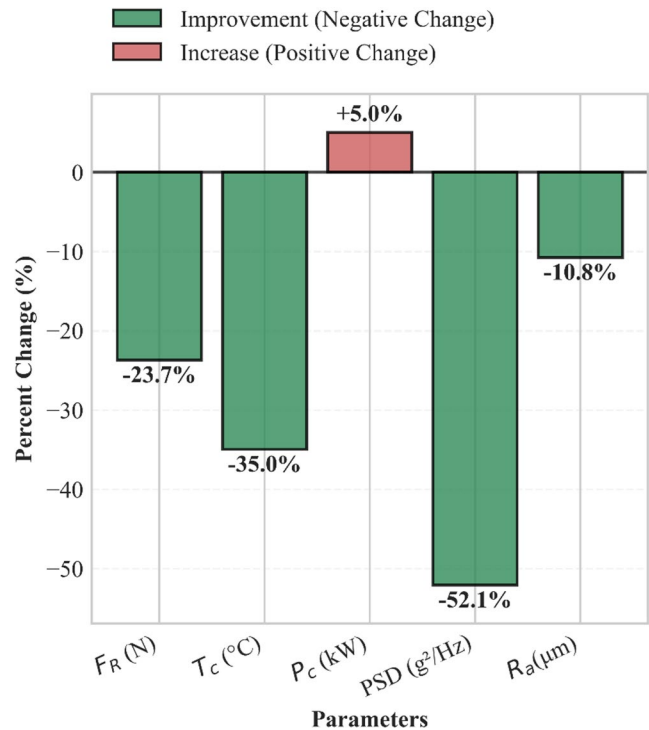


Fig. 13 Variation of performance variables under optimal conditions relative to initial conditions

performance outcomes under optimal parameters, relative to the initial parameters, are summarized in Fig. 13.

The cutting force, measured at 218 N under initial conditions, decreased to 166.3 N under optimal conditions, corresponding to a 23.7% reduction. The machining temperature, recorded at 81.5 °C under initial conditions, decreased to 53 °C with optimal parameters, a 35.0% decrease. Regarding vibration behavior, the PSD value was as 3.37 g²/Hz under optimal conditions compared to 7.036 g²/Hz under initial conditions, representing a 52.1% reduction. Surface roughness (R_a) decreased from 0.929 µm under initial conditions to 0.829 µm under optimal parameters, yielding an improvement of 10.8%. Conversely, power consumption was measured at 2.1 kW under optimal conditions, compared to 2.0 kW under initial conditions, 5.0% increase.

4 Discussion

This study investigates how cryogenic holding time (CHT) and cutting parameters influence the milling performance of AA7075-T6. Beyond statistical evaluation (ANOVA and Entropy-GRA), the observed trends are interpreted based on underlying microstructural evolution and thermomechanical mechanisms.

4.1 Microstructural Evolution Induced by Cryogenic Treatment

A collective evaluation of the obtained BSE, EDS, and XRD findings regarding the effects of cryogenic treatment on the microstructural properties of AA7075 alloy indicates that no fundamental change occurred in the phase structure; however, distinct stress-induced microstructural rearrangements took place within the matrix (Figs. 3 and 4). BSE images revealed that Cu-, Mg-, and Zn-rich intermetallic phases aligned along the extrusion direction persisted after cryogenic treatment and preserved their morphological integrity (Fig. 3a). Nevertheless, due to the spatial resolution of BSE and the detection limits of EDS, the direct resolution of minute changes that might occur in the fine precipitate population is limited with these techniques.

In XRD analyses, trace reflections belonging to the $\alpha(\text{Al})$ matrix phase and MgZn_2 (η) precipitates were detected in both pre- and post-treatment specimens (Fig. 4). The shift of the main diffraction peaks towards higher 2θ values after cryogenic treatment suggests a limited reduction in the matrix lattice parameters. This shift is attributed to microstress fields resulting from the differences in thermal expansion coefficients between the matrix and intermetallic phases during cooling, rather than a phase transformation [37]. Although some researchers [22, 38, 47] have suggested that coarse secondary phases partially dissolve into the matrix during cryogenic treatment, this interpretation remains debatable due to the extremely limited diffusion coefficients at such low temperatures [43]. The findings obtained in the present study do not support the hypothesis of phase dissolution; instead, they indicate that the observed variations can be better explained by microstructural rearrangements caused by internal stress fields arising from thermal contraction differences and the accompanying limited increase in dislocation density [48, 49].

The limited increase of hardness measured after cryogenic treatment is attributed to these stress-induced microstructural rearrangements within the matrix [45]. The modest nature of this increase is consistent with the restricted diffusion at low temperatures and the absence of a distinct change in precipitate morphology on a macro scale. In future studies, quantitative analysis of microstrain (e.g., peak broadening analysis, Williamson-Hall/Rietveld methods) and evaluation of the precipitate structure via TEM would contribute to a more precise interpretation of the microstructural mechanisms of cryogenic treatment.

4.2 Influence of Machining Parameters on Performance Criteria

4.2.1 Effect of Feed Rate on Cutting Force Mechanisms

The significant influence of f_z on cutting force can be attributed to the increase in chip volume generated within the cutting zone and the alterations in the tool–chip contact mechanism. An increase in f_z causes the cutting tool to interact with a larger amount of material per revolution, thereby increasing the undeformed chip thickness [50, 51]. This increase in chip volume increases the cutting resistance, thereby requiring a higher cutting force from the tool [52, 53]. Furthermore, the literature reports that an elevation in f_z expands the uncut cross-sectional area, prolongs the tool–chip contact time, and intensifies the average pressure on the tool, which, in turn, leads to increased friction and temperature [54, 55].

Upon examining the data in Fig. 6, a clear increase rise in cutting forces with increasing feed rate is evident. This observed increasing trend can be attributed to the augmented unit chip load and the consequently elevated resistance to plastic deformation. Consequently, the results of this study confirm the determinant role of the feed parameter in cutting dynamics and align with the general consensus in the literature.

4.2.2 Dominant Parameters Affecting Cutting Temperature

Statistical analyses (Table 6) identified CHT as the most influential parameter affecting cutting temperature, exhibiting a statistically significant impact ($p < 0.001$) with a dominant contribution rate of 54% and a high F-value ($F = 41.37$). This suggests that, without inducing a distinct phase transformation (Sect. 4.1), cryogenic treatment may exert an indirect influence on heat generation and/or heat partition (chip–tool–workpiece) during cutting, potentially through limited alterations in microstress distribution and/or precipitate–matrix interface conditions within the matrix [43, 49].

As shown in Fig. 7, the highest values of temperature, force, and vibration were recorded in untreated specimens (CHT=0 h); conversely, a distinct improvement in machinability was observed with the extended CHT. Thermal analysis findings reveal that while cutting temperatures generally tended to decrease with increasing CHT, this reduction exhibited a non-linear and fluctuating distribution. Theoretically, the increase in hardness expected with cryogenic treatment [56–58] would raise the energy required

for plastic deformation in the primary shear zone, thereby increasing the temperature. However, the potential of cryogenic treatment to alter the material's thermal conductivity may counterbalance this effect by influencing the rate of heat evacuation through the chips. Consequently, the influence of CHT on temperature can be largely attributed to the mechanism of heat evacuation via chips.

The consensus in the literature posits that an increase in V_c elevates cutting temperatures by intensifying friction and plastic deformation at the tool–chip interface [59, 60]. In contrast, an examination of the thermal analysis results obtained in the present study (Fig. 7a–c) reveals a decrease in temperature values inversely proportional to the increase in V_c . This phenomenon can be explained by the improvement in chip flow dynamics with increasing speed and the heat evacuation mechanism, wherein the heat generated in the cutting zone is largely absorbed and removed by the chip before being conducted to the tool [61]. At high V_c , the chip's residence time in the cutting zone is extremely short. Consequently, there is insufficient time for the generated heat to be conducted into the workpiece or tool; instead, the heat is predominantly concentrated within the chip and evacuated along with it [59].

On the other hand, the non-linear trend observed in temperature variation is attributed to process stability. Inappropriate selection of cutting parameter combinations may disrupt the deformation mechanism, leading to increases in cutting forces, friction, chip flow resistance, and vibrations. This state of instability can trigger sudden temperature spikes in the cutting zone, contradicting the expected cooling trend.

4.2.3 Interpretation of Power Consumption Behavior

V_c was identified as the most influential parameter on power consumption, with a contribution rate of 57% and a high level of significance ($F = 26.34$, $p < 0.001$) (Table 6). The significant impact of V_c on power consumption has been corroborated by numerous studies [62–66].

As the V_c increases, the spindle rotational speed also rises, necessitating the motor to operate at higher velocities. This escalation increases the total power demand by elevating not only mechanical energy requirements but also losses in motor drives and transmission systems [67–70]. Furthermore, while the contact time between the tool and the workpiece decreases at high cutting speeds, the volume of material removed per unit time and the rate of plastic deformation increase [71], which leads to higher energy consumption [72]. Additionally, the frequency of periodic and interrupted cutting loads generated by to increased V_c also increases; this situation amplifies the energy density of the system's dynamic frequency responses. These

aforementioned mechanical and dynamic losses can be attributed to the overall increase in system energy [73–77].

It is important to emphasize that while CHT significantly reduced the resultant cutting forces (F_R) by approximately 23.7%, this mechanical improvement did not translate into a dominant reduction in the total power consumption (P_c). This apparent discrepancy is attributed to the fact that P_c represents the total energy demand of the machine tool system, where the high-speed spindle rotation and the associated electromechanical losses—driven primarily by V_c —statistically overshadow the energy savings achieved through force reduction. In this study, the contributions of CHT and f_z factors on power consumption were found to be low and statistically limited (CHT: 5%, $p = 0.583$; f_z : 7%, $p = 0.0568$). Consequently, within the examined parameter range, V_c is the primary determinant of power consumption, and no statistical evidence was obtained to suggest that CHT significantly alters the total electrical power requirements. This result suggests that cryogenic treatment is more effective on responses such as temperature and/or surface integrity, where the modification of the material's microstructural state plays a direct role, rather than the overall system power consumption.

4.2.4 Key Factors Governing Vibration Characteristics (PSD Response)

ANOVA results (Table 6) revealed that V_c was the most influential parameter governing vibration. The variations in vibration amplitude depending on V_c , f_z , and CHT variables are presented in Fig. 14. It is clearly observed in the graph that vibration power density significantly decreased at increasing V_c .

This trend can be explained within the scope of milling dynamics using the stability lobe approach. With an increase in V_c , the system can move away from resonance bands and operate in 'stable pockets,' thereby reducing the tendency for chatter. In their study analytically modeling Stability Lobe Diagrams (SLD) in milling processes, Budak and Altıntaş [78] demonstrated both theoretically and experimentally the existence of stable zones at high rotational speeds (high V_c). Similarly, Smith and Tlustý [79] showed that operating at high speeds allows for achieving much higher Material Removal Rates (MRR) in a vibration-free manner compared to low speeds.

On the other hand, when the effect of f_z on vibration is examined, it was determined that increasing feed values increased the vibration power density (Fig. 9). An increase in f_z directly increases the uncut chip thickness. This situation leads to the growth of cutting forces ($F \propto f_z$) and the intensification of elastic deformations in the tool–workpiece system. The increased dynamic forces excite

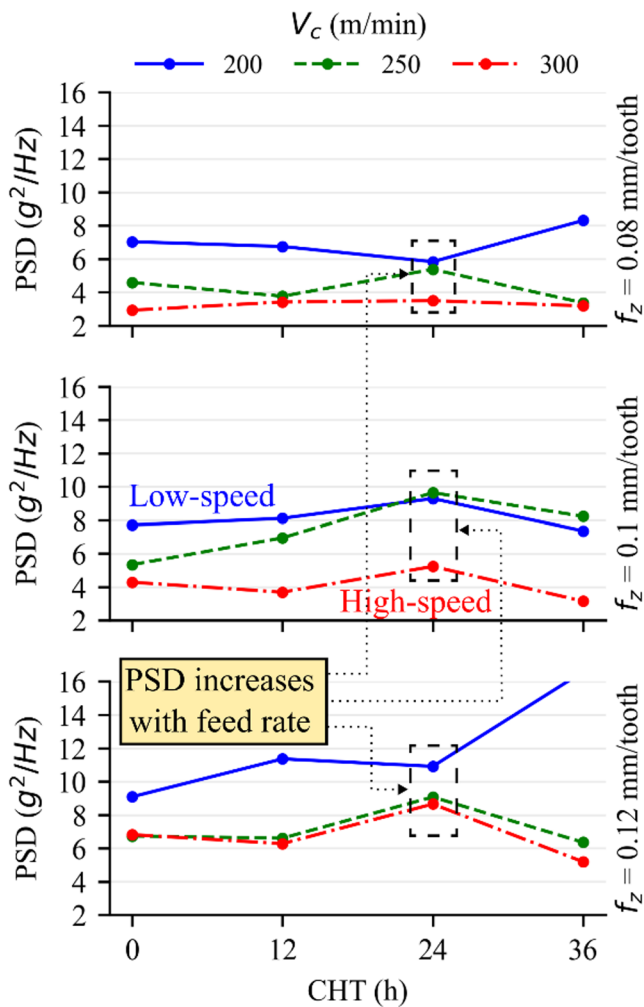


Fig. 14 Variation of vibration amplitude depending on process parameters

the natural frequencies of the system with higher energy, causing an increase in the PSD values of the vibration signals. This result is consistent with studies in the literature [80, 81] reporting that increasing chip load increases vibration amplitude.

4.2.5 Parametric Effects on Surface Roughness (R_a) and Topography

Theoretically, in milling operations, an increase in f_z amplifies the amplitude and width of the feed marks left by the cutting tool on the workpiece, thereby causing a deterioration in surface roughness [4, 82–85]. Furthermore, when this result is evaluated in conjunction with the finding regarding “the amplification of vibration by f_z ” determined in the previous sections of this study, it becomes evident that the increased dynamic forces and vibration directly degrade the surface quality, and these two findings mutually corroborate each other.

On the other hand, the effects of V_c and CHT parameters on the model remained more limited. Both parameters contributed approximately 5% to the total variance. From a statistical perspective, while the effect of V_c exhibited marginal significance ($p = 0.0519$), the effect of the CHT parameter was not found to be statistically significant ($p = 0.143$). Nevertheless, the general trend of the experimental results indicates that increasing V_c reduces surface roughness, and cryogenic treatment possesses the potential to improve surface quality.

4.3 Correlation Between Microstructural Rearrangements and Machining Mechanics

ANOVA results demonstrate that CHT is the primary driver of cutting temperature (T_c), with a contribution of 54%, while its influence on cutting force, power, vibration, and surface roughness is 15%, 5%, 4%, and 5%, respectively. This impact on T_c highlights a significant mechanistic relationship between the cryogenic-induced microstructural state and the thermo-mechanical processes at the tool-workpiece interface.

A statistically significant increase was observed with increasing CHT (from 173.6 HB to 179.6 HB). While the simultaneous reduction in cutting forces (F_R) may appear counterintuitive, this phenomenon can be explained by the specific effects of cryogenic treatment on the AA7075 microstructure. The literature often suggests that cryogenic conditions increase dislocation density and stabilize the distribution of precipitate phases (η and η' phases), thereby redistributing macro-scale residual stresses into a more homogeneous internal energy state. However, as discussed in Sect. 4.1, the hypothesis of coarse phase dissolution is controversial for this study due to limited diffusion at low temperatures. Instead, the observed improvements are attributed to micro-stress fields arising from thermal contraction mismatches, a limited increase in dislocation density, and the reduction of macro-scale residual tensile stresses, which collectively stabilize plastic deformation behavior.

To accurately correlate CHT-induced microstructural changes with deformation mechanisms, chip morphology analysis is essential. However, isolating the independent influence of CHT requires constant cutting parameters, which contrasts with the full factorial design where V_c , f_z , and CHT were varied simultaneously. Due to the resulting non-uniform deformation conditions, decoupling the specific effect of CHT on chip formation was not feasible in the present study. Accordingly, comprehensive chip characterization was excluded and remains a focus for future investigation.

From a cutting mechanics perspective, this behavior may be interpreted as a consequence of a more stable material

response in the primary shear zone after cryogenic treatment [86]. A more homogeneous microstructural state may promote more uniform plastic deformation and reduce fluctuations in shear localization, thereby lowering the specific cutting energy required for chip formation. In addition, changes in the material response at the tool–chip interface may contribute to more favorable tribological conditions, which can also support the observed reduction in cutting force (F_R).

Furthermore, cryogenic treatment promotes microstructural homogeneity, reducing tool-chip contact length and friction. The resulting reduction in friction lowers heat generation in the secondary deformation zone while stabilizing chip formation. Consequently, improved flow dynamics accelerate heat removal via the chips, preventing thermal accumulation at the tool-workpiece interface.

From a thermomechanical perspective, this behavior can also be interpreted through the classical energy balance model of metal cutting proposed by Shaw [87]. In machining processes, the mechanical power supplied to the cutting zone is primarily transformed into heat through plastic deformation in the primary shear zone and friction at the tool-chip interface. The total heat generation can be expressed as the sum of shear and frictional heat contributions:

$$Q_{total} = Q_s + Q_f \quad (12)$$

where Q_s represents the heat generated by plastic deformation in the primary shear zone, and Q_f denotes the frictional heat generated at the tool-chip interface. According to Shaw's energy partition model, the generated heat is distributed among the chip, tool, and workpiece, as schematically illustrated in Fig. 15. In this framework, the heat generated in the primary shear zone and the secondary deformation zone is partitioned among the chip, tool, and workpiece according to the heat partition coefficients for each region.

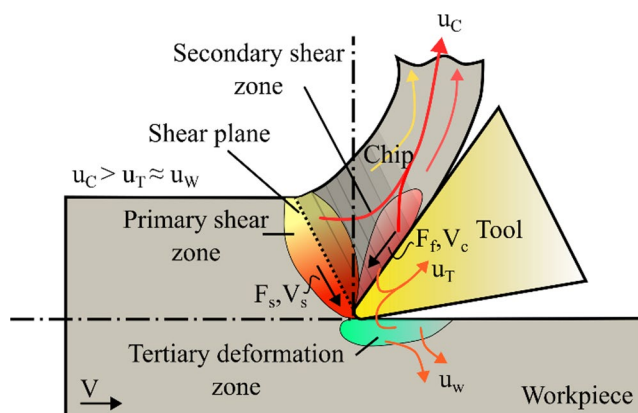


Fig. 15 Theoretical model of heat generation and distribution in the metal cutting process (three-zone orthogonal cutting)

$$u_C = R_1 u_S + R_2 u_F \quad (13)$$

$$u_T = (1 - R_2) u_F \quad (14)$$

$$u_W = (1 - R_1) u_S \quad (15)$$

where u_S and u_F represent the shear and friction energy per unit volume, while R_1 and R_2 denote the heat partition coefficients associated with the shear zone and the tool-chip interface, respectively. In metal cutting, the shear and friction energies are directly related to the cutting force, which can be expressed as

$$u_S \propto F_c, u_F \propto F_c \quad (16)$$

Consequently, the total heat generated in the cutting zone can be written as

$$Q_{total} = Q_s + Q_f \propto F_c V \quad (17)$$

where F_c is the cutting force, and V is the cutting speed. Since cryogenic treatment reduces the cutting force and the frictional interaction at the tool–chip interface, both the shear energy (u_S) and the friction energy (u_F) decrease proportionally. As a result, the total heat generation in the cutting zone is reduced, leading to lower cutting temperatures and improved thermal stability during machining.

Regarding dynamic stability, the limited 4% contribution of CHT to vibration (PSD) indicates that the vibration response is governed primarily by cutting speed (40%) and feed rate (30%). Therefore, the effect of CHT should be interpreted as secondary under the present experimental conditions. This limited contribution may be related to subtle changes in the material response after cryogenic treatment, such as variations in deformation stability and frictional behavior during cutting. However, because cutting speed, feed rate, and CHT were varied simultaneously in the present full factorial design, the direct effect of CHT on vibration mechanisms could not be isolated reliably. Further studies under constant cutting parameters are therefore needed to clarify this relationship in more detail.

4.4 Cutting Parameters and CHT

Although CHT significantly influenced cutting temperature and cutting force, the results indicate that vibration, surface roughness, and power consumption were predominantly governed by cutting parameters, particularly feed per tooth. This suggests that while cryogenic treatment modifies the intrinsic material response, the dynamic behavior of the machining process remains strongly dependent on process parameters.

The dominant influence of feed rate on surface roughness and vibration can be explained by its direct control over chip thickness and tool–workpiece interaction. Higher feed rates increase mechanical loading and surface irregularities, leading to higher vibration amplitudes and degraded surface quality. These findings are in agreement with established machining theory and previous experimental studies.

4.5 Multi-Response Interpretation of Optimal Machining Condition

The multi-criteria optimization results further highlight the importance of considering coupled performance responses rather than single-output evaluation. The optimal condition identified through Entropy-weighted GRA represents a balanced trade-off between thermal, mechanical, and dynamic responses.

Notably, while power consumption slightly increased under optimal conditions, significant reductions in cutting force, temperature, and vibration indicate an overall improvement in process stability and machining efficiency. This confirms that minimizing all responses simultaneously may not be feasible, and that optimization should focus on achieving a balanced, stable machining regime.

4.6 Dynamic Response Characteristics under Cutting Forces

The vibration analyses conducted clearly demonstrate the impact of cutting forces on the dynamic behavior of the system during the milling process. In particular, the distinct increase in the amplitudes of high-energy harmonics observed across all axes within the 0–4 kHz frequency range under cutting load indicates that these components are directly excited by periodic cutting forces. The independent manifestation of these harmonics, regardless of cutting parameters, suggests that the system exhibits an inherent response to forced excitation within this frequency band.

Conversely, the presence of harmonics in the approximate 14–16 kHz band, which exhibit amplitude growth solely under load and demonstrate sensitivity to varying cutting parameters, reveals that this region possesses dynamic characteristics responsive to machining conditions. This

phenomenon is critical for process monitoring and control, suggesting that optimal machining parameters can be utilized to mitigate vibration levels in this specific frequency region. Furthermore, the harmonics around 12 kHz and 24 kHz, which maintained similar amplitudes under both load and no-load conditions, are thought to be associated with the system's structural natural frequencies or background components originating from the measurement system [88]. These findings demonstrate that vibration responses generated during milling are shaped not only by the loading effect but also by the structural characteristics of the system, thereby underscoring the necessity of a multi-dimensional analysis approach.

4.7 Comparison with the Literature

Cryogenic treatment, particularly Deep Cryogenic Treatment (DCT), is among the prominent methods that significantly influence the machining/forming processes and the microstructure–property–performance relationship. In this context, two main axes emerge in the literature: (i) machinability/surface integrity (surface roughness, tool wear, cutting temperature/tribology) [43, 89], and (ii) mechanical properties/deformability (yield-tensile strength, hardness, forming behavior performance). Notably, investigations into the machinability of aluminum alloys subjected to cryogenic treatment (specifically DCT) remain quite limited.

In this study, under optimal conditions, reductions of 23.7%, 35.0%, and 52.1% were obtained in F_R , T_c , and PSD , respectively, while an improvement of 10.8% in R_a and an increase of 3.46% in hardness were observed (Table 5). This trend is generally consistent with previous studies reporting improvements in surface integrity and machinability of cryogenically treated Al alloys. For instance, while Bektaş and Samtaş [90] reported significant improvements in surface roughness and tool wear for AA6061-T651, Zhang et al. [43] reported limited yet consistent improvements in R_a and cutting forces after cryogenic treatment in the high-speed milling of AA7075. Additionally, Altas et al. [38] demonstrated that DCT could enhance mechanical properties and tribological behavior; this finding is consistent with the limited hardness increase observed in the present study.

Table 5 Results for selected studies employing the cryogenic treatment approach

Material	Cryogenic	$F_R/F_{x,y,z}$	T_c	P_c	PSD	R_a	Hardness	Wear
AA6061-T651 [90]	Workpiece/tool	-	↓ 7.1%	-	-	↓ 48.9%	↑ 2.8%	↓ 2.8%
AA7075-T6 [38]	Workpiece	-	-	-	-	-	↑ 5.9%	↓ 11.1%
AA7075-T6/ T614 [43]	Workpiece	↓ 1.5% ↓ 11.8% ↓ 10.5%	-	-	-	↓ 6.2%	-	-
AA7075-T6 (This study)	Workpiece	↓ 23.71%	↓ 35.0%	↑ 5.0%	↓ 52.10%	↓ 10.77%	↑ 3.46%	-

* Some values were not explicitly reported in the relevant studies and were approximately determined based on graphical data

On the other hand, it is known that the relationship between PSD and V_c in the literature is not unidirectional. While some studies associate the increase in vibration/PSD at high V_c with resonance and dynamic rigidity effects [91–94], a decrease in total vibration energy was observed with increasing V_c in the present study. Possible reasons for this divergence include: (i) the evaluation of vibration using a triaxial resultant PSD metric rather than a single axis, (ii) machine–tool–fixturing rigidity and modal properties, (iii) the interaction of tool geometry and tooth passing frequency with stability zones, and (iv) the indirect modification of material behavior by cryogenic treatment. Consequently, this study provides complementary evidence to the literature by demonstrating that multiple performance outputs can be simultaneously optimized in the milling of DCT-treated AA7075 and that the dynamic response can also be improved under appropriate speed–feed combinations.

5 Conclusions

This study investigated the coupled effects of deep cryogenic treatment (DCT) and milling parameters (cutting speed, V_c , and feed per tooth, f_z) on the machinability of AA7075-T6 using a full factorial design ($3 \times 3 \times 4$) with three replicates per condition (108 trials). The main conclusions can be summarized as follows:

1. Microstructural response to cryogenic treatment: BSE/EDS observations and XRD patterns indicate no formation of new phases after cryogenic holding. Nevertheless, the slight shift of the main Al reflections toward higher 2θ values and the marginally enhanced visibility of weak η – MgZn_2 reflections suggest limited but detectable changes in the lattice strain state. Consistently, Brinell hardness increased modestly yet significantly with CHT, reaching 179.6 HB after 36 h compared with 173.6 HB in untreated conditions.
2. Dominant factors governing individual performance responses: ANOVA-based contribution analysis revealed distinct controlling parameters depending on the response. Feed per tooth (f_z) dominated the cutting force (F_R) and surface roughness (R_a), with contribution levels of 33% and 67%, respectively. CHT was the primary driver of cutting temperature, contributing 54%, whereas V_c governed power consumption with a 57% contribution. For the vibration response (PSD), V_c (40%) and f_z (30%) were the most influential factors, while the linear effect of CHT was comparatively limited.
3. Overall trends in thermo-mechanical responses: Increasing CHT reduced cutting force and cutting temperature, indicating improved thermo-mechanical stability. In contrast, vibration, surface roughness, and power consumption were primarily governed by cutting parameters, with no significant direct influence of CHT on vibration.
4. Multi-response optimization and confirmation: Entropy-weighted GRA successfully integrated the multiple criteria into a single performance index (GRG) and identified the optimal combination as CHT=36 h, $V_c = 250$ m/min, and $f_z = 0.08$ mm/tooth. Relative to the baseline condition (CHT = 0 h, $V_c = 200$ m/min, $f_z = 0.08$ mm/tooth), the optimized condition reduced F_R by 23.7%, temperature by 35.0%, PSD by 52.1%, and R_a by 10.8%, while power increased by 5.0%, representing an acceptable trade-off given the substantial gains in thermo-mechanical and dynamic stability.
5. Implications for dynamic stability: A notable observation is the reduction in resultant (three-axis) vibration energy with increasing V_c within the tested range. This trend may reflect the combined effects of (i) using a triaxial resultant PSD metric rather than a single-axis evaluation, (ii) the machine–tool–fixture stiffness and modal characteristics, (iii) tooth passing frequency interacting with stable regions of the milling stability lobes, and (iv) indirect changes in material response induced by cryogenic treatment. Overall, the results indicate that, following DCT, AA7075-T6 milling performance can be jointly improved across multiple outputs, and that appropriate speed–feed combinations can also enhance the dynamic response.

Future work should include the quantification of microstrain and precipitation features (e.g., via Williamson–Hall/Rietveld analysis and TEM), and the extension of the optimization framework to include tool wear and surface integrity metrics (e.g., residual stress and microhardness gradients) to further strengthen industrial relevance.

Appendix 1: Supplementary Data and Additional Results

Table 6 Analysis of variance and model statistics for individual response variables

Source	df	Seq SS	C	Adj SS	Adj MS	F	P	Response Variable
V_c	2.00	5765.00	25%	5765	2882.60	13.23	9.03E-05	Force (F_R)
CHT	3.00	3568.00	15%	3568	1189.30	5.46	4.40E-03	
f_z	2.00	7665.00	33%	7665	3832.50	17.59	1.13E-05	
Residual	28.00	6102.00	26%	6102	217.90			
Total	35.00	23100.00	100%					
R-sq. 0.74 Adj. R-sq. 0.67 Pred. R-sq. 0.56								
V_c	2.00	1410.00	27%	1410	705.10	31.42	6.99E-08	Temperature (T_C)
CHT	3.00	2785.00	54%	2785	928.40	41.37	2.02E-10	
f_z	2.00	340.00	7%	340	170.10	7.58	2.34E-03	
Residual	28.00	628.00	12%	628	22.40			
Total	35.00	5164.00	100%					
R-sq. 0.88 Adj. R-sq. 0.85 Pred. R-sq. 0.80								
V_c	2.00	6.00	57%	6.01	3.00	26.34	3.67E-07	Power (P_C)
CHT	3.00	1.00	5%	0.55	0.20	1.62	2.07E-01	
f_z	2.00	1.00	7%	0.73	0.40	3.18	5.68E-02	
Residual	28.00	3.00	30%	3.20	0.10			
Total	35.00	10.00	100%					
R-sq. 0.70 Adj. R-sq. 0.62 Pred. R-sq. 0.50								
V_c	2.00	115.00	40%	115	57.50	22.38	1.56E-06	Vibration (PSD)
CHT	3.00	11.00	4%	11	3.70	1.43	2.56E-01	
f_z	2.00	87.00	30%	87	43.30	16.87	1.56E-05	
Residual	28.00	72.00	25%	72	2.60			
Total	35.00	285.00	100%					
R-sq. 0.75 Adj. R-sq. 0.68 Pred. R-sq. 0.58								
V_c	2.00	0.00	5%	0.21	0.10	3.29	5.19E-02	Surface Roughness (R_a)
CHT	3.00	0.00	5%	0.19	0.10	1.96	1.43E-01	
f_z	2.00	3.00	67%	2.67	1.30	41.45	4.28E-09	
Residual	28.00	1.00	23%	0.90	0.00			
Total	35.00	4.00	100%					
R-sq. 0.77 Adj. R-sq. 0.72 Pred. R-sq. 0.62								

Table 7 Axis-wise and total PSD values for all experiments

Runs	X	Y	Z	Total PSD
1	5.39	0.622	1.024	7.036
2	6.092	0.64	0.984	7.716
3	7.161	0.756	1.168	9.085
4	2.375	1.101	1.111	4.587
5	2.443	1.494	1.408	5.345
6	2.995	1.898	1.836	6.729
7	1.528	0.604	0.795	2.927
8	2.074	1.031	1.187	4.292
9	3.256	1.443	2.114	6.814
10	5.189	0.564	0.995	6.747
11	6.432	0.603	1.082	8.116
12	8.518	1.06	1.781	11.359
13	1.767	1.012	0.987	3.766
14	2.724	2.259	1.966	6.95
15	2.915	1.886	1.801	6.602
16	1.372	0.466	1.584	3.421
17	1.646	0.832	1.217	3.695
18	3.323	1.307	1.643	6.274
19	4.44	0.534	0.862	5.836
20	7.01	0.95	1.334	9.295
21	8.106	1.141	1.664	10.911
22	2.845	1.308	1.223	5.377
23	3.672	3.157	2.817	9.646
24	3.886	2.638	2.547	9.071
25	1.864	0.766	0.869	3.499
26	2.043	0.796	2.399	5.238
27	3.102	1.046	4.503	8.651
28	6.418	0.83	1.061	8.309
29	5.861	0.649	0.851	7.362
30	12.798	1.641	2.148	16.587
31	1.609	0.929	0.832	3.37
32	4.206	2.166	1.861	8.233
33	2.865	1.895	1.589	6.35
34	1.923	0.665	0.597	3.185
35	1.534	0.819	0.802	3.155
36	2.227	1.163	1.794	5.185

Table 8 Entropy weighted GRA analysis results

Runs	Deviation sequence					GRG					Weighted GRG					Rank
	F_R	T_C	P_C	PSD	R_a	F_R	T_C	P_C	PSD	R_a	F_R	T_C	P_C	PSD	R_a	
1	0.477	0.822	0.095	0.301	0.294	0.477	0.512	0.378	0.840	0.624	0.630			0.630	20	
2	0.586	0.913	0.190	0.351	0.868	0.586	0.461	0.354	0.724	0.588	0.365			0.365	31	
3	0.910	1.000	0.333	0.451	0.764	0.910	0.355	0.333	0.600	0.526	0.396			0.396	35	
4	0.471	0.780	0.190	0.122	0.274	0.471	0.515	0.391	0.724	0.804	0.646			0.646	18	
5	0.292	0.901	0.286	0.177	0.347	0.292	0.631	0.357	0.636	0.739	0.590			0.590	22	
6	0.570	0.889	0.143	0.278	0.749	0.570	0.467	0.360	0.778	0.642	0.400			0.400	29	
7	0.406	0.458	0.571	0.000	0.239	0.406	0.552	0.522	0.467	1.000	0.676			0.676	15	
8	0.627	0.569	0.905	0.100	0.383	0.627	0.444	0.468	0.356	0.833	0.566			0.566	28	
9	1.000	0.802	0.810	0.285	0.630	1.000	0.333	0.384	0.382	0.637	0.442			0.442	36	
10	0.350	0.307	0.000	0.280	0.164	0.350	0.588	0.620	1.000	0.641	0.753			0.753	4	
11	0.651	0.270	0.095	0.380	0.422	0.651	0.434	0.650	0.840	0.568	0.542			0.542	12	
12	0.836	0.277	0.190	0.617	0.496	0.836	0.374	0.643	0.724	0.448	0.502			0.502	21	
13	0.137	0.520	0.190	0.061	0.142	0.137	0.785	0.490	0.724	0.891	0.779			0.779	6	
14	0.376	0.584	0.238	0.295	0.320	0.376	0.571	0.461	0.677	0.629	0.610			0.610	17	
15	0.283	0.792	0.238	0.269	0.632	0.283	0.639	0.387	0.677	0.650	0.442			0.442	25	
16	0.225	0.032	0.429	0.036	0.129	0.225	0.690	0.940	0.538	0.933	0.794			0.794	2	
17	0.310	0.176	0.619	0.056	0.162	0.310	0.617	0.740	0.447	0.899	0.755			0.755	7	
18	0.838	0.193	1.000	0.245	0.986	0.838	0.374	0.721	0.333	0.671	0.336			0.336	27	
19	0.297	0.614	0.095	0.213	0.188	0.297	0.627	0.449	0.840	0.701	0.727			0.727	9	
20	0.695	0.713	0.190	0.466	0.461	0.695	0.418	0.412	0.724	0.518	0.521			0.521	26	
21	0.613	0.903	0.333	0.584	0.719	0.613	0.449	0.356	0.600	0.461	0.410			0.410	33	
22	0.020	0.545	0.619	0.179	0.178	0.020	0.962	0.479	0.447	0.736	0.737			0.737	10	
23	0.357	0.765	0.524	0.492	0.429	0.357	0.584	0.395	0.488	0.504	0.538			0.538	30	
24	0.560	0.916	0.429	0.450	0.689	0.560	0.472	0.353	0.538	0.526	0.421			0.421	34	
25	0.527	0.181	0.762	0.042	0.000	0.527	0.487	0.735	0.396	0.923	1.000			1.000	5	
26	0.273	0.295	0.619	0.169	0.372	0.273	0.647	0.629	0.447	0.747	0.574			0.574	14	
27	0.582	0.248	0.524	0.419	0.556	0.582	0.462	0.669	0.488	0.544	0.473			0.473	23	
28	0.252	0.307	0.190	0.394	0.220	0.252	0.665	0.620	0.724	0.559	0.694			0.694	8	
29	0.478	0.191	0.381	0.325	0.680	0.478	0.511	0.724	0.568	0.606	0.424			0.424	16	
30	0.700	0.339	0.571	1.000	1.000	0.700	0.417	0.596	0.467	0.333	0.333			0.333	32	
31	0.000	0.116	0.143	0.032	0.217	0.000	1.000	0.811	0.778	0.939	0.697			0.697	1	
32	0.195	0.364	0.762	0.388	0.640	0.195	0.720	0.579	0.396	0.563	0.439			0.439	24	
33	0.260	0.396	0.381	0.251	0.581	0.260	0.658	0.558	0.568	0.666	0.463			0.463	19	
34	0.345	0.000	0.571	0.019	0.206	0.345	0.592	1.000	0.467	0.964	0.708			0.708	3	
35	0.485	0.134	0.667	0.017	0.402	0.485	0.508	0.789	0.429	0.968	0.554			0.554	11	
36	0.308	0.161	0.714	0.165	0.518	0.308	0.618	0.757	0.412	0.752	0.491			0.491	13	
Weights																

Weights

$$F_r = 0.182, T_c = 0.324, P_c = 0.193, PSD = 0.089 \text{ and } R_a = 0.213$$

Data Availability Data will be made available on request.

Declarations

Ethics Statement This study does not contain any studies involving human or animal participants.

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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