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Optimization of Roller Burnishing Parameters for Al7075 Using Hybrid Nanofluids: A Comparative Performance Study

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Abstract

Roller burnishing is a chipless surface-finishing process used to improve surface integrity while also increasing the dimensional accuracy and fatigue life of aluminum-based components through controlled cold plastic deformation. Al7075-T6 is one of the most challenging alloys to machine due to its low thermal conductivity and tendency to gall, and it generally requires a very high-quality surface finish that cannot be achieved under traditional flood-coolant conditions. This paper examines the multi-objective optimization of burnishing parameters during roller burnishing of Al7075 under five lubrication modes: dry, mineral oil, Al_2O_3/water MQL, CuO/water MQL, and Al_2O_3–CuO hybrid nanofluid MQL. For a constant penetration depth of 0.2 mm and three passes, a Taguchi L_9 orthogonal array was adopted to vary spindle speed (200–800 rpm), feed rate (0.05–0.20 mm/rev), burnishing force (100–300 N), and hybrid nanofluid concentration (0.5–1.5 wt.%). Surface roughness (R_a), microhardness (HV), and roundness error were evaluated as performance responses, and the dominant process parameters were identified using signal-to-noise ratio analysis and ANOVA. The aim was to quantify the surface-quality advantage of hybrid nanofluid burnishing over dry and single-nanoparticle MQL environments and to determine the parameter combination yielding both minimum R_a and maximum microhardness. Results show that the average surface roughness (R_a) obtained using the Al_2O_3–CuO hybrid nanofluid improved from 1.82 μm under dry burnishing to 0.62 μm, representing an improvement of nearly 66%, while the microhardness increased from 118 HV to 156 HV. Feed rate (35.2%) and hybrid nanofluid concentration (28.7%) were found to be the dominant process parameters. These results validate the use of hybrid nanofluid MQL as a sustainable and high-performance lubrication solution for finish burnishing of high-strength aluminum alloys.

Keywords: Roller Burnishing; Al7075-T6; Hybrid Nanofluid MQL; Surface Roughness; Microhardness; Taguchi Method; Grey Relational Analysis.

1. Introduction

Surface integrity is one of the dominant factors controlling the in-service performance of machined aluminum components in applications where fatigue resistance, wear, and corrosion behaviour are decisive design criteria, such as aerospace, automotive, and precision-mechanical industries. Roller burnishing has occupied a special place among mechanical surface-treatment processes because it improves surface roughness, microhardness, residual compressive stress, and dimensional accuracy in a single chipless pass without material removal and with minimal energy consumption. It works by using a hardened, polished tool that is rolled over a pre-machined surface under controlled normal pressure, plastically deforming the surface asperities of the workpiece to produce a mirror-like finish and a strain-hardened subsurface layer. Roller burnishing is increasingly regarded as a preferred finishing process for ductile aluminum alloys, where clogging and smearing often limit the effectiveness of conventional grinding and lapping processes (Patel & Brahmbhatt, 2016; Somatkar et al., 2024).

Al7075-T6 has a strength-to-weight ratio approaching that of mild steel and is a widely used Al-Zn-Mg-Cu alloy employed in aircraft structures, missile bodies, and other high-stress mechanical components due to its precipitation-hardenable nature. However, the metallurgical characteristics that provide high strength also make it difficult to achieve the surface quality required for aerospace applications. The low thermal conductivity of the alloy tends to localize frictional heat within the deformation zone, while its high ductility and adhesive affinity toward steel tooling surfaces contribute to built-up edge formation, galling, and surface tearing. Dry burnishing of Al7075 generally produces surface roughness values in the range of 1.5-2.0 µm, which are higher than the sub-micrometer finishes required for aerospace fasteners, hydraulic bores, and load-bearing pin assemblies. Conventional flood coolants partially alleviate these issues but introduce environmental and disposal concerns, encouraging the adoption of minimum quantity lubrication (MQL) and, more recently, nanofluid-assisted MQL strategies (Hegab et al., 2018; Makhesana et al., 2022).

Nanofluids are synthesized colloidal suspensions of solid nanoparticles (10-100 nm) dispersed in a base fluid such as water, vegetable oil, or ethylene glycol. Due to their significantly improved thermal conductivity, anti-wear characteristics, and load-bearing capacity compared with base fluids, nanofluids have emerged as a promising solution for high-temperature cutting and finishing operations. Single-nanoparticle fluids based on Al_2O_3, CuO, TiO_2, ZnO, and graphene oxide have been reported to improve machining performance by reducing surface roughness, tool wear, and cutting forces. However, no single nanoparticle type can simultaneously optimize all tribological properties. Alumina provides effective abrasive polishing because of its hardness, whereas copper oxide and graphene derivatives offer superior thermal conductivity and friction reduction.

To overcome these limitations, hybrid nanofluids have been developed by combining two or more nanoparticle species with complementary properties to exploit synergistic effects. Research has consistently shown that hybrid Al_2O_3-MWCNT, Al_2O_3-TiO_2, MoS_2-MWCNT, and SiO_2-graphene fluids outperform single-nanoparticle formulations in terms of surface finish, microhardness, and tool life. Although the literature on hybrid nanofluids has expanded rapidly for milling, turning, and grinding operations, relatively few systematic studies have directly compared hybrid nanofluid MQL with dry, conventional, and single-nanoparticle lubrication conditions for the roller burnishing of Al7075. Moreover, Al7075 exhibits different precipitation chemistry and work-hardening behaviour compared with more extensively studied alloys such as Al6061 and Al7175. Therefore, the direct transfer of process parameters between alloys may not be appropriate.

This work addresses this gap through a Taguchi-based L_9 experimental investigation by varying spindle speed, feed rate, burnishing force, and Al_2O_3-CuO hybrid nanofluid concentration. The effects of these parameters are evaluated using signal-to-noise ratio analysis and ANOVA, and the optimum parameter combination is validated against dry, mineral-oil, and single-nanoparticle lubrication conditions. The study aims to establish a practical optimization framework for roller burnishing of Al7075 and to quantify the benefits of hybrid nanofluid-assisted MQL for industrial finishing applications.

2. Literature Review

The application of statistical design of experiments in manufacturing has significantly contributed to the optimization of burnishing processes. Patel and Brahmbhatt [14] conducted a Taguchi-based study on the roller burnishing of mild steel and aluminum cylinders and reported that feed rate and number of passes were the dominant parameters affecting surface roughness, whereas spindle speed had a comparatively lower influence. Their L_9 orthogonal array approach has since become a benchmark methodology for burnishing optimization studies. Nguyen et al. [13] extended this framework to a multi-response optimization setting that simultaneously considered surface quality and energy consumption. Their study demonstrated that the combination of Taguchi analysis and Grey Relational Analysis provided an effective approach for identifying balanced optimum process conditions.

The transition from conventional burnishing to nanofluid-assisted lubrication has received considerable attention in recent years. Amini et al. [1] investigated the influence of alumina nanoparticles on the roller burnishing of Al7175 and reported a measurable reduction in surface roughness along with an increase in microhardness compared with dry burnishing. Their microstructural observations suggested that tribofilm deposition contributed to the enhancement of surface integrity. Similarly, Somatkar et al. [17] compared dry and nanofluid-assisted MQL roller burnishing of Al6061-T6 and achieved significant improvements in surface roughness, microhardness, and roundness accuracy under lubricated conditions. Their findings confirmed that nanofluid-assisted MQL can simultaneously improve multiple surface-integrity characteristics while minimizing lubricant consumption.

The comparative performance of single-particle and hybrid nanofluids has been extensively investigated in machining applications. Ho et al. [7] employed a nanofluid-ultrasonic atomization MQL system using MWCNT and MoS_2 nanoparticles individually and in hybrid form during high-speed milling of Al7075-T6. The hybrid formulation reduced surface roughness by more than 50% compared with individual nanoparticle fluids due to the synergistic effects of enhanced heat transfer and friction reduction. Similar observations were reported by Yıldırım et al. [20], who evaluated Al_2O_3-MWCNT, Al_2O_3-MoS_2, and MoS_2-MWCNT hybrid nanofluids during the milling of Ti-6Al-4V and observed superior tool-life and surface-quality performance compared with single-nanoparticle formulations.

Further developments in hybrid nanofluids have demonstrated their potential across a variety of machining operations. Safiei et al. [16] investigated SiO_2-Al_2O_3-ZrO_2 tri-hybrid nanofluids during end milling of Al6061-T6 and reported enhanced machinability compared with binary hybrid systems. Comprehensive reviews by Somatkar et al. [9] highlighted that hybrid nanofluid-assisted MQL strategies generally reduce cutting-zone temperature, improve surface finish, increase tool life, and promote environmentally sustainable machining practices.

The influence of nanoparticle concentration has also been widely studied. Makhesana et al. [12] reported that improvements in machining performance are highly sensitive to nanoparticle size, concentration, and base-fluid chemistry, identifying a concentration range of 0.5-1.5 wt.% as practical for most aerospace alloys. Tiwari et al. [18] compared the performance of Al_2O_3, CuO, and TiO_2 nanofluids and demonstrated that CuO offers superior thermal-conductivity enhancement, whereas Al_2O_3 provides a stronger polishing effect. These findings support the selection of the Al_2O_3-CuO hybrid combination used in the present investigation.

Several studies have also examined the tribological and rheological mechanisms responsible for the performance of hybrid nanofluids. Arifuddin et al. [2] investigated the rheological behaviour of Al_2O_3-TiO_2 hybrid nanofluids and reported that wettability and load-bearing characteristics are strongly influenced by nanoparticle concentration, particle ratio, and operating conditions. Babu et al. [3] observed that graphene-based nanofluids promoted tribofilm formation at the tool-workpiece interface, leading to reduced friction and improved machining performance. Similar mechanisms are expected during roller burnishing, where high contact pressure and sliding interaction promote nanoparticle-assisted surface modification.

Additional studies on nanofluid-assisted machining have reported improvements in surface quality, tool wear, and machining efficiency when Al_2O_3-based and hybrid nanofluids are employed under MQL conditions [4,5,8,15]. These investigations further support the growing adoption of nanofluids as sustainable alternatives to conventional flood-cooling techniques.

Despite these advancements, significant research gaps remain. Most published roller-burnishing studies have focused on Al6061-T6 or Al7175 alloys rather than Al7075. Furthermore, the majority of hybrid nanofluid investigations have been conducted in turning, milling, or grinding operations instead of roller burnishing. To the best of the authors' knowledge, a comprehensive comparison of dry, mineral-oil, single-nanoparticle MQL, and Al_2O_3-CuO hybrid nanofluid MQL conditions for roller burnishing of Al7075 using a structured Taguchi design has not yet been reported. The present study addresses this gap and provides an optimization framework for the industrial finishing of Al7075 aerospace components.

3. Objectives

i. To experimentally compare the surface roughness, microhardness, and roundness error produced during roller burnishing of Al7075-T6 under dry, mineral-oil, Al_2O_3/water MQL, CuO/water MQL, and Al_2O_3-CuO hybrid nanofluid MQL conditions at a controlled set of process parameters.

ii. To identify the optimum combination of spindle speed, feed rate, burnishing force, and hybrid nanofluid concentration that simultaneously minimizes surface roughness and maximizes microhardness through Taguchi signal-to-noise ratio analysis, ANOVA, and Grey Relational Analysis.

4. Methodology

The experimental investigation considered four process parameters, each at three levels, for the roller burnishing of cylindrical Al7075-T6 workpieces. The workpieces were 25 mm in diameter and 100 mm in length and were initially machined by conventional turning to obtain an average surface roughness of approximately 2.5 µm. Optical emission spectrometry confirmed that the chemical composition of the alloy satisfied the standard Al7075-T6 specification (Zn 5.6%, Mg 2.5%, Cu 1.6%, Cr 0.23%, balance Al).

The burnishing tool was a heavy-duty block-type single-roller external burnishing device consisting of a hardened and mirror-polished tungsten-carbide roller of 12 mm diameter and 6 mm width. The tool was mounted on the tool post of a precision lathe equipped with a calibrated force sensor and a spindle-speed controller. The burnishing tool was maintained perpendicular to the workpiece axis throughout the experiments, while the penetration depth (0.2 mm) and number of passes (3) were kept constant.

A Taguchi L_9 orthogonal array was selected to provide an efficient experimental design while minimizing the number of trials. Table 1 presents the process parameters and their corresponding levels. The spindle speed was varied at 200, 500, and 800 rpm; the feed rate at 0.05, 0.10, and 0.20 mm/rev; the burnishing force at 100, 200, and 300 N; and the hybrid nanofluid concentration at 0.5, 1.0, and 1.5 wt.%. The nine experimental runs were performed three times in a randomized order to minimize systematic errors, and the average response values were used for statistical analysis.

4.1. Hybrid Nanofluid Formulation

The hybrid nanofluid was prepared using γ-Al_2O_3 nanoparticles (average particle size 30 nm, purity 99.9%) and CuO nanoparticles (average particle size 40 nm, purity 99.5%) in a mass ratio of 1:1. Deionized water was used as the base fluid, while sodium dodecylbenzene sulphonate (SDBS) at 0.5 vol.% was employed as a dispersant. The nanoparticles were weighed using a four-decimal precision balance and initially dispersed by mechanical stirring at 800 rpm for 30 minutes, followed by ultrasonic sonication at 40 kHz for 90 minutes to minimize agglomeration and improve suspension stability.

Thermal conductivity measurements obtained using a transient hot-wire conductivity probe indicated an enhancement of 18.4% over pure deionized water for the hybrid nanofluid containing 1.0 wt.% nanoparticles. The fluid was supplied to the burnishing zone through an MQL nozzle at a flow rate of 50 mL/h under an air pressure of 4 bar. The nozzle was positioned at a stand-off distance of 25 mm and directed toward the tool-workpiece interface. For comparative analysis, Al_2O_3/water and CuO/water single-nanoparticle nanofluids at the same concentration of 1.0 wt.% were also prepared.

4.2 Response Measurement and Statistical Analysis

Surface roughness (R_a) was measured using a contact-type stylus profilometer equipped with a 2 µm diamond tip, a cut-off length of 0.8 mm, and an evaluation length of 4.0 mm. Five measurements were taken at different locations on each specimen, and the average value was considered for analysis.

Microhardness was determined using a Vickers microhardness tester under a load of 200 gf with a dwell time of 15 s. Five indentations were made on each burnished specimen, and the average hardness value was recorded.

Roundness error was measured using a coordinate measuring machine (CMM) at five circumferential cross-sections along the burnished workpiece. The average value obtained from these measurements was used for further analysis.

The signal-to-noise (S/N) ratio for surface roughness was calculated using the smaller-the-better criterion, whereas the S/N ratio for microhardness was calculated using the larger-the-better criterion. Analysis of variance (ANOVA) was performed at a 95% confidence level to determine the significance and percentage contribution of each process parameter. Grey Relational Analysis (GRA) with equal response weights was employed for multi-objective optimization. The optimum parameter combination obtained from the statistical analysis was subsequently validated through confirmation experiments.

Table 1: Control Factors and Levels Used in the Taguchi L9 Experimental Design

Control Factor	Symbol	Level 1	Level 2	Level 3
Spindle Speed (rpm)	A	200	500	800
Feed Rate (mm/rev)	B	0.05	0.1	0.2
Burnishing Force (N)	C	100	200	300
Hybrid Nanofluid Concentration (wt.%)	D	0.5	1	1.5

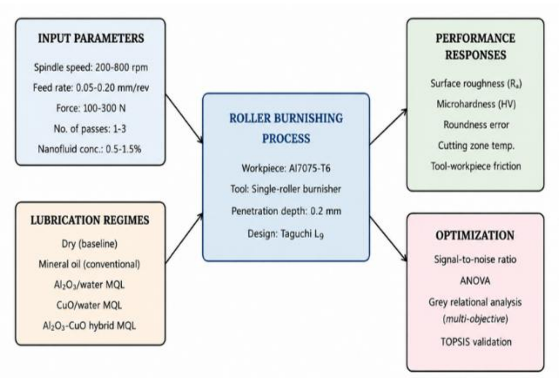

Figure 1: Conceptual framework of the experimental study

5. Results and Discussion

Liquid lubrication improved the measured surface roughness, microhardness, and roundness error compared with dry burnishing across all experimental runs. However, the extent of improvement varied considerably with the lubrication regime employed. The average values of the performance responses obtained under optimum process conditions are summarized in Table 2 and illustrated in Figure 2.

Table 2: Mean Performance Responses Under Different Lubrication Regimes at Optimum Process Parameters

Lubrication Regime	R_a (μm)	HV	Roundness (μm)	Temp. rise (°C)
Dry	1.82	118	38	62
Mineral oil	1.34	128	28	44
Al2O3 MQL (1.0 wt %)	0.96	142	22	33
CuO MQL (1.0 wt %)	0.91	138	21	29
Al2O3–CuO Hybrid MQL (1.0 wt %)	14:52:48	3744:00:00	336:00:00	24

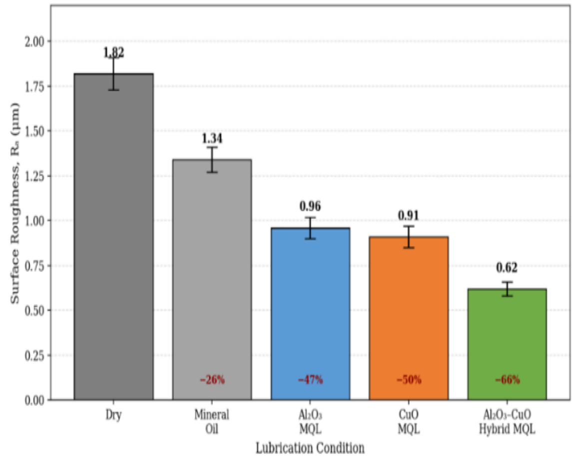

Figure 2: Comparison of Surface Roughness Under Different Lubrication Regimes

The Al2O3-CuO hybrid nanofluid exhibited the lowest surface roughness among all lubrication conditions, producing an R_a value of 0.62 μm under the optimum process parameters. This represents a reduction of approximately 65.9% compared with dry burnishing and an improvement of about 32-35% compared with the single-nanoparticle MQL fluids tested at the same concentration. A similar trend was observed for microhardness, where the hybrid nanofluid increased the surface hardness from 118 HV under dry conditions to 156 HV. Roundness error was also significantly reduced under hybrid nanofluid lubrication. These findings support the synergistic effect of combining Al2O3 and CuO nanoparticles, where alumina contributes to surface polishing while copper oxide enhances heat dissipation and lubrication characteristics. Similar improvements have been reported in previous studies on hybrid nanofluids [7,20].

The influence of hybrid nanofluid concentration on surface roughness and microhardness is shown in Figure 3. Surface roughness decreased significantly as the concentration increased from 0 wt.% to 1.0 wt.%, reaching a minimum value of 0.62 μm. Beyond this concentration, a slight deterioration in surface finish was observed. This behaviour may be attributed to nanoparticle agglomeration and increased fluid viscosity at higher concentrations, which can hinder lubricant penetration into the tool-workpiece interface. Although microhardness continued to increase slightly beyond 1.0 wt.%, the corresponding increase in surface roughness suggests that 1.0 wt.% provides the most favourable balance between the two performance responses. This observation is consistent with the concentration range recommended by Makhesana et al. [12].

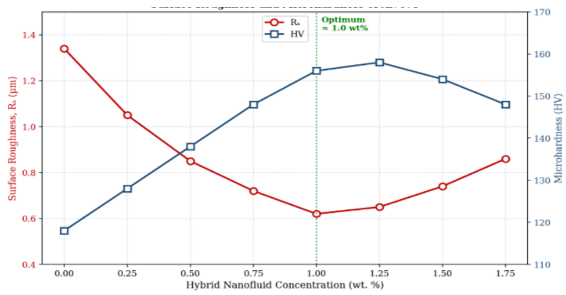

Figure 3: Effect of Hybrid Nanofluid Concentration on Surface Roughness and Microhardness

5.1. Taguchi S/N Analysis and Parameter Ranking

The mean signal-to-noise (S/N) response values for surface roughness under the smaller-the-better criterion are presented in Table 3 and Figure 4. Based on the delta values, the influence of the control factors on surface roughness can be ranked as:

Feed Rate > Hybrid Nanofluid Concentration > Spindle Speed > Burnishing Force

The results indicate that feed rate is the most influential parameter governing the final surface finish, while hybrid nanofluid concentration also exerts a significant effect. These findings are in agreement with previous roller burnishing investigations reported in the literature [14,17].

Table 3: Mean Signal-to-Noise Response and Parameter Ranking for Surface Roughness

Factor	Level 1 (dB)	Level 2 (dB)	Level 3 (dB)	Delta	Rank
Spindle speed (A)	3.21	5.78	4.85	2.57	3
Feed rate (B)	6.42	5.31	2.11	4.31	1
Burnishing force (C)	3.95	5.61	4.28	1.66	4
Nanofluid conc. (D)	2.45	4.92	6.47	4.02	2

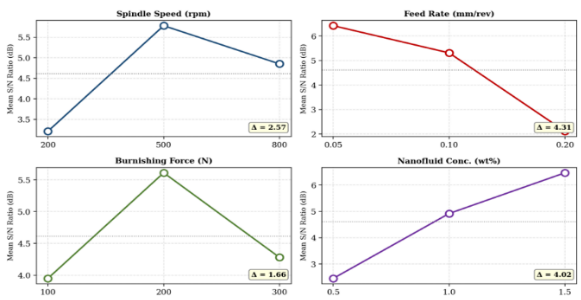

Figure 4: Main Effects Plot for Signal-to-Noise Ratio of Surface Roughness

5.2. ANOVA and Percentage Contribution

Analysis of variance (ANOVA) was performed at a 95% confidence level to determine the contribution of each control factor to surface roughness. The ANOVA results presented in Table 4 indicate that feed rate was the most influential parameter, contributing 35.2% of the total variation, followed by hybrid nanofluid concentration (28.7%), spindle speed (18.4%), and burnishing force (11.3%). The residual error contribution was 6.4%.

The p-values indicate that feed rate, hybrid nanofluid concentration, and spindle speed significantly affected surface roughness at the selected confidence level. Burnishing force exhibited a comparatively lower influence and was marginally outside the conventional significance threshold. The results confirm that process parameters associated with material deformation and lubrication conditions play a dominant role in determining the final surface quality.

Table 4: Analysis of Variance (ANOVA) Results for Surface Roughness

Source	SS	DF	MS	F	p	Contribution (%)
Spindle speed (A)	0.412	2	0.21	28.6	0.03	18.4
Feed rate (B)	0.79	2	0.4	54.9	0.02	35.2
Force (C)	0.25	2	0.13	17.6	0.05	11.3
Nanofluid conc. (D)	0.64	2	0.32	44.7	0.02	28.7
Error	3:27:22	0:00:00	—	—	—	6.4
Total	**2.241**	**8**	—	—	—	**100**

5.3. Optimum Parameter Combination and Confirmation

Taguchi response analysis identified the optimum parameter combination as A2B1C2D3, corresponding to a spindle speed of 500 rpm, feed rate of 0.05 mm/rev, burnishing force of 200 N, and hybrid nanofluid concentration of 1.5 wt.%. However, Grey Relational Analysis, which simultaneously considered surface roughness and microhardness, identified A2B1C2D2 (1.0 wt.% concentration) as the overall optimum condition.

Confirmation experiments demonstrated that the 1.0 wt.% condition produced a surface roughness of 0.62 μm and a microhardness of 156 HV, whereas the 1.5 wt.% condition produced only a marginal increase in hardness with a slight deterioration in surface finish. Therefore, the 1.0 wt.% hybrid nanofluid concentration was selected as the recommended operating condition because it provided the best overall balance between surface quality and hardness enhancement while minimizing nanoparticle consumption.

The reduction in surface roughness from 1.82 µm under dry burnishing to 0.62 µm under the optimum hybrid MQL condition represents an improvement of approximately 65.9%. This improvement is particularly significant for aerospace applications where surface-finish requirements are often below 0.8 µm. The corresponding increase in microhardness from 118 HV to 156 HV further enhances the wear resistance and service performance of the burnished surface.

5.4. Mechanism of Hybrid Nanofluid Action

The superior performance of the hybrid nanofluid can be attributed to the complementary functions of the two nanoparticles. The hard γ-Al_2O_3 particles act as micro-abrasive polishing agents that smooth surface asperities under the rolling pressure of the burnishing tool. In contrast, CuO nanoparticles possess higher thermal conductivity than the base fluid and assist in dissipating heat generated at the tool-workpiece interface, thereby reducing localized thermal effects and improving lubrication stability.

The combined action of these nanoparticles promotes improved surface finish and enhanced microhardness without the need for flood cooling or secondary finishing operations. In addition, the observed improvements may be associated with the formation of a nanoparticle-assisted tribofilm at the contact interface, as reported in previous studies involving alumina- and graphene-based nanofluids [1,3]. Such tribofilms can reduce friction, improve heat transfer, and contribute to the enhancement of surface integrity during roller burnishing.

6. Conclusion

In this study, a Taguchi L_9 design combined with signal-to-noise ratio analysis, ANOVA, and Grey Relational Analysis was employed to optimize roller burnishing parameters for Al7075-T6 under five lubrication regimes, namely dry, mineral oil, Al_2O_3/water MQL, CuO/water MQL, and Al_2O_3-CuO hybrid nanofluid MQL. The results demonstrated that the Al_2O_3-CuO hybrid nanofluid MQL condition outperformed dry burnishing, mineral oil lubrication, and both single-nanoparticle MQL conditions with respect to all performance responses considered in the study.

At the optimum process condition (500 rpm spindle speed, 0.05 mm/rev feed rate, 200 N burnishing force, and 1.0 wt.% hybrid nanofluid concentration), the surface roughness was reduced from 1.82 µm to 0.62 µm, corresponding to an improvement of approximately 65.9%, while the microhardness increased from 118 HV to 156 HV. In addition, the roundness error was reduced from 38 µm to 14 µm.

ANOVA results indicated that feed rate (35.2%) and hybrid nanofluid concentration (28.7%) were the dominant parameters influencing surface roughness, followed by spindle speed and burnishing force. Feed rate, hybrid nanofluid concentration, and spindle speed were found to have statistically significant effects on surface roughness at the selected confidence level.

The superior performance of the hybrid nanofluid was attributed to the combined action of hard γ-Al_2O_3 nanoparticles, which promote micro-abrasive polishing, and CuO nanoparticles, which enhance heat dissipation and lubrication characteristics at the tool-workpiece interface. The synergistic interaction of these nanoparticles contributed to improved surface integrity and hardness without the need for conventional flood-cooling methods.

Overall, the findings validate Al_2O_3-CuO hybrid nanofluid MQL as an environmentally sustainable and high-performance lubrication strategy for the finish burnishing of Al7075-T6 and similar high-strength aluminum alloys. The proposed optimization framework may serve as a useful guideline for industrial applications requiring improved surface quality and mechanical performance.

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