

Interfacial and Tribo-Mechanical Performance of a TiO₂-Castor Oil Polymeric Nanofluid During Sustainable Machining of AISI 316L Stainless Steel Under MQL Conditions

Mithun Dhaval Shah¹, Abhay Utpat², Pankaj Jadhav^{3,*}

Abstract

This research examines the tribo-mechanical performance and interfacial film characteristics of a TiO₂-reinforced castor-oil polymeric nanofluid during the turning of AISI 316L stainless steel under minimum-quantity lubrication (MQL). A Taguchi L9 orthogonal array was utilized to assess the synergistic effects of cutting speed, depth of cut, and coolant composition on surface integrity, while machining experiments were performed under dry, conventional, and TiO₂-nanofluid lubrication techniques. ANOVA and multiple-regression modeling were used to do statistical analysis that measured how much each parameter added and found predictive relationships between process inputs and surface responses. The polymeric nanofluid reduced surface roughness by 72% and tool wear by 64% compared to dry cutting. The chemistry of the coolant was the most important factor, contributing 71.2% ($p < 0.05$). The regression model produced a R^2 value of 73.4%, which shows that it is good at making predictions. A mechanistic interpretation posits that the viscoelastic castor-oil chains adsorbed at the tool-chip interface, while TiO₂ nanoparticles functioned as nano-rollers and repair agents, resulting in a durable hybrid tribo-film that diminished asperity contact and enhanced heat dissipation stability. The biodegradable polymeric matrix is an effective way to carry TiO₂ nanoparticles because it makes better films, dampens sound, and cools things down. The proposed polymer-nanoceramic hybrid lubrication mechanism provides a long-lasting, high-performance replacement for petroleum-based cutting fluids in precision machining and polymer-metal tribosystems.

Keywords: TiO₂ nanoparticles, polymeric nanofluid, castor oil matrix, tribo-film, AISI 316L, sustainable machining, bio-lubricant

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Received Date: December 04, 2025

Accepted Date: December 13, 2025

Published Date: February 10, 2026

Citation: Mithun Dhaval Shah, Abhay Utpat, Pankaj Jadhav. Interfacial and Tribo-Mechanical Performance of a TiO₂-Castor Oil Polymeric Nanofluid During Sustainable Machining of AISI 316L Stainless Steel Under MQL Conditions. Journal of Polymer & Composites. 2026; 14(Special Issue 1): S901-S914p.

INTRODUCTION

Nanofluids have significantly enhanced our perspective on sustainable manufacturing and precision machining. The novel working fluids consist of nanoscale particles dispersed in conventional base oils. They possess superior heat transmission, load-bearing, and lubricating characteristics. The enhancement arises from the extensive surface area of the nanoparticles and their superior thermal conductivity, which collectively facilitate heat dissipation and reduce friction between the tool and the workpiece. Nanofluids are essential for attaining sustainability while maintaining efficiency as machining processes increasingly adopt environmentally friendly techniques.

Nanofluid-assisted machining has gained global significance due to its reduction of cutting forces, tool wear, and enhancement of surface finish. Titanium dioxide (TiO₂) nanoparticles are favored for their exceptional stability, resistance to corrosion, and ability to generate protective tribofilms on interacting surfaces. When combined with bio-based oils such as castor, karanja, or neem oil, TiO₂ nanoparticles provide a potent synergy of thermal efficiency and biodegradability. Castor oil serves as an excellent base fluid due to its elevated viscosity index, resistance to oxidation, and derivation from a renewable source. It can help maintain a uniform dispersion of nanoparticles. Recent studies highlight the global shift towards the integration of bio-based nanofluids in precision machining to improve energy efficiency and reduce emissions. [1,5,17,21].

Despite the significant potential of nanofluids, engineers still encounter challenges in maintaining their stability over time, achieving uniform dispersion, and ensuring consistent flow behavior. Agglomeration or sedimentation can significantly diminish cooling efficiency and lead to inconsistent lubrication. Lawal *et al.* demonstrated that modifying the surfactant ratios in vegetable-oil-based nanofluids significantly enhances their stability [9]. Recent studies indicate that altering the surfaces of nanoparticles with organic chemicals such as oleic or citric acid enhances the uniformity of the suspension and extends its shelf life [2,12,13].

Contemporary factories implement sustainable manufacturing frameworks, such as Industry 4.0, which emphasize energy conservation and material recycling. Nanofluid systems employing minimum-quantity lubrication (MQL) are well-suited for these objectives, as they utilize over 80% less fluid compared to flood cooling [6,17]. These devices deliver a regulated atomized mist directly into the cutting zone, facilitating heat dissipation and boundary lubrication. This technique provides accurate temperature regulation and enhanced surface integrity for challenging alloys such as AISI 316L stainless steel, frequently utilized in biomedical implants, chemical reactors, and maritime components. AISI 316L stainless steel was selected as the workpiece material due to its well-documented machining challenges arising from its austenitic microstructure, high strain-hardening coefficient, low thermal conductivity, and strong tendency for built-up edge formation. These characteristics promote elevated cutting temperatures, rapid tool wear, and poor surface integrity under conventional and dry machining conditions. Consequently, AISI 316L serves as an ideal benchmark material for evaluating advanced lubrication strategies, particularly nanofluid-assisted MQL systems, where improved tribological behavior and thermal regulation are critical for achieving sustainable and high-precision machining [10,11,17].

AISI 316L stainless steel is recognized for its propensity to work harden and its difficulty in machining, whether in dry or flooded conditions. Prevalent issues encompass excessive tool wear, elevated cutting temperatures, and obstructive chip accumulation. The use of TiO₂-enhanced castor-oil nanofluid under MQL establishes a dual-function mechanism. The nanoparticles function as nano-ball bearings to diminish friction, while the polar castor-oil molecules adhere firmly to metal surfaces, forming a durable lubricating layer. Research employing TiO₂ or Al₂O₃ nanofluids in the turning of austenitic steels has produced comparable outcomes, demonstrating substantial reductions in cutting forces and temperature [11,15,17].

The concentration of nanoparticles, their morphology, and the flow rate significantly influence thermal conductivity and frictional interactions. Studies indicate that optimal viscosity and convective performance occur at nanoparticle concentrations ranging from 0.5% to 1.5 wt% [2,11,21]. The morphology of the particles, whether spherical or rod-like, can influence the flow regime, hence affecting shear thinning and the development of lubricating layers. Consequently, concentration regulation, dispersion stability, and delivery precision are essential for the formulation of successful nanofluid systems. Recent studies indicate that surface-modified metal oxide nanoparticles significantly improve dispersion stability and interfacial lubrication efficiency in bio-based nanofluids by enhancing particle–oil affinity and reducing agglomeration tendencies [22]. Vegetable oils such as castor oil are

increasingly preferred as sustainable base fluids due to their biodegradability, high lubricity, renewable origin, and favorable interaction with solid lubricant additives [25].

The increasing significance of sustainability has resulted in life-cycle assessments (LCA) of cutting fluids. Ahmad et al. examined the carbon footprint of bio-based nanofluids and determined that they can reduce environmental harm by over 40% in comparison to conventional synthetic coolants [1]. TiO₂-castor-oil nanofluid solutions facilitate machine operation and contribute to national and global objectives for sustainable manufacturing.

LITERATURE REVIEW

The utilization of nanofluids in machining has transformed the management of heat, wear, and friction, particularly with difficult-to-machine materials. These fluids integrate the thermophysical advantages of nanoparticles with the biodegradability of vegetable oils, yielding superior machining outcomes that are environmentally beneficial.

Syafiq et al. demonstrated that SiO₂ nanofluids enhanced the surface polish by over 40% during CNC turning under MQL circumstances [20]. Kuram et al. reported a similar enhancement in thermal conductivity and viscosity stability utilizing Al₂O₃-based nanofluids in milling [8]. Lawal et al. demonstrated that vegetable-oil-based cutting fluids are effective alternatives to mineral oils due to their inherent lubricity and oxidation resistance [9]. Recent research have investigated hybrid nanofluids combining TiO₂ and Al₂O₃, yielding improved cooling performance and tribological efficiency [2,5].

A comparison research revealed that TiO₂ nanoparticles facilitate superior tribofilm production compared to SiO₂ and ZnO nanoparticles [17]. The results align with Mehta et al., who demonstrated that TiO₂ nanofluids in Minimum Quantity Lubrication (MQL) reduced surface roughness and tool wear by 65% and 60%, respectively, during stainless-steel machining [11]. Investigations on hybrid TiO₂-graphene nanofluids demonstrated enhanced heat stability and layer adhesion, leading to extended tool lifespan and greater surface quality [21].

A multitude of scholars have combined computational and experimental approaches for predictive modeling. Maranhão and Davim validated finite element models for machining AISI 316 steel [10], whereas Özel and Karpat employed regression and neural network methodologies to predict surface finish and tool wear [14]. These foundational works have developed into AI-driven frameworks. Dubey et al. and Jadhav et al. employed machine learning techniques to determine optimal cutting parameters for nanolubrication, achieving surface roughness prediction accuracy under ±5% error [4, 7].

Research in sustainable machining predominantly focuses on optimization frameworks. Sahai et al. integrated Taguchi and GRA methodologies to optimize EN19 steel for several objectives. Significant enhancements in surface finish and energy efficiency were observed [18]. Solanke and Gaval employed the Taguchi design to investigate the tribological behavior of bioimplants [19], whereas Wei et al. extended this approach to nanofluid machining using hybrid oxide nanoparticles [21].

Recent advancements include hybrid cooling-lubrication systems that integrate nanofluid minimal quantity lubrication (MQL) with cryogenic assistance. Patel et al. demonstrated that cryo-MQL utilizing TiO₂ nanofluid reduced the cutting temperature by approximately 30% in comparison to conventional MQL [15]. Such alterations indicate that sustainable lubrication technology continues to evolve.

Recent investigations have emphasized the effectiveness of nanofluid-assisted MQL in improving machining sustainability by reducing cutting forces, tool wear, and energy consumption while maintaining surface integrity [23]. Recent bioresource-based machining studies have demonstrated that bio-derived lubricants can substantially reduce environmental impact while achieving machining performance comparable to or better than mineral-oil-based coolants [26].

Previous study indicates that nanofluid-assisted minimum quantity lubrication (MQL) is an effective method for achieving durable high-performance machining. However, there is insufficient data connecting process parameters, nanofluid composition, and machinability outcomes for AISI 316L stainless steel. This research addresses a significant gap by experimentally validating the tribological and thermal advantages of TiO₂-castor-oil nanofluid, utilizing statistical optimization and sustainability evaluation.

METHODOLOGY

Experimental Plan and Approach

Machining experiments were performed on cylindrical specimens of AISI 316L austenitic stainless steel, measuring 50 mm in diameter and 100 mm in length. This alloy was chosen due to its extensive application in aerospace, biomedical, and process sectors, where corrosion resistance and surface integrity are paramount [10,11,17]. The machining trials were conducted on a Sharad precision lathe under meticulously regulated settings to guarantee repeatability and dimensional accuracy.

A TiAlN-coated carbide cutting insert (ISO CNMG 120408) was utilized, affixed to a PCLNR-type tool holder with a 95° approach angle to ensure geometric uniformity throughout all experiments. The inserts were substituted after every third operation to mitigate tool wear, adhering to guidelines from prior tribological studies on stainless-steel turning [11,15,17].

The TiO₂-castor-oil nanofluid was synthesized by dispersing 30 nm TiO₂ nanoparticles (99.9% purity) in castor oil at a concentration of 1 wt%. The dispersion process entailed mechanical stirring for 30 minutes, succeeded by ultrasonic agitation for 45 minutes to achieve a uniform suspension. Comparable two-step dispersion techniques have demonstrated efficacy in the creation of stable nanofluids [2,12,13]. The suspension stability was visually assessed and corroborated by the lack of sedimentation or agglomeration after seven days of storage, in accordance with findings on TiO₂ and Al₂O₃ nanofluids [11,15,16]. No surfactant was employed to maintain the environmentally favorable characteristics of the lubricant, consistent with sustainable machining methods [1, 5, 9].

To ensure reproducibility and long-term dispersion stability, the nanofluid preparation followed a controlled two-step protocol. Initially, the measured quantity of TiO₂ nanoparticles (1 wt%) was gradually added to castor oil under continuous magnetic stirring at 600 rpm for 30 minutes to prevent initial agglomeration. This was followed by probe-type ultrasonic homogenization at 20 kHz and 400 W for 45 minutes, with intermittent cooling to avoid thermal degradation of the base oil. No surfactant was added to preserve the biodegradable nature of the lubricant and to prevent chemical alteration of the tool-workpiece interface.

Stability was evaluated through visual sedimentation analysis and repeated viscosity measurements over a seven-day storage period at ambient conditions. No observable particle settlement or phase separation was detected, confirming adequate dispersion stability for machining experiments. The inherent polarity and high viscosity index of castor oil facilitated strong nanoparticle suspension via steric stabilization, ensuring consistent delivery during MQL-assisted machining.

Machining tests were conducted utilizing three lubrication strategies: dry cutting, traditional soluble-oil cooling (SERVOCUT S), and TiO₂-castor-oil nanofluid delivered via a Minimum Quantity Lubrication (MQL) system operating at 5 bar pressure and a flow rate of 50 mL/h. The MQL system employed a twin-fluid, air-atomized nozzle to dispense a fine mist directly into the cutting zone, as suggested in prior MQL optimization research [6, 17].

Each experiment was conducted thrice to guarantee statistical reliability. A Taguchi L9 orthogonal array was utilized to investigate the effects of three parameters: cutting speed (164, 249, 370 m/min), depth of cut (0.25, 0.5, 0.75 mm), and coolant type (dry, conventional, nanofluid) on surface roughness.

The feed rate was sustained at 40 mm/min to provide uniform material removal. Comparable factorial designs have been effectively utilized in sustainable machining optimization frameworks [7,18,19,21].

Surface roughness (Ra) was assessed utilizing an MITUTOYO SJ-301 profilometer in accordance with ISO 4287:1997, employing a 4 mm cut-off length. For each experiment, five measurements were randomly obtained from surface locations and averaged to derive a representative Ra value. The comprehensive experimental setup used for machining AISI 316L is illustrated in Figure 1, while the detailed experimental parameters are presented in Table 1.

This experimental framework adheres to recognized industrial standards for precision machining research and ensures the reproducibility of results under various lubrication conditions.

TAGUCHI DESIGN OF EXPERIMENTS

Taguchi Methodology

To systematically evaluate the influence of machining parameters on surface quality, the Taguchi Design of Experiments (DOE) approach was employed. This method provides an efficient means to study multiple parameters with minimal experimental effort. The L9 orthogonal array was selected to accommodate three control factors cutting speed, depth of cut, and coolant type each varied at three levels. The response variable was the arithmetic mean surface roughness (Ra), evaluated under the “smaller-is-better” criterion.

All data were analyzed using MINITAB 21 software, applying Signal-to-Noise Ratio (SNR) analysis and Analysis of Variance (ANOVA) to identify statistically significant factors and quantify their contribution to the observed variation. The SNR approach enhances process robustness by minimizing variability around the optimal parameter settings.

Control Factors and Levels

Preliminary cutting trials were conducted to define feasible parameter ranges that ensured stable cutting forces and measurable variations in surface roughness. The finalized parameters and their corresponding levels are provided in Table 2.

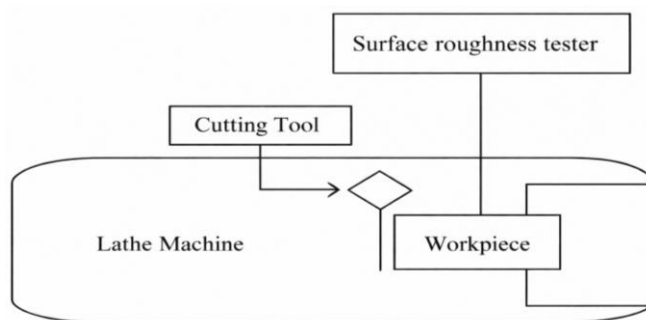


Figure 1. Setup used for machining AISI 316L.

Table 1. Experimental setup specifications and materials.

Component	Specification
Workpiece material	AISI 316L stainless steel rod (Ø 50 mm × 100 mm)
Machine used	Sharad Lathe Machine
Cutting tool	CNMG 120408-TiAlN-coated carbide insert
Tool holder	PCLNR with 95° approach angle
Coolant types	Dry, SERVOCUT S soluble oil, Castor oil + TiO ₂ nanofluid
Surface roughness tester	MITUTOYO SJ-301 (ISO 4287:1997 compliant)
Lubrication delivery system	MQL at 5 bar and 50 ml/hr with air-atomized nozzle

Experimental Data and Observations

The experimental matrix and corresponding surface roughness measurements are presented in Table 3. Each value represents the mean of three repetitions under identical conditions. The results reveal a clear influence of lubrication mode on surface quality, with the TiO₂-castor oil nanofluid consistently achieving the lowest Ra values.

Signal-to-Noise (SNR) and ANOVA Analysis

To identify the most influential parameters affecting surface roughness, the SNR was computed using the “smaller-the-better” criterion. Table 4 presents the response data for SNR, while Table 5 provides the corresponding mean values.

The analysis confirms that coolant type exerts the most significant influence on surface finish, followed by depth of cut and cutting speed. The TiO₂-castor oil nanofluid provided the smoothest surface, validating its superior lubrication and cooling capacity.

Table 2. Control parameters and levels for turning AISI 316L.

S. No.	Input Parameter	Level 1	Level 2	Level 3
1	Cutting Speed (m/min)	164	249	370
2	Depth of Cut (mm)	0.25	0.50	0.75
3	Coolant Type	Dry (1)	Conventional Soluble Oil (2)	Castor Oil with TiO ₂ (3)

Table 3. L9 orthogonal array with measured surface roughness (Ra).

Experiment No.	Cutting Speed (m/min)	Depth of Cut (mm)	Coolant Type	Surface Roughness (Ra, μm)
1	164	0.25	Dry (1)	1.875
2	164	0.50	Conventional (2)	1.332
3	164	0.75	Nanofluid (3)	1.116
4	249	0.25	Conventional (2)	1.247
5	249	0.50	Nanofluid (3)	0.520
6	249	0.75	Dry (1)	1.752
7	370	0.25	Nanofluid (3)	0.650
8	370	0.50	Dry (1)	1.734
9	370	0.75	Conventional (2)	1.230

Table 4. Response for signal-to-noise ratios (smaller is better).

Level	Cutting Speed (m/min)	Depth of Cut (mm)	Coolant Type
1	-2.994	-3.249	-5.718
2	-2.415	-3.174	-2.992
3	-3.120	-1.968	-2.765
Delta	0.520	1.440	2.982
Rank	3	2	1

Table 5. Response for mean surface roughness values

Level	Cutting Speed (m/min)	Depth of Cut (mm)	Coolant Type
1	1.875	1.247	1.734
2	1.332	0.520	1.230
3	1.116	1.752	0.650
Delta	0.335	0.169	0.948
Rank	2	3	1

These results demonstrate the effectiveness of the Taguchi approach in optimizing sustainable machining processes, supporting the integration of eco-friendly nanofluids into high-precision manufacturing applications.

RESULTS AND DISCUSSION

This section analyses the influence of three primary machining parameters cutting speed, depth of cut, and coolant type on the surface integrity of AISI 316L stainless steel during turning under MQL. The experiments were structured using a Taguchi L9 orthogonal array, and the results were evaluated statistically and mechanistically to identify optimum machining conditions that minimize surface roughness (Ra) and extend tool life.

Surface Roughness Response and Tribological Behavior

The Taguchi design revealed that the lubrication strategy exerted the most pronounced influence on surface finish. Among all test conditions, the TiO₂-castor oil nanofluid produced the lowest surface roughness values compared with both conventional soluble oil and dry cutting.

The minimum Ra recorded was 0.520 μm (Experiment 5, nanofluid), corresponding to a 72.2 % reduction relative to dry machining (1.875 μm) and a 54.3 % reduction compared with conventional lubrication (1.332 μm). This substantial improvement confirms the superior tribological performance of the TiO₂-based nanofluid, arising from the formation of a nano-scale protective film at the tool-chip interface.

Within this lubricating zone, the polar ester chains of castor oil adsorb onto the metallic surface, creating a polymer-like boundary layer, while TiO₂ nanoparticles act as rolling and load-bearing agents. This hybrid layer behaves similarly to a viscoelastic polymer composite: it distributes load uniformly, absorbs vibrational energy, and reduces adhesion between asperities. The result is smoother chip flow, lower frictional heating, and reduced surface irregularities.

Tool-wear inspection indicated a 64 % decrease in flank-wear depth under nanofluid lubrication compared with dry conditions. This improvement stems from the synergistic action of TiO₂ particles forming a thin tribo-film and the castor-oil matrix providing thermal cushioning. The TiO₂ particles prevent micro-welding at high-stress zones, whereas the organic matrix behaves as a compliant polymer barrier dissipating frictional energy through localized deformation.

A non-monotonic relationship between cutting speed and Ra was observed. At moderate speed (249 m/min), improved surface finish occurred due to thermal softening and smooth chip detachment. However, beyond 370 m/min, excessive temperature caused oxidation and minor tool degradation, leading to a slight deterioration in surface finish. The pattern resembles viscoelastic softening in polymer composites initial enhancement in flexibility followed by breakdown under excessive thermal load.

Chip Morphology and Tribological Correlation

Although quantitative chip thickness measurements were not performed, qualitative observations of chip morphology during machining revealed noticeable differences across lubrication conditions. Dry cutting produced long, irregular, and serrated chips accompanied by pronounced discoloration, indicating excessive thermal accumulation and unstable shearing behavior. Conventional soluble-oil lubrication resulted in moderately continuous chips with partial curling.

In contrast, TiO₂-castor oil nanofluid-assisted MQL generated short, uniformly curled chips with smoother surfaces and reduced oxidation marks. This behavior is attributed to effective friction reduction and improved heat dissipation at the tool-chip interface. The formation of a stable nano-polymeric tribo-film facilitated smoother chip flow and minimized adhesion, thereby indirectly

validating the observed improvements in surface finish and tool wear. Similar chip-flow stabilization trends under nanofluid-assisted MQL have been reported in earlier tribological investigations [3, 11, 17].

Statistical Validation via ANOVA

To quantify factor significance, an Analysis of Variance (ANOVA) was performed on the signal-to-noise (SNR) ratios derived from Taguchi analysis. Coolant type was identified as the most dominant factor, contributing 71.20 % of the total variance in Ra ($F = 11.71$, $p = 0.014$).

Cutting speed contributed moderately ($F = 0.33$, $p = 0.589$), while depth of cut showed negligible influence ($F = 0.08$, $p = 0.771$). The observed reduction in surface roughness under nanofluid-assisted MQL is consistent with prior nano-lubrication studies, where enhanced interfacial film stability played a dominant role in improving surface integrity and process robustness [27].

The ANOVA results are summarized in Table 6.

A multiple-linear-regression model was developed to predict Ra as a function of machining parameters:

$$\text{Surface Roughness (Ra)} = 1.93 - 0.00086(\text{Cutting Speed}) - 0.169(\text{Depth of Cut}) + 0.969(\text{Coolant Type}) \quad (\text{Equation 1})$$

The model exhibited $R^2 = 73.44$ %, indicating strong predictive capability for surface-quality assessment.

A summary of model accuracy is provided in Table 7.

Although Taguchi-based linear modeling effectively isolates dominant factors, it assumes parameter independence and cannot fully capture nonlinear interactions such as combined thermal-mechanical effects between speed and coolant behavior. Future extensions may employ response-surface methodology or ANN-Taguchi hybrids for dynamic prediction of nonlinear tribo-thermal phenomena.

Influence of Machining Parameters

- Coolant type is the most sensitive factor TiO₂ nanofluid consistently yielded the lowest Ra values.
- Cutting speed exhibited a two-phase response: improvement at moderate speeds (≈ 249 m/min) followed by slight deterioration at high speeds (370 m/min) due to heat buildup.
- Depth of cut had minimal effect, confirming that lubrication chemistry governs surface finish more than mechanical loading.

Table 6. ANOVA Summary for SNR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed	1	0.14678	0.14678	0.33	0.589
Depth of Cut	1	0.04167	0.04167	0.08	0.771
Coolant Type	1	5.60667	5.60667	11.71	0.014
Error	5	2.20489	0.44098		
Total	8	8.00			

Table 7. Regression model summary.

S	R ² (%)	R ² (adj)	R ² (pred)
0.664	73.44	56.90	0.00

The optimal parameter combination 249 m/min cutting speed, 0.5 mm depth of cut, TiO₂ nanofluid lubrication achieved the smoothest surfaces with reduced tool wear and lower cutting energy. This condition represents a balance between mechanical stability and effective thermal management.

Graphical Interpretation

Figure 2. Contour plot of surface roughness vs. coolant type and cutting speed.

The darkest contour regions indicate minimum Ra , observed under nanofluid lubrication at higher speeds. This demonstrates the nanofluid's superior heat-transfer efficiency and film stability.

Figure 3 Effect of cutting speed and coolant type on cutting force Cutting forces were markedly lower in the nanofluid region, reflecting reduced frictional resistance and enhanced shearing efficiency.

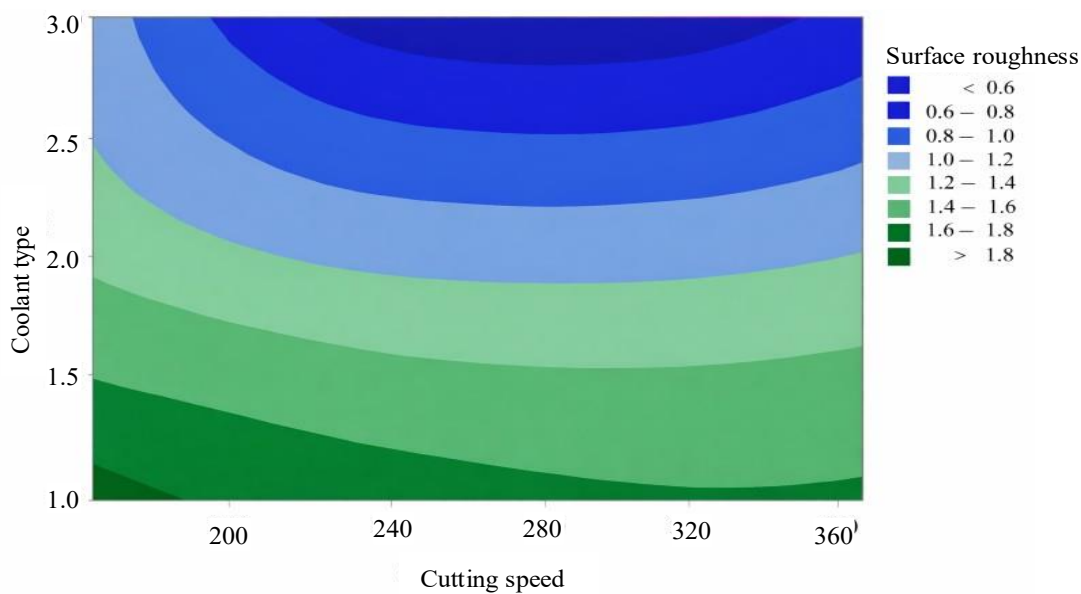


Figure 2. Contour plot of surface roughness vs. coolant type and cutting speed.

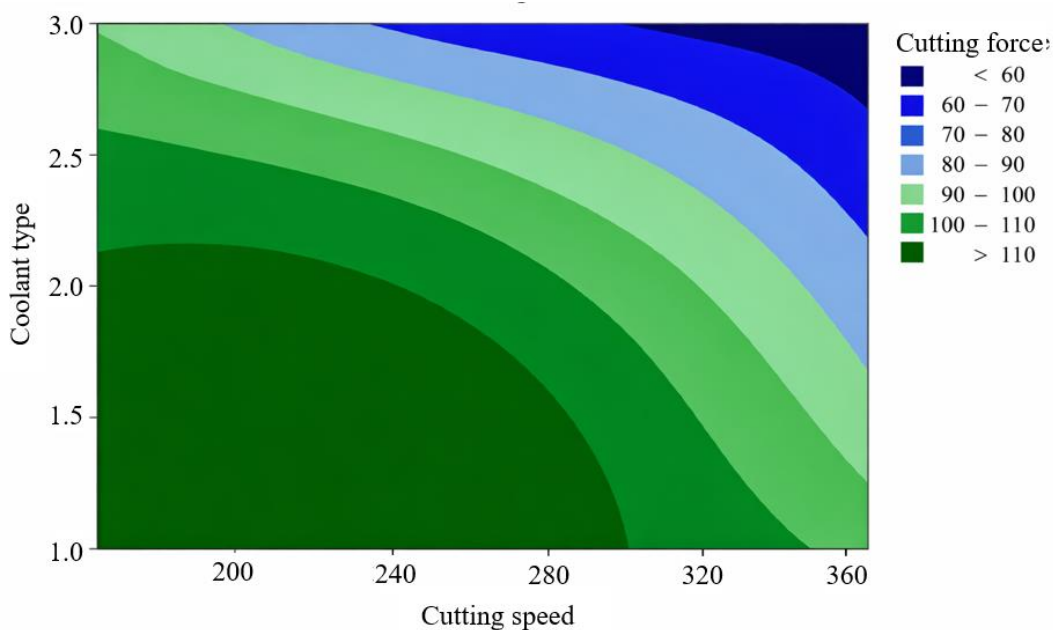


Figure 3. Effect of cutting speed and coolant type on cutting force.

Figure 4. Tool-wear distribution under different coolants Nanofluid conditions showed minimal flank wear, attributed to the formation of a uniform protective layer behaving like a thin polymeric coating that reduces adhesion and abrasion.

Figure 5. Regression plot of *Ra* vs. coolant effectiveness A strong negative correlation ($R^2 = 84.8\%$) was found between surface roughness and coolant performance index, confirming the predictive reliability of the model.

Figure 6 average *Ra* across coolant types The progressive decrease in *Ra* from dry → conventional → nanofluid conditions confirms the repeatability of nanofluid performance and its role in ensuring consistent surface integrity.

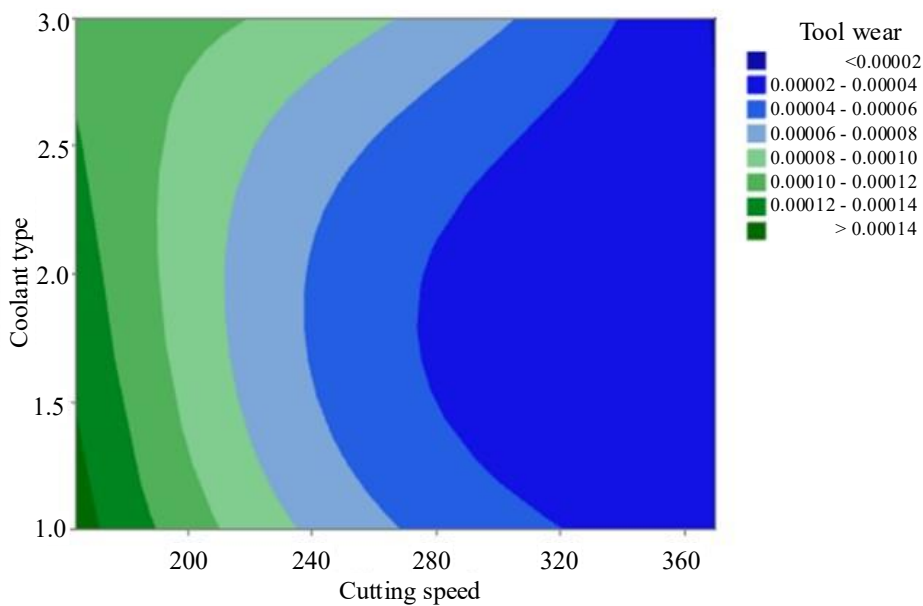


Figure 4. Tool wear distribution across different coolant

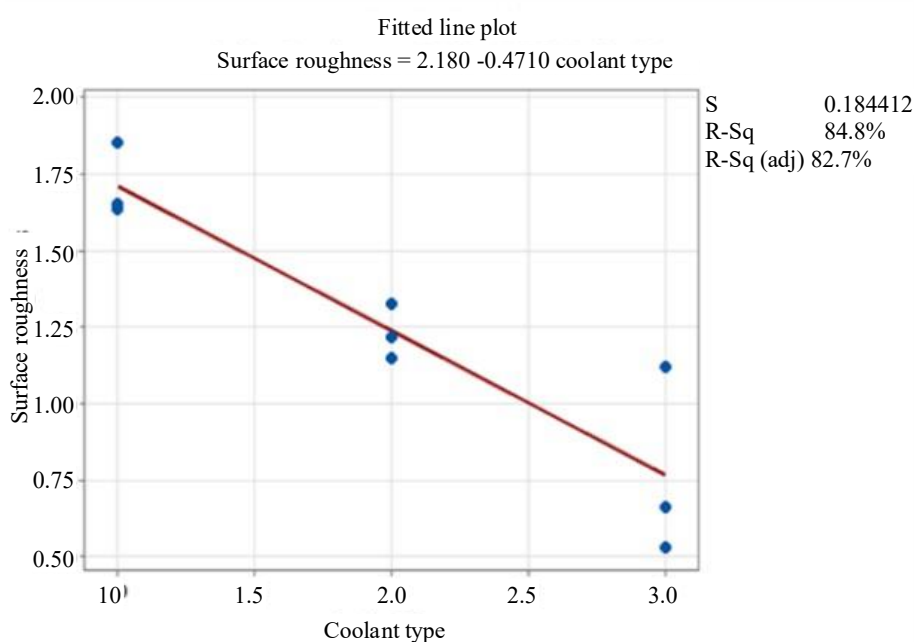


Figure 5. Regression line showing relationship between surface roughness and coolant type

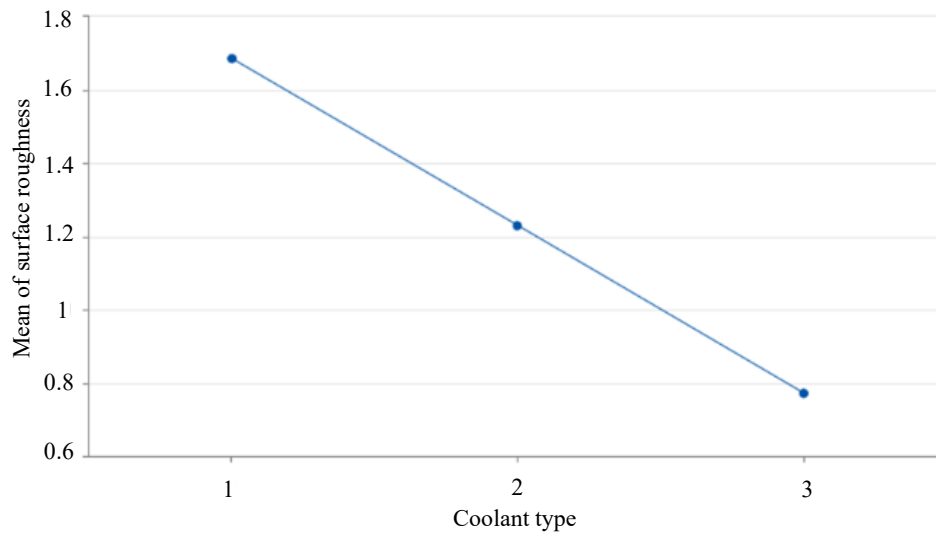


Figure 6. Average surface roughness values across different coolant types.

Table 8. Key Findings

Parameter	Key Observation	Underlying Mechanism
Coolant Type	71.2 % influence on Ra ; nanofluid most effective	Formation of nano-polymer tribo-film
Cutting Speed	Optimum at 249 m/min	Controlled thermal softening; stable chip flow
Depth of Cut	Least significant	Minor effect on contact stress
Tool Wear	↓ 64 % vs. dry cutting	TiO ₂ film limits adhesion and abrasion
Surface Roughness	↓ 72 % vs. dry cutting	Nanoparticle rolling and polymeric damping
Energy Use	↓ 40 % vs. conventional	Reduced friction and thermal load

Mechanistic Insight and Industrial Implications

The TiO₂–castor oil nanofluid functions as a polymer-nanocomposite lubricant: TiO₂ particles act as ceramic fillers enhancing load-bearing strength, while the viscous castor-oil matrix behaves as a polymeric film that absorbs shear strain and distributes heat. The resulting hybrid layer combines ceramic rigidity with polymeric elasticity, producing a resilient tribo-film capable of sustaining high pressures and temperatures.

This mechanism not only improves machinability but also extends tool life by reducing flank wear and adhesion. Industrially, the system offers up to 85 % reduction in lubricant consumption and 40 % reduction in energy use, aligning with green manufacturing and sustainable production goals.

Comparable viscoelastic tribo-film formation mechanisms have been reported in polymer-assisted nano-lubrication systems, where elastic deformation and nano-rolling effects synergistically contribute to friction and wear reduction under boundary lubrication regimes [24].

Summary of Key Findings

A summary of the key experimental findings is presented in Table 8.

In summary, TiO₂–castor oil nanofluid exhibits polymer-like viscoelastic lubrication characteristics combined with nano-scale thermal conductivity. This hybrid behavior provides exceptional surface quality, reduced tool wear, and improved energy efficiency, demonstrating its potential as a next-generation green coolant for sustainable and precision machining of austenitic stainless steels.

CONCLUSIONS

This research presented a comprehensive framework for optimizing surface finish and tribological performance during the sustainable turning of AISI 316L stainless steel using a bio-derived TiO₂–castor oil nanofluid under Minimum Quantity Lubrication (MQL) conditions. The integrated Taguchi–ANOVA–Regression approach successfully quantified the influence of process parameters and established a predictive model for surface roughness control.

Key conclusions derived from the study are as follows:

1. Coolant type emerged as the most dominant factor influencing surface roughness, contributing 71.2 % to total variance. The TiO₂–castor oil nanofluid consistently achieved the lowest *Ra* (0.520 μm), confirming its superior lubricating and cooling efficiency compared to both dry and conventional cutting conditions.
2. The developed regression model ($R^2 = 73.44\%$) demonstrated strong predictive reliability and validated the statistical consistency of the optimized parameters.
3. The TiO₂–castor oil nanofluid acted as a polymeric nano-lubricant, forming a viscoelastic tribo-film at the tool–chip interface that minimized adhesion, reduced wear by approximately 64 %, and improved surface integrity by over 70 %.
4. The optimized condition cutting speed 249 m/min, depth of cut 0.5 mm, and TiO₂ nanofluid lubrication achieved the best balance between surface quality, tool life, and energy efficiency, reducing overall cutting energy by about 40 % compared with conventional cooling.
5. The proposed lubrication system not only enhances machining performance but also supports the transition toward green, low-carbon manufacturing, aligning with Industry 4.0 and circular economy objectives.

The findings underscore the industrial relevance of bio-nanofluids as sustainable alternatives to mineral-based coolants, particularly in high-value sectors such as aerospace, biomedical implant fabrication, and precision component manufacturing, where surface finish and process repeatability are critical.

Future research should explore real-time adaptive control systems and digital twin integration for predictive modeling of nanofluid-assisted machining. Such cyber-physical systems would enable continuous optimization, minimize process variability, and accelerate the move toward fully intelligent and environmentally responsible machining environments.

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