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RESEARCH ARTICLE OPEN ACCESS

EFFECT OF CVD COATED MULTILAYER CARBIDE INSERT ON SURFACE FINISH OF CRYOGENICALLY TREATED EN31 HARDENED ALLOY STEEL USING BOX-BEHNKEN DESIGN

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ABSTRACT

The present study is focusing on cryogenically treated (CT) EN31 hardened alloy steels. The experimental runs were designed by using Box-Behnken approach of RSM using multiple process parameters- cutting speed (v, 160-260 m/min), feed (f, 0.1-0.2 mm/rev), depth of cut (d, 0.05-0.15 mm), tool nose radius (re, 0.4-1.2 mm), and hardness (HR, 45-49 HRC) for optimizing surface finish. The specimens and inserts underwent a 24-hour socking time in nitrogen medium (-196° C) as part of the deep cryogenic treatment and hardness of the materials were measured before and after the treatments. In experimentation wet turning was performed on LMW Make LX20T L5 CNC machine with multilayer TiCN+Al2O3+TiN CVD coated inserts. According to the study, Ra dramatically rises with an increase in d and falls with an increase in v. When comparing Ra to the f, re, and HR, comparable variations are seen. The Box-behnken approach of RSM is more capable of predicting surface finish by 99.96% utilizing a polynomial quadratic equation.

I. INTRODUCTION

Cryogenic treatment enhances hardness, wear resistance, dimensional stability, and mechanical performance in steels and tool materials [1], [2]. Barron identified key sub-zero processing methods such as slow cooling, long soaking, and precise temperature control to prevent thermal shock and ensure complete austenite-to-martensite transformation [1]. Amini and Das found that deep cryogenic treatment (DCT) refines martensite and promotes fine carbide distribution, reducing retained austenite and improving surface properties in tool steels such as AISI D2 and M2 [3], [4]. Baldissera and Bensely reported increased strength and wear resistance in carburized and case-hardened steels, attributing these improvements to uniform microstructure and stable carbide formation [5], [6]. Gill and Yong highlighted the significance of DCT in machining applications, reporting increased tool life and reduced flank wear under both dry and coolant-assisted cutting conditions [7], [8]. He and Idayan observed improvements in hardness, toughness, and rolling contact fatigue behaviour of maraging steels and bearing steels following cryogenic processing [9], [10].

Huang and Rhyim reported secondary carbide precipitation, martensitic refinement, and improved fracture surface characteristics as the dominant strengthening mechanisms in cryogenically treated steels [11], [12]. Pellizzari and Kalsi emphasized the importance of applying DCT prior to tempering and maintaining low cooling rates to prevent microcracking and to maximize beneficial phase transformations [13], [14]. Across automotive, tooling, manufacturing, and structural applications, collective research demonstrates that cryogenic treatment consistently improves wear resistance, hardness, and dimensional stability [2], [15-18]. When followed by appropriate tempering cycles, toughness is preserved or enhanced without compromising strength [14], [17]. Studies on steels such as EN31, EN52, EN353, AISI 440C, and powder-metallurgy high-speed steels confirm that DCT is a versatile, robust, and economically viable extension of conventional heat-treatment processes [2], [6], [10].

II. LITERATURE REVIEW

Research over the past few decades consistently demonstrates that deep cryogenic treatment (DCT) significantly alters the microstructure and properties of steels and tool materials. Barron reported that slow cooling and soaking at liquid-nitrogen temperatures are essential to achieve stable martensite formation without inducing thermal shock [1]. Amini showed that tool steels treated at −196 °C exhibited refined martensite, reduced retained austenite, and improved hardness and wear resistance [3]. Baldissera reported that cryogenically treated carburized steels exhibited hardness improvements of up to 2.4 HRC and tensile strength enhancement of approximately 11%, primarily due to uniform carbide precipitation [5]. Bensely demonstrated reduced wear and deformation in cryogenically treated EN353 gears, supported by scanning electron microscopy observations showing fewer carbide pull-outs and smoother worn surfaces [6].

Cajner and Candane further reported that DCT significantly improves dimensional stability by homogenizing carbide distribution and minimizing retained austenite [19], [20]. Investigations on cold-work tool steels, particularly AISI D2, revealed that optimal soaking durations of approximately 36 h produce maximum wear resistance through uniform carbide refinement [4]. Machining-related studies by Dhananchezian showed that liquid-nitrogen cooling during orthogonal cutting significantly reduced cutting temperature, modified chip morphology, and improved surface integrity [21]. Gill applied Taguchi optimization techniques to cryogenically treated M2 high-speed steel tools and reported significant reductions in flank wear [7]. Yong reported that cryogenically treated carbide cutting tools achieved 30–40% improvement in tool life during both dry and wet machining conditions [8], [22]. Leskovšek demonstrated that cryogenically treated high-speed steel drills exhibited up to 77% improvement in tool life when combined with appropriate tempering cycles [23].

Studies on specialty alloys revealed that cryogenic treatment promotes near-complete austenite-to-martensite transformation in maraging steels, resulting in enhanced strength and toughness [9]. Microstructural investigations by Huang confirmed that secondary carbide precipitation plays a critical role in improving wear resistance of cryogenically treated M2 steels [11]. Rhyim and Pellizzari further reported that applying DCT between quenching and tempering results in finer, more stable carbides and improved dimensional stability [12], [13], [16]. Cryogenic treatment of structural steels has also been widely investigated. By [24] reported improvements in hardness, impact energy, tensile strength, and residual stress behaviour in cryogenically treated EN31 steel due to martensitic refinement and carbon clustering [17], [25]. Vimal observed up to 75% reduction in wear rate in cryogenically treated EN31 steel, attributing the improvement to uniform carbide dispersion [2].

Thornton reported that cryogenically treated automotive brake discs exhibited significantly lower wear rates, enhancing braking efficiency and service life [18]. Vadivel demonstrated that combining cryogenic treatment with surface coatings produced synergistic improvements in wear resistance, surface finish, and flank wear suppression [26]. Additional investigations by Collins and Jaswin confirmed that the effectiveness of cryogenic treatment strongly depends on alloy composition, prior heat treatment, and cryogenic cycle parameters [27], [28]. Overall, the literature confirms that deep cryogenic treatment is a scientifically validated and industrially effective extension of conventional heat treatment, offering significant improvements in hardness, wear resistance, dimensional stability, toughness, and tool life when properly optimized [2], [14], [15].

III. EXPERIMENTAL PROGRAM

The experimental program consisting the information of raw material specifications, inserts, CNC, hardening and cryogenic treatments, machining process parameters, and surface finish. The experimental program of the present study begins with experimentation on multiple hardened EN31 alloy steel. The chemical composition of EN31 alloy steel shows the significant contribution of alloying elements such as carbon, manganese, and chromium. In contrast, nickel, silicon, molybdenum, and sulfur contribute marginally to enhancing the steel's hardness performance. Table 1 shows the alloying elements with their % contribution in EN31 alloy steel.

Table 1: Alloying elements with their % contribution in EN31 alloy steel.

Alloying Elements	Required (%)	Actual (%)
Carbon (C)	0.90 to 1.20	1.10
Silicon (Si)	0.10 to 0.35	0.19
Manganese (Mn)	0.30 to 0.75	0.52
Phosphorous (P)	0.05 max.	0.034
Sulfur (S)	0.05 max.	0.050
Chromium (Cr)	1.00 to 1.60	1.19

Source: Authors, (2026).

The experimentation was performed in batches to evaluate the performance of machining process parameters on surface finish by considering 40 samples of cryogenically treated EN31 hardened alloy steels with 5 machining process parameters. Initially, the raw material's hardness was evaluated with a Rockwell hardness tester and observed to be 27±2 HRC. Furthermore, the EN31 alloy steel specimen was sliced in accordance with the surface response method's prescribed runs. The specimens were prepared for experimentation, with plane turning and facing operations done first, followed by the standard hardening process. After hardening, the hardness of all specimens was measured again, and the experiment was carried out on 25 mm diameter EN31 alloy steel utilizing LMW Make LX20T L5 CNC machine on cryogenically treated hardened alloy steels hardness ranging from 45±2 HRC to 49±2 HRC.

Multilayer CVD inserts were introduced for turning operations because high carbon, high chromium steel required stronger inserts for machining; uncoated carbide inserts are more frequently employed. The Sandvik Coromant TNMG 160404, 160408, 160412 series insert with TiCN+Al2O3+TiN CVD coatings were used in the current study for turning operations. While alumina (Al2O3) offers superior thermal resistance to the cutting edge at high temperatures, titanium carbonate (TiCN) adds hardness and wear resistance, and titanium nitride (TiN) prolongs tool life by drastically lowering friction and premature wear.

A wet turning operation has been performed on specimens under considerations by using WW COOL SS cutting fluid as a coolant. Figure 1 shows the actual experimentation of the specimens. EN31 steel's mechanical properties, including hardness, toughness, and wear resistance, are significantly enhanced through heat treatment. This meticulous procedure involves stress relief at 500-550℃, hardening, and a phase transition from ferrite to austenite at 820-850℃. Castrol oil is used for rapid quenching, providing increased wear resistance and hardness. After quenching, tempering is repeated at 320-350℃ for 90 minutes to redefine the steel's microstructure. This comprehensive hardening process ensures the steel's appropriate hardness. Figure 2 shows the hardening process for steel materials.

Figure 1: Actual Experimentation.
Source: Authors, (2026).

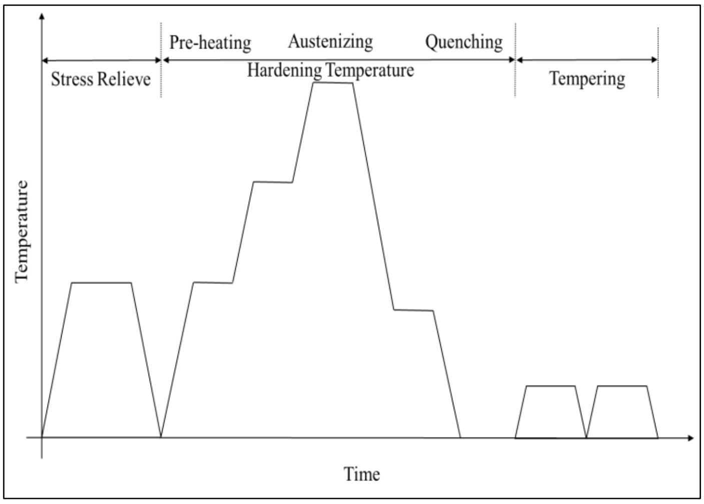

Figure 2: Hardening process for steels.
Source: Authors, (2026).

A cryogenic treatment (CT) consists of four stages called descending, soaking, ascending and tempering process. A CT was performed on all specimens under considerations and coated carbide insert in a nitrogen medium for 24 hours soaking time. A temperature of -84° C is achieved with shallow cryogenic treatment (SCT), whereas -196° C is achieved through deep cryogenic treatment (DCT). The Box-Behnken Design (BBD) is a statistical method used in Response Surface Methodology (RSM) to establish the link between dependent and independent variables.

Its unique feature is its rotatability, ensuring constant variance prediction. The BBD structure considers the number of variables and uses three experimental points: factorial, center, and no axial. This design minimizes the chance of unfavorable elements and ensures optimal performance. BBD offers efficiency, ease of use, and security, requiring less runs than factorial and CCD. However, it only works with factors between three and seven and doesn't cover the entire factor space. The experimental runs N and second order polynomial quadratic equations were designed by using formula,

$$N = 2k(k-1) + C_p \tag{1}$$

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i<j} \beta_{ij} X_i X_j \tag{2}$$

Whereas, k = No. of factors, Cp = center points, Y = Output, Xi, Xj = Independent variables, and β0, βi, βii, βij = Coefficients. The factors and their levels for the present study are given in Table 2 and Table 3 shows the experimental run calculations for CT steels.

Table 2: Factors and their levels.

Factors	**Symbol**	**Unit**	**Levels**		
			-1	**0**	**+1**
Cutting speed	*V*	*m/min*	160	210	260
Feed	*f*	*mm/rev*	0.10	0.15	0.20
Depth of cut	*d*	*mm*	0.05	0.10	0.15
Tool nose radius	r_e	*mm*	0.40	0.80	1.20
Hardness	*HR*	*HRC*	45	47	49

Source: Authors, (2026).

The quadratic equation developed though Box-behnken approach of RSM for Ra calculations is given in equation 4. With this equation the predicted Ra’s are calculated and compared with the experimental.

$$R_a = 1.52 + 0.0345r_e - 0.01414v - 0.0094f + 0.2728d + 0.0006HR + 0.0000r_e * v + 0.0000r_e * f + 0.0000r_e * d + 0.0000r_e * HR + 0.0000v * f + 0.0113v * d - 0.0000v * HR + 0.0023f * d - 0.0000f * HR + 0.0000d * HR - 0.0000r_e^2 - 0.0038v^2 - 0.0008f^2 - 0.0045d^2 + 0.0000HR^2 \tag{3}$$

Table 3: Experimental run calculations for CT steels.

Run	V	f	d	r_e	HR	Exp. Ra	Pred. Ra	Residual
1	260	0.15	0.05	0.8	47	1.07	1.09	-0.0160
2	210	0.15	0.10	1.2	45	1.55	1.55	-0.0023
3	260	0.20	0.10	0.8	47	1.37	1.36	0.0034
4	160	0.15	0.05	0.8	47	1.39	1.39	-0.0058
5	210	0.15	0.10	0.4	49	1.48	1.49	-0.0023
6	210	0.20	0.10	1.2	47	1.54	1.54	-0.0021
7	160	0.15	0.10	0.8	49	1.66	1.66	-0.0002
8	210	0.15	0.10	0.4	45	1.48	1.48	-0.0023
9	260	0.15	0.15	0.8	47	1.65	1.65	-0.0047
10	210	0.20	0.15	0.8	47	1.78	1.78	-0.0010
11	260	0.15	0.10	1.2	47	1.41	1.41	0.0032
12	260	0.15	0.10	0.8	49	1.38	1.38	0.0032
13	160	0.15	0.15	0.8	47	1.92	1.91	0.0055
14	210	0.15	0.15	0.4	47	1.75	1.75	0.0012
15	210	0.10	0.10	0.8	45	1.53	1.53	-0.0009
16	260	0.10	0.10	0.8	47	1.39	1.38	0.0045
17	210	0.10	0.05	0.8	47	1.26	1.25	0.0024
18	160	0.15	0.10	0.8	45	1.66	1.66	-0.0002
19	210	0.15	0.05	0.8	49	1.25	1.24	0.0034
20	260	0.15	0.10	0.8	45	1.38	1.37	0.0032
21	210	0.15	0.05	0.8	45	1.25	1.24	0.0034
22	210	0.15	0.15	0.8	49	1.79	1.79	0.0012
23	210	0.20	0.10	0.8	49	1.51	1.51	-0.0021
24	260	0.15	0.10	0.4	47	1.34	1.34	0.0032
25	210	0.10	0.10	0.4	47	1.49	1.49	-0.0009
26	210	0.10	0.10	0.8	49	1.53	1.53	-0.0009
27	210	0.10	0.10	1.2	47	1.56	1.56	-0.0009
28	160	0.15	0.10	0.4	47	1.62	1.62	-0.0002
29	210	0.15	0.05	1.2	47	1.28	1.28	0.0034
30	160	0.15	0.10	1.2	47	1.69	1.69	-0.0002
31	210	0.15	0.15	1.2	47	1.82	1.82	0.0012
32	210	0.20	0.05	0.8	47	1.24	1.23	0.0059
33	160	0.10	0.10	0.8	47	1.67	1.67	0.0012
34	160	0.20	0.10	0.8	47	1.65	1.65	0.0000
35	210	0.10	0.15	0.8	47	1.79	1.79	-0.0045
36	210	0.20	0.10	0.8	45	1.51	1.51	-0.0021
37	210	0.20	0.10	0.4	47	1.47	1.48	-0.0021
38	210	0.15	0.10	1.2	49	1.55	1.55	-0.0023
39	210	0.15	0.15	0.8	45	1.79	1.79	0.0012
40	210	0.15	0.05	0.4	47	1.21	1.21	0.0034

Source: Authors, (2026).

IV. RESULTS AND DISCUSSIONS

The results and discussion mainly focussed on experimental results of surface finish compared with machining process parameters and 3D surface plot and contour plots are plotted based on BBD of RSM. Figure 3 illustrates the process parameters versus surface finish for CT steels. Figure 3 (a) illustrates the variations in v and Ra. A decreasing trend observed in Ra when v is increasing as the E31 hardened alloy steel specimens are cryogenically treated (CT). CT enhances the surface finish as already seen in the open literature. The range given for 160 m/min and 260 m/min shows the outliers whereas maximum specimens Ra are covered at 210 m/min v. Figure 3(b) shows the variations in f and Ra for CT steels. A comparable differences are observed for f's under considerations. An increasing trend is observed in d and Ra shown in Figure 3(c). The values of d significantly affects the Ra as d increases with increase in Ra observed. Outliers in Ra are observed at 0.05 mm and 0.15 mm d. Again a comparable differences are observed in Ra when compared with re's and HR's as shown in Figure 3(d) and 3(e).

A wide variety of specimens are covered at 0.8 mm re and 47 HRC CT steels. In EN31 hardened alloy steels, a cryogenic treatment reduced the Ra to some extent by enhancing the material and inserts mechanical properties. Figure 4 shows the (a) 3D surface plot and (b) contour plot re and v versus Ra for CT steels. A comparable differences are observed in Ra values when re's and v's are increasing. The Ra's are observed within the range of 1.4 to 1.6 µm. Figure 5 shows the (a) 3D surface plot and (b) contour plot re and f versus Ra for CT steels. The re's and f's are having no effect on Ra's. The value of Ra is observed almost constant i.e. 1.5 µm for the considered range of re's and f's. Figure 6 shows the (a) 3D surface plot and (b) contour plot re and d versus Ra for CT steels.A significant variations are observed in Ra's due to increase in d's whereas marginal variations are observed with increase in re's. The Ra values ranged between 1.4 to 1.6 µm in a linear trend.

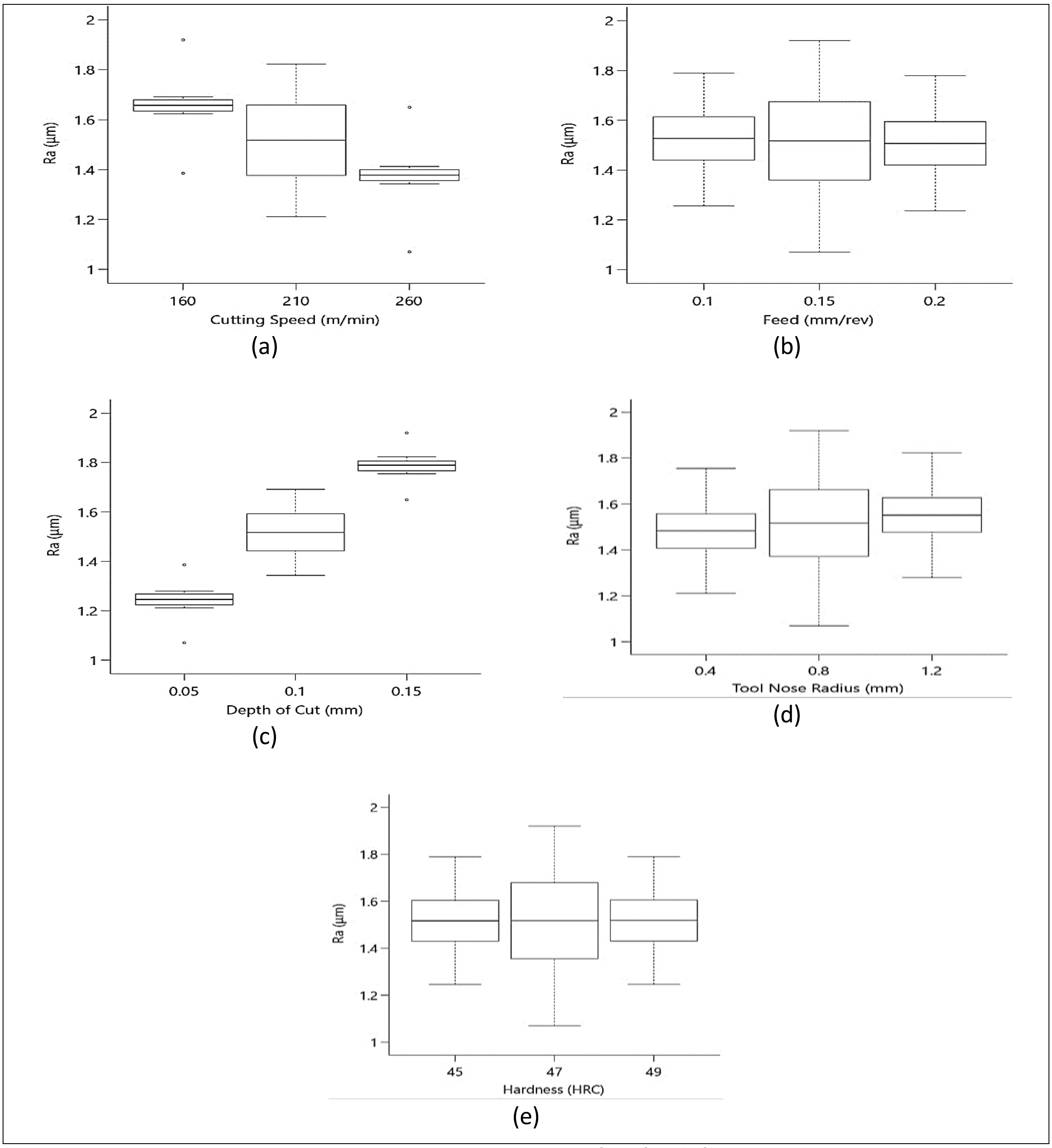

Figure 3: Process parameters versus surface finish for CT steels.
Source: Authors, (2026).

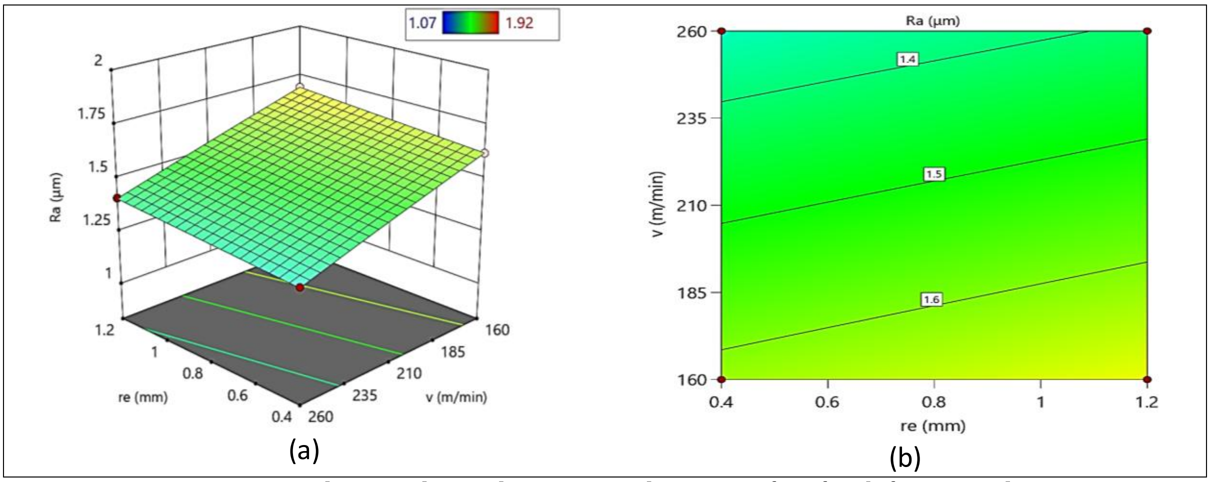

Figure 4: Tool nose radius and cutting speed versus surface finish for CT steels.
Source: Authors, (2026).

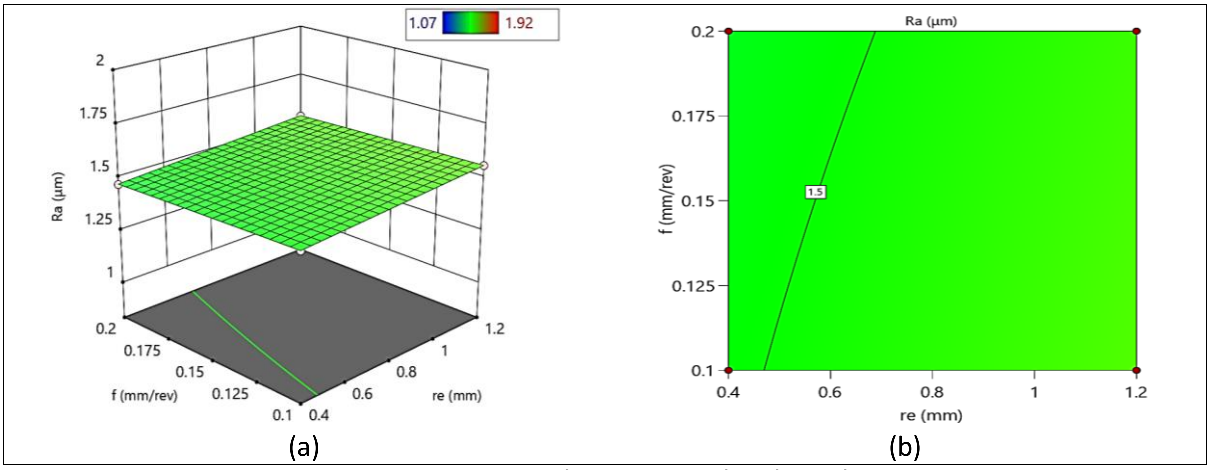

Figure 5: Tool nose radius and feed versus surface finish for CT steels.
Source: Authors, (2026).

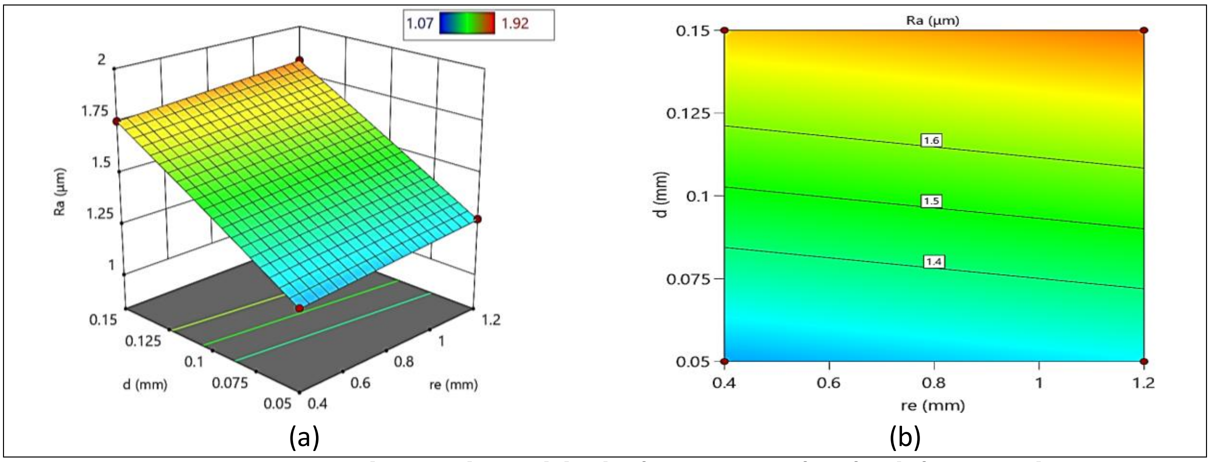

Figure 6: Tool nose radius and depth of cut versus surface finish for CT steels.
Source: Authors, (2026).

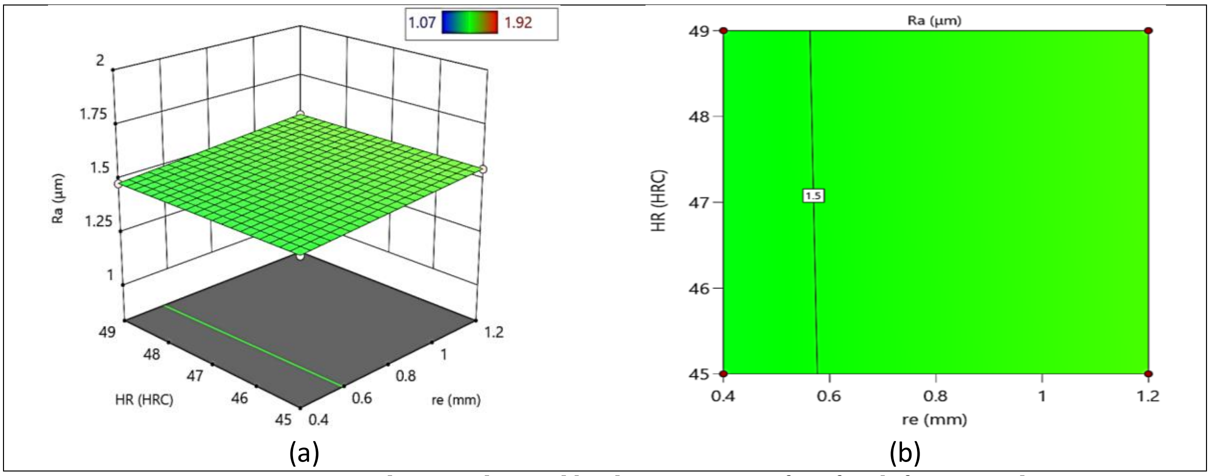

Figure 7: Tool nose radius and hardness versus surface finish for CT steels.
Source: Authors, (2026).

Figure 7 shows the (a) 3D surface plot and (b) contour plot re and HR versus Ra for CT steels. Similar to figure 5, the re's and HR's are having no effect on Ra's. The value of Ra is observed almost constant i.e. 1.5 µm for the considered range of re's and HR's. Figure 8 shows the (a) 3D surface plot and (b) contour plot v and f versus Ra for CT steels. Similar to figure 4, a comparable differences are observed in Ra values when v's and f's are increasing. The Ra's are observed within the range of 1.4 to 1.6 µm. Figure 9 shows the (a) 3D surface plot and (b) contour plot v and d versus Ra for CT steels.

A significant variations are observed in Ra's due to increase in d's whereas a comparable decrement is observed with increase v's. Ra observed greater than 1.6 µm where d is higher than by 0.1 mm. The Ra's are observed with the range of 1.4 to 1.6 µm. Figure 10 shows the (a) 3D surface plot and (b) contour plot v and HR versus Ra for CT steels. Similar to figure 8, a comparable differences are observed in Ra values when v's is decreasing and HR's are increasing.

The Ra's are observed within the range of 1.4 to 1.6 µm. Figure 11 shows the (a) 3D surface plot and (b) contour plot f and d versus Ra for CT steels. A significant effect on Ra is observed due to increase in d's whereas comparable increment is observed due to increase in f's. The Ra's are observed within the range of 1.4 to 1.6 µm.

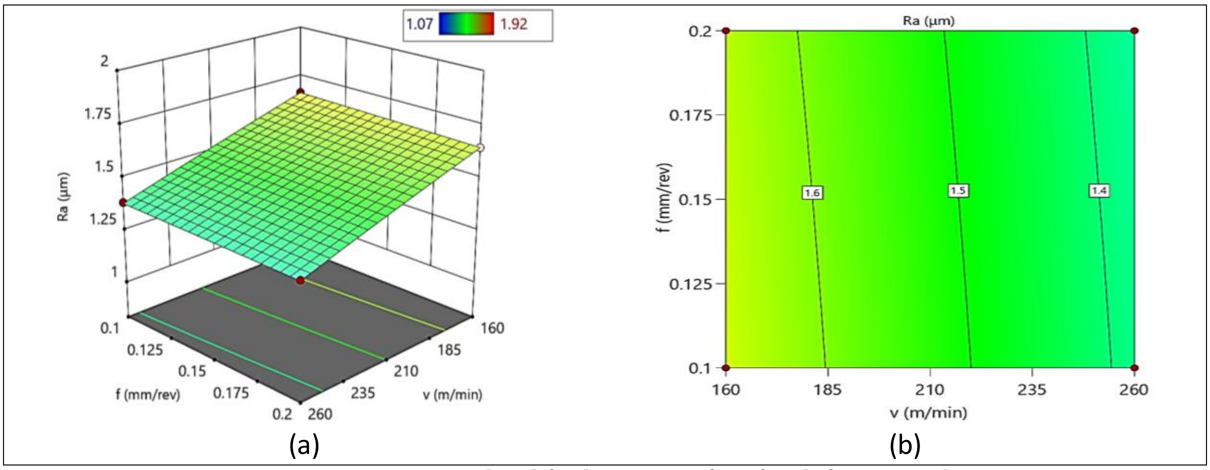

Figure 8: Cutting speed and feed versus surface finish for CT steels.
Source: Authors, (2026).

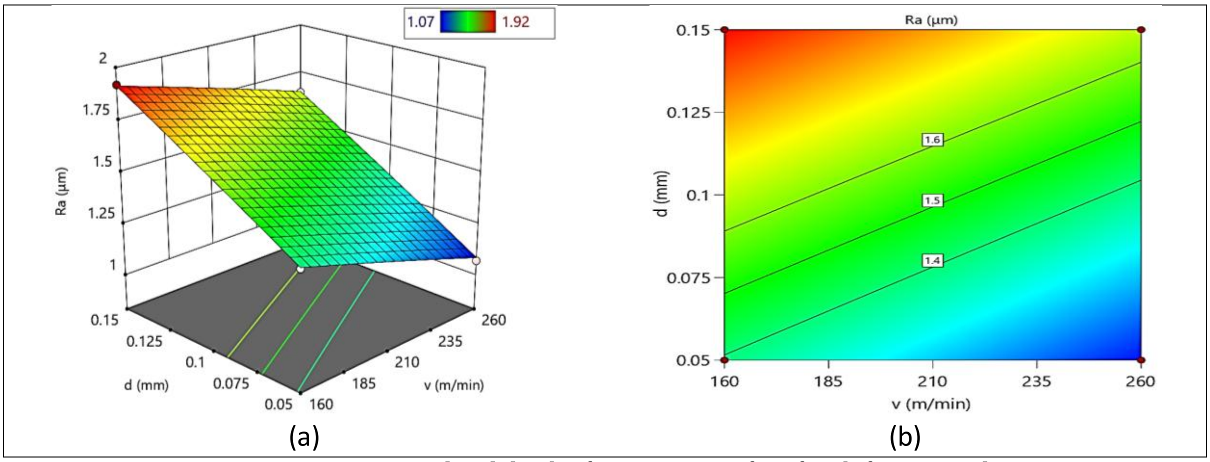

Figure 9: Cutting speed and depth of cut versus surface finish for CT steels.
Source: Authors, (2026).

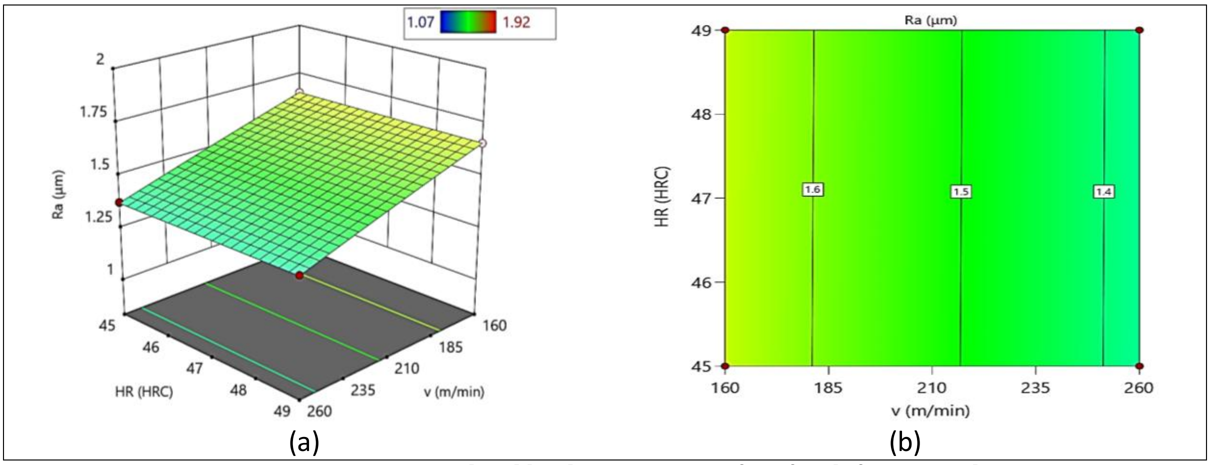

Figure 10: Cutting speed and hardness versus surface finish for CT steels.
Source: Authors, (2026).

Figure 12 shows the (a) 3D surface plot and (b) contour plot f and HR versus Ra for CT steels. Almost no effect is observed due to increase in f's and HR's on Ra values. The Ra's are observed within the range of 1.52408 to 1.5241 µm. Figure 13 shows the (a) 3D surface plot and (b) contour plot d and HR versus Ra for CT steels. Almost no effect is observed due to increase in d's and HR's on Ra values. The Ra's are observed within the range of 1.51909 to 1.5241 µm. Cryogenic treatment has provided surface finish benefits to EN31 hardened alloy steels. It has enhanced surface finish to some extent by reducing residual stresses, thermal temperature differences in cutting zones, etc. a multilayer CVD coated insert also contributes into the enhancement of surface finish.

After performing cryogenic treatment a surface finish has been observed within the range of 1.07 to 1.90 µm for all the specimens under considerations. Figure 14 illustrates the experimental runs versus comparison of surface finish. The significant deviation is observed at run number 1 and marginal deviations are observed for run number 3, 5, 16, 17, 19, 21, 32, and 37. Figure 15 shows the comparison of exp. and pred. surface finish. The surface finish for cryogenically treated steels are predicted with an accuracy of 99.96%.

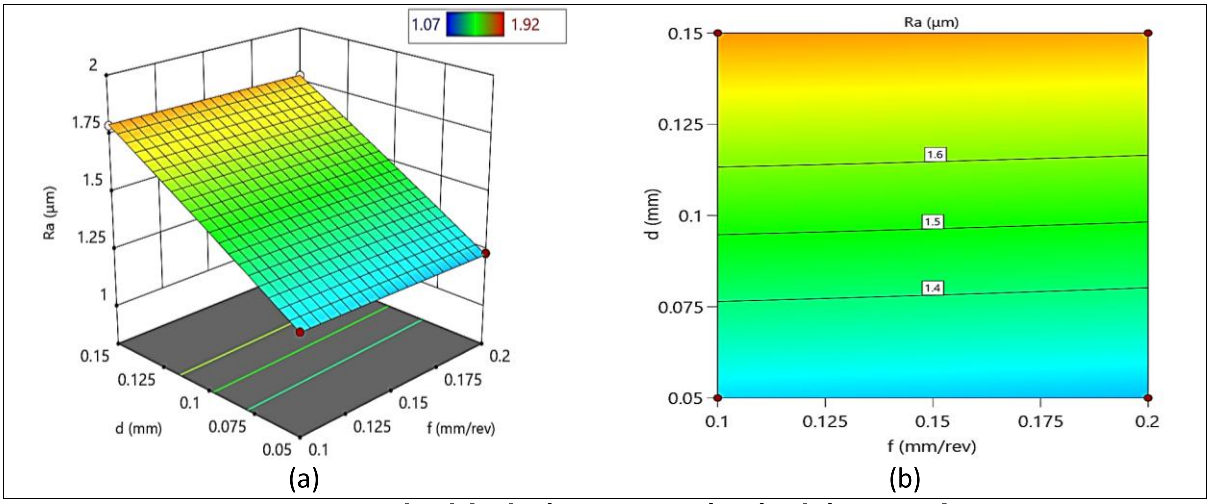

Figure 11: Feed and depth of cut versus surface finish for CT steels.
Source: Authors, (2026).

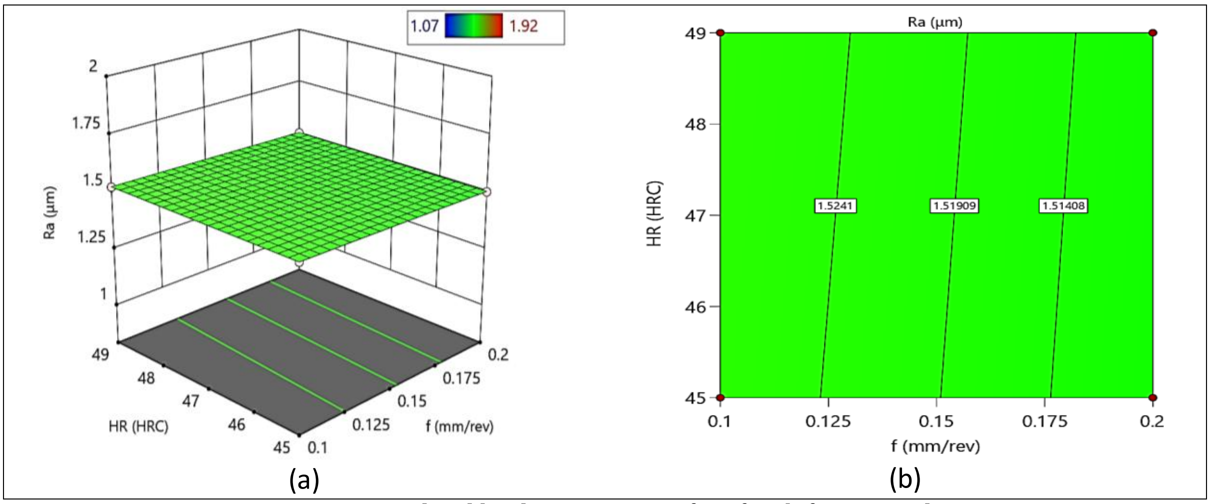

Figure 12: Feed and hardness versus surface finish for CT steels.
Source: Authors, (2026).

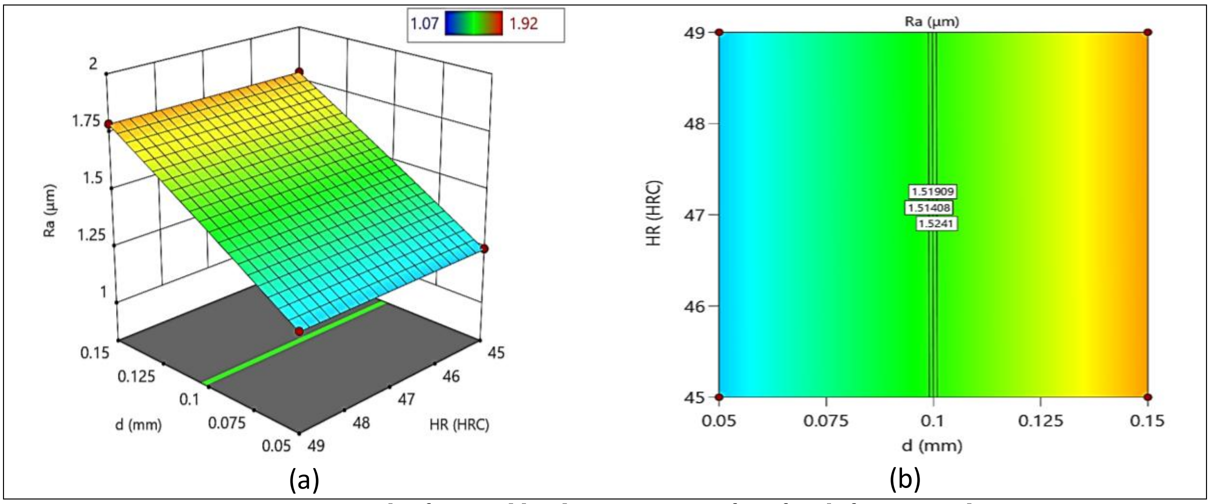

Figure 13: Depth of cut and hardness versus surface finish for CT steels.
Source: Authors, (2026).

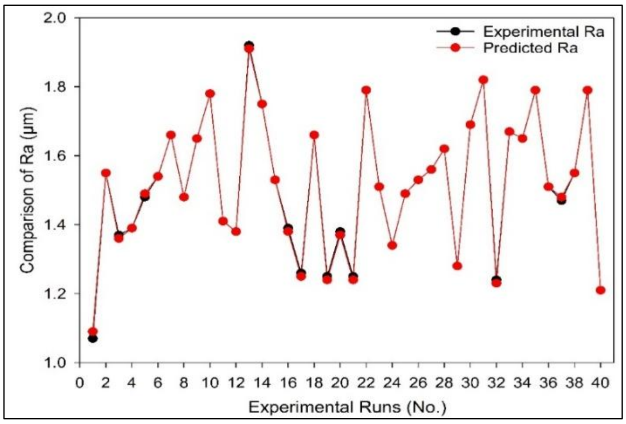

Figure 14: Experimental runs versus surface finish.
Source: Authors, (2026).

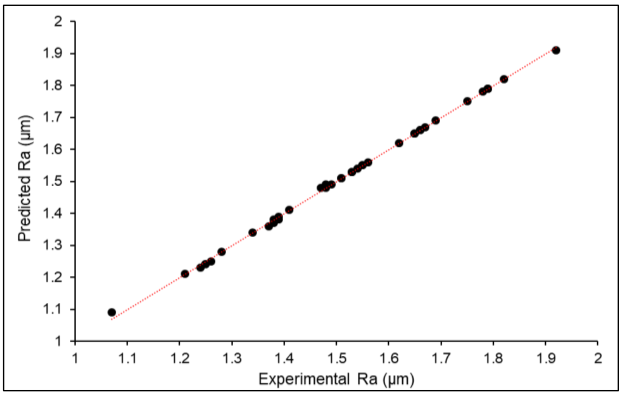

Figure 15: Comparison of exp. and pred. Ra with five process parameters for CT steels with five process parameters for CT steels.
Source: Authors, (2026).

V. CONCLUSIONS

This study demonstrates that deep cryogenic treatment at -196°C for 24 hours enhanced the machining stability of EN31 steel, producing surface roughness values consistently between 1.07-1.90 µm during hard turning. Experimental data combined with the Box–Behnken RSM approach yielded a predictive quadratic model with 99.96% accuracy, confirming its reliability. Cutting speed showed a clear inverse relationship with surface roughness, as increasing speed from 160 to 260 m/min reduced Ra, while depth of cut emerged as the most influential factor; raising d from 0.05 to 0.15 mm increased Ra beyond 1.6 µm. In contrast, feed rate changes between 0.10–0.20 mm/rev, tool nose radius from 0.4-1.2 mm, and hardness from 45-49 HRC had minimal impact, with Ra remaining close to 1.5 µm.

The parameter combination centered on v = 210 m/min, f = 0.15 mm/rev, d = 0.10 mm, re = 0.8 mm, and HR = 47 HRC consistently produced Ra values near 1.48-1.55 µm, indicating an optimal machining range. The maximum deviation between predicted and experimental Ra was only ±0.016, confirming strong agreement across trials. Overall, cryogenic treatment improved microstructural stability, enabling most interactions of machining parameters to maintain roughness within 1.4-1.6 µm, demonstrating the process's effectiveness in achieving uniform surface finish.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Shivaji Bhivsane.
Methodology: Shivaji Bhivsane.
Investigations: Shivaji Bhivsane.
Results and Discussion: Shivaji Bhivsane
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