

A FORGÁCSOLÓERŐ, A REZGÉS, A FELÜLETI ÉRDESSÉG ÉS A HENGERESSÉG VIZSGÁLATA C45 ACÉL ESZTERGÁLÁSA SORÁN

INVESTIGATION OF CUTTING FORCE, VIBRATION, SURFACE ROUGHNESS, AND CYLINDRICITY DURING TURNING OF C45 STEEL

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ABSTRACT

This study investigates cutting force, vibration acceleration, surface roughness, and geometric deviations during dry CNC turning of C45 steel (EN 1.0503). A Taguchi L9 design was implemented using cutting speeds of 160, 180, and 210 m/min, feed rates of 0.10, 0.20, and 0.30 mm/rev, and depths of cut of 0.5, 1.0, and 1.5 mm. Each of the nine conditions was repeated three times (27 machining trials). Force and vibration were monitored during cutting, and surface texture and geometric accuracy were evaluated after machining. The supplied nine-row results summary shows cutting force from 257.12 to 522.86 N, RMS vibration from 5.20 to 10.21 m/s², Ra from 2.90 to 9.64 μm, and cylindricity deviation from 11.23 to 20.92 μm. Maximum force and vibration occurred under condition 3, while the greatest Ra and Rz occurred under condition 7. Descriptive and exploratory correlation analyses are reported for the nine supplied summary rows; inference about within-condition repeatability requires the individual measurements from all 27 trials. The combined assessment illustrates the importance of evaluating mechanical loading, dynamics, surface texture, and form accuracy together.

Keywords: C45 steel; turning; cutting force; vibration; surface roughness; cylindricity; MPU6050 sensor.

1. INTRODUCTION

Turning is widely used to manufacture rotational components where dimensional precision and surface integrity are critical. Cutting speed, feed rate, and depth of cut influence chip formation, cutting resistance, tool–workpiece dynamics, surface texture, and geometric deviations [1–3]. C45 (EN 1.0503) is a medium-carbon steel used for shafts and machine components. Reliable process selection requires assessment of mechanical loading alongside the quality of the generated surface [1,2].

Cutting force reflects the mechanical interaction during material removal, whereas vibration provides information on dynamic stability and potential chatter [2,3]. Surface roughness, commonly expressed through

Ra and Rz, describes profile texture but does not alone establish form accuracy. Cylindricity (CYLt), roundness (RONt), and straightness (STRt) characterize different geometric departures from ideal shape; their interpretation depends on the evaluation procedure [4–6]. The present work investigates these responses together during dry turning of C45 steel. A three-factor, three-level Taguchi L9 array with three repetitions per condition was used. The objective is to compare the influence of the cutting parameters and explore associations between force, vibration, roughness, and form deviation without assuming that statistical association establishes causation C45 (EN 1.0503) is used in rotational components where both surface finish and geometric form are important. Cutting forces can affect deflection and mechanical loading, whereas vibration can reflect dynamic excitation, of the tool–workpiece system. Consequently, force and vibration should be interpreted together with roughness and form measurements rather than used as interchangeable quality indicators [1–3].

Roundness, straightness, and cylindricity quantify different aspects of form and need not respond in the same direction to changes in cutting conditions. Geometric product specification principles distinguish these characteristics and the operators used to evaluate them [5,6]. The present work therefore combines mechanical, dynamic, texture, and form responses in one L9 experimental framework; the reported nine condition-level values are analyzed without assuming that the 27 underlying trial records are available.

2. MATERIALS AND METHODS

2.1. Material, workpiece and turning arrangement

Three C45 medium-carbon steel (EN 1.0503) cylindrical specimens were machined in a segmented configuration to provide distinct evaluation regions. The schematic shows a three-jaw chuck, a supported workpiece, a cutting tool, and a tool-holder-mounted acceleration sensor (Fig. 1). The machining setup photograph illustrates the prepared segmented cylindrical workpiece (Fig. 2). Turning was performed dry on a

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Hunor PNC721 CNC lathe. Cutting insert grade, nose radius, workpiece diameter, and tool geometry should be checked against the laboratory log before submission.

Experimental investigations were conducted on C45 steel (EN 1.0503) using a Hunor PNC721 CNC lathe under dry cutting conditions. Cylindrical workpieces (40 mm diameter, 200 mm length) were machined using a DSDNN 2020K 12 tool holder with Sandvik Coromant SNMG 120416-PR 4425 carbide inserts [1,2]. Cutting forces were measured using a Kistler 9257A three-component dynamometer, Kistler 5011A charge amplifiers, and an NI CompactDAQ-9171 system, with data recorded in LabVIEW 2018 SP1. Vibrations were monitored using an MPU6050 accelerometer mounted near the cutting insert and connected to an ESP32-based data acquisition system

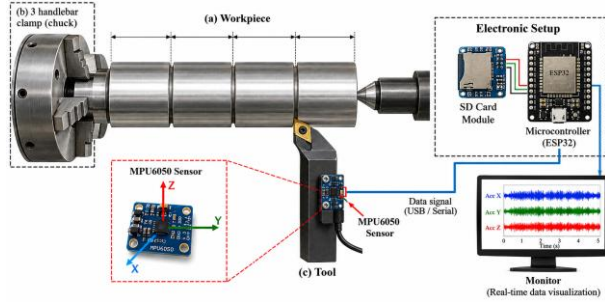


Figure 1. Schematic of segmented workpiece, tool, MPU6050 vibration sensor, ESP32 and recording arrangement.

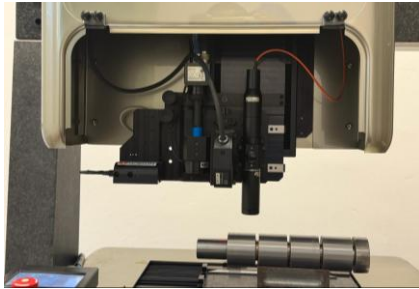


Figure 2. Photograph of the segmented workpiece in the measurement arrangement.

2.2. Experimental design

A Taguchi L9 (3^3) orthogonal array was used. The factors were cutting speed $V_c = 160, 180, 210$ m/min; feed $f = 0.10, 0.20, 0.30$ mm/rev; and depth of cut $a_p = 0.5, 1.0, 1.5$ mm. Each condition was machined three times, giving 27 trials.

Table 1. Experimental design

Run	V_c (m/min)	f (mm/rev)	a_p (mm)
1	160	0.10	0.5
2	160	0.20	1.0
3	160	0.30	1.5
4	180	0.10	1.0
5	180	0.20	1.5
6	180	0.30	0.5
7	210	0.10	1.5
8	210	0.20	0.5
9	210	0.30	1.0

The nine values supplied for each response are treated here as condition-level reported results; whether they are three-trial means must be verified. The L9 design primarily supports estimation of main effects; interactions are not independently resolved.

2.3. Cutting force and vibration monitoring

Cutting force signals were acquired using a Kistler 9257A dynamometer in combination with Kistler 5011A charge amplifiers, NI CDAQ-9171 data acquisition hardware, and LabVIEW software. The resulting force response was represented by $AF(N)$. To characterize the overall force level during the turning process, the root mean square (RMS) value of the measured force signal was calculated and used as the representative cutting-force parameter. This approach provides a reliable measure of the effective force magnitude by considering the complete force signal over the sampling interval rather than individual instantaneous values.

Tool-holder vibrations were monitored using an MPU6050 three-axis accelerometer mounted directly on the tool holder. The vibration acquisition system consisted of an ESP32 microcontroller, an SD-card module for data storage, and a computer-based display interface, as illustrated in Fig. 1. The acceleration data collected along the three orthogonal axes were combined to determine the resultant acceleration magnitude, which was used to evaluate the vibration behavior of the cutting system throughout the machining process. The calculated acceleration magnitude provided a single parameter representing the overall vibration intensity during dry turning.

The RMS value of the force signal was calculated according to Equation (1), while the resultant acceleration magnitude was obtained using Equation (2).

$$x_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2} \quad (1)$$

$$a = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (2)$$

2.4. Surface roughness and form measurement

R_a and R_z were evaluated using an Altisurf 520 surface-measurement system. R_a is the mean absolute height of the roughness profile over the evaluation length; the exact R_z definition depends on the applicable profile standard and processing settings [4]. Cutoff, evaluation length and trace positions require confirmation. Cylindricity (CYLT), roundness (RONt), and straightness (STRt) were measured with a Taylor Hobson Talysond 365 system (Fig. 3), following geometrical product specification concepts [5,6]. The figure shows the specimen mounted vertically on the rotary table with a contacting probe. The filtering criteria and mathematical fitting methods used to determine the form parameters followed the standard settings of the

Taylor Hobson Talyrond 365 system. After acquisition, the data were exported to Microsoft Excel, where statistical processing, data organization, and comparative analyses among the machining conditions were performed.



Figure 3. Talyrond measurement setup with vertically mounted machined specimen and contact probe.

2.5. Data processing and statistical approach

The experimental results obtained from the nine machining conditions of the Taguchi L9 orthogonal array were subjected to statistical analysis to evaluate the relationships among the measured responses. For each response variable, descriptive statistics, including minimum and maximum values, were determined to characterize the range of variation across the experimental conditions. In addition, Pearson correlation analysis was performed to assess the strength and direction of the linear relationships between the machining responses. Because the analysis was conducted using nine condition-level observations rather than the complete set of 27 individual measurements, the resulting correlations should be considered exploratory. Consequently, any associated p-values should not be interpreted as formal significance tests based on 27 independent observations. More comprehensive statistical analyses, such as repetition-level means, standard deviations, confidence intervals, and residual-error analysis of variance (ANOVA), would require access to the complete dataset containing all experimental repetitions. Furthermore, due to the limited number of observations in the L9 design, any regression models or main-effect trends derived from the data should be interpreted with caution and used primarily to support the understanding of general response tendencies. The Pearson correlation coefficient used to quantify the linear relationships among variables was calculated according to Equation (3).

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (3)$$

3. RESULTS AND DISCUSSION

3.1. Experimental response overview

Table 2 presents the nine supplied condition-level response records. All trials were performed without coolant. Cutting force ranged from 257.12 N (run 9) to 522.86 N (run 3). RMS vibration ranged from 5.20 m/s² (run 8) to 10.21 m/s² (run 3). The Ra range was 2.90–9.64 μm, and Rz was 27.53–42.44 μm. Geometric deviations varied across the conditions: STRt 0.40–5.27 μm, RONt 2.20–9.21 μm, and CYLt 11.23–20.92 μm.

Table 2. Supplied condition-level measurements (Ra, Rz, STRt, RONt, CYLt in μm; vibration RMS).

Run	AF N	Ra	Rz	STRt	RONt	CYLt	Vib
1	300.9	4.5	31.6	3.2	3.4	17.1	9.3
2	356.1	3.3	27.5	0.6	3.1	20.7	9.9
3	522.9	8.2	34.4	0.4	3.1	20.9	10.2
4	410.7	6.3	35.2	1.7	2.2	11.2	8.1
5	510.8	4.1	31.9	5.3	4.7	19.6	9.6
6	260.7	2.9	28.4	0.5	3.2	18.3	7.1
7	430.6	9.6	42.4	0.7	2.6	14.5	7.3
8	365.0	7.9	36.5	1.6	9.2	16.4	5.2
9	257.1	4.8	32.5	2.3	8.1	17.4	5.9

The maximum force and maximum vibration were both observed in run 3 ($V_c = 160$ m/min, $f = 0.30$ mm/rev, $a_p = 1.5$ mm). In contrast, the highest Ra (9.64 μm) and Rz (42.44 μm) were observed in run 7 (210 m/min, 0.10 mm/rev, 1.5 mm). Maximum RONt occurred in run 8 (9.21 μm), whereas maximum STRt occurred in run 5 (5.27 μm). These differing extrema show that the highest mechanical load did not coincide with the worst value for every surface or form response.

3.2. Effects of machining conditions

For the nine reported values, the lowest cutting force occurred in run 9 despite its relatively high cutting speed and feed. Run 3, with high depth of cut and feed, generated the largest force. However, individual factor effects cannot be isolated by comparing two arbitrary runs because more than one parameter changes. A balanced main-effect comparison or ANOVA should use the full experimental design and preferably all three repetitions.

The roughness results are not monotonic with feed across the L9 conditions: for example, run 7 at $f = 0.10$ mm/rev had the largest Ra. This suggests that surface generation depends on multiple interacting physical mechanisms, potentially including tool condition and dynamics; the present summary alone does not identify their causes. Cylindricity also showed no simple one-to-one correspondence with force or vibration.

3.3. Exploratory response correlations

The correlations in Table 3 quantify associations among condition-level responses only. They should not be interpreted as causal links or as substitutes for analysis of the 27 underlying trials. The small sample size, multiple comparisons, and possible averaging of replicates limit statistical confidence. A final repeatability analysis should report the within-condition standard deviation and ideally uncertainty intervals for each response.

Table 3. Exploratory Pearson correlations across nine supplied rows; *p*-values

Pair	Pearson <i>r</i>	<i>p</i> (n=9)
Vibration–force	0.529	0.143
Vibration–Ra	-0.222	0.566
Vibration–CYLt	0.462	0.211
Force–CYLt	0.124	0.750
Ra–Rz	0.929	0.000

3.4. Cutting-force response and factor effects

As shown in Table 2, the cutting force varied substantially across the nine machining conditions. Figure 4 compares the condition-level forces, with the highest value of 522.86 N in Run 3 and the lowest value of 257.12 N in Run 9. Figure 9 summarizes the mean cutting force at each cutting-parameter level, using the balanced L9 design. These descriptive main effects should not be interpreted as independent interaction estimates or as a replicated-trial ANOVA.

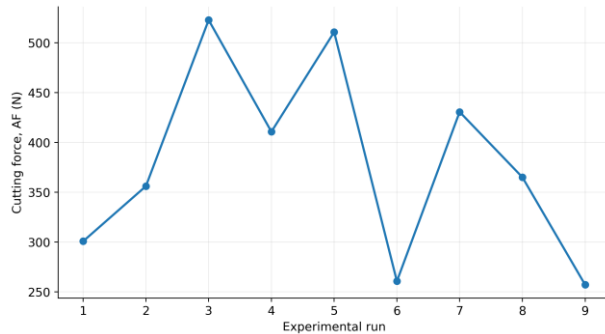


Figure 4. Cutting force measured across the nine Taguchi L9 turning conditions.

3.5. Vibration acceleration

The vibration values in Table 2 ranged from 5.20 to 10.21 m/s². Figure 5 shows the RMS vibration response for each cutting condition. Run 3 produced the highest reported vibration magnitude (10.21 m/s²), coinciding with the maximum cutting force, whereas Run 8 had the lowest vibration (5.20 m/s²). This agreement at one condition does not establish a causal relationship between the two signals.

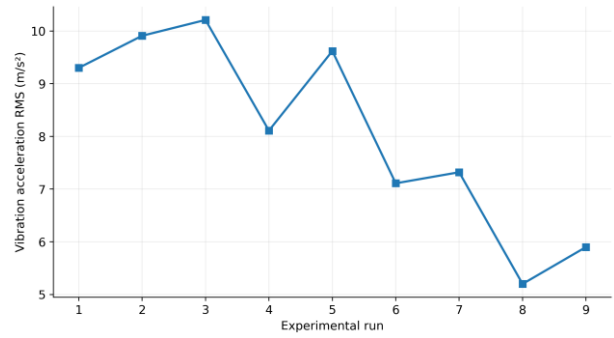


Figure 5. RMS vibration acceleration across the nine turning conditions.

3.6. Surface roughness and geometric quality

Figure 6 illustrates the variation in Ra and Rz from Table 2. Both roughness measures reached their maximum in Run 7 (Ra = 9.64 μm; Rz = 42.44 μm), rather than in Run 3, where the cutting force was greatest. Figure 7 presents STRt, RONt and CYLt. The maximum cylindricity deviation occurred in Run 3 (20.92 μm), maximum roundness deviation in Run 8 (9.21 μm), and maximum straightness deviation in Run 5 (5.27 μm). These different peak conditions indicate that individual machining-quality responses should be assessed separately.

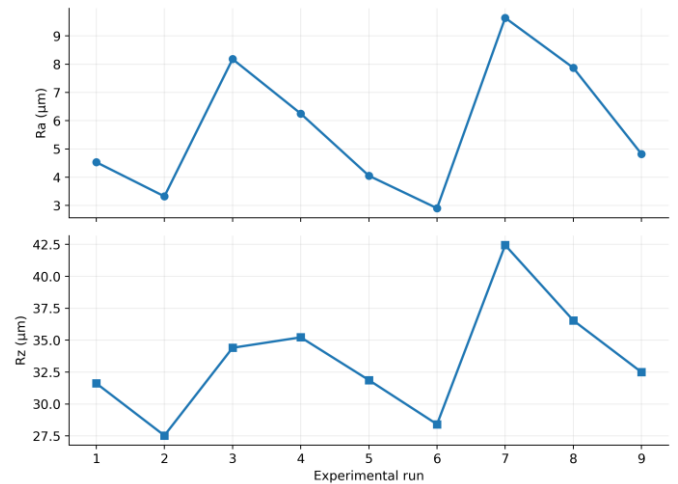


Figure 6. Variation of surface roughness parameters Ra and Rz across the experimental conditions.

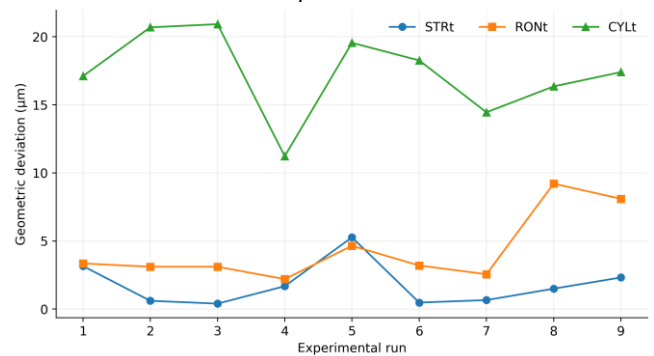


Figure 7. Straightness, roundness and cylindricity deviations across the experimental conditions.

3.7. Relationships among machining responses

The Pearson coefficients in Table 3 are visualized in Figure 8 as a correlation matrix. These associations were computed from nine condition-level records ($n = 9$), not the 27 individual repetitions. For example, the cutting force–vibration correlation is positive ($r \approx 0.529$), but its two-sided unadjusted p-value is approximately 0.143. Correlation strength should therefore be interpreted cautiously, without claiming statistical significance or causality from these limited data.

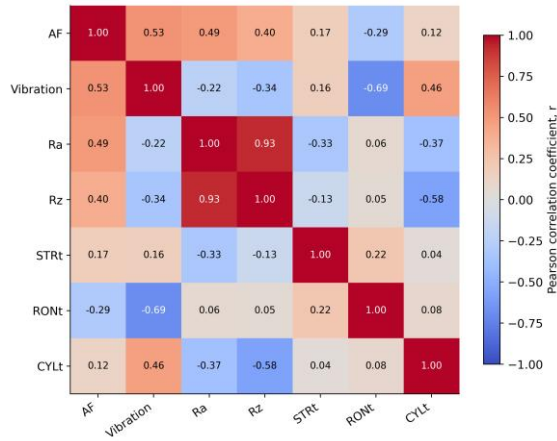


Figure 8. Pearson correlation heatmap of cutting force, vibration, surface roughness and geometric deviations ($n = 9$ condition-level records).

To better illustrate the influence of the machining parameters on cutting force, the average force values were calculated for each level of cutting speed, feed rate, and depth of cut based on the Taguchi L9 experimental design. The results indicate that cutting force remained relatively stable between cutting speeds of 160 and 180 m/min but decreased at 210 m/min. Feed rate exhibited a non-monotonic effect, with the highest mean cutting force observed at 0.20 mm/rev. In contrast, depth of cut showed the strongest influence on cutting force, increasing substantially as the depth of cut increased from 0.5 mm to 1.5 mm. This behavior is consistent with the increase in the uncut chip cross-sectional area, which directly affects the cutting load generated during machining. The trends shown in Figure 9 are descriptive and represent the average response at each factor level within the L9 design.

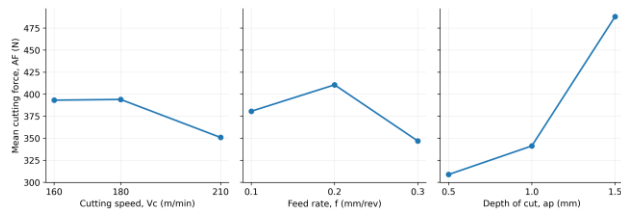


Figure 9. Descriptive main effects of cutting speed, feed rate, and depth of cut on cutting force.

3.8. Three-dimensional response surfaces for geometric accuracy

To complement the measured geometric deviations in Table 2 and the condition-by-condition comparison in Figure 7, Figure 10 presents modeled response surfaces for roundness (RONT), straightness (STRt), and cylindricity (CYLt) as functions of cutting speed and feed rate. The surfaces are descriptive predictions from additive regression models fitted to the nine supplied L9 response records, with depth of cut held at 1.0 mm. They should not be interpreted as directly observed measurements at the interpolated grid points.

Figure 10(a) concerns roundness, which ranged from 2.20 μm in Run 4 to 9.21 μm in Run 8. The additive model explained approximately 61% of the nine-point variation ($R^2 \approx 0.61$). Figure 10(b) illustrates straightness, ranging from 0.40 μm in Run 3 to 5.27 μm in Run 5. Its model fit was weak ($R^2 \approx 0.05$), so the apparent surface slope is not robust evidence of a systematic trend. Figure 10(c) depicts cylindricity, ranging from 11.23 μm in Run 4 to 20.92 μm in Run 3; the corresponding additive model explained approximately 65% of variation ($R^2 \approx 0.65$).

These surfaces suggest that the geometric responses need not improve simultaneously under a single combination of cutting parameters. The Taguchi L9 arrangement cannot independently resolve all factor interactions, and the three-repetition raw records are unavailable for a replicated model validation. Consequently, the response surfaces should be used as exploratory visualization, not as validated optimization maps.

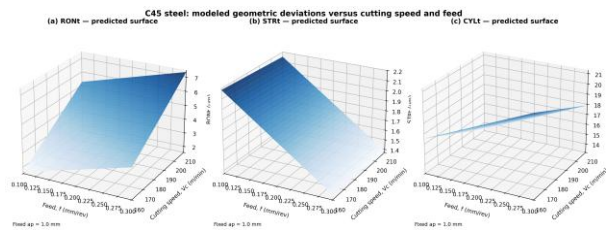


Figure 10. Modeled three-dimensional response surfaces for (a) roundness deviation (RONT), (b) straightness deviation (STRt), and (c) cylindricity deviation (CYLt), as functions of cutting speed and feed rate at $a_p = 1.0$ mm.

3.9. Limitations and practical implications

The available data support descriptive comparisons across nine machining conditions. Although 27 trials were performed, their separate measurements were not supplied; therefore, no valid within-run repeatability statistics or replicated-trial ANOVA is claimed. Further reporting should include tool geometry, sensor acquisition settings, roughness evaluation parameters, Talyrond filtering, and a clear definition of AF. Joint monitoring remains useful because force, vibration, surface roughness, and form deviations describe different aspects of machining quality.

3.10. Discussion and Comparison with Previous Studies

The experimental results obtained in the present investigation are compared with published research on the turning of C45 steel and related machining processes. Particular attention is given to cutting force, vibration acceleration, surface roughness, and geometric accuracy. The present study found that cutting force varied from 257.12 to 522.86 N, while surface roughness Ra ranged from 2.90 to 9.64 μm . The maximum cutting force and vibration occurred in Run 3, whereas the highest surface roughness was observed in Run 7. This difference indicates that mechanical loading and surface quality are not necessarily governed by identical machining conditions. Duong [7] investigated the optimization of cutting parameters during C45 steel turning using the Taguchi method and identified feed rate as the most influential factor affecting surface roughness, followed by cutting speed and depth of cut. Similar findings were reported by Huynh et al. [8], who demonstrated the dominant influence of feed rate on surface roughness using Taguchi design and ANOVA. In contrast, the present investigation showed a non-monotonic roughness response, with the highest Ra occurring at the lowest investigated feed rate. This difference suggests that surface generation may depend on additional factors, including tool geometry, cutting dynamics, and experimental conditions. Şap et al. [9] investigated the machinability of CK45 steel under dry, minimum quantity lubrication (MQL), and nanofluid conditions. Their results showed that lubrication significantly improved surface quality, with minimum reported Ra values of 2.168, 1.341, and 0.965 μm , respectively. The minimum Ra obtained in the present dry-turning investigation was 2.90 μm , which was higher than their reported values. However, differences in cutting parameters, machining operations, tooling, and lubrication conditions prevent direct attribution of this difference to any single factor. Regarding geometric accuracy, the present results revealed weak correlations between cutting force and cylindricity ($r = 0.124$) and between vibration and surface roughness Ra ($r = -0.222$). These findings indicate that neither mechanical loading nor RMS vibration acceleration alone adequately describes the observed surface and form quality. Unlike the cited investigations, which primarily emphasized roughness optimization or lubrication performance, the present study jointly evaluated cutting force, vibration, surface roughness, straightness, roundness, and cylindricity.

4. CONCLUSION

Dry turning of C45 steel was examined using nine Taguchi L9 cutting conditions, each repeated three times. Across the nine reported response records, cutting force ranged from 257.12 to 522.86 N and RMS vibration from 5.20 to 10.21 m/s^2 . Ra ranged from 2.90 to 9.64 μm , Rz from 27.53 to 42.44 μm , and cylindricity from 11.23 to 20.92 μm . Run 3 exhibited both the highest force and

vibration, whereas run 7 had the highest Ra and Rz. Different runs produced the maxima of roundness and straightness deviations, confirming that no single measured response completely represents overall machining quality. The nine-row dataset enables descriptive and exploratory analysis; reliable estimation of trial-to-trial variability and formal replicated-trial inference requires the individual measurements from all 27 experiments.

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