

Article

Experimental Analysis and Process Monitoring of Cutting Force, Vibration, Surface Roughness, and Cylindricity in Turning of C45 Steel

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Featured Application

The proposed measurement and analysis framework can support low-cost monitoring of cutting force, vibration, surface roughness, and geometric accuracy in CNC turning. The approach is intended as a process-screening and condition-monitoring framework rather than as a statistically validated optimization method.

Abstract

This study examines the effects of cutting speed, feed rate, and depth of cut on cutting force, vibration, surface roughness, and geometric accuracy during dry turning of C45 steel (EN 1.0503) using a Taguchi L9 orthogonal design. Cutting force, RMS acceleration, surface roughness (Ra and Rz), and form deviations (straightness, roundness, and cylindricity) were measured for nine machining conditions. Vibration decreased with increasing cutting speed and increased with increasing depth of cut, whereas cutting force showed no consistent dependence on cutting speed and increased at the largest depth of cut. Ra and Rz were generally lower at higher cutting speeds. The maximum active cutting force was 730.60 N in Experiment 7, while the maximum RMS vibration was 19.09 m/s² in Experiment 3. Exploratory Pearson analysis across the nine conditions indicated $r = 0.678$ between vibration and Ra, $r = -0.769$ between vibration and cylindricity deviation, and $r = 0.329$ between cutting force and vibration. Because no independent machining repetitions were performed, these relationships are descriptive and do not establish causality, statistical factor significance, or a validated predictive model. The study therefore presents the integrated force–vibration–surface–geometry measurements as a process-screening framework and identifies methodological requirements for subsequent replicated and frequency-resolved experiments. The vibration indicator is the RMS acceleration derived from the tangential and radial components; the sensor specification provides a programmable low-pass-filter range up to 260 Hz, although the actual internal filter setting used during acquisition was not documented.

Keywords: turning of C45; cutting force; vibration; surface roughness; cylindricity; process monitoring; MPU6050 sensor

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1. Introduction

Among engineering materials, medium-carbon steels occupy an important position because they offer a favorable balance between strength, toughness, wear resistance, and economic viability. One of the most widely used grades is C45 steel (EN 1.0503) [1], which contains approximately 0.45% carbon and is commonly employed in the manufacture of shafts, gears, bushings, pins, connecting rods, and other mechanical components subjected to moderate and high loads [2]. Unlike alloyed steels, the properties of C45 are primarily determined by its carbon content and heat-treatment condition rather than by significant additions of alloying elements such as chromium, nickel, or molybdenum [2]. In the normalized condition, C45 typically exhibits a ferritic–pearlitic microstructure, while quenching and tempering produce a tempered martensitic structure with improved hardness and strength [3]. These characteristics make C45 steel particularly suitable for applications requiring a balance between mechanical performance and machinability, such as cutting forces, vibration behavior, surface roughness, and geometric accuracy during turning operations.

C45 steel is popular for its mechanical properties and suitability for heat-treatment processes such as quenching and tempering [2]. Although C45 steel is generally considered machinable, cutting conditions, tool geometry, chip formation, thermal effects, and tool wear can still affect practical machining performance [4,5]. These factors can influence surface roughness, dimensional accuracy, geometric tolerances, and tool life. Consequently, understanding C45 steel behavior during turning operations is important for selecting favorable machining conditions and ensuring consistent product quality. Cutting force is one of the most important indicators of machining performance. Cutting forces arise from the interaction between the cutting tool and the workpiece material and drive material removal during turning. The magnitude of these forces directly influences power consumption, tool wear, vibration, dimensional accuracy, and surface integrity [6]. Therefore, analyzing cutting forces provides valuable information regarding machinability and process stability. During turning, the resultant cutting force can be resolved into three orthogonal components, as illustrated in Figure 1. These components are the tangential cutting force ($\vec{F}_c$), the axial force ($\vec{F}_f$), and the radial force ($\vec{F}_r$).

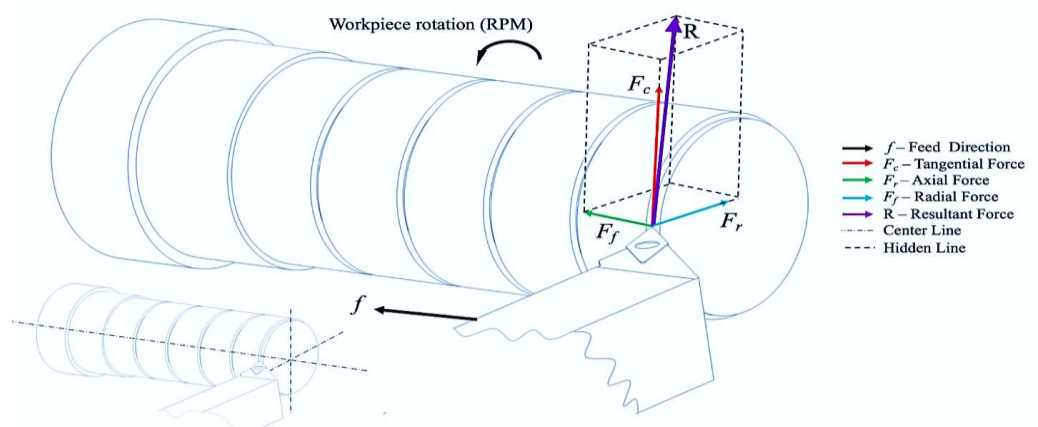


Figure 1. Cutting-force components in the turning operation.

The tangential force ($\vec{F}_c$), acts in the direction of workpiece rotation and represents the primary cutting force responsible for material shearing. This force accounts for the largest proportion of energy consumption during machining and strongly influences tool wear and cutting power requirements. The axial force ($\vec{F}_f$) acts parallel to the workpiece axis

and opposite to the feed direction. It affects the feed mechanism and contributes to the longitudinal loading of both the cutting tool and the workpiece. Excessive axial forces can cause tool deflection and dimensional inaccuracies. The *radial force* ($\overrightarrow{F_f}$) acts perpendicular to the machined surface toward the workpiece's center. Although it does not directly contribute to material removal, it plays a significant role in process stability by influencing tool deflection, vibration generation, and geometric accuracy. High radial forces often increase chatter, degrade surface finish, and cause dimensional errors. The combined effect of these three force components is represented by the resultant cutting force ($\overrightarrow{F_e}$), which can be calculated using Equation (1):

$$F_e = \sqrt{F_c^2 + F_f^2 + F_r^2} \quad (1)$$

The resultant force represents the total mechanical load acting on the cutting tool during machining and provides an overall indication of cutting severity. In addition to cutting forces, vibration is another critical factor affecting machining performance. Machining vibrations, often referred to as chatter, can significantly reduce process stability and product quality. Excessive vibration may lead to increased tool wear, poor surface finish, dimensional inaccuracies, reduced tool life, and even damage to machine tool components [7].

Taylor conducted the earliest investigations of machining vibrations and identified vibration as a major limitation to machining productivity [8]. Subsequently, researchers such as Arnold [9], Tobias and Fishwick [10], and Tlustý et al. [11] established the theoretical foundations of machining stability and regenerative chatter phenomena. Their work showed that variations in chip thickness and cutting forces can lead to self-excited vibrations that compromise machining quality. Like cutting forces, machining vibration can be resolved into three orthogonal directions: tangential vibration (V_t), radial vibration (V_r), and axial vibration (V_a). In the present study, V_t , V_r , and V_a denote measured acceleration components, expressed in m/s^2 . The reported effective vibration is defined from the tangential and radial acceleration components as the resultant acceleration magnitude (V_e), as given by Equation (2). Accordingly, Equation (2) represents acceleration rather than displacement or velocity.

$$V_e = \sqrt{V_t^2 + V_r^2} \quad (2)$$

In this study, we excluded the axial acceleration component from the reported vibration magnitude because the analysis focused on the tangential and radial directions. We calculated the effective vibration magnitude from these two acceleration components and then obtained the RMS value over the recorded time history. We use this RMS acceleration as a scalar process-monitoring indicator; it is not interpreted as vibration displacement. Because the original measurement workflow did not include frequency-domain processing, we did not derive frequency-specific displacement or chip-formation-frequency amplitudes. This distinction is important when interpreting the relationship between vibration and surface roughness. Numerous studies have investigated how machining parameters affect cutting force, vibration, and surface quality. The present work therefore treats vibration as one component of a combined monitoring framework rather than assuming a one-to-one relationship between vibration amplitude and cutting force or surface roughness.

Recent advances in tool condition monitoring have also enabled the integration of sensors and intelligent data-acquisition systems into machining environments. Modern monitoring systems employ force sensors, accelerometers, acoustic emission sensors, and machine-learning techniques to detect process abnormalities and improve manufacturing efficiency [12,13]. Low-cost MEMS accelerometers have attracted attention because they

can provide real-time vibration measurements at substantially lower implementation cost than conventional piezoelectric systems [14,15]. Previous studies have used accelerometer signals for process monitoring and for cutting-force or surface-quality assessment [16,17,18]. However, relatively few studies have examined cutting force, vibration, surface roughness, and geometric deviations together in a single C45 turning configuration. This motivates the present study. This work therefore does not claim that the relationships among these responses are new in themselves, but that it examines them together under the specific C45 dry-turning configuration, using simultaneous force and MEMS vibration monitoring alongside surface and form measurements.

- (a) Experimentally evaluate the effects of cutting speed, feed rate, and depth of cut on cutting force, vibration, surface roughness, and cylindricity during the turning of C45 steel.
- (b) Investigate the observed associations among cutting force, vibration, surface roughness, and cylindricity under the tested machining conditions using descriptive analysis and an exploratory correlation analysis.
- (c) Develop qualitative recommendations for favorable machining conditions that may improve machining performance, process stability, and product quality in the turning of C45 steel.

Based on these objectives, the study addresses the following hypotheses:

Alternatively, these hypotheses may be expressed as the following research questions:

Q1: *How do cutting speed, feed rate, and depth of cut influence cutting force, vibration, surface roughness, and cylindricity in turning C45 steel?*

Q2: *What relationships exist among cutting force, vibration, surface roughness, and cylindricity, and how can these relationships be utilized to improve machining performance and product quality, as reflected in the hypotheses?*

2. Materials and Methods

2.1. Workpiece Material

The material selected for this investigation was C45 steel (EN 1.0503), a medium-carbon, non-alloy structural steel widely used in mechanical engineering applications for its favorable combination of strength, toughness, wear resistance, and cost-effectiveness [19]. Therefore, the nominal chemical composition of C45 steel, as specified in EN 10083, used in this study is presented in Table 1.

Table 1. Chemical composition of C45 steel (1.0503) according to EN 10083-2 [20].

Element	C	Si	Mn	P max	S max	Cr max	Ni	Mo
Weight (%)	0.42–0.50	≤0.40	0.50–0.80	≤0.045	≤0.045	≤0.40	≤0.40	≤0.10

Experimental workpieces were manufactured from C45 steel shafts with an initial diameter of 60 mm and a total length of 240 mm. Each shaft was divided into five 40 mm long machining sections, separated by 5 mm wide grooves. A 35 mm reduced-diameter segment was machined at one end to ensure secure clamping in the machine chuck. Four identical shafts were produced, yielding twenty machining sections, of which eighteen were used in the experimental trials. Each section was assigned to a machining condition in the experimental program. The use of separate sections reduced overlap between successive cutting conditions; however, the exact axial position of each experimental section relative to the chuck was not treated as an experimental factor. Because workpiece stiffness and dynamic response can vary with the distance from the clamping point, this

positional effect remains a limitation of the present study. Figure 2 shows the geometry and dimensions of the workpiece.

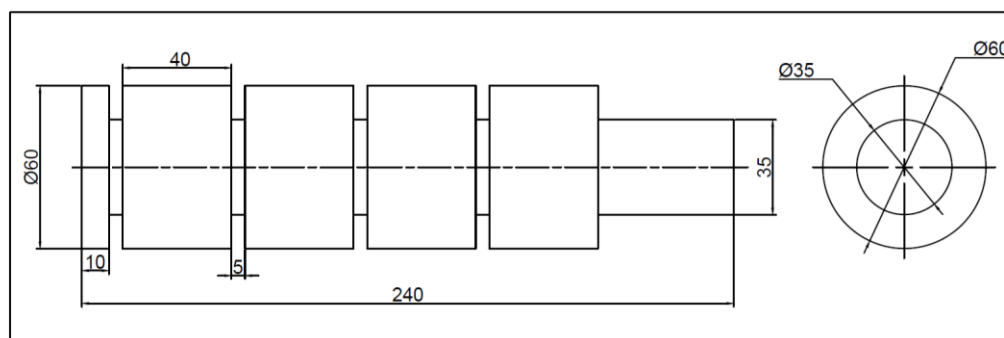


Figure 2. Drawing of workpiece specimen.

2.2. Machine Tool and Cutting Tool

The machining experiments were conducted on a conventional horizontal CNC lathe with a flat-bed design and a PNC FS1 control system. The available experimental records do not verify the spindle motor power, the machine's manufacturing year or age, or its static stiffness at the tool–workpiece interface; these specifications were therefore not assumed or estimated. Machine stiffness and dynamic compliance may affect the measured force, vibration, and form deviations, and their absence is a limitation of the study. Cutting forces were measured using a piezoelectric dynamometer installed between the tool holder and the turret and connected to charge amplifiers. An MPU6050 micro-electromechanical system (MEMS) accelerometer was mounted on the tool holder for vibration monitoring. The same cutting edge was reused throughout the nine experimental conditions, as recorded in the experimental notes. Tool wear was not quantitatively measured before or after each condition, so wear progression remains an uncontrolled source of possible variation. The insert nose radius was 1.6 mm. Under ideal kinematic turning conditions, the theoretical arithmetic mean roughness associated with feed marks can be approximated by $R_a \approx f^2/(32r_\epsilon)$, where f is feed per revolution, and r_ϵ is the nose radius. For $r_\epsilon = 1.6$ mm and feeds of 0.10, 0.20, and 0.30 mm/rev, the corresponding estimates are approximately 0.20, 0.78, and 1.76 μm . The measured R_a values (2.13–3.66 μm) were higher than these idealized estimates, indicating that feed geometry alone does not explain the measured finish. Vibration, cutting-edge condition, material variability, and process dynamics may contribute. A larger nose radius can reduce ideal feed-mark height, but it may also increase radial loading and sensitivity to tool/workpiece deflection, which can affect geometric accuracy.

The cutting-parameter levels were selected to provide a practical low-to-high exploratory window for the tested coated-carbide/C45 configuration: cutting speed $V_c = 150, 200$, and 250 m/min; feed $f = 0.10, 0.20$, and 0.30 mm/rev; and depth of cut $a_p = 0.5, 1.0$, and 1.5 mm. The levels span conditions expected to produce measurable differences in material-removal load, vibration, surface texture, and geometric accuracy while keeping the screening matrix to nine conditions. However, the available experimental records do not contain a manufacturer recommendation table confirming these exact levels, nor a separate preliminary-trial dataset demonstrating how they were selected. Accordingly, the values are described as a literature-informed exploratory range [21,22,23], not as a verified manufacturer-prescribed setting or an experimentally established optimum. Table 2 lists the cutting tool and insert specifications used in the experiments.

Table 2. Tool description of DSDNN 2020K 12 with insert SNMG 12 04 16-PR 4425.

Tool Holder Code	Insert Code	Shank Height (H)	Shank Width (B)	Holder Type	Insert Shape	Nose Radius	Clamping System	Cutting Edge Length
DSDNN 2020K 12	SNMG120416-PR 4425	20 mm	20 mm	Right-hand	Square (S)	1.6 mm	Double clamp	12 mm

2.3. Experimental Design

Figure 3 illustrates the experimental setup. All turning experiments were conducted on a CNC lathe equipped with a DSDNN 2020K 12 tool holder and Sandvik Coromant SNMG 120416-PR 4425-coated carbide inserts. The DSDNN 2020K 12 tool holder and SNMG 120416-PR 4425 coated carbide inserts were supplied by Sandvik Coromant (Sandviken, Sweden). The experimental design applied the specified machining conditions to segmented C45 steel shafts. A three-component piezoelectric dynamometer was installed between the tool holder and the machine turret to simultaneously acquire tangential, radial, and feed force components during turning. The resulting signals were amplified with three Kistler 5011A charge amplifiers and acquired via a National Instruments CompactDAQ-9171 data acquisition system. We monitored, visualized, and recorded force signals in real time using NI LabVIEW 2018 SP1 software.

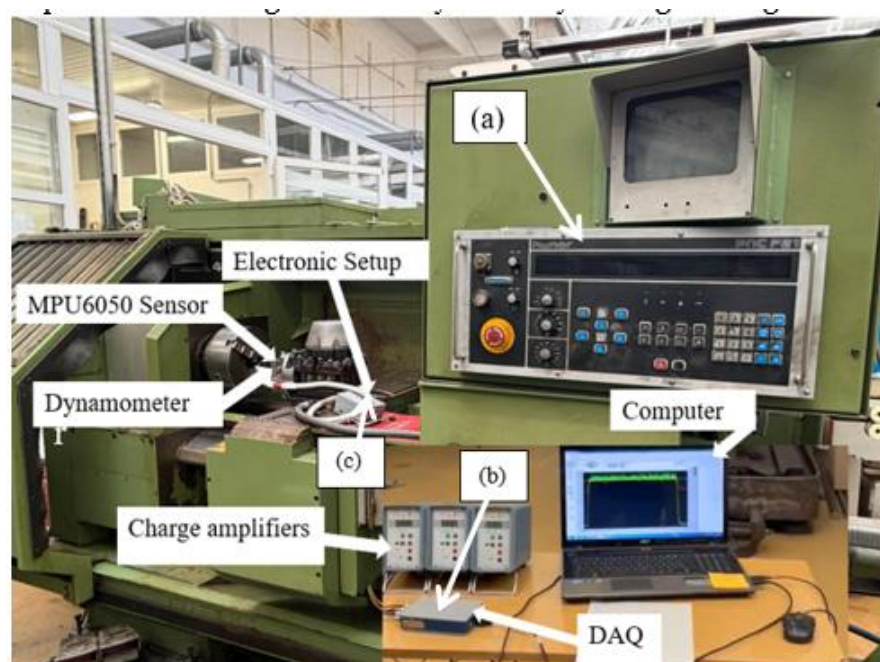


Figure 3. CNC turning lathe (a), cutting-force acquisition system (b), and electronic vibration-monitoring setup (c).

Machining vibrations were monitored using an MPU6050 MEMS accelerometer integrated into a custom-designed electronic measurement unit developed for this research. The sensor was mounted directly on the cutting tool holder to capture tool vibrations during machining. Vibration data were continuously recorded and stored for subsequent signal processing and analysis. The sensor configuration and nominal sensitivity were based on the MPU6050 manufacturer's specifications [24].

Figure 3 presents the principal components of the experimental setup: (a) the CNC turning lathe used for machining trials, (b) the cutting-force acquisition system consisting of Kistler charge amplifiers, an NI CompactDAQ-9171 module, and a computer-based monitoring interface, and (c) the force and vibration monitoring arrangement, which

includes the Kistler 9257A dynamometer, an MPU6050 accelerometer, and a custom electronic measurement unit mounted on the machine tool. This integrated setup enabled simultaneous monitoring of cutting forces and vibrations, facilitating the investigation of their relationships to surface roughness and cylindricity during turning of C45 steel.

2.4. Force and Vibration Measurement

Machining vibrations were monitored using an MPU6050 MEMS accelerometer integrated into a custom-designed, 3D-printed monitoring device developed for this study. The sensor was mounted directly on the cutting tool holder to capture vibrations generated during turning. The accelerometer was operated in the ± 2 g full-scale range, with a nominal sensitivity of 16,384 LSB/g and a sampling frequency of 1000 Hz. According to the manufacturer, the accelerometer has a specified nonlinearity of approximately 0.5% and an initial sensitivity calibration tolerance of $\pm 3\%$ for the ± 2 g range [24]. The manufacturer specifies a programmable accelerometer low-pass-filter range of 5–260 Hz and an output-data-rate range up to 1000 Hz; however, the original experimental acquisition did not document the actual internal filter setting used. The available manufacturer specification does not list an accelerometer mechanical-resonance frequency in the accelerometer specification table; therefore, we assume and report no resonance value here. The 1000 Hz sampling rate gives a Nyquist frequency of 500 Hz, so the dataset can represent only frequency content below 500 Hz and cannot support claims about higher-frequency vibration components. The sensor axes were aligned with the dynamometer coordinate system, where the X-, Y-, and Z-axes corresponded to the tangential, radial, and axial (feed) directions, respectively. We took the nominal sensor sensitivity and operating specifications from the manufacturer's documentation [24]. The available experimental documentation does not include an independent, traceable calibration certificate for the complete sensor-and-electronics assembly; therefore, the vibration values are treated as comparative process-monitoring measurements rather than fully traceable metrological quantities.

Although the sensor was mounted directly on the cutting tool holder, the original documentation does not record a reproducible coordinate or distance from the insert seat, clamping point, or tool-holder reference surfaces. The vibration measurement system consisted of an MPU6050 MEMS accelerometer connected to an ESP32 microcontroller and an SD card module for data storage, as illustrated in Figure 4. The MPU6050 sensor was rigidly mounted directly on the turning tool holder, close to the cutting insert, to maximize sensitivity to vibrations generated during cutting.

The sensor was mounted on the side surface of the tool holder, immediately below the cutting-insert position and adjacent to the tool tip. This describes the documented qualitative location; the exact distance from the insert seat, clamping point, or tool-holder reference surfaces was not recorded, so the mounting cannot be reproduced to a precise coordinate from the available records. The sensor axes were aligned with the machine-coordinate directions used in the analysis. The location was intended to capture local tool-holder acceleration, but measured acceleration is also influenced by the mounting interface and local structural dynamics.

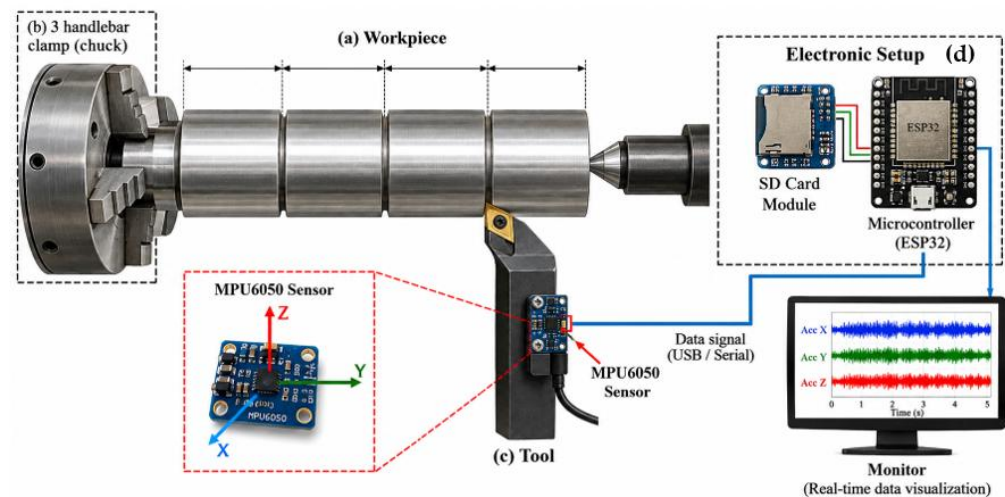


Figure 4. Turning test setup: (a) workpiece, (b) chuck, (c) tool holder with MPU6050 sensor, and (d) ESP32-based data acquisition system.

The MPU6050 was connected to an ESP32 microcontroller via an I²C interface, which performed real-time data acquisition and stored it on an SD card module. The electronic acquisition system was mounted externally to the machine tool and operated independently of the CNC controller. Figure 4 presents the complete experimental arrangement, including the workpiece, cutting tool, sensor position, electronic acquisition hardware, and monitoring interface.

Sensor Calibration and Measurement Verification

The MPU6050 accelerometer was checked before testing using static gravitational reference measurements along each sensor axis. The sensor response was evaluated under stationary conditions to verify the expected gravitational response, stable zero-level behavior, and correct axis response. The measurement chain was configured with the manufacturer-specified ± 2 g range and nominal sensitivity of 16,384 LSB/g [24]. The available experimental records do not include recorded offset values or a traceable calibration certificate for the complete sensor-and-electronics assembly. Accordingly, no experimentally determined calibration factor or uncertainty budget is reported. Acceleration data were converted from sensor output using the manufacturer's nominal sensitivity and were used for comparative process monitoring across the nine machining conditions. This distinction is important because the reported vibration values should not be interpreted as independently traceable metrological measurements.

For signal verification, the sensor axes were aligned with the intended tangential, radial, and axial directions during installation. Raw acceleration signals were converted from digital counts (LSB) (Least Significant Bit), the sensor's digital output, using the manufacturer's nominal sensitivity, which is expressed as $\text{LSB} \cdot \text{g}^{-1}$. Where appropriate, the corresponding SI acceleration unit, m/s^2 , has also been provided for clarity, converted from LSB using the manufacturer's nominal sensitivity. The DC component associated with gravity and sensor offset was removed before calculating the effective vibration magnitude. No additional digital filtering or frequency-domain transformation was applied or documented. Consequently, the present analysis is intentionally based on the time-domain RMS acceleration and does not claim to identify vibration frequencies, chip-formation frequencies, or frequency-specific displacement amplitudes. With a 1000 Hz sampling rate, the theoretical Nyquist limit is 500 Hz. A complete spectral assessment of all nine experiments would require the original time histories to be processed consistently

using a documented frequency-domain procedure; such an analysis was outside the scope of the original measurement workflow. The effective vibration magnitude was calculated from the tangential and radial acceleration components, and the reported result is the RMS value over the complete machining pass. The RMS calculation was performed according to Equation (3), where x_i is the instantaneous resultant vibration acceleration in m/s^2 , and N is the number of acquired samples.

$$RMS = \sqrt{\left[\left(\frac{1}{N}\right) \sum_{i=1}^N x_i^2\right]} \quad (3)$$

The experimental program used a Taguchi L9 orthogonal array to screen the combined influence of cutting speed (V_c), feed rate (f), and depth of cut (a_p) on cutting force, vibration, surface roughness, and cylindricity (Table 3) [25,26]. Each factor was tested at three levels: $V_c = 150, 200$, and 250 m/min; $f = 0.10, 0.20$, and 0.30 mm/rev; and $a_p = 0.5, 1.0$, and 1.5 mm. These levels were chosen as a literature-informed exploratory window for the specific coated-carbide/C45 configuration, spanning relatively low to high cutting conditions while limiting the initial screening to nine combinations. The records do not verify a specific manufacturer recommendation table or a separate preliminary-trial dataset for the exact values; therefore, the levels should not be presented as manufacturer-validated or optimized settings [21,22,23]. The L9 array reduced the number of required trials, but the nine conditions provide limited information about interactions and do not support strong statistical inference.

Table 3. L9 orthogonal experimental design and tested cutting conditions.

Experiment No.	Cutting Speed (V) (m/min)	Feed Rate (f) (mm/rev)	Depth of Cut (a_p) (mm)
1	150	0.10	0.5
2	150	0.20	1.0
3	150	0.30	1.5
4	200	0.10	1.0
5	200	0.20	1.5
6	200	0.30	0.5
7	250	0.10	1.5
8	250	0.20	0.5
9	250	0.30	1.0

The experiments were conducted under dry conditions. Dry turning was used as a controlled baseline in which the effects of the three machining parameters could be examined without the additional thermal and lubrication effects introduced by MQL or flood cooling. Dry machining is also industrially relevant for C45 because it can eliminate cutting-fluid purchase, circulation, maintenance, and disposal requirements when acceptable tool life and surface quality can be maintained. However, this study does not establish that dry cutting is superior to MQL or flood cooling; such a comparison requires matched experiments under the same tool and parameter conditions [19,25].

Interaction effects were not estimated as independent statistical terms. With only nine L9 runs and three three-level factors, the present design provides efficient main-effect screening but does not provide sufficient independent degrees of freedom to estimate all $V_c \times f$, $V_c \times a_p$, and $f \times a_p$ interactions without aliasing/confounding. Accordingly, the observed response changes should not be interpreted as pure main effects. This limitation is particularly relevant because previous C45 turning research using a factorial design has reported a significant interaction between cutting speed and feed rate for surface

roughness [22]. A future factorial or response-surface design with replicated runs is therefore required to quantify the interaction terms.

Figure 5 illustrates the experimental setup used to measure cutting forces and machining vibrations during the turning of C45 steel. The workpiece was clamped in a three-jaw chuck to ensure accurate centering and stable positioning throughout machining. Cutting forces were measured using a Kistler 9257A three-component piezoelectric dynamometer mounted between the cutting tool holder and the machine turret, enabling measurement of tangential, radial, and feed/axial force components. The force system was acquired through the Kistler charge amplifiers and NI CompactDAQ/LabVIEW chain, whereas the MPU6050 vibration system was recorded by a separate custom electronic unit. The available records document that both systems monitored the same machining passes, but they do not document a common hardware trigger, shared clock, or cross-system timestamp. Therefore, ‘simultaneous’ in this manuscript means acquisition during the same machining pass rather than verified sample-by-sample time synchronization. This distinction does not affect the present condition-level correlation analysis, which uses one RMS value per condition, but exact synchronization would be required for future phase-, time-, or frequency-domain force–vibration coupling analysis.

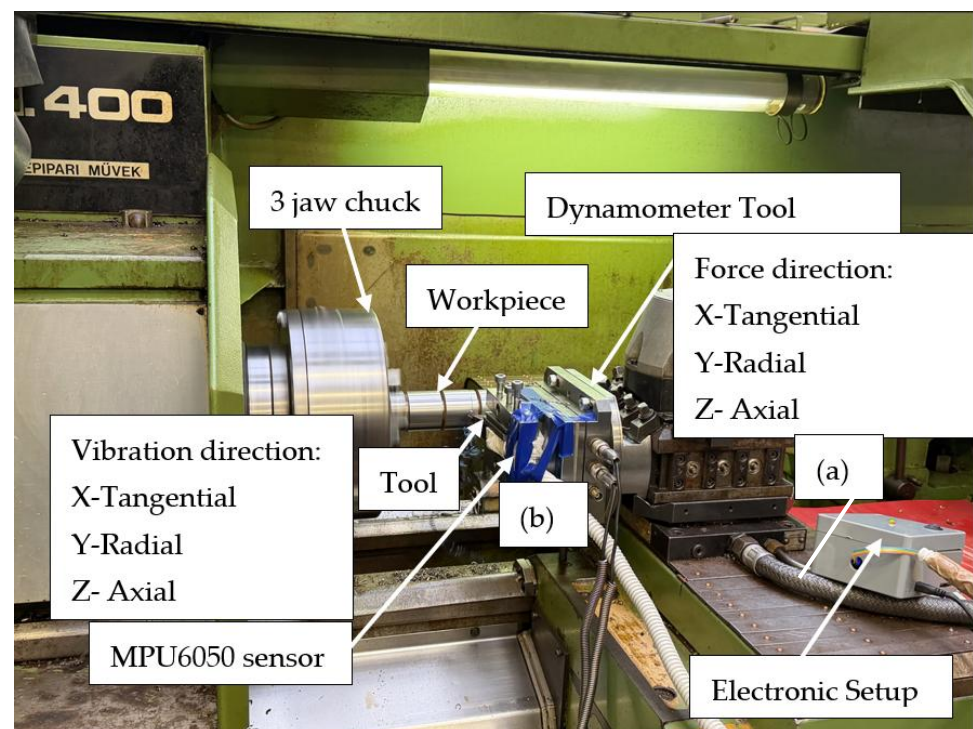


Figure 5. Simultaneous cutting-force and vibration measurement arrangement: (a) experimental setup; (b) sensor and dynamometer mounting.

2.5. Surface Roughness and Form Measurement

After the turning experiments, the surface quality of the machined C45 steel specimens was evaluated using an AltiSurf 520 surface measurement system, as illustrated in Figure 6. This system was equipped with a CL2 confocal chromatic sensor, a non-contact optical device capable of high-resolution three-dimensional surface characterization. The workpieces were positioned on the measuring stage, and surface profiles were acquired under controlled laboratory conditions to minimize environmental variation and ensure measurement consistency. For each experimental condition, surface roughness measurements were taken over a 10 mm sampling length. To reduce the influence of local surface variation, five measurements were taken from each machined section and averaged. These

five measurements are repeated measurements of the same machined surface, not independent machining repeats; they characterize within-section measurement variation only. The mean values were subsequently used for comparison among the experimental conditions and are reported in the results section. Surface profiles were recorded with a vertical measurement scale of 100 μm . The surface quality evaluation focused on R_a and R_z , established profile parameters for characterizing surface texture [27]. R_a represents the arithmetic mean height of the roughness profile, whereas R_z describes the maximum profile height parameter as defined by the applicable surface-texture standard [27].

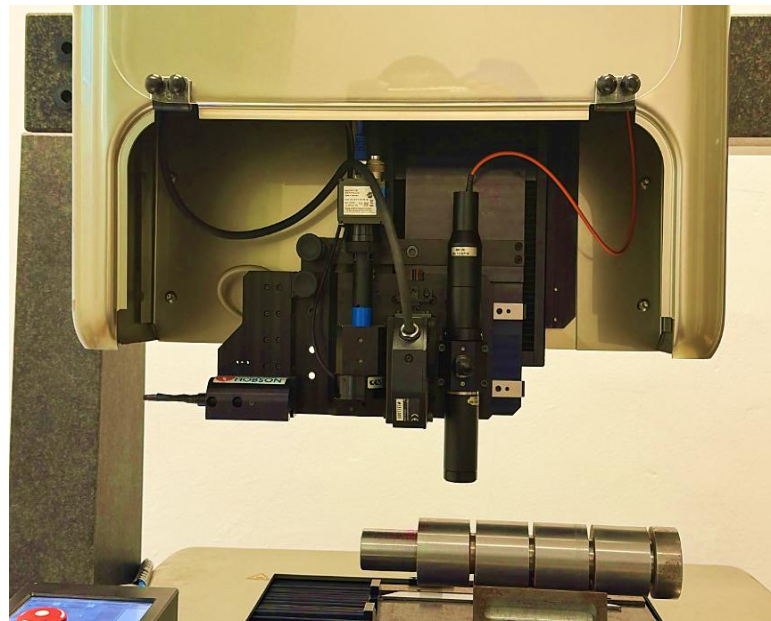


Figure 6. AltiSurf 520 surface measurement setup for roughness characterization.

2.6. Geometric Accuracy Measurement

After the turning experiments, the geometric accuracy of the machined workpieces was evaluated using a Taylor Hobson Talyrond 365 roundness and form measurement system, as illustrated in Figure 7. This instrument assessed the cylindricity and concentricity of the machined sections, delivering high-precision measurements of form deviations produced during turning. For each experimental condition, the workpiece was precisely mounted on the Talyrond 365 rotary table and aligned to ensure accurate measurement of the cylindrical surfaces. A high-resolution stylus probe scanned the surface as the workpiece rotated about its axis. The instrument's analysis software processed the resulting data to generate form profiles and quantify geometric deviations from the ideal cylindrical geometry. The geometric terminology and interpretation are consistent with the principles of geometrical product specification [20].

Cylindricity measurements assessed the overall deviation of the machined surface from a perfect cylinder, accounting for variations in roundness, straightness, and taper along the measured length. Concentricity measurements assessed the alignment of the machined sections with respect to the workpiece's reference axis. These parameters are essential indicators of dimensional and geometric accuracy, especially for components that require precise rotational motion and assembly fit. The Talyrond 365 system provided detailed profile information and reliable quantification of form errors, facilitating investigation of the effects of cutting parameters, cutting forces, and machining vibrations on the geometric quality of the turned C45 steel specimens. The experimental setup for cylindricity and concentricity measurements is shown in Figure 7.



Figure 7. Taylor Hobson Talyrond 365 setup for cylindricity and concentricity measurement.

2.7. Statistical and Correlation Analysis

Descriptive statistics were used to evaluate the responses under the nine L9 machining conditions. Each condition involved a single machining pass, so the nine condition-level observations were treated as individual experimental realizations rather than repeated machining samples. Mean surface roughness was calculated from five measurements on the same machined section; these repeated measurements characterize within-section measurement variation and do not constitute independent machining replicates. In addition to descriptive comparisons, an exploratory Pearson correlation analysis was performed across the nine condition-level observations for the principal responses (active force, vibration, R_a , R_z , and cylindricity). Two-sided p -values and Fisher-transformation 95% confidence intervals were calculated for selected correlations to quantify the uncertainty associated with $n = 9$. A smaller-is-better Taguchi S/N ratio was also calculated descriptively for each response to summarize condition-level variation; because each condition has only one machining realization, the S/N results are not used to estimate repeatability or establish statistically optimal factor levels. No inferential ANOVA or p -value-based factor significance analysis was performed because an independent estimate of experimental error was unavailable.

3. Results

The vibration, cutting forces, surface roughness, and cylindricity were measured in each experiment to understand the relationships among and behavior of the machining parameters.

3.1. Vibration Analysis

The vibration results in Table 4 are the RMS values calculated from the continuous acceleration signal recorded during a single machining pass for each experimental condition. Consequently, the reported values represent individual experimental realizations rather than means across repeated machining trials. Vibration magnitude was determined

from the resultant acceleration in the tangential and radial directions and expressed as RMS acceleration. Recorded vibration magnitudes ranged from 5.38 m/s² to 19.09 m/s². The highest vibration level occurred in Experiment 3 ($V_c = 150$ m/min, $f = 0.30$ mm/rev, $a_p = 1.5$ mm), with an RMS value of 19.09 m/s². The lowest vibration magnitude was observed in Experiment 9 ($V_c = 250$ m/min, $f = 0.30$ mm/rev, $a_p = 1.0$ mm), at 5.38 m/s². Because the acquisition rate was 1000 Hz, the corresponding Nyquist frequency was 500 Hz. The present study therefore uses RMS acceleration as a time-domain process indicator and does not interpret the results as a complete spectral characterization of the machining vibration.

Table 4. Experimental conditions and vibration RMS magnitude.

No.	Depth of Cut (a_p) mm	Cutting Speed (V_c) m/min	Feed Rate(f) mm/rev	Coolant	Time (s)	Vibration Magnitude (RMS) (m/s ²)
1	0.5	150	0.10	Dry	14.80	9.30
2	1.0	150	0.20	Dry	16.30	14.85
3	1.5	150	0.30	Dry	19.20	19.09
4	1.0	200	0.10	Dry	22.10	11.72
5	1.5	200	0.20	Dry	10.70	10.14
6	0.5	200	0.30	Dry	11.50	7.85
7	1.5	250	0.10	Dry	13.90	12.41
8	0.5	250	0.20	Dry	18.60	5.99
9	1.0	250	0.30	Dry	17.80	5.38

Only RMS acceleration was retained as the reported vibration descriptor. Peak acceleration, crest factor, FFT spectra, dominant frequencies, and frequency-band amplitudes were not calculated from the available dataset. Although the 1000 Hz acquisition rate gives a theoretical Nyquist limit of 500 Hz, the MPU6050 internal low-pass-filter setting used during the original acquisition was not documented. Consequently, no frequency-specific interpretation is added retrospectively. Future experiments should preserve the raw synchronized acceleration waveform and report peak/RMS values together with FFT or order-spectrum results.

3.2. Active Cutting-Force Analysis

Table 5 summarizes the active cutting-force results from the turning experiments, and Figure 8 presents the corresponding force signals. The active force (AF) was calculated from the measured components and reported as the RMS value. Recorded cutting-force values ranged from 257.07 N to 730.60 N. The highest cutting force occurred in Experiment 7 ($V_c = 250$ m/min, $f = 0.10$ mm/rev, $a_p = 1.5$ mm), reaching 730.60 N. The lowest cutting force was observed in Experiment 9 ($V_c = 250$ m/min, $f = 0.30$ mm/rev, $a_p = 1.0$ mm), at 257.07 N. At 150 m/min, cutting force increased from 300.79 N to 522.86 N across Experiments 1–3. At 200 m/min, force values ranged from 410.71 N to 590.85 N, whereas at 250 m/min they ranged from 257.07 N to 730.60 N. Thus, cutting force did not exhibit a consistent monotonic dependence on cutting speed alone. The stronger increase observed at the 1.5 mm depth-of-cut level is consistent with the larger material-removal load, but the individual condition results also show that feed rate and cutting speed jointly affect the measured force. Figure 8 presents the recorded active cutting-force signals for the nine experimental conditions. The signal acquisition duration varied with the machining time required for each cutting condition (10.7–22.1 s).

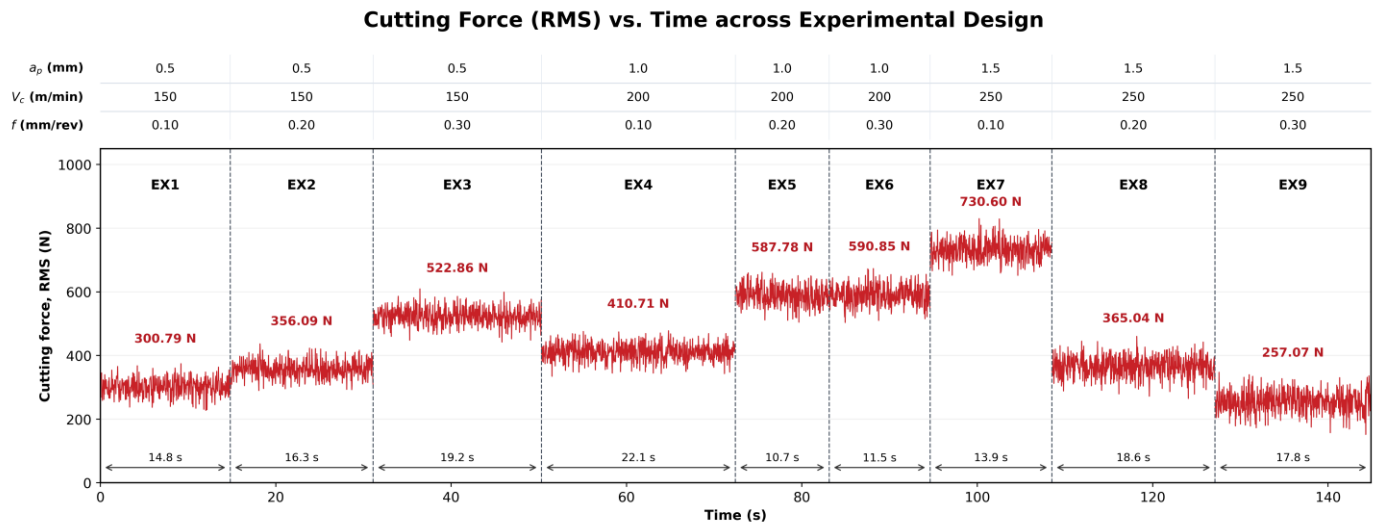


Figure 8. Recorded active cutting force as a function of time for the nine L9 machining conditions.

Table 5. Experimental conditions and active cutting force (AF RMS).

No.	Depth of Cut (a_p) mm	Cutting Speed (V_c) m/min	Feed Rate(f) mm/rev	Coolant	Time (s)	AF (RMS) (N)
1	0.5	150	0.10	Dry	14.80	300.79
2	1.0	150	0.20	Dry	16.30	356.09
3	1.5	150	0.30	Dry	19.20	522.86
4	1.0	200	0.10	Dry	22.10	410.71
5	1.5	200	0.20	Dry	10.70	587.78
6	0.5	200	0.30	Dry	11.50	590.85
7	1.5	250	0.10	Dry	13.90	730.60
8	0.5	250	0.20	Dry	18.60	365.04
9	1.0	250	0.30	Dry	17.80	257.07

3.3. Surface Roughness Analysis

Table 6 presents the surface roughness measurements from the turning experiments. Surface quality was assessed using R_a and R_z . The reported values are the means of five measurements taken at different locations on each machined section; these measurements characterize within-section measurement variation but do not represent repeated machining trials. The individual five readings were not retained in the dataset available for the present analysis, so a measurement-level standard deviation cannot be reconstructed without introducing unsupported values. The manuscript therefore reports the mean values transparently and identifies the absence of within-section standard deviations as a data-availability limitation.

Table 6. Mean surface roughness parameters (R_a and R_z) obtained from five surface measurements for each machining condition.

No.	Depth of Cut (a_p) mm	Cutting Speed (V_c) m/min	Feed Rate(f) mm/rev	Coolant	Time (s)	Mean R_a (μm)	Mean R_z (μm)
1	0.5	150	0.10	Dry	14.80	2.60	17.62
2	1.0	150	0.20	Dry	16.30	2.92	18.34
3	1.5	150	0.30	Dry	19.20	3.38	16.98
4	1.0	200	0.10	Dry	22.10	3.66	19.14
5	1.5	200	0.20	Dry	10.70	2.29	15.64

6	0.5	200	0.30	Dry	11.50	2.13	14.78
7	1.5	250	0.10	Dry	13.90	2.19	12.17
8	0.5	250	0.20	Dry	18.60	2.13	10.78
9	1.0	250	0.30	Dry	17.80	2.30	10.83

3.4. Geometric Accuracy Analysis

Geometric accuracy of the machined workpieces was evaluated using straightness deviation (STRt), roundness deviation (RONt), and cylindricity deviation (CYLt), as shown in Table 7. These parameters were used to assess the form accuracy of the turned C45 steel specimens. Measured cylindricity deviations ranged from 21.18 μm to 37.40 μm . The lowest CYLt occurred in Experiment 3 ($V_c = 150$ m/min, $f = 0.30$ mm/rev, $a_p = 1.5$ mm), with CYLt = 21.18 μm , while the highest occurred in Experiment 8 ($V_c = 250$ m/min, $f = 0.20$ mm/rev, $a_p = 0.5$ mm), at 37.40 μm . Straightness deviation ranged from 0.40 μm to 5.27 μm , and roundness deviation ranged from 2.56 μm to 9.21 μm . Across the three cutting-speed levels, cylindricity did not follow a single monotonic trend: the mean CYLt increased from 22.96 μm at 150 m/min to 25.15 μm at 200 m/min and 30.79 μm at 250 m/min. These results indicate that geometric accuracy is more sensitive to the combined machining condition and the machine-tool/workpiece system than to vibration or cutting force alone.

Table 7. Experimental conditions and measured form deviations: straightness (STRt), roundness (RONt), and cylindricity (CYLt).

No.	Depth of Cut (a_p) mm	Cutting Speed (V_c) m/min	Feed Rate(f) mm/rev	Coolant	Time (s)	STRt (μm)	RONt (μm)	CYLt (μm)
1	0.5	150	0.10	Dry	14.80	3.16	5.36	25.79
2	1.0	150	0.20	Dry	16.30	0.61	3.07	21.92
3	1.5	150	0.30	Dry	19.20	0.40	3.02	21.18
4	1.0	200	0.10	Dry	22.10	1.68	4.96	27.55
5	1.5	200	0.20	Dry	10.70	5.27	5.94	22.26
6	0.5	200	0.30	Dry	11.50	0.48	3.02	25.65
7	1.5	250	0.10	Dry	13.90	0.66	2.56	21.35
8	0.5	250	0.20	Dry	18.60	1.50	9.21	37.40
9	1.0	250	0.30	Dry	17.80	2.32	7.02	33.63

The material removal rate (MRR) was calculated as $\text{MRR} = 1000 V_c f a_p$, where V_c is in m/min, f is in mm/rev, and a_p is in mm. The undeformed chip cross-sectional area was approximated as $f \times a_p$. Because AF is a resultant RMS force rather than the tangential cutting-force component F_c , the ratio $\text{AF}/(f \times a_p)$ is reported only as a force-to-chip-area screening ratio; it must not be interpreted as a standard specific cutting-force coefficient. MRR ranged from 7500 mm^3/min in Experiment 1 to 75,000 mm^3/min in Experiment 9 (Table 8). $a_p \cdot f \text{AF}/a_p \cdot f$

$$\text{MRR} = 1000 \cdot V_c \cdot f \cdot a_p \quad (4)$$

Table 8. Calculated material removal rate (MRR), undeformed chip area, and force-to-chip-area ratio for each machining condition.

Exp.	V _c (m/min)	f (mm/rev)	a _p (mm)	MRR (mm ³ /min)	a _p · f (mm ²)	AF/a _p · f (N/mm ²)
1	150	0.10	0.5	7500	0.050	6015.8
2	150	0.20	1.0	30,000	0.200	1780.4
3	150	0.30	1.5	67,500	0.450	1161.9
4	200	0.10	1.0	20,000	0.100	4107.1
5	200	0.20	1.5	60,000	0.300	1959.3
6	200	0.30	0.5	30,000	0.150	3939.0
7	250	0.10	1.5	37,500	0.150	4870.7
8	250	0.20	0.5	25,000	0.100	3650.4
9	250	0.30	1.0	75,000	0.300	856.9

Table 9 presents the mean response values at each cutting parameter level across the nine Taguchi L9 machining conditions, highlighting the effects of cutting speed (V_c), feed rate (f), and depth of cut (a_p) on vibration, cutting force, surface roughness, and geometric accuracy.

Table 9. Mean response values at each factor level across the nine L9 machining conditions.

Factor	Level	Vibration (m/s ²)	AF RMS (N)	Ra (μm)	Rz (μm)	STRt (μm)	RONt (μm)	CYLt (μm)
V _c	150	14.41	393.25	2.97	17.65	1.39	3.82	22.96
V _c	200	9.90	529.78	2.69	16.52	2.48	4.64	25.15
V _c	250	7.93	450.90	2.21	11.26	1.49	6.26	30.79
f	0.1	11.14	480.70	2.82	16.31	1.83	4.29	24.90
f	0.2	10.33	436.30	2.45	14.92	2.46	6.07	27.19
f	0.3	10.77	456.93	2.60	14.20	1.07	4.35	26.82
a _p	0.5	7.71	418.89	2.29	14.39	1.71	5.86	29.61
a _p	1	10.65	341.29	2.96	16.10	1.54	5.02	27.70
a _p	1.5	13.88	613.75	2.62	14.93	2.11	3.84	21.60

3.5. Exploratory Correlation Analysis

Pearson correlation analysis was performed using the nine condition-level observations. For variables X and Y, Pearson's linear correlation coefficient is calculated using Equation (5):

$$r = \frac{\sum_{i=1}^n [(X_i - \bar{X})(Y_i - \bar{Y})]}{n} \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2 \cdot \sum_{i=1}^n (Y_i - \bar{Y})^2}{n}} \quad (5)$$

Here, $\bar{X} = (1/n)\sum X_i$ and $\bar{Y} = (1/n)\sum Y_i$ are the arithmetic means of the observed values of X and Y, respectively; X_i and Y_i denote the i-th paired observations, and n = 9 is the number of paired machining-condition observations. The numerator measures joint deviations from the arithmetic means, and the denominator normalizes these deviations by the corresponding sums of squared deviations.

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Values near +1 or −1 indicate strong positive or negative linear associations, respectively, whereas values near zero indicate weak linear associations. For example, the Pearson correlation coefficient between active cutting force and vibration, based on nine paired observations, was r = 0.329. Because only nine machining conditions were evaluated and no independent machining repetitions were performed, the correlation coefficients should

be treated as exploratory. Therefore, they should not be interpreted as evidence of causal relationships or as support for statistically validated predictive models. The correlation results are presented in Table 10.

Table 10. Pearson correlation matrix for measured machining responses ($n = 9$).

Variable	AF	Vibration	Ra	Rz	STRt	RONt	CYLt
AF	1.000	0.329	−0.197	−0.076	−0.143	−0.561	−0.595
Vibration	0.329	1.000	0.678	0.610	−0.360	−0.699	−0.769
Ra	−0.197	0.678	1.000	0.766	−0.217	−0.304	−0.299
Rz	−0.076	0.610	0.766	1.000	0.028	−0.481	−0.586
STRt	−0.143	−0.360	−0.217	0.028	1.000	0.485	0.061
RONt	−0.561	−0.699	−0.304	−0.481	0.485	1.000	0.865
CYLt	−0.595	−0.769	−0.299	−0.586	0.061	0.865	1.000

The strongest absolute correlation is between RONt and CYLt ($r = 0.865$), indicating that these two geometric-error measures tend to vary together across the tested conditions. Vibration also shows a comparatively strong association with Ra ($r = 0.678$). Some correlations are weak because force, vibration, surface roughness, and geometric accuracy respond to different mechanisms. Cutting force is strongly affected by chip cross-sectional area and cutting conditions, whereas vibration additionally depends on structural dynamics and tool–workpiece interaction. Ra and Rz depend on profile geometry and cutting dynamics, whereas STRt, RONt, and CYLt also reflect workpiece stiffness, machine-tool alignment, and geometric behavior. The L9 design also changes several factors simultaneously, so a simple pairwise coefficient can be weak even when a response is physically influenced by a parameter.

Table 11 presents the selected Pearson correlation coefficients, two-sided p -values, and 95% confidence intervals for the nine experimental conditions. The strongest positive correlation was observed between RONt and CYLt ($r = 0.865$, $p = 0.003$), followed by Ra and Rz ($r = 0.766$, $p = 0.016$), while vibration and CYLt exhibited a strong negative correlation ($r = -0.769$, $p = 0.015$).

Table 11. Selected Pearson correlations with two-sided p -values and 95% confidence intervals ($n = 9$).

Relationship	r	p -Value	95% CI for r	Interpretation
AF–vibration	0.329	0.387	[−0.429, 0.815]	Not nominally significant (unadjusted)
Vibration–Ra	0.678	0.045	[0.025, 0.925]	Nominally significant (unadjusted $p < 0.05$)
Vibration–Rz	0.610	0.081	[−0.091, 0.907]	Not nominally significant (unadjusted)
Vibration–CYLt	−0.769	0.015	[−0.949, −0.215]	Nominally significant (unadjusted $p < 0.05$)
RONt–CYLt	0.865	0.003	[0.474, 0.971]	Nominally significant (unadjusted $p < 0.01$)
Ra–Rz	0.766	0.016	[0.206, 0.948]	Nominally significant (unadjusted $p < 0.05$)

Figure 9 presents the Pearson correlation matrix of the measured machining responses during C45 steel turning. The strongest positive correlation was observed between RONt and CYLt ($r = 0.87$), followed by Ra and Rz ($r = 0.77$), while vibration and CYLt exhibited the strongest negative correlation ($r = -0.77$).

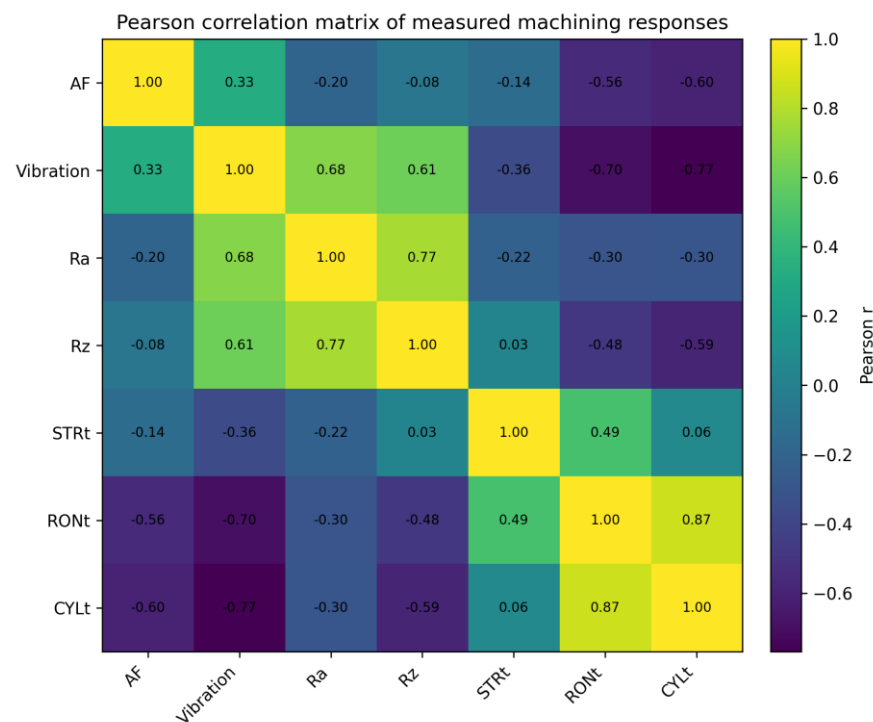


Figure 9. Pearson correlation matrix for active cutting force, vibration, surface roughness, and geometric accuracy parameters during turning of C45 steel.

Table 12 presents the exploratory linear regression results for selected machining response relationships across the nine experimental conditions. The strongest relationship was observed between CYLt and RONt ($R^2 = 0.749$), followed by Ra and vibration ($R^2 = 0.460$), Rz and vibration ($R^2 = 0.372$), and vibration and cutting force ($R^2 = 0.108$).

Table 12. Exploratory linear regression summaries for selected response relationships ($n = 9$).

Relationship	Linear Regression Equation	Pearson r	R^2
Ra vs. Vibration	$Ra = 1.666 + 0.089Vibration$	0.678	0.460
Rz vs. Vibration	$Rz = 10.316 + 0.449Vibration$	0.610	0.372
Vibration vs. AF	$Vibration = 6.579 + 0.009AF$	0.329	0.108
CYLt vs. RONt	$CYLt = 15.400 + 2.222RONt$	0.865	0.749

The 95% confidence intervals show the uncertainty caused by the small condition-level sample. For example, the force–vibration correlation was $r = 0.329$ ($p = 0.387$; 95% CI -0.429 to 0.815), so the data do not support a reliable linear association for this pair. The vibration–Ra correlation was $r = 0.678$ ($p = 0.045$; 95% CI 0.025 to 0.925), while vibration–Rz was $r = 0.610$ ($p = 0.081$; 95% CI -0.091 to 0.907). The vibration–CYLt and RONt–CYLt correlations were stronger, but their intervals remain wide. These p -values and intervals are descriptive inferential summaries of the nine tested conditions; they should not be treated as evidence of general population-level or causal effects, especially because no independent machining repetitions were performed. The p -values are nominal and unadjusted for the multiple pairwise correlations examined; consequently, the $p = 0.045$ result should be interpreted cautiously and requires confirmation in a larger, independently replicated study.

$$Rz = 3.885 + 4.293Ra; R^2 = 0.586 \quad (6)$$

$$s_e = \left[\frac{\sum (Rz_i - \hat{Rz}_i)^2}{n - 2} \right]^{1/2} = 2.209 \mu\text{m} \quad (7)$$

Equation (6) gives the fitted linear regression relationship between Ra and Rz, whereas Equation (7) defines the residual standard deviation; these equations describe different quantities and are not duplicates. The coefficient of determination, $R^2 = 1 - \sum_i (y_i - \hat{y}_i)^2 / \sum_i (y_i - \bar{y})^2$, measures the fraction of the observed variation in the dependent variable Rz accounted for by the fitted linear regression on Ra (for an intercept-containing ordinary least-squares model). It does not quantify predictive accuracy on independent data or establish causation. The residual standard deviation (standard error of regression) is $s = \sqrt{[\sum_i (y_i - \hat{y}_i)^2 / (n - 2)]}$ for a fitted straight line with intercept and slope, where y_i is the observed Rz, $\hat{y}_i$ is its fitted value, and $n = 9$. This quantity, expressed in μm for Rz, describes the typical deviation of experimental points from the regression line. It is distinct from R^2 and should be interpreted descriptively given the small unreplicated dataset.

Figure 10 illustrates the relationship between the surface roughness parameters Ra and Rz, showing a positive linear correlation ($r = 0.766$, $R^2 = 0.586$). The results indicate that Rz generally increases with increasing Ra across the nine experimental conditions.

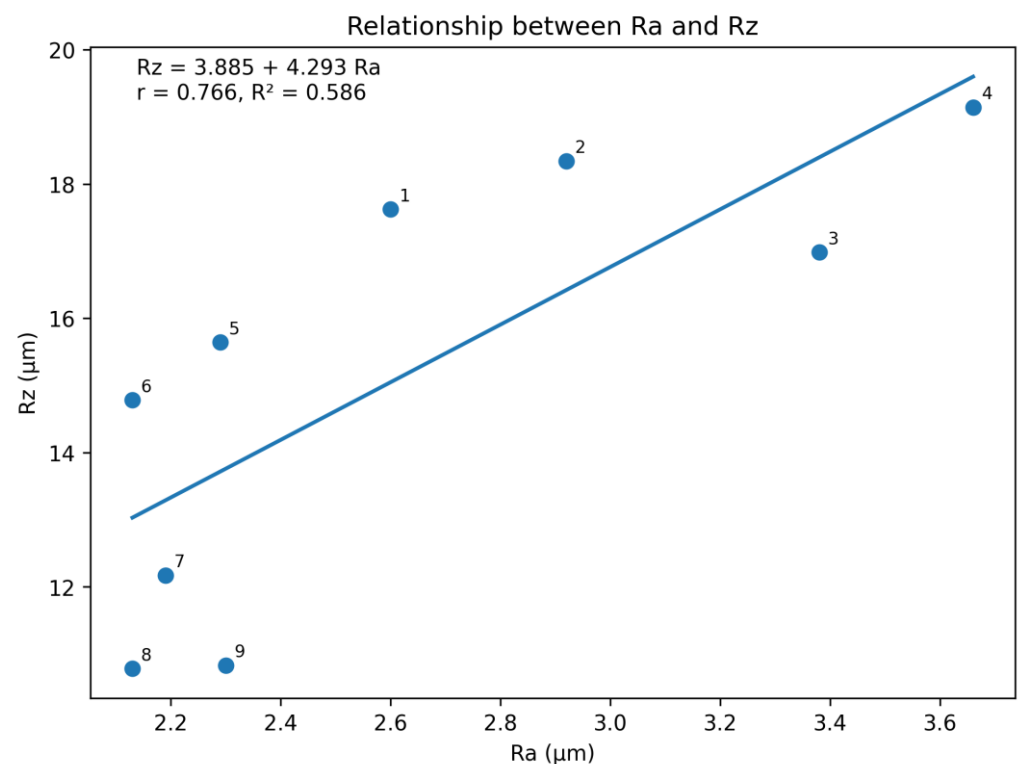


Figure 10. Relationship between Ra and Rz with a linear regression trendline. Numbers 1–9 represent the nine experimental conditions (EX1–EX9) of the Taguchi L9 orthogonal design.

4. Additional Analysis

4.1. Relationship Between Ra and Rz

Ra is the arithmetic mean of the absolute profile deviations, whereas Rz is a peak-to-valley-type height parameter and is more sensitive to pronounced individual peaks and valleys. In the present dataset, Ra and Rz show a positive linear association ($r = 0.766$, $R^2 = 0.586$), as quantified by the relationship fitted in Equation (6).

The relationship is not perfect because isolated high peaks or deep valleys can change Rz more strongly than they change the average absolute deviation.

4.2. Taguchi S/N Ratio Analysis

Table 13 shows the S/N ratios for all experiments, calculated using Equation (8).

$$Ra = 2.60 \text{ } \mu\text{m, so}$$

$$\frac{S}{N} = -20 \log_{10}(2.60) = -8.30 \text{ dB} \quad (8)$$

Table 13. Condition-level Taguchi S/N ratios using the smaller-is-better criterion (dB).

Exp	AF	Vibration	Ra	Rz	STRt	RONt	CYLt
1	−49.57	−19.37	−8.30	−24.92	−9.99	−14.58	−28.23
2	−51.03	−23.43	−9.31	−25.27	4.29	−9.74	−26.82
3	−54.37	−25.62	−10.58	−24.60	7.96	−9.60	−26.52
4	−52.27	−21.38	−11.27	−25.64	−4.51	−13.91	−28.80
5	−55.38	−20.12	−7.20	−23.88	−14.44	−15.48	−26.95
6	−55.43	−17.90	−6.57	−23.39	6.38	−9.60	−28.18
7	−57.27	−21.88	−6.81	−21.71	3.61	−8.16	−26.59
8	−51.25	−15.55	−6.57	−20.65	−3.52	−19.29	−31.46
9	−48.20	−14.62	−7.23	−20.69	−7.31	−16.93	−30.53

Table 14 presents the mean signal-to-noise (S/N) ratios at each cutting parameter level using the smaller-is-better criterion. The results show how cutting speed (V_c), feed rate (f), and depth of cut (a_p) affect cutting force, vibration, surface roughness, and geometric accuracy. The S/N ratios are interpreted descriptively because each machining condition has only one result, preventing the assessment of within-condition repeatability.

Table 14. Mean S/N ratios by factor level for the smaller-is-better criterion.

Factor	Level	AF	Vibration	Ra	Rz	STRt	RONt	CYLt
V_c	150	−51.65	−22.81	−9.40	−24.93	0.75	−11.31	−27.19
V_c	200	−54.36	−19.80	−8.34	−24.31	−4.19	−13.00	−27.98
V_c	250	−52.24	−17.35	−6.87	−21.02	−2.41	−14.79	−29.53
f	0.1	−53.04	−20.87	−8.79	−24.09	−3.63	−12.22	−27.87
f	0.2	−52.55	−19.70	−7.69	−23.27	−4.55	−14.83	−28.41
f	0.3	−52.67	−19.38	−8.13	−22.89	2.34	−12.04	−28.41
a_p	0.5	−52.08	−17.61	−7.14	−22.99	−2.38	−14.49	−29.29
a_p	1	−50.50	−19.81	−9.27	−23.87	−2.51	−13.53	−28.72
a_p	1.5	−55.68	−22.54	−8.19	−23.40	−0.96	−11.08	−26.69

5. Discussion

The results indicate that machining responses depend on the combined settings of cutting speed, feed rate, and depth of cut rather than on any single parameter. The clearest effect in the present dataset is the reduction in vibration with increasing cutting speed: the mean vibration decreased from 14.41 m/s² at 150 m/min to 7.93 m/s² at 250 m/min. This tendency is consistent with recent C45 turning studies reporting that cutting speed can influence process stability and surface quality [21,22]. The depth-of-cut response was also more pronounced: mean vibration increased from 7.71 m/s² at a_p = 0.5 mm to 13.88 m/s² at a_p = 1.5 mm, while mean active force increased from 418.89 N to 613.75 N. This is physically plausible because a larger depth of cut increases the material-removal cross-section and therefore the mechanical load on the tool–workpiece system. Previous C45 investigations likewise identify cutting parameters, particularly feed and depth of cut, as important contributors to cutting load and chip deformation [5,23]. However, the present L9 results

do not show a monotonic feed-rate effect on force or vibration, so a stronger statement would require repeated experiments and formal factor-effect analysis.

The exploratory correlation analysis also highlights the complex relationship between cutting force and vibration. Across the nine conditions, the Pearson correlation between active force and vibration was $r = 0.329$. This indicates only a weak-to-moderate positive linear association within the tested conditions and does not imply that higher vibration necessarily produces higher cutting force. In machining, force and vibration are coupled through the dynamic tool–workpiece–machine system, while structural stiffness, damping, excitation frequency, workpiece geometry, and cutting conditions can modify that relationship. The present data therefore support combined force and vibration monitoring as a descriptive approach, but they do not support a one-to-one force-to-vibration model.

Surface roughness showed a moderate positive Pearson correlation with vibration for both R_a ($r = 0.678$) and R_z ($r = 0.610$). Thus, within the nine tested conditions, higher vibration tended to occur with higher roughness. This observation is consistent with the general machining mechanism in which dynamic motion can be transferred to the generated surface and contribute to surface texture. It is also compatible with previous C45 turning studies reporting that cutting parameters influence R_a and R_z and that suitable cutting speeds can improve surface quality [21,22,28,29]. Nevertheless, the present data cannot establish vibration as the cause of the roughness differences. Built-up edge formation, tool wear, thermal effects, chip formation, and tool geometry may also contribute to surface generation [30], but none of these phenomena was directly measured in this study. They should therefore be described as possible contributing mechanisms rather than demonstrated explanations.

The measured R_a range of 2.13–3.66 μm is within the broad range reported for C45/1045-class steels but is higher than the 0.192–1.207 μm range reported by Milošević et al. for dry C45 turning in a different experimental window and with different insert geometries [31]. Their study used approximately 300–400 m/min, feeds of 0.10–0.25 mm/rev, depths of cut of 2–3 mm, and both standard and wiper inserts, so the numerical ranges are not directly equivalent. A recent C45 Taguchi study combining dry and MQL conditions reported R_a values of 1.12–1.95 μm and found feed rate to be an important factor [25]. The present higher R_a values are therefore plausibly related to the specific tool geometry, dry condition, vibration level, and tested parameter combinations rather than indicating an intrinsically poorer C45 machinability.

Geometric accuracy behaved differently from surface roughness. The Pearson correlation between vibration and cylindricity deviation was negative ($r = -0.769$), whereas the correlation between active force and cylindricity was also negative but weaker ($r = -0.595$). These signs do not support the simple assumption that greater vibration or greater force must always produce larger cylindricity error. Cylindricity is a system-level response that can reflect radial force, tool-holder compliance, workpiece deflection, chuck/support conditions, alignment, section position along the shaft, thermal deformation, and the interaction between static deflection and dynamic motion. These mechanisms are plausible explanations, not measured causal contributions in the present experiment. In the present experiments, the mean CYLt increased from 22.96 μm at 150 m/min to 30.79 μm at 250 m/min even though mean RMS vibration decreased from 14.41 to 7.93 m/s². This divergence indicates that vibration amplitude alone is insufficient to explain form error. The 1.6 mm nose radius can also increase radial contact/loading and therefore make geometric accuracy sensitive to compliance. Because machine stiffness, workpiece deflection, thermal state, and exact section position were not measured as independent variables, these mechanisms remain plausible interpretations rather than experimentally isolated causes. Previous experimental investigations have also examined the influence of cutting

parameters on geometric tolerances in machining [32]; however, the present condition-level associations should not be interpreted as evidence of causality.

A complementary C45 turning investigation by Le et al. [33] combined experiments and computational modeling to examine cutting-parameter effects on chip formation and temperature near the cutting tool. Their study emphasizes the influence of depth of cut on chip morphology and the importance of thermal phenomena. In contrast, the present work measured force, RMS vibration acceleration, surface roughness, and geometric deviations without measuring temperature or chip morphology. Accordingly, the studies provide complementary, rather than directly equivalent, evidence on C45 machining behavior.

Comparison with the six relevant studies helps contextualize the present results. Şap et al. [28] evaluated CK45 machining with nanofluid-assisted minimum-quantity lubrication, whereas the present experiments were performed under dry cutting; their findings therefore provide a useful contrast in lubrication strategy rather than a direct like-for-like benchmark. Duong [29] investigated cutting-parameter selection for reducing roughness in C45 turning, and Tran [30] developed an adaptive neuro-fuzzy approach to predicting roughness in CNC-turned C45 steel. In contrast, the present nine-condition study reports observed roughness and exploratory correlations without claiming validated optimization or prediction. Desai et al. [32] studied built-up-layer formation in a different high-strength free-cutting steel; that mechanism is relevant as a possible explanation of surface formation, but built-up layers were not measured here. Milošević et al. [31] considered dimensional deviation, flank wear, roughness, and material removal rate during dry C45 turning, providing the closest multi-response comparison while using a different experimental window. Finally, Akyl and Bican [34] examined the effects of cutting parameters on geometric tolerances; their work supports including form accuracy among machining responses, but does not establish the cause of the correlations observed in the present dataset.

Taken together, the results support an integrated monitoring perspective based on cutting force, vibration, surface roughness, and geometric accuracy. The contribution of the present study is the combined examination of these responses in the specific C45 dry-turning configuration rather than a claim that their relationships are novel in isolation. The L9 design provides a practical screening framework for the tested parameter combinations, while the descriptive and exploratory analyses identify promising patterns for future work. The L9 design is used only as an experimental design and does not provide a statistically validated optimum; the recommended conditions should therefore be regarded as favorable or promising within the tested parameter window.

The Ra–Rz regression has $R^2 = 0.586$ and a residual standard deviation of $2.209\ \mu\text{m}$. The selected linear regressions provide an additional quantitative description of these associations. For vibration versus Ra, $r = 0.678$ and $R^2 = 0.460$; thus, approximately 46% of the observed condition-level variation in Ra is represented by the linear relationship with vibration. For vibration versus Rz, $R^2 = 0.372$; for vibration versus AF, $R^2 = 0.108$; and for CYLt versus RONt, $R^2 = 0.749$. These equations are exploratory fits to the nine tested conditions, not validated predictive models. No train/test split, cross-validation, independent confirmation experiment, or external validation dataset was available. Their coefficients should therefore be used to describe the present dataset rather than to predict untested machining conditions.

Thermal effects were not measured in the present dry-turning experiments. The discussion of temperature is therefore mechanistic rather than measurement-based. Future experiments should add tool–workpiece temperature measurements, infrared thermography, or another traceable thermal method so that thermal effects can be separated from mechanical and dynamic contributions to roughness and geometric error.

Although the dynamometer measured tangential, radial, and feed/axial force components, the present manuscript reports only the resultant active-force RMS value (AF). The individual F_c , F_r , and F_f component histories were not retained in the dataset used for this analysis. Consequently, directional cutting-mechanics interpretations cannot be made from the present results. Future work should report the three components separately and relate them to chip area, tool geometry, and vibration direction.

5.1. Achievement of Objectives

Objective (a)

To experimentally evaluate the effects of cutting speed, feed rate, and depth of cut on cutting force, vibration, surface roughness, and cylindricity during the turning of C45 steel.

Achieved descriptively. The nine L9 conditions produced distinct responses. Higher cutting speed was associated with lower vibration and lower roughness, while the largest depth of cut was associated with the highest mean active force and vibration. Cutting force did not show a consistent monotonic dependence on cutting speed, and feed rate did not show a monotonic effect across the nine observations. These results therefore support descriptive evaluation of the tested parameter combinations rather than a statistical ranking of factor significance.

Objective (b)

To investigate the observed associations among cutting force, vibration, surface roughness, and cylindricity under varying cutting conditions.

Achieved through exploratory analysis. Pearson correlations were calculated for the nine condition-level observations. The results showed a weak-to-moderate association between active force and vibration, moderate positive associations between vibration and surface roughness, and an inverse association between vibration and cylindricity deviation. Because $n = 9$ and there were no independent machining repeats, these associations are exploratory and not predictive or causal.

Objective (c)

To develop screening recommendations for improving machining performance, process stability, and product quality in the turning of C45 steel.

Achieved as a condition-level screening exercise. The equal-weight exploratory MPI ranked Experiment 9 first (MPI = 0.220), while Experiment 3 gave the lowest cylindricity deviation (21.18 μm) and Experiments 6 and 8 gave the lowest R_a (2.13 μm). Because these choices involve trade-offs among force, vibration, surface finish, form accuracy, and MRR, they should not be interpreted as statistically validated optima.

5.2. Verification of Hypotheses

H1. *Cutting speed, feed rate, and depth of cut produce observable differences in cutting force, vibration, surface roughness, and cylindricity during the turning of C45 steel.*

Descriptively supported. The nine experimental conditions produced different response levels, and clear trends were observed for some responses, particularly the decrease in vibration with cutting speed and the increase in force and vibration at the largest depth of cut. However, the small number of conditions and absence of independent machining repeats prevent statistical claims about factor significance or general effects.

H2. *Observable associations exist among cutting force, vibration, surface roughness, and cylindricity in the tested turning conditions, such that their combined consideration may provide useful information for assessing machining performance and quality.*

Partially supported. The exploratory correlations indicate associations among several responses, particularly vibration with Ra, Rz, and cylindricity. However, the active-force/vibration association was only $r = 0.329$, and the direction of the vibration–cylindricity association was opposite to the simple expectation that higher vibration should produce larger cylindricity error. H2 is therefore supported only as an exploratory observation of response associations, not as evidence of a general or causal relationship.

5.3. Answer to the Research Question

The findings show that cutting speed, feed rate, and depth of cut jointly influence the measured machining responses, but their effects are not uniform across all outputs. Higher cutting speed was associated with lower vibration and lower roughness in the tested conditions, while the largest depth of cut was associated with the highest mean force and vibration. The feed-rate response was not monotonic across the nine conditions. The exploratory correlations indicate that vibration and surface roughness tended to increase together, whereas geometric accuracy followed a different pattern. These results support considering cutting force, vibration, surface roughness, and geometric accuracy together when screening machining conditions for C45 steel, while recognizing that the present evidence is limited to the tested parameter combinations.

5.4. Exploratory Machining Performance Index

To provide a practical multi-response screening metric, an exploratory machining performance index (MPI) was calculated from the four responses AF, RMS vibration, Ra, and CYLt, as shown in Equation (10). Each response was normalized using the lower-the-better transformation, as shown in Equation (9), and equal weights were assigned. Lower MPI values indicate a more balanced response across the nine tested conditions. This index is not a standardized industrial metric, and the equal weights are not experimentally validated; it is presented only as a transparent way to compare the tested conditions simultaneously.

$$x^* = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \quad (9)$$

$$MPI = \frac{AF + \text{Vibration} + Ra + CYLt}{4} \quad (10)$$

Table 15 presents the exploratory equal-weight machining performance index (MPI) for the nine experimental conditions, considering cutting force, vibration, and other machining responses. Experiment 9 exhibited the lowest MPI (0.220), indicating the most favorable overall performance among the tested conditions, while Experiment 3 showed the highest MPI (0.595), indicating the least favorable performance under the selected weighting criteria.

Table 15. Exploratory equal-weight machining performance index (MPI) for the tested conditions.

Exp.	V _c	f	a _p	AF (N)	Vibration (m/s ²)	MPI
9	250 m/min	0.30	1.0	257.07	5.38	0.220
1	150 m/min	0.10	0.5	300.79	9.30	0.242
6	200 m/min	0.30	0.5	590.85	7.85	0.290
5	200 m/min	0.20	1.5	587.78	10.14	0.304

8	250 m/min	0.20	0.5	365.04	5.99	0.318
2	150 m/min	0.20	1.0	356.09	14.85	0.365
7	250 m/min	0.10	1.5	730.60	12.41	0.391
4	200 m/min	0.10	1.0	410.71	11.72	0.545
3	150 m/min	0.30	1.5	522.86	19.09	0.595

The equal-weight MPI ranked Experiment 9 ($V_c = 250$ m/min, $f = 0.30$ mm/rev, $a_p = 1.0$ mm) first (MPI = 0.220), followed by Experiment 1 (150 m/min, 0.10 mm/rev, 0.5 mm; MPI = 0.242). However, Experiment 9 had a relatively large cylindricity deviation of 33.63 μm , so it should not be selected where geometric accuracy is the dominant requirement. Experiment 3 produced the lowest CYLt (21.18 μm), with AF = 522.86 N and the highest RMS vibration (19.09 m/s²). Experiments 6 and 8 produced the lowest Ra (2.13 μm), but Experiment 8 had the highest CYLt (37.40 μm). These results demonstrate why a multi-response index can be useful for screening, while the preferred condition still depends on the production objective and required geometric tolerance.

5.5. Study Limitations

The findings of the present work should be interpreted in light of the following limitations. (1) Only nine experimental conditions were evaluated using a Taguchi L9 orthogonal design. (2) No independent machining repetitions were performed; therefore, experimental variability could not be quantified. The five roughness measurements per condition are repeated measurements on the same machined section and do not represent independent machining replicates. (3) Because independent machining replicates were unavailable, an independent experimental-error term could not be estimated and inferential ANOVA, confidence intervals for factor effects, and formal factor-significance testing were not performed. (4) The L9 design does not permit all two-factor interactions to be independently estimated without aliasing/confounding; dedicated factorial or response-surface experiments are required. (5) Pearson correlations and linear regression analyses are exploratory and based on nine condition-level observations; confidence intervals are wide, and no validated predictive model was established. (6) The S/N ratios are descriptive only and cannot establish statistically optimal parameter levels without independent replication. (7) The 1000 Hz vibration sampling rate imposes a 500 Hz Nyquist limit. No frequency-domain analysis or peak-acceleration analysis was performed, and the actual MPU6050 internal low-pass-filter setting was not documented. (8) The force and vibration systems were operated during the same machining passes, but the available records do not document a shared trigger, clock, or sample-level synchronization. (9) The exact reproducible mounting coordinates of the MPU6050 on the tool holder were not documented. (10) The available machine-tool records do not include spindle power, machine age, or quantified machine stiffness. (11) The same cutting edge was reused throughout the nine conditions, but its wear was not systematically measured before or after each condition. (12) Individual standard deviations for the five roughness measurements were not retained and therefore cannot be reconstructed. (13) Although three force components were measured, only the resultant AF RMS was retained for the present analysis; separate F_c , F_r , and F_f results are not reported. (14) Thermal effects, built-up-edge formation, chip morphology, and workpiece/tool compliance were not measured directly. (15) The MRR and force-to-chip-area values introduced here are calculated screening quantities and do not replace direct power, energy, or specific-cutting-force measurements. Future work should include independent machining replicates, an interaction-capable factorial/RSM design, common-trigger multi-channel acquisition, traceable multi-point vibration calibration, documented sensor coordinates, peak and spectral vibration analysis, separate force components, systematic tool-wear characterization, thermal measurements,

machine-dynamics characterization, roughness measurement standard deviations, and confirmatory experiments over an expanded parameter region.

6. Conclusions

The combined effects of cutting speed, feed rate, and depth of cut produced distinct machining responses under the investigated C45 turning conditions. Higher cutting speed was associated with lower vibration (RMS acceleration of the tangential and radial components, m/s^2 , acquired with an MPU6050 whose manufacturer-specified internal low-pass-filter range extends up to 260 Hz) and surface roughness, whereas the largest depth of cut was linked to the highest mean active force and vibration. Cutting force did not show a consistent monotonic dependence on cutting speed, and the feed-rate effect was not monotonic across the nine experimental conditions. The actual internal low-pass-filter setting was not documented; therefore, the effective measurement bandwidth cannot be asserted to be exactly 0–260 Hz. The 1000 Hz sampling rate also limits the theoretically resolvable frequencies to below 500 Hz. The measured R_a range was 2.13–3.66 μm , RMS vibration was 5.38–19.09 m/s^2 , AF was 257.07–730.60 N, and CYLt was 21.18–37.40 μm . MRR ranged from 7500 to 75,000 mm^3/min . Within this experimental window, Experiment 9 (250 m/min , 0.30 mm/rev , 1.0 mm) provided the lowest equal-weight exploratory MPI (0.220), whereas Experiment 3 (150 m/min , 0.30 mm/rev , 1.5 mm) produced the lowest cylindricity deviation (21.18 μm) but also the highest RMS vibration (19.09 m/s^2). Experiments 6 and 8 achieved the lowest measured R_a (2.13 μm), but their geometric responses differed substantially. Thus, no single condition is universally optimal; the practical choice should be based on the relative importance of force, vibration, surface finish, geometric accuracy, and productivity.

For future work, vibration measurements extending to at least 20 kHz are recommended to characterize higher-frequency machining dynamics that could not be captured by the present MPU6050 acquisition system. This requires a suitable high-bandwidth accelerometer, documented anti-alias filtering, and a sampling rate above 40 kHz (preferably with additional margin), followed by frequency-domain analysis. The present results should not be extrapolated to that frequency range.

Based on the tested conditions, the following quantitative screening recommendations are made: (a) for a balanced low-force/low-vibration screening objective, Experiment 9 had the lowest equal-weight MPI (0.220), but its CYLt of 33.63 μm must be checked against the required form tolerance; (b) when cylindricity is prioritized, Experiment 3 gave the lowest CYLt (21.18 μm), although it also had the highest RMS vibration (19.09 m/s^2) and AF = 522.86 N; (c) when surface roughness is prioritized, Experiments 6 and 8 gave the lowest R_a (2.13 μm), but Experiment 8 had CYLt = 37.40 μm ; and (d) for productivity screening, Experiment 9 gave the highest MRR (75,000 mm^3/min). These values are recommendations within the tested parameter window only and require independent confirmation before industrial adoption.

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Abbreviations

AF	Active cutting force
C45	Medium-carbon steel EN 1.0503
CYLt	Total cylindricity deviation
MEMS	Micro-electromechanical system
MPU6050	Three-axis MEMS accelerometer/gyroscope sensor
Ra	Arithmetic mean surface roughness
RONt	Total roundness deviation
Rz	Maximum height of the roughness profile
S/N	Signal-to-noise ratio
STRt	Total straightness deviation
V _c	Cutting speed
f	Feed rate
a _p	Depth of cut
MPI	Machining performance index
x^*	Lower-the-better transformation
MRR	Material removal rate

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