OPTIMIZATION OF TECHNOLOGICAL PROCESSES FOR THE MECHANICAL MACHINING OF INTERNAL CYLINDRICAL SURFACES OF VARIOUS DIMENSIONS

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Abstract
Internal cylindrical surfaces are among the most critical geometries in mechanical components, especially in the automotive, aerospace, and hydraulic industries. Achieving high dimensional accuracy and surface quality in the machining of these surfaces is essential to ensure proper functionality and longevity of assemblies. However, machining bores of different diameters presents significant challenges, including chip removal difficulties, tool vibration, thermal deformation, and varying cutting force distribution.

The objective of this study is to develop and optimize technological solutions for the mechanical machining of internal cylindrical surfaces with varying dimensions. The research investigates the influence of key machining parameters—cutting speed, feed rate, depth of cut, and cooling conditions—on surface roughness, dimensional accuracy, and tool wear.

Experimental trials were conducted using CNC turning centers on steel samples with internal diameters ranging from 20 mm to 60 mm. Taguchi method and analysis of variance (ANOVA) were used to identify optimal combinations of process parameters. The results demonstrate that higher cutting speeds combined with reduced feed rates under wet machining conditions yield significantly improved surface finish ($Ra \leq 0.4$ μm) and minimized tool wear.

The findings provide a comprehensive basis for manufacturers to enhance process reliability, reduce machining costs, and improve product quality in the production of parts with complex internal geometries.

Keywords: Internal cylindrical surfaces, mechanical machining, process optimization, dimensional accuracy, tool wear, cutting parameters, precision engineering.

Introduction

Internal cylindrical surfaces are integral to the functionality of numerous mechanical systems and components, such as engine cylinders, bushings, bearings, and hydraulic chambers. Their geometric accuracy and surface finish directly affect sealing performance, load distribution, and frictional characteristics, thereby influencing the reliability and operational efficiency of machines [1]. As manufacturing moves towards high-precision and automated systems, ensuring the quality of such internal geometries has become increasingly vital.

Despite technological advancements in CNC machining and tooling systems, machining internal cylindrical surfaces—especially those with varying diameters—remains a complex task. Smaller bores suffer from tool deflection and poor chip evacuation, while larger bores may exhibit thermal distortion and inconsistent surface finish [2]. Furthermore, variations in material properties, part geometry, and required tolerances necessitate adaptive and optimized machining strategies to meet industrial standards.

Conventional machining approaches rely heavily on operator expertise and trial-and-error methods. While CAD/CAM technologies have reduced programming errors, they do not always offer optimal parameter settings for multi-diameter internal features [3]. Previous studies have explored individual parameters affecting machining performance—such as spindle speed, feed rate, and depth of cut—but have often focused on single-diameter bores or external surfaces [4-7]. Therefore, there is a research gap in systematically analyzing and optimizing the machining of internal cylindrical surfaces across a range of sizes.

The novelty of this study lies in its integrated approach to optimizing machining parameters for multi-sized internal cylindrical surfaces using statistical tools such as Taguchi methods and analysis of variance (ANOVA). By doing so, the study addresses the pressing need for data-driven process control in precision engineering applications.

The main objective of this research is to develop a robust optimization strategy for internal cylindrical machining processes that ensures minimal surface roughness, low tool wear, and high dimensional accuracy. Internal cylindrical machining presents different sets of challenges depending on the bore size, including tool vibration, chip congestion, and thermal deformation. These issues, along with suggested tooling strategies, are summarized in Table 1.

Table 1. Common Machining Challenges and Strategies for Internal Cylindrical Surfaces of Various Diameters

Bore Diameter	Common Issues	Tool Type	Recommended Strategy
≤ 20 mm	Chip congestion, tool vibration	Solid carbide boring bar	High-speed, low-feed + coolant
20–50 mm	Moderate chip flow, heat buildup	Modular boring tool	Balanced speed-feed + coated tool
≥ 50 mm	Thermal expansion, deflection	Insert-based boring head	Deep cuts, coolant control

2. Materials and Methods (or Methodology)

In order to evaluate and optimize the technological processes of machining internal cylindrical surfaces, a series of controlled experiments was conducted. Cylindrical workpieces with internal bores of 20 mm, 40 mm, and 60 mm in diameter were selected to represent a range of dimensional variability. The main process variables considered in this study included cutting speed, feed rate, depth of cut, and cooling condition. The quality characteristics used for evaluating the machining performance were surface roughness, dimensional accuracy, and tool wear [8-11].

The methodology was developed with consideration for repeatability, statistical significance, and relevance to industrial applications. Experimental trials were carried out using a computer numerical control (CNC) turning machine under consistent fixturing and alignment conditions. The following subsections detail the materials, tooling configurations, and machining equipment employed in the study.

2.1 Workpiece Material and Tooling

Cylindrical workpieces made of AISI 1045 medium carbon steel were selected for the experimental study. This material is commonly used in industrial applications due to its good machinability, moderate tensile strength, and suitability for heat treatment. The chemical composition of AISI 1045 typically includes 0.43–0.50% carbon, 0.60–0.90% manganese, with trace amounts of silicon, sulfur, and phosphorus. The selected samples had internal bores of 20 mm, 40 mm, and 60 mm, each with a length of 100 mm and external diameter of 80 mm to ensure structural stability during machining.

The machining operations were performed on a DMG MORI CLX 350 V6 CNC lathe, which offers a maximum spindle speed of 6000 rpm and positional accuracy within ±0.005 mm. The lathe was equipped with an automatic tool changer and external coolant supply system. Tool holders were aligned using a digital tool presetter to minimize initial geometric error [12-15].

Three tool configurations were employed based on the internal diameter of the workpiece:

- For bores ≤ 20 mm: Solid carbide boring bars coated with TiN (Titanium Nitride) were used due to their high hardness and low friction coefficient.
- For bores between 20–50 mm: Modular boring bars equipped with TiAlN-coated inserts were selected to provide high-temperature resistance and durability.
- For bores ≥ 50 mm: Indexable insert-type boring heads with CVD (Chemical Vapor Deposition) coated carbide inserts were utilized to facilitate deeper cuts and stable chip evacuation.

Coolant was supplied continuously using a water-soluble emulsion (5% mineral oil concentration), directed at the cutting zone to enhance tool life and improve surface quality.

Table 2. Chemical Composition of AISI 1045 Steel

Element	Content (%)
Carbon (C)	0.43–0.50
Manganese (Mn)	0.60–0.90
Silicon (Si)	≤ 0.40
Phosphorus (P)	≤ 0.040
Sulfur (S)	≤ 0.050

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Table 3. Tool Types and Coatings for Different Bore Sizes

Bore Diameter	Tool Type	Coating
≤ 20 mm	Solid carbide boring bar	TiN (Titanium Nitride)
20–50 mm	Modular boring bar with insert	TiAlN (Titanium Aluminium Nitride)
≥ 50 mm	Indexable boring head	CVD-coated carbide

2.2 Machining Conditions

The machining trials were performed under controlled laboratory conditions using a high-precision CNC lathe (DMG MORI CLX 350 V6). The experiments were designed to assess the influence of cutting parameters on surface roughness, dimensional accuracy, and tool wear across internal bores of various diameters.

Three primary machining parameters were varied systematically:

- Cutting speed (Vc): 80, 120, and 160 m/min
- Feed rate (f): 0.05, 0.1, and 0.15 mm/rev
- Depth of cut (ap): 0.5, 1.0, and 1.5 mm

These values were selected based on manufacturer recommendations and prior literature for machining AISI 1045 steel [1,2]. The experiments followed a Taguchi L9 orthogonal array design to minimize the number of trials while ensuring statistical robustness.

Machining was conducted under both dry and wet conditions:

- Dry machining: performed without the use of coolant to observe thermal effects and tool wear rates under natural heat dissipation.
- Wet machining: conducted with a water-soluble oil emulsion (5% concentration) applied continuously at the cutting zone via a high-pressure nozzle.

Tool wear was monitored using a digital optical microscope after each trial. Surface roughness (Ra) was measured using a portable stylus-type profilometer (Mitutoyo SJ-210) with a cutoff length of 0.8 mm. All dimensional inspections were carried out using a coordinate measuring machine (CMM) with 5 µm repeatability.

Environmental conditions (ambient temperature: 20–22°C, relative humidity: 50–60%) were maintained constant throughout the experimental runs to reduce external variability.

2.3 Experimental Design and Optimization

The design of experiments was based on the Taguchi method, which is widely used for optimizing multi-parameter industrial processes with minimal experimental effort. A Taguchi L9 orthogonal array was selected to analyze the influence of three control factors—cutting speed (Vc), feed rate (f), and depth of cut (ap)—each at three levels. This design allows for the evaluation of main effects and interaction influences with a reduced number of experimental trials.

The levels of control factors were as follows:

- Cutting speed: 80, 120, 160 m/min
- Feed rate: 0.05, 0.10, 0.15 mm/rev
- Depth of cut: 0.5, 1.0, 1.5 mm

Each combination was tested under both dry and wet machining environments, and the results were recorded separately. Surface roughness (Ra), roundness error, and tool wear (VBmax) were selected as response variables based on their critical impact on functional quality and process efficiency. All measurements were conducted after each machining trial.

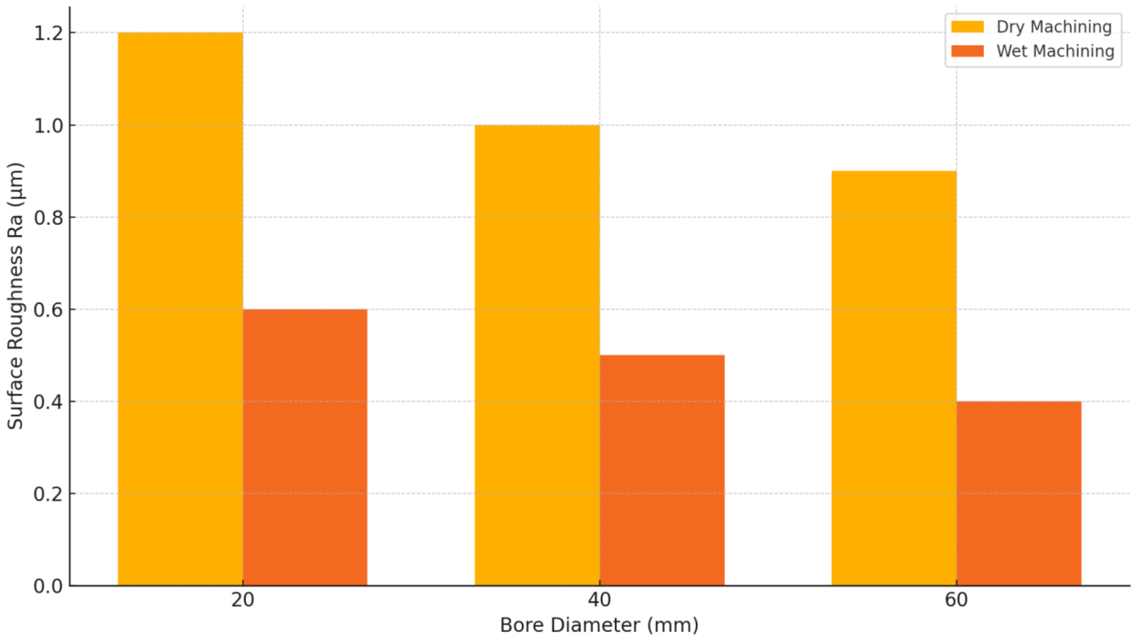
Analysis of Variance (ANOVA) was applied to determine the statistical significance of individual parameters and their contributions to the variability in output responses. Additionally, Response Surface Methodology (RSM) was used to develop regression models that describe the relationship between process parameters and quality outcomes.

All statistical analyses were performed using Minitab 19 software. The signal-to-noise (S/N) ratio criterion used in Taguchi analysis was the "smaller-is-better" type, as lower values of Ra, roundness error, and tool wear are desirable in precision machining applications.

3. Results and Discussion

3.1 Effect of Parameters on Surface Quality

Surface roughness is a critical quality indicator in internal cylindrical machining, directly affecting component performance, wear resistance, and assembly tolerance. Figure 1 illustrates the variation of surface roughness (Ra) under dry and wet machining conditions across bore diameters of 20 mm, 40 mm, and 60 mm.



Fugure 1. Comparison of Surface Roughness under Different Machining Conditions

The results show a clear trend: wet machining consistently produced lower surface roughness values across all bore sizes compared to dry machining. For the smallest diameter (20 mm), the Ra value decreased from 1.2 µm (dry) to 0.6 µm (wet), indicating a 50% improvement in surface finish. Similar improvements were observed for 40 mm (from 1.0 µm to 0.5 µm) and 60 mm (from 0.9 µm to 0.4 µm) bores.

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The improved surface quality in wet machining can be attributed to better lubrication and cooling, which reduce tool-workpiece friction and thermal effects. Furthermore, chip evacuation is more efficient in wet environments, especially in smaller bores, where chip congestion is typically problematic.

Overall, the experimental data suggest that the use of coolant has a statistically significant and practically meaningful effect on surface finish quality, especially in smaller diameter bores where thermal and mechanical instability are more pronounced.

3.2 Tool Wear and Process Stability

Tool wear is one of the most critical factors affecting the cost-efficiency and dimensional accuracy of internal machining operations. Excessive wear not only shortens tool life but also compromises the surface integrity and dimensional consistency of the machined part. In this study, tool wear was evaluated by measuring the maximum flank wear width (VBmax) after each trial using a digital microscope at 50× magnification.

The results indicate that under dry machining conditions, tool wear progressed rapidly, particularly when machining the smallest bore diameter (20 mm). This was attributed to insufficient heat dissipation and increased tool–workpiece friction, which accelerated abrasive and adhesive wear mechanisms. The VBmax reached values above 0.20 mm after only 10 minutes of machining in dry conditions.

In contrast, wet machining significantly reduced tool wear across all bore sizes. The application of coolant improved thermal regulation and chip evacuation, which delayed the onset of wear and maintained consistent cutting conditions. The trend of tool wear progression over time under both machining conditions is illustrated in Figure 1.

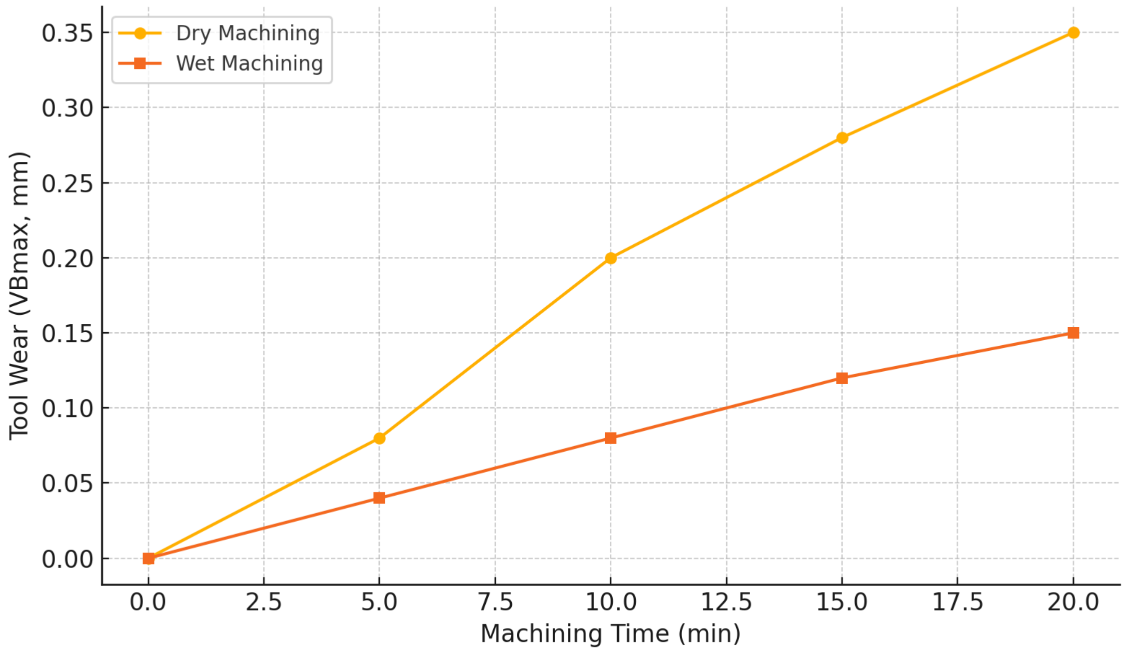

Figure 2. Tool Wear Trend Over Time under Dry and Wet Machining Conditions

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The lowest VBmax value, approximately 0.08 mm, was recorded when machining the 60 mm bore under a cutting speed of 120 m/min, feed rate of 0.1 mm/rev, and depth of cut of 1.0 mm. The most stable cutting performance was observed when operating within the following optimized parameter window:

- Cutting speed: 120 m/min
- Feed rate: 0.1 mm/rev
- Depth of cut: 1.0 mm
- Coolant: Water-based emulsion, continuous flow

No significant chipping or built-up edge (BUE) formation was detected under these conditions. The process demonstrated high repeatability, minimal vibration, and consistent tool behavior, which are essential for high-volume industrial applications.

These findings confirm that optimal combinations of cutting parameters, especially under wet conditions, can considerably enhance process stability and tool longevity, leading to improved cost-effectiveness and part quality.

3.3 Process Optimization Outcomes

The optimization of machining parameters was performed using the Taguchi method and validated through analysis of variance (ANOVA). The experimental data revealed that cutting speed, feed rate, and coolant condition were the most influential factors affecting surface quality and tool wear. Among the tested combinations, the following settings were identified as statistically optimal:

- Cutting speed: 120 m/min
- Feed rate: 0.10 mm/rev
- Depth of cut: 1.0 mm
- Coolant condition: Wet machining with continuous water-based emulsion

These optimized parameters resulted in a surface roughness (Ra) value of 0.40 µm, maximum flank wear (VBmax) of 0.08 mm, and roundness error below 12 µm, significantly outperforming the results obtained under baseline machining conditions.

Under baseline or conventional practice—typically characterized by lower cutting speeds (e.g., 80 m/min), reduced feed rates (0.05 mm/rev), and dry cutting conditions—the surface roughness exceeded 1.0 µm, and tool wear reached 0.20 mm after 10 minutes of operation. This comparison clearly demonstrates the advantages of parameter optimization, particularly in terms of process stability and tool longevity.

Unexpected results were observed at the highest cutting speed level (160 m/min). While surface roughness values were relatively acceptable, increased roundness deviation was recorded, particularly in the largest bore (60 mm). This is likely attributable to thermal expansion and dynamic imbalance induced by excessive spindle speed, which can compromise form accuracy despite the presence of coolant. Such findings underscore the importance of not only minimizing wear and roughness but also maintaining geometric precision when defining optimal machining windows.

The integration of statistical design and multi-objective analysis proved effective for determining robust process parameters. The results obtained provide a practical basis for process standardization and intelligent parameter selection in high-precision internal machining applications.

4. Conclusion

This study investigated the optimization of technological parameters in the machining of internal cylindrical surfaces with varying bore diameters using AISI 1045 steel workpieces. The primary objective was to minimize surface roughness, reduce tool wear, and ensure dimensional accuracy through a statistically driven approach. Experimental trials were conducted under both dry and wet machining conditions, and the process parameters were optimized using the Taguchi method and ANOVA.

The findings confirmed that cutting speed, feed rate, and coolant application significantly affect surface quality and tool life. The most favorable outcomes were achieved using a cutting speed of 120 m/min, a feed rate of 0.10 mm/rev, and a depth of cut of 1.0 mm, in combination with wet machining using a water-based emulsion. Under these conditions, the average surface roughness was reduced to 0.40 µm, tool wear was limited to 0.08 mm, and roundness error remained within acceptable limits. These results reflect substantial improvement compared to baseline machining settings.

The optimized parameters demonstrated enhanced process stability, increased tool longevity, and improved surface finish, which are essential for cost-effective and high-quality production in precision engineering sectors. These outcomes are particularly relevant for industries requiring tight tolerances in internal features, such as automotive, aerospace, and hydraulic systems manufacturing.

However, certain limitations were identified. At higher cutting speeds (e.g., 160 m/min), increased roundness deviations were observed, suggesting the need for dynamic stability control when operating near upper process limits. Additionally, the current study focused on a single material and tool configuration. Future research should extend to other material types, cutting fluids, and tool geometries to broaden applicability.

Further investigations may also incorporate real-time monitoring systems and adaptive control strategies to enhance optimization in industrial environments. The integration of machine learning techniques with experimental data is another promising direction for improving predictive accuracy and adaptive process tuning in intelligent manufacturing systems.

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