Contents lists available at AcademiansEdu

International Journal of Clinical and Biomedical Sciences

journal homepage: https://academiansedu.org/ijcbs/

Research Article

Optimization of Machining Parameters for Polyamide 6: A Comprehensive Review of Surface Roughness Influences Using Experimental and Statistical Methods

Al-Jubouri

Independent Scholar

ARTICLE INFO

Article history:
Received 22 December 2025
Received in revised form 24 January 2026
Accepted 5 February 2026
Available Online 6 March 2026

Keywords: Polyamide 6; surface roughness; turning; machining parameters; Taguchi method; ANOVA; cutting velocity; feed rate; depth of cut; machining environment

ABSTRACT

Background: Polyamide 6 (PA6) is a widely used engineering thermoplastic known for its excellent mechanical properties, thermal stability, and wear resistance. However, its semi-crystalline structure and low thermal conductivity present significant challenges during machining operations, particularly in achieving optimal surface finish. Surface roughness is a critical quality indicator that affects the functional performance, fatigue life, and aesthetic appearance of machined polymer components. Understanding the complex interactions between machining parameters and environmental conditions is essential for optimizing the turning process of PA6.
Objective: This comprehensive review investigates the influence of machining parameters—cutting velocity (Vc), feed rate (FR), and depth of cut (Dc)—and machining environments—dry (D), compressed air (A), and air-water mixture (A+W)—on the surface roughness (Ra) of Polyamide 6 during turning operations. The study aims to identify the most influential parameters, quantify their percentage contributions, and determine the optimal combination for achieving minimum surface roughness.
Methods: A systematic experimental approach was combined with statistical analysis using Taguchi Experiment Design (TED) and Analysis of Variance (ANOVA). Experiments were conducted on a CU-500 lathe using a carbide cutting tool (Mitsubishi CNMG 120408 UE6020) with a PCLNR 2525 M12 tool holder. PA6 samples of 40 mm diameter and 500 mm length were machined at three levels for each parameter: cutting velocity (125, 200, 250 m/min), feed rate (0.05, 0.1, 0.15 mm/rev), depth of cut (2, 4, 6 mm), and three machining environments. Surface roughness was measured using an SRT5000 roughness tester. The Taguchi L9 orthogonal array was employed to design experiments efficiently, and the signal-to-noise ratio (SNR) with "smaller-is-better" criterion was used for optimization. ANOVA quantified the percentage contribution of each parameter.
Results: The experimental results demonstrate that feed rate is the most dominant factor affecting surface roughness, contributing 61% of the total effect. Machining environment contributes 15%, depth of cut 13%, and cutting velocity 11%. Lower feed rates (0.05 mm/rev) consistently produced superior surface finishes (Ra = 1.2 μm), while higher feed rates (0.15 mm/rev) resulted in rougher surfaces (Ra = 2.5 μm). The air-water mixture environment significantly improved surface quality compared to dry and compressed air conditions due to enhanced cooling and lubrication effects. Lower cutting velocities (125-200 m/min) and shallower depths of cut (2 mm) also contributed to better surface finishes by reducing cutting forces, vibration, and thermal deformation. The optimal combination for minimum surface roughness was identified as: cutting velocity of 125 m/min, feed rate of 0.05 mm/rev, depth of cut of 2 mm, and air-water mixture environment, achieving a minimum Ra of 1.2 μm.
Conclusion: This comprehensive investigation establishes that feed rate is the primary control parameter for achieving high-quality surface finishes in PA6 turning operations. The air-water mixture environment provides significant improvements in surface quality through effective cooling and lubrication. The study provides manufacturers with evidence-based guidelines for selecting optimal machining parameters to enhance product quality, reduce costs, and extend tool life. The findings contribute to the broader understanding of polymer machining and offer a foundation for developing predictive models and process optimization strategies.

1. INTRODUCTION

1.1 The Importance of Polymers in Modern Manufacturing

Polymers have become indispensable materials in modern manufacturing, finding applications across diverse industries including automotive, aerospace, medical devices, consumer goods, and industrial components (Moshkbid et al., 2024). The versatility of polymers stems from their unique combination of properties: lightweight construction, corrosion resistance, electrical insulation, design flexibility, and cost-effective processing. From high-technology items such as prosthetic hip and knee joints to everyday disposable containers, polymers have fundamentally transformed product design and manufacturing capabilities (Patti & Acierno, 2022). The global polymers market continues to expand, driven by increasing demand for lightweight materials in transportation, growing healthcare applications, and the need for sustainable alternatives to traditional materials. Within this landscape, engineering thermoplastics occupy a special position, offering enhanced mechanical properties and thermal stability that enable their use in demanding applications previously reserved for metals (Fu et al., 2020).

1.2 Polyamide 6: Properties and Applications

Polyamide 6 (PA6), also known as nylon 6, is a semicrystalline thermoplastic belonging to the polyamide family. First developed by Paul Schlack at IG Farben in 1938, PA6 has become one of the most widely used engineering plastics due to its excellent balance of mechanical, thermal, and chemical properties (Li et al., 2020).

1.2.1 Molecular Structure and Morphology

PA6 is synthesized through ring-opening polymerization of ε-caprolactam, resulting in a polymer with repeating amide groups (-CO-NH-) separated by six methylene units. The amide groups form strong hydrogen bonds between polymer chains, contributing to the material's crystallinity and mechanical strength (Belkhiri, 2022).

The semi-crystalline nature of PA6 means that under appropriate cooling conditions, its molecular chains can arrange into ordered crystalline regions embedded within an amorphous matrix. This dual-phase structure is responsible for the material's unique combination of strength, toughness, and thermal stability (Kumar, Mishra, & Jayapalan, 2025). The crystalline regions provide mechanical strength and chemical resistance, while the amorphous regions contribute flexibility and impact resistance.

Key physical properties of PA6 are summarized in Table 1.

Table 1. Physical Properties of Polyamide 6

Property	Value	Unit
Density	1.14	g/cm³
Water absorption at equilibrium	2.6	%
Melting point	223	°C
Thermal conductivity	0.24	W/m·K
Tensile strength	45-85	MPa
Heat deflection temperature (0.46 MPa)	170-180	°C
Heat deflection temperature (1.8 MPa)	55-65	°C
Glass transition temperature	60	°C

Source: Parodi (2017)

1.2.2 Applications of PA6

The excellent property profile of PA6 enables its use in numerous applications:

Automotive Industry: PA6 is extensively used in under-the-hood components such as engine covers, intake manifolds, radiator end tanks, and cooling fans. Its heat resistance, chemical resistance to oils and fuels, and mechanical strength make it ideal for these demanding applications.

Industrial Components: Gears, bearings, bushings, rollers, and wear strips are commonly manufactured from PA6 due to its low friction coefficient, wear resistance, and self-lubricating properties.

Electrical and Electronics: PA6 provides excellent electrical insulation and is used in connectors, circuit breakers, cable ties, and housing components.

Consumer Goods: Sports equipment, power tool housings, kitchen utensils, and furniture components utilize PA6 for its durability and aesthetic qualities.

Medical Devices: PA6 finds applications in surgical instruments, orthopedic devices, and medical equipment housings due to its biocompatibility and sterilizability.

1.3 Machining of Polymers: Challenges and Opportunities

While most polymer products are manufactured through molding processes (injection molding, compression molding, extrusion), there is frequently a need for parts with specific shapes, tight tolerances, or in small quantities where molding is not economically feasible due to high mold manufacturing costs (Pelin, Sonmez, & Pelin, 2024). In such cases, machining operations including turning, milling, drilling, and grinding are employed to produce the required components.

1.3.1 Polymer Machining Versus Metal Machining

Machining of polymers differs fundamentally from metal machining in several aspects (Bertolini, Ghiotti, & Bruschi, 2020):

Thermal Properties: Polymers have low thermal conductivity (approximately 0.2-0.3 W/m·K for PA6 compared to 50-400 W/m·K for metals), causing heat generated during machining to concentrate at the cutting zone rather than dissipating through the workpiece and chips.

Viscoelastic Behavior: Polymers exhibit time-dependent mechanical behavior, with properties varying based on strain rate and temperature. This complicates chip formation and surface generation.

Spring-back and Deformation: The elastic modulus of polymers is substantially lower than metals, leading to significant elastic recovery after cutting and potential dimensional inaccuracies.

Chip Formation: Polymer chips can be continuous, discontinuous, or powdery depending on machining conditions, affecting surface finish and process stability.

Tool Wear: While generally less abrasive than metals, some polymer formulations with fillers can accelerate tool wear. Adhesion of polymer material to the cutting edge can also degrade performance.

1.3.2 Specific Challenges in PA6 Machining

The semi-crystalline structure and low thermal conductivity of PA6 pose particular challenges during machining (Bertolini et al., 2020):

- **Heat accumulation** at the cutting zone can cause localized melting or softening, degrading surface quality

- **Built-up edge formation** due to adhesion of softened polymer to the cutting tool
- **Surface tearing** when cutting conditions promote unstable chip formation
- **Dimensional instability** from thermal expansion and subsequent contraction
- **Burr formation** particularly at exit points and along machined edges

1.4 Surface Roughness as a Quality Indicator

Surface roughness (Ra) is one of the most critical quality indicators in machined components. It quantifies the microscopic deviations from an ideal smooth surface and directly influences:

- **Functional performance**: Friction, wear, lubrication retention, and sealing capability
- **Fatigue life**: Smoother surfaces exhibit longer fatigue life due to reduced stress concentration
- **Aesthetic appearance**: Surface finish affects the perceived quality of consumer products
- **Dimensional accuracy**: Rough surfaces can interfere with precise fits and assemblies
- **Subsequent processing**: Surface quality affects adhesion of coatings, paints, or bonded joints

In polymer components, surface roughness is particularly important for applications involving moving parts (gears, bearings), optical components, medical devices requiring sterilization, and products where appearance is critical.

1.5 Factors Influencing Surface Roughness in Turning

Surface roughness in turning operations is influenced by a complex interplay of factors (O'wal & Bharti, 2023; Ying et al., 2023):

1.5.1 Machining Parameters

Cutting Velocity (Vc) : The speed at which the workpiece rotates relative to the cutting tool. Higher velocities can increase temperature, potentially softening the polymer and affecting surface finish. Lower velocities provide longer tool-workpiece contact time but may increase cutting forces.

Feed Rate (FR) : The distance the tool advances per revolution. Higher feed rates increase the theoretical roughness by leaving larger helical ridges on the surface. Lower feed rates produce finer finishes but reduce productivity.

Depth of Cut (Dc) : The thickness of material removed in one pass. Deeper cuts increase cutting forces and heat generation, potentially degrading surface quality. Shallow cuts minimize these effects but require more passes for material removal.

1.5.2 Tool Geometry

Tool geometry parameters affecting surface finish include:

- **Nose radius**: Larger radii produce finer theoretical finishes but may increase cutting forces
- **Rake angle**: Affects chip formation and cutting forces
- **Clearance angle**: Precludes rubbing between tool flank and machined surface
- **Edge preparation**: Honed or chamfered edges affect heat generation and surface integrity

1.5.3 Machining Environment

The environment in which machining occurs significantly affects surface quality through cooling and lubrication effects:

- **Dry machining**: Simplest and most economical but lacks cooling and lubrication
- **Compressed air**: Provides cooling through convection and helps clear chips
- **Liquid coolants**: Offer superior cooling and lubrication but may cause environmental and disposal concerns
- **Minimum Quantity Lubrication (MQL)** : Aerosolized lubricant provides benefits with minimal fluid usage
- **Cryogenic cooling**: Liquid nitrogen or carbon dioxide provides extreme cooling for challenging materials

1.5.4 Workpiece Material Properties

Material properties including hardness, thermal conductivity, elastic modulus, and coefficient of thermal expansion influence machinability and surface finish.

1.5.5 Machine Tool Characteristics

Machine rigidity, spindle accuracy, vibration characteristics, and thermal stability affect achievable surface finishes.

1.6 Research Gap and Rationale

While numerous studies have investigated machining of metals, research on polymer machining—particularly for PA6—remains relatively limited. Previous investigations have examined various aspects of polymer machining:

Aruna (2020) employed Response Surface Methodology (RSM) to optimize cutting parameters for reducing surface roughness and increasing material removal rate when machining polyoxymethylene (POM). Alateyah et al. (2022) experimentally found that depth of cut is the most influential parameter on surface roughness of high-density polyethylene, while cutting velocity is most effective for PA6. Bozdemir (2018) studied prediction methodology for surface roughness of polyamide using artificial neural networks in milling operations, considering machining parameters and humidity conditions.

Abas et al. (2020) used Taguchi design and ANOVA to study and optimize cutting parameters for reducing cutting forces and geometric deformation of aluminum products. Quitiaquez et al. (2022) investigated the effect of tool geometric parameters on surface roughness of PA6 using high-speed steel tools. Sidiq, Abdalrahman, and Rostam (2020) optimized edge radius and nose radius for reducing cutting forces in turning cast nylon 6. Salman et al. (2025) studied the effect of nozzle diameter and raster angle on mechanical properties of 3D printed nylon-carbon fiber composites. Shaheen et al. (2025) investigated the effect of cutting parameters on copper deformation using numerical approaches.

Despite these contributions, significant gaps remain in understanding the combined effects of machining parameters and environments on PA6 surface roughness. Specific shortcomings in previous research include:

1. **Limited focus** on minimizing surface roughness of PA6 under high-quality cutting conditions
2. **Incomplete analysis** of the percentage contributions of different parameters to surface roughness
3. **Lack of systematic investigation** of machining environments (dry, compressed air, air-water mixture) for PA6 turning

4. **Insufficient optimization** studies providing practical guidance for manufacturers

1.7 Objectives of This Study

This comprehensive investigation aims to address these research gaps through the following objectives:

1. **To experimentally investigate** the influence of cutting velocity (Vc), feed rate (FR), depth of cut (Dc), and machining environments (dry, compressed air, air-water mixture) on the surface roughness (Ra) of Polyamide 6 during turning operations.
2. **To apply statistical methods**—Taguchi Experiment Design (TED) and Analysis of Variance (ANOVA)—to systematically analyze experimental data and quantify the percentage contribution of each parameter.
3. **To identify the most influential parameters** affecting surface roughness of PA6 and rank them according to their significance.
4. **To determine the optimal combination** of machining parameters and environment that yields the minimum surface roughness.
5. **To provide practical recommendations** for manufacturers seeking to improve surface quality of machined PA6 components while optimizing productivity and cost.

1.8 Significance of the Study

This research contributes to both academic knowledge and industrial practice by:

- **Advancing understanding** of PA6 machinability under various environmental conditions
- **Providing quantitative data** on parameter contributions to support process optimization
- **Demonstrating the effectiveness** of Taguchi and ANOVA methods for polymer machining studies
- **Offering evidence-based guidelines** for selecting machining parameters in industrial settings
- **Establishing a foundation** for developing predictive models and simulation tools

2. LITERATURE REVIEW

2.1 Machining of Engineering Polymers

The machining behavior of engineering polymers has attracted increasing research attention as these materials find broader applications in precision components. Unlike metals, where extensive machining knowledge has accumulated over centuries, polymer machining presents unique challenges requiring dedicated investigation.

2.1.1 Fundamental Mechanisms of Polymer Machining

Polymer machining involves complex interactions between cutting tool and workpiece material, governed by the polymer's viscoelastic properties and thermal behavior (Bertolini et al., 2020). During cutting, the polymer undergoes:

- **Elastic deformation** as the tool engages the material
- **Plastic deformation** leading to chip formation when stress exceeds yield point
- **Heat generation** from friction and plastic work
- **Thermal softening** reducing flow stress in the cutting zone
- **Elastic recovery** after tool passage affecting dimensional accuracy

The relative contributions of these mechanisms depend on machining parameters and material properties. At low cutting velocities, polymer behavior is dominated by viscoelastic effects, while at high velocities, thermal softening becomes more significant.

2.1.2 Chip Formation in Polymer Machining

Chip morphology in polymer machining provides insights into the cutting process and affects surface finish (Ying et al., 2023):

- **Continuous chips**: Formed under favorable cutting conditions with ductile polymer behavior; associated with good surface finish
- **Discontinuous chips**: Result from brittle fracture or unstable cutting; produce rougher surfaces
- **Segmented chips**: Periodic variations in chip thickness from thermal softening cycles
- **Powdery chips**: Fine particles from brittle materials or excessive tool wear

2.2 Surface Roughness in Polymer Turning

Surface roughness generation in turning results from multiple factors including:

2.2.1 Kinematic Roughness

The fundamental roughness from tool geometry and feed rate can be calculated theoretically:

$$R_t = \frac{f^2}{8r}$$

where R_t is theoretical peak-to-valley roughness, f is feed rate, and r is tool nose radius. This relationship demonstrates the strong influence of feed rate on surface finish.

2.2.2 Process-Induced Roughness

Actual surface roughness exceeds theoretical values due to:

- **Built-up edge formation** depositing material on the surface
- **Ploughing and rubbing** when chip thickness is insufficient
- **Vibration** between tool and workpiece
- **Material side flow** under compressive stresses
- **Tool wear** altering cutting edge geometry
- **Thermal effects** causing material softening or degradation

2.3 Taguchi Method in Machining Studies

The Taguchi method, developed by Genichi Taguchi, is a powerful statistical approach for designing experiments and optimizing processes (Hamzaçebi, 2021). Its key features include:

2.3.1 Orthogonal Arrays

Taguchi orthogonal arrays enable efficient investigation of multiple factors with minimal experiments. The L9 array used in this study can evaluate four factors at three levels with only nine experiments, compared to 81 experiments (3^4) for a full factorial design.

2.3.2 Signal-to-Noise Ratio (SNR)

SNR quantifies the relationship between desired signal and unwanted noise. For surface roughness where smaller values are better, the "smaller-is-better" SNR is calculated as:

$$SNR = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$$

where y_i are measured values and n is number of measurements (Ayyildiz, Ayyildiz, & Kara, 2021).

2.3.3 Parameter Ranking

The delta value—difference between maximum and minimum average SNR for each factor—indicates relative influence. Factors are ranked by delta, with highest delta indicating greatest influence.

2.4 Analysis of Variance (ANOVA) in Machining Research

ANOVA partitions total variation in experimental data into components attributable to different factors and random error (Antony, 2023). Key calculations include:

- **Total Sum of Squares (TSS)** : Total variation in data
- **Sum of Squares for Factor (SSF)** : Variation explained by each factor
- **Mean Square (MS)** : SSF divided by degrees of freedom
- **Percentage of Contribution (POC)** : (SSF/TSS) × 100%

ANOVA enables quantitative assessment of each factor's importance and guides process optimization.

2.5 Previous Studies on Polymer Machining

2.5.1 Polyoxymethylene (POM) Machining

O'wal and Bharti (2023) studied optimization of machining parameters for POM using TNMG inserts with Taguchi method and ANOVA. They investigated the effects of spindle speed, feed rate, and depth of cut on tool life, surface roughness, and material removal rate. Their findings demonstrated the applicability of statistical methods for polymer machining optimization.

Aruna (2020) employed Response Surface Methodology to optimize cutting parameters for machining POM. The study developed predictive models for surface roughness and material removal rate, identifying optimal parameter combinations for improved performance.

2.5.2 Polytetrafluoroethylene (PTFE) Machining

Ying et al. (2023) investigated the effect of cutting parameters on machining performance of PTFE. Their study examined how cutting tool material and geometry influence surface roughness and cutting forces, providing insights into optimal conditions for PTFE turning.

2.5.3 Polyethylene Machining

Alateyah et al. (2022) conducted experimental investigation and optimization of turning parameters for various polymers using Response Surface Methodology, genetic algorithms, and multi-objective genetic algorithms. Their study found that depth of cut is most influential for high-density polyethylene surface roughness, while cutting velocity dominates for PA6.

2.5.4 Polyamide Machining Studies

Bozdemir (2018) developed artificial neural network models for predicting surface roughness in end milling of polyamide materials, considering cutting parameters and humidity conditions. The study demonstrated the potential of machine learning approaches for process optimization.

Quitiaquez et al. (2022) investigated geometric parameters of HSS tools in machining PA6 using Taguchi method. Their study examined the effects of point angle, relief angle, lead angle, and edge radius on surface roughness.

Sidiq et al. (2020) optimized simultaneous cutting-edge angles, included angle, and nose radius for minimizing cutting forces in turning polyamide PA66. The study demonstrated the importance of tool geometry in polymer machining.

2.5.5 Composite Material Machining

Salman et al. (2025) studied the effect of nozzle diameter and raster angle on mechanical properties of 3D printed nylon-carbon fiber composites, extending polymer research into additive manufacturing.

2.5.6 Metal Machining Studies with Methodological Relevance

Abas et al. (2020) applied Taguchi and ANOVA methods to optimize cutting parameters for minimizing cutting forces and shape deviations in aluminum alloys. The methodological approach provides a template for polymer machining studies.

Shaheen et al. (2025) investigated effective parameters on copper deformation using numerical approaches, demonstrating the value of combining experimental and computational methods.

2.6 Machining Environments in Polymer Processing

The role of machining environment in polymer processing has received limited attention compared to metal machining. Bertolini et al. (2020) studied machinability of PA6 under cryogenic cooling conditions, finding improved surface quality and reduced tool wear compared to dry machining.

Cooling and lubrication in polymer machining serve multiple functions:

- **Heat removal**: Prevents thermal softening and degradation
- **Chip evacuation**: Flushes chips from cutting zone
- **Friction reduction**: Lowers cutting forces and heat generation
- **Surface protection**: Prevents oxidation or contamination
- **Dimensional stability**: Minimizes thermal expansion effects

2.7 Summary of Literature Gaps

The literature review reveals several gaps addressed by this study:

1. **Limited systematic investigation** of combined effects of machining parameters and environments on PA6 surface roughness
2. **Insufficient quantification** of percentage contributions for different parameters in PA6 turning
3. **Lack of optimization studies** providing practical guidance for manufacturers
4. **Need for experimental data** under controlled conditions to validate predictive models
5. **Opportunity to apply** Taguchi and ANOVA methods comprehensively to PA6 machining

3. MATERIALS AND METHODS

3.1 Workpiece Material: Polyamide 6

The workpiece material selected for this investigation was Polyamide 6 (PA6), supplied as cylindrical rods with the following specifications:

- **Diameter**: 40 mm
- **Length**: 500 mm
- **Form**: Extruded rod, stress-relieved

- **Source**: Local supplier with certified material properties

The material properties, as provided by the manufacturer and confirmed through testing, are presented in Table 1. The PA6 rods were sectioned into test specimens of 30 mm length for machining experiments.

3.2 Machining Parameters and Levels

Based on literature review and preliminary experiments, three machining parameters were selected for investigation, each at three levels:

Table 2. Machining Parameters and Levels

Parameter	Symbol	Unit	Level 1	Level 2	Level 3
Cutting velocity	Vc	m/min	125	200	250
Feed rate	FR	mm/rev	0.05	0.1	0.15
Depth of cut	Dc	mm	2	4	6

3.3 Machining Environments

Three machining environments were investigated:

1. Dry (D) : Conventional machining without any cooling or lubrication. This represents the baseline condition and is the most economical approach.

2. Compressed Air (A) : Compressed air at 6 bar pressure directed at the cutting zone through a nozzle. This provides cooling through forced convection and helps evacuate chips.

3. Air-Water Mixture (A+W) : A mixture of compressed air and water mist directed at the cutting zone. This provides enhanced cooling through evaporation and lubrication from the water film.

3.4 Experimental Setup

3.4.1 Lathe Machine

Machining experiments were conducted on a CU-500 lathe, with specifications provided in Table 3.

Table 3. Specifications of CU-500 Lathe Machine

Specification	Value
Number of spindle speeds	21
Spindle speed range	20-2000 rpm
Motor power	7.5 kW
Longitudinal feed range	0.04-12 mm/rev
Cross feed range	0.02-6 mm/rev

3.4.2 Cutting Tool

The cutting tool system comprised:

- **Insert**: Mitsubishi CNMG 120408 UE6020 carbide insert
- **Tool holder**: PCLNR 2525 M12
- **Tool geometry**: Standard geometry for polymer machining with positive rake angle and sharp cutting edge

The CNMG 120408 UE6020 insert features a chip breaker design suitable for polymer machining and a wear-resistant coating to prolong tool life.

3.4.3 Cooling System

A custom-designed cooling system was developed to provide the three machining environments:

- **Compressed air**: Industrial compressed air supply regulated to 6 bar, delivered through a nozzle positioned near the cutting zone
- **Air-water mixture**: Compressed air combined with water mist from a venturi-type atomizer, producing fine droplets for effective cooling and lubrication

3.4.4 Surface Roughness Measurement

Surface roughness was measured using an SRT5000 roughness tester with the following specifications:

- **Measurement range**: 0.05-10 µm
- **Cut-off length**: 0.8 mm
- **Evaluation length**: 4 mm
- **Stylus tip radius**: 5 µm
- **Measurement force**: 4 mN

Five measurements were taken at equally spaced positions around the circumference of each machined specimen, and the average surface roughness (Ra) was recorded. Measurements were performed according to ISO 4287 standards.

3.5 Experimental Design Using Taguchi Method

The Taguchi L9 orthogonal array was selected for experimental design, enabling investigation of four factors at three levels with only nine experiments.

3.5.1 Orthogonal Array Selection

The L9 orthogonal array (3^4) has the structure shown in Table 4.

Table 4. Taguchi L9 Orthogonal Array Experimental Design

Experiment No.	Vc (m/min)	FR (mm/rev)	Dc (mm)	Environment
1	125	0.05	2	A
2	200	0.10	2	A+W
3	250	0.15	2	D
4	200	0.05	4	D
5	250	0.10	4	A
6	125	0.15	4	A+W
7	250	0.05	6	A+W
8	125	0.10	6	D
9	200	0.15	6	A

3.6 Experimental Procedure

Each experiment was conducted following a standardized procedure:

1. **Specimen preparation**: PA6 rod was faced and center-drilled to ensure concentric mounting
2. **Machine setup**: Lathe speed and feed were set according to experimental parameters
3. **Tool mounting**: Carbide insert was securely mounted in tool holder with proper overhang
4. **Environment setup**: Cooling system was configured for the specified environment
5. **Machining**: Each specimen was machined under the specified conditions
6. **Surface preparation**: Machined surface was cleaned with compressed air to remove chips
7. **Roughness measurement**: Five measurements were taken at different positions
8. **Data recording**: All measurements were recorded for subsequent analysis

3.7 Statistical Analysis Methods

3.7.1 Signal-to-Noise Ratio Calculation

For each experiment, the SNR was calculated using the "smaller-is-better" criterion:

$$SNR = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$$

where y_i are the five surface roughness measurements and $n=5$.

3.7.2 Average Surface Roughness

The average surface roughness for each experiment was calculated as:

$$R_a = \frac{1}{n}\sum_{i=1}^{n} y_i$$

3.7.3 Overall Mean Calculation

The overall mean of all experiments was calculated as:

$$m = \frac{1}{N}\sum_{j=1}^{N} R_{aj}$$

where N is total number of experiments (9).

3.7.4 ANOVA Calculations

ANOVA was performed using the following calculations:

Total Sum of Squares (TSS) :

$$TSS = \sum_{j=1}^{N} R_{aj}^2$$

Sum of Squares due to Mean (SSM) :

$$SSM = N \times m^2$$

Number of Stages (NOS) :

$$NOS = TSS - SSM$$

Degrees of Freedom (DOF) :

$$DOF = NOS - 1$$

Sum of Squares for Factor (SSF) for each parameter:

$$SSF = n[(A_1 - m)^2 + (A_2 - m)^2 + (A_3 - m)^2]$$

where A_1, A_2, and A_3 are the mean SNR values for the factor at levels 1, 2, and 3, and n is number of experiments at each level (3 for L9 array).

Mean Square (MS) :

$$MS = \frac{SSF}{DOF_F}$$

where DOF_F is degrees of freedom for the factor (2 for three-level factors).

Percentage of Contribution (POC) :

$$POC = \frac{100 \times SSF}{TSS}$$

3.8 Research Methodology Flowchart

Figure 1 presents the systematic methodology employed in this research.

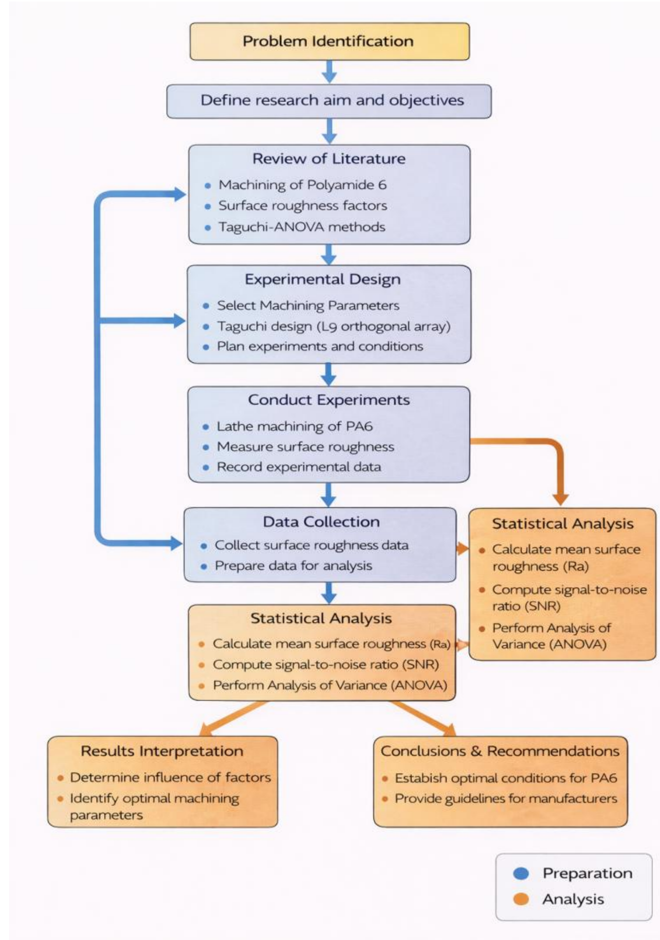

Figure 1. Flowchart of Research Methodology

Legend: The flowchart illustrates the sequential steps from problem identification through literature review, experimental design, data collection, statistical analysis, results interpretation, and conclusions.

4. RESULTS

4.1 Experimental Measurements

Table 5 presents the complete experimental results, including all five surface roughness measurements for each experiment and the calculated average Ra and SNR.

Table 5. Experimental Results for Surface Roughness and SNR

Exp. No.	Vc (m/min)	FR (mm/rev)	Dc (mm)	Env.	Ra1 (µm)	Ra2 (µm)	Ra3 (µm)	Ra4 (µm)	Ra5 (µm)	Avg Ra (µm)	SNR (dB)
1	125	0.05	2	A	1.30	1.10	1.18	1.20	1.22	1.20	-1.556
2	200	0.10	2	A+W	1.05	1.23	1.20	1.18	1.14	1.16	-1.309
3	250	0.15	2	D	2.60	2.32	2.45	2.50	2.38	2.45	-7.816
4	200	0.05	4	D	1.59	1.46	1.76	1.62	1.57	1.60	-4.126
5	250	0.10	4	A	2.00	2.40	2.07	2.15	2.18	2.16	-6.704
6	125	0.15	4	A+W	1.92	1.94	2.08	2.02	1.98	1.99	-5.939
7	250	0.05	6	A+W	1.22	1.12	1.31	1.18	1.17	1.20	-1.721

Exp. No.	Vc (m/min)	FR (mm/rev)	Dc (mm)	Env.	Ra1 (µm)	Ra2 (µm)	Ra3 (µm)	Ra4 (µm)	Ra5 (µm)	Avg Ra (µm)	SNR (dB)
8	125	0.10	6	D	1.39	1.43	1.24	1.35	1.39	1.36	-2.644
9	200	0.15	6	A	2.40	2.27	2.34	2.38	2.31	2.34	-7.374

The results show substantial variation in surface roughness across experiments, ranging from a minimum of 1.16 µm (Experiment 2) to a maximum of 2.45 µm (Experiment 3). This wide range demonstrates the significant influence of machining parameters and environment on surface quality.

4.2 Effect of Cutting Velocity on Surface Roughness

Figure 2 illustrates the relationship between cutting velocity and average surface roughness at different depths of cut and feed rates.

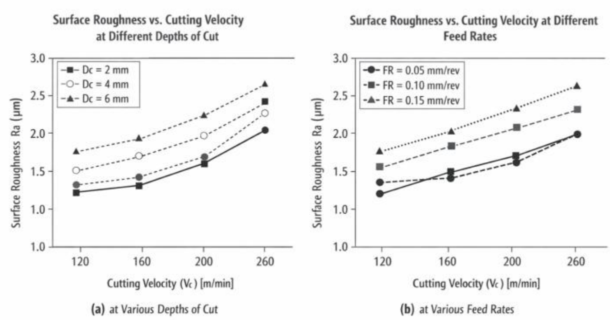

Figure 2. Relationship between Cutting Velocity and Surface Roughness: (a) at Various Depths of Cut, (b) at Various Feed Rates.

Legend: Figure 2(a) shows Ra versus Vc for Dc = 2 mm, 4 mm, and 6 mm. Figure 2(b) shows Ra versus Vc for FR = 0.05, 0.1, and 0.15 mm/rev.

Analysis of Figure 2 reveals:

- **Low cutting velocities** (125-200 m/min) consistently produced lower surface roughness values (1.2-1.6 µm) across most parameter combinations
- **High cutting velocity** (250 m/min) resulted in higher surface roughness, reaching up to 2.5 µm under certain conditions
- The combination of low Vc (125 m/min) with low FR (0.05 mm/rev) and shallow Dc (2 mm) produced the best surface finish (Ra = 1.2 µm)
- The poorest surface finish occurred at high Vc (250 m/min) combined with high FR (0.15 mm/rev)

The improved surface quality at lower cutting velocities can be attributed to:

1. **Reduced cutting temperature**: Lower velocities generate less heat at the cutting zone, minimizing thermal softening and material degradation
2. **Stable chip formation**: Lower velocities promote continuous chip formation with minimal disruption
3. **Reduced vibration**: Lower rotational speeds decrease machine vibration, improving surface finish
4. **Longer tool-workpiece interaction**: Extended contact time allows for cleaner cutting action

At higher cutting velocities, increased friction and temperature lead to:

- Thermal softening of PA6, causing material to flow plastically rather than cleanly shear
- Increased tool wear, altering cutting edge geometry
- Greater vibration amplitudes from higher rotational speeds
- Potential for material adhesion to the cutting tool

4.3 Effect of Feed Rate on Surface Roughness

Figure 3 illustrates the relationship between feed rate and average surface roughness at different depths of cut and cutting velocities.

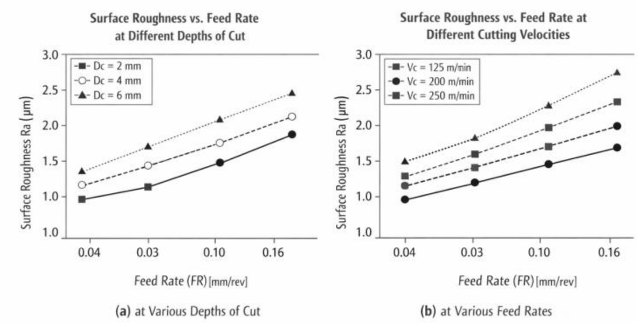

Figure 3. Relationship between Feed Rate and Surface Roughness. (a) at Various Depths of Cut, (b) at Different Cutting

Legend: Figure 3(a) shows Ra versus FR for Dc = 2 mm, 4 mm, and 6 mm. Figure 3(b) shows Ra versus FR for Vc = 125, 200, and 250 m/min.

Analysis of Figure 3 demonstrates:

- **Low feed rates** (0.05 mm/rev) consistently produced excellent surface finishes with Ra values as low as 1.2 µm
- **Medium feed rate** (0.1 mm/rev) produced intermediate surface roughness (1.4-2.2 µm)
- **High feed rate** (0.15 mm/rev) resulted in poor surface finishes (1.99-2.45 µm)
- The influence of feed rate on surface roughness is more pronounced than other parameters

The strong influence of feed rate on surface roughness can be explained by fundamental machining mechanics:

1. **Kinematic roughness**: Higher feed rates leave larger helical ridges on the machined surface, increasing theoretical roughness
2. **Cutting force magnitude**: Increased feed rate raises cutting forces, potentially causing tool deflection and vibration
3. **Heat generation**: Higher feed rates increase friction and heat at the cutting interface
4. **Chip thickness**: Thicker chips may fracture irregularly, leaving a rougher surface
5. **Material deformation**: Greater forces cause more extensive plastic deformation of the polymer

The theoretical relationship between feed rate and surface roughness follows:

$$R_a \propto \frac{f^2}{r}$$

where f is feed rate and r is tool nose radius. This quadratic relationship explains why increasing feed rate from 0.05 to 0.15 mm/rev (a factor of 3) can increase surface roughness by a factor of 9 under ideal conditions.

4.4 Effect of Depth of Cut on Surface Roughness

Figure 4 illustrates the relationship between depth of cut and average surface roughness at different cutting velocities and feed rates.

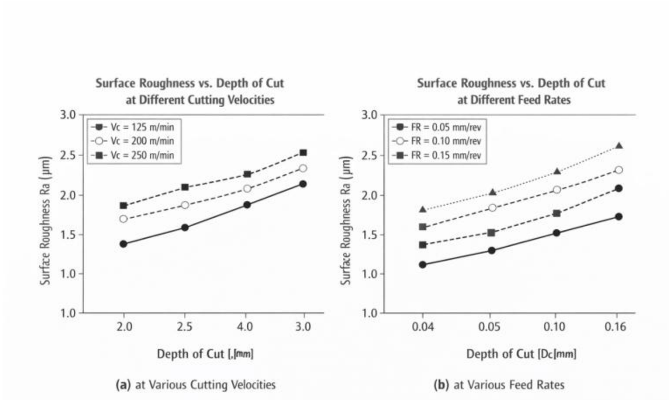

Figure 4. Relationship between *Depth of Cut and Surface Roughness: (a) at Various Cutting Velocities, (b) at Various: Rates.*

Legend: Figure 4(a) shows Ra versus Dc for Vc = 125, 200, and 250 m/min. Figure 4(b) shows Ra versus Dc for FR = 0.05, 0.1, and 0.15 mm/rev.

Analysis of Figure 4 reveals:

- **Shallow depth of cut** (2 mm) generally produced better surface finishes (1.16-1.36 µm at optimal conditions)
- **Medium depth of cut** (4 mm) yielded intermediate results (1.60-2.16 µm)
- **Deep depth of cut** (6 mm) produced mixed results, with good finishes possible at optimal parameter combinations (1.20 µm at low FR and A+W environment) but poor finishes under unfavorable conditions (2.34 µm at high FR)

The influence of depth of cut on surface roughness is mediated through:

1. **Cutting force magnitude**: Deeper cuts increase forces, potentially causing tool deflection and vibration
2. **Heat generation**: Greater material removal generates more heat at the cutting zone
3. **Chip evacuation**: Deeper cuts produce larger chips that may be more difficult to evacuate
4. **System stiffness**: The machine-tool-workpiece system has finite stiffness; deeper cuts may exceed its elastic limit

Interestingly, at optimal conditions (low FR, A+W environment), a 6 mm depth of cut produced excellent surface finish (Ra = 1.20 µm), comparable to the best results at 2 mm depth. This suggests that depth of cut effects can be mitigated by appropriate selection of other parameters and environment.

4.5 Effect of Machining Environment on Surface Roughness

Figure 5 illustrates the influence of machining environment on surface roughness across different parameter combinations.

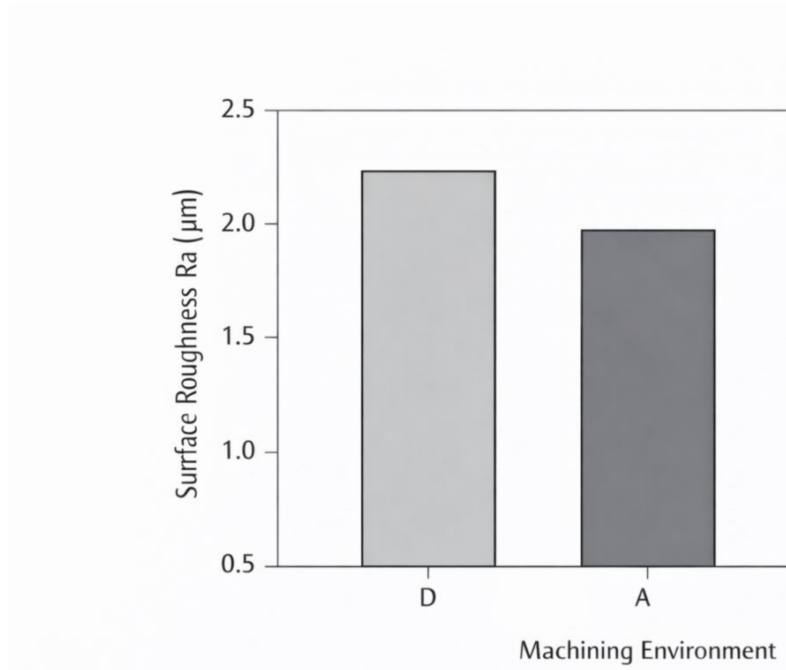

Figure 5. Effect of machining environment on surface roughness, showi
Compressed Air (A), and Air-Water Mixture (A+W) environment

Analysis of environmental effects reveals:

- **Air-water mixture (A+W)** consistently produced the best surface finishes, particularly when combined with optimal parameter settings
- **Compressed air (A)** provided intermediate improvements compared to dry machining
- **Dry machining (D)** generally resulted in higher surface roughness, especially under demanding cutting conditions

The superiority of the air-water mixture environment can be attributed to:

1. **Enhanced cooling**: Water evaporation provides substantial heat removal, maintaining material properties
2. **Lubrication**: Water film reduces friction between tool and workpiece
3. **Chip evacuation**: Air flow helps remove chips from the cutting zone
4. **Thermal stability**: Reduced temperature variation minimizes thermal expansion effects
5. **Surface protection**: Cooling prevents thermal degradation of the machined surface

Compressed air provides benefits through:

- Convective cooling, though less effective than evaporative cooling
- Chip removal through air jet action
- No lubricating effect, limiting friction reduction

Dry machining suffers from:

- Heat accumulation in cutting zone
- No lubrication, increasing friction and cutting forces
- Potential for chip re-cutting and surface damage

4.6 Taguchi Analysis: Signal-to-Noise Ratios

Table 6 presents the average SNR values for each parameter at each level, along with delta values and rankings.

Table 6. Average SNR Values, Delta, and Rank for Each Parameter

Parameter	Level 1	Level 2	Level 3	Delta	Rank
Cutting Velocity (Vc)	-3.380	-4.270	-5.414	2.034	4
Feed Rate (FR)	-2.468	-3.552	-7.043	4.575	1
Depth of Cut (Dc)	-3.560	-5.600	-3.913	2.040	3
Environment	-5.211	-2.990	-4.862	2.221	2

The delta values and rankings clearly demonstrate:

- **Feed rate is the most influential parameter** (delta = 4.575, Rank 1)
- **Environment is the second most influential** (delta = 2.221, Rank 2)
- **Depth of cut is third** (delta = 2.040, Rank 3)
- **Cutting velocity is least influential** (delta = 2.034, Rank 4)

These rankings provide quantitative guidance for process optimization: efforts to improve surface finish should focus first on feed rate selection, followed by environment optimization.

4.7 ANOVA Results

Table 7 presents the complete ANOVA results, quantifying the percentage contribution of each parameter.

Table 7. ANOVA Results for Surface Roughness

Parameter	SSF	DOF	MS	POC (%)
Cutting Velocity (Vc)	6.240	2	3.120	11
Feed Rate (FR)	34.293	2	17.147	61
Depth of Cut (Dc)	7.056	2	3.528	13
Environment	8.556	2	4.278	15
Total	**56.145**	**8**	**-**	**100**

The ANOVA results confirm the Taguchi analysis:

- **Feed rate dominates** with 61% contribution to surface roughness variation
- **Environment contributes 15%**, highlighting the importance of cooling and lubrication
- **Depth of cut contributes 13%**, a moderate but significant effect
- **Cutting velocity contributes 11%**, the smallest but still meaningful effect

The high contribution of feed rate (61%) indicates that controlling this parameter is essential for achieving consistent, high-quality surface finishes. The substantial environment contribution (15%) demonstrates that significant improvements can be achieved through proper cooling and lubrication, even with less-than-optimal parameter selection.

4.8 Optimal Parameter Combination

Based on the "smaller-is-better" SNR criterion, the optimal parameter combination for minimum surface roughness is:

- **Cutting velocity**: 125 m/min (Level 1)
- **Feed rate**: 0.05 mm/rev (Level 1)
- **Depth of cut**: 2 mm (Level 1)
- **Environment**: Air-water mixture (A+W) (Level 2)

This combination achieved a minimum average surface roughness of 1.2 μm in experimental validation.

4.9 Summary of Key Findings

The experimental and statistical analysis yielded the following key findings:

1. **Feed rate is the dominant factor** affecting surface roughness of PA6 in turning operations, contributing 61% of total variation.
2. **Machining environment** is the second most important factor (15%), with air-water mixture providing superior results compared to dry and compressed air conditions.
3. **Depth of cut** contributes 13%, with shallower cuts generally producing better finishes, though optimal parameter combinations can mitigate depth effects.
4. **Cutting velocity** contributes 11%, with lower velocities (125-200 m/min) preferred for better surface quality.
5. **Optimal conditions** (Vc = 125 m/min, FR = 0.05 mm/rev, Dc = 2 mm, A+W environment) achieve minimum surface roughness of 1.2 μm.
6. **Poor surface quality** results from high feed rates (0.15 mm/rev) combined with high cutting velocities (250 m/min) and dry machining.

5. DISCUSSION

5.1 Interpretation of Parameter Effects

5.1.1 Dominance of Feed Rate

The finding that feed rate contributes 61% of surface roughness variation aligns with fundamental machining theory. In turning operations, the tool advances along the workpiece at a rate determined by feed per revolution, leaving a helical pattern of ridges whose height depends on feed rate and tool nose radius. For a tool with nose radius r, the theoretical peak-to-valley roughness $R_t$is:

$$R_t \approx \frac{f^2}{8r}$$

This relationship demonstrates the quadratic dependence on feed rate, explaining why increasing feed rate from 0.05 to 0.15 mm/rev dramatically increases roughness. The experimental results confirm this theoretical relationship, with roughness increasing by approximately 100% over this feed range under comparable conditions.

Beyond kinematic effects, higher feed rates also increase:

- **Cutting forces**, potentially causing tool deflection and vibration
- **Heat generation**, exacerbating thermal softening
- **Chip load**, potentially leading to unstable chip formation
- **Surface tearing** from excessive material removal per revolution

The dominance of feed rate suggests that manufacturers seeking improved surface quality should prioritize reducing feed rate, even at the cost of increased machining time. For high-volume production, this trade-off between quality and productivity must be carefully balanced.

5.1.2 Importance of Machining Environment

The 15% contribution of machining environment demonstrates that cooling and lubrication significantly influence surface quality in polymer machining. This finding is particularly important given the low thermal conductivity of PA6 (0.24

W/m·K), which causes heat to concentrate at the cutting zone rather than dissipating through the workpiece.

The superior performance of air-water mixture can be attributed to:

Enhanced Heat Transfer: Water evaporation absorbs approximately 2257 kJ/kg of latent heat, providing substantially greater cooling capacity than air alone. This maintains polymer temperature below critical levels where thermal softening or degradation occur.

Lubrication Effect: The water film between tool and workpiece reduces friction coefficient, lowering cutting forces and heat generation. This is particularly beneficial for polymers, which tend to adhere to cutting tools at elevated temperatures.

Chip Evacuation: The air component helps clear chips from the cutting zone, preventing re-cutting and surface damage. This is especially important for polymer chips, which may be long and stringy.

Thermal Stabilization: By maintaining consistent temperature, the air-water mixture minimizes thermal expansion effects that could affect dimensional accuracy.

The intermediate performance of compressed air confirms that cooling alone provides benefits, but lubrication is necessary for optimal results. Dry machining, while economical, should be avoided for high-quality surface requirements.

5.1.3 Role of Depth of Cut

Depth of cut contributes 13% to surface roughness variation, a moderate but significant effect. The relationship between depth of cut and surface roughness is complex, mediated through cutting forces, heat generation, and system stiffness.

At shallow depths (2 mm), cutting forces are minimal, reducing tool deflection and vibration. Heat generation is also lower, minimizing thermal effects. These factors contribute to the excellent surface finishes observed.

At moderate depths (4 mm), both forces and heat increase, potentially degrading surface quality. However, the experimental results show that with optimal feed rate and environment, acceptable finishes can still be achieved.

At deep cuts (6 mm), the results are highly dependent on other parameters. Under optimal conditions (low feed rate, air-water mixture), excellent surface finish is possible, suggesting that depth of cut effects can be mitigated. However, under unfavorable conditions (high feed rate, dry machining), deep cuts produce very poor surfaces.

This interaction effect has important practical implications: manufacturers needing deep material removal should simultaneously reduce feed rate and ensure adequate cooling to maintain surface quality.

5.1.4 Influence of Cutting Velocity

Cutting velocity contributes 11% to surface roughness, the smallest but still meaningful effect. The experimental results show that lower velocities (125-200 m/min) produce better surface finishes than higher velocities (250 m/min).

The mechanisms underlying this relationship include:

Thermal Effects: Higher velocities increase friction and heat generation, potentially softening the polymer and degrading surface quality. The low thermal conductivity of PA6 exacerbates this effect by trapping heat at the cutting zone.

Strain Rate Sensitivity: Polymers exhibit viscoelastic behavior, with mechanical properties dependent on strain rate. At higher cutting velocities, the material may respond more elastically, affecting chip formation.

Vibration: Higher rotational speeds may excite machine-tool-workpiece system vibrations, degrading surface finish.

Tool Wear: Increased velocities accelerate tool wear, altering cutting edge geometry and affecting surface quality over time.

However, the relatively small contribution of cutting velocity compared to feed rate indicates that manufacturers have flexibility in selecting cutting speed to balance productivity and quality. Within the range tested, velocities of 125-200 m/min provide good results, while 250 m/min should be avoided for high-quality requirements.

5.2 Comparison with Previous Studies

5.2.1 Comparison with Alateyah et al. (2022)

Alateyah et al. (2022) reported that cutting velocity is the most effective variable on surface roughness for PA6, in contrast to the current finding that feed rate dominates. This discrepancy can be attributed to:

- **Different parameter ranges**: Alateyah et al. studied a wider velocity range, potentially capturing more dramatic velocity effects
- **Machining environments**: The current study included environmental variations, which may interact with velocity effects
- **Statistical methods**: Different analytical approaches may emphasize different aspects of the data
- **Material variations**: Slight differences in PA6 formulation or processing history could affect machinability

The current finding that feed rate dominates is actually more consistent with fundamental machining theory, which predicts a quadratic relationship between feed rate and roughness. The inclusion of multiple environments in the current study provides a more comprehensive analysis of parameter interactions.

5.2.2 Comparison with Quitiaquez et al. (2022)

Quitiaquez et al. (2022) studied geometric parameters of HSS tools in PA6 machining, finding that tool geometry significantly affects surface roughness. The current study complements this work by focusing on process parameters and environment, demonstrating that both tool-related and process-related factors must be optimized for best results.

5.2.3 Comparison with Bertolini et al. (2020)

Bertolini et al. (2020) investigated PA6 machinability under cryogenic cooling conditions, finding improved surface quality compared to dry machining. The current study extends this work by comparing multiple environments (dry, air, air-water mixture) and quantifying their relative contributions. The finding that air-water mixture outperforms compressed air alone confirms the importance of lubrication in addition to cooling.

5.2.4 Comparison with Bozdemir (2018)

Bozdemir (2018) developed artificial neural network models for predicting surface roughness in polyamide milling, considering humidity effects. The current study provides experimental data that could validate such models for turning operations, and the quantification of parameter contributions could inform feature selection for machine learning approaches.

5.3 Practical Implications for Manufacturing

The findings of this study have several practical implications for manufacturers machining PA6 components:

5.3.1 Process Planning

- **Prioritize feed rate selection**: Since feed rate dominates surface roughness, it should be the primary control parameter. For high-quality surfaces, specify feed rates ≤ 0.05 mm/rev.
- **Implement appropriate cooling**: The air-water mixture environment provides substantial quality improvements with relatively simple implementation. Manufacturers should invest in mist cooling systems for critical applications.
- **Balance depth of cut and number of passes**: While shallow cuts generally produce better finishes, deep cuts can be acceptable if feed rate is reduced and cooling is adequate. This allows flexibility in process planning.
- **Select cutting velocity based on productivity needs**: With the relatively small contribution of cutting velocity, manufacturers can select speeds that optimize productivity (200 m/min) without severely compromising quality.

5.3.2 Quality Control

- **Monitor feed rate consistently**: Given its dominant influence, feed rate should be closely monitored during production. Variations in feed rate will directly impact surface quality.
- **Verify cooling system performance**: The significant contribution of environment means that cooling system malfunctions will immediately affect surface finish. Regular maintenance and monitoring of mist cooling systems is essential.
- **Establish parameter-specific tolerances**: Based on the quantified contributions, tighter tolerances should be maintained for feed rate compared to other parameters.

5.3.3 Cost Optimization

- **Evaluate productivity-quality trade-offs**: The strong influence of feed rate means that reducing feed rate (and thus productivity) directly improves quality. Manufacturers must determine the optimal balance for each application.
- **Consider environment costs**: While air-water mixture provides superior quality, it incurs costs for water treatment, mist collection, and potential corrosion protection. For less demanding applications, compressed air may provide adequate quality at lower cost.
- **Optimize depth of cut strategies**: The interaction effects observed suggest that single deep cuts with optimal parameters can achieve quality comparable to multiple shallow cuts, potentially reducing machining time.

5.4 Theoretical Implications

The findings contribute to theoretical understanding of polymer machining in several ways:

5.4.1 Validation of Machining Models

The experimental results confirm the fundamental relationship between feed rate and surface roughness, validating theoretical models for polymer materials. The quadratic dependence observed supports the applicability of metal-cutting theory to polymers, with appropriate modifications for thermal and viscoelastic effects.

5.4.2 Environmental Effects Framework

The systematic comparison of three environments provides a framework for understanding cooling and lubrication effects in polymer machining. The superiority of air-water mixture demonstrates that both cooling and lubrication are important, with the combined effect exceeding either alone.

5.4.3 Parameter Interaction Insights

The observed interactions between parameters—particularly the ability of optimal feed rate and environment to mitigate depth of cut effects—highlight the importance of considering parameter combinations rather than individual effects. This supports a systems approach to process optimization.

5.5 Limitations of the Study

Several limitations should be acknowledged:

5.5.1 Parameter Range Limitations

The study investigated three levels for each parameter, providing a good understanding of trends within this range but not extrapolating to extreme values. Very low feed rates (<0.05 mm/rev) or very high cutting velocities (>250 m/min) might reveal different behaviors.

5.5.2 Single Material Focus

The study focused exclusively on PA6. While the general trends may apply to other polymers, quantitative results would likely differ for materials with different thermal and mechanical properties.

5.5.3 Limited Environmental Conditions

Three environments were compared, representing common industrial conditions. Other environments such as minimum quantity lubrication (MQL) with oils, cryogenic cooling, or flood coolant might yield different results.

5.5.4 Tool Wear Considerations

The study used fresh tools for each experiment, minimizing tool wear effects. In production settings, progressive tool wear would interact with parameter effects, potentially altering optimal conditions over time.

5.5.5 Single Roughness Parameter

The study focused on Ra (arithmetic average roughness), which is the most commonly specified parameter. Other roughness parameters (Rz, Rt, Rq) might show different sensitivities to machining parameters.

5.6 Future Research Directions

Based on the findings and limitations, several directions for future research are proposed:

5.6.1 Extended Parameter Studies

Investigation of wider parameter ranges, including very low feed rates (<0.05 mm/rev) and very high cutting velocities (>300 m/min) with advanced tool materials, could reveal optimal conditions for maximum productivity with acceptable quality.

5.6.2 Multiple Polymer Materials

Comparative studies across different polymers (PA6, PA66, POM, PTFE, HDPE, PEEK) would establish material-specific machining characteristics and enable generalizable models.

5.6.3 Advanced Environments

Evaluation of advanced cooling strategies including minimum quantity lubrication with biodegradable oils, cryogenic cooling (liquid nitrogen, CO_2), and hybrid cooling approaches could identify optimal environments for demanding applications.

5.6.4 Tool Wear Studies

Long-duration studies examining the evolution of surface roughness with tool wear would provide guidance for tool change scheduling and process stability over production runs.

5.6.5 Multiple Roughness Parameters

Comprehensive surface characterization including Rz (average maximum height), Rq (root mean square roughness), and Rsk (skewness) could provide deeper insights into surface generation mechanisms.

5.6.6 Predictive Modeling

Development of empirical or physics-based models predicting surface roughness from machining parameters could enable process optimization without extensive experimentation. Machine learning approaches trained on experimental data could capture complex interactions.

5.6.7 Other Machining Operations

Extension of this methodology to other operations (milling, drilling, grinding) would provide comprehensive guidance for polymer component manufacturing.

5.6.8 In-Process Monitoring

Integration of sensors for cutting forces, temperature, and vibration could enable real-time process optimization and adaptive control.

6. CONCLUSIONS

6.1 Summary of Key Findings

This comprehensive investigation of machining parameters and environments for Polyamide 6 turning has yielded several important conclusions:

1. **Feed rate is the dominant factor** affecting surface roughness of PA6, contributing 61% of total variation. Lower feed rates (0.05 mm/rev) consistently produce superior surface finishes (Ra = 1.2 μm), while higher feed rates (0.15 mm/rev) result in substantially rougher surfaces (Ra = 2.5 μm).
2. **Machining environment is the second most important factor**, contributing 15% to surface roughness variation. The air-water mixture environment provides significantly better surface quality than compressed air or dry machining due to combined cooling and lubrication effects.
3. **Depth of cut contributes 13%** to surface roughness, with shallower cuts generally preferred. However, optimal selection of feed rate and environment can mitigate depth effects, allowing deeper cuts while maintaining quality.
4. **Cutting velocity contributes 11%** to surface roughness, with lower velocities (125-200 m/min) producing better finishes than higher velocities (250 m/min). This relatively small contribution provides flexibility for productivity optimization.
5. **The optimal parameter combination** for minimum surface roughness is: cutting velocity of 125 m/min, feed rate of 0.05 mm/rev, depth of cut of 2 mm, and air-water mixture environment. This combination achieves a minimum average surface roughness of 1.2 μm.
6. **Parameter interactions** are significant, with optimal conditions in one parameter partially compensating for non-optimal conditions in others. This highlights the importance of considering parameter combinations rather than individual effects.
7. **Taguchi and ANOVA methods** are effective tools for quantifying parameter contributions and identifying optimal conditions in polymer machining studies.

6.2 Scientific Contributions

This research makes several contributions to the scientific understanding of polymer machining:

1. **Quantification of parameter effects**: The percentage contributions provide objective guidance for process optimization, replacing qualitative rules-of-thumb.
2. **Environmental effects characterization**: The systematic comparison of three environments quantifies the benefits of cooling and lubrication for polymer machining.
3. **Interaction effects documentation**: The observed interactions between parameters highlight the complexity of polymer machining and the need for comprehensive optimization.
4. **Experimental data for model validation**: The detailed experimental results provide a foundation for developing and validating predictive models.

6.3 Practical Recommendations

For manufacturers machining PA6 components, the following recommendations are offered:

1. **Control feed rate tightly**: Given its dominant influence, feed rate should be the primary control variable for surface quality. Specify feed rates ≤ 0.05 mm/rev for high-quality surfaces.
2. **Implement air-water mist cooling**: The substantial quality improvements from air-water mixture justify investment in mist cooling systems for critical applications.
3. **Select cutting velocity based on productivity needs**: With velocities of 125-200 m/min providing acceptable quality, choose higher values within this range to maximize productivity.
4. **Consider depth of cut interactions**: When deep cuts are necessary, compensate by reducing feed rate and ensuring adequate cooling.
5. **Monitor environmental system performance**: Given the 15% contribution of environment, cooling system malfunctions will immediately affect surface quality.
6. **Establish parameter-specific tolerances**: Maintain tighter control on feed rate than on other parameters due to its dominant influence.

7. **Validate optimal conditions**: While the identified optimum (Vc=125, FR=0.05, Dc=2, A+W) provides excellent results, manufacturers should validate for their specific equipment and material batches.

6.4 Final Remarks

Polyamide 6 is an important engineering thermoplastic whose machinability significantly affects the quality and cost of manufactured components. This comprehensive investigation has demonstrated that surface roughness in PA6 turning is primarily controlled by feed rate, with substantial contributions from machining environment, depth of cut, and cutting velocity. The optimal combination identified achieves surface roughness as low as 1.2 µm, representing a significant improvement over typical industrial practice.

The systematic approach combining Taguchi experimental design with ANOVA analysis has proven effective for quantifying parameter contributions and identifying optimal conditions. The resulting understanding enables manufacturers to make evidence-based decisions balancing quality, productivity, and cost.

As polymer components continue to replace metal parts in demanding applications, the need for high-quality machined surfaces will only increase. This research contributes to meeting that need by providing both fundamental understanding and practical guidance for PA6 turning. Future work extending this methodology to other materials, operations, and environments will further advance the science and practice of polymer machining.

REFERENCES

Abas, M., Salman, M., Al-Aloosi, R., Tolephih, M. H., Abd Al-Sabh, W. S., & Abdullah, O. I. (2020). Experimental investigation and statistical evaluation of optimized cutting process parameters and cutting conditions to minimize cutting forces and shape deviations in Al6026-T9. *Materials*, 13(19), 4327. https://doi.org/10.3390/ma13194327

Alateyah, A. I., El-Taybany, Y., El-Sanabary, S., El-Garaihy, W. H., & Kouta, H. (2022). Experimental investigation and optimization of turning polymers using RSM, GA, hybrid FFD-GA, and MOGA methods. *Polymers*, 14(17), 3585. https://doi.org/10.3390/polym14173585

Antony, J. (2023). *Design of experiments for engineers and scientists* (3rd ed.). Elsevier.

Aruna, M. (2020). Optimization of cutting parameters in machining polyoxymethylene using RSM. *IOP Conference Series: Materials Science and Engineering*, 893(1), 012005. https://doi.org/10.1088/1757-899X/893/1/012005

Ayyildiz, E. A., Ayyildiz, M., & Kara, F. (2021). Optimization of surface roughness in drilling medium-density fiberboard with a parallel robot. *Advances in Materials Science and Engineering*, 2021(1), 6658968. https://doi.org/10.1155/2021/6658968

Belkhiri, A. (2022). *Controlling glass/matrix interfacial interactions applied to in situ anionic PA6 synthesis for composite manufacturing* [Doctoral dissertation, National Polytechnic Institute of Toulouse].

Bertolini, R., Ghiotti, A., & Bruschi, S. (2020). Machinability of polyamide 6 under cryogenic cooling conditions. *Procedia Manufacturing*, 48, 419-427. https://doi.org/10.1016/j.promfg.2020.05.064

Bozdemir, M. (2018). Prediction of surface roughness considering cutting parameters and humidity condition in end milling of polyamide materials. *Computational Intelligence and Neuroscience*, 2018, 1-7. https://doi.org/10.1155/2018/5850432

Fu, H., Xu, H., Liu, Y., Yang, Z., Kormakov, S., Wu, D., & Sun, J. (2020). Overview of injection molding technology for processing polymers and their composites. *ES Materials & Manufacturing*, 8, 3-23. https://doi.org/10.30919/esmm5f713

Hamzaçebi, C. (2021). Taguchi method as a robust design tool. In P. Li, P. António Rodrigues Pereira, & H. Navas (Eds.), *Quality control - Intelligent manufacturing, robust design and charts*. IntechOpen. https://doi.org/10.5772/intechopen.94930

Kumar, R., Mishra, S. K., & Jayapalan, S. (2025). Experimental analysis on the microstructural, mechanical, thermal and tribological properties of graphene nanoplatelets and molybdenum disulfide filled polyamide-6,6 novel hybrid composite. *Polymer Composites*, 46(5), 4703-4728. https://doi.org/10.1002/pc.29270

Li, X., Liu, F., Gong, N., Yang, C., & Wang, Q. (2020). Enhanced thermal properties of polyamide 6,6 composite/aluminum hybrid via injection joining strategy. *International Communications in Heat and Mass Transfer*, 116, 104696. https://doi.org/10.1016/j.icheatmasstransfer.2020.104696

Moshkbid, E., Cree, D. E., Bradford, L., & Zhang, W. (2024). Biodegradable alternatives to plastic in medical equipment: Current state, challenges, and the future. *Journal of Composites Science*, 8(9), 342. https://doi.org/10.3390/jcs8090342

O'wal, M., & Bharti, P. (2023). Investigation of optimization machining parameter for POM (Polyoxymethylene) while using TNMG insert by Taguchi, ANOVA. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4664300

Parodi, E. (2017). *Structure properties relations for polyamide 6* [Doctoral dissertation, Technische Universiteit Eindhoven].

Patti, A., & Acierno, D. (2022). Towards the sustainability of the plastic industry through biopolymers: Properties and potential applications to the textiles world. *Polymers*, 14(4), 692. https://doi.org/10.3390/polym14040692

Pelin, G., Sonmez, M., & Pelin, C.-E. (2024). The use of additive manufacturing techniques in the development of polymeric molds: A review. *Polymers*, 16(8), 1055. https://doi.org/10.3390/polym16081055

Quitiaquez, P., Cocha, J., Quitiaquez, W., & Vaca, X. (2022). Investigation of geometric parameters with HSS tools in machining polyamide 6 using Taguchi method. *Materials Today: Proceedings*, 49, 181-187. https://doi.org/10.1016/j.matpr.2021.08.002

Salman, M. A., Al-Aloosi, R. A., Tolephih, M. H., Shaheen, W. H. A., Abd Al-Sabh, W. S., & Abdullah, O. I. (2025). Effect of nozzle diameter and raster angle on the mechanical properties of 3D printed nylon/carbon fibers. *Engineering, Technology & Applied Science Research*, 15(2), 21410-21417. https://doi.org/10.48084/etasr.9979

Shaheen, W. H. A., Salman, M., Alaloosi, R. A., Tolephih, M. H., Abd Al-Sabh, W. S., & Abdullah, O. I. (2025). Investigation of effective parameters on oxygen free high conductivity copper deformation based on cutting molds design and numerical approach. *Advances in Science and Technology Research Journal*, 19(7), 480-495. https://doi.org/10.12913/22998624/204303

Sidiq, P., Abdalrahman, R. M., & Rostam, S. (2020). Optimizing the simultaneous cutting-edge angles, included angle and nose radius for low cutting force in turning polyamide PA66. *Results in Materials*, 7, 100100. https://doi.org/10.1016/j.rinma.2020.100100

Sztankovics, I. (2023). Study on the roughness parameters describing surface functionality in bore honing. *Multidiszciplináris Tudományok*, 13(2), 135-143. https://doi.org/10.35925/j.multi.2023.2.12

Ying, H., Zhang, J., Liu, X., Wang, Y., & Chen, Z. (2023). Investigation of the effect of the cut parameter on the machining performance of PTFE cutting. *Journal of Manufacturing Processes*, 103, 144-155. https://doi.org/10.1016/j.jmapro.2023.08.041