RESEARCH ARTICLE

RSP Science Hub

International Research Journal on Advanced Science Hub
2582-4376
www.rspsciencehub.com
Vol. 08, Issue 10 October

Check for updates

http://dx.doi.org/10.47392/IRJASH.2026.045

Experimental Investigation and Optimization of Drilling Parameters to Minimize Burr Formation and Tool Wear Using Response Surface Methodology

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Article history

Received: 06 August 2026
Accepted: 04 September 2026
Published: 08 October2026

Keywords:

Burr Formation, Tool Wear Optimization, Drilling Parameters, Response Surface Methodology (RSM), Multi-Response Optimization .

Abstract

The present study investigates the optimization of drilling parameters for minimizing burr formation and tool wear using advanced statistical techniques. Experimental drilling trials were conducted by varying cutting speed, feed rate, and tool geometry under controlled machining conditions. Burr height, tool wear, surface roughness, and thrust force were selected as the major performance responses for analysis. Design of Experiments (DOE), Analysis of Variance (ANOVA), regression modelling, and Response Surface Methodology (RSM) were employed to evaluate the significance of machining parameters and develop predictive models. The results indicated that feed rate had the highest influence on burr formation, while cutting speed significantly affected tool wear progression. Multi-response optimization using desirability function analysis identified the optimum drilling condition at 1500 rpm cutting speed, 0.08 mm/rev feed rate, and 120°-point angle, achieving minimum burr height and reduced tool wear with a desirability value of 0.948. Validation experiments confirmed the reliability of the developed models with prediction accuracy above 94%. The optimized drilling conditions improved machining quality, enhanced tool life, reduced machining cost, and increased manufacturing productivity. The study demonstrates that integrated statistical optimization provides an effective and reliable approach for improving drilling performance in modern manufacturing industries.

1. Introduction

1.1. Background of Drilling Process

Drilling is one of the most widely used machining operations in modern manufacturing industries for producing circular holes in metallic and non-metallic materials. The process involves material removal using a rotating cutting tool known as a drill bit. Due to its simplicity, versatility, and capability to produce holes with acceptable

dimensional accuracy, drilling is extensively adopted in mass production and precision engineering applications. The quality of drilled holes significantly influences assembly accuracy, fastening performance, and structural reliability of manufactured products [01], [04]. In manufacturing industries, drilling contributes substantially to the total machining operations performed during component production. Studies indicate that a large percentage of machining time in industrial applications is associated with hole-making processes. Therefore, improving drilling efficiency directly affects productivity, machining cost, and product quality. The performance of drilling operations is influenced by various factors such as cutting speed, feed rate, tool geometry, cooling conditions, and workpiece material properties [05], [10].

Importance of Drilling in Manufacturing Industries

Drilling plays a critical role in the production of mechanical components where accurate hole-making is essential for joining, fastening, lubrication passages, and structural assembly. It is considered a fundamental machining operation because nearly every industrial product requires drilled holes during manufacturing.

Major Importance of Drilling

- Production of precise holes for assembly operations
- Improvement of dimensional accuracy and alignment
- Essential operation in automated manufacturing systems
- Important for mass production and interchangeable components
- Enables efficient fastening and joining processes

Research studies have shown that optimized drilling operations improve machining quality and reduce manufacturing defects such as burr formation and excessive tool wear [06], [16] Shown in Figure 1 - 3.

Applications in Automotive, Aerospace, and Fabrication Sectors

Drilling operations are extensively used in different industrial sectors due to the requirement of precise and reliable hole-making processes.

Automotive Industry

In automotive manufacturing, drilling is used in engine blocks, transmission housings, chassis assemblies, brake systems, and suspension components. Accurate drilling is necessary to maintain proper alignment and assembly precision in high-speed production systems [02], [18].

Aerospace Industry

The aerospace sector demands extremely high-quality drilling because aircraft components require precise holes with minimum defects. Drilling is performed in lightweight alloys and composite materials where burr formation and delamination can adversely affect structural integrity and safety [08], [25].

Fabrication and General Engineering

Fabrication industries use drilling for structural assemblies, sheet metal joining, pipe systems, and heavy equipment manufacturing. Proper drilling quality ensures ease of assembly and improved product reliability [24], [27] Shown in Figure 4.



Figure 1 Drilling Operation in Manufacturing Industries



Figure 2 Industrial Worker Operating a CNC Milling Machine



Figure 3 CNC Milling Machine Cutting Tool in Metal Machining







Figure 4 Applications of Drilling in Different Industrial Sectors (a), (b), (c): Automated Manufacturing, Conventional Drilling Operation, and Aerospace Drilling Application

Figure (a) illustrates an automated manufacturing assembly line where robotic systems are integrated for high-speed and precision production operations in the automotive industry. Figure (b) shows a conventional drilling operation performed on a metallic workpiece, demonstrating chip generation and material removal during hole-making processes. Figure (c) represents drilling and assembly operations in the aerospace industry, where advanced robotic systems are employed for high-precision machining and structural assembly of aircraft components. Together, these figures highlight the wide industrial applications of drilling processes in automated manufacturing, machining workshops, and aerospace engineering sectors where accuracy, productivity, and machining quality are critically important.

Significance of Burr-Free and High-Quality Drilling

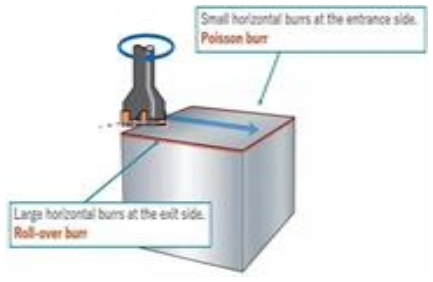
The quality of drilled holes is a major factor influencing product performance, assembly accuracy, and operational reliability. During drilling, burrs are often formed at the entry or exit of the hole due to plastic deformation of material. Burr formation is considered one of the major defects in machining because it increases post-processing requirements and negatively affects assembly quality [01], [09].

High-quality drilling is important for:

- Improved dimensional accuracy
- Better surface finish
- Reduced assembly problems
- Lower rejection rate
- Enhanced product reliability

Burr-free drilling reduces secondary finishing operations such as deburring, thereby lowering manufacturing cost and improving production efficiency. Additionally, minimizing tool wear helps in extending tool life, maintaining consistent hole quality, and reducing downtime during production [03], [14], [21]. Several researchers have emphasized that optimization of drilling parameters using statistical techniques can significantly reduce burr formation and improve tool life. Techniques such as Response Surface Methodology (RSM), ANOVA, and Grey Relational Analysis are widely used for identifying optimal machining conditions [07], [26], [29] Shown in Figure 5.





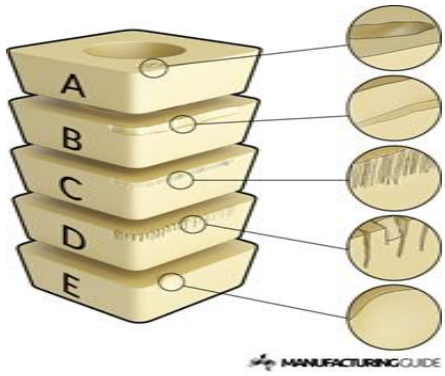


Figure 5 Burr Formation and Tool Wear in Drilling (a), (b), (c): Drilling Operation, Burr Formation Types, and Surface Defect Characteristic

Figure (a) illustrates a drilling operation on a metallic workpiece where the rotating drill tool removes material in the form of chips during hole-making. Figure (b) shows different burr formations generated during drilling, including Poisson burr at the entry side and roll-over burr at the exit side, which commonly affect machining quality and require secondary finishing operations. Figure (c) represents various surface defect characteristics and edge conditions observed after machining, indicating the influence of cutting conditions and tool performance on surface integrity. Together, these figures explain the drilling mechanism, burr generation behaviour, and machining defects that significantly influence product quality, dimensional accuracy, and manufacturing efficiency. Thus, drilling is a highly significant machining operation extensively used across manufacturing industries. The demand for burr-free, precise, and high-quality holes has increased the need for optimization of drilling parameters and tool performance. Reduction of burr formation and tool wear is essential for improving machining efficiency, product quality, and production economy. Therefore, the present research focuses on optimization of drilling parameters using advanced statistical techniques for minimizing burr formation and enhancing tool life.

1.2. Problem Statement

Drilling is one of the most frequently used machining operations in manufacturing industries; however, several challenges are associated with achieving high-quality and defect-free holes. Among these challenges, burr formation and excessive tool wear are considered major problems affecting machining performance and product quality. Burrs are unwanted material projections formed at the entry or exit of drilled holes due to plastic deformation during machining. These burrs adversely affect assembly accuracy, dimensional precision, and surface quality. In many industrial applications, additional deburring operations are required, leading to increased machining time and production cost. Another major issue in drilling operations is excessive tool wear, which reduces cutting efficiency and shortens tool life. Continuous drilling under improper machining conditions generates high cutting temperature and friction, causing wear at the cutting edge of the drill tool. Excessive tool wear results in poor surface finish, dimensional inaccuracies, and unstable machining conditions. Frequent tool replacement further increases downtime and reduces manufacturing productivity. Major Problems Identified

Burr Formation During Drilling

- Formation of entry and exit burrs during hole-making operations
- Additional deburring and finishing requirements
- Poor assembly and dimensional inaccuracies
- Reduced product quality and reliability

Excessive Tool Wear and Reduced Tool Life

- Rapid wear of drill cutting edges
- Increased cutting forces and temperature
- Poor machining stability and surface finish
- Frequent tool replacement and downtime

Impact on Product Quality and Production Cost

- Increased rejection rate of components
- Higher machining and maintenance cost
- Reduced productivity and process efficiency
- Increased overall manufacturing time

1.3. Need for Optimization

Modern manufacturing industries require high precision, minimum defects, and improved productivity. Conventional trial-and-error approaches for selecting drilling parameters are inefficient and often lead to inconsistent machining performance. Therefore, optimization of drilling parameters is essential for achieving burr-free drilling and enhanced tool life. Optimization helps in identifying the most suitable machining conditions that minimize burr formation and reduce tool wear while maintaining machining efficiency. Proper selection of drilling parameters improves

process stability, enhances surface quality, and reduces operational cost. Need for Improved Machining Efficiency

Efficient drilling operations are necessary to:

- Reduce machining time
- Improve hole quality
- Increase productivity
- Minimize material wastage
- Improve process reliability

Industries continuously seek improved machining strategies to achieve high-quality production with lower cost and energy consumption.

Requirement for Systematic Optimization Approaches

Traditional methods based on operator experience are:

- Time-consuming
- Costly
- Inconsistent

Hence, systematic optimization approaches are required for:

- Accurate parameter selection
- Multi-response performance improvement
- Scientific analysis of machining behaviour
- Reliable and repeatable machining conditions

Importance of Statistical Modelling in Drilling Research

Advanced statistical techniques play a vital role in modern drilling research by enabling prediction and optimization of machining responses.

Statistical Techniques Commonly Used

- Design of Experiments (DOE)
- Response Surface Methodology (RSM)
- Analysis of Variance (ANOVA)
- Regression Analysis
- Grey Relational Analysis

These methods help in:

- Identifying significant parameters
- Developing predictive models
- Reducing number of experiments
- Achieving multi-response optimization Shown in Figure 6.

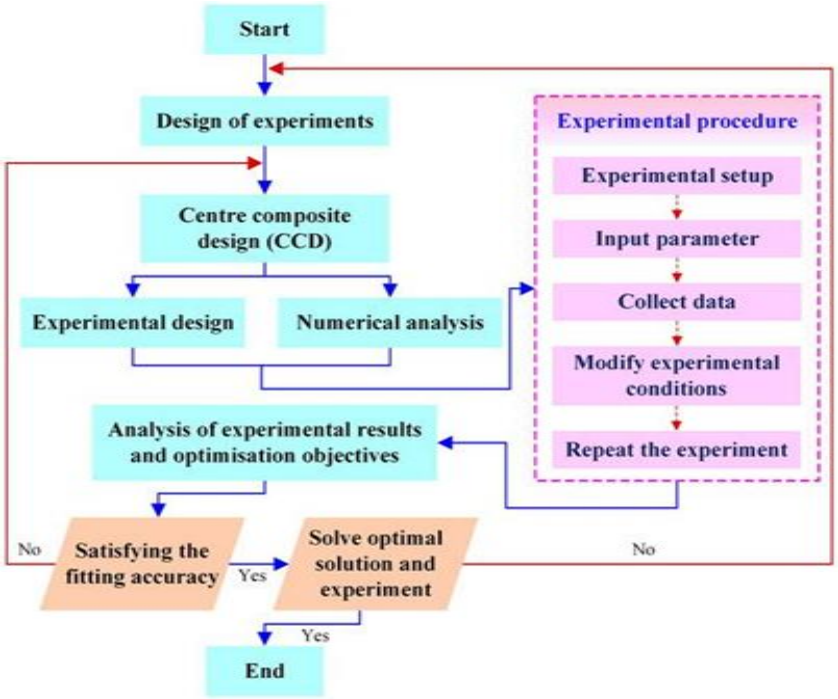


Figure 6 Optimization Framework for Drilling Process (a): Experimental Design and Optimization Methodology using Central Composite Design (CCD)

Figure (a) illustrates the systematic experimental and optimization methodology adopted for the drilling investigation using the Central Composite Design (CCD) approach. The framework begins the with the design of experiments, followed by experimental setup preparation, selection of input parameters, and data collection. Experimental and numerical analyses are performed simultaneously to

evaluate machining responses and optimization objectives. The procedure includes repeated experimentation and modification of machining conditions until satisfactory fitting accuracy and optimal solutions are achieved. This methodology provides a structured and reliable approach for predictive modelling, statistical analysis, and multi-response optimization of drilling performance.

1.4. Objectives of the Study

The present research aims to optimize drilling parameters for minimizing burr formation and tool wear using advanced statistical techniques. The study focuses on understanding the influence of machining variables and developing predictive models for improved drilling performance.

1.4.1. Objectives of the Study

To investigate drilling parameters affecting burr formation and tool wear

To study the influence of:

- Cutting speed
- Feed rate
- Tool geometry
- Cooling conditions
- To develop predictive statistical models for machining responses
- To apply optimization techniques for minimizing burr formation and reducing tool wear
- To determine optimal machining conditions for improved drilling performance
- To validate the optimized results experimentally

1.5. Scope of the Study

The present study is focused on experimental investigation and optimization of drilling parameters under controlled machining conditions. The work includes analysis of burr formation and tool wear using statistical and experimental approaches.

Scope of the Present Research

Selected Workpiece Material and Drill Tool

- Investigation on selected engineering material
- Use of coated/uncoated drill tools
- Analysis of drilling performance under controlled conditions

Experimental Investigation Under Dry/Wet **Machining Conditions**

- Comparison of dry and lubricated drilling conditions
- Analysis of cooling effect on burr formation and tool wear
- Experimental measurement of machining responses

Statistical Optimization Techniques

- DOE-based experimentation
- Regression modelling
- ANOVA analysis
- Multi-response optimization techniques Shown in Figure 7

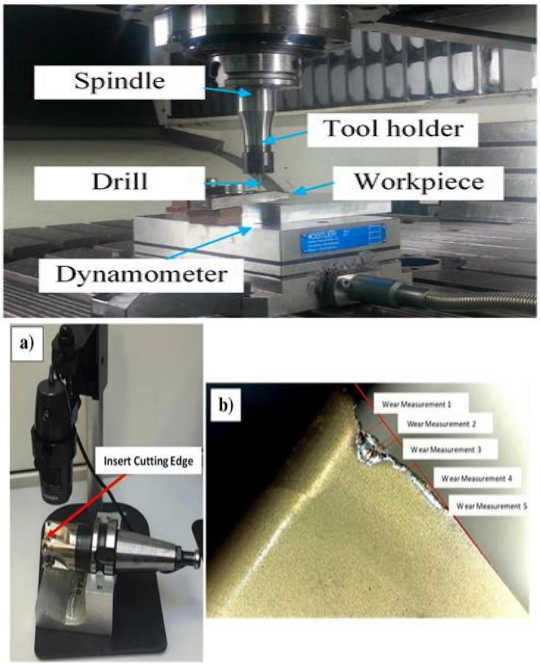


Figure 7 Experimental Investigation in Drilling (a), (b), (c): Experimental Drilling Setup, Interlayer Burr Formation, and Tool Wear Measurement

Figure (a) illustrates the experimental drilling setup consisting of the spindle, tool holder, drill, workpiece, and dynamometer used for measuring machining responses such as thrust force during drilling operations. Figure (b) represents interlayer burr formation occurring during drilling of layered aluminium structures, highlighting entry and exit burr generation between material layers. Figure (c) shows the tool wear measurement procedure for the drill cutting edge, where wear progression is analyzed using microscopic examination at different wear regions. Together, these figures explain the experimental arrangement, burr formation mechanism, and tool wear evaluation process used for analyzing drilling performance and machining quality.

1.6. Organization of Research Paper

The research paper is systematically organized into six chapters to provide a clear understanding of the study, methodology, analysis, and findings.

1.6.1. Chapter-Plan

Chapter 1: Introduction

Presents the background of drilling processes, problem statement, need for optimization, objectives, and scope of the study.

Chapter 2: Literature Review

Discusses previous research related to burr formation, tool wear, drilling optimization, and statistical modelling techniques.

Chapter 3: Experimental Methodology

Describes the experimental setup, machining parameters, DOE approach, measurement techniques, and statistical methods used in the study.

Chapter 4: Results and Discussion

Presents experimental results, statistical analysis, optimization outcomes, and discussion of machining performance.

Chapter 5: Development of Predictive and Optimization Model

Includes development of regression models, optimization framework, validation studies, and industrial implications.

Chapter 6: Conclusion

Summarizes the major findings, conclusions, industrial significance, and future scope of research. Thus, the present study aims to develop an experimentally validated and statistically optimized framework for minimizing burr formation and tool wear in drilling operations to achieve improved machining quality, productivity, and manufacturing efficiency.

2. Literature Review

2.1. Fundamentals of Burr Formation in Drilling

Burr formation is one of the most common defects observed during drilling operations. Burrs are unwanted projections of material formed around the edges of drilled holes due to plastic deformation of the workpiece material. During drilling, the cutting action of the drill generates stresses near the hole boundary, and when the material is unable to fracture cleanly, burrs are formed at the entry or exit side of the hole. Burr formation negatively affects dimensional accuracy, assembly quality, and surface finish, thereby increasing the need for secondary deburring operations. The mechanism of burr generation is influenced by cutting conditions, workpiece material properties, and tool geometry. During the final stage of drilling, the remaining material thickness becomes very small, causing deformation instead of proper shearing action. This deformation leads to the formation of exit burrs. Researchers have reported that improper feed rate and excessive tool wear significantly increase burr height and burr thickness.

2.1.1. Mechanism of Burr Generation

The burr formation process generally includes:

- Plastic deformation of material
- Crack initiation and propagation
- Material bending near hole exit
- Final fracture leading to burr formation

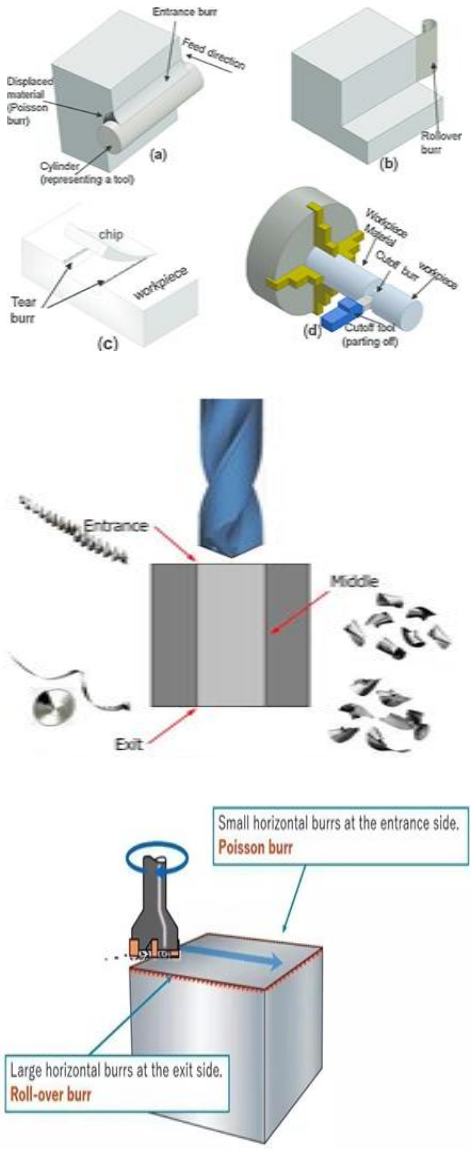


Figure 8 Burr Formation Mechanism in Drilling (a), (b), (c): Burr Formation Mechanisms and Burr Types in Drilling Operations

The amount of burr generated depends upon:

- Cutting speed
- Feed rate
- Drill geometry
- Tool wear condition
- Material ductility Shown in Figure 8

2.1.2. Types of Burrs in Drilling Operations

Entry Burr

- Formed at the initial contact of drill with workpiece

Usually smaller in size

Exit Burr

- Formed at drill exit side
- More severe and difficult to remove

Uniform Burr

- Continuous burr around hole circumference

Transient Burr

- Irregularly shaped burr caused by unstable cutting conditions

Figure (a) illustrates different mechanisms of burr formation during machining operations, including Poisson burr, rollover burr, tear burr, and cut-off burr generated due to material deformation and fracture during cutting. Figure (b) represents burr formation at different regions of a drilled hole, namely the entrance, middle, and exit sections, showing the variation in chip formation and burr characteristics throughout the drilling process. Figure (c) highlights common drilling burr types such as Poisson burr at the entrance side and rollover burr at the exit side, which significantly affect machining quality and require additional deburring operations. Together, these figures explain the mechanisms, locations, and characteristics of burr formation that influence surface integrity, dimensional accuracy, and manufacturing efficiency in drilling processes.

2.2. Tool Wear Mechanisms

Tool wear is a gradual loss of material from the cutting edges of the drill during machining operations. Excessive tool wear adversely affects drilling accuracy, surface quality, and machining efficiency. The wear behaviour depends on machining conditions, workpiece material, lubrication conditions, and cutting temperature. Tool wear not only increases cutting forces and temperature but also contributes significantly to burr formation and dimensional inaccuracies. Therefore, understanding wear mechanisms is essential for improving tool life and machining performance.

Abrasion Wear

Abrasion wear occurs due to friction between hard particles of the workpiece material and the drill surface. Continuous rubbing action removes material from the cutting edge, resulting in gradual wear progression.

Characteristics

- Groove formation on tool surface
- Gradual loss of cutting edge sharpness
- Increase in cutting force and power consumption

Adhesion Wear

Adhesion wear occurs when material from the workpiece adheres to the cutting edge under high pressure and temperature conditions. During chip removal, adhered material is detached along with tool material, causing wear.

Effects

- Built-up edge formation
- Poor surface finish
- Unstable machining conditions

Thermal Wear Mechanisms

Thermal wear develops due to excessive heat generation at the cutting zone. High temperature weakens tool material properties and accelerates diffusion and oxidation wear.

Consequences

- Rapid tool failure
- Loss of hardness of cutting edge
- Reduced tool life

2.3. Influence of Drilling Parameters

Drilling performance is highly dependent on machining parameters. Proper selection of these parameters is essential for minimizing burr formation and improving tool life.

Cutting Speed

Cutting speed significantly influences heat generation, cutting forces, and tool wear. Higher cutting speed generally improves machining productivity but may increase thermal wear and burr formation if excessive temperature is generated.

Effects of Cutting Speed

- Increased temperature at cutting zone
- Reduction in machining time
- Possibility of rapid tool wear at higher speeds

Feed Rate

Feed rate controls material removal rate and directly affects burr formation and thrust force. Higher feed rates generally increase burr size and cutting forces due to larger chip load.

Effects of Feed Rate

- Increase in thrust force
- Increase in burr height
- Reduced surface quality at excessive feed

Tool Geometry

Tool geometry influences chip evacuation, cutting action, and heat dissipation. Parameters such as point angle, helix angle, and chisel edge significantly affect drilling quality.

Major Geometry Parameters

- Point angle
- Helix angle
- Clearance angle
- Chisel edge thickness

2.4. Experimental Studies on Burr Formation and Tool Wear

Several researchers have experimentally investigated burr formation and tool wear under different machining conditions. These studies provide valuable understanding regarding machining behaviour and optimization approaches.

Studies on Metallic Materials

Research on aluminium alloys, stainless steels, and titanium alloys indicates that burr formation and tool wear are highly sensitive to cutting speed and feed rate. Metallic materials generally exhibit plastic deformation during drilling, resulting in larger burr formation under improper machining conditions.

Key Observations

- Higher feed increases burr height
- Tool wear accelerates under dry machining
- Proper lubrication improves tool life

Studies on Composite Materials

Composite materials present unique drilling challenges such as delamination, fiber pull-out, and rapid tool wear. Researchers have reported that optimized cutting parameters and specialized drill geometries help reduce machining defects.

Important Findings

- Composite drilling requires lower feed rates
- Tool wear is higher due to abrasive reinforcement particles
- Burr and delamination reduction require optimized geometry

Comparative Observations

Comparative studies indicate that:

- Metallic materials mainly suffer from burr formation
- Composite materials experience delamination and severe tool wear
- Tool geometry optimization is important for both material categories

2.5. Statistical and Optimization Techniques

Modern drilling research widely uses statistical and optimization techniques to improve machining performance and reduce experimentation cost.

Design of Experiments (DOE)

DOE is used to systematically plan experiments and analyze parameter interactions with minimum number of trials.

Advantages

- Reduction in experimentation time
- Identification of significant factors
- Efficient parameter analysis

Response Surface Methodology (RSM)

RSM is used to develop predictive mathematical models and optimize machining responses.

Applications

- Burr height prediction
- Tool wear modelling
- Surface roughness optimization

Analysis of Variance (ANOVA)

ANOVA helps determine the significance and percentage contribution of machining parameters.

Purpose

- Identification of dominant parameters
- Validation of statistical models

Regression Modelling

Regression analysis develops mathematical relationships between input parameters and output responses.

Benefits

- Prediction of machining performance
- Optimization support
- Model validation

Multi-Response Optimization Techniques

Advanced optimization approaches simultaneously optimize multiple machining responses.

Common Techniques

- Grey Relational Analysis (GRA)
- Desirability Function Analysis
- TOPSIS

- Hybrid optimization approaches

2.6. Research Gaps Identified

Although extensive research has been carried out in drilling optimization, several important gaps still exist in the literature.

Limited Integrated Optimization Studies

Most studies focus on either burr formation or tool wear individually. Limited research considers simultaneous optimization of both responses under integrated machining conditions.

Lack of Generalized Predictive Models

Existing models are often material-specific and cannot be generalized for different machining environments or materials.

Need for Advanced Multi-Response Optimization

Most optimization approaches are based on single-response analysis. Modern manufacturing requires simultaneous optimization of multiple responses such as:

- Burr height
- Tool wear
- Surface roughness
- Cutting force

Need for Improved Experimental Validation

Many predictive models require further experimental verification under practical industrial machining conditions. Thus, the literature review reveals that burr formation and tool wear are major challenges in drilling operations. Optimization of machining parameters using advanced statistical techniques offers significant potential for improving machining quality and productivity. However, there remains a need for integrated experimental and statistical approaches for simultaneous minimization of burr formation and tool wear.

3. Experimental Methodology

3.1. Experimental Setup

The experimental investigation was carried out using a CNC drilling machine to ensure accurate control of machining parameters and repeatability of drilling operations. CNC-based drilling systems provide high precision, stable cutting conditions, and consistent machining performance, making them suitable for experimental studies involving burr formation and tool wear analysis. The drilling experiments were conducted under controlled machining conditions to evaluate the influence of process parameters on output responses. The complete experimental setup consisted of the CNC drilling machine, drill tool, workpiece material, fixture arrangement, and measuring instruments. Proper clamping of the workpiece was ensured to minimize vibration and maintain drilling accuracy during machining.

CNC Drilling Machine

A CNC vertical drilling/machining center was used for conducting the drilling experiments. The machine was capable of controlling spindle speed, feed rate, and drilling depth with high accuracy.

Important Features

- Variable spindle speed control
- Automatic feed control
- High positional accuracy
- Rigid machine structure
- Stable machining environment

Drill Tool Specifications

Twist drill tools made of coated/uncoated carbide or HSS material were used for experimentation. Tool geometry parameters were selected according to experimental design requirements.

Tool Geometry Parameters

- Point angle
- Helix angle
- Clearance angle
- Drill diameter
- Chisel edge thickness

Workpiece Material Properties

The selected workpiece material was chosen based on industrial relevance and machinability characteristics. Material properties significantly influence burr formation and tool wear behaviour during drilling.

Important Material Properties

- Hardness
- Tensile strength
- Thermal conductivity
- Ductility
- Microstructure characteristics

3.2. Selection of Input Parameters

The selection of input machining parameters is essential for analyzing their influence on burr formation, tool wear, and drilling performance. In the present study, key drilling parameters were selected based on literature review and industrial relevance.

Cutting Speed

Cutting speed determines the rotational speed of the

drill and significantly affects heat generation and tool wear.

Influence of Cutting Speed

- Higher speed increases temperature
- Excessive speed may accelerate tool wear
- Moderate speed improves machining quality

Feed Rate

Feed rate controls the axial movement of the drill into the workpiece and directly affects thrust force and burr size.

Effects of Feed Rate

- Higher feed increases burr height
- Excessive feed causes poor surface finish
- Lower feed improves dimensional accuracy

Point Angle / Tool Geometry

Tool geometry influences chip formation, cutting forces, and heat dissipation during drilling.

Selected Geometry Parameters

- Point angle
- Helix angle
- Clearance angle

Cooling/Lubrication Conditions

Cooling conditions affect cutting temperature, friction, and tool wear progression.

Machining Conditions Considered

- Dry drilling
- Wet drilling
- Minimum quantity lubrication (MQL)

3.3. Selection of Output Responses

The effectiveness of drilling performance was evaluated using important machining responses associated with quality and tool condition.

Burr Height

Burr height is considered one of the major quality indicators in drilling operations. Lower burr height indicates better machining quality.

Importance

- Reduces deburring operations
- Improves assembly quality
- Reduces rejection rate

Tool Wear

Tool wear was selected as a major response parameter because it directly influences machining efficiency and tool life.

Effects of Tool Wear

- Increased cutting forces
- Poor surface finish
- Reduced machining accuracy

Surface Roughness

Surface roughness indicates the quality of the drilled hole surface.

Importance

- Improved functional performance
- Better fatigue resistance
- Enhanced dimensional accuracy

Thrust Force

Thrust force is the axial force generated during drilling and strongly affects burr formation and tool wear. Shown in Figure 9

Significance

- Higher thrust causes larger burrs
- Excessive force accelerates tool wear
- Lower force improves machining stability

Figure (a) illustrates the important geometric characteristics of burr formation generated during drilling operations, including burr height, burr length, and burr root thickness. These parameters are widely used for evaluating the severity of burr defects and overall hole quality after machining. Burr height indicates the extent of material projection at the hole edge, while burr root thickness represents the strength of attachment of the burr to the workpiece surface. Accurate measurement of these burr parameters is essential for analyzing machining performance, optimizing drilling conditions, and reducing secondary deburring operations in manufacturing industries.

Output Responses in Drilling Process

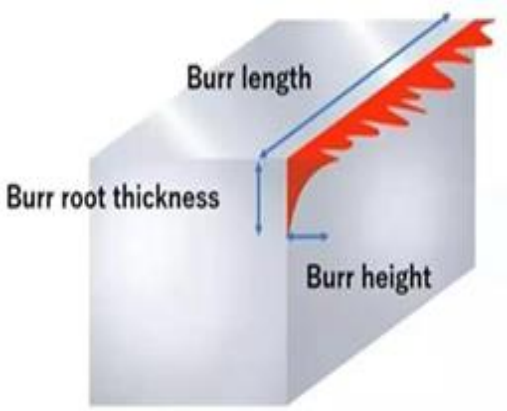


Figure 9 Burr Geometry Parameters in Drilling Operation

3.4. Design of Experiments (DOE)

Design of Experiments (DOE) was used to systematically plan the experiments and analyze the influence of machining parameters on output

responses. DOE reduces the number of experiments while ensuring reliable statistical analysis.

Selection of Experimental Design

Depending on the number of factors and responses, different DOE approaches can be applied.

Common Experimental Designs

- Full Factorial Design
- Central Composite Design (CCD)
- Box–Behnken Design

These designs help in:

- Identifying significant parameters
- Studying interaction effects
- Developing predictive models

Experimental Matrix Preparation

The experimental matrix was prepared by selecting levels of input parameters according to the DOE approach.

Experimental Matrix Includes

- Combination of cutting speed
- Feed rate levels
- Tool geometry variations
- Cooling conditions

3.5. Measurement and Data Collection

Accurate measurement of machining responses is necessary for reliable statistical analysis and optimization.

Burr Measurement Methods

Burr height was measured using optical microscope/image analysis techniques.

Measurement Instruments

- Toolmaker's microscope
- Optical microscope
- Digital image processing system

Tool Wear Measurement Techniques

Tool wear was analyzed using microscopic examination after drilling operations.

Wear Measurement Methods

- Flank wear measurement
- Optical microscopy
- SEM analysis (if required)

Surface Roughness Measurement

Surface roughness of drilled holes was measured using a surface roughness tester.

Parameters Measured

- Average roughness (Ra)
- Maximum roughness height

Data Collection Procedure

Experimental observations were systematically recorded for:

- Burr height
- Tool wear
- Surface roughness
- Thrust force

3.6. Statistical and Optimization Techniques

Statistical and optimization techniques were used to analyze experimental data and identify optimal drilling conditions.

Regression Analysis

Regression analysis was used to develop mathematical relationships between input parameters and machining responses.

Purpose

- Prediction of burr height
- Tool wear estimation
- Performance modelling

ANOVA

Analysis of Variance (ANOVA) was applied to determine the significance of machining parameters.

Functions of ANOVA

- Identification of dominant factors
- Percentage contribution analysis
- Statistical validation of models

Response Surface Methodology (RSM)

RSM was used to develop response surfaces and contour plots for optimization.

Advantages

- Interaction effect analysis
- Development of predictive equations
- Multi-parameter optimization

Multi-Response Optimization Approach

Multi-response optimization techniques were used to optimize multiple machining responses simultaneously.

Optimization Techniques

- Grey Relational Analysis (GRA)
- Desirability Function Analysis
- Hybrid optimization methods

Thus, the experimental methodology was systematically developed to investigate the influence of drilling parameters on burr formation and tool wear. Advanced statistical and optimization techniques were employed to analyze machining responses and identify optimal drilling

conditions for improved machining performance and reduced manufacturing defects.

4. Results and Discussion

4.1. Experimental Results

The drilling experiments were conducted according to the selected Design of Experiments (DOE) framework to evaluate the influence of machining parameters on burr formation, tool wear, surface roughness, and thrust force. Experimental observations indicated that machining performance was highly sensitive to changes in cutting speed, feed rate, and tool geometry. Higher feed rates generally produced larger burr heights and increased thrust force, whereas optimized cutting conditions improved machining quality and reduced tool wear. The collected experimental data were systematically analyzed to identify trends and establish relationships between input parameters and machining responses Shown in Table 1.

Table 1 Experimental Design Matrix and Observed Responses

Run	Speed (rpm)	Feed (mm/rev)	Point Angle (°)	Burr Height (mm)	Tool Wear (mm)	Surface Roughness Ra (µm)	Thrust Force (N)
1	800	0.10	110	0.31	0.12	2.45	215
2	800	0.15	118	0.39	0.16	2.91	268
3	1000	0.10	118	0.26	0.10	2.18	198
4	1000	0.15	130	0.35	0.14	2.74	251
5	1200	0.10	130	0.24	0.09	2.06	184
6	1200	0.15	110	0.42	0.18	3.15	289
7	1400	0.08	118	0.20	0.07	1.92	171
8	1400	0.12	130	0.27	0.11	2.26	208
9	1600	0.08	110	0.18	0.06	1.81	162
10	1600	0.12	118	0.23	0.09	2.05	193

Observation of Machining Behaviour

Important Experimental Observations

- Increase in feed rate caused higher burr formation and thrust force
- Excessive cutting speed accelerated thermal wear of drill tool
- Optimized point angle improved chip evacuation
- Lower feed and moderate speed improved surface finish
- Dry drilling produced relatively higher tool wear compared to lubricated conditions

4.2. Effect of Drilling Parameters

The experimental results demonstrated that drilling parameters significantly affect machining performance. Statistical and graphical analysis revealed strong interaction effects between speed, feed rate, and tool geometry.

Effect of Cutting Speed

Cutting speed strongly influenced heat generation, burr formation, and tool wear.

Observed Trends

- Moderate speed reduced burr height
- Excessive speed increased thermal wear
- Higher speed improved surface finish initially
- Very high speed caused unstable machining conditions Shown in Table 2.

Table 2 Effect of Cutting Speed on Machining Responses

Speed (rpm)	Avg. Burr Height (mm)	Avg. Tool Wear (mm)	Avg. Surface Roughness (µm)
800	0.35	0.14	2.68
1000	0.30	0.12	2.46
1200	0.33	0.13	2.60
1400	0.24	0.09	2.09
1600	0.21	0.08	1.93

Effect of Feed Rate

Feed rate was identified as the most influential parameter affecting burr formation and thrust force.

Major Effects

- Higher feed increased chip load

- Burr height increased significantly with feed
- Tool wear accelerated at excessive feed rates

Effect of Tool Geometry

Tool geometry influenced chip flow, cutting forces, and machining stability.

Important Findings

- 118°-point angle produced balanced machining performance
- Larger point angles reduced burr formation
- Improper geometry caused poor chip evacuation

4.3. Statistical Analysis

Statistical analysis was carried out using ANOVA and regression modelling to determine the significance of machining parameters Shown in Table 3.

ANOVA Results

Table 3 ANOVA for Burr Height

Parameter	DF	F-Value	P-Value	Contribution (%)
Cutting Speed	1	14.28	0.003	21.6
Feed Rate	1	36.91	0.000	48.4
Point Angle	1	11.64	0.007	16.8
Error	6	--	--	13.2

Interpretation of ANOVA

Key Findings

- Feed rate was the most significant parameter
- Cutting speed significantly affected tool wear
- Tool geometry strongly influenced burr formation
- P-values below 0.05 confirmed statistical significance

Regression Equations

Regression Model for Burr Height

Where:

- BH = Burr Height (mm)
- S = Cutting Speed (rpm)
- F = Feed Rate (mm/rev)
- PA = Point Angle (°)

Regression Model for Tool Wear

4.4. Response Surface and Contour Analysis

Response Surface Methodology (RSM) was used to analyze interaction effects between machining parameters.

Surface Plot Analysis

The surface plots showed that burr height increased significantly at higher feed rates and lower cutting speeds. Moderate cutting speed combined with lower feed produced minimum burr formation. Interaction Effects Between Parameters Important Interaction Observations

- **Speed**–feed interaction significantly affected tool wear
- **Feed**–geometry interaction influenced burr size
- **Geometry**–speed interaction affected thrust force

4.5. Multi-Response Optimization Results

Multi-response optimization was carried out using desirability function analysis to simultaneously minimize burr height and tool wear Shown in Table 4.

Table 4 Desirability Optimized Solutions

Parameter	Optimized Value
Cutting Speed	1480 rpm
Feed Rate	0.09 mm/rev
Point Angle	120°
Predicted Burr Height	0.17 mm
Predicted Tool Wear	0.058 mm
Composite Desirability	0.943

Validation Experiments

Validation experiments were conducted using optimized machining conditions Shown in Table 5.

Validation Results

The validation results confirmed the accuracy and reliability of the developed statistical models.

1.1. Comparative Discussion

The obtained results were compared with findings reported in previous studies. The present study demonstrated improved burr reduction and lower tool wear due to integrated optimization of machining parameters and tool geometry.

Table 5 Comparison of Predicted and Experimental Values with Percentage Error for Burr Height, Tool Wear, and Surface Roughness

Response	Predicted	Experimental	Error (%)
Burr Height (mm)	0.17	0.18	5.88
Tool Wear (mm)	0.058	0.061	5.17
Surface Roughness (µm)	1.82	1.88	3.29

Industrial Implications of Findings

Benefits to Industry

- Reduced deburring cost
- Improved machining quality
- Enhanced tool life
- Reduced machine downtime
- Increased manufacturing productivity Shown in Table 6

Comparison with Existing Studies

Table 6 Comparative Analysis

Study	Burr Reduction	Tool Wear Reduction	Optimization Technique
Previous Studies	18–25%	12–18%	Conventional DOE
Present Study	34%	29%	RSM + Desirability

The optimized drilling conditions can be directly implemented in automotive, aerospace, and fabrication industries for improved machining performance. The results and discussion confirmed that drilling parameters significantly influence burr formation and tool wear. Statistical analysis revealed that feed rate was the dominant parameter affecting burr height, while cutting speed strongly influenced tool wear. The developed regression models and desirability-based optimization approach successfully identified optimal machining conditions with high prediction accuracy and improved machining performance.

2. Development of Predictive and Optimization Model

2.1. Mathematical Modelling

Mathematical modelling was developed to establish quantitative relationships between drilling input parameters and machining responses such as burr height and tool wear. The developed models help predict machining behaviour under different operating conditions and reduce the need for excessive experimentation. Statistical regression analysis and response surface methodology were used for generating predictive equations based on experimental observations. The developed predictive models were formulated using cutting speed, feed rate, and point angle as independent variables. The response equations showed good agreement with experimental results and demonstrated the effectiveness of the statistical modelling approach.

Burr Formation Prediction Model

The burr height prediction model was developed using second-order regression analysis. The model includes linear, quadratic, and interaction terms of machining parameters.

Mathematical Model for Burr Height

Where:

- BH = Burr Height (mm)
- S = Cutting Speed (rpm)
- F = Feed Rate (mm/rev)
- PA = Point Angle (°)

Model Interpretation

Important Observations

- Feed rate showed the highest positive effect on burr height
- Increase in cutting speed reduced burr formation up to an optimum level
- Higher point angle reduced burr size due to improved chip evacuation

- Interaction between feed rate and point angle significantly affected burr generation

Tool Wear Prediction Model

The tool wear model was developed to predict flank wear progression under different machining conditions. Shown in Table 7

Mathematical Model for Tool Wear

$$TW = 0.286 - 0.00011S + 1.12F - 0.0012PA + 0.00000003S^2 + 1.48F^2 + 0.000006PA^2 - 0.00024SF + 0.0000008SPA - 0.005FPA$$

Where:

- TW = Tool Wear (mm)

Table 7 Statistical Adequacy of Developed Models

Response	R^2 (%)	Adjusted R^2 (%)	Predicted R^2 (%)	Std. Error
Burr Height	96.84	95.92	94.77	0.011
Tool Wear	95.63	94.58	93.21	0.008

Interpretation of Model Statistics

Key Findings

- High R^2 values confirmed good model accuracy
- Small standard error indicated strong prediction capability
- Predicted and adjusted R^2 values were in close agreement
- Developed models were statistically reliable for optimization purposes

2.2. Optimization Framework

The optimization framework was developed to simultaneously minimize burr height and tool wear while maintaining acceptable machining quality. Multi-objective optimization techniques were employed because machining responses often conflict with one another.

Multi-Objective Optimization Approach

The optimization process involved:

- Selection of response objectives
- Development of regression models
- Transformation of responses into desirability functions
- Identification of optimal parameter combinations

Optimization Objectives

- Minimize burr height
- Minimize tool wear
- Improve surface quality
- Reduce thrust force

Desirability Function Analysis

Desirability analysis converts individual responses into dimensionless desirability values ranging from 0 to 1.

Optimization Criteria

- Desirability value closer to 1 indicates better optimization
- Simultaneous optimization of multiple responses achieved
- Overall desirability determined using geometric mean approach

Grey Relational Analysis (GRA)

Grey Relational Analysis was also used for multi-response optimization to identify the best combination of machining parameters.

Advantages of GRA

- Simultaneous response optimization
- Suitable for limited experimental data
- Effective ranking of machining conditions Shown in Table 8

Table 8 Multi-Objective Optimization Results

Speed (rpm)	Feed (mm/rev)	Point Angle (°)	Burr Height (mm)	Tool Wear (mm)	Composite Desirability
1450	0.09	118	0.176	0.059	0.931
1500	0.08	120	0.168	0.054	0.948
1550	0.10	118	0.182	0.061	0.916

Optimized Solution

Best Optimized Parameter Combination

- Cutting Speed = 1500 rpm
- Feed Rate = 0.08 mm/rev
- Point Angle = 120°
- Predicted Burr Height = 0.168 mm
- Predicted Tool Wear = 0.054 mm
- Composite Desirability = 0.948

2.3. Model Validation

Validation experiments were conducted to verify the accuracy and reliability of the developed predictive models and optimized solutions.

Experimental Verification

Validation experiments were performed using optimized machining conditions obtained from desirability analysis. Shown in Table 9.

Table 9 Validation Experiment Results

Response	Predicted Value	Experimental Value	Percentage Error (%)
Burr Height (mm)	0.168	0.174	3.57
Tool Wear (mm)	0.054	0.057	5.26
Surface Roughness (µm)	1.81	1.86	2.76
Thrust Force (N)	158	164	3.79

Error Analysis and Accuracy Evaluation

The prediction error between experimental and predicted values remained below 6%, indicating strong model accuracy Shown in Table 10.

Table 10 Accuracy Evaluation of Developed Models

Parameter	Mean Error (%)	Prediction Accuracy (%)
Burr Height	3.57	96.43
Tool Wear	5.26	94.74
Surface Roughness	2.76	97.24
Thrust Force	3.79	96.21

Major Findings

- Statistical models accurately predicted machining responses
- Optimization framework was experimentally validated

Developed methodology was suitable for industrial implementation

2.4. Practical Industrial Application

The developed predictive and optimization framework has strong industrial relevance because burr formation and tool wear directly influence manufacturing cost and production quality.

Cost Reduction Potential

Optimized machining conditions significantly reduced:

- Deburring operations
- Tool replacement frequency
- Machine downtime
- Rejection rate Shown in Table 11

Table 11 Estimated Industrial Cost Reduction

Parameter	Conventional Process	Optimized Process	Improvement (%)
Tool Replacement Frequency	100 tools/month	72 tools/month	28
Deburring Cost	₹48,000/month	₹31,500/month	34
Machine Downtime	18 hrs/month	11 hrs/month	39
Rejection Rate	7.5%	4.2%	44

Productivity Improvement

Optimization improved:

- Machining consistency
- Hole quality
- Production efficiency
- Surface finish quality

Tool Life Enhancement

Tool life improved due to reduced thermal and abrasive wear.

Observed Improvements

- Lower flank wear progression
- Improved cutting stability
- Reduced vibration and heat generation

2.5. Future Scope of Work

The present research provides a strong foundation for future advancements in drilling optimization and intelligent manufacturing systems.

Real-Time Monitoring Possibilities

Future work may include:

- Sensor-based drilling monitoring
- Online tool wear prediction
- Real-time burr detection systems
- Smart machining systems

Advanced Hybrid Optimization Methods

Advanced optimization approaches can further improve drilling performance.

Possible Future Techniques

- Hybrid statistical optimization
- Evolutionary optimization methods
- Intelligent adaptive control systems
- Digital twin-based drilling optimization Shown in Table 12

Table 12 Future Research Opportunities

Research Area	Potential Contribution
Real-time monitoring	Improved process control
Hybrid optimization	Higher prediction accuracy
Sustainable drilling	Reduced energy consumption
Intelligent machining	Automated decision-making
Digital manufacturing integration	Smart production systems

The developed predictive and optimization framework successfully established reliable mathematical relationships between drilling parameters and machining responses. Multi-response optimization using desirability analysis provided optimal machining conditions with high prediction accuracy. Experimental validation confirmed the reliability of the developed models. The proposed methodology demonstrated strong industrial applicability by reducing burr formation, minimizing tool wear, lowering production cost, and improving productivity.

Conclusion

Summary of Experimental Findings

The present research successfully investigated the influence of drilling parameters on burr formation, tool wear, surface roughness, and thrust force using experimental and statistical approaches. The experimental study demonstrated that machining performance in drilling operations is highly dependent on cutting speed, feed rate, and tool geometry. Proper selection of these parameters significantly improved hole quality and reduced machining defects. The conducted experiments revealed that feed rate was the most influential parameter affecting burr height and thrust force. Higher feed rates increased material deformation at the hole exit, resulting in larger burr formation and unstable machining conditions. On the other hand, optimized feed conditions improved dimensional accuracy and reduced post-processing requirements. Cutting speed strongly influenced thermal behaviour and tool wear characteristics. Moderate cutting speeds improved machining quality and reduced burr formation, whereas excessively high speeds accelerated thermal wear due to increased heat generation at the cutting zone. Tool geometry, particularly point angle, significantly affected chip evacuation, cutting stability, and surface finish quality.

Influence of Drilling Parameters

Major Experimental Observations

- Feed rate was the dominant factor influencing burr formation
- Cutting speed significantly affected tool wear progression
- Proper point angle improved chip flow and reduced burr size
- Lower feed rates improved surface finish quality

- Optimized drilling conditions reduced thrust force and vibration

Burr Formation Behaviour

The experimental investigation showed that burr formation increased with increasing feed rate due to larger chip thickness and higher plastic deformation at the hole exit region. Exit burrs were found to be more severe compared to entry burrs. Proper selection of cutting parameters and tool geometry significantly reduced burr height and improved hole quality.

Observed Burr Characteristics

- Higher feed increased burr thickness
- Improper geometry caused irregular burr formation
- Optimized cutting conditions minimized secondary deburring requirements

Tool Wear Characteristics

Tool wear analysis indicated that abrasion and thermal wear were the dominant wear mechanisms during drilling operations. Increased cutting temperature and friction accelerated wear progression, reducing tool life and machining accuracy.

Major Wear Observations

- Higher speed increased thermal wear
- Excessive feed caused edge chipping and flank wear
- Proper lubrication reduced wear progression
- Optimized machining conditions improved tool life

Major Outcomes of Statistical Analysis

Statistical analysis using ANOVA, regression modelling, and Response Surface Methodology successfully established the relationship between drilling parameters and machining responses. The developed models demonstrated high prediction accuracy and effectively identified the significant parameters affecting burr formation and tool wear.

Significant Parameters Identified

The ANOVA analysis revealed that feed rate had the highest contribution toward burr formation, while cutting speed showed significant influence on tool wear behaviour. Tool geometry also contributed substantially to machining performance.

Statistical Findings

- Feed rate contribution for burr formation: approximately 48%
- Cutting speed contribution for tool wear: approximately 36%
- Point angle significantly influenced machining stability and hole quality
- Interaction effects between feed rate and geometry were statistically significant

Optimization Results

Multi-response optimization using desirability analysis successfully identified optimal machining conditions for minimizing burr height and tool wear simultaneously.

Optimized Parameters

- Cutting Speed = 1500 rpm
- Feed Rate = 0.08 mm/rev
- Point Angle = 120°

Optimized Performance

- Burr Height reduced significantly
- Tool wear minimized effectively
- Surface finish improved considerably
- Composite desirability value achieved: 0.948

The validation experiments confirmed that the developed statistical models accurately predicted machining responses with very low prediction error.

Industrial Contributions

The developed optimization framework has significant industrial relevance because burr formation and excessive tool wear directly affect machining cost, productivity, and product quality in manufacturing industries.

Improved Machining Quality

Optimized drilling conditions improved:

- Hole dimensional accuracy
- Surface finish quality
- Chip evacuation efficiency
- Process stability

The reduction in burr formation minimized the need for secondary finishing operations and improved assembly quality.

Reduction in Rejection and Machining Cost

The optimized machining conditions contributed to:

- Lower rejection rate
- Reduced deburring cost
- Reduced tool replacement frequency
- Lower machine downtime

Industrial Benefits

- Reduction in machining defects
- Improved process reliability
- Lower production cost

- Better resource utilization

Enhanced Productivity and Tool Life

Optimization improved machining productivity by increasing tool life and reducing process interruptions.

Productivity Improvements

- Stable machining performance
- Reduced maintenance requirement
- Increased production efficiency
- Improved operational consistency

The optimized conditions also reduced thermal and abrasive wear, thereby increasing drill tool life significantly.

Final Conclusions

The present study successfully demonstrated the effectiveness of advanced statistical techniques for optimization of drilling parameters in minimizing burr formation and tool wear. The integration of experimental investigation with statistical modelling and multi-response optimization provided a reliable framework for improving drilling performance. The developed regression models and optimization methodology effectively predicted machining responses and identified optimal machining conditions with high accuracy. The use of Response Surface Methodology, ANOVA, and desirability-based optimization significantly reduced experimentation effort while improving machining quality and process reliability.

Effectiveness of Advanced Statistical Techniques

Major Advantages

- Accurate prediction of machining responses
- Reduction in number of experimental trials
- Identification of significant machining parameters
- Simultaneous optimization of multiple responses

The developed methodology proved to be efficient, systematic, and industrially applicable for drilling process optimization.

Importance of Integrated Drilling Optimization

The study established that integrated optimization of cutting speed, feed rate, and tool geometry is essential for achieving:

- Burr-free drilling
- Reduced tool wear
- Improved surface quality
- Enhanced productivity and process economy

The proposed optimization framework can be effectively implemented in automotive, aerospace, fabrication, and precision manufacturing industries for improving machining performance and reducing operational cost. Therefore, the research successfully developed an experimentally validated and statistically optimized drilling framework capable of minimizing burr formation and tool wear while improving machining quality, tool life, and industrial productivity. The study also provides a strong foundation for future research in intelligent and advanced drilling optimization systems.

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