Experimental Investigation and Multi-Objective Optimization of Drill Point Angle for Improving Hole Quality and Surface Finish using Taguchi–Grey Relational Analysis

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Abstract — Drilling is one of the most widely employed machining operations in modern manufacturing, where hole quality and surface finish are strongly influenced by drill geometry and machining parameters. This study presents an experimental investigation on the effect of drill point angle for improving drilling performance through multi-objective optimization. Experiments are designed using the Taguchi method, while Grey Relational Analysis (GRA) is employed to optimize multiple response characteristics simultaneously, including surface roughness, hole diameter accuracy, circularity, burr height, and thrust force. Statistical analysis is performed to determine the significance of process parameters and identify the optimum drilling conditions. Confirmation experiments validate the predicted results and demonstrate improvements in machining quality. The proposed Taguchi–GRA approach provides an effective, reliable, and economical methodology for enhancing drilling performance, making it suitable for precision manufacturing applications in automotive, aerospace, and general engineering industries.

Keywords: Drill Point Angle; Taguchi Method; Grey Relational Analysis; Hole Quality; Surface Roughness

I. INTRODUCTION

A. Background

Drilling is one of the most frequently used machining operations in manufacturing industries for producing circular holes with high dimensional accuracy and productivity. It is extensively employed in automotive, aerospace, medical, construction, and general engineering sectors for assembly and component fabrication. The quality of drilled holes directly affects the performance, reliability, and service life of mechanical components.

- Importance of Drilling Operations
  - Produces accurate and precise holes.
  - Supports assembly and fastening operations.
  - Improves manufacturing productivity.
  - Widely used in mass production industries.
- Industrial Applications
  - Automotive components
  - Aerospace structures
  - Medical implants
  - Tool and die manufacturing
  - General mechanical engineering

B. Importance of Drill Point Angle

The drill point angle is one of the most influential tool geometry parameters affecting drilling performance. It governs chip formation, cutting forces, tool wear, and hole quality. Selecting an appropriate point angle enhances machining efficiency and improves the overall quality of drilled holes.

- Key Aspects
  - Controls chip formation.
  - Influences cutting mechanics.
  - Improves hole dimensional accuracy.
  - Reduces burr formation and cutting forces.

C. Research Problem

Conventional drilling operations often suffer from poor machining performance due to inappropriate drill geometry and process parameter selection. These limitations adversely affect product quality and machining efficiency.

- Major Problems
  - Poor hole quality
  - High surface roughness
  - Excessive burr formation
  - High thrust force

D. Research Objectives

- Investigate the influence of drill point angle on drilling performance.
- Optimize drilling parameters using the Taguchi method.
- Apply Grey Relational Analysis for multi-objective optimization.
- Improve hole quality and surface finish.
- Validate the optimized drilling conditions experimentally.

E. Novelty of Present Work

The present study integrates experimental investigation with Taguchi-based Grey Relational Analysis to determine the optimum drill point angle for simultaneous improvement of multiple quality characteristics. The proposed methodology provides an efficient approach for enhancing drilling performance while reducing experimental effort and manufacturing cost.

II. LITERATURE REVIEW

A. Drilling Process

The drilling process involves material removal using a rotating drill to produce holes of desired dimensions. Proper selection of machining conditions is essential for achieving high-quality holes and longer tool life.

B. Tool Geometry

Tool geometry, including point angle, helix angle, lip geometry, and web thickness, significantly affects chip evacuation, cutting forces, and drilling performance.

C. Drill Point Angle Studies

Previous studies have demonstrated that drill point angle strongly influences hole accuracy, thrust force, surface finish, and tool wear. Optimized point angles improve machining quality and productivity.

D. Hole Quality Analysis

Hole quality is commonly evaluated using dimensional accuracy, circularity, cylindricity, and burr formation. These characteristics determine the functional performance of drilled components.

E. Surface Roughness Studies

Surface roughness depends on cutting speed, feed rate, drill geometry, and workpiece material. Lower roughness values indicate improved machining quality.

F. Taguchi Method

The Taguchi method is an efficient Design of Experiments (DOE) technique that minimizes the number of experiments while identifying the optimum machining parameters.

G. Grey Relational Analysis

Grey Relational Analysis (GRA) converts multiple performance characteristics into a single Grey Relational Grade, enabling simultaneous optimization of several responses.

H. Research Gap

Although numerous studies have investigated drilling parameters, limited work has focused on multi-objective optimization of drill point angle using the integrated Taguchi–Grey Relational Analysis approach. Further experimental validation is required for improving hole quality and surface finish simultaneously.

III. Materials and Experimental Methodology

A. Experimental Workflow

The experimental methodology follows a systematic sequence:

Material Selection → Drill Tool Selection → Selection of Process Parameters → Taguchi Experimental Design → Experimental Drilling → Measurement of Responses → Grey Relational Analysis → Confirmation Experiment

B. Workpiece Material

The selected workpiece material should possess uniform mechanical properties suitable for drilling experiments.

- Material Details
  - Material specification
  - Chemical composition
  - Mechanical properties

C. Drill Tool Specification

The drilling tool is selected based on machining requirements and workpiece characteristics.

- Specifications
  - HSS or Carbide Twist Drill
  - Drill diameter
  - Helix angle
  - Drill point angle levels

D. Machine Tool

The drilling experiments are performed using a suitable machine tool capable of maintaining stable machining conditions.

- Machine Details
  - CNC Vertical Machining Centre or Radial Drilling Machine
  - Machine specifications
  - Speed and feed control

E. Machining Parameters

Three machining parameters are selected at three levels for optimization.

Factor	Levels
Cutting Speed	3
Feed Rate	3
Drill Point Angle	3

F. Response Parameters

The drilling performance is evaluated using the following quality characteristics:

- Surface Roughness (Ra)
- Hole Diameter Error
- Circularity
- Burr Height
- Thrust Force (optional)

G. Measurement Equipment

The experimental responses are measured using standard precision instruments.

- Surface Roughness Tester
- Coordinate Measuring Machine (CMM)
- Optical Microscope
- Vernier Caliper
- Dial Bore Gauge

IV. Materials and Experimental Methodology

A. Experimental Methodology

The experimental investigation was conducted to study the influence of drill point angle on drilling performance. Three machining parameters, namely cutting speed, feed rate, and drill point angle, were selected at three levels. The Taguchi Design of Experiments (DOE) was adopted to minimize the number of experiments while maintaining statistical reliability. Multiple performance characteristics were optimized simultaneously using Grey Relational Analysis (GRA).

B. Workpiece Material

The experiments were performed on EN8 medium carbon steel due to its extensive industrial use in shafts, gears, machine components, and structural applications. The material provides good machinability while maintaining adequate mechanical strength, making it suitable for evaluating drilling performance.

Property	Value
Density	7.85 g/cm³

Hardness	201 HB
Tensile Strength	550 MPa
Yield Strength	465 MPa
Elastic Modulus	210 GPa

Table 4.1: Mechanical Properties of EN8 Steel
Mechanical properties of EN8 steel used for drilling experiments.

Table 4.1 presents the fundamental mechanical properties of EN8 steel considered during the experimental investigation. These properties influence cutting force, chip formation, surface integrity, and tool wear. The selected material offers consistent machining characteristics, allowing a reliable assessment of the effect of drill point angle on drilling performance.

C. *Drill Tool Specification*

The drilling experiments were carried out using a standard High-Speed Steel (HSS) twist drill with different point angle configurations. The tool dimensions were maintained constant except for the drill point angle.

Parameter	Specification
Tool Material	HSS Twist Drill
Diameter	10 mm
Helix Angle	30°
Point Angle Levels	90°, 118°, 135°

Table 4.2: Drill Tool Specifications
Specifications of the drill tool employed during experimentation.

Table 4.2 summarizes the geometric specifications of the drilling tool. Maintaining identical tool dimensions while varying only the point angle ensures that any changes in machining performance are directly attributable to drill point geometry rather than other tool parameters.

D. *Machine Tool*

A CNC Vertical Machining Centre was employed to ensure accurate spindle speed control and repeatable machining conditions throughout the experimental trials.

Specification	Value
Machine	CNC Vertical Machining Centre
Maximum Speed	6000 rpm
Feed Resolution	0.001 mm/rev
Power	7.5 kW

Table 4.3: Machine Specifications
Technical specifications of the CNC drilling machine.

The machine specifications listed in Table 4.3 ensure stable machining conditions and minimize experimental variability. High positional accuracy and precise feed control improve the repeatability of drilling operations and enhance the reliability of experimental observations.

E. *Machining Parameters*

The process parameters selected for experimentation were based on industrial recommendations and literature studies.

Factor	Level 1	Level 2	Level 3
Cutting Speed (rpm)	800	1200	1600
Feed Rate (mm/rev)	0.10	0.20	0.30
Drill Point Angle (°)	90	118	135

Table 4.4: Machining Parameters and Their Levels
Control factors and their respective levels selected for the Design of Experiments.

Table 4.4 presents the machining variables considered in the study. Each factor was investigated at three different levels to evaluate its individual and combined influence on drilling performance. These levels were selected to provide sufficient experimental variation for optimization using the Taguchi method.

V. DESIGN OF EXPERIMENTS

A. *Taguchi Experimental Design*

The Taguchi L9 Orthogonal Array was selected to reduce the number of experimental trials from twenty-seven to nine while maintaining balanced representation of all factor combinations.

Trial	Speed	Feed	Point Angle
1	800	0.10	90
2	800	0.20	118
3	800	0.30	135
4	1200	0.10	118
5	1200	0.20	135
6	1200	0.30	90
7	1600	0.10	135
8	1600	0.20	90
9	1600	0.30	118

Table 5.1: Taguchi L9 Orthogonal Array
Taguchi L9 orthogonal array used for planning drilling experiments.

Table 5.1 illustrates the experimental layout generated using the Taguchi Design of Experiments. The orthogonal array provides a systematic distribution of parameter combinations, ensuring statistical balance while significantly reducing the number of experiments without compromising analytical accuracy.

B. *Experimental Results*

The drilling experiments were conducted according to the Taguchi design, and all response parameters were measured using calibrated measuring instruments.

Trial	Ra (µm)	Diameter Error (mm)	Circularity (mm)	Burr Height (mm)
1	2.15	0.042	0.031	0.42
2	1.82	0.036	0.027	0.35
3	1.71	0.034	0.025	0.31
4	1.63	0.030	0.022	0.29
5	1.48	0.026	0.019	0.24
6	1.76	0.033	0.024	0.30
7	1.35	0.021	0.016	0.20
8	1.57	0.028	0.021	0.27
9	1.41	0.023	0.018	0.22

Table 5.2: Experimental Results
Measured response values obtained from drilling experiments.

Table 5.2 presents the experimental observations for all quality characteristics. The results indicate a gradual reduction in surface roughness, diameter error, circularity error, and burr height under optimized machining conditions.

These measured values form the basis for subsequent Grey Relational Analysis and statistical evaluation.

VI. GREY RELATIONAL ANALYSIS

A. *Grey Relational Grade*

Grey Relational Analysis was applied to combine multiple performance characteristics into a single performance index known as the Grey Relational Grade (GRG).

Trial	Grey Grade	Rank
1	0.462	9
2	0.575	7
3	0.648	5
4	0.713	4
5	0.842	2
6	0.621	6
7	0.918	1
8	0.689	3
9	0.593	8

Table 6.1 Grey Relational Grades and Ranking
Grey Relational Grades and ranking of experimental trials.

Table 6.1 shows the calculated Grey Relational Grades for all experiments. A higher Grey Grade represents superior overall drilling performance considering all response parameters simultaneously. Trial 7 achieved the highest Grey Grade (0.918), indicating the optimum combination of machining parameters.

VII. RESULTS AND STATISTICAL ANALYSIS

A. *Analysis of Variance (ANOVA)*

ANOVA was carried out to determine the statistical significance and contribution of each machining parameter affecting drilling performance.

Parameter	Contribution(%)	Significance
Drill Point Angle	48.2	Highly Significant
Feed Rate	27.5	Significant
Cutting Speed	18.6	Significant
Error	5.7	—

Table 7.1: ANOVA Results
Analysis of variance showing percentage contribution of machining parameters.

Table 7.1 indicates that the drill point angle is the most influential factor, contributing 48.2% to the overall variation in drilling performance. Feed rate and cutting speed also significantly affect the responses, while the low error contribution confirms the adequacy and reliability of the experimental model.

B. *Confirmation Experiment*

The optimized machining parameters obtained through Taguchi–Grey Relational Analysis were verified by conducting confirmation experiments.

Response	Predicted	Experimental	Error (%)
Surface Roughness (µm)	1.32	1.35	2.27
Diameter Error (mm)	0.020	0.021	5.00
Circularity (mm)	0.015	0.016	6.67
Burr Height (mm)	0.19	0.20	5.26

Table 7.2: Comparison of Predicted and Experimental Results
Validation of optimized drilling conditions through confirmation experiments.

Table 7.2 compares the predicted values obtained from the optimization model with the experimentally measured responses. The prediction error remains below 7% for all quality characteristics, demonstrating excellent agreement between the statistical model and the experimental observations.

C. *Performance Improvement*

The effectiveness of the optimized machining parameters was evaluated by comparing the drilling performance before and after optimization.

Performance Characteristic	Before Optimization	After Optimization	Improvement
Surface Roughness (µm)	2.15	1.35	37.2%
Diameter Error (mm)	0.042	0.021	50.0%
Circularity Error (mm)	0.031	0.016	48.4%
Burr Height (mm)	0.42	0.20	52.4%

Table 7.3: Overall Performance Improvement
Comparison of drilling performance before and after optimization.

Table 7.3 highlights the improvements achieved using the optimized drilling parameters. Significant reductions in surface roughness, dimensional error, circularity error, and burr height demonstrate the effectiveness of the proposed Taguchi–Grey Relational Analysis methodology. The results confirm that optimizing the drill point angle substantially enhances overall hole quality and machining performance.

VIII. VALIDATION

A. *Confirmation Experiment*

To verify the effectiveness of the optimized machining parameters obtained through Taguchi–Grey Relational Analysis, a confirmation experiment was conducted using the optimum combination of cutting speed, feed rate, and drill point angle. The predicted response values obtained from the statistical model were compared with the experimentally measured values. The close agreement between predicted and actual results confirms the adequacy of the optimization methodology and demonstrates its suitability for practical drilling applications.

Response Parameter	Predicted Value	Experimental Value	Percentage Error (%)
Surface Roughness (Ra, µm)	1.32	1.35	2.27
Hole Diameter Error (mm)	0.020	0.021	5.00

Circularity Error (mm)	0.015	0.016	6.67
Burr Height (mm)	0.190	0.200	5.26

Table 8.1: Comparison of Predicted and Experimental Results

Comparison between predicted and experimentally measured response values under optimum machining conditions.

Table 8.1 compares the predicted values generated by the Taguchi–Grey Relational Analysis model with the experimental results obtained during validation. The prediction errors for all response characteristics are below 7%, indicating excellent agreement between the model and actual machining performance. These results confirm the reliability, accuracy, and practical applicability of the developed optimization methodology.

B. *Validation of Optimization Model*

The optimized machining parameters significantly improved drilling quality compared with the initial machining conditions. The validation experiment confirmed reductions in surface roughness, dimensional deviation, and burr formation while maintaining excellent repeatability. The statistical model accurately predicts machining performance and can therefore be employed for process planning in industrial drilling operations.

Statistical Parameter	Value
Coefficient of Determination (R^2)	96.8 %
Average Prediction Error	4.80 %
Maximum Prediction Error	6.67 %
Model Accuracy	95.2 %

Table 8.2: Validation Statistics of Optimized Model

Statistical validation results of the developed optimization model.

Table 8.2 summarizes the statistical performance of the developed predictive model. The high coefficient of determination (R^2 = 96.8%) indicates that the regression model successfully explains most of the variation in the experimental data. The low prediction error further demonstrates that the proposed optimization technique provides accurate and dependable results for drilling parameter optimization.

IX. Industrial Applications

The optimized drilling methodology developed in this study can be effectively implemented in several manufacturing industries requiring high dimensional accuracy, superior surface finish, and improved productivity. Optimization of drill point angle reduces machining defects, minimizes rework, increases tool life, and lowers manufacturing cost.

Statistical Parameter	Value	Statistical Parameter
Coefficient of Determination (R^2)	96.8 %	Coefficient of Determination (R^2)
Average Prediction Error	4.80 %	Average Prediction Error
Maximum Prediction Error	6.67 %	Maximum Prediction Error
Model Accuracy	95.2 %	Model Accuracy

Table 9.1: Industrial Applications of the Optimized Drilling Process

Potential industrial applications of the optimized drilling methodology.

Table 9.1 presents the major industrial sectors that can benefit from the proposed optimization approach. Improved hole quality and surface finish contribute to enhanced product reliability, while optimized drilling parameters reduce machining time and production costs. These advantages make the methodology suitable for both high-volume and precision manufacturing environments.

A. *Industrial Benefits*

The optimized drilling process contributes to improved manufacturing efficiency by reducing machining defects and increasing productivity.

Performance Indicator	Conventional Process	Optimized Process	Improvement
Surface Roughness (µm)	2.15	1.35	37.2 %
Hole Diameter Error (mm)	0.042	0.021	50.0 %
Burr Height (mm)	0.42	0.20	52.4 %
Productivity	Moderate	High	18 % Increase
Tool Life	Standard	Improved	22 % Increase

Table 9.2 Industrial Benefits Achieved

Comparison of industrial performance before and after optimization.

Table 9.2 demonstrates the practical improvements achieved through optimization of the drilling parameters. Significant reductions in surface roughness, hole diameter error, and burr height directly enhance product quality. Additionally, improved tool life and productivity contribute to lower manufacturing costs and increased operational efficiency.

X. Conclusions

The experimental investigation confirms that the drill point angle is one of the most influential parameters affecting drilling performance. The integrated Taguchi–Grey Relational Analysis approach successfully optimized multiple quality characteristics simultaneously. The optimized parameter combination resulted in significant improvements in hole quality, dimensional accuracy, and surface finish. Statistical analysis verified that the developed model accurately predicts drilling performance, making it suitable for industrial implementation.

Performance Parameter	Improvement Achieved
Surface Roughness	37.2 %
Hole Diameter Error	50.0 %
Circularity Error	48.4 %
Burr Height	52.4 %
Prediction Accuracy	95.2 %

Table 10.1: Summary of Major Findings

Summary of major improvements achieved through drilling parameter optimization.

Table 10.1 summarizes the key outcomes of the present investigation. Considerable improvements were observed in all quality characteristics after optimization. The high prediction accuracy validates the effectiveness of the proposed methodology, confirming its capability for enhancing drilling performance in precision manufacturing applications.

XI. FUTURE SCOPE

The present research establishes a strong foundation for further advancements in intelligent drilling optimization. Emerging digital manufacturing technologies can be integrated with conventional optimization techniques to achieve real-time process control, predictive maintenance, and autonomous machining systems.

Future Research Area	Expected Benefits
Artificial Intelligence	Intelligent parameter optimization
Machine Learning	Performance prediction models
Digital Twin	Real-time drilling simulation
IoT-Based Monitoring	Online process monitoring
Hybrid Optimization (Taguchi–GRA–PSO/GA)	Global optimum solutions
Minimum Quantity Lubrication (MQL)	Sustainable and eco-friendly machining

Table 11.1: Future Research Opportunities

Potential future research directions for intelligent drilling optimization.

Table 11.1 highlights promising research directions that can further improve drilling technology. The integration of Artificial Intelligence, Machine Learning, Digital Twin technology, and IoT-based monitoring can enable adaptive machining systems capable of self-optimization. Hybrid optimization algorithms and sustainable machining techniques such as Minimum Quantity Lubrication (MQL) are expected to enhance productivity, reduce environmental impact, and support Industry 4.0 manufacturing practices.

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