

A Comprehensive Review on Modelling and Optimization of Surface Roughness in Fiber Laser Beam Machining Using Response Surface Methodology

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Abstract— Fiber Laser Beam Machining (FLBM) has emerged as one of the most advanced non-conventional machining processes because of its capability to produce high-precision cuts with excellent dimensional accuracy, narrow kerf width, and superior surface quality. Surface roughness is one of the most important quality characteristics that directly influences the functional performance, wear resistance, fatigue life, and serviceability of machined components. Consequently, considerable research has been devoted to modeling and optimizing laser machining parameters for achieving improved surface finish while maintaining high productivity. This review presents a comprehensive analysis of recent developments in the modeling and optimization of surface roughness in fiber laser beam machining using Response Surface Methodology (RSM). More than thirty research articles published between 2020 and 2025 are critically reviewed to examine the influence of laser power, cutting speed, assist gas pressure, focal position, pulse frequency, and stand-off distance on surface roughness. The review also compares RSM with other optimization techniques, including Taguchi methods, Artificial Neural Networks (ANN), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Grey Relational Analysis (GRA), Genetic Algorithms (GA), and other hybrid approaches. Current research trends, limitations, and future opportunities are discussed. The review indicates that RSM remains one of the most reliable and widely adopted optimization techniques because of its statistical robustness, ability to model interaction effects, and relatively low experimental requirements. This article provides researchers and industrial practitioners with a consolidated understanding of current advances and future directions in optimizing fiber laser beam machining processes.

Index Terms— Fiber Laser Beam Machining, Surface Roughness, Response Surface Methodology, Optimization, Central Composite Design, ANOVA, Artificial Neural Networks.

I. INTRODUCTION (HEADING 1)

The demand for high-quality machining processes has increased significantly with the rapid growth of advanced manufacturing industries. Conventional machining methods often face limitations when processing high-strength alloys, composite materials, and precision engineering components because of excessive cutting forces, tool wear, and thermal damage. These limitations have encouraged the adoption of non-conventional machining processes, among which Fiber Laser Beam Machining (FLBM) has gained considerable industrial importance. Fiber laser machining employs a highly concentrated laser beam to melt and vaporize material without physical contact between the cutting tool and the workpiece. Compared with conventional machining processes, fiber laser systems offer superior beam quality, higher energy efficiency, lower maintenance requirements, faster cutting speeds, and improved dimensional accuracy. These advantages have led to their widespread use in the automotive, aerospace, biomedical, electronics, shipbuilding, and precision manufacturing industries.

Among the numerous quality characteristics associated with fiber laser machining, surface roughness (Ra) is one of the most critical performance indicators. Surface roughness directly affects wear resistance, fatigue strength, corrosion behaviour, friction, dimensional accuracy, and the overall functional performance of machined components. Achieving lower surface roughness reduces the need for secondary finishing operations, thereby improving manufacturing efficiency and reducing production costs. Surface quality during fiber laser machining depends on several interacting process parameters, including laser power, cutting speed, assist gas pressure, focal position, pulse frequency, nozzle stand-off distance, and material properties. Because these variables interact in a nonlinear manner, optimization through systematic statistical techniques is more effective than conventional trial-and-error experimentation. Response Surface Methodology (RSM) has become one of the most widely adopted optimization techniques for modelling machining responses and identifying optimum process conditions. Using designed experiments such as Central Composite Design (CCD) or Box–Behnken Design (BBD), RSM develops mathematical regression models that describe the relationship between input parameters and output responses while minimizing the number of experimental trials. In recent years, RSM has also been integrated with Artificial Neural Networks (ANN), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Grey Relational Analysis (GRA), Genetic Algorithms (GA), and other machine-learning approaches to improve prediction accuracy and support multi-objective optimization. Despite these advances, RSM continues to be widely used because of its interpretability, statistical rigor, and practical implementation in manufacturing environments.

The objective of this review is to critically evaluate recent research on modelling and optimization of surface roughness in fiber laser beam machining using Response Surface Methodology. The paper summarizes the influence of machining parameters, compares optimization techniques, identifies current research trends, highlights existing knowledge gaps, and suggests future research directions.

Topic	Coverage
Machining Process	Fiber Laser Beam Machining
Main Response	Surface Roughness (Ra)
Optimization Technique	Response Surface Methodology (RSM)
Literature Period	2020–2025
Types of Materials	Steels, Titanium Alloys, Composites, Polymers and Advanced Engineering Materials
Number of Research Articles Reviewed	More than 30

Table 1. Scope of the Present Review

II. FUNDAMENTALS OF FIBER LASER BEAM MACHINING

2.1 Fiber Laser Beam Machining

Fiber Laser Beam Machining (FLBM) is an advanced thermal material removal process that uses a high-intensity laser beam generated through an optical fiber to melt, vaporize, or burn the workpiece material. Unlike conventional machining processes, fiber laser machining is a non-contact process, eliminating mechanical cutting forces and reducing tool wear. The process offers high precision, narrow kerf width, excellent dimensional accuracy, and minimal heat-affected zone (HAZ), making it suitable for machining complex geometries and difficult-to-machine materials.

The laser beam generated by the fiber laser source is transmitted through an optical fiber and focused onto the workpiece using a focusing lens. The concentrated laser energy raises the temperature of the material above its melting or vaporization point. Simultaneously, an assist gas such as oxygen, nitrogen, or compressed air removes the molten material from the cutting zone, resulting in a clean and precise cut. Because of its superior beam quality, higher electrical efficiency, and lower maintenance requirements, fiber laser technology has largely replaced conventional CO₂ laser systems in modern manufacturing industries.

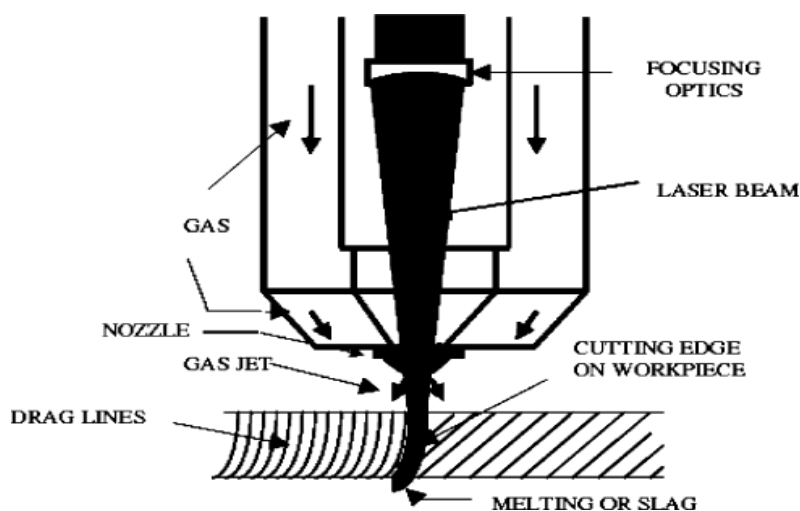


Figure 1 Cutting principle

2.2 Working Principle

The machining process begins with the generation of laser radiation within the fiber laser source. The beam is transmitted through an optical fiber to the focusing optics, where it is concentrated into a small spot on the workpiece surface. The absorbed laser energy rapidly increases the local temperature, causing melting or vaporization of the material. An assist gas is supplied coaxially with the laser beam to remove molten material from the cutting zone and to improve cut quality. Depending on the workpiece material and process requirements, oxygen, nitrogen, or compressed air may be used. The combined action of laser heating and assist gas results in precise material removal with minimal mechanical deformation.

2.3 Advantages of Fiber Laser Beam Machining

Fiber laser machining offers several advantages over conventional machining and earlier laser technologies.

Advantage	Description
High Precision	Produces accurate cuts with tight dimensional tolerances.
Non-contact Machining	Eliminates tool wear and mechanical cutting forces.
Narrow Kerf Width	Reduces material loss and improves dimensional accuracy.
High Cutting Speed	Enhances productivity and reduces machining time.
Minimal Heat-Affected Zone	Reduces thermal distortion and residual stresses.
Low Maintenance	Fiber lasers require less maintenance than CO ₂ lasers.
High Energy Efficiency	Converts electrical energy into laser energy more efficiently.

Table 2. Advantages of Fiber Laser Beam Machining

2.4 Limitations of Fiber Laser Beam Machining

Despite its advantages, fiber laser machining also has certain limitations.

Limitation	Description
High Initial Cost	Fiber laser systems require significant investment.
Material Reflectivity	Highly reflective materials may reduce cutting efficiency.
Thermal Damage	Improper parameter selection can increase HAZ and recast layer.
Process Sensitivity	Machining quality is highly dependent on parameter selection.

Table 3. Limitations of Fiber Laser Beam Machining

2.5 Process Parameters Affecting Surface Roughness

Surface roughness is influenced by several machining parameters that control energy input, material removal, and molten metal ejection.

The most commonly investigated parameters include:

- Laser Power
- Cutting Speed
- Assist Gas Pressure
- Focal Position
- Pulse Frequency
- Nozzle Stand-off Distance
- Material Thickness

Among these, **laser power**, **cutting speed**, and **assist gas pressure** are consistently identified as the dominant factors affecting surface finish in fiber laser machining.

2.6 Applications of Fiber Laser Beam Machining

Fiber laser machining is widely used across manufacturing sectors because of its precision and versatility.

Industry	Typical Applications
Automotive	Chassis parts, gears, body panels, exhaust systems
Aerospace	Turbine blades, titanium components, aircraft structures
Medical	Surgical instruments, implants, precision devices
Electronics	Printed circuit boards, connectors, micro-components
Tool and Die	Dies, molds, punches, precision tooling
General Manufacturing	Sheet metal fabrication and precision cutting

Table 4. Industrial Applications of Fiber Laser Beam Machining

III. REVIEW OF PUBLISHED RESEARCH ON MODELLING AND OPTIMIZATION OF SURFACE ROUGHNESS

3.1 Overview of Recent Research

During the last decade, significant research has been carried out on improving machining quality in fiber laser beam machining through statistical modelling and optimization techniques. The majority of studies have focused on minimizing surface roughness, reducing kerf width, improving dimensional accuracy, minimizing the heat-affected zone (HAZ), and enhancing material removal efficiency. Researchers have investigated different engineering materials, including carbon steels, stainless steels, titanium alloys, aluminium alloys, nickel-based superalloys, polymer composites, and hybrid composite materials. Response Surface Methodology (RSM) has emerged as one of the most frequently adopted optimization techniques because it can efficiently model the relationship between process parameters and machining responses while requiring relatively few experimental trials. Recent investigations have also combined RSM with Artificial Neural Networks (ANN), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Grey Relational Analysis (GRA), Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and other machine learning approaches to improve prediction accuracy and optimize multiple performance characteristics simultaneously.

3.2 Review of Recent Studies

Sr. No.	Author(s) & Year	Key Contribution	Process Parameters / Responses
1	Desai et al. (2024)	Developed a multi-objective optimization framework using GRA, Regression and ANN.	Laser power, cutting speed, pulse frequency, assist gas; Responses: SR, kerf, MRR, taper, HAZ.
2	Eaysin et al. (2024)	Optimized LBM parameters for AISI P20 using ANFIS.	Laser power, cutting speed, gas pressure; Responses: SR, kerf width.
3	Hegde et al. (2025/2026)	Deep learning and multi-objective optimization of XG3 steel.	Cutting speed, gas pressure, focus position; Responses: SR, machining time, burr.
4	Ji et al. (2024)	GA-ANFIS based kerf width optimization.	Laser power, cutting speed, pulse frequency, gas pressure; Responses: kerf width, SR.
5	Kharche & Patil (2024)	Systematic review of optimization techniques in LBM.	Laser power, cutting speed, gas pressure, focal position; Responses: SR, kerf, HAZ, MRR.
6	Liu et al. (2024)	ANN-based optimization for high-power fiber laser cutting.	Laser power, cutting speed, gas pressure; Responses: kerf width, SR, HAZ.
7	Mandal et al. (2024)	RSM and MODA based multi-objective optimization (EDM).	Current, pulse-on time, duty cycle; Responses: MRR, EWR.
8	Naresh et al. (2024)	Comparison of RSM, ANN and ANFIS.	Feed rate, cutting speed, laser power; Responses: cutting force, SR.
9	Sen et al. (2024)	ANN+MOGA+RSM for PMMA micro-channeling.	Laser power, pulse frequency, scan speed; Responses: channel depth, cut width.
10	Sobri et al. (2025)	CO ₂ laser cutting optimization of WPC.	Feed rate, gas pressure; Responses: cutting depth, HAZ, cut quality.
11	Ürgin et al. (2024)	Metaheuristic optimization for CO ₂ laser cutting.	Laser power, cutting speed, standoff distance; Responses: kerf width, kerf depth.
12	Nguyen et al. (2022)	Comparison of Taguchi and RSM for SS304 laser cutting.	Laser power, cutting speed, nitrogen pressure; Responses: dimensional error, edge quality.

Table 5. Summary of Literature Review

The reviewed literature demonstrates that Response Surface Methodology remains one of the most reliable optimization techniques for fiber laser beam machining because of its ability to develop predictive mathematical models, evaluate interaction effects, and determine optimal machining conditions with relatively few experiments. Although artificial intelligence-based approaches provide higher prediction accuracy for highly nonlinear systems, RSM continues to be widely adopted because of its simplicity, statistical robustness, and ease of industrial implementation. The next section identifies the key research gaps and discusses future research opportunities in this field.

3.3 Comparative Analysis of Optimization Techniques

Different optimization techniques have been employed by researchers to improve machining performance. Each technique possesses distinct advantages and limitations depending on the complexity of the machining process and the available experimental data.

Technique	Advantages	Limitations	Typical Applications
Response Surface Methodology (RSM)	Simple, accurate regression models, interaction analysis	Limited to polynomial relationships	Process optimization and modelling
Taguchi Method	Simple experimental design, reduced experiments	Limited interaction analysis	Robust parameter design
Artificial Neural Network (ANN)	High prediction accuracy, handles nonlinear relationships	Requires large datasets and training	Prediction and optimization
Adaptive Neuro-Fuzzy Inference System (ANFIS)	Excellent nonlinear modelling capability	Higher computational complexity	Intelligent process prediction
Grey Relational Analysis (GRA)	Suitable for multi-response optimization	Dependent on normalization methods	Multi-objective optimization
Genetic Algorithm (GA)	Global optimization capability	Computationally intensive	Multi-objective optimization
Particle Swarm Optimization (PSO)	Fast convergence, easy implementation	May converge to local optima	Parameter optimization

Table 6. Comparison of Optimization Techniques

IV. RESEARCH GAPS AND FUTURE RESEARCH DIRECTIONS

4.1 Research Gaps Identified from the Literature

The comprehensive review of recent studies indicates that considerable progress has been made in the modelling and optimization of fiber laser beam machining processes. Researchers have successfully applied Response Surface Methodology (RSM), Artificial Neural Networks (ANN), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Genetic Algorithms (GA), Grey Relational Analysis (GRA), and other optimization techniques to improve machining quality. However, several important research gaps still remain.

Most published investigations have focused on optimizing multiple responses such as kerf width, material removal rate (MRR), taper angle, and heat-affected zone (HAZ), while comparatively fewer studies have specifically addressed the optimization of surface roughness as the primary response. Since surface roughness directly affects fatigue life, wear resistance, corrosion behaviour, and dimensional accuracy, more detailed investigations are required.

Research Area	Current Status	Identified Gap
Workpiece Materials	Extensive studies on stainless steel, titanium alloys, composites and polymers	Limited investigations on AISI 1045 and other medium-carbon steels
Optimization Objective	Multiple responses frequently optimized	Limited focus on surface roughness as the primary response
Optimization Techniques	RSM, ANN, ANFIS, GA widely applied	Need for hybrid RSM–AI approaches
Experimental Parameters	Laser power, cutting speed and gas pressure widely studied	Limited investigation of focal position, stand-off distance and beam quality
Industrial Application	Laboratory-scale optimization	Limited industrial validation and real-time implementation
Process Monitoring	Mostly offline measurements	Need for online monitoring and adaptive process control

Table 7. Research Gaps Identified from the Literature

These research gaps indicate significant opportunities for developing hybrid optimization models for improving surface roughness prediction in fiber laser beam machining.

Based on the identified research gaps, several promising research opportunities can be recommended for future investigations.

- The integration of **Response Surface Methodology with Artificial Intelligence techniques** such as Artificial Neural Networks, Deep Learning, Explainable Artificial Intelligence (XAI), Adaptive Neuro-Fuzzy Inference Systems, and Reinforcement Learning can improve prediction accuracy while maintaining statistical interpretability.
- Future research should also focus on **multi-objective optimization** by simultaneously minimizing surface roughness, kerf width, taper angle, heat-affected zone, and energy consumption. Such integrated optimization approaches will provide more comprehensive solutions for industrial manufacturing.
- Another important direction is the development of **digital twin models** for fiber laser machining. Digital twins can combine experimental data, numerical simulations, and machine-learning algorithms to enable real-time prediction, monitoring, and adaptive control of machining processes.
- The application of **Industry 4.0 technologies**, including Internet of Things (IoT), cloud manufacturing, cyber-physical systems, and intelligent sensors, is expected to transform laser machining into a fully automated and self-optimizing manufacturing process.
- Future studies should also investigate environmentally sustainable machining by optimizing energy consumption, reducing assist gas usage, minimizing material waste, and improving overall process efficiency.
- Finally, there is significant scope for extending optimization studies to advanced engineering materials such as high-entropy alloys, functionally graded materials, metal matrix composites, ceramic composites, and additive-manufactured components.

The preferred spelling of the word “acknowledgment” in America is without an “e” after the “g”. Avoid the stilted expression, “One of us (R. B. G.) thanks . . .” Instead, try “R. B. G. thanks”. Put applicable sponsor acknowledgments here; DO NOT place them on the first page of your paper or as a footnote.

V. CONCLUSION

Fiber Laser Beam Machining (FLBM) has become a widely adopted non-conventional machining process because of its ability to produce high-quality components with excellent dimensional accuracy and surface finish. This review highlights that surface roughness is primarily influenced by laser power, cutting speed, and assist gas pressure. Among the various optimization techniques, **Response Surface Methodology (RSM)** remains one of the most effective and widely used methods due to its ability to develop predictive models, analyze parameter interactions, and optimize machining conditions with a limited number of experiments. Recent studies also demonstrate increasing integration of RSM with artificial intelligence techniques such as ANN and ANFIS to improve prediction accuracy. The review identifies the need for further research on advanced materials, intelligent optimization methods, real-time process monitoring, and sustainable manufacturing practices. Overall, this review provides a comprehensive understanding of current research trends and future opportunities in the modelling and optimization of surface roughness in fiber laser beam machining using Response Surface Methodology.

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