Study of Fiber Optic Laser Beam Parameters on the Hardness of Inconel 718 – A Review

Gaurav A. Pawar[1], Dr. Sachin Borse[2]

[1]*Student, Dept. of Mechanical Engineering, Deogiri Institute of Engineering & Management studies, Chh. Sambhajinagar.*

[2]*Professor, Dept. of Mechanical Engineering, Deogiri Institute of Engineering & Management studies, Chh. Sambhajinagar.*

---***---

Abstract - *Inconel 718, a nickel-based superalloy, is widely used in aerospace, turbine, and high-temperature engineering due to its exceptional strength, corrosion resistance, and thermal stability. These physical characteristics make it indispensable in aerospace turbine engines, nuclear reactors, and high-temperature pressure sensors. However, these same properties induce severe machinability challenges during conventional mechanical processing, including rapid tool wear, work-hardening, and localized thermal accumulation. Non-contact thermal processes, particularly Fiber Laser Beam Machining (LBM), offer a precise, tool-wear-free alternative for producing intricate micro-features such as cooling passages and micro-slots. This paper presents a review of recent developments in the micromachining and laser processing of Inconel 718. It examines material behaviour, compares traditional micro-cutting against non-conventional techniques. Provides a methodology to study the impact of variation of Fibre Optic Laser Beam Machining parameters on Surface Hardness.*

Key Words: Inconel 718, Fiber Laser Beam Machining, Micromachining

1. INTRODUCTION

Inconel 718 is an austenitic nickel-based superalloy engineered for extreme operating environments requiring high mechanical strength, resistance to creep deformation, and surface endurance against oxidation and corrosion at operating temperatures up to 650 °C [1]. The alloy matrix (γ-phase) is primarily composed of nickel, chromium, and iron, strengthened by precipitation hardening phases including face-centred tetragonal γ” (Ni_3Nb) and face-centred cubic γ’ ($Ni_3[Al, Ti]$) [5, 8]. The nominal chemical composition of Inconel 718 is presented in Table 1 [1]. Due to these robust physical properties, Inconel 718 serves as a cornerstone material in aerospace turbine blades, rocket engines, turbocharger impellers, nuclear reactor components, and specialized high-pressure fluid sensors [1, 9].

1.1 Machinability Challenges in Conventional Processing

Despite its structural advantages, Inconel 718 is classified as one of the most difficult-to-machine materials [8, 9]. Conventional mechanical cutting operations such as micro-milling, turning, and drilling suffer from severe operational limitations:

- Low Thermal Conductivity: Heat generated at the cutting tool interface cannot dissipate efficiently into the workpiece, causing intense localized heat accumulation at the tool tip [8, 9].
- High Work-Hardening Rate: Plastic deformation during chip formation causes rapid surface hardening, accelerating abrasive and notch wear on cutting tools [1, 6].
- High Cutting Forces & Tool Chattering: Exceptional mechanical strength maintained at high temperatures causes elevated cutting forces, leading to tool deflection, micro-burr formation, and poor surface finish (Ra) [1, 10].

Unconventional processes like Electrical Discharge Machining (EDM) and Electrochemical Machining (ECM) offer non-contact machining options; however, EDM exhibits slow material removal rates and leaves a thick re-solidified recast layer, while ECM requires corrosive electrolytes and complex tooling design [2, 3].

Table -1: Chemical Composition of Inconel 718

Element	Composition (in %)
Nickel	50.0 ~ 55.0
Chromium	17.0 ~ 21.0
Iron	Balance
Niobium	4.75 ~ 5.50
Molybdenum	2.80 ~ 3.30
Titanium	0.65 ~ 1.15
Aluminum	0.20 ~ 0.80
Cobalt	1.0 max.
Carbon	0.08 max.
Manganese	0.35 max.
Silicon	0.35 max.
Phosphorus	0.015 max.
Sulfur	0.015 max.
Boron	0.006 max.
Copper	0.30 max.

1.2 Principle of Fiber Laser Beam Machining (LBM)

Fiber Laser Beam Machining (LBM) has emerged as a high-speed, non-contact technique for micro-feature fabrication (e.g., cooling micro-channels, micro-slots, precision orifices) in superalloys [2, 7, 11]. Fiber lasers operate at a fundamental wavelength of 1064 nm, delivering high beam quality, fine spot focus, and high energy density [3, 7]. When the focused laser beam impinges upon the Inconel 718 substrate, photonic energy is absorbed by the material surface and instantaneously converted into thermal energy [3, 4]. This heat elevates the local temperature beyond the melting (1260 - 1336°C) and vaporization points of the alloy, removing material through combined melting, vaporization, and melt ejection [4, 11].

However, because LBM relies purely on thermal energy, localized heat conduction into the adjacent solid bulk material forms a distinct Heat-Affected Zone (HAZ) [3, 4]. Within the HAZ, extreme thermal gradients induce phase transformations, grain coarsening, dissolution of strengthening precipitates (γ''), and thermal stress accumulation [4, 5]. Consequently, changes in surface and subsurface microhardness occur, directly impacting component fatigue life, wear resistance, and operational reliability [1, 4].

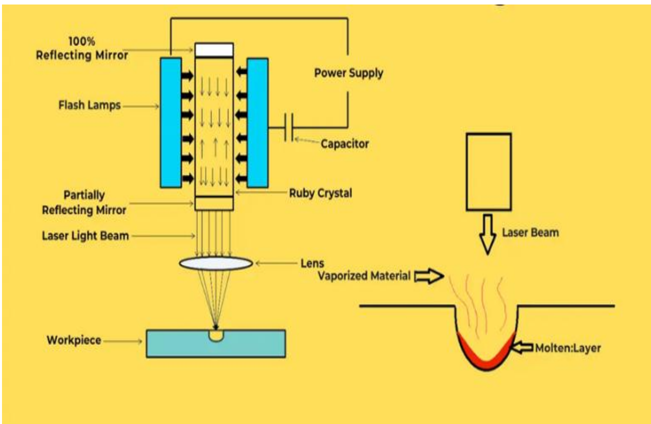

Fig. 1: Experimental setup of Laser Beam Machining (richconn.com)

2. LITERATURE REVIEW & RESEARCH GAP

- Zhang et al. (2023) [1]: Investigated laser-assisted micro-milling (LAMM) of Inconel 718 using finite element modelling (Johnson–Cook formulation) and experimental validation. The authors demonstrated that laser preheating reduced cutting forces by ~ 40%, suppressed burr formation, and achieved superior surface finish (Sa = 137 nm).

- Shinde et al. (2021) [2]: Reviewed non-traditional micromachining techniques (LBMM, EDMM, EBMM) for superalloys, emphasizing that laser spot focus and pulse repetition rates are critical for dictating geometrical tolerances and surface integrity.

- Pawar et al. (2023) [3]: Summarized the parametric effects of fiber laser parameters (power, speed, frequency, assist gas) on Inconel 718, identifying that unoptimized thermal input produces undesirable recast layers and microstructural abnormalities.

- Petru et al. (2021) [4]: Evaluated the mechanical property degradation of Inconel 718 following laser drilling. Static uniaxial tensile tests at 23°C and 550 °C proved that recast layer thickness and microcracks induced by laser heating significantly diminish elevated-temperature fatigue and tensile strength.

- Shivam et al. (2017) [5]: Evaluated laser machining of various Inconel grades, reporting that localized heating directly causes grain growth and microhardness variation across the HAZ.

- Sarkar et al. (2017) [6]: Analyzed end-milling of Inconel 718 using Response Surface Methodology (RSM), concluding that depth of cut and feed rate dominate surface roughness under both wet and dry cutting environments.

- Borse and Kadam (2018) [7]: Analyzed layer-by-layer fiber laser micro-milling of Inconel 718 using a Central Composite Design (CCD). They observed that laser power and scanning speed significantly govern MRR and surface roughness, with high power causing severe thermal degradation after a threshold limit.

• Frifita et al. (2020) [8]: Optimized conventional turning parameters for Inconel 718 using RSM and Desirability Function, identifying tool nose radius and cutting speed as major determinants of power consumption and surface quality.

• Lonikar (2015) [9]: Developed thermal models for Laser-Assisted Machining (LAM) of Inconel 718 (46 HRC), demonstrating a 40% reduction in tool wear and a 18% drop in cutting forces due to localized thermal softening prior to tool engagement.

• Tehami et al. (2025) [10]: Implemented a hybrid laser micro-milling technique optimized via Taguchi Grey Relational Analysis (GRA) and RSM, achieving significant reductions in surface roughness (23.08%) and burr height (23.64%).

• Panda and Bal (2018) [11]: Evaluated fiber laser micro-milling on Inconel 718 using a 20 W pulsed laser (1064 nm), demonstrating that lower pulse frequencies (~ 59 kHz) improved surface smoothness while high power maximized MRR.

2.2 Literature Summary and Identified Research Gap

The literature establishes that fiber laser machining provides substantial advantages in processing Inconel 718 [1, 3, 7]. However, existing studies overwhelmingly prioritize geometrical parameters (Ra, kerf width) and MRR, while giving limited attention to:

1. Quantitative empirical modelling of surface hardness as a function of pulse frequency, speed, and power [3, 7].
2. Identifying specific parametric thresholds that prevent thermal softening and preserve mechanical properties in the subsurface bulk [4, 5].

3. EXPERIMENTAL SETUP & METHODOLOGY

3.1 Material Preparation and Experimental Setup

Flat plate specimens of Inconel 718 to be prepared and surface-cleaned with acetone to eliminate oxidation and contaminants. Fiber laser machining runs will be performed using a CNC-controlled Fiber Laser System (1064 nm wavelength) capable of precise beam positioning.

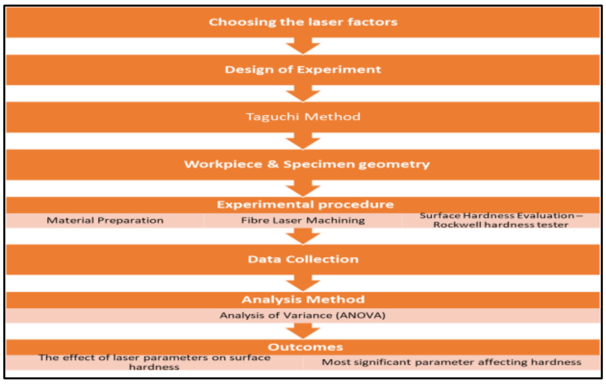

Fig. 2: Methodology flow chart

3.2 Design of Experiments (Taguchi L9 Matrix)

A Taguchi L9 (3^3) orthogonal array is selected to evaluate the main effects and interactions of the process parameters with minimal experimental runs. Three control factors to be evaluated across three discrete levels:

1. Laser Power (P)
2. Scanning Speed (S)
3. Pulse Frequency (F)

Based on literature review and machine capability, the following input parameters to be selected:

Table -2: Control factors & levels

Parameter	Symbol	Unit	Level 1	Level 2	Level 3
Laser Power	P	W	10	15	20
Scanning Speed	S	mm/s	200	400	600
Pulse Frequency	F	kHz	20	40	60

3.3 Microhardness Evaluation Protocol

Following laser processing, surface microhardness to be measured using a standardized Rockwell Hardness Tester utilizing the Rockwell Scale A (HRA, diamond cone indenter under a 60 kgf major load). To ensure statistical accuracy and account for localized metallurgical variations, three independent hardness indentations (HV1, HV2, HV3) will be recorded for each experimental run, and the mean value to be calculated.

4. CONCLUSION

This review highlights the state of research regarding non-traditional processing and fiber laser micromachining of Inconel 718. Key takeaways include:

1. **Machinability Barrier:** Inconel 718's low thermal conductivity and high work-hardening rate limit conventional mechanical cutting, making non-contact processing essential for complex micro-features.
2. **Thermal Trade-Offs:** Fiber laser machining eliminates tool wear and cutting forces, but its thermal nature introduces challenges such as recast layers, HAZ formation, and microhardness loss.

5. FUTURE SCOPE

To address the gaps, subsequent empirical research will focus on:

1. Conducting systematically controlled fiber laser machining trials on Inconel 718 using a Taguchi L9 experimental matrix.
2. Measuring surface and subsurface microhardness (HRA) variations using Rockwell and Vickers testing.
3. Applying Analysis of Variance (ANOVA) and linear regression modelling to develop predictive mathematical equations for surface hardness as a function of power, speed, and frequency.

REFERENCES

1) Haijun Zhang, Fei Chen, Zengqiang Li, Wangjie Hu, Tao Sun and Junjie Zhang, "Investigation of Laser-Assisted Micro-Milling Process of Inconel 718", Center for Precision Engineering, Harbin Institute of Technology, Harbin 150001, China

2) Indrayani Shinde, Prof. Sachin borse, Prof. M. L. Jadhav, "Micromachining using Laser Beam Machining on Inconel 718 – A Review", International Research Journal of Engineering and Technology (IRJET), Volume: 08 Issue: 10 | Oct 2021

3) Investigation and TGRA based optimization of laser beam drilling process during machining of Nickel Inconel 718 alloy

4) Sushil Vikas Pawar, Mr. R. R. Kolekar, Dr. S. C. Borse, "A REVIEW ON INVESTIGATING THE EFFECTS OF INPUT PARAMETERS FOR FIBER LASER MACHINING OF INCONEL 718", Journal of Emerging Technologies and Innovative Research (JETIR), 2023 JETIR July 2023, Volume 10, Issue 7

5) Jana Petru, Marek Pagac, Martin Grepl, "Laser Beam Drilling of Inconel 718 and its Effect on Mechanical Properties Determined by Static Uniaxial tensile testing at Room and Elevated temperatures", Materials (Basel) 2021 June

6) Akshee Shivam, Santanu Chakraborty, B.B. Pradhan, "LASER BEAM MACHINING OF INCONEL ALLOYS: A REVIEW", International Journal on Design & Manufacturing Technologies Vol.11 No.1 January 2017

7) Bapi Sarkar, Moola Mohan Reddy and Sujan Debnath, "Effect of machining parameters on surface finish of Inconel 718 in end milling", MATEC Web of Conferences I CMME 2016

8) Sachin C. Borse, Prof. M. S. Kadam, "Experimental Study in Micro milling of Inconel 718 by Fiber Laser Machining", Published by Elsevier B.V. Peer-review under responsibility of the scientific committee of the 2ndInternational Conference on Materials Manufacturing and Design Engineering.

9) Wassila Frifita, Sahbi Ben Salem, Abdelkrim Haddad, and Mohamed Athmane Yallese, "Optimization of machining parameters in turning of Inconel 718 Nickel-base super alloy", Mechanics & Industry 21, 203 (2020)

10) Kartikeya Vinayak Lonikar, "Laser Assisted Machining (LAM) of Inconel 718 with Thermal Modeling and Analysis of Process Parameters", International Journal of Engineering Research & Technology (IJERT) ISSN: 2278-0181 Vol. 4 Issue 07, July-2015

11) Ahmad Waqar Tehami, Muhammad Rizwan ul Haq, Syed Husain Imran Jaffery, Muhammad Ali Khan, Muhammad Iftikhar Faraz, Jana Petru, "Machinability analysis of Inconel 718 through parametric optimization using novel laser hybrid micro milling technique", Materials Today Communications 50 (2026) 114387

12) Debasish Panda, Dinesh Kumar Bal, "INVESTIGATION ON FIBER LASER MACHINING OF INCONEL 718 IN MICRO MILLING", Dogo Rangsang Research Journal ISSN: 2347-7180