

Laser Machining of Inconel: A Review

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Abstract — Inconel is a nickel-based alloy known for its ability to endure extremely high temperatures while maintaining most of its mechanical strength. Inconel super-alloys are challenging to machine due to their robustness at high cutting temperatures and sensitivity to heat generated by conventional methods like drilling, milling, and grinding. These traditional techniques struggle with poor surface quality, high tool wear, and unexpected tool failure, largely due to the alloy's low thermal conductivity. To address these challenges, non-traditional methods are employed to effectively machine super-alloys. Laser machining for Inconel, a non-traditional technique is employed which takes into account factors like depth of cut, laser power, distance from the laser to the workpiece, cutting speed, and feed rate. Key outputs, such as surface roughness, surface finish, cutting forces, machining temperature, etc. are closely monitored. This review paper aims to provide an overview of various experiments conducted on Inconel using Laser beam machining and Laser-assisted machining.

Keywords: Laser Machining, Inconel

I. INTRODUCTION

Inconel is a family of nickel-chromium-based super-alloys that are known for their high strength, resistance to oxidation, and exceptional corrosion resistance at high temperatures. These properties make Inconel alloys ideal for use in extreme environments where both heat and corrosion resistance are critical. Its unique combination of chemical and mechanical properties makes it essential in applications ranging from aerospace to chemical processing. However, Inconel is difficult to machine due to its high strength and hardness. Specialized tools and techniques are often required for the machining.

With a wide range of applications in industries, there are different conventional and non-conventional machining methods implemented for machining of Inconel. Conventional machining involves traditional techniques like turning, milling, drilling, and grinding, where material is removed through direct contact between a cutting tool and the workpiece. However, Inconel's hardness, toughness, and tendency to work-harden during machining make these processes particularly difficult. The high temperatures generated during cutting and the rapid wear of tools necessitate specialized approaches, making conventional machining of Inconel a complex yet essential task in manufacturing high-performance components. Non-conventional machining processes, such as Electrical Discharge Machining (EDM), Laser Beam Machining (LBM), and Abrasive Water Jet (AWJ) machining, offer effective solutions. Unlike conventional methods, non-conventional techniques do not involve direct contact between the tool and the workpiece, minimizing tool wear and preventing issues like work-hardening. Also, machining Inconel material with traditional methods is much more expensive compared to advanced techniques like laser

machining [11]. These advanced processes enable the precise and efficient machining of Inconel, particularly for complex geometries and intricate designs, making them invaluable in manufacturing components that demand both high precision and durability.

In the Conventional machining processes where material is removed through direct contact between the tool and the workpiece. The methods may involve various challenges as follows:

- **Work-Hardening:** Inconel has a tendency to harden rapidly during machining, which increases the difficulty of cutting and can lead to premature tool wear.
- **High Cutting Temperatures:** The heat resistance of Inconel means that significant heat is generated during machining, which is not easily dissipated. This can degrade the tool and affect the surface quality of the workpiece.
- **Tool Wear:** The hardness and toughness of Inconel lead to accelerated tool wear, requiring the use of specialized, often expensive, tooling materials such as carbide or ceramic tools.
- **Low Material Removal Rate (MRR):** The need for low cutting speeds to prevent overheating and tool wear results in a lower MRR, making conventional machining of Inconel less efficient.

Various methodologies such as use of coolants, specialized tools and Optimized Cutting Parameters can help in improving the machinability in conventional machining. Rakesh et al. [12] experimentally proved that of the four cooling conditions i.e. Dry machining, MQL, nMQL and Cryo N2 (l) tested, the cryogenic machining using an N2 (l)-air mixture as a coolant resulted in the lowest Ra, Flank wear, and main Fc values. The finding suggests that cryogenic coolants are highly effective for machining INCONEL 625 alloys. Kumar et al. [13] investigated the effects of machining conditions and machining environments on surface finish during the turning of Inconel 718. They found that employing MQL during the turning operation significantly improved tool life and resulted in enhancement of the surface finish. Cantero et al. [14] experimentally determined that during the turning of Inconel, tool wear is primarily influenced by machining speed, with feed rate and depth of cut also playing significant roles. The use of coated tools resulted in better surface finish and longer tool life compared to uncoated tools. Additionally, the side cutting edge angle was found to be a critical factor in the tool wear mechanism. E.O.Ezugwu et al. [18] have concluded in the study that modern advancements in cutting tool materials, particularly ceramics and coated carbide tools, have significantly enhanced the efficiency and effectiveness of machining nickel-based alloys. Also, various machining parameters such as depth of cut, cutting speed, and feed rate are optimised that significantly influence the performance of both the workpiece and the cutting tool material. The studies by Grzesik et al., Devillez et al., Celik et al., and Thakur et al. [15-18] highlight key findings on the

machining parameters of superalloy Inconel. Grzesik et al.[15] observed that TiAlN and AlTiN coatings can extend tool life by 60 minutes at a machining speed of 80 m/min, with tool life heavily influenced by the coating type. Devillez et al.[16] found that tool wear significantly impacts surface integrity, increasing tensile stress and compressive stress layers when using worn tools. Celik et al. [17] identified diffusion-based tool wear as the primary wear mechanism during milling with SiAlON tools. Thakur et al. [18] noted that while machining forces decrease with higher speeds, tool wear increases with higher speeds and feed rates, with feed being the most influential factor on tool-chip contact length.

Although a lot of experiments are carried out for machining by the conventional methods, non-conventional machining processes do not involve direct contact between the tool and the workpiece, making them suitable compared to the conventional methods. Laser Beam Machining offers high precision, flexibility, and efficiency, along with minimal thermal and mechanical effects, making it highly advantageous for machining Ni-based alloys compared to other non-conventional machining methods. These attributes are particularly important in industries where material integrity and precision are critical.

Optimized methods like ANN, genetic algorithms, ANOVA, Taguchi, and response surface methodology are also useful to achieve better results.

II. LASER-ASSISTED MACHINING AND LASER BEAM MACHINING

Laser Beam Machining (LBM) and Laser Assisted Machining (LAM) are both processes that utilize lasers in material processing, but they differ significantly in their principles, applications, and outcomes. Among common types of lasers such as CO₂ lasers, Nd:YAG lasers, and diode lasers, diode lasers offer high output and energy efficiency, CO₂ lasers are ideal for ceramics due to their absorption rate, and Nd:YAG lasers, with low wavelength and high energy density, are effective for heating metals with minimal hardening depth.[20]. The quality, precision, and accuracy of the cut depend on choosing the right laser and process parameters. Laser machining can be carried out either via continuous wave or pulsed laser machining. A CW (Continuous Wave) laser emits a continuous, steady beam of light, providing consistent power output over time. This makes it ideal for processes that require prolonged exposure to heat, such as cutting, welding, or large-scale material removal. However, due to the continuous energy, there is a higher risk of overheating or thermal damage if not carefully controlled. In contrast, a pulsed laser delivers energy in short, controlled bursts, allowing for precise control over the duration and intensity of the laser exposure. This makes pulsed lasers suitable for delicate applications, such as fine engraving or micro-machining, where minimizing thermal impact and preventing damage to surrounding materials is crucial. Pulsed lasers offer greater precision and are often used when material sensitivity or precision is required. Depending on the applications either continuous wave or pulse laser is used in machining.

A. Laser Assisted Machining

Laser Assisted Machining (LAM) improves the machinability of Ni-based alloys by utilizing a laser to preheat the material before cutting with a conventional tool. This preheating process softens the alloy, decreasing its strength and hardness, which in turn reduces cutting forces and minimizes tool wear. This is particularly valuable for Ni-based superalloys, known for causing rapid tool degradation during traditional machining. By extending tool life, enhancing surface finish, and lowering cutting costs, LAM proves highly advantageous. Additionally, it helps reduce surface defects and residual stresses, making it ideal for manufacturing high-performance components. [21]

Advantages:

- Reduced cutting forces: Preheating the material reduces its resistance to cutting, lowering the forces on the tool.
- Increased tool life: The laser's assistance reduces tool wear, especially when machining tough materials like Ni-based alloys.
- Improved surface finish: The process can enhance surface quality by reducing roughness.

Limitations:

- Complex setup: LAM requires precise synchronization between the laser and the cutting tool.
- Limited by material properties: Not all materials respond well to laser preheating, especially those with poor thermal conductivity.

B. Laser Beam Machining

LBM provides a solution by utilizing a high-intensity laser beam to remove material directly through processes like melting, vaporization, or ablation. This method is especially effective for machining intricate geometries and small features in Ni-based superalloys, such as Inconel 718. Since it is a non-contact process, LBM offers high precision, minimizes mechanical stress, and eliminates tool wear. However, the intense heat produced can form a heat-affected zone (HAZ), which may alter the material properties around the machined area, raising concerns for critical components. [22]

Advantages:

- Non-contact process: There is no tool wear since no physical contact occurs between the tool and the workpiece.
- High precision: The laser can be focused to a small spot size, resulting in very accurate cuts.
- Wide range of materials: LBM is effective on various materials, including difficult-to-machine alloys like Ni-based superalloys.

Limitations:

- Thermal effects: Material removal generates heat, which can create a heat-affected zone (HAZ) and affect the material's properties near the machining area.
- High power consumption: LBM requires a significant amount of energy to vaporize or melt material.

- The following table gives us an idea of various studies available on Laser beam machining and Laser-assisted machining

Sr no.	Author	Summary	Applications
1.	Akshee shivam et al.	This review evaluates various laser beam machining processes on Inconel alloys, highlighting improvements in micro-hardness, tensile strength, and thermal properties.	Aerospace, nuclear industries, gas turbines, jet engines.
2.	Manoj Samson et al.	This study analyzes the effects of process parameters like laser power and cutting speed on surface roughness and material removal rate, optimizing for better machining performance.	High-pressure turbine components, aerospace structural components.
3.	Prashant Kumar Shrivastava et al.	This study optimizes the machining of Inconel-718 using a pulsed Nd laser by employing Response Surface Methodology (RSM) and multiobjective genetic algorithm (MOGA) to refine cutting parameters for precision. The optimized ranges for gas pressure, standoff distance, cutting speed, and laser power ensure accurate cuts with minimal deviations in kerf width.	nuclear reactors, submarines, automobiles, petrochemical equipment
4.	Adam Khan M et al.	The study examines the impact of laser power and travel speed on kerf wall inclination, material removal rate (MRR), surface roughness, and metallurgical changes in laser cutting of nickel-based superalloys.	Marine and Medical applications
5.	Ahmet Hascalik et al.	This study examines the effects of CO ₂ laser cutting parameters on recast layer thickness, surface roughness, and kerf taper ratio in Inconel 718. Laser power significantly impacts recast layer thickness, while cutting speed has a greater effect on surface roughness and kerf taper.	gas turbine engines
6.	Haijun Zhang et al.	This study investigates the laser-assisted micro-milling process of Inconel 718 using experiments and finite element simulations. It found that laser assistance reduces cutting forces and enhances surface integrity.	Aerospace, Automotive
7.	Iban Arriola et al.	This study concludes that LAM is more effective for harder materials, with optimal conditions for cutting force reduction linked to laser power, cutting speed, and tool proximity. While LAM can reduce tool life in carbide inserts, it minimizes notching and improves surface finish and integrity compared to conventional machining.	cryogenic storage tanks, nuclear fuel element spacers, pump body components
8.	Giacomo Leopardi et al.	This paper presents a statistical analysis of active machining force (Fa), passive force (Fp), and tool wear (VBmax) in laser-assisted milling (LAM). It concludes that LAM reduces Fa and VBmax due to material softening and lower tool wear, and recommends down-milling for machining Inconel 718.	Aerospace Industries
9.	K. Venkatesan et al.	The study shows that optimal machining conditions, including a laser power, speed, and feed, significantly improve performance, reducing forces, tool wear, and surface roughness by up to 50% compared to conventional methods. The chip morphology analysis supports the improved machinability of Inconel 718 under LAHM.	Aerospace applications
10.	H. Attia et al.	The optimum conditions for laser-assisted finish turning of IN718 using a SiAlON ceramic tool result in a significant reduction in cutting forces, a 25% improvement in surface finish, and an 800% increase in material removal rate. Additionally, these conditions maintain surface integrity without introducing defects or phase changes, while promoting favorable compressive residual stresses.	Aerospace Applications

III. OBSERVATIONS

The review paper on "Laser Machining of Inconel " provides an in-depth analysis of the challenges associated with machining Inconel alloys using conventional methods and highlights the benefits of adopting non-conventional techniques such as Laser Beam Machining (LBM) and Laser-Assisted Machining (LAM). It presents a comprehensive comparison between traditional and advanced machining processes, emphasizing the superior performance of laser-

based methods in overcoming issues like tool wear, surface roughness, and material removal rates.

Key observations from the review include:

- Challenges in Conventional Machining: Inconel alloys exhibit high strength, work-hardening tendencies, and poor thermal conductivity, leading to issues such as excessive tool wear, high cutting temperatures, and poor surface quality when using traditional techniques.
- Advantages of Non-Conventional Machining: LBM and LAM offer solutions by employing high-precision laser

technology, reducing tool wear, and enhancing surface finish. LAM, in particular, is effective in preheating the material to soften it, thus reducing cutting forces and improving machinability.

- Process Optimization: The review details the significance of optimizing parameters like laser power, cutting speed, and feed rates to improve performance. Various studies have shown that optimized conditions can significantly enhance tool life, surface quality, and machining efficiency.
- Thermal Effects and HAZ: While laser-based machining reduces mechanical stress, the heat generated can create a heat-affected zone (HAZ), which may affect material properties near the machining area. This is a critical consideration in applications requiring high material integrity.
- Applications and Industrial Relevance: The findings underscore the importance of LBM and LAM in industries such as aerospace, nuclear, and gas turbines, where precision and durability are essential.

The review highlights the growing importance of laser-assisted techniques in machining difficult-to-machine alloys like Inconel, offering enhanced efficiency, precision, and cost-effectiveness over traditional methods.

REFERENCES

- [1] Akshee shivam, Santanu Chakraborty, B.B.Pradhan, "LASER BEAM MACHINING OF INCONEL ALLOYS: A REVIEW" International Journal on Design & Manufacturing Technologies, Volume 11, Issue 1, p9 (2017)
- [2] Manoj Samson, Ranjith, Nirmal and Geethapriyan "Performance analysis of process variables on laser beam machining of inconel-718 alloy" IOP Conference Series: Materials Science and Engineering, Volume 912 (2020)
- [3] Prashant Kumar Shrivastava, Bhagat Singh, Yogesh Shrivastava, Arun Kumar Pandey and Durgesh Nandan "Investigation of optimal process parameters for laser cutting of Inconel-718 sheet" Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Volume 234, Issue 8, Pages: 1581 – 1597 (2020)
- [4] Adam Khan M, Kapil Gupta "Experimental evaluation of surface quality characteristics in laser machining of nickel-based superalloy" Optik - International Journal for Light and Electron Optics, Volume 196, 163199 (2019)
- [5] Ahmet Hascalik, Mustafa Ay "CO2 laser cut quality of Inconel 718 nickel-based superalloy" Optics & Laser Technology, Volume 48, Page 554–564 (2013)
- [6] Haijun Zhang, Fei Chen, Zengqiang Li, Wangjie Hu, Tao Sun and Junjie Zhang "Investigation of Laser-Assisted Micro-Milling Process of Inconel 718" Journal of Manufacturing and Material Process. (2023)
- [7] Virginia Garcia Navas, Iban Arriola, Oscar Gonzalo, Josu Leunda "Mechanisms involved in the improvement of Inconel 718 machinability by laser assisted machining" International Journal of Machine Tools & Manufacture, Volume 74 page 19–28 (2013)
- [8] Giacomo Leopardi, Flaviana Tagliaferri, Carlo Rüger, and Martin Dix "Analysis of Laser Assisted Milling (LAM) of Inconel 718 with Ceramic Tools" Procedia CIRP, Volume 33, Pages 514-519 (2015)
- [9] K. Venkatesan, R. Ramanujam "Improvement of machinability using laser-aided hybrid machining for Inconel 718 alloy" Mater. Manuf. Process. 31, 1825–1835 (2016)
- [10] H. Attia, S. Tavakoli, R. Vargas, V. Thomson "Laser-assisted high-speed finish turning of superalloy Inconel 718 under dry conditions" CIRP Annals – Manufacturing Technology 59, 83-88 (2010)
- [11] Venkatesan K and Ramanujam R. "Statistical approach for optimization of influencing parameters in laser assisted machining (LAM) of Inconel alloy" Measurement, Volume 89, Pages 97-108 (2016)
- [12] Rakesh, P.R.; Chakradhar, D. Machining performance comparison of Inconel 625 superalloy under sustainable machining environments. J. Manuf. Process. (2023)
- [13] S. Kumar, D. Singh, N.S. Kalsi "Experimental Investigations of Surface Roughness of Inconel 718 under different Machining Conditions" Materials Today: Proceedings 4, Pages 1179-1185 (2017)
- [14] J.L. Cantero, J.D.-Alvarez, M.H. Miguelez, N.C. Marin "Analysis of tool wear patterns in finishing turning of Inconel 718", Volume 297, Issues 1–2, Pages 885-894 (2013)
- [15] W. Grzesik, P. Nieslony, W. Habrat, J. Sieniawski, P. Laskowski "Investigation of tool wear in the turning of Inconel 718 superalloy in terms of process performance and productivity enhancement" Tribology International 118, Pages 337-346 (2018)
- [16] A. Devillez, G.L. Coz, S. Dominiak, D. Dudzinski "Dry machining of Inconel 718 workpiece surface integrity" Journal of Materials Processing Technology, Volume 211, Issue 10, Pages 1590-1598 (2011)
- [17] A. Çelik, M.S. Alağaç, S. Turan, A. Kara, F. Kara "Wear behavior of solid SiAlON milling tools during high speed milling of Inconel 718" Volumes 378–379, Pages 58-67 (2017)
- [18] D.G. Thakur, B. Ramamoorthy, L. Vijayaraghavan "Study on the machinability characteristics of superalloy Inconel 718 during high speed turning" Materials & Design Volume 30, Issue 5, Pages 1718-1725 (2009)
- [19] E.O. Ezugwu, J. Bonney, Y. Yamane "An overview of the machinability of aeroengine alloys" Journal of Materials Processing Technology, Volume 134, Issue 2, Pages 233-253 (2003)
- [20] Vignesh M and Ramanujam R, "Chapter 9-Laser-assisted high speed machining of Inconel 718 alloy" High Speed Machining, Pages 243-262 (2020)
- [21] Srinivasa Rao Nandam, A. Venugopal Rao, Amol A. Gokhale & Suhas S. Joshi "Laser Surface Modification of Single-Crystal Nickel-Based Superalloy: Geometry, Microstructure, Crack Morphology, and Microhardness" J. of Mater Eng and Perform 33, 7054–7073 (2023)
- [22] Liu, D., Yang, X., Zhao, A. et al. "Preparation of nickel-based composite coatings by laser cladding technology: a review" Int J Adv Manuf Technol 134, 3107–3137 (2024)