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Review on Milling Process of Inconel 718 superalloy

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Abstract
Inconel refers to a group of nickel-based superalloys recognized for their remarkable physical and mechanical characteristics, making them highly suitable for aerospace manufacturing. Despite their advantages, these materials are notoriously difficult to machine due to their poor machinability and the formation of hard precipitates. Inconel alloys are valued for their high shear strength, low thermal conductivity, and ability to maintain structural integrity and hardness at elevated temperatures. These properties contribute to their widespread use in critical industries such as aerospace, defense, aviation, and gas turbine production. In particular, Inconel 718 is one of the most commonly utilized grades due to its balanced performance. Extensive research has been carried out to improve its machinability under various conditions, focusing on tool electrode selection and geometric optimization. This review mainly considers the influence of process parameters on the milling of Inconel alloy, and also provides a comparison between conventional and non-conventional cutting fluids.

Keywords: *Inconel, machinability, Milling, lubricating, machining*

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I. INTRODUCTION

Inconel 718 is a nickel-chromium-based superalloy known for its exceptional mechanical properties, including high yield strength, tensile strength, and resistance to creep rupture—even at temperatures reaching 1300°F. Compared to other nickel-based alloys, it offers improved weldability. When exposed to elevated temperatures, Inconel 718 naturally develops a protective oxide layer that shields its surface from further degradation. While conventional metals like aluminum and steel tend to lose strength due to creep at high temperatures, Inconel 718 maintains its mechanical integrity across a broad temperature range. This thermal resilience is primarily attributed to strengthening mechanisms such as precipitation hardening and solid solution strengthening [1].

Inconel 718 is exceptionally resistant to oxidation and corrosion, making it ideal for applications in extreme environments involving high temperatures and pressures. During age hardening, a small amount of niobium interacts with nickel to form the intermetallic compound Ni_3 Nb, which effectively impedes creep and slip at elevated temperatures [2]. However, the alloy's tendency to undergo continuous work hardening presents significant challenges during machining, especially with conventional techniques. This hardening leads to plastic deformation of both the cutting tool and the workpiece surface. As a result, machining typically involves slow, aggressive cuts using hard tool materials to minimize surface damage. Pre-machining stress relief or using a solutionized form of Inconel 718 can reduce surface hardness and suppress work hardening, thereby lowering tool wear and improving surface quality [3]. Due to its durability under harsh conditions, Inconel 718 is used in a wide range of critical components such as combustors, turbine blades, heat exchangers, turbocharger rotors and seals, nuclear reactor parts, motor shafts, electric submersible well pumps, and high-pressure vessels. It is also employed in cryogenic storage systems and wellhead components. In the aerospace sector, it serves structural roles such as securing solid rocket boosters on launch platforms [4]. When turning Inconel 718, optimizing cutting parameters is crucial for managing cutting temperature, tool life, and machining forces. Elevated temperatures during machining can alter the microstructure of the material, so minimizing tool-chip contact length is essential for thermal control. Tool wear in turning primarily results from abrasion and plastic deformation, and its severity is strongly influenced by the tool-chip interaction [5]. The application of cutting fluids significantly enhances machining by reducing friction and dissipating heat. In drilling operations, minimum quantity lubrication (MQL) has been shown to outperform both dry cutting and flood cooling methods [6]. Additionally, surface finish and topography during drilling are primarily determined by cutting speed and feed rate. Excessive heat generated at high cutting speeds can increase microhardness and surface roughness, leading to poorer surface quality—hence the use of coolants is recommended during high-speed drilling [7].

This paper presents a concise review of existing research on the machining of Inconel 718, a nickel-based superalloy, using various processes such as turning, drilling, and milling under different cooling conditions—including dry machining, cryogenic cooling, and minimum quantity lubrication (MQL). The review explores the correlation between machining parameters and key performance indicators such as surface finish, cutting temperature, and tool wear. Additionally, it examines how different cooling and lubrication strategies influence the overall efficiency and effectiveness of machining Inconel 718.

II. EFFECT OF VARIOUS MACHINING OPERATION ON THE PERFORMANCE OF MILLING INCONEL SUPERALLOY

Technological parameters play a crucial role in determining the efficiency and effectiveness of the milling process for Inconel 718. Various studies have explored the impact of machining conditions—such as cutting speed, feed rate, and cooling methods—on key outcomes like tool wear, cutting force, and surface quality. Li et al. investigated electrode wear and cutting force variations during up and down end milling of Inconel 718 using coated carbide tools [8]. Their findings showed that flank wear and chipping were the dominant wear mechanisms, with faster wear propagation observed in up milling. Tool wear progression led to a consistent increase in cutting force magnitudes. Variations in force during a single pass were attributed to thermal effects, while longer-term increases were due to cumulative tool wear. S. Zhang et al. examined the influence of minimum quantity cooling lubrication (MQCL) on tool wear and cutting forces during end milling [9]. Under MQCL, tool life was extended by 1.57 times compared to dry conditions. This improvement was due to the lubricating film formed by fine droplets and the cooling effect of compressed cryogenic air, which collectively reduced friction and temperature at the tool–chip interface. Jawaid et al. compared PVD TiN-coated and uncoated carbide tools during face milling [10]. The uncoated tool outperformed the coated one at lower speeds due to its resistance to abrasive wear, while the TiN-coated tool showed superior performance at higher speeds because of its low thermal conductivity and wear resistance. However, at speeds above 75 m/min, the coated tool exhibited severe flank wear and rapid degradation, limiting its effective tool life to under one minute. Alauddin et al. evaluated tool life during full and partial engagement end milling of Inconel 718 using uncoated tungsten carbide under dry conditions [11]. Full engagement yielded better tool longevity due to more consistent thermal loads, whereas partial engagement introduced thermal cycling stresses that accelerated tool wear. Liao et al. studied Inconel 718 during slot and side milling with cemented carbide tools [12]. They found low-speed cutting problematic due to heat buildup and strain hardening. Higher speeds improved tool life, as thermal softening of the alloy facilitated machining. In slot milling, excessive speeds (above 113.1 m/min) caused chip welding within the slot, while in side milling, minor flank wear was seen at low speeds. At higher speeds (above 135.7 m/min), chip adhesion increased cutting forces and temperatures. Sharman et al. examined high-speed ball nose milling with TiAlN and CrN-coated tungsten carbide tools [13]. The TiAlN coating delivered the best tool life at 90 m/min, while CrN performed poorly at 150 m/min, especially when machining inclined surfaces. Built-up edge (BUE) and coating delamination were key wear modes, with CrN showing greater chemical affinity to Inconel 718 and more severe BUE formation. Rahman et al. assessed machinability using two coated carbide tools—EH20Z-UP (PVD-TiN) and AC25 (CVD-TiN) [14]. The best results were achieved at a side cutting edge angle (SCEA) of 45°, where both tools showed extended life. As speed and feed increased, tool life dropped due to greater heat generation. Flank wear was the limiting factor for EH20Z-UP, while DOC-related indentation wear dominated for AC25. Overall, recommended cutting speeds and feeds for Inconel 718 remained in the lower range due to thermal sensitivity. Tian et al. explored the effect of cutting speeds between 600–3000 m/min in high-speed face milling using Sialon ceramic tools [15]. Cutting forces initially decreased and then increased with speed. At low speeds, down milling showed better performance. Indentation wear was the primary failure mode at lower speeds, while adhesion wear dominated at higher speeds. Down milling caused more severe damage to the rake and flank faces, favoring up milling for better tool integrity. Li et al. evaluated the effect of tool wear on surface integrity and fatigue life using PVD-TiN-coated carbide inserts [16]. Contrary to expectation, higher tool wear sometimes correlated with improved surface conditions due to enhanced cooling effects from the intermittent contact in milling. Moderate tool wear did not significantly impact fatigue life, with no failure observed up to 4 million cycles for wear levels below VB = 0.2 mm. Aramcharoen and Chuan conducted an experimental analysis of cryogenic milling of Inconel 718 and its sustainability [17]. Cryogenic cooling effectively lowered cutting zone temperatures and improved cooling efficiency at the tool–chip interface. It also enhanced lubrication performance and reduced contact friction. Tool wear patterns under cryogenic conditions resembled those under conventional oil-based coolant, suggesting comparable tool degradation mechanisms.

III. EFFECT OF COOLING/LUBRICATING METHODS

In present days, there is an increase in demand for cost-efficient and environment-friendly machining process so the researchers are taking a keen interest in new cooling conditions and coolants so the comparison between different cooling environments are being made in this literature review paper. Today green machining technology consistsof dry machining, near-dry machining or minimum quantity lubrication, mist lubrication cooling, compressed air cooled system, liquid nitrogen cooling technology and uses of cooling gases.

Dry machining involves heat removal without using coolants and for machining harder specimen it requires high performing machining tools like CBN /ceramic which are expensive and requires for tremendously rigid machine tools. MQL cooling system is near to dry machining technique, it is stuck between dry and wet machining. It mixes a small amount of machining fluid with dense air and falls exactly on the machining zone between workpiece and tool. New developments are made in the field of machining tool materials and coating technologies have given many advantageous conditions for the function of MQL during machining of Inconel. Abrasion and adhesion are the most dominant factors which result in wear mechanism while machining of Inconel 718. Cryogenic cooling not only reduces the friction between workpiece and tool but it also proves good lubrication during the machining operation. While using cryogenic cooling during machining of Inconel 718 produced better surface finish and longer life of the tool as compared to the other cooling system [18]. Aramcharoen and Chuan investigated the effect of cryogenic cooling during milling of Inconel as compared with oil-based coolant and dry environment cooling. Cryogenic cooling displayed better surface finish, lower wear of the tool and increased the productivity. Cryogenic machining was found both environmental and operator friendly but on the other hand oil based cooling resulted in carcinogenic [17]. He et al. compared dry environment and cryogenic environment machining during turning operation of Inconel. It was experimentally found that the machining forces for dry and cryogenic machining wear almost same but cryogenic machining generated less tensile stress on the surface of the workpiece as compared to dry machining [19]. Iturbe et al. researched on replacement of conventional machining fluid by MQL using liquid nitrogen for industrial purpose while machining of Inconel [20]. It was experimentally found that by a combination of MQL with cryogenic machining resulted in improvement in machining performance for short machining time when compared with dry and only MQL machining. But this combination of MQL and cryogenic machining did not proveeffective for long and continuous machining as during longer machining the life of the tool was found much shorter as compared to long machining using conventional machining. So using combined MQL and cryogenic machining was found only effective during short time machining only. Kumar et al. explored the outcome of machining condition and machining environment on the surface finish while turning operation of Inconelsuper alloy [21]. Using MQL during turning operation showed high improvement in life of the tool and around 12-17% enhancement in the surface finish was marked. It was experimentally found that nose radius is the most important parameter which affects the surface roughness followed by feed rate. Shokrani et al. studied the effect of hybrid cooling technology during CNC milling of Inconel [22]. A hybrid cooling system consists of MQL using vegetable oil and cryogenic cooling using liquid nitrogen. It was observed that only cryogenic cooing was inadequate in improving the machinability of Inconel as it often results in greater tool wear and material hardness. On the other hand using hybrid cooling system resulted in around double life of the tool and surface finish. Paturi researched on the effect of micron-sized tungsten disulfide (Solid lubricant) assisted MQL system during turning operation on the surface roughness of the machined surface [23]. Experimental results showed around 35% improvement in the surface finish as compared with MQL machining system. So it was found that solid lubricant WS2 has the potential to be used as a potential additive in emulsifier oil based machining fluid. Yazid experimentally observed that MQL condition generated improved surface finish as compared to dry condition during turning operation using PVD coated machining tool. During lower machining speed of around 90-120 m/minute the MQL 50 ml displayed better surface quality as compared to dry condition and MQL 100 ml condition [24].

IV. CONCLUSION

This review focuses on the milling of Inconel 718, highlighting the influence of machining parameters on outcomes such as surface finish, tool life, wear, and chip formation. Given the growing demand for sustainable and cost-effective processes, recent studies emphasize the role of advanced cooling methods. The literature compares various cooling strategies, underlining the importance of selecting an appropriate cutting environment.

Key findings include:

- Abrasive wear at the tool's trailing edge is the predominant wear mechanism. Coated tools yield superior surface finishes at high speeds, with tool wear primarily affected by cutting speed, followed by feed rate and depth of cut.

- Cryogenic cooling effectively minimizes friction and heat at the tool–workpiece interface, leading to improved surface quality and extended tool life compared to conventional cooling methods.
- Most heat is generated at the rake face near the cutting edge, and targeted coolant application significantly reduces this thermal load. Cutting speed is the main contributor to tool wear, followed by temperature effects.
- Higher cutting speeds, along with lower feed and depth of cut, enhance surface finish. Tool wear showed minimal influence on surface roughness in some cases.

Future research may explore nanofluid-based cooling methods, including MQL variants and multi-nozzle systems, as well as optimized tool geometries to further enhance Inconel 718 machinability.

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