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A brief review of ultrasonic assisted milling of Inconel 718

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ABSTRACT

Ultrasonic Assisted Milling (UAM) offers an effective means to both increase productivity and decrease tool wear. In this review, UAM for milling Inconel 718 will be discussed along with its principles and effects. Factors affecting machining performance such as spindle speed, ultrasonic amplitude, tool geometry, and fluid usage, such as ultrasonic amplitude modulated parameters, are examined and optimized accordingly. This review investigates the effects of ultrasonic vibration on cutting force, tool wear, and surface roughness, as well as methods for monitoring and controlling the (UAM) process. Ultimately, this investigation explores its potential application to machining Inconel 718 with (UAM), providing insights for improved performance as well as wider industrial applications.

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1.0 INTRODUCTION

Inconel 718 is an exceptional nickel-based superalloy known for its outstanding properties and a wide array of applications. Composed primarily of nickel (approximately 50–55%), chromium (17–21%), iron (17–21%), and other elements such as niobium (4.75–5.5%), molybdenum (2.8–3.3%), titanium (0.65–1.15%), and aluminum (0.2–0.8%), it provides exceptional mechanical properties and corrosion resistance properties (Hosseini & Popovich 2019). These elements combine to produce exceptional mechanical properties as well as corrosion-resistant properties (Hosseini & Popovich 2019). This combination gives Inconel 718 its superior properties and corrosion resistance (Hosseini & Popovich 2019).

Inconel 718 exhibits outstanding high-temperature strength properties, which allow it to maintain its structural integrity even at higher temperatures. Borisov et al. (2022) found it to have excellent corrosion and oxidation resistance, making it suitable for use in harsh environments like saltwater or acidic gases (Borisov et al.). Also, this alloy exhibits superior fatigue and creep resistance properties, enabling it to withstand repeated cycles of loading at high temperatures without deformation or failure (Periane et al., 2021; Yu et al., 2021). Inconel 718 boasts superior weldability, making it easy to join using various welding techniques. It can even be joined either underage-hardened or solution-annealed conditions (Sonar et al., 2021; Yin et al., 2020). Welding allows for more efficient manufacturing processes and allows the creation of complex and intricate components, while its ease of use also simplifies repair and maintenance operations, reducing downtime costs associated with aircraft maintenance.

However, this alloy does present some weldability challenges, such as micro-fissuring and solidification cracking (Tharappel & Babu, 2018). The mechanical properties of alloy 718 weldments tend to lag behind those of their base metal (Sonar et al., 2021). Inconel 718 welding can also experience hot cracking, HAZ liquid cracking, segregation, and phase formation in its weld zone (Sonar et al., 2021). However, despite these issues, Inconel 718 remains considered excellent when aged and hardened (Tharappel & Babu 2018; Muralidharan et al. 1996).

Inconel 718 finds wide use across multiple industries. Aerospace applications of Inconel 718 include components like turbine blades, engine casings, combustion chambers, and structural parts due to its high-temperature strength and corrosion resistance (Akca & Gursel 2015; Blakey-Milner et al. 2021; Melih Cemal Kushan 2012). Meanwhile, the gas turbine industry uses Inconel 718 due to its ability to withstand extreme temperatures in components like discs, rotors, and seals (Subbarao & Chakraborty 2018; Amigo et al. 2021).

Inconel 718's corrosion resistance and mechanical strength make it ideal for nuclear reactor applications such as fuel assemblies, reactor core components, and control rods (Lu et al., 2019). Furthermore, Inconel 718 is widely employed in chemical processing equipment like valves, pumps, and reactors where high temperatures and corrosion resistance are critical (Hunt and Inc., n.d.). Furthermore, Inconel 718 finds application in making airplanes and military equipment, as well as being combined with aluminum for combined applications to produce low weight and high thermal properties (Marques et al., 2023).

Inconel 718 is a nickel-based superalloy with exceptional properties. Composed largely of nickel, among other alloying elements, Inconel 718 exhibits superior high-temperature strength, corrosion resistance, fatigue resistance, and fatigue resistance properties that make it widely used across aerospace, gas turbines, nuclear reactors, and chemical processing industries. Due to this alloy's unique combination of properties, it can withstand demanding environments while performing reliably even in harsh environments such as nuclear reactors.

1.1 The significance of Ultrasonic Assisted Milling (UAM) in machining processes and its potential benefits

Ultrasonic Assisted Milling (UAM) plays an essential role in Inconel 718 machining processes due to its challenging material properties of high strength and heat resistance. By combining traditional milling with ultrasonic vibrations, this technique offers several potential benefits specific to Inconel 718 (Xu et al. 2023; Hafiz et al. 2018; Wu et al. 2018; He et al. 2019; and Singh 2023).

UAM plays an invaluable role in the machining of Inconel 718 by providing solutions to meet its specific challenges. Inconel 718 can be difficult to machine due to its high hardness and tendency for excessive heat generation during cutting (M.S.A. Hafiz et al. 2017; He Y et al. 2019; Martins H. 2023), but UAM provides solutions and unlocks numerous potential advantages.

Ultrasonic assistance when machining Inconel 718 provides several key benefits, with material removal rates increasing as a result of high-frequency vibrations breaking up chips produced during cutting for easier evacuation from the cutting zone and thus increasing cutting speeds and material removal rates, resulting in reduced machining times and greater overall productivity (Xu et al. 2023; Hafiz et al. 2018; Wu et al. 2023; Hee et al. 2019; and Singh 2023).

UAM can also bring to Inconel 718 work an improved surface finish through vibrational aid. By minimizing contact between the cutting tool and workpiece, vibrations help minimize surface imperfections such as roughness (Xu et al. 2023; Hafiz et al. 2018; Wu et al. 2018; He et al. 2019; Singh et al. 2023). By breaking chips into smaller pieces, the vibrations further contribute to creating smoother finishes without extensive post-processing operations (Xu et al., 2023; Hafiz et al., 2018; Wu et al., 2018; He et al., 2019; Singh, 2023).

UAM in Inconel 718 machining processes has also proven beneficial, contributing to extended tool life and reduced tool wear and breakage risks, leading to a longer tool lifespan, lower tooling costs, and overall increased efficiency (Hafiz et al. 2018).

Economics is one of the driving forces behind constant technical progress, with machine shops seeking cost-reduction solutions like ultrasound cutting. Milling metals is one of the most frequently utilized traditional machining processes for achieving complex geometries and dimensions. Due to a paucity of theoretical research (Hafiz et al., 2018) on cutting dynamics and characteristics that would provide predictive theories and quantitative models that enable further optimization of complex material machining processes (Lu et al., 2019; Hafiz et al., 2018), applying ultrasonic technology in this operation has proven difficult.

Overall, the significance of (UAM) in machining Inconel 718 lies in its potential to overcome the challenges associated with this demanding material. By utilizing ultrasonic vibrations, this technique enables improved material removal rates, enhanced surface finish, and extended tool life when working with Inconel 718. These benefits ultimately contribute to increased productivity, cost savings, and improved quality in machining processes involving Inconel 718, making (UAM) a valuable approach in industries such as aerospace, automotive, and energy, where Inconel 718 is extensively used. As a result, the purpose of this paper is to explain the technology's basic concepts and offer answers.

2.0 HISTORY AND DEVELOPMENT: A HISTORICAL JOURNEY OF MILESTONES AND ADVANCEMENTS

The history and development of Ultrasonic Assisted Milling (UAM) techniques, as shown in Figure 1, have been marked by significant milestones and advancements, as evidenced by the significant milestones depicted here. UAM is an advanced machining technique that utilizes high-frequency vibrations for material removal processes. UAM can be traced back to its inception during the 1950s when researchers explored using ultrasonic vibrations for hard and brittle materials; however, experimental investigations began gaining steam during the 1970s. Researchers began to recognize the benefits of ultrasonic vibrations for increasing cutting efficiency, decreasing tool wear, and improving surface finish (Zhichao Y et al. 2020; Lupien et al. 2020). Since that time, Ultrasonic Assisted Milling (UAM) systems have emerged from traditional ultrasonic machining (USM), where high-frequency vibration is applied to one or more components of a machining system (Martins H. et al.,2023). UAM has several useful applications when used on materials that are more fragile and sensitive than metals, such as ceramics, carbides, glass precious stones, and hardened steel (Lupien et al.,2020).

Researchers began combining ultrasonic vibrations with milling techniques for machining improvement.

Ultrasonic Assisted Milling (UAM) technique was developed to tackle tough materials like Inconel 718

Focus on controlling vibrations, optimizing parameters, and enhancing tool materials

Improved tools with special coatings were introduced for better performance

Techniques for precise vibration control emerged, aiding chip breaking and reducing cutting forces

New cooling methods like minimum quantity lubrication and cryogenic cooling were explored

Monitoring systems developed for tracking tool wear and forces, leading to adaptive control

Advanced simulations improved understanding of material behavior and tool wear

UAM evolves with ongoing integration of material, technology, and process advancements

Figure 1: Milestones in the evolution of UVAM over time.

According to milestones in the evolution of UVAM over time (Zhichao Y et al., 2020). At first, researchers in the 1970s and 1980s focused their experiments on understanding how ultrasonic vibrations affected tool wear and surface roughness in milling operations. Prototype UAM machines were constructed, typically employing piezoelectric transducers for vibration generation. As technology advanced during the 1990s, so too did UAM, with more efficient and reliable ultrasonic transducers being developed specifically for milling applications—magnetostrictive transducers as well as Langevin transducers—being extensively explored for their effect on performance analysis (Zhichao Y et al., 2020).

Integrating Ultrasonic Assisted Milling (UAM) and computer numerical control (CNC) systems became a central topic of study during the 2000s. This allowed for precise control over cutting parameters, optimizing machining processes, and expanding industrial applicability. Researchers developed innovative milling strategies such as spiral tool paths and trochoidal milling that increase material removal rates and productivity, while advancements in cutting tool geometries, materials, and coolant delivery systems contributed significantly to increased UAM efficiency (Zhichao Y et al. 2020; Verma & Pandey 2019).

Notable advancements in UAM have focused on producing superior surface finishes, reducing burr formation, and improving dimensional accuracy. Researchers have introduced novel tool coatings, such as diamond-like carbon (DLC) or nanocomposite coatings, to minimize tool wear and extend tool life (Zhichao Y et al., 2020). These advancements have enabled (UAM) to be successfully applied to various materials, including hard metals, ceramics, composites, and even biological tissues (Zhichao Y et al., 2020 & Muralidharan, et al., 1996). As a result, (UAM) has found applications in industries such as aerospace, automotive, medical, and precision engineering (Zhichao Y et al., 2020 & Verma & Pandey, 2019).

Through ongoing study and technological breakthroughs, the historical background and development of ultrasonic-aided milling processes have made significant progress. (UAM) has gained popularity as a viable machining technique from its early experimental stages through its integration with CNC systems. Surface quality, material removal rates, and the range of applications have all improved. It is anticipated that ultrasonic-aided milling techniques will become more and more important to the manufacturing sector as research and development in this area continue. (UAM) has made significant strides in the areas of improved surface finishes, minimizing burr development, and enhancing dimensional accuracy. Researchers have developed cutting-edge tool coatings such as diamond-like carbon (DLC) and nanocomposite coatings to reduce tool wear and increase tool life, including diamond-like carbon (DLC) and nanocomposite coatings. Thanks to this research, UAM can now be successfully used on biological tissues, hard metals, ceramics, and composite materials like biological tissues; consequently, it has found use across various sectors such as precision engineering, aerospace, automobile, and medical industries (Zhichao Y et al., 2020; Amini et al., 2021).

2.1 Notable Breakthroughs and Improvements

There have been significant advancements in the development of UAM specifically for Inconel 718, an advanced superalloy with excellent strength, heat resistance, and corrosion resistance but notoriously difficult to machine. UAM allows machine shops to produce parts more effectively using this high-strength material than ever before. To address these issues and enhance the milling process for Inconel 718, scientists and engineers have investigated the use of UAM (Hafiz et al., 2018; Txomin Ostra et al.,2019; Holland et al., 2019).

(Hafiz et al. 2018 & Txomin Ostra et al.,2019) reviewed the feasibility study of UAM on Inconel 718 alloy parts for reducing tool damage and cutting. In this paper, the high-speed milling experiments and Finite Element Simulation of Inconel 718 are carried out by using PVD TiAlN-coated carbide tools.

Early studies (M.S.A Hafiz et al., 2017; Holland et al., 2019; Bai et al., 2018) centered on comprehending how ultrasonic vibrations affect the machining of Inconel 718. It became clear that for this difficult material, ultrasonic vibrations might increase cutting efficiency, lower tool wear, and improve surface smoothness. On top of this foundation, later developments considerably improved (UAM) methods designed for Inconel 718.

There have been significant developments and advancements in Inconel 718's (UAM). First of all, cutting parameter optimization has been important. To increase material removal rates while guaranteeing tool longevity and surface quality, scientists have carefully labored to identify the right ratio of cutting speed, feed rate, and tool engagement. To aid in the selection of the best parameters for the efficient and effective (UAM) of Inconel 718, experimental research and simulation models have been created (Hafiz et al., 2018; M.S.A Hafiz et al., 2017; Yin et al., 2020; Holland et al., 2019; Uhlmann et al., 2007).

Second, significant advancement has been made as a result of tooling advancements. Specialized cutting tools with cutting-edge tool coatings including polycrystalline diamond (PCD) and ceramic-based coatings have been developed specifically for (UAM) of Inconel 718. These coatings are successful in lengthening tool life and decreasing wear. Moreover, the improvement of cutting tool geometries, such as flute shape and edge preparation, has enhanced chip evacuation and minimized cutting forces [Yin et al., 2020; Holland et al., 2019; Ng et al., 2000).

Additionally, improvements in (UAM) for Inconel 718 have led to better dimensional accuracy and surface polish. Surface roughness has been reduced, and burr formation has been prevented or minimized, by combining ultrasonic vibrations with optimized cutting parameters. This development is especially important for applications requiring high-quality surface finishes, including aircraft components (Hafiz et al., 2018; M.S.A. Hafiz et al., 2017; Yin et al., 2020).

Last but not least, (UAM) has shown improved Inconel 718 material removal rates. Utilizing high-frequency vibrations makes cutting more effective, which increases production and decreases machining time (Hafiz et al., 2018; Yin et al., 2020).

These significant developments and advancements in (UAM) for Inconel 718 have increased the range of machining options for this difficult superalloy. The accomplishments to date have set the path for better effectiveness, improved surface quality, and increased productivity in milling Inconel 718, even though continuous research and development continue to push the envelope. (UAM) techniques are anticipated to become more and more important as time goes on in the production of components composed of Inconel 718 and other challenging-to-machine materials.

3.0 PRINCIPLES OF ULTRASONIC ASSISTED MILLING (UAM)

The fundamental idea behind a UAM machine is the use of high-frequency vibrations to speed up the removal of material. To increase cutting efficiency, prolong tool life, and improve surface smoothness, this technology incorporates ultrasonic vibrations into the standard milling operation. The machine produces micro-scale oscillations in the cutting tool by applying high-frequency vibrations, which are typically in the range of 20 kHz to 50 kHz. Improved machining performance is the result of these vibrations' assistance in breaking up the chips and reducing the cutting forces (Martins H. et al.,2023; Amini et al., 2021; Verma & Pandey, 2019; Reolon LW et al., 2021). The most prevalent alternative, vibrating tool systems, is frequently investigated using the motion of the cutting tips. Approach, contact, immersion, and back off are the four fundamental movements that make up the discontinuity between the two surfaces (Figure 2) and repeat cyclically with the applied frequency.

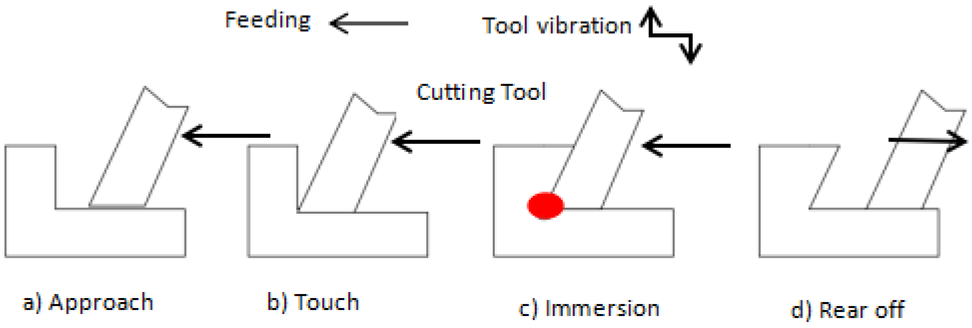

Figure 2: Fundamental stages of the tool's movement in a vibration cycle.

The mechanisms of a (UAM) machine depend on the interactions between the tool, workpiece, and cutting fluid. As the tool makes contact with the workpiece, ultrasonic vibrations are transmitted to the cutting edge. These vibrations generate a series of minuscule hits that break up the substance into smaller pieces. The high-frequency vibrations enhance chip formation by reducing cutting forces and improving chip evacuation (Martins H. et al.,2023 & Park et al., 2014). It is particularly difficult to use ultrasonic technology in this operation since there isn't enough theoretical research on dynamics and cutting (Martins H. et al.,2023). In a milling operation, vibration can be applied in three directions, with a schematic of the three scenarios. These relateto vibration in the x, y, and z axes—respectively, the principal cutting (feed), crossfeed, and depth of cut directions.

Empirical research has been done to examine the relationship between ultrasonic vibration and several machining variables, such as feed rate, tool rotation speed, and cutting fluid (Amini et al., 2021). To get around these restrictions, novel alternative machining technologies, such as Ultrasonic Assisted Machining (UAM), have emerged (Martins H. et al.,2023).

Moreover, in ultrasonic-assisted milling, the cutting fluid is crucial (Park et al., 2014). In addition to lubricating the interface between the tool and the workpiece and cooling the cutting zone, it also removes chips and dirt (Martins H. et al.,2023 & Park et al., 2014). Cutting fluid facilitates heat dissipation throughout the machining process and keeps the cutting tool's temperature within a desirable range. It also lessens friction between the tool and workpiece, minimizing tool wear and enhancing machining efficiency in general (Verma & Pandey, 2019 & Amini et al., 2021).

In a (UAM) machine, the interaction between the tool, workpiece, and cutting fluid improves material removal effectiveness (Martins H. et al.,2023 & Yan et al., 2019). The material is broken down by high-frequency vibrations, which also reduce cutting forces and increase chip formation, improving surface polish and dimensional accuracy in the process (Amini et al., 2021 & Abootorabi et al., 2012). By effectively supplying cooling, lubrication, and chip evacuation, the cutting fluid further improves the machining process and ensures stable and effective operation (Martins H. et al.,2023; Yan et al., 2019; Abootorabi et al., 2012).

In conclusion, a (UAM) machine functions on the premise that high-frequency vibrations are applied to facilitate the removal of material. To achieve ideal machining conditions and enhanced performance, the interaction between the tool, workpiece, and cutting fluid is crucial. (UAM) machines benefit greatly from these mechanisms in terms of improved cutting efficiency, prolonged tool life, and greater surface polish.

4.0 EXPERIMENTAL SETUP AND PARAMETERS

The typical experimental setups and arrangements for (UAM) of Inconel 718 are created to incorporate all necessary elements for effective machining. These setups commonly use an ultrasonic transducer as the main source of high-frequency vibrations in the milling machine [Hafiz et al., 2018; M.S.A Hafiz et al., 2017; Martins H. et al.,2023; Sadaf Zahoor et al., 2022). The transducer is properly positioned and connected to the cutting tool or spindle to ensure that the vibrations are transmitted to the tool-workpiece interface. The test device is primarily made up of a wireless transmission system, an ultrasonic tool holding, a force measuring system, and a temperature measuring system. The wireless transmission system transfers the ultrasonic power supply's electric energy to the transducer during operation. To mill materials, the output from a transducer is amplified using an amplitude transformer before being sent directly to a cutter tool.

Setup for milling Inconel 718 with ultrasonic assistance must take several key considerations into account. Selecting appropriate cutting equipment is of utmost importance; tools should include those specifically designed to absorb and transmit vibrations effectively and provide effective vibration transmission and absorption capabilities. To meet the demands of Inconel 718 cutting, the material, and geometry of tools are designed with heat resistance, wear resistance, and chip evacuation in mind (Martins H et al., 2023; Zheng L et al., 2020).

As part of their study on ultrasonic-assisted milling technology in milling Inconel 718 alloy parts (Zheng L et al. 2020), researchers carried out an exhaustive evaluation of tool life, wear forms, and wear in milling Inconel 718 using ultrasonic vibration-assisted turning (Martins H et al. 2023). Furthermore, with an aim towards minimizing tool damage and cutting, a feasibility review was performed on Inconel 718 alloy parts using UAM technology (M.S.A. Hafiz et al. 2017). The Taguchi orthogonal array, L9, was used in an experiment in which variables including ultrasonic frequency, feed rate, cutting speed, and cutting condition types were changed (Hafiz et al., 2018). The analysis of these elements tries to determine how ultrasonic machining affects the surface quality of Inconel 718, finally concluding that cutting tool durability can be increased by ultrasonic vibrations by increasing surface roughness (Zheng, L et al., 2020).

Numerous significant variables, including cutting speed, feed rate, depth of cut, vibration frequency, and tool geometry, have an impact on the (UAM) process. Cutting speed, defined as the linear velocity of the cutting tool to the workpiece, has a significant impact on the rate of material removal and surface finish (Martins H. et al., 2023 & Verma & Pandey, 2019). To achieve the perfect balance between productivity and machining quality, the appropriate cutting speed must be chosen.

The rate of material removal and surface finish are directly impacted by cutting speed. When working with Inconel 718, spindle speeds of 6,000 to 12,000 RPM are generally recommended for high-speed machining, although it's important to consult the machine manufacturer's guidelines for specific recommendations (Eric, 2020). High cutting speeds can produce excessive heat in the case of Inconel 718, which can hasten tool wear and cause work hardening. A low cutting speed, on the other hand, could lead to ineffective material removal. Finding the ideal cutting speed is essential to balancing productivity and machining quality while taking Inconel 718's material characteristics into account. To achieve the necessary balance between productivity and machining performance for Inconel 718, the cutting speed is normally established by experimental testing and optimization (Hafiz et al., 2018; Wu et al., 2018; Abootorabi et al., 2012; Zheng, L et al., 2020; Peng, Zhang, & Zhang, 2021b). Studies have been conducted to investigate the effect of cutting speed and vibration amplitude on cutting forces in (UAM) (Abootorabi et al., 2012). Additionally, the Taguchi design has been utilized to determine the significant impact of (UAM) cutting parameter performance on Inconel 718 material (Hafiz et al., 2018).

Table 1: Cutting Speeds Recommendations for Material Inconel 718 (Eric, 2020).

Application	**Vc (m/min)**	**Vc (SFM)**
Turning	35-45	110-150
Milling	25-35	80-110
Parting	20-30	70-100
Grooving	30-40	100-130
Drilling	30-40	100-130

The feed rate is the pace at which the cutting tool advances per rotation or per interval of time. Milling feed rates have an extensive effect on several milling-related factors, including chip thickness, cutting forces, tool wear, and surface polish. To maximize material removal effectiveness and achieve desired machining results, selecting an optimal feed rate is of vital importance. Higher feed rates can result in thinner chips with a faster rate of material removal, but they may also increase cutting pressures and wear on tools; conversely, lower feed rates lead to slower material removal rates while simultaneously decreasing productivity by reducing cutting pressures and tool wear.

To successfully mill Inconel 718 with ultrasonic assistance, its feed rate must be properly balanced. This requires taking into account both its material characteristics (high strength and work hardening tendency) as well as the capabilities of both milling machines and cutting equipment. When milling Inconel 718, experimental testing and optimization are often done to determine the ideal feed rate that assures effective material removal, reduces tool wear, and delivers the appropriate surface polish (Hafiz et al., 2018; Wu et al., 2018; Sadaf Zahoor et al., 2022; Peng, Zhang, & Zhang, 2021b). Studies have been conducted to investigate the effect of feed rate and vibration amplitude on cutting forces in (UAM). Additionally, the Taguchi design has been utilized to determine the significant impact of (UAM) cutting parameter performance on Inconel 718 material (Sadaf Zahoor et al., 2022; Peng, Zhang, & Zhang, 2021b).

The depth of cut has a considerable impact on the Inconel 718 (UAM) process. It describes the thickness of the material that is removed by each cutting tool pass (Yan et al., 2019). For machining to produce the best results, choosing the right depth of cut is essential. A deeper cut results in higher cutting pressures, heat generation, and tool wear while simultaneously speeding up the pace at which material is removed (Yan et al., 2019; Zheng, L et al., 2020). However, a shallower cut may result in slower material removal while reducing cutting pressures and tool wear (Yan et al., 2019., 2019; Zheng, L et al., 2020). Finding the ideal balance between the depth of cut and the Inconel 718 material's qualities, the capabilities of the cutting tool, and the intended machining results is crucial. When milling Inconel 718, the procedure can be improved to achieve effective material removal, reduce tool wear, and generate the appropriate surface polish (Hafiz et al., 2018; Martins H. et al., 2023; Yan et al., 2019; Zheng, L et al., 2020; Peng, Zhang, & Zhang, 2021b).

According to (Zheng, Chen, and Huo, 2020), Vibration-assisted micro-milling is a cost-effective way to process hard and brittle materials by imposing high-frequency small amplitude vibration to the cutting tool or workpieces. Compared with the conventional machining process, several advantages can be obtained, such as burr suppression, lower cutting force, better surface quality, higher machining accuracy, and functional surface texture generation.

According to the research (Song et al.,2014) we can determine the frequency of the high-frequency vibrations applied to the cutting tool during the milling operation is referred to as the vibration frequency. For effective material removal and improved overall machining efficiency, choosing the optimal vibration frequency is essential. The frequency used is determined by several variables, including Inconel 718's material characteristics and the milling operation's desired results. Higher vibration frequencies typically result in greater surface quality and more effective chip breaking. The high-frequency vibrations aid in chip evacuation, cutting force reduction, and chip breakup. As a result, tool wear is decreased and chip formation is improved (Rakesh & Datta, 2019; Zhang, S et al., 2013; Liu, et al., 2021). According to research by (Wan et al., 2019) Vibration-assisted milling has been shown to reduce cutting force and improve surface quality for Ti–6Al–4V. In addition, vibration-assisted milling has been applied to generate various surface textures on the workpiece.

However, the milling machine's and the cutting tool's limitations in handling high-frequency vibrations must be taken into account, though. To ensure stable and dependable operation, the vibration frequency needs to be within the capabilities of the tool and the machine. According to the research (Wu & Lin, 2021), vibration energy levels at specific frequencies, such as 469-470 Hz, can be classified as spindle rotating speed-unrelated features in the milling process of Inconel 718. Besides that, (Wu & Lin, 2021) also found the vibration signal under different spindle rotating speeds was analyzed and the frequencies at which the signal energy is concentrated were found to vary. According to research (Unune & Mali, 2017), low-frequency workpiece vibration was found to have a positive influence on material removal rate (MRR) and frontal edge wear (FEW) during micro-electro discharge (µ-ED) milling of Inconel 718. The natural frequency of vibration of Inconel 718 was obtained by modal analysis according to the research of (Dominguez et al., 2020), and the value was 20101.7 Hz.

Experimental studies are conducted to determine the ideal vibration frequency for Inconel 718 ultrasonic-aided milling, considering factors such as tool life, surface quality, and material removal rate. Relevant findings include an experiment using Taguchi orthogonal array to establish the optimal ultrasonic frequency, feed rate, and cutting speed (Hafiz et al., 2018), identification of vibration energy levels at frequencies like 469-470 Hz as spindle rotating speed-unrelated features in the milling process (Wu & Lin, 2021), recognition of ultrasonic vibration-assisted turning as a promising method for machining difficult-to-cut materials like Inconel 718 due to its high cutting stability (Lotfi & Amini, 2017), acknowledgment of ultrasonic vibration-assisted grinding (UVAG) as an effective approach for machining hard-to-cut materials like Inconel 718 (CAO et al., 2022], and the discovery of the positive influence of low-frequency workpiece vibration on material removal rate (MRR) and frontal edge wear (FEW) during micro-electro discharge (μ-ED) milling of Inconel 718. Consequently, the ideal vibration frequency for Inconel 718 ultrasonic-aided milling is determined through these experimental studies, with the optimal frequency varying based on specific milling conditions and parameters.

Tool geometry is a crucial factor that greatly affects the (UAM)of Inconel 718. The correct tool shape must be chosen to remove material effectively and prolong tool life. The number of cutting edges, flute form, and edge preparation are all factors considered while developing a tool's geometry. The number of cutting edges affects how cutting forces are distributed and how chips are evacuated, while the flute shape controls how chips develop and are evacuated. By integrating a protective coating or a specific edge shape, edge preparation can also boost tool durability and prevent built-up edge formation (Eric, 2020).

The tool geometry significantly affects the machining process, according to a study on the impact of tool geometry on the cutting forces, surface roughness, and burr development in the micro-milling process (Kubilay Aslantaş & Khaleel, 2020). A theoretical foundation for the mechanism of cutting tool wear and the choice of cutting tool geometrical parameters in high-speed milling is provided by the study (Ma et al., 2017). According to the research (Corporation, 2021), the VGM end mill, which encourages smooth and steady cutting with low cutting forces, is an example of a tool that has been successfully utilized to manufacture Inconel 718.

In conclusion, improving the tool shape can result in more efficient material removal, better surface polish, and longer tool life when milling Inconel 718. When developing a tool's geometry, it's crucial to take the number of cutting edges, the flute form, and edge preparation into account.

5.0 TOOLING AND TOOL MATERIALS

To get the best results when ultrasonic-aided milling Inconel 718, a variety of equipment and materials must be used. Let's examine the various materials and tool types employed during this procedure and consider their traits, benefits, and drawbacks before discussing three popular choices: diamond tools, carbide tools, and composite tools.

Diamond tools are known for their exceptional hardness and resistance to wear, making them the ideal solution for cutting hard materials like Inconel 718. Their extended tool life and high-quality surface finishes (Mustafa et al., 2022) make them highly suitable for cutting hard materials like Inconel 718. In one study examining how various machining parameters affect Inconel 718's machinability, it was revealed that diamond-like carbon-coated carbide tools could be utilized successfully (Mustafa et al., 2022). Unfortunately, due to their expense, they should only be used where their benefits outweigh the expenses (Mustafa et al., 2022).

Other tools used to machine Inconel 718 include solid Si3N4 ceramic cutting tools, tungsten carbides with appropriate coating combinations, Cubic Boron Nitrides (CBNs), and composite tools (Finkeldei et al. 2019; Jose Diaz-Alvarez et al. 2018). Composite tools offer a hybrid approach by integrating various materials for maximum benefits, such as diamond for its cutting power in combination with carbide's toughness (Mustafa et al., 2022). Solid Si3N4 ceramic tools can exploit temperature-softening effects caused by high cutting speeds for improved machining efficiency (Finkeldei et al. 2019).

Carbide tools are composed of tungsten carbide and cobalt. When coated correctly, tungsten carbides provide excellent durability, thermal stability, and adaptability despite the intense heat and cutting pressure (Pedroso et al., 2023b; Devillez et al., 2007). CBNs have become popular options for Inconel 718 machining due to their thermal conductivity, hardness, and wear resistance (Jose Diaz-Alvarez et al., 2018; Pedroso et al., 2023b).

To achieve optimal results when machining Inconel 718, it is critical to pay close attention to the wear behavior of cutting tools and increase their tool life. High-speed machining, stress relieving the material, and using sturdy work-holding devices combined with a 10-12% coolant mix and high coolant pressure are all helpful in reaching this goal (Peng et al., 2021b; Finkeldei et al., 2019).

It is essential to take the specific needs of the machining operation into account when choosing tools and materials for milling Inconel 718 with ultrasonic assistance. The cutting environment, the characteristics of the material, and the intended results should all be considered. Carbide tools are versatile and economical, whereas diamond tools offer outstanding hardness and endurance. Composite tools combine the benefits of many materials, yet they may be more expensive. The qualities, benefits, and drawbacks of various tool designs and materials should be carefully considered so that manufacturers may decide how best to optimize their ultrasonic-aided milling operations for Inconel 718.

6.0 SURFACE INTEGRITY AND QUALITY

Surface roughness, tool wear and life, residual stresses, and microstructure are some of the variables that must be considered when analyzing how (UAM) affects the integrity and quality of Inconel 718 surfaces. Understanding the total effect of (UAM) on this particular material requires analysis of these parameters.

Surface roughness is a critical aspect that directly affects the quality of the machined surface. Reduced surface roughness in Inconel 718 can benefit from ultrasonic help. When high-frequency vibrations are used to split the chips into smaller pieces during milling, the surface finish is improved (Hafiz et al., 2018; M.S.A. Hafiz et al., 2017; Xu et al., 2020). Ultrasonic-assisted technology has proven effective for Inconel 718 milling, and the precise milling parameters of amplitude and frequency must be properly optimized to achieve the necessary surface roughness (Wu et al., 2018).

In a study on the feasibility of (UAM) in aircraft component manufacturing, it was found that lower surface roughness is rarely achieved through conventional machining due to the interrupted cutting force phenomenon that is affecting the machine (M.S.A Hafiz et al., 2017). Another study evaluated the performance of high-speed ultrasonic vibration cutting for improving the machinability of Inconel 718 with coated carbide tools. The study compared tool life and tool wear forms and wear mechanisms at different cutting speeds and found that (UAM) can improve surface quality and reduce tool wear in Inconel 718 (Peng, Zhang, & Zhang, 2021b).

To achieve the best results when (UAM) Inconel 718, it is important to focus on the wear behaviors of cutting tools and increase cutting tool life. High-speed machining, stress relieving the Inconel material, and using sturdy work holding devices, a 10-12% coolant mix, and high coolant pressure can all help achieve this goal (Yin et al., 2023; Peng, Zhang, & Zhang, 2021b).

Tool wear and tool life are important considerations in the (UAM) of Inconel 718. Due to the special dynamics that the high-frequency vibrations introduce, (UAM) might affect tool wear. In some circumstances, the vibrations can lengthen the life of the tool by enhancing chip evacuation and reducing tool wear. However, high cutting forces or poor ultrasonic parameter management might result in increased tool wear and perhaps shorten tool life. Therefore, in (UAM), it's critical to strike the correct balance between improving tool performance and reducing wear (Xu et al., 2023; Wu et al., 2018; Singh et al., 2023; M.S.A Hafiz et al., 2017); Zheng, L et al., 2020). Experimental investigations have been performed to elucidate the fundamental machining characteristics involving the Inconel 718 workpiece, including the effects of the ultrasonic vibration and the cutting/grinding speed on the work-surface finish, chip formation, material removal rate, and grinding wheel wear. The findings revealed that the cutting force and cutting temperature are reduced considerably in ultrasonic vibration-assisted machining (Xu et al., 2023).

Residual stresses are a significant factor to consider in (UAM) of Inconel 718. The machined surface of Inconel 718 may experience compressive residual strains as a result of ultrasonic vibrations imparted during milling. These compressive pressures may improve the material's overall mechanical qualities and fatigue resistance (M.S.A Hafiz et al., 2017; Zheng, L et al., 2020). However, tensile residual stresses may be caused by insufficient control of ultrasonic parameters or high cutting forces and may harm the functionality and integrity of the material (Wu et al., 2018). Experimental investigations have been performed to optimize the surface residual stresses using (UAM) for wire-arc additive manufactured Ni alloy components. Ultrasonic assistance exhibits a significant influence within the DOE. The maximum principal residual stresses of the conventional milling (CM) process are predominantly tensile residual stresses (Engelking et al., 2023). The findings revealed that the cutting force and cutting temperature are reduced considerably in ultrasonic vibration-assisted machining (UVAM) (Xu et al., 2023).

The microstructure of Inconel 718 can be affected by (UAM). The grain structure and grain size distribution may be affected by the high-frequency vibrations, potentially producing finer microstructures. Modifying materials with this approach can enhance their mechanical qualities, including higher strength and greater resistance to fatigue and wear (Lotfi et al., 2022). But to prevent undesired microstructural changes such as excessive grain growth or the development of undesirable phases during milling (Wu et al., 2018), controlling heat generation during milling is of vital importance (Wu et al.). Experimental investigations were carried out to prove the feasibility of ultrasonic-assisted technology for milling Inconel 718. Their findings show that cutting force and temperature can both be significantly decreased using ultrasonic vibration-assisted machining (Xu et al., 2023). In another study, Inconel 718 specimens under ultrasonic peening milling and traditional milling processing were compared. Ultrasonic peening milling was found to improve surface integrity (Yin et al., 2023).

To maximize UAM results when milling Inconel 718, careful optimization and control of milling parameters are key to reaching optimal results in terms of UAM properties. Here are a few factors that should keep in mind:

a. The feed rate should be selected to achieve desirable surface roughness while limiting tool wear (Hafiz et al., 2018).
b. Cutting Speed: Cutting speed should be carefully managed to manage residual stresses and promote beneficial microstructural changes (Zheng L. et al., 2020; Wu et al., 2018).
c. Tool geometry: Selecting appropriate cutting tools and coatings that can withstand the demands of (UAM) is essential for achieving the desired surface integrity and quality (Lotfi et al., 2022; Zheng, L et al., 2020).
d. Cooling Methods: Appropriate cooling methods should be implemented during milling to effectively manage heat generation and avoid undesirable microstructural modifications (Zheng L. et al. 2020).
e. Ultrasonic Vibration Amplitude and Frequency: Milling parameters such as Amplitude and Frequency must be optimally set to achieve desired surface roughness without incurring excessive tool wear (Lotfi et al., 2022; Wu, 2018).

Experimental investigations were carried out to demonstrate the feasibility of ultrasonic-assisted technology for milling Inconel 718. Results demonstrated that cutting force and temperature reductions can be realized through ultrasonic vibration-assisted machining (Wu et al. 2018; Xu et al. 2023), therefore making ultrasonic vibration-assisted machining (UAM) an attractive approach for improving Inconel 718's machinability.

Overall, analyzing residual stresses, microstructure, tool wear and life, surface roughness, and microstructural integrity and quality for Inconel 718 components requires considering all factors. Manufacturers can achieve an improved surface finish, prolonged tool life, desirable residual stresses, and refined microstructures for improved overall performance and integrity of Inconel 718 components by optimizing milling parameters, managing tool wear, controlling residual stresses, and understanding microstructural changes.

7.0 PROCESS OPTIMIZATION AND PARAMETERS

Selecting the proper process parameters is integral to optimizing the UAM process of Inconel 718 and reaching desired outcomes such as improved material removal rate, surface finish quality, and tool life. Below are five common strategies used when selecting parameters:

a. Experimental design is an important approach in (UAM) of Inconel 718. This approach involves systematically varying process parameters, such as cutting speed, feed rate, and tool vibration frequency while keeping other variables constant. Manufacturers can identify the parameter combination that yields the desired outcomes by conducting a series of experiments and analyzing the results. This iterative process helps fine-tune the parameters for optimal performance (Xu et al., 2023 & Zheng, L et al., 2020). To evaluate the performance of (UAM) of Inconel 718, several experimental investigations have been performed. For example, the design and manufacture of a rotary (UAM) tool were carried out in one study (Mohammad Hassan Lotfi et al., 2022). Another study compared tool life and tool wear forms and wear (Zheng, L et al., 2020 & Coelho et al. 2004) studied the effects of the tool chamfer edge geometry on residual stress in the turning process of Inconel 718 (M.S.A Hafiz et al., 2017). The findings revealed that the cutting force and cutting temperature are reduced considerably in ultrasonic vibration-assisted machining (UVAM) (M.S.A Hafiz et al., 2017). In addition, the performance of ultrasonic-assisted micro-electrical discharge machining of Inconel 718 superalloy using rotary tool electrodes was studied (Singh et al., 2023). These studies demonstrate the effectiveness of (UAM) in improving the machinability of Inconel 718.
b. The Taguchi method is a statistical approach that aims to find the optimal parameter settings while considering the effects of noise factors. It uses an orthogonal array design to conduct a limited number of experiments. By analyzing the signal-to-noise ratio, manufacturers can determine the best combination of parameters that leads to improved material removal rate, surface finish, and tool life. Several experimental investigations have been performed using the Taguchi method to optimize (UAM) of Inconel 718. For example, Taguchi's experimental design was used to clarify the influence of various machining parameters on the machining characteristics of Inconel 718 (Hsu et al., 2008). An experiment using Taguchi orthogonal array was conducted to optimize the (UAM) of Inconel 718 (Hafiz et al., 2018). In another study, the Taguchi method was used to determine the significant impact of (UAM) cutting parameter performance on Inconel 718

material (Ram et al., 2005). These studies demonstrate the effectiveness of the Taguchi method in optimizing (the UAM) of Inconel 718.

c. Response surface methodology (RSM) is another technique employed to optimize (UAM) Inconel 718 by creating mathematical models that depict the relationship between process parameters and desired outcomes. By performing several experiments and fitting their data into models, manufacturers can estimate the optimal parameter values. Response surface methodology provides a method to quickly identify optimal parameter settings that maximize desired outcomes while mitigating negative side effects (Yin et al., 2023; Zheng L. et al., 2020). Response surface methodology was employed in numerous experiments to optimize the UAM of Inconel 718. As one example, an experiment on turning Inconel 718 using tungsten carbide and cermet insert tools with ultrasonic assistance using response surface methodology was carried out (Mustafa et al., 2022). Response surface methodology was employed in another study to optimize the finishing and surface treatment of Inconel 718 alloy using high-speed ultrasonic vibration cutting (Zheng, L. et al., 2020). These studies demonstrate the usefulness of response surface methodology in optimizing Inconel 718 UAM.

d. Computer-based simulations and modeling techniques play a crucial role in parameter selection for (UAM) of Inconel 718. By creating virtual models of the milling process and inputting different parameter combinations, manufacturers can analyze and predict their effects on material removal rate, surface finish, and tool life. Simulation allows for evaluating multiple scenarios and optimizing parameters without the need for extensive physical trials (Martins H. et al., 2023). Several studies have used simulation and modeling techniques to optimize (UAM) of Inconel 718. For example, a study used a modified material model to simulate the machining of Inconel 718 and optimize the cutting parameters (Martins H. et al., 2023). Another study used a Taguchi method to optimize (the UAM) of Inconel 718 and create a prediction model for the material removal rate (Hafiz et al., 2018). In addition, a study used a simulation model to analyze the chipping mechanism of Inconel 718 during ultrasonic-assisted drilling (Wang et al., 2023). These studies demonstrate the effectiveness of simulation and modeling techniques in optimizing (UAM) of Inconel 718.

e. Expert knowledge and experience are crucial in parameter selection for (UAM) of Inconel 718. Experienced machinists and engineers can provide valuable insights for achieving optimal outcomes by drawing on their knowledge of Inconel 718 properties, milling machine capabilities, and practical considerations. They can also leverage their experience from previous milling operations and understanding of the nuances of material and machine interaction to guide the identification of appropriate parameter values. Experimental investigations have been performed to optimize (UAM) of Inconel 718, but expert knowledge and experience are also important. For example, a study used a modified material model to simulate the machining of Inconel 718 and optimize the cutting parameters (Hafiz et al., 2018; M.S.A Hafiz et al., 2017; Zheng, L et al., 2020; Lotfi et al., 2022; (Hsu et al., 2008). Another study compared tool life and tool wear forms and wear (Zheng, L et al., 2020). In addition, a study used a simulation model to analyze the chipping mechanism of Inconel 718 during ultrasonic-assisted drilling (Zheng, L et al., 2020; Lotfi et al., 2022; He et al., 2019). However, the expertise of experienced machinists and engineers is still invaluable in parameter selection for (UAM) of Inconel 718.

By taking these approaches, manufacturers can select the optimal process parameters for ultrasonic-assisted milling of Inconel 718. When choosing process parameters, it is essential to take into account specific material characteristics, machine capabilities, desired goals, and continuous monitoring and adjustments as necessary to reach improvements in material removal rate, surface finish quality, and tool life.

8.0 APPLICATIONS AND CASE STUDIES

Ultrasonic Assisted Milling (UAM) has become increasingly prevalent across a range of industries, from aerospace to automotive and energy sectors. Due to its unique capabilities, UAM is particularly suitable for handling the challenging and high-strength alloys commonly found in these sectors, such as Inconel 718. Here is an overview of applications and case studies of UAM in various industries that utilize Inconel 718:

a. Aerospace Industry: UAM has proven invaluable in the aerospace sector, where Inconel 718 components such as turbine blades are commonly found. UAM allows precise and efficient machining of complex shapes such as airfoil profiles while still maintaining high surface quality and dimensional accuracy (M.S.A. Hafiz et al. 2017; Lotfi et al. 2022); its ultrasonic vibrations assist in reducing cutting forces while minimizing tool wear while improving chip control; these advantages contribute to enhanced productivity while reducing costs as well as better component performance (M.S.A. Hafiz et al. 2017; Lotfi et al. 2022; 73 Ning & Cong 2020; Xie et al. 2022).
b. Automotive Industry: Inconel 718 can be found in various automotive applications, such as exhaust systems, turbocharger components, and high-performance engine parts. Ultrasonic vibrations help break up chips that clog tools and prevent tool clogging to help improve chip evacuation and reduce machining times (Dominguez-Caballero et al., 2023); additionally, UAM contributes to enhanced part quality and dimensional accuracy, leading to improved overall performance (Martins H. et al., 2023; Li et al., 2022).
c. Energy Industry: Inconel 718 has proven itself in the power generation and oil and gas sectors as an ideally suitable material to withstand high temperatures and corrosion (Martins H. et al., 2023). UAM has successfully been utilized for the machining of turbine components, valves, and heat exchangers made out of Inconel 718. The ultrasonic vibrations assist in reducing cutting forces, which is crucial for achieving precise machining in these intricate parts. UAM also helps minimize heat generation, resulting in reduced thermal distortion and improved surface integrity (Martins H. et al., 2023; Li et al., 2022).
d. Medical Industry: According to the research by (He et al., 2019), Inconel 718 has found applications in the medical field, particularly in the production of medical implants and instruments. Ultrasonic-assisted milling assists in the manufacturing of orthopedic implants, dental implants, and surgical tools. The technique enables the production of complex shapes and intricate designs with high precision, ensuring the desired fit and functionality of medical devices.

Overall, UAM applications in various industries such as aerospace, automotive, energy, and medicine demonstrate its ability to overcome the difficulties associated with milling Inconel 718 alloy (Martins H. et al., 2023; He et al., 2019; Li et al., 2022). By taking advantage of UAM technology's benefits, manufacturers can improve productivity, cost savings, and component performance, making this technology indispensable when dealing with Inconel 718 for multiple industrial uses.

9.0 CHALLENGES AND FUTURE DIRECTIONS

Ultrasonic-assisted milling offers many advantages; however, its application for Inconel 718 machining presents certain difficulties and limitations. Some of these challenges include:

a. Inconel 718 is an extremely abrasive and heat-resistant material, leading to rapid tool wear. Milling processes involve intensive cutting forces at high temperatures that cause tool degradation (Wu et al. 2018; M.S.A Hafiz et al 2017; Martins H 2023; He et al 2019) Finding appropriate tool materials and coatings capable of withstanding ultrasonic-assisted milling is vital to meeting this challenge.
b. Surface Integrity: Ultrasonic vibrations during milling processes can significantly compromise surface integrity (M.S.A. Hafiz et al., 2017; He Y et al., 2019; Yin et al., 2023). High vibration amplitudes or inadequate damping may cause irregular surface irregularities such as chatter marks or waviness (He et al. 2019). To preserve desired surface finish quality and dimensional accuracy, vibration levels must be controlled through proper tool engagement to achieve the desired surface finish/dimensional accuracy balance (He et al. 2019).
c. Maintaining Process Stability: Establishing process stability during ultrasonic-assisted milling can be a formidable task. The interaction between ultrasonic vibrations and milling forces may create unstable cutting conditions (He et al., 2019; Yang et al., 2020), leading to decreased accuracy and surface quality (Hafiz et al., 2018; Yin et al., 2023). Balancing milling parameters like vibration amplitude and frequency and cutting parameters is critical to creating consistent and predictable machining results.
d. Cost: Implementing ultrasonic-assisted milling on Inconel 718 may incur additional expenses when compared to traditional milling processes, particularly the equipment, and tooling required to generate and transmit ultrasonic vibrations (Peng, Zhang, & Zhang 2021b). Furthermore, selecting suitable tools designed for Inconel 718 machining may incur higher costs (Hafiz et al. 2018; Wu et al. 2018). Therefore, manufacturers must carefully analyze the cost-benefit ratio to assess the economic feasibility of adopting ultrasonic-assisted milling on Inconel 718 alloy.
e. Optimizing Ultrasonic-Assisted Milling Process: Optimizing Inconel 718's ultrasonic-assisted milling process requires in-depth knowledge of material behavior, tool options, and process parameters (Hafiz et al. 2018; Wu et al. 2018; Martins H. et al. 2023; He et al. 2019). Finding an optimum combination of cutting speed, feed rate, vibration frequency, and amplitude requires time-intensive experimentation and analysis; additionally, it may vary based on component geometry or requirements (Hafiz et al. 2018; Martins H. et al. 2023).

To address these challenges, researchers and engineers are focusing on the development of ultrasonic-assisted milling in the following directions:

a. Process Parameter Optimization: Researchers are studying the effects of various cutting parameters, such as cutting speed, feed rate, and depth of cut, in combination with ultrasonic vibration parameters. By optimizing these parameters, they aim to find the best balance between tool life, material removal rate, and surface quality (Yue et al., 2021; Saravanamurugan et al., 2021).
b. Tool Materials and Coatings: Developing cutting tools with advanced materials and coatings that can withstand the harsh conditions of machining Inconel 718 is essential. Researchers

are exploring novel tool materials and coatings that offer improved wear resistance and thermal stability (De Bartolomeis et al., 2021; Fan et al., 2020; Zhao et al.,2018).

c. Vibration Frequency and Amplitude Control: Controlling the frequency and amplitude of ultrasonic vibrations is crucial for effectively breaking chips, reducing cutting forces, and enhancing material removal rates. Research is being conducted to find the optimal vibration parameters for Inconel 718 machining (CAO et al., 2022; He et al.,2019).
d. Cooling and Lubrication Techniques: Effective cooling and lubrication strategies are being investigated to counteract the high temperatures generated during machining. This includes exploring techniques like minimum quantity lubrication and cryogenic cooling to minimize thermal effects (Shokrani et al., 2017; Gong et al., 2023)
e. Monitoring and Adaptive Control Systems: Developing real-time monitoring systems to detect tool wear, vibrations, and cutting forces can enable adaptive control systems (Mohamed et al., 2022; Burek et al., 2017). These systems would adjust machining parameters on the fly to maintain optimal cutting conditions and improve machining efficiency (Burek et al., 2017; Choudhury & Appa Rao, 1999; Oyelola et al., 2020).
f. Modeling and Simulation: Advanced modeling and simulation techniques are being used to gain insights into the complex interactions between the tool, workpiece, and ultrasonic vibrations (Rinaldi et al., 2019). These models help in predicting material behavior, chip formation, and tool wear, aiding in process optimization (Hsu et al.; 2009; (He et al., 2019).

The development of Ultrasonic Assisted Milling for Inconel 718 is concentrated on optimizing process parameters, upgrading tool materials, managing ultrasonic vibrations, improving cooling procedures, putting monitoring systems in place, and employing cutting-edge modeling approaches. By overcoming the difficulties in machining Inconel 718, these initiatives hope to create manufacturing procedures that are more effective and economical.

CONCLUSIONS

In conclusion, ultrasonic-assisted milling (UAM) of Inconel 718 provides several key findings and insights. Ultrasonic-assisted milling offers significant benefits when it comes to material removal rate, surface finish, and tool life when milling Inconel 718 alloy, which presents challenging machining conditions and is high-strength in nature. Ultrasonic vibrations reduce cutting forces, improve chip control, and limit tool wear, leading to improved productivity and cost savings. Ultrasonic milling has proven its worth across industries such as aerospace, automotive, and energy. Its ability to efficiently machine complex shapes while meeting stringent dimensional accuracy requirements makes ultrasonic milling an invaluable technique in these sectors.

Ultrasonic-assisted milling's significance in Inconel 718 machining lies in its potential to overcome limitations and challenges associated with traditional milling methods. Employing ultrasonic vibrations, manufacturers can improve process stability, reduce tool wear, enhance surface integrity, and ultimately produce better machining outcomes. Furthermore, the review highlights recent advancements in tooling materials, coatings, and process optimization techniques that further expand ultrasonic-assisted milling for Inconel 718.

Ultrasonic-assisted milling offers great promise for future advancement. Through continued research and development efforts, ultrasonic milling may become even more advanced; process parameters, tool designs, and material selection for Inconel 718 machining can all be optimized further. Meanwhile, innovative approaches such as hybrid machining methods combining ultrasonic milling with other technologies may offer further increases in efficiency and precision; advanced sensing and control systems enable real-time monitoring and adaptive control to increase process reliability and performance.

Overall, this review highlights the significance of UAM for Inconel 718 machining. Its ability to improve material removal rate, surface finish, and tool life, coupled with successful applications across various industries, highlights its relevance and potential. With ongoing advancements and research, ultrasonic milling holds promise for further enhancing the machining capabilities for Inconel 718, contributing to increased productivity and quality in the manufacturing industry.

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