ISSN No.: 2455-6130
Volume 6, Issue 5, 2025, pp. 10-19

website: www.ijoetr.com

International Journal of Emerging Trends in Research

Experimental Investigation and Multi-Objective Optimization of Rotary Ultrasonic Drilling of Inconel 718

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Abstract

Nickel-based superalloys such as Inconel 718 are widely used in aerospace applications but exhibit poor machinability under conventional drilling. This study investigates rotary ultrasonic machining (RUM) as an effective hybrid technique for drilling Inconel 718. The influence of tool rotation speed, feed rate, ultrasonic power, and diamond abrasive grit size on machining rate (MR) and surface roughness (Ra) is analyzed using Response Surface Methodology (RSM). Quadratic regression models are developed and validated through analysis of variance. Results indicate that feed rate is the most significant factor affecting both MR and Ra. Higher feed rate increases material removal but degrades surface finish, whereas higher tool rotation and ultrasonic power improve surface quality. Multi-objective optimization using a desirability function identifies optimal machining conditions for achieving high productivity with improved surface integrity.

Keywords: Ultrasonic machining; Inconel 718; Superalloy; RSM; Multi-objective Optimization; Diamond abrasive tool

1. Introduction

Nickel-based superalloys are extensively employed in aerospace, nuclear, and chemical industries due to their excellent mechanical strength, oxidation resistance, and stability at elevated temperatures [1]. Among these materials, Inconel 718 is one of the most widely used alloys because of its superior creep resistance and corrosion resistance [2]. These properties make it suitable for turbine components, combustion chambers, and high-temperature fasteners. However, the same characteristics that enhance service performance significantly degrade machinability, leading to excessive tool wear, high cutting temperatures, and poor surface quality during conventional machining [3].

Inconel 718 exhibits strong work-hardening behavior and contains hard carbide precipitates within its microstructure, which promotes abrasive wear and built-up edge formation during cutting [4]. The localization of plastic deformation in the shear zone produces serrated chips and increases cutting forces, thereby accelerating flank and crater wear on cutting tools [5]. Conventional carbide and coated tools show limited performance when machining such alloys, even under optimized cutting conditions [6]. Advanced cutting tool materials such as cubic boron nitride (CBN) have been proposed for machining superalloys; however, their high cost and limited toughness restrict widespread industrial application [7].

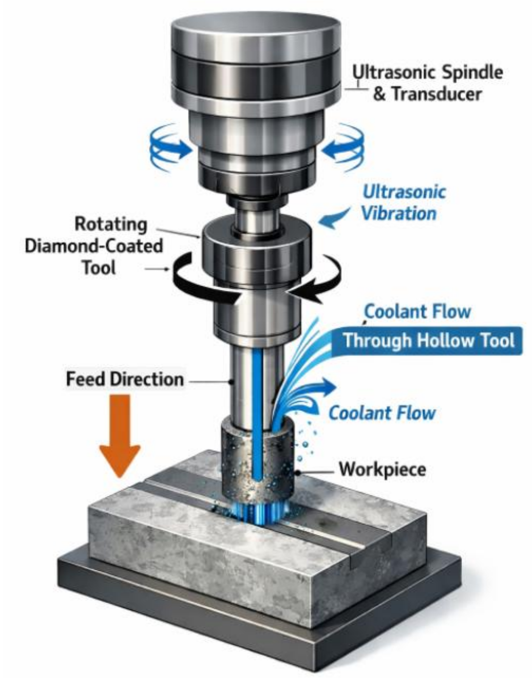

Fig. 1: Rotary Ultrasonic Machining

To overcome these limitations, hybrid machining processes have been developed by combining conventional cutting with auxiliary energy sources. Rotary ultrasonic machining (RUM) is one such hybrid process in which a diamond-impregnated rotating tool is superimposed with high-frequency ultrasonic vibration in the axial direction [8]. This intermittent cutting action reduces cutting forces, improves chip evacuation, and enhances surface integrity. RUM has been successfully applied for machining brittle and hard-to-machine materials such as ceramics, glass, and composite materials [9–11].

Several researchers have investigated the influence of RUM parameters on machining performance. Zhang et al. [12] reported that spindle speed has a limited effect on material removal rate in ultrasonic drilling of glass. Hu et al. [13] observed that higher ultrasonic power improves material removal rate in zirconia ceramics. Lauwers et al. [14] demonstrated that feed rate significantly influences cutting forces in ultrasonic grinding of ceramic materials. Li et al. [15] confirmed that RUM improves hole quality and reduces fiber pull-out when machining ceramic matrix composites. Singh and Singhal [16,17] employed response surface methodology to optimize machining parameters for alumina and quartz ceramics and reported that feed rate is the dominant factor affecting material removal rate.

Although extensive studies have been carried out on RUM for ceramics, composites, and titanium alloys [18,19], very limited work has been reported on nickel-based superalloys using this process. In particular, the combined effects of tool rotation speed, feed rate, ultrasonic power, and abrasive grit size on machining rate and surface roughness of Inconel 718 have not been sufficiently explored. Moreover, most previous studies focus on single-response optimization, while practical machining requires simultaneous improvement of productivity and surface quality.

Therefore, the present study aims to experimentally investigate the drilling of Inconel 718 using rotary ultrasonic machining and to establish empirical models for machining rate and surface roughness using Response Surface Methodology. Statistical analysis is performed to identify significant process parameters and their interactions. Furthermore, a desirability-based multi-objective optimization technique is employed to determine optimal machining conditions that maximize material removal while minimizing surface roughness. The findings of this work are expected to provide useful guidelines for the efficient machining of nickel-based superalloys using hybrid ultrasonic techniques.

2. Materials and Methods

2.1 Rotary Ultrasonic Machining System

All experiments were carried out on a rotary ultrasonic machining (RUM) setup (Sonic-Mill Series 10, USA). In this system, high-frequency electrical energy is converted into mechanical vibration using a piezoelectric transducer. The generated ultrasonic vibration is transmitted to the tool through a horn assembly, producing axial oscillations at a frequency of approximately 20 kHz. Simultaneously, the tool is rotated by an electric spindle motor, enabling combined rotary and ultrasonic-assisted material removal. A continuous flow of coolant was supplied to the cutting zone in order to minimize heat generation and flush away debris. A water-soluble cutting fluid mixed with oil in a ratio of 20:1 was used as the coolant medium [8,9].

2.2 Workpiece Material

Inconel 718, a nickel-based superalloy, was selected as the workpiece material due to its widespread industrial use and poor machinability under conventional cutting conditions. Rectangular plates of size 50 mm × 50 mm × 5 mm were prepared for the experiments. The material possesses high mechanical strength and thermal stability, with a yield strength of approximately 1035 MPa, an ultimate tensile strength of 1240 MPa, and a hardness of about 97 HRB [2,3]. The chemical composition of Inconel 718 primarily consists of nickel, chromium, iron, niobium, molybdenum, and minor alloying elements that contribute to its precipitation hardening and corrosion resistance.

2.3 Cutting Tool

A metal-bonded diamond core drill was used as the cutting tool for all experimental trials. The tool had an outer diameter of 8 mm and an inner diameter of 6.5 mm. The diamond abrasives embedded in the metallic bond acted as the primary cutting edges during machining. As the bond material gradually wore out, fresh diamond particles were exposed, ensuring sustained cutting performance throughout the process. Metal-bonded diamond tools are particularly suitable for ultrasonic machining of hard and brittle materials due to their high wear resistance and ability to withstand cyclic impact loads generated by ultrasonic vibration [10,11].

2.4 Experimental Design

Response Surface Methodology (RSM) based on a Central Composite Design (CCD) was employed to plan the experimental trials and analyze the influence of process parameters. Four machining parameters were selected as independent variables: tool rotation speed, feed rate, ultrasonic power, and diamond abrasive grit size. Each parameter was varied over five levels, and a total of 21 experimental runs were conducted. The selected parameter ranges are listed in Table 1. The RSM approach enables the development of second-order regression models with a limited number of experiments and provides quantitative information on parameter interactions [16,17].

Table 1. Process parameters and their levels used in RSM design

No.	Input Parameter	Symbol	Level −2	Level −1	Level 0	Level +1	Level +2
1	Tool rotation speed (rpm)	A	4200	4600	5000	5400	5800
2	Feed rate (mm/s)	B	0.01	0.0125	0.015	0.0175	0.02
3	Ultrasonic power (%)	C	55	60	65	70	75
4	Diamond abrasive grit size (mesh)	D	80	100	120	140	160

2.5 Measurement of Machining Rate

Machining rate (MR) was determined using the gravimetric method. The workpiece was weighed before and after each experiment using an electronic balance with an accuracy of ±0.0002 g. The mass difference was converted into volume removed using the known density of Inconel 718. Machining rate was then calculated by dividing the removed volume by the machining time for each trial. To improve accuracy, each measurement was repeated twice and the average value was used for analysis [13].

$$MR = \frac{Volume\ removed}{Machining\ time}$$

2.6 Measurement of Surface Roughness

Surface roughness (Ra) of the drilled holes was measured using a stylus-based surface profilometer (Surfcom Flex). Measurements were taken at multiple locations along the inner wall of each drilled hole, and the average Ra value was reported. Care was taken to ensure that the stylus traced along the axial direction of the hole to obtain representative roughness data. Surface roughness was selected as a key performance indicator due to its importance in fatigue life and dimensional accuracy of aerospace components [14].

2.7 Statistical Modeling

Quadratic regression models were developed to express the relationship between the input parameters and the response variables (MR and Ra). The general second-order model used is given by:

$$Y = b_0 + \sum b_i x_i + \sum b_{ij} x_i x_j + \sum b_{ii} x_i^2$$

where Y represents the response, b_0 is the intercept, b_i are linear coefficients, b_{ij} are interaction coefficients, and b_{ii} are quadratic coefficients. Analysis of variance (ANOVA) was employed to evaluate the statistical significance of the models and individual terms. Insignificant terms were eliminated using backward elimination while maintaining model hierarchy. Model adequacy was assessed using the coefficient of determination (R^2), adjusted R^2, predicted R^2, lack-of-fit test, and adequate precision ratio [26].

3. Results and Discussion

The experimental data obtained from the central composite design were analyzed using Response Surface Methodology to establish relationships between machining parameters and performance measures, namely machining rate (MR) and surface roughness (Ra). Quadratic regression models were developed and evaluated using analysis of variance (ANOVA). Model adequacy was confirmed through high coefficients of determination (R^2), insignificant lack-of-fit values, and close agreement between predicted and experimental results.

3.1 Statistical Model Adequacy

The developed regression models for MR and Ra were statistically significant at a 95% confidence level. The ANOVA results indicated that the quadratic models adequately represented the experimental data, with high R^2 and adequate precision values. Normal probability plots of residuals showed that the residuals were randomly distributed along a straight line, confirming the validity of the regression assumptions [25,26]. Predicted-versus-actual plots further demonstrated good agreement between measured and modeled responses, indicating that the developed models can reliably be used for prediction and optimization.

3.2 Effect of Process Parameters on Machining Rate

Feed rate was identified as the most influential parameter affecting machining rate. An increase in feed rate led to a substantial rise in MR due to greater penetration depth of diamond abrasives into the workpiece surface. This enhanced the fracture and shearing of material, resulting in higher volumetric removal per unit time. Similar observations have been reported in ultrasonic and rotary ultrasonic machining of ceramics and composites [13,16]. Interaction plots of tool wear and feed rate for MR. Figure 2 shows the Interaction plots of parameters for MR.

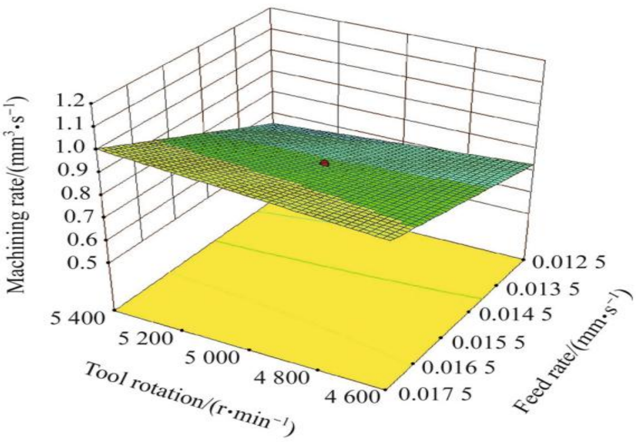

Fig. 2: Interaction plots of two variables for MR

Tool rotation speed exhibited a relatively smaller influence on MR when considered independently. However, interaction analysis revealed that high tool rotation combined with high feed rate significantly increased MR. This behavior can be attributed to the increased number of abrasive-workpiece contacts per unit time, which promotes more frequent micro-fracture and material removal [8,15]. Ultrasonic power showed a nonlinear effect on MR. At moderate power levels, vibration amplitude enhanced the hammering action of the abrasives, improving material removal efficiency. However, excessive power did not result in a proportional increase in MR, which may be due to unstable cutting conditions and energy dissipation in vibration rather than cutting [12,13].

Abrasive grit size also demonstrated a quadratic influence on machining rate. Coarser grits produced deeper indentations and larger material fragments, leading to higher MR, whereas very fine grits reduced cutting aggressiveness and lowered MR. Similar trends have been observed in ultrasonic drilling and grinding of brittle materials [10,11].

3.3 Effect of Process Parameters on Surface Roughness

Surface roughness was strongly affected by feed rate, tool rotation speed, and abrasive grit size. Increasing feed rate resulted in a significant rise in Ra due to deeper abrasive penetration and irregular material fracture. Higher feed rates promote rough cutting and the formation of larger grooves and pits on the machined surface, which deteriorates surface quality [14,17]. Figure 3 shows the interaction effect of process parameters on surface roughness of the machined product.

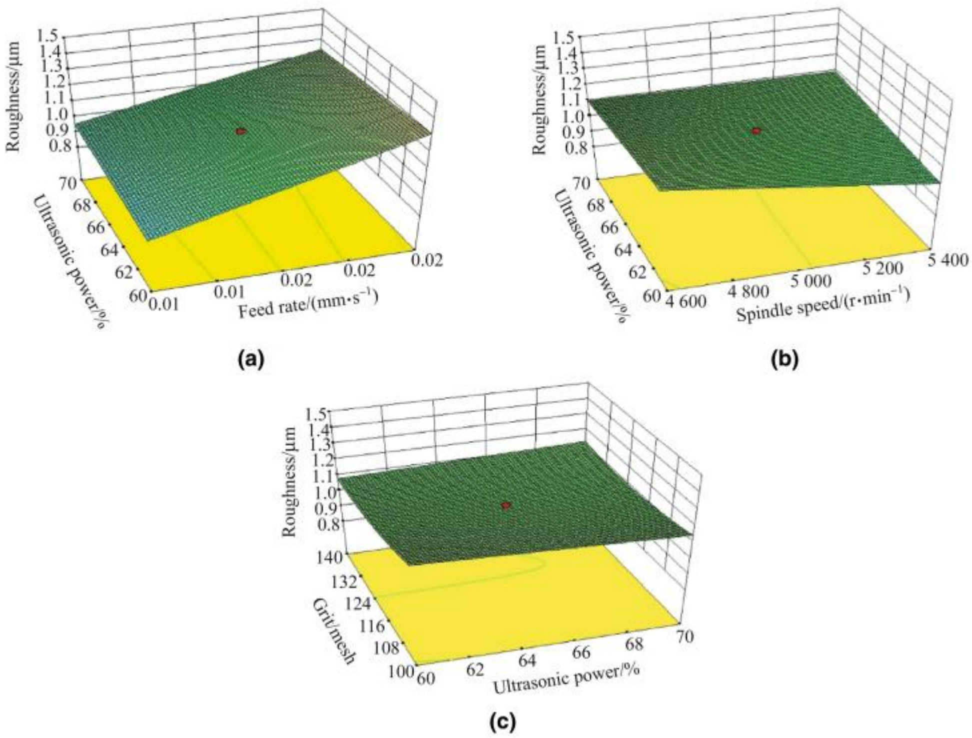

Fig. 3: Two variables interaction plots for Ra

In contrast, increasing tool rotation speed reduced surface roughness. Higher rotational speed improves the grinding action of the diamond tool and promotes a polishing effect on the machined surface. The combined rotary motion and ultrasonic vibration facilitate ductile-mode material removal, thereby reducing surface asperities [8,18]. Ultrasonic power also contributed to improved surface finish by increasing vibration amplitude, which enhanced micro-chipping and reduced plowing effects [13,19].

Abrasive grit size showed a nonlinear influence on Ra. Intermediate grit sizes produced the lowest surface roughness due to a balance between cutting efficiency and polishing action. Very coarse grits generated deep scratches, while very fine grits were prone to clogging and inefficient debris removal, leading to surface irregularities [11,15].

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3.4 Interaction Effects

Interaction plots revealed that the combined influence of feed rate and ultrasonic power significantly affected surface roughness. At higher feed rates, increasing ultrasonic power reduced Ra by improving material removal uniformity and reducing tool-workpiece adhesion. Similarly, the interaction between abrasive grit size and ultrasonic power indicated that higher power levels were more effective when used with moderate grit sizes, leading to smoother surfaces. These findings are consistent with reported results for ultrasonic machining of glass, ceramics, and titanium alloys [9,18,19].

The interaction between feed rate and tool rotation speed showed that maximum MR could be achieved at high levels of both parameters, whereas minimum Ra was obtained at high tool speed and low feed rate. This confirms the conflicting nature of productivity and surface quality, highlighting the need for multi-objective optimization [16,17].

4. Optimization

In rotary ultrasonic machining of Inconel 718, machining rate (MR) and surface roughness (Ra) exhibit conflicting behavior. Higher feed rates and aggressive cutting conditions increase material removal but simultaneously degrade surface quality. Therefore, a multi-objective optimization approach is required to determine a suitable compromise between productivity and surface integrity.

In the present study, a desirability function method was adopted for simultaneous optimization of MR and Ra. This approach, originally proposed by Derringer and Suich [28], transforms each response into a dimensionless desirability value ranging from 0 to 1. For machining rate, a “larger-the-better” criterion was applied, whereas for surface roughness, a “smaller-the-better” criterion was selected. The overall desirability was computed as the geometric mean of the individual desirability values, allowing both objectives to be optimized simultaneously. Figure 4 shows the 3D plots for desirability.

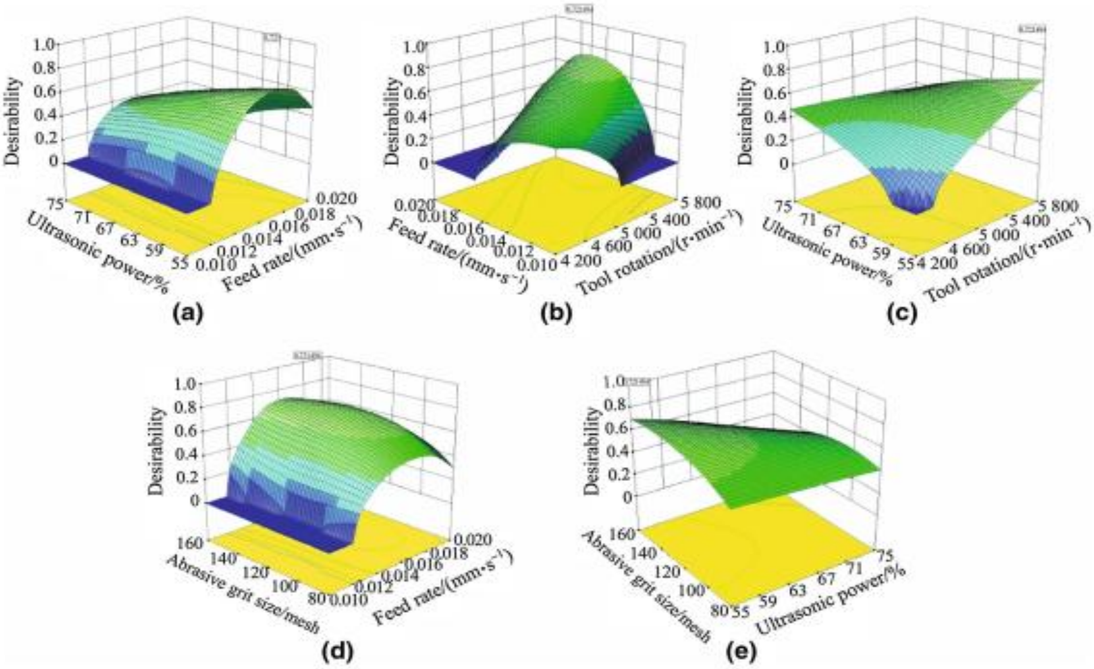

Fig. 14: 3D plots for desirability

The input parameters considered for optimization were tool rotation speed, feed rate, ultrasonic power, and abrasive grit size. Each parameter was constrained within the experimental range to ensure physical and practical feasibility. The response constraints were defined to maximize MR while minimizing Ra. Equal importance was assigned to both responses to achieve a balanced optimization solution.

The optimization results indicated that the maximum overall desirability was achieved at a tool rotation speed of approximately 5800 rpm, a feed rate of about 0.017 mm/s, an ultrasonic power level of 55%, and an abrasive grit size of 140 mesh. Under these optimal conditions, the predicted machining rate was approximately 0.98 mm^3/s, and the predicted surface roughness was about 0.95 µm. These values showed close agreement with the experimentally observed results, confirming the validity of the developed regression models and the optimization procedure.

The optimization trends reveal that moderate feed rate and high tool rotation speed provide a favorable balance between material removal and surface finish. Lower ultrasonic power combined with moderate abrasive grit size enhances vibration-assisted cutting without causing excessive surface damage. Similar optimization behavior has been reported in rotary ultrasonic machining of ceramics and titanium alloys, where feed rate was found to be the dominant factor and surface roughness improved with higher spindle speed and controlled vibration amplitude [16–19].

Overall, the desirability-based optimization approach provides a robust and systematic method for selecting optimal machining conditions in rotary ultrasonic machining of nickel-based superalloys. The optimized parameter combination obtained in table 2 serve as a practical guideline for industrial drilling of Inconel 718 using hybrid ultrasonic machining techniques.

Table 12 Solutions for RUM of Inconel 718

Tool rotation (rpm)	**Feed rate (mm/s)**	**Ultrasonic power (%)**	**Diamond abrasive size (mesh)**	**MR (Predicted) (mm^3/s)**	**Ra (Predicted) (µm)**	**MR (Observed) (mm^3/s)**	**Ra (Observed) (µm)**	**Desirability**
4600	0.017	55	140	1.0042	0.9710	0.9825	0.9510	0.721

5. Conclusions

This study investigated the machining behaviour of Inconel 718 using rotary ultrasonic machining (RUM) and established empirical models for machining rate (MR) and surface roughness (Ra) through Response Surface Methodology. The developed quadratic models were statistically significant and exhibited high predictive accuracy, as confirmed by analysis of variance and diagnostic tests [25,26]. The results demonstrated that feed rate is the most influential parameter affecting both material removal and surface quality, which is consistent with trends reported in ultrasonic machining of ceramics and composite materials [13,16].

An increase in feed rate enhanced machining rate due to greater penetration of diamond abrasives into the workpiece, but simultaneously increased surface roughness because of deeper indentation and irregular fracture. Tool rotation speed and ultrasonic power mainly influenced surface finish by improving grinding action and vibration-assisted material removal, thereby promoting ductile-mode cutting and reducing surface irregularities [8,18,19]. Abrasive grit size exhibited a nonlinear effect, with intermediate grit sizes producing the best surface quality due to a balance between cutting aggressiveness and polishing action [11,15].

Multi-objective optimization using a desirability function approach yielded an optimal parameter combination that provided a favorable compromise between productivity and surface integrity. The optimized settings resulted in a machining rate of approximately 0.98 mm^3/s and a surface roughness of about 0.95 µm. These findings confirm that rotary ultrasonic machining is a viable and efficient technique for drilling nickel-based superalloys, and the developed models can be effectively used for process planning and parameter selection in industrial applications [16–19].

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