Faculty of Industrial and Manufacturing Technology and Engineering

OPTIMIZING THE MACHINABILITY OF INCONEL 718 IN THE ROTARY ABRASIVE WATER JET CUTTING PROCESS

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DEDICATION

I would like to dedicate this thesis to my parents, who have been my emotional anchors through my entire life. They gave the little they had to ensure I would have the opportunity of an education. Their efforts and struggles have allowed me to successfully complete this research journey.

ABSTRACT

The Abrasive Waterjet (AWJ) process is a cutting-edge technique utilized in modern machining for working with challenging materials. Leveraging its erosive effect, this method enables the precise machining of hard and brittle engineering materials. The incorporation of hard abrasive particles into the water jet facilitates a robust cutting process. Notably, the absence of thermal effects during AWJ operations eliminates concerns related to distortion, microstructure changes, and mechanical softening issues. Currently, AWJ applications are predominantly limited to cylindrical materials, particularly in the machining of Inconel 718. This study aims to assess the process parameters involved in cutting Inconel 718 using Abrasive Waterjet Turning (AWJT). Employing a Design of Experiments (DOE) approach, specifically the Box-Behken Design (BBD) with five center-point designs, the study explores rotational speeds of 60 and 90 rpm, feeds of 1.0 and 3.0 mm/min, and cutting depths of 0.1 and 0.5 mm. Parametric study data is analyzed using ANOVA. Surface roughness evaluation involves assessing 10 machining paths based on conventional turning operations. Surface conditions are characterized through elemental analysis and surface morphology. From the experimental result, a predictive model for the surface roughness within the experimental ranges was develop, highlighting the depth of cut and feed rate as the most influential parameters. Notably, a minimum surface roughness range of 2.09–2.61 µm, falling within the N7 grade is observed. Lower feed rates result in reduced striation, and optimal surface roughness is achieved with high rotational speed, low feed, and low cutting depth. Comparisons with traditional machining reveal a surface finish comparable to the turning process. After multi-objective parameter optimization targeting surface roughness, dimensional accuracy, and roundness, a 0.14 - 0.27% improvement in surface roughness is achieved. Microstructure analysis confirms the absence of deformation, indicating no alterations at the subsurface level. One-factor effect plots illustrate that enhancing the barrel shape and implementing a clockwise cutting direction result in improved surface texture with nearly imperceptible striations. This research underscores the viability of AWJT as a credible alternative to turning processes, particularly for machining hard materials.

PENGOPTIMUMAN KEBOLEHMESINAN INCONEL 718 DALAM PROSES PEMOTONGAN JET AIR LELAS BERPUTAR

ABSTRAK

Proses Abrasive Waterjet (AWJ) adalah satu teknik pemotongan terkini yang digunakan dalam industri pembuatan moden untuk mengendalikan bahan-bahan yang sukar untuk proses pemesinan. Dengan memanfaatkan kesan abrasi, kaedah ini membolehkan pemesinan yang tepat khusus bagi bahan kejuruteraan yang keras dan rapuh. Penambahan zarah abrasif keras ke dalam jet air memudahkan proses pemotongan yang jitu. Di samping itu, ketiadaan kesan suhu semasa proses pemotongan pemesinan AWJ dapat menghindarkan kesan keburukan berkaitan dengan distorsi, perubahan mikrostruktur dan isu penyerapan mekanikal. Pada masa ini, aplikasi AWJ terhad kepada bahan silinder, terutama dalam pemesinan Inconel 718. Kajian ini bertujuan menilai parameter-proses yang terlibat dalam pemotongan Inconel 718 menggunakan teknik Abrasive Waterjet Turning (AWJT). Dengan menggunakan pendekatan Reka Bentuk Eksperimen (DOE), khususnya Reka Bentuk Box-Behken (BBD) dengan lima reka bentuk titik pusat, kajian ini meneroka kesan parameter pemesinan merangkumi kelajuan putaran 60 dan 90 rpm, suapan 1.0 dan 3.0 mm/min, dan kedalaman pemotongan 0.1 dan 0.5 mm. Data kajian parametrik dianalisis menggunakan ANOVA. Penilaian kekasaran permukaan melibatkan penilaian 10 ujian eksperimental melalui proses pemesinan konvensional. Keadaan permukaan dicirikan melalui analisis elemen dan morfologi permukaan. Dari hasil kajian, model prediktif bagi kekasaran permukaan dalam julat eksperimen telah dibangunkan, hasilnya menunjukkan kedalaman pemotongan dan kadar suapan sebagai parameter yang paling berpengaruh. Julat kekasaran permukaan minimum yang diperolehi adalah 2.09–2.61 µm, yang termasuk dalam gred N7. Kadar suapan yang rendah menghasilkan kesan hakisan yang berkurang dan kekasaran permukaan optimum dicapai dengan kelajuan putaran tinggi, suapan rendah, dan kedalaman pemotongan rendah. Perbandingan dengan pemesinan tradisional mengungkapkan hasil permukaan yang sebanding dengan proses pemesinan larik. Selepas optimisasi parameter multi-objektif melibatkan pengurangan kekasaran permukaan, ketepatan dimensi dan kebulatan, hasilnya terdapat peningkatan sebanyak 0.14 - 0.27% dalam kekasaran permukaan. Analisis mikrostruktur mengesahkan ketiadaan deformasi, menunjukkan tiada perubahan pada tahap sub-permukaan. Plot kesan satu faktor mengilustrasikan bahawa penambahbaikan bentuk barel dan penggunaan arah pemotongan arah jam menghasilkan tekstur permukaan yang lebih baik dengan kesan hakisan yang hampir tidak kelihatan. Kajian ini menekankan AWJT sebagai proses pemesinan alternatif yang boleh dipercayai bagi proses larikan, terutama untuk pemesinan bahan keras.

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LIST OF SYMBOLS

a_p	-	Depth of cut
DOP	-	Depth of penetration
F_r	-	Feed Rate
L_C	-	Length of cut
F_D	-	Direct force, N
F_t	-	Tangential Force
$\alpha 1=\alpha 2$	-	Angular
r	-	Radius of cylindrical bar
A_o	-	Area of nozzle orifice, mm^2
µ	-	(Micron) metric unit denoting a factor of 10^{-6} or represent small
df	-	Degrees of Freedom
k	-	Number of factors in design
R^2	-	Index of determination
n	-	Number of observations in sample
P	-	Probability value
Ra	-	Arithmetic average surface roughness
γ'	-	gamma prime γ' face ordered Ni3(Al,Ti)
γ"	-	gamma double prime γ” bct ordered Ni3Nb
δ	-	delta δ orthorhombic Ni3Nb
Vs	-	Vstream
Vt	-	Vtraverse

LIST OF ABBREVIATIONS

ANOVA	-	Analysis of variance
AWJ	-	Abrasive WaterJet
AWJT	-	Abrasive WaterJet Turning
CO	-	Carbon monoxide
CH_4	-	methane
C.V	-	Coefficient of Variation
CAD	-	Computer Aided Design
CAM	-	Computer Aided Manufacturing
CNC	-	Computer Numerical Control
ECDM	-	Electrical Chemical Discharge Machining
EDM	-	Electrical Discharge Machining
EDX	-	Energy Dispersive X-ray
FCC	-	Face centered cubic
FESEM	-	Field Emission Scanning Electron Microscopy
HAZ	-	Heat Affected zone
HSM	-	High Speed Machining
ISO	-	International Standardization Organization
LBM	-	Laser beam machining
M	-	Metric
MACH	-	Ratio of an object's speed in a given medium to the speed of sound
MOHS	-	Mineral's hardness of its relative resistance to scratching

MRR	-	Material Removal Rate
N (Grade)	-	New ISO Scale Numbers
NaOH	-	Sodium hydroxide
$NaNO_3$	-	Sodium nitrate
RSM	-	Response Surface Methodology
RPM	-	Revolution per minute
SEM	-	Scanning Electron Microscopy
SOD	-	Stand Off Distance
V	-	V Console table
Vs	-	V sample

LIST OF PUBLICATIONS

The followings are the list of publications related to the work on this thesis

JOURNAL

W.N.F Mohamad, M.S Kasim, M.Y Norazlina, M.S.A Hafiz, R. Izamshah, S.B. Mohamed., 2023. Effect of standoff distance on the kerf characteristic during abrasive water jet machining. *Results in Engineering*, vol 6, pp.100101. (ISI indexed, Q1, IF = 4.06 (2023)

M.S Kasim, M.S.A Hafiz, J.A Ghani, R. Izamshah, M.N.A Rahman, W.N.F Mohamad, S.B Mohamed, 2023. The effect of pulsating lubrication method on rake face cutting tool during end milling of inconel 718. Results in Engineering, vol 17, pp.100764. (ISI indexed, Q1, IF = 4.06 (2023)

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N.H.N. Husshini, M.S. Kasim, R. Izamshah, W.N.F. Mohamad, M.A.B.M. Ali, M.S.A. Hafiz, M. Hadzley, 2021. Current Summary of Surface Integrity When Machining Inconel 718 Under Different Cooling and Lubrication Strategies. *Jurnal Tribologi*, vol 29 (September), pp. 144–155.

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PROCEEDING

N.H.N. Husshini, M.S. Kasim, W.N.F. Mohamad. Tool Life and Surface Roughness of Inconel 718 During End Milling Under Dry, Chilled Air and Chilled MQL. Symposium on Intelligent Manufacturing and Mechatronics, pp.415-423

CHAPTER 1

INTRODUCTION

1.1 Background

Nickel alloy proves to be a versatile material characterized by outstanding resistance to rust and the ability to withstand elevated temperatures. (Mankins and Lamb, 1990). Due to these benefits, Nickel alloy is an excellent material for gas turbines, rocket engines, and nuclear reactors (Ezugwu, 2005). Nickel Alloy exhibits exceptional ductility, featuring a face-centered cubic lattice crystal structure (FCC) that allows easy molding of components with intricate geometries This alloy has many applications in the aerospace industry because to its high creep resistance (Rahman et al., 1997). This Nickel alloy is also utilised in the production of temperature-controlled tool points, glass processing (Devillez et al., 2007), paper processing, the oil and gas industry, and the health sciences sector (Mankins and Lamb, 1990).

There are numerous Nickel alloys available today, including Nimonic, Udimet, Waspaloy, Astroloy, Hasteloy, and Inconel. Of these alloys, Inconel combinations are the most commonly utilised, particularly Inconel 718 due to its ability to withstand temperatures as high as 700°C (Faheem, 2009). It is also more conspicuous than other Inconel alloys due to the significant amounts of γ', γ'' and δ and that it precipitates (Čapek et al., 2021). Nevertheless, Inconel 718 is a weak thermal conductor and has low thermal diffusion characteristics, which makes its machining extremely difficult. As a result, this alloy is still cut at a low rate of speed and is deemed less productive as the need for cuts increases.

During the Inconel 718 cutting process, practically all of the mechanical energy is converted to heat energy, leading to elevated temperatures at the cutting edge (Bhatt et al., 2010). The rate at which mechanical energy is converted to thermal energy is highly hinging on machining factors like cutting speed. Increased cutting speeds require more mechanical energy, which in turn generates additional thermal energy, elevating the temperature in the cutting area. This problem exacerbates when machining metals possessing low heat conduction properties, such as Inconel 718, because during machining with common tool points, the majority of the heat energy generated within the cutting process, it does not exit the cutting zone, and is instead concentrated in the contact area between the tip of the tool and the work material (Ezugwu et al., 1998). Thus, heat localisation occurs in close proximity to the cutting edge. It is anticipated that over 80% of the heat energy transformed from the mechanical energy concentrated on the tool point on the edge of the face of the bed tool points that accelerate tool point failure is lost to the surrounding environment (Sharman et al., 2006).

Besides its limited thermal conductivity, Inconel 718 has its own shortcomings that make the cutting process more complicated. The most major disadvantage of cutting Inconel 718 is the alloy's tendency to harden at temperatures exceeding 900°C, when the formation of the hard phase occurs. Cutting such a hard metal necessitates a greater amount of mechanical energy, which will be converted to thermal energy, hence increasing the temperature of cutting and accelerating the rate of work material hardening and adhesive synthesis. Because of the elevated temperature in the primary cutting region, specifically in the flow-zone, which constitutes the interface between the tool and the workpiece, fringe build up frequently occurs and adheres to the tool's eye material. This results in the loss of surface integrity of the manufactured work material (Devillez et al., 2007). The utilization of this material under elevated temperatures increases the danger of failure due to its poor surface integrity. Hence, the cutting of Inconel 718 not only has a detrimental effect on the point of the tool due to the concentration of heat energy in the point of the tool, but also causes the degradation of the surface integrity of the workpiece due to the increase in edge-built. For these reasons, Inconel 718 falls into the category of challenging-to-machine materials (Konig, 1999).

The selection of machining settings and tool points is a complex and crucial operation. This is to ensure that the cost of metal cutting is reasonable enough to generate high-quality, functional work materials, particularly materials that are challenging to machine, like Inconel 718, result in this outcome. Thus, Inconel 718 was still cut with a carbide-coated tool tip using the flood method at a low cutting speed (Obikawa et al., 2008). This procedure, however, is inefficient, and the HSM method is highlighted.

High speed machining (HSM) can achieve an equivalent or superior surface finish at significantly higher material removal rates with surface speeds of up to 250 m/min, and occasionally even faster. The procedure is carried out with minimal cut depths and feed rates, demanding extensive machining time. Therefore, the capabilities of the machine tool should include high stiffness, high surface speed, continuous surface speed for the to-be-finished profile, and high precision with the needed surface finish. In the majority of turning operations, coolant is not used. However, the absence of coolant shortens the life of the tools and makes the surface rougher. Although HSM is an amazing procedure because to its capacity to substitute grinding as a finishing operation, the process-induced white layer causes significant variances in the service performance of the component. Despite its limitations, an Abrasive Water Jet (AWJ) proves highly advantageous within the workshop setting. due to its superior for prolonged operations and higher quality to that of others.

A novel non-traditional machining method called abrasive waterjet turning (AWJT) enables the use of waterjet's benefits in the production of axisymmetric parts using a regular waterjet cutting equipment. The workpiece rotates throughout the AWJT process while the cutting head moves axially over the workpiece. To achieve the desired dimension, the depth of cut (DOC) can be altered by manipulating the nozzle location perpendicular to the workpiece centre line. It's interesting how different DOC can result in complex profile geometries. The abrasive waterjet (AWJT) process offers several advantages over traditional turning. Unlike traditional turning, AWJT uses a flexible tool to remove material, making it less sensitive to the shape of the workpiece. It also allows for deep cuts in a single pass and produces greater material removal rates (MRRs), particularly for difficult-to-machine materials. Additionally, the low cutting forces used during the process make it unaffected by the length to diameter ratio of the workpiece, enabling it to turn lengthy pieces with small dimensions. AWJT is particularly effective on materials with a high degree of hardness and low machinability, such as glass, titanium, Inconel 718, and composites.

However, it is important to investigate the process reactions and side effects with regard to fluctuations in the process parameters and identify methods to regulate them to accurately predict AWJT and enhance its technological and economical capabilities. To achieve this, it is necessary to identify important variables and interactions that significantly affect the rate of material removal, the roughness, roundness, and geometrical errors of the workpiece.

Since there hasn't been a systematic experimental investigation on AWJT up to this point, it is worthwhile to explore abrasive waterjet offset-mode (the position of the jet nozzle tangential to the workpiece) turning of Inconel 718 alloy. A response surface methodology (RSM) experimental design was used, taking into account three machining factors feed rate, rotational speed, and depth of cut. Seventeen tests were conducted using a Box-Behken design (BBD). The analysis of variance (ANOVA) technique was used to examine the main effects and interactions of the machining parameters to determine the relationship between input and output.