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Machining Ni-Cr-Fe based superalloy using abrasive water jet cutting process and its surface studies

Adam Khan M[a], Kapil Gupta[a]

[a, b] *Mechanical and Industrial Engineering Technology, University of Johannesburg, Doornfontein, Johannesburg 2028,South Africa*

Abstract

In this paper, the machinability of Ni-Cr-Fe based superalloy is studied using abrasive water jet cutting process. Experiments have been performed by varying the cutting process parameters namely: water jet pressure (240, 260 and 280 MPa), jet travel speed (20, 30 and 40mm/min) and stand-off-distance (1, 2 and 3mm). Material removal rate (MRR), kerf, and average surface roughness are measured as response parameters to evaluate process productivity and surface quality simultaneously. The influence of individual process parameters is identified using analysis of variance. Subsequently, the wear tracks are studied using electron microscopy. From the analysis, it is found that the jet travel speed is the most significant parameter. Conclusively, abrasive water jet cutting at 260 MPa jet pressure, 30 mm/min jet travel speed, and 1 mm stand-off-distance resulted in optimum responses i.e. kerf (0.0428), MRR (37.1835 mm3/min) and Ra (3.757 µm).

Keywords: Abrasive; Machining; Superalloy; Surface; Wear

1. Introduction

These days, advanced machining processes are rapidly replacing traditional methods, specially, when machining complex shapes or features and cutting hard materials [1]. Machined surfaces are highly sensitized by heat generated (between tool and work), white cast layer and other surface defects; with few machining processes. The inherent quality of the work material should not be varied while machining. Selection of appropriate machining process depends upon material removal, surface quality, energy applied, tool cost and operating time. Inappropriate machining process may lead to many issues namely; tool blending, poor surface finish, higher production cost, work hardening and other surface issues [2]. These are the common issues faced in conventional machining processes. Thus, the demand on machining has been satisfied by selecting advanced processes. Abrasive water jet cutting (AWJC) process is one among the best advanced machining processes. It is a versatile machining process and also sustainable in many aspects. The basic principle behind the AWJC is make use of mechanical and fluid dynamics. The combination of hard erodent / abrasives and water at a high velocity are used to pass through a small orifice to cut the material [3]. AWJC is a flexible and multi directional cutting process [4]. Naresh et al [5] investigated and reported that the AWJC process imparts mechanical stress with less cutting force, elimination in thermal distortion and free from heat affected zone. Jet pressure, jet traverse speed and stand-off distance (SOD) are the three process parameters to be controlled during abrasive water jet cutting [6]. Major machinability indicators in abrasive water jet cutting are- kerf wall inclination, material removal rate and surface roughness etc. [7]. Failure in selection of optimized machining parameters may affect machinability in terms of deterioration in surface quality, excessive environmental footprints, and low productivity [8, 9].

Machining surface qualities are also interconnected with selection of hard abrasive particle based on work material. The size and shape of the abrasive particles determine the ability of the cutting process, and it's a major factor while cutting hard materials. Extensive literatures are available to discuss on machinability of metals and non-metals while cutting by abrasive water jet process [10-13]. However, the study reported on surface quality of machining nickel-based superalloys using abrasive water jet cutting is very less. Nickel based superalloys are one among the difficult to machine hard materials. Original properties of the superalloy have been made material to extend in different applications over aerospace, petroleum, and nuclear energy industries etc. A systematic detail on the properties and applications of superalloys can be found in [14].

From the literature, it is clear to infer that the machining studies on superalloy materials are very less. At the same, selection of advanced machining process to cut the material is very rare. Therefore, and attempt is tried to study the machining quality on Ni-Cr-Fe based superalloy using abrasive water jet cutting process. The process parameters such as jet velocity, jet traverse speed and stand-off distances are varied to study the kerf wall inclination, and surface roughness along with material removal rate.

2. Materials and Methods

As cast nickel – based superalloy in the combination of Ni-Cr-Fe also known as hastealloy has been selected as a work material in the present research. Ainnovative International make CNC abrasive water jet cutter model DWJ1313-FB has been used a machine tool in the present work. Table 1 presents the chemical composition of this material. The tip of the jet nozzle (orifice diameter) is 0.76mm. Figure 1 shows the abrasive water jet cutting machine. The operations are control by alpha numerical coding systems. The details of cutting parameters and their levels for experimentation are given in Table 2.

Table 1. Nominal element wait percentage of Ni – Cr – Fe based superalloy used for AWJ

Elements	Ni	Cr	Fe	Mo	Si	W	C	Nb, Mn, Al, Ti, Cu, P, B & S
Wt.%	*47*	*22*	*18*	*9*	*1*	*0.60*	*0.1*	*Traces*

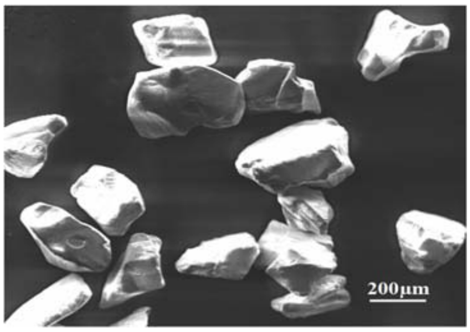


Fig. 1 Abrasive water jet cutting machine used in the present work. Fig. 2 Micrograph of hard abrasive particle used for AWJC

The size of abrasive particles ranges from 180-200 microns. Figure 2 depicts the electron micrograph of hard abrasive particle used for cutting process. While abrasive water jet cutting are performed, FLIR Thermal imaging camera is used to study the amount of heat generated during the machining process.

Table 2. The details on abrasive water jet parameters and cutting conditions

Parameters	Units	Conditions
Water jet pressure	MPa	240, 260 and 280
Traverse speed	mm/min	20, 30 and 40
Standoff distance	mm	1, 2 and 3
Abrasive	--	Garnet
Abrasive flow	g/sec	2 – 3
Abrasive size	Mesh size	80
Impact angle	Degree (°)	90

To find the kerf wall inclination, the samples are abrasive water jet cutting are dried to room temperature first. Optical microscope is used to study the kerf. Along with the process parameter effects, the hardness and thickness of the work piece also affects the variation in kerf width. Equation 1 below has been used to calculate the kerf taper-

$$\text{Kerf taper} = [(W_t - W_b) / (2t) \qquad (1)$$

Where,

W_t – top width,

W_b – bottom width, and

t- thickness of the sample.

The depth of penetration, kerf width and traverse speed of the cutting nozzle are used to calculate material removal rate (MRR). Following equation represents the calculation of MRR-

$$MRR = h_t\, d_i\, v_f \quad (2)$$

Where,

h_t – the depth penetration

d_i – diameter of focusing tube or nozzle

$$d_i = (Wt + Wb) / 2 \quad (3)$$

v_f – traverse speed

Subsequently, the samples are sliced to individual pieces to easily measure the average surface roughness 'R_a' on the machined area. Further, the scan electron microscope (SEM) is used to study the surface morphology and wear mechanism of the machined surface.

3. Results and discussion

The investigations are carried out on Ni – Cr – Fe based superalloy with a pre-defined machining condition. While machining, the heat generated during machining process was measured using FLIR Thermal Camera. Photo image for the abrasive water jet cutting with the heat gradients are shown in Figure 3. It shows that the maximum temperature generated during machining with a jet pressure of 260 MPa is 47.1ºC. This is common to all the other machining conditions and the temperature range falls between 27-52ºC. However, in conventional machining process it has been reported that, high heat / temperature is generated at cutting tool and work interface on dry machining [15]. Thus, the surface deterioration due to thermal effect on the machined surface as reported by the early researchers from their work was eliminated [16 – 18].

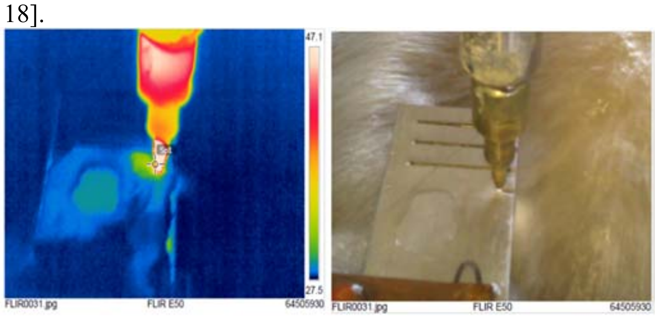


Fig. 3. Thermal imaging while cutting hastealloy by abrasive water jet machining at 260 MPa water jet pressure.

While machining Ni-Cr-Fe alloy using abrasive water jet cutting, the band gap width between the machined zone are measured in terms of kerf top and kerf bottom. Using the empirical relation, the kerf wall inclination is calculated and plotted in Figure 4. At highest travel speed the maximum kerf wall inclination was achieved. However, there are slight variations in kerf based on the water jet pressure. The mechanical reason behind the kerf wall inclination at slow travel speed is slurry jet lapping effect. The water jets with hard abrasive are induced to remove the hard material continuously (over a small surface with repeated force) at lower speed. When there is increase in travel speed, intensity of the water jet pressure will be reduced. The effect on such parameters is not influencing MRR. With reference to travel speed, the material removal rate has been continuously increasing as shown in Figure 5. There is no influence on change in jet pressure. The removal of material is same for all the conditions.

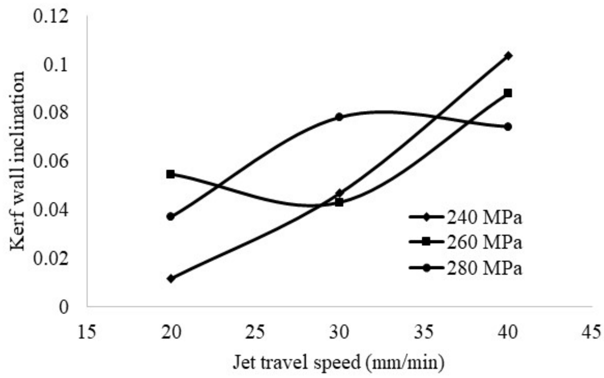


Fig. 4. Influence of abrasive water jet cutting parameters for kerf wall inclination.

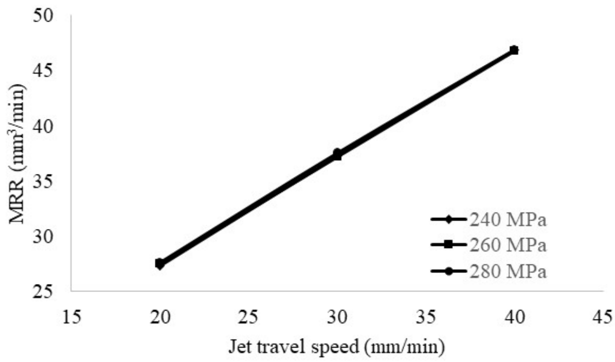


Fig. 5. Variation in material removal rate with reference to jet travel speed.

However, the surface finish has wide variation with reference to jet pressure and travel speed (Fig. 6). At slow travel speed, the minimum surface roughness was observed and gradually increasing at a jet pressure of 240MPa. For 260MPa and 280MPa jet pressure, parabolic movement observed on surface roughness in eclectic range. The optimal surface roughness can be found out at 30 mm/min travel speed. At minimum and maximum travel speed of 20mm/min and 40mm/min, the roughness ranges are maximum. To study the influenced of individual process parameters, the experimental results are mathematically evaluated using analysis of variance (ANOVA). The contributions are considered for three responses – kerf wall inclination, material removal rate and surface roughness. The outcome from the experiments are validated and plotted in graph (Fig. 7).

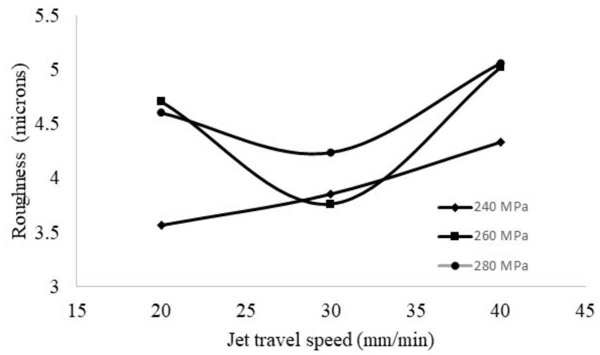
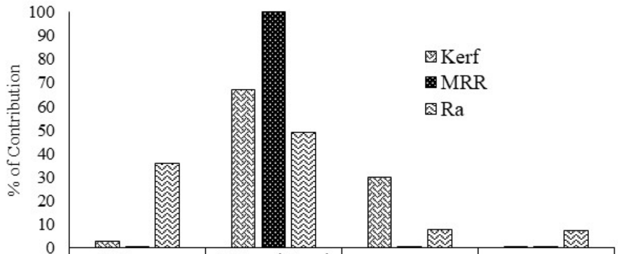


Fig. 6. Observations on surface roughness measured while machining Ni -Cr -Fe based alloy.



	Jet Pressure (MPa)	Jet travel Speed (mm/min)	SOD (mm)	Error
Kerf	2.923	67.174	29.778	0.125
MRR	0.012	99.982	0.006	0.000
Ra	36.063	48.831	7.608	7.498

Fig. 7. Bar chart to infer the contribution of process parameters.

Jet travel speed has a maximum contribution (67.17%, 99.98% and 48.83% respectively) towards all the three responses, compared to jet pressure and SOD. Subsequently SOD has 29.77% of contribution for kerf and jet pressure has 36.06% of contribution for surface roughness. Rate of error in kerf and MRR are completely eradicated. The effect on roughness has produced maximum error and recorded (from the calculation on roughness) value is 7.49%, it is due to the irregularity in surface finish area under micro level. It has been evidently proved with surface studies on machined surface using electron microscope.

The surface morphology of the machined surface at 260MPa and 280MPa at 30mm/min are observed with SEM. Figure 8 shows the wear scars of Ni – Cr – Fe alloy machined at 260MPa – 30mm/min jet pressure and travel speed. At this condition, the surface revealed with severe in plastic deformation and lip formation. Wear tracks are clear with shear zone from top to bottom of the surface observed. Figure 9 shows complete deformation on machined surface at 280MPa – 30mm/min jet pressure and travel speed. At high jet pressure the surface is prone to undergo maximum shear and complete pulling of bulk material.

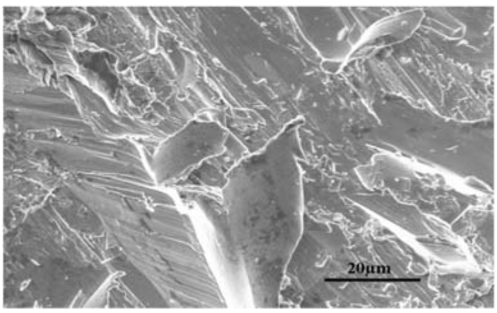


Fig. 8. Wear scars on Ni – Cr – Fe alloy machined at 260MPa – 30mm/min jet pressure and travel speed.

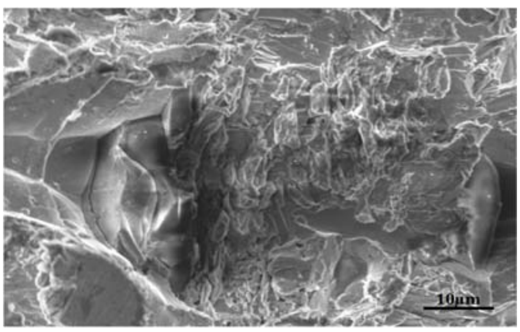


Fig. 9. Micrograph of machined surface at 280MPa – 30mm/min jet pressure and travel speed.

4. Conclusions

This paper reports a comprehensive investigation conducted on abrasive water jet cutting of Ni – Cr – Fe based superalloy. The following conclusions can be drawn from this investigation-

1. The jet pressure, jet travel speed, and stand-off distance significantly affected kerf wall inclination.
2. Jet travel speed is the predominant factor to be considered for removal of material. When the travel of jet is maximum, the rate of removal is high with significant contribution of jet pressure.
3. However, the jet pressure is the cutting and jet travel speed is the lapping tool to generated controlled surface finish.
4. The best value of average roughness obtained is 3.57 µm.
5. It can be said that it is possible to machine Ni – Cr – Fe superalloy type hard material by AWJC process provided using appropriate combination of process parameters. As regards to the current conditions, it can be a maximum jet pressure of 260MPa and SOD of 1mm by varying the jet travel speed in the range of 30 mm/min.

Acknowledgements

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