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Characterisation of abrasive water-jet process for pocket milling in Inconel 718

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Abstract

Experiments were carried out in Inconel 718 in order to investigate the possibility of using the abrasive water-jet process for producing 3D features such as pockets. A design of experiments approach was taken, considering variables such as water pressure, nozzle stand-off distance, traverse speed, nozzle orifice diameter, abrasive mass flow rate and tool-path step over distance. The experimental variables were related to depth of cut and pocket geometry. Statistical analysis was carried out in order to develop mathematical models which include process variable interactions and quadratic terms. This led to models with high correlation and prediction power which allow a better understanding of the process and can form the base for further process optimisation. The models were validated with additional experiments and showed good agreement with the water-jet system. The results showed that water pressure has a non-linear behaviour and is of paramount importance for controlling the depth of cut and geometrical errors. Additionally, nozzle diameter and the interaction between feed rate and abrasive mass flow are critical factors affecting the depth of cut.

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Open access under [CC BY-NC-ND license](https://creativecommons.org/licenses/by-nc-nd/4.0/).*Keywords:* Waterjet machining; Milling; Pocketing.

1. Introduction

Abrasive water jetting (AWJ) is a process that involves the entrainment of abrasive particles into a high velocity jet of water. The slurry of particles and water is used as the cutting tool. AWJ is commonly used in through cutting material. The advantages that have been reported for the process are: no thermal distortion on the work-piece, high machining versatility to cut virtually any materials, high flexibility to cut in any direction, small cutting forces [1, 2].

AWJ for non-through cutting, where the depth of cut (DOC) is controlled has been less reported. AWJ milling presents an opportunity to minimize machining costs and increase process flexibility. Various researchers have investigated AWJ milling of non-open areas such as pockets by using a mask to cover the jet of water from surfaces around the machining area [3, 4]. However, this

process restricts the flexibility and applicability of AWJ milling.

Modelling the different parameters of AWJ milling has been another approach for understanding and implementing the non-through cutting process [5-7]. However, existing models focus on analysing one variable at the time without considering the interrelations between the complex water-jet process parameters. Thus, the main objective of the present work is to develop mathematical models capable of predicting pocket geometry in terms of different process parameters and their interactions.

2. Experimental work

Experimental work was carried out in order to characterise the AWJ process for the production of pockets in Inconel 718. Characterisation of the AWJ system consisted in understanding the relationships between critical process parameters (CPPs) and the

system's Critical Quality Attributes (CQAs). In order to investigate the effect of CPPs on system CQAs, a Design of Experiments (DoE) approach was used. DoE is a useful statistical technique to identify important CPPs and their impact on the CQAs by generating mathematical models and evaluating whether or not CPPs are statistically significant in the process. The models can be used to analyse the behaviour of the system and make predictions of CQAs. After characterisation, system optimisation and robustness testing usually follow [8].

The CPPs involved in AWJ have been classified as [9]:

- cutting factors: stand-off distance, traverse direction, traverse rate, impact angle, number of passes;
- hydraulic factors: water pressure, orifice diameter;
- abrasive factors: abrasive feed rate, abrasive material, particle diameter, abrasive mass flow rate, abrasive size distribution, abrasive particle shape, abrasive hardness;
- mixing factors: focus diameter, focus length, abrasive feeding direction, material of focusing tube.

The DoE selected for this study incorporates six CPPs: stand-off distance, traverse rate, water pressure, focusing tube/ orifice diameter (nozzle), abrasive feed rate and step over distance. Step over distance refers to the distance between single slotting passes which form the tool-path. Fig. 1 shows a schematic of the tool-path; the water pump was switched on at the beginning of each slot and turned off at the end.

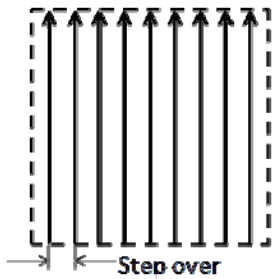


Fig. 1 Schematic representation of a tool-path composed of single slots separated by a step-over distance

The DOE consisted of a fractional factorial design with six factors (one qualitative) and two levels. The DoE was of resolution IV (two factor interactions were confounded with each other) and included six center points (three for each qualitative setting); this led to 22 experimental runs. The inclusion of replicates of the center point allows the variability and repeatability of the system to be estimated and any non-linearity in the system's responses to be detected. Table 1 provides a list of the DoE factors and their corresponding levels. The analysis was carried out using MODDE 9.1 software by

Umetrics, using the Partial Least Squares (PLS) method. Theoretical and actual design plans were identical.

Table 1 CPPs and their corresponding levels

CPP, units (abbreviation)	Level	
	Low	High
Water Pressure, Psi (Pre)	10,000	15,000
Stand-off distance, mm (Sdis)	2	4
Feed Rate, mm/min (Frt)	80	16
Abrasive mass flow, kg/min (Amf)	0.55	0.8
Step-over, mm (Sov)	0.5	0.8
Nozzle/orifice diameter, mm (Noz)	0.25/0.76	0.35/1.0

The experiments were carried out on a 3-axis ZX-513 WardJet AWJ system (www.wardjet.com); equipped with a 50HP water pump. Garnet mesh 80 was used as abrasive for all experimental runs. The experiments consisted of creating a number of 20 x 20 mm pockets in Inconel 718, with the experimental parameters based on the parameters in Table 1 which produced samples with different DOCs. A picture of the experimental set-up is shown in Fig. 1.



Fig. 2 Experimental set-up; the inconel plate is clamped onto the AWJ table and pockets are cut

3. Results and Analysis

The data was analysed using statistical software MODDE 9.1 by Umetrics. Prior to analysis, the raw data was transformed into a logarithmic scale using Equation [1].

$$y = \text{Log}(y+1) \quad [1]$$

Macrographs were taken using a tool-makers' microscope. The geometry of the experimental samples was characterised by the mean depth of cut, measured from the top of the surface sample up to the distance of

material removal; and an undercut, identified at the beginning of the tool-path. Measurements were taken of the mean DOC and undercut as shown in Fig. 3.

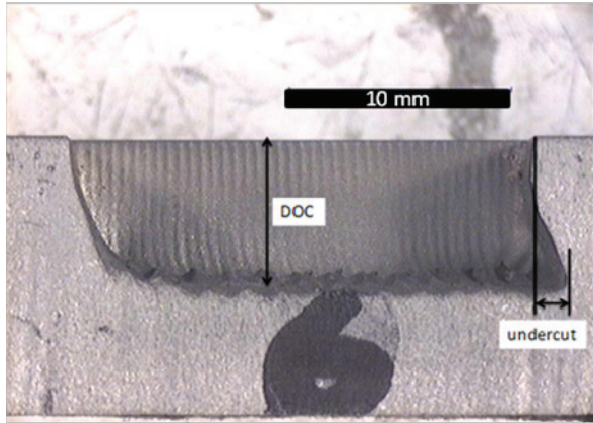


Fig. 3 Characterisation of pocket geometry; DOC and undercut

3.1. Modelling depth of cut

The variation in the experimental runs with respect to the mean DOC is shown in Fig. 4. The experiment produced a wide range of pocket depths from 0.17 to 13.26 mm. The depth of cut of two out of the three replicates was quite close to each other; however, one of the replicates of each setting varied considerably (replicate index 18 and 20).

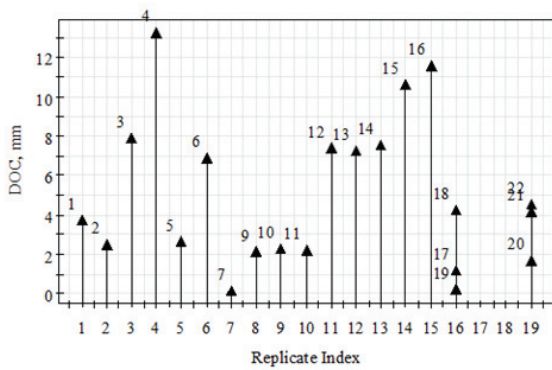


Fig. 4 Plot of replications for mean DOC

The coefficient plot illustrated in Fig. 5 shows the statistically significant model terms which have the highest influence on DOC. The quadratic term of pressure is the most significant parameter followed by the nozzle combination (diameter). Lower DOCs are achieved with the smaller nozzle diameter combination. Using a larger nozzle diameter produces a bigger kerf size; which causes a higher overlap between the line slots, hence deeper pockets. The interaction between stand-off distance and nozzle diameter is important. For

bigger nozzles a high stand-off distance produces a high DOC; on the other hand, for smaller nozzles a small stand-off distance produces a high DOC. Feed rate has a small effect on depth of cut but the interaction between feed rate and abrasive rate has a strong effect. A high feed rate combined with a high abrasive mass rate produces a high DOC; but if the feed rate is reduced, a low abrasive mass flow is needed to produce a high DOC. The model developed had a very good fit as expressed by the statistic R2 (0.833) and a good prediction power, with a Q2 of 0.472.

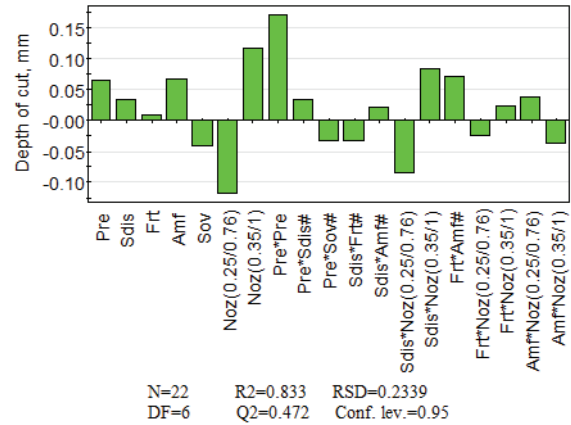


Fig. 5 Scaled and centred coefficients for mean DOC

Contour plots can be produced using the mathematical model developed. A contour plot shows a map of a CQA, in this case mean DOC, for different settings of CPPs; such a plot is shown in Fig. 6. The non-linear behaviour of the water pressure can be seen; the same mean DOC can be achieved with two different settings of pressure, a low one and a higher one, with the other parameters constant.

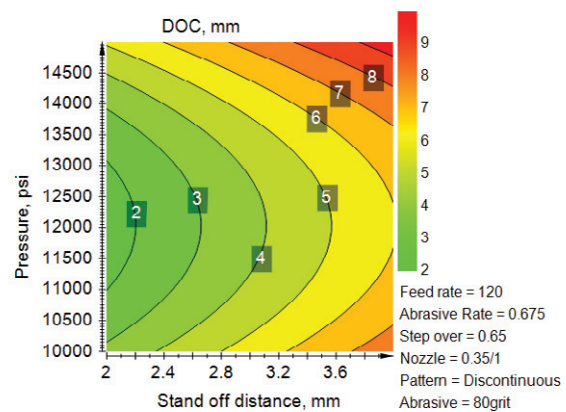


Fig. 6 Contour plot for mean DOC

3.2. Modelling undercut

Fig. 7 plots the variation in the experimental runs for measurements of the undercut. The experiment produced a good range of undercut sizes. Most of the experimental runs had an undercut less than 0.5 mm; the maximum undercut was 4.08 mm. The repeatability of the centre points was rather good and resembled that of the mean DOC model; with replicate 18 and 20 different.

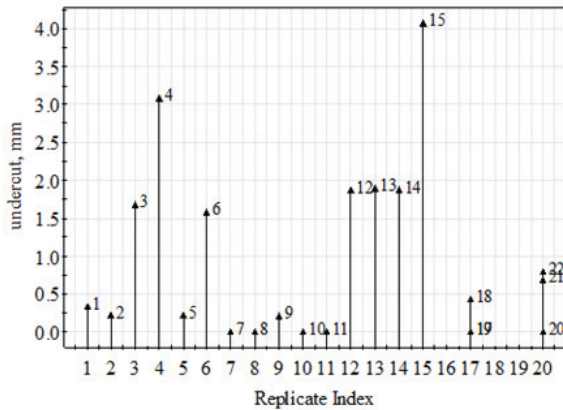


Fig. 7 Plot of replications for undercut

The CPPs and their influence on the undercut are shown in the coefficient plot in Fig. 8. The main effect on the undercut is the quadratic term on water pressure; followed by the step-over size. Increasing the step-over size decreases the undercut as this minimises the jet overlap between individual slots. Nozzle combination is an important factor that contributes to the undercut; decreasing the nozzle diameter minimises the undercut. The interactions that had a significant contribution to the model were stand-off distance / nozzle combination and feed rate / abrasive mass flow. For a high stand-off distance and a small nozzle diameter the undercut decreases; whereas a low stand-off distance is preferred for a bigger nozzle diameter in order to minimise the undercut. Similarly, high feed rates combined with low abrasive mass rate produces a low undercut; reducing the feed rate will require a higher abrasive mass rate to minimise the undercut. The model had a good fit and prediction power expressed by the R^2 and Q^2 statistic (0.872 and 0.602 respectively).

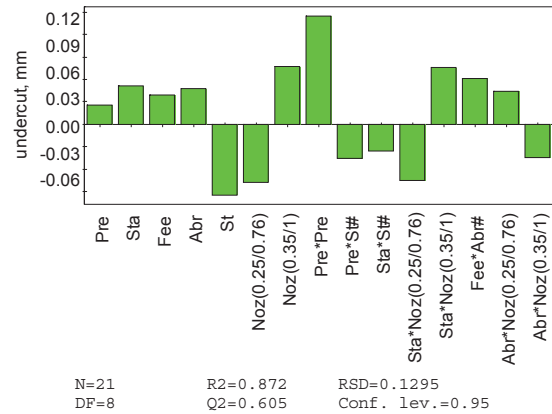


Fig. 8 Scaled and centred coefficients for undercut

A contour plot produced using the mathematical model developed is shown in Fig. 9. The contour plot shows a map of the relationship between water pressure and stand-off distance for other fixed settings. The same level of undercut can be produced with a high and low pressure with other parameters fixed; the undercut is reduced for pressures between 12,000 and 12,500 psi at a stand-off distance of 2mm.

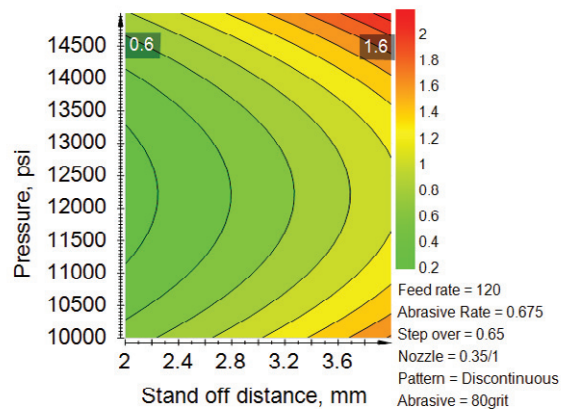


Fig. 9 Contour plot for undercut

3.3. Model validation

An additional experimental run was carried out in order to validate the mathematical models developed. The depth of cut measured was 2.69 mm with an undercut of 0.225 mm, Fig. 10. The models gave an error of 3% for the DOC and 2.4% for the undercut; which shows a good agreement with the models developed.

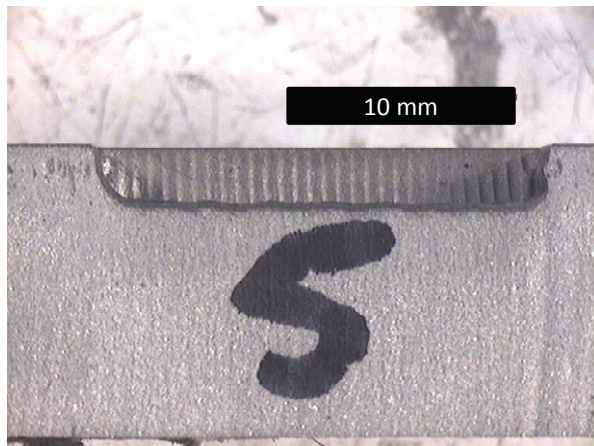


Fig. 10 Macrograph of model validation run

4. Conclusions and further work

Mathematical models, based on experimental observations, using six different process parameters and their interactions were developed for characterising the geometry of pockets created with abrasive water jet. The geometry of the pockets was defined by a depth of cut where the quadratic term of water pressure was found to be a main effect; the same depth of cut can be produced using two different pressure settings (low and high) with all other parameters fixed. This has implications with respect to power consumption and system wear. Feed rate did not have a strong effect on depth of cut; thus can be optimised to increase productivity. However, the interaction between feed rate and abrasive rate was important; higher abrasive rates are needed to achieve a high depth of cut with lower feed rates.

An undercut was present at the beginning of the tool-path of the experimental samples. The main factor controlling the undercut is the water pressure, which had a quadratic behaviour. Step-over also had a strong effect on undercut which will require optimisation if pockets with minimum undercut are to be achieved. The undercut decreases with decreasing nozzle diameter.

The models can be extended to include additional critical quality attributes such as surface roughness of the bottom of the samples, microstructural features (material embedment), etc. The models will also benefit from investigating different critical process parameters such as abrasive type, abrasive grit, tool-paths, etc.

Acknowledgements

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