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Paper

3D NEAR NET SHAPING OF HARD TO MACHINE MATERIALS VIA ABRASIVE WATERJET CONTROLLED-DEPTH MILLING

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ABSTRACT

Nickel alloys e.g. Inconel 718 have outstanding mechanical, thermal and corrosive properties. Despite its wide range of use Inconel 718 can still be considered as a hard to cut material using conventional cutting processes e.g. milling or turning. The abrasive waterjet (AWJ) technology has the capability to machine these hard to cut materials reliably with reduced mechanical and thermal damages at the same time. Being able to create notches with predictable depths, high aspect ratios and low predictable notch base irregularities via AWJ can lead to a substantial increase of machining performance of hard to cut materials. Thus, 3D near net shaping as a roughening process prior to conventional cutting processes is possible. The goal of this investigation was to analyze the correlation between AWJ settings parameters and the notch depth as well as the notch base irregularity when machining Inconel 718. A prediction model including the main effects, interactions and quadratic effects was developed using design of experiments.

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1. INTRODUCTION

The constant development of new materials with enhanced mechanical or chemical properties results in great challenges for the manufacturing technology. These improved material properties often lead to difficulties for cutting processes e.g. long machining times or high tool wear. An economic industrial application of these materials is only possible with an adequate manufacturing method. Despite its wide range of use Inconel 718 can still be considered as a hard to cut material. Inconel 718 shows a good long period creep resistance at temperatures up to 700 °C, resistance to oxidation up to 1,000 °C and excellent corrosive properties at high and low temperatures. Due to this combination Inconel 718 is used in a variety of applications e.g. aircraft engines or cryogenic tanks.

One of the advantages of the abrasive waterjet technology is its wide range of machinable materials. Even hard to cut materials can be economically and reliably processed with AWJ with reduced mechanical or thermal damages. At the moment the industrial use of AWJ is limited to machining operations where the workpiece is completely penetrated e.g. cutting or drilling operations.

In the late 1980s Hashish introduced the abrasive waterjet controlled depth milling technology (AWJ-CDM) to create notches in different materials using multiple passes with a high feed velocity. He identified the feed velocity as a critical setting parameter for the notch depth irregularity and suggested a minimum value of 960 mm/min [1]. He also concluded that already induced irregularities in the notch base cannot be corrected by further passes but rather aggravated [2]. Therefore, the initial state of the surface being machined is of importance and must be considered at the beginning of the machining operation. Laurinat et al. [3], Öjmertz et al. [4] and Kong et al. [5] presented mathematical models to describe the notch depth for small notch depths (< 3 mm). In order to use AWT-CDM as a pre-shaping process of bulk material as shown in Figure 1 [6], a greater notch depth with predictable depth and irregularity in the base is necessary. Also roundings at the sides of the workpiece must be prevented. Fowler [7] suggested the use of so called “butt masks” at the sides of the workpiece as shown in Figure 2.

The goal of this investigation was to provide an empirical model to describe the notch depth and notch base irregularity as a function of the setting parameters for high aspect ratios (50:1) in Inconel 718. By using design of experiments (DoE) main effects as well as parameter interactions and quadratic effects could be included in the model. This model was then applied to create a notch with a depth of 50 mm with a notch base irregularity of less than 0.5 mm. The roundings at the sides of the test specimen were not part of the investigation.

2. EXPERIMENTAL INVESTIGATION

2.1 Technical objective and applied statistical method

The scope of this investigation was to develop an empirical model of the average notch depth t_K and its irregularity in the base Δt_K for notches with high aspect ratios (50:1) in nickel alloy Inconel 718 using AWJ-CDM, Figure 3. In screening experiments significant parameters and adequate parameter ranges were determined. The investigated parameters were the jet pressure p, the feed velocity v_f, the abrasive flow rate $\dot{m}_A$ and the number of passes z. The stand-off distance was kept constant at $s_0 = 2$ mm. A central composite design (CCD) followed by a linear regression was used to analyze main effects but also parameter interactions and second order effects on the target values. The applied CCD consists of three successive experimental steps. A factorial design with two parameter setting levels is used to determine main effects and parameter interactions. Including a center point indicates a nonlinear behavior. A set of axial points are used to analyze the curvature of the function. By using linear regression empirical models can be developed. The general mathematical equations for the target values are:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i<j=2}^{k} \beta_i x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \epsilon \tag{1}$$

The CCD is described in detail by Myers et al. [8]. The structure of the design is shown in Figure 4. The investigated parameters and parameter ranges are summarized in Table 1.

2.2 Test setup

For the experimental investigation a six-axis robot was used for jet manipulation with a maximum traverse speed of up to 2.5 m/s. The water pressure was realized with a 45 kW hydraulic high pressure intensifier delivering up to 600 MPa and a maximum flow rate of 2.5 l/min. The abrasive flow rate could continuously be varied from 50 to 500 g/min. A standard combination of orifice with a diameter of 0.25 mm and focus with a diameter of 0.76 mm and a length of 76 mm were selected. Garnet sand Mesh 80 was used as abrasive. The tested material was nickel alloy Inconel 718 (2.4668). The used machining system is shown in Figure 5.

2.3 Measurement method

To measure the notch depth and its irregularity in the base, the test specimens were separated along the notch base after the experiments using wire EDM. These target values were determined by the optical measuring device FRT microProf 100 using white light interferometry. A range of 30 mm x 3 mm with a resolution of 300 pixels x 300 pixels was measured. An example of a measured notch depth irregularity is shown in Figure 6.

2.4 Results for the notch depth

The analysis of the data for AWJ-CDM on Inconel 718 specimen showed that all four investigated parameters have a significant main effect on the notch depth t_K. Furthermore, two factor parameter interactions and quadratic effects could be observed by the use of CCD, Figure 7. Using linear regression an empirical model could be developed to predict the notch depth t_K. The coefficient of determination showed to be excellent ($R^2 = 0.99$). The empirical model to describe the notch depth t_K is:

$$t_K = 28.94 + 6.95\, p - 6.51\, v_f + 2.08\, \dot{m}_A + 2.24\, z - 1.41\, p\, v_f + 1.47\, p\, \dot{m}_A + 0.50\, p\, z - 0.50\, v_f\, \dot{m}_A - 0.51\, v_f\, z + 1.55\, v_f^2 - 1.35\, z^2 \tag{2}$$

Figure 8 shows examples the modeled notch depths for the pressure, feed velocity, abrasive flow rate and number of passes. For this representation the remaining parameters are kept constant on “center-level”.

As expected, with rising pressure and number of passes the notch depth increased in a linear behavior. By raising the feed velocity the notch depth was reduced in a regressive behavior. For the abrasive flow rate a maximum notch depth at about 150 g/min was found. This location of the maximum was dependent on the used pressure. Furthermore, two factor parameter interactions and quadratic effects could be observed by the use of CCD. An example for the parameter interaction is shown in Figure 9, left. Increasing the pressure and lowering the feed velocity at the same time resulted in a higher notch depth than it would be expected when examining the parameters independently.

In detail, the significant effects are:

Main effects

Pressure p
Feed velocity v_f
Abrasive flow rate $\dot{m}_A$
Number of passes z

Parameter interactions:

Pressure p x feed velocity v_f
Pressure p x abrasive flow rate $\dot{m}_A$
Pressure p x number of passes z
Feed velocity v_f x abrasive flow rate $\dot{m}_A$
Feed velocity v_f x number of passes z

Quadratic effects:

(Feed velocity $v_f)^2$
(Abrasive flow rate $\dot{m}_A)^2$

For using the model to calculate the target value, the parameter settings must be entered in standardized form. An example to create a notch depth of t_K = 50 mm is shown in Figure 10. The deviation of the calculated and achieved depth was in a range of 0.1 mm.

2.3 Results for the notch depth irregularity

As in the analysis of the notch depth, the behavior of the notch depth irregularity showed to be nonlinear. The parameters pressure p, feed velocity v_f and the abrasive flow rate $\dot{m}_A$ have a significant main effect on the target value. The number of passes did not show to have a significant effect within the tested parameter range. Also one two-factor interaction and quadratic effects could be observed, Figure 11. Using the same mathematical analysis as for the notch depth an empirical model to describe the notch depth irregularity Δt_K as a function of the setting parameters was obtained. The coefficient of determination showed to be good ($R^2 = 0.82$). The equation to predict the notch depth irregularity Δt_K is:

$$\Delta t_K = 0.54 + 0.25\,p - 0.20\,v_f - 0.19\,m_A - 0.13\,p\,v_f + 0.11\,p^2 + 0.13\,v_f^2 + 0.14\,m_A^2 \tag{3}$$

Figure 8 shows examples the modeled notch depth irregularity for the pressure, feed velocity, abrasive flow rate and number of passes. For this representation the remaining parameters are again kept constant on “center-level”.

With rising pressure the notch depth irregularity increased in a linear behavior. Raising the feed velocity resulted in a much lower notch depth irregularity. Remarkably, the irregularity increased with lower abrasive flow rate. This behavior can be explained by the use of a relatively long abrasive feeding tube, due to the use of a robot for jet guidance. Due to air vibrations inside of the abrasive feeding tube the abrasive did not enter the cutting head continuously, but in waves. This effect was stronger for low abrasive flow rates and resulted in an increased notch depth irregularity which was aggravated with every pass as explained in [2]. One two factor interaction and quadratic effects could be observed. The parameter interaction of pressure and feed velocity is shown in Figure 9, right. Lowering the pressure and increasing the feed velocity at the same time resulted in a much lower notch depth irregularity than it would be expected when analyzing the main effects only. In detail, the significant effects are:

Main effects	**Quadratic effects:**
Pressure p	(Pressure p)^2
Feed velocity v_f	(Feed velocity v_f)^2
Abrasive flow rate $\dot{m}_A$	(Abrasive flow rate $\dot{m}_A$)^2

Parameter interactions:
Pressure p x feed velocity v_f

To calculate the target value, the parameter settings must again be entered in the equation in standardized form. An example to create a notch depth of $t_K = 50$ mm is shown in Figure 10. The deviation of the calculated and achieved notch depth irregularity was in a range of 1.3 mm.

3. CONCLUSION

The investigation showed that for estimating the notch depth and notch depth irregularity not only main effects but also parameter interactions as well as quadratic effects have a significant influence on the target values and must be considered. By using a central composite design followed by a regression analysis an empirical model to estimate the notch depth and notch base irregularity for high aspect ratios in Inconel 718 using AWJ-CDM was generated. This model was then applied for a machining example creating a notch with $t_K = 50.1$ mm with an irregularity in the base of $\Delta t_K = 0.3$ mm. By overlapping these notches 3D near net shaping prior to conventional cutting processes would be an adequate machining solution for hard to cut materials.

4. ACKNOWLEDGMENTS

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5. REFERENCES

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6. NOMENCLATURE

Parameter	**Symbol**	**Unit**
Orifice diameter	d_D	mm
Focus diameter	d_F	mm
Modeled notch depth	$t_{K,m}$	mm
Modeled notch depth irregularity	$\Delta t_{K,m}$	mm
Abrasive flow rate	$\dot{m}_A$	g/min
Coefficient of determination	R^2	-
Correlation coefficient	β_0	-
Correlation coefficient	β_i	-
Correlation coefficient	ε	-
Feed velocity	v_f	mm/min
Notch depth	t_K	mm
Notch depth irregularity	Δt_K	mm
Number of passes	z	-
Parameter setting	x_i	-
Parameter setting	x_j	-
Pressure	p	MPa
Pixels	px	-

Stand-off distance	s_0	mm
Target value	y	-

Abbreviation

AWJ	Abrasive waterjet
CCD	Central composite design
CDM	Controlled depth milling
DoE	Design of experiments
EDM	Electro-discharge machining

7. TABLES

Table 1. Investigated parameters and parameter ranges using DoE-CCD

Parameter	**Symbol**	**Unit**	**- α**	**- 1**	**0**	**+ 1**	**+ α**
Pressure	p	MPa	100	125	150	175	200
Feed velocity	v_f	mm/min	2000	2750	3500	4250	5000
Abrasive flow rate	$\dot{m}_A$	g/min	50	88	125	163	200
Number of passes	z	-	250	275	300	325	350

8. GRAPHICS

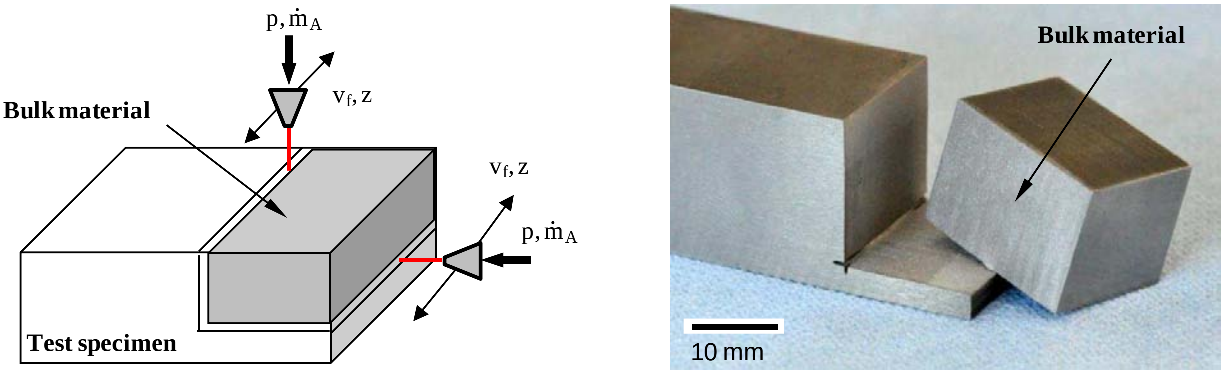


Figure 1. Removal of bulk material with AWJ-CDM [6]

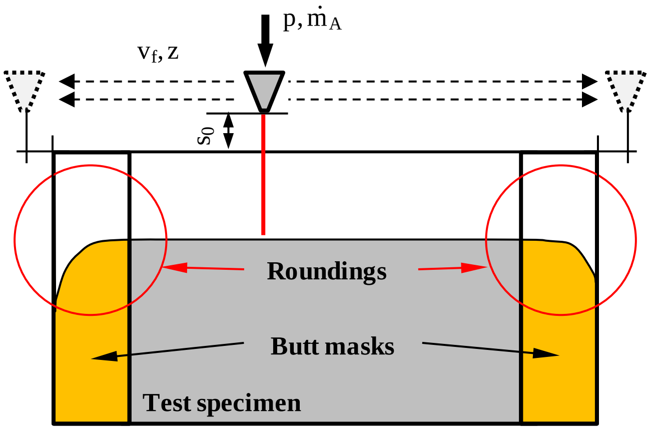
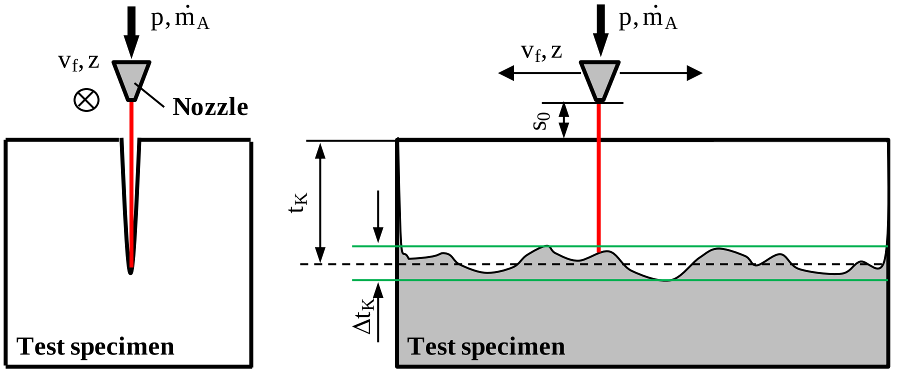


Figure 2. Removal of bulk material with AWJ-CDM using butt masks



Parameters:	
Pressure	p
Feed velocity	v_f
Abrasive flow rate	$\dot{m}_A$
Number of passes	z
Stand-off distance	s_0
Target values:	
Notch depth	t_K
Notch base irregularity	Δt_K

Figure 3. Schematic representation of the target values

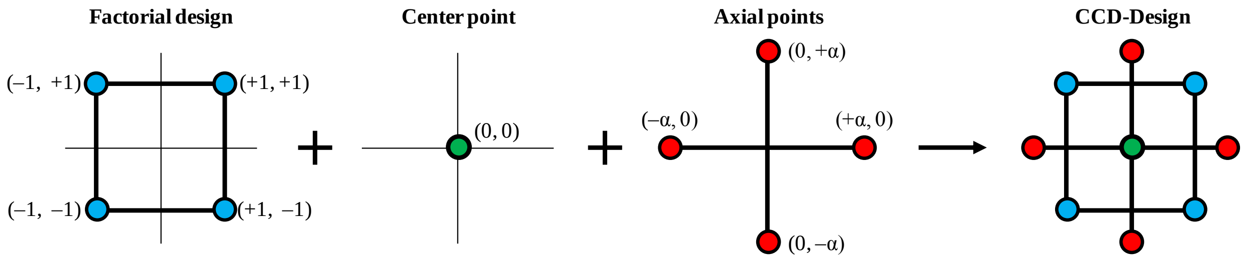
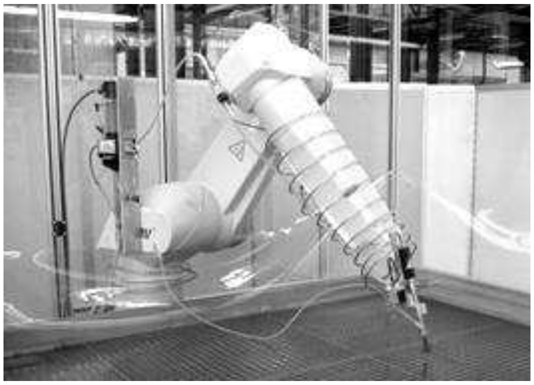


Figure 4. Structure of a central composite design



MaximatorJET HRX 160L
Working space:
2.200 x 1.200 x 900 mm³
Jet guiding system:
Stäubli RX160L
Water pump:
UHDE HPS 6045
Abrasive dosing system
STM Mini Hopper

Figure 5. Robot guided AWJ-machine: MaximatorJET HRX 160L

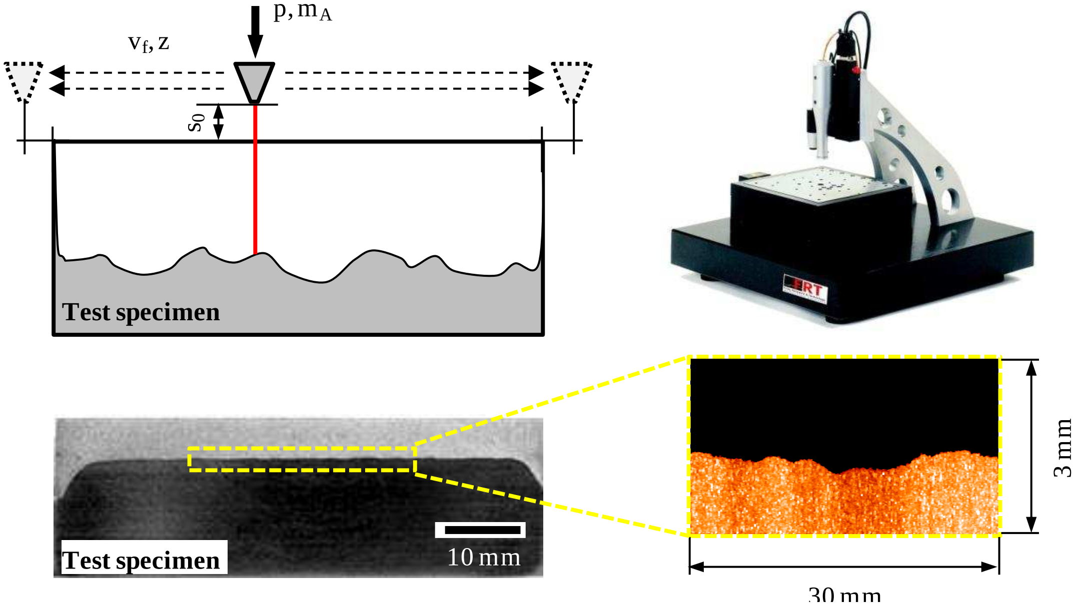
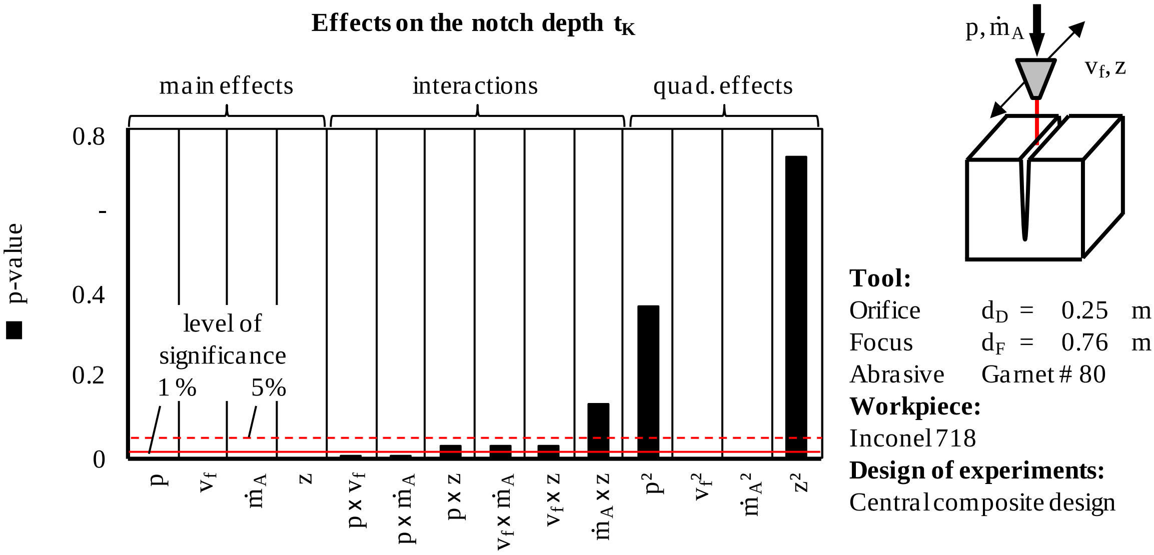


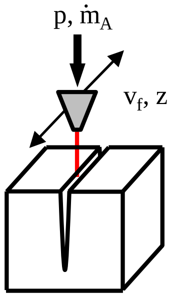
Figure 6. Measuring method

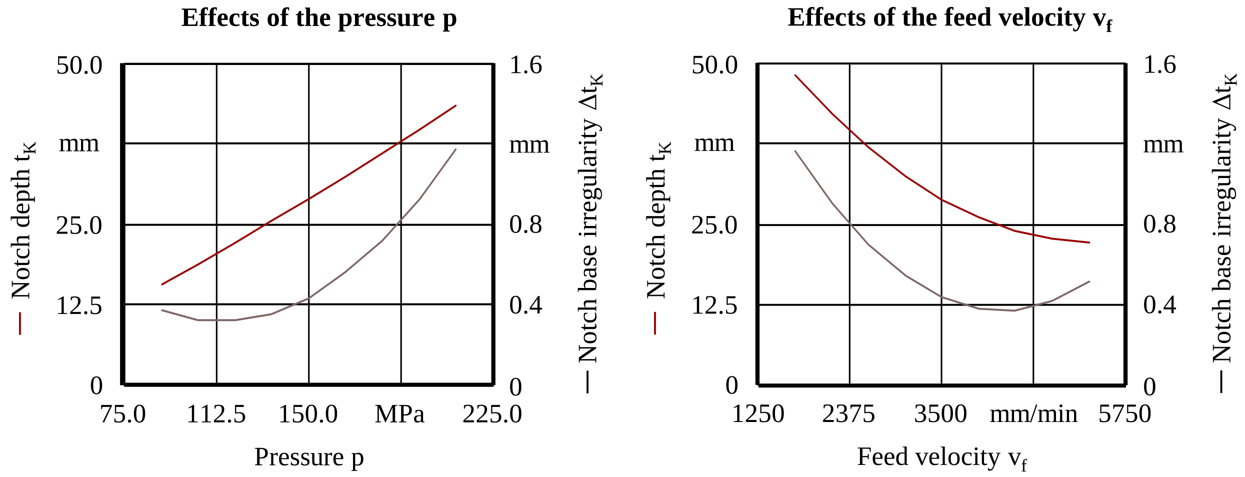


Tool:
Orifice d_D = 0.25 mm
Focus d_F = 0.76 mm
Abrasive Garnet # 80
Workpiece:
Inconel 718
Design of experiments:
Central composite design

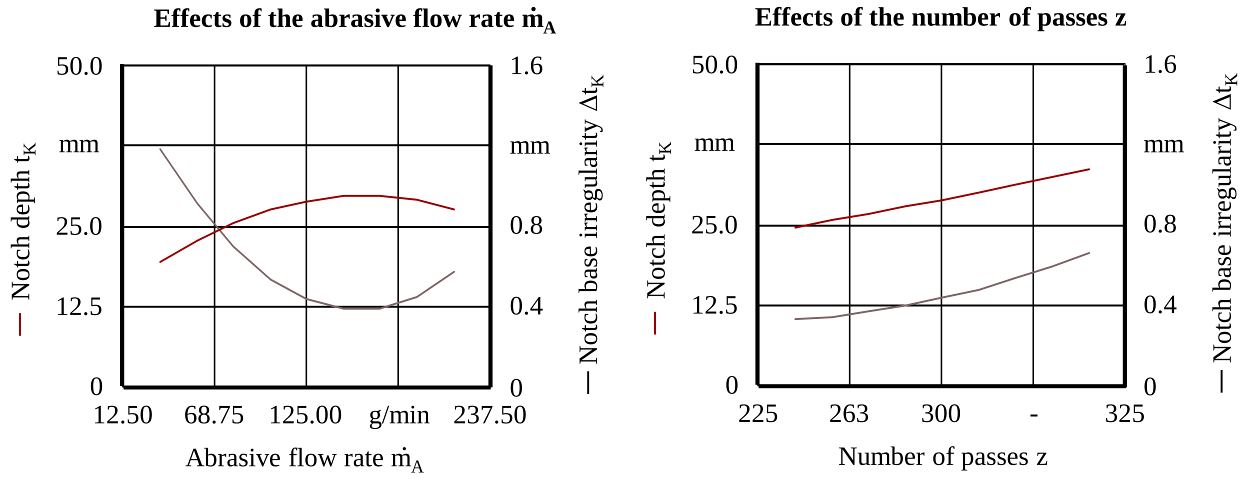
Figure 7. Main effects, interactions and quadratic effects on the notch depth t_K

Tool:				
Orifice	d_D	=	0.25	mm
Focus	d_F	=	0.76	mm
Abrasive	Garnet #80			
Workpiece:				
Inconel 718				
Parameters on center-level:				
Pressure	p	=	150	MPa
Feed velocity	v_f	=	3500	mm/min
Abrasive flow rate	$\dot{m}_A$	=	125	g/min
Number of passes	z	=	300	-




Effects of the pressure p

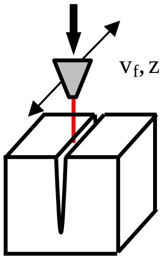
Effects of the feed velocity v_f

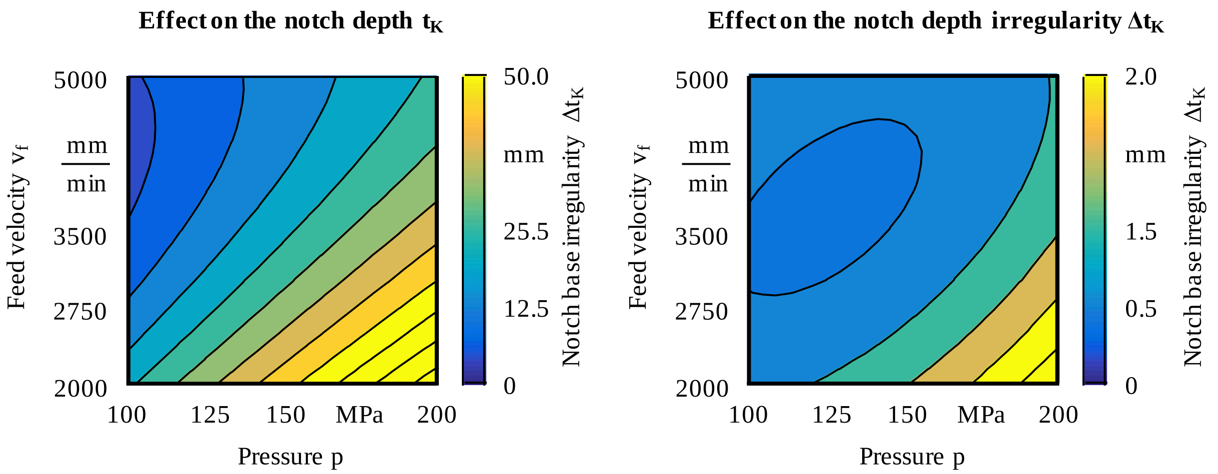

Effects of the abrasive flow rate $\dot{m}_A$

Effects of the number of passes z

Figure 8. Effects on the notch depth t_K and notch depth irregularity Δt_K

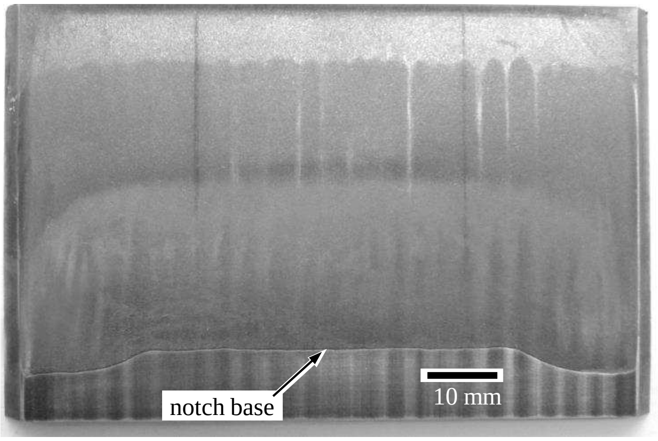
Tool:				
Orifice	d_D	=	0.25 mm	
Focus	d_F	=	0.76 mm	
Abrasive	Garnet # 80			
Workpiece:				
Inconel 718				
Parameters:				
Abrasive flow rate	$\dot{m}_A$	=	125	g/min
Number of passes	z	=	300	-




Effect on the notch depth t_K

Effect on the notch depth irregularity Δt_K

Figure 9. Contourplots of the interactions on the notch depth t_K and notch depth irregularity Δt_K



Tool:				
Orifice	d_D	=	0.25	mm
Focus	d_F	=	0.76	mm
Abrasive	Garnet #80			
Workpiece:				
Inconel 718				
Parameters:				
Pressure	p	=	188	MPa
Feed velocity	v_f	=	3330	mm/min
Abrasive flow rate	m_A	=	163	g/min
Number of passes	z	=	340	-
Results:				
Modeled notch depth	$t_{K,m}$	=	50.0	mm
Notch depth	t_K	=	50.1	mm
Modeled notch base irregularity	$\Delta t_{K,m}$	=	1.6	mm
Notch base irregularity	Δt_K	=	0.3	mm

Figure 10. Machining example of AWJ-CDM of Inconel 718

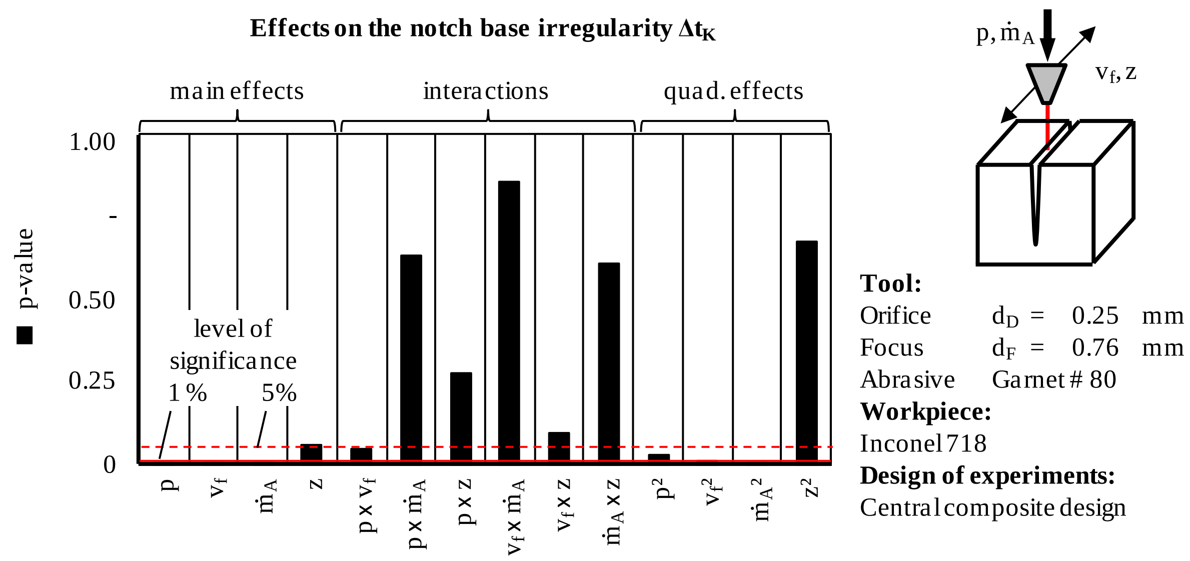


Figure 11. Main effects, interactions and quadratic effects on the notch base irregularities Δt_K