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Optimization of high-pressure jet assisted turning process by Taguchi method

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A B S T R A C T

This paper outlines the Taguchi optimization methodology, which is applied to optimize cutting parameters in high-pressure jet assisted turning when machining Inconel 718. Turning parameters evaluated are the diameter of the nozzle D_n, the pressure of the jet P, the cutting speed V_c, the feed rate f and the distance between the impact point of the jet and the cutting edge d. The experiments were conducted by using $L_{27}(3^{13})$ orthogonal array as suggested by Taguchi. Signal-to-Noise (S/N) ratio and Analysis of Variance (ANOVA) are employed to analyze the effect of high-pressure jet assisted turning parameters on the main cutting force and surface roughness, in other words to find optimal levels of the process parameters. The study shows that the Taguchi method is suitable to solve the stated problem with minimum number of trials.

A R T I C L E   I N F O

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1. Introduction

All engineering materials are often divided into easy-to-machine or difficult-to-machine materials. There are new alloys especially difficult for machining, for instance, hardened steels, Cr-Co alloys, Ti-based, and Ni-based alloys. Cutting of nickel-based alloys is a topic of high interest for today's industrial production and scientific research. Nickel-based alloys commonly used materials in aerospace industry (engines), power production (power plant generators), environmental protection and waste management (flue gas desulphurization plants), chemical industry (cauldrons, heat exchangers, valves, pumps). According to [1], Inconel 718 is the most commonly employed nickel superalloy and represents 25–45 % of the annual volume production.

Nickel-based alloys are well known to yield a very poor machining performance. Different assistance methods have been developed to replace the "conventional cutting process". One of them is high-pressure jet assisted turning (HPJA), which aims at upgrading conventional machining using the thermal and mechanical properties of high-pressure jet of water or emulsion directed into cutting zone [2]. High pressure jet assisted turning (HPJA) presents an innovative method of lubricating and/or cooling the cutting zone during machining. This machining alternative offer reduced costs, avoidance or reduction of health and environmentally hazardous.

Determination of optimal machining parameters in HPJA turning is continuous engineering task which goals are to reduce the production costs and to achieve the desired product quality. Following modern production requests and technologic-economic analysis of processing operations, during the designing process, it is necessary to determine optimal cutting parameters in order to achieve minimal expenses or minimal production time [3].

Classical experimental design method, i.e., rotatable central composite design, is too complex and not easy to use. A large number of experiments have to carried out especially when the number of process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments. The Taguchi method of experimental design is one of the widely accepted techniques for off line quality assurance of products and processes.

Subject of this study is to analysis dependence of the main cutting force F_c and roughness parameter R_a on the following five HPJA turning parameters: the diameter of the nozzle D_n, the pressure of the jet P, the cutting speed V_c, the feed rate and distance between the impact point of the jet and the cutting edge d. Taguchi method and ANOVA analysis are used to analyze the effect of cutting parameters on the main cutting force and surface roughness.

2. Taguchi method

Robust Design method, also called the Taguchi method, pioneered by Genichi Taguchi, greatly improves engineering productivity. The Taguchi method is a well-known technique that provides a systematic and efficient methodology for process optimization and this is a powerful tool for the design of high quality systems. Taguchi parameter design is based on the concept of fractional factorial design. The main objective of parameter design is to minimize the process or product variation and to design robust and flexible processes or products that are adaptable to environmental conditions [4]. Taguchi's approach to design of experiments is easy to adopt and apply for users with limited knowledge of statistics; hence it has gained a wide popularity in the engineering and scientific community. This is an engineering methodology for obtaining product and process condition, which are minimally sensitive to the various causes of variation, and which produce high-quality products with low development and manufacturing costs. Many companies around the world have saved hundreds of millions of dollars by using the method in diverse industries: automobiles, xerography, telecommunications, electronics, software, etc.

Taguchi proposed a standard procedure for applying his method for optimizing any process. The steps suggested by Taguchi are [5]:

1. Determine the quality characteristic to be optimized
2. Identify the noise factors and test conditions
3. Identify the noise factors and test conditions
4. Design the matrix experiment and define the data analysis procedure
5. Conduct the matrix experiment
6. Analyze the data and determine the optimum levels for control factors
7. Predict the performance at these levels

Signal to noise ratio (S/N ratio) and orthogonal array are two major tools used in robust design. Orthogonal arrays allow designers to study many design parameters simultaneously and can be used to estimate the effects of each factor independently. S/N ratio measures quality with emphasis on variation and orthogonal arrays accommodate many design factors simultaneously [6].

The S/N ratio characteristics can be divided into three categories when the characteristic is continuous:

nominal is the best

$$S/N = 10 \log \frac{\bar{y}}{s_y^2} \tag{1}$$

smaller the better

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \tag{2}$$

and larger is better characteristics

$$S/_{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{3}$$

where $\bar{y}$ is the average of observed data, s_y^2 the variance of y, n is the number of replication and y_i is the measured value of output variable.

For each type of the characteristics, with above S/N ratio transformation, the higher S/N ratio the better is the result. To objective of experiment is to optimize the HJPA turning parameters to get better (i.e. low value) the main cutting force and surface roughness values, the "smaller the better" characteristics are used, equation (2). The influence of each control factor can be more clearly presented with response graphs [7, 8]. Optimal cutting conditions of control factors can be very easily determined from S/N response graphs, too.

Parameters design is the key step in Taguchi method to achieve reliable results without increasing the experimental costs. The experimental layout for the machining parameters using L_{27} (3^{13}) orthogonal array was used in this study. The experimental results were analyzed with Analysis of Variance (ANOVA), which is used for identifying the factors significantly affecting the performance measures.

3. Experimental work

High pressure jet assisted turning (HPJA) is a process where cooling lubrication fluid (CLF) is delivered into the cutting zone region under extremely high pressure of up to P = 300 MPa and at a lower volume flow rate than in the conventional case, providing improved lubrication, cooling and chip breaking effects, Fig. 1 [9]. This is innovative method of lubricating and/or cooling the cutting zone during machining.

The lathe should be fitted with high pressure equipment. This involves high pressure pump, high pressure tubing, and outlet nozzle fixed beside tool holder. A pump is supplied with filtered water or emulsion. A complete machine tool set is presented in Fig. 2 [10].

Some potential benefits of this machining are [9]: more sustainable machining through lower flow rates of CLF in comparison to conventional machining, decreasing the cutting tool-chip contact length, resulting in lower cutting forces and longer tool life, drastic improvement in chip breakability etc.

The experimental work was carried out at the Laboratory for Machining, the Faculty of Mechanical Engineering in Ljubljana. The experiments were conducted in longitudinal turning process on conventional lathe, fitted with a Hammelmann high-pressure plunger pump of 150 MPa pressure and 8 l/min capacity. The fluid used was the Vasco 5000 cooling lubricant from Blaser Swisslube Inc., a 5.5 % emulsion without chlorine on the basis of vegetable oil mixed with water (pH 8.5–9.2).

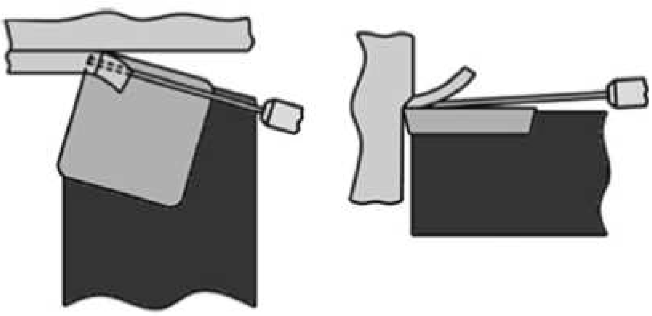

Fig. 1 HPJA CLF delivery jet direction sketch

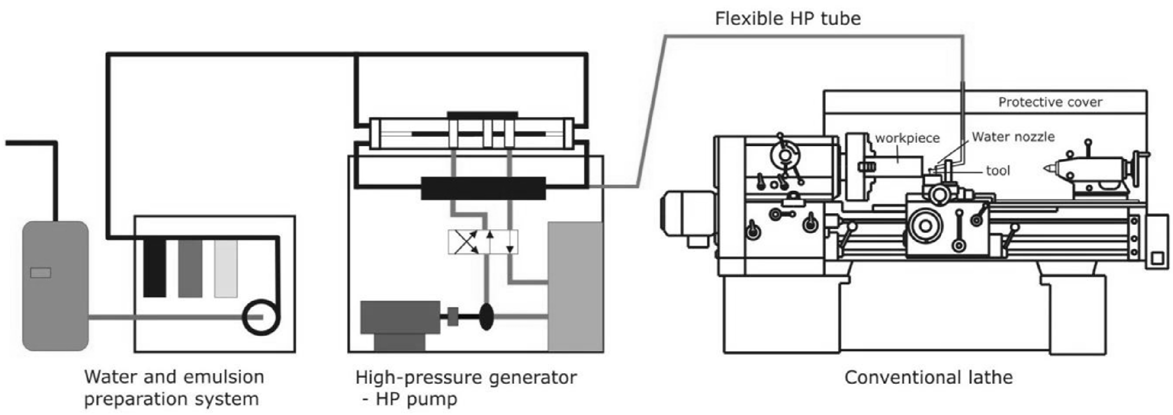

Fig. 2 System configuration for turning with HPCL

Machining performance was investigated according to the following HPJA parameters: the diameter of the nozzle D_n (0.25, 0.3 and 0.4 mm), the pressure of the jet P (50, 90 and 130 MPa), the cutting speed V_c (46, 57 and 74 m/min), the feed rate f (0.2, 0.224 and 0.25 mm/rev) and the distance between the impact point of the jet and the cutting edge d (0, 1.5 and 3 mm).

All experiments were carried out using the nickel-based alloy Inconel 718 supplied as bars (145 mm diameter x 300 mm long) with hardness between 36 HRc and 38 HRc by orthogonal arrays with three levels (coded by: 1, 2 and 3), Table 1. A PVD TiAlN-coated carbide tool (grade P25) SNMG 12 04 08–23 has been chosen.

The cutting tool was mounted on the static dynamometer (Kistler® 9259A). The measurement chain also included a charge amplifier (Kistler® 5001), a data acquisition hardware (NI® USB-6218 BNC) and a graphical programming environment (NI® LabVIEW) for data analysis and visualization. Experimental setup is shown in Fig. 3 [10].

Surface roughness was measured with a stylus-type instrument Mitutoyo-Surftest SJ-301, Fig. 4 [11]. The surface roughness response is the average reading of three consecutive measurements.

Table 1 Machining parameters and their levels

Symbol	Parameters	Levels		
		1	2	3
A	Diameter of the nozzle, D_n (mm)	0.25	0.3	0.4
B	Distance between the impact point of the jet and the cutting edge, d (mm)	0	1.5	3.0
C	Pressure of the jet, P (MPa)	50	90	130
D	Cutting speed, V_c (m/min)	46	57	74
E	Feed rate, f (mm/rev)	0.2	0.224	0.25

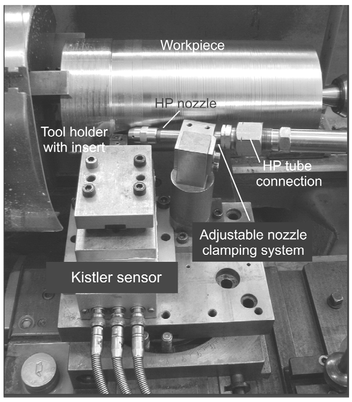

Fig. 3 Machine tool setup used in experimental work

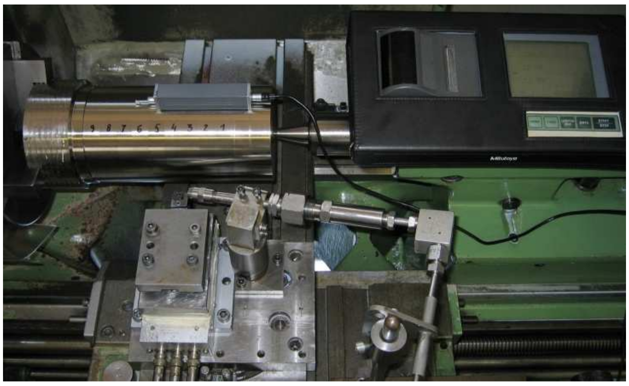

Fig. 4 Measurement of 2D roughness parameters

4. Results and discussion

Experimental results, together with their transformations into signal-to-noise ratios are given in Table 2. In this study all the analysis based on Taguchi method is done by Minitab14 software to determine the main effects of the cutting parameters, to perform the Analysis of Variance (ANOVA) and establish the optimum conditions.

From Table 2 it can be determined which control factors have strong influence on roughness parameter R_a and the main cutting force F_c in high-pressure jet assistance turning (HPJA). Optimal cutting conditions of these control factors can be very easily determined from the S/N response graphs.

In Fig. 5, the response graphic of roughness parameter R_a has been shown for all five factors. The best roughness parameter R_a is at the higher S/N values in the response graphs. Parameter influence on output process variable shows angle of inclination of the line which connects different parameter levels.

Table 2 Orthogonal array $L_{27}(3^{13})$ with experimental results and calculated S/N ratio

No.	Factors					Parameters					Measured parameters		Calculated S/N	
	A D_n	B d	C P	D V_c	E f	D_n (mm)	d (mm)	P (MPa)	V_c (m/min)	f (mm/rev)	R_a (μm)	F_c (N)	S /N for R_a	S /N for F_c
1	1	1	1	1	1	0.25	0	50	46	0.2	2.54	1270.73	−8.09	−62.077
2	1	1	1	1	2	0.25	0	50	46	0.224	2.77	1373.93	−8.85	−62.754
3	1	1	1	1	3	0.25	0	50	46	0.25	3.76	1485.73	−11.50	−63.435
4	1	2	2	2	1	0.25	1.5	90	57	0.2	2.86	1159.44	−9.12	−61.290
5	1	2	2	2	2	0.25	1.5	90	57	0.224	3.09	1262.64	−9.80	−62.029
6	1	2	2	2	3	0.25	1.5	90	57	0.25	4.07	1374.44	−12.19	−62.767
7	1	3	3	3	1	0.25	3	130	74	0.2	2.63	1156.29	−8.40	−61.267
8	1	3	3	3	2	0.25	3	130	74	0.224	2.86	1259.49	−9.12	−62.008
9	1	3	3	3	3	0.25	3	130	74	0.25	3.85	1371.29	−11.71	−62.748
10	2	1	2	3	1	0.3	0	90	74	0.2	2.63	1172.08	−8.40	−61.379
11	2	1	2	3	2	0.3	0	90	74	0.224	2.85	1275.28	−9.09	−62.111
12	2	1	2	3	3	0.3	0	90	74	0.25	3.84	1387.08	−11.68	−62.836
13	2	2	3	1	1	0.3	1.5	130	46	0.2	3.10	1093.16	−9.82	−60.773
14	2	2	3	1	2	0.3	1.5	130	46	0.224	3.33	1196.36	−10.45	−61.555
15	2	2	3	1	3	0.3	1.5	130	46	0.25	4.31	1308.16	−12.69	−62.333
16	2	3	1	2	1	0.3	3	50	57	0.2	2.54	1243.91	−8.09	−61.890
17	2	3	1	2	2	0.3	3	50	57	0.224	2.76	1347.11	−8.81	−62.588
18	2	3	1	2	3	0.3	3	50	57	0.25	3.75	1458.91	−11.48	−63.282
19	3	1	3	2	1	0.4	0	130	57	0.2	2.52	1181.97	−8.02	−61.453
20	3	1	3	2	2	0.4	0	130	57	0.224	2.75	1285.17	−8.78	−62.185
21	3	1	3	2	3	0.4	0	130	57	0.25	3.74	1396.97	−11.45	−62.898
22	3	2	1	3	1	0.4	1.5	50	74	0.2	2.45	1214.62	−7.78	−61.692
23	3	2	1	3	2	0.4	1.5	50	74	0.224	2.68	1317.82	−43.76	−62.399
24	3	2	1	3	3	0.4	1.5	50	74	0.25	3.67	1429.62	−11.30	−63.107
25	3	3	2	1	1	0.4	3	90	46	0.2	2.41	1248.82	−7.64	−61.932
26	3	3	2	1	2	0.4	3	90	46	0.224	2.63	1352.02	−8.40	−62.620
27	3	3	2	1	3	0.4	3	90	46	0.25	3.62	1463.82	−11.17	−63.311

It can be seen from the presented graphs that feed rate has the greatest influence on the roughness parameter R_a. The diameter of the nozzle D_n, distance between the impact point of the jet and the cutting edge d and pressure P have small influence. Cutting speed has insignificant influence on the roughness parameter R_a.

Optimal cutting conditions for roughness parameter R_a are shown in Table 3. The optimization of cutting parameters inside offered factors levels, with regard to criterion "smaller is better", gives the combination of control factors: A = 3, B = 3, C = 1, D = 3, E = 1. This combination enables the lowest roughness parameter R_a. A verification test has to be performed after optimal settings of control factors have been determined with the goal to approve the calculated value of the quality characteristic. Difference between the calculated and yielded value of roughness parameter R_a is very small.

The response graphic S/N of main cutting force has been shown for all five factors, Fig. 6. It can be seen from the presented graphs that feed rate has the greatest influence on the main cutting force. Pressure P has certain influence but distance between the impact point of the jet and the cutting edge d and the diameter of the nozzle D_n have less influence. Cutting speed has insignificant influence on the main cutting force.

Optimal cutting conditions for the main cutting force F_c are shown in Table 4. The optimization of cutting parameters inside offered factors levels, with regard to criterion "smaller is better", gives the combination of control factors: A = 2, B = 2, C = 3, D = 3, E = 1. This combination enables the lowest the main cutting force.

Analysis of Variance (ANOVA) can be useful for determining influence of any given input parameter from a series of experimental results by design of experiments for machining process and it can be used to interpret experimental data. The experimental results were analyzed with ANOVA, which is used for identifying the factors significantly affecting the performance measures are shown in Table 5. Percentage contribution of parameter is obtained by dividing the sum of squares for each parameter with total sum squares.

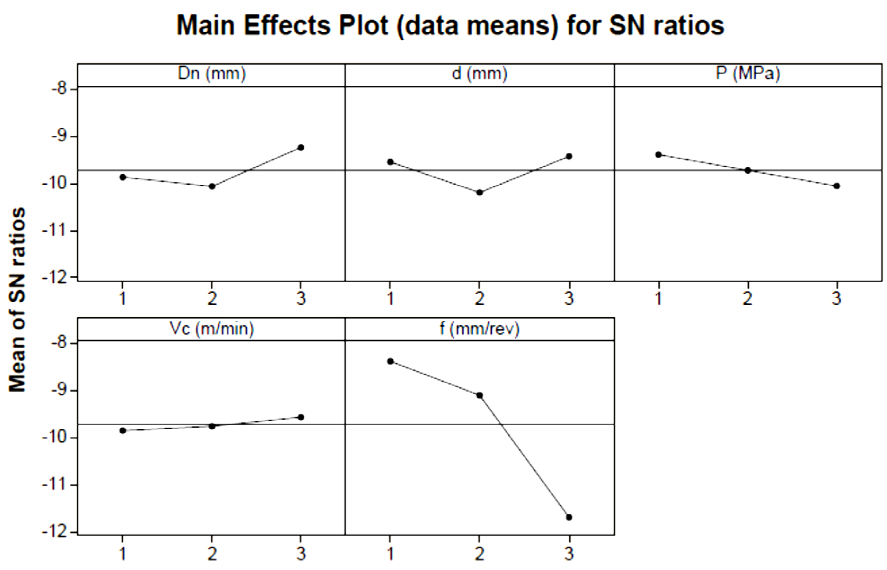

Fig. 5 S/N response graphs for surface roughness R_a

Table 3 Optimal settings of control parameters for R_a

Control parameters	Level	Setting		R_a obtained using Taguchi method	R_a obtained using verification test
D_n (mm)	3	0.4	Require add. experiment	S/N = −7.109	R_a = 2.45 µm
d (mm)	3	3.0			
P (MPa)	1	50		R_a = 2.267 µm	
V_c (m/min)	3	74			
f (mm/rev)	1	0.20			

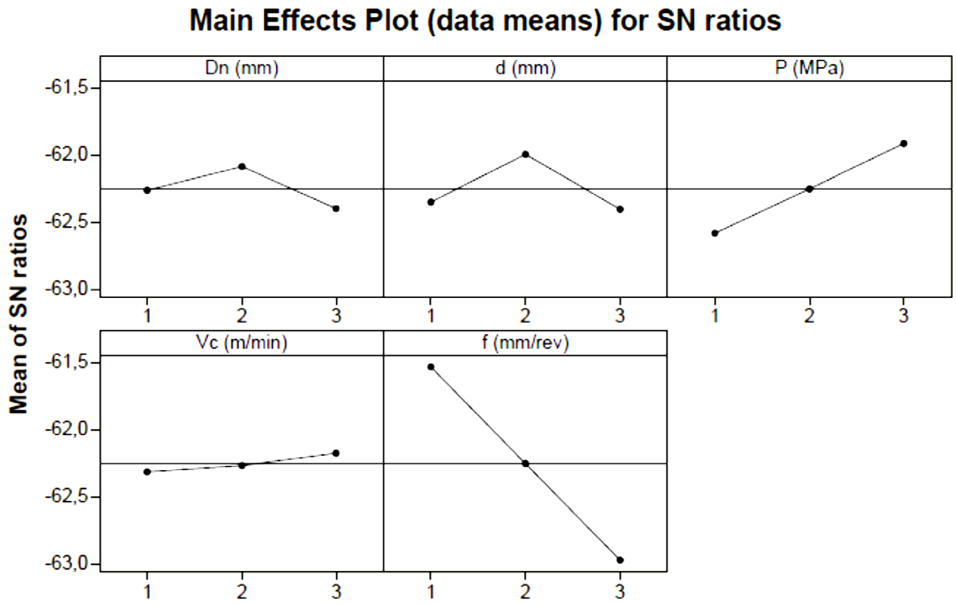

Fig. 6 S/N response graphs for the main cutting force F_c

Table 4 Optimal settings of control parameters for F_c

Control parameters	Level	Setting		F_c obtained using Taguchi method	F_c obtained using verification test
D_n (mm)	2	0.3	Require add. experiment	S/N = −60.697	F_c = 1099 N
d (mm)	2	1.5			
P (MPa)	3	130		F_c = 1083.55 N	
V_c (m/min)	3	74			
f (mm/rev)	1	0.20			

Table 5 ANOVA results for surface roughness R_a and the main cutting force F_c

Parameter	DOF	Sum of squares		Variance		F-ratio		Pure Sum		Percent %	
		R_a	F_c	R_a	F_c	R_a	F_c	R_a	F_c	R_a	F_c
D_n	2	3.345	0.443	1.672	0.221	126.87	1233.7	3.32	0.44	5.22	3.46
d	2	3.047	0.899	1.523	0.449	115.52	2500.8	3.02	0.90	4.75	7.01
P	2	1.992	2.008	0.996	1.004	75.53	5583.9	1.97	2.01	3.10	15.67
V_c	2	0.381	0.101	0.19	0.05	14.47	282.4	0.36	0.10	0.55	0.79
f	2	54.52	9.362	27.26	4.681	2067.05	26027.9	54.5	9.36	85.82	73.03
Other errors	16	0.21	0.002	0.013	0					0.56	0.04
Total		65.50	12.82							100	100

5. Conclusion

This paper has discussed dependence of the main cutting force F_c and roughness parameter R_a of the five high-pressure jet assistance turning (HPJA) parameters. Taguchi method has been used to determine the main effects, significant factors and optimum machining conditions to the value of the main cutting force F_c and roughness parameter R_a. From analysis using Taguchi's method, results indicate that among the all-significant parameters, feed rate is the most significant. Results obtained from Taguchi method closely match with ANOVA.

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