JOURNAL OF PRODUCTION ENGINEERING VOL. 27, NO. 1 (2024)
DOI: 10.24867/JPE-2024-01-001

Original research article

Journal of
Production Engineering

https://jpe.ftn.uns.ac.rs/index.php/jpe
ISSN: 1821-4932 (print), ISSN: 2956-2252 (online)

Optimizing main cutting force in high-pressure jet-assisted turning using Taguchi method

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ABSTRACT

In high pressure turning, the optimization of cutting forces is crucial to improve the efficiency and precision of machining. In this study, the Taguchi method is used to systematically investigate and optimize the input parameters that influence the cutting forces. By using an orthogonal array and analyzing the signal-to-noise ratio, the main factors affecting the cutting force are identified and their optimal values are determined. The effectiveness of the optimization is confirmed by validation tests, which show a significant improvement in cutting performance. The results provide actionable insights for machining and lead to better decision-making and process control in high-pressure turning. This research not only highlights the benefits of the Taguchi method in process optimization, but also contributes to advancing machining techniques by minimizing cutting forces and improving overall process stability.

ARTICLE INFO

Received: 1 February 2024
Revised: 5 April 2024
Accepted: 10 April 2024

KEYWORDS:
Pressure of the jet;
Cutting speed;
Feed;
Nozzle.

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1. INTRODUCTION

Superalloys, which are known for their remarkable strength properties, require significantly higher cutting forces during machining than conventional steel. These materials are known for their exceptional properties such as corrosion resistance, oxidation resistance, high toughness and strength. However, coping with these high cutting forces is still a challenge and often requires innovative machining techniques. High pressure jet turning (HPJAT) is a promising approach to improve the machinability of superalloys [1, 2].
Accurate prediction and optimization of cutting forces in the HPJAT process are crucial for dimensional accuracy, quality and cost efficiency of manufacturing. Cutting forces have a major impact on tool clamping, workpiece fixturing and the stability of machine components, which in turn affects machining accuracy [3].
In addition, optimized cutting forces contribute to greater safety during machining by reducing the likelihood of tool breakage and other accidents [4, 5]. Furthermore, a thorough understanding of cutting force dynamics allows manufacturers to tailor their machining processes to specific materials and applications, resulting in greater versatility and adaptability in production. Ultimately, by optimizing cutting forces, manufacturers can remain competitive in the marketplace by delivering the highest quality products while reducing production costs and increasing profitability [6].
Numerous studies have dealt with the optimization of cutting forces in turning by applying Taguchi optimization. The study by Gupta and Singh is characterized by a thorough investigation of the effects of blast pressure and other parameters on cutting forces, using Taguchi optimization to determine the optimal process parameters [7]. Chen and Wang also set out to optimize cutting forces in high-pressure turning of titanium alloys, using the Taguchi method to fine-tune parameters such as jet pressure, cutting speed and feed rate [8]. In addition, Rao and Reddy adopted a multi-objective approach, considering both cutting force and surface roughness as targets and using Taguchi optimization to determine the most effective combination of parameters [9]. In parallel, Li and Zhang proposed a mathematical model to predict the

Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.

cutting forces in high-pressure jet turning of nickel-based superalloys and applied Taguchi optimization to improve the overall machining performance [10]. Through these various efforts, significant progress continues to be made in optimization strategies and machining efficiency in the field of high-pressure turning.

In the study by Mozammel et al., predictive models were developed for various machining parameters in the turning of Ti-6Al-4V alloy using soft computing techniques such as artificial neural networks (ANN) and support vector machines (SVM) [6]. The models took into account input variables such as cutting speed, feed rate, cutting conditions and rotational forces to predict parameters such as average surface roughness and temperature at the chip-tool interface. The study highlights the importance of considering machining environment variables in predictive models to improve machining performance. In a separate study by Mirmohammadsadeghi, high-pressure jet turning was investigated as an effective method for reducing cutting forces and surface roughness when finishing AISI 304 stainless steel [11]. The study made it clear that the process parameters, especially the blasting pressure, need to be optimized in order to effectively achieve the desired machining improvements. In addition, Dahlman investigated the effects of high-pressure jet cooling pressure and flow rate on heat dissipation during turning operations [12]. The study showed the importance of the relationship between pressure and flow for optimal temperature reduction, especially for materials with different ductility. Nasr et al. experimentally investigated the effects of high-pressure jet machining (HPJAM) on tool wear mechanisms in the machining of nickel-based superalloys [3]. The study showed the importance of optimizing pressure and cutting parameters to improve tool life, material removal rates and control of tool wear mechanisms in the HPJAM process. These studies highlight the importance of optimizing machining parameters and considering environmental factors to improve machining performance and efficiency.

This study focuses on the optimization of the primary cutting force in high-pressure turning using the Taguchi method. Using Taguchi's L9 orthogonal arrangement, experimental investigations are conducted to analyze the main parameters affecting the HPJAT process of Inconel 718. The Taguchi method enables a systematic exploration of the parameter space and leads to the identification of optimal settings to minimize cutting forces. Statistical analyzes, including ANOVA and performance metrics such as mean absolute error, mean square error and coefficient of determination, are used to verify the effectiveness of the optimized parameters. The results confirm the utility of the Taguchi method to improve the machining performance of HPJAT by optimizing the cutting forces.

2. METHODOLOGY

The experiments were conducted on a conventional VDF Boehringer lathe, using a Hammelmann high-pressure plunger pump with a pressure of 150 MPa and a capacity of 8 liters per minute. A 5.5% aqueous emulsion cutting fluid based on vegetable oils, specifically Blaser Vasco 5000, was employed, excluding the addition of chlorine. The high-pressure jet was directed through a standard nozzle with a constant diameter of 0.4 mm, commonly used in water jet cutting applications. This nozzle was mounted on a specially designed clamping and positioning device, allowing for precise placement of the high-pressure jet, as illustrated in Fig. 1.

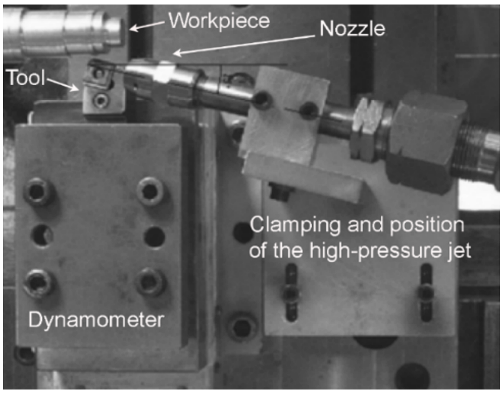

Fig. 1 *The HPJAT settings*

The tests were conducted using a PSBNR 2020K 12 tool holder fitted with SNMG 120408–23 carbide inserts, which were coated with TiAlN via PVD technology. Machining tests were carried out on a shaft with an approximate diameter of 145 mm and a length of 300 mm, made of Inconel 718 with a hardness of 36-38 HRc.

The cutting forces were measured with a three-component dynamometer (Kistler 9259A). After the high-pressure coolant was introduced, the measurement amplifier (Kistler 5001) was reset. The signal from the charge amplifier (NI DAQ 9172) was then transmitted via an acquisition card (NI9215) to the PC, where it was recorded and analyzed. Both the vector and the magnitude of the primary cutting force can be derived from the values of the three cutting force components of the dynamometer.

In this study, experiments are conducted using Taguchi's L9 orthogonal array to investigate the high-pressure jet-twisting method (HPJAT), Table 1.

Table 1 – *Taguchi L9 orthogonal array.*

No.	*d* [mm]	*P* [MPa]	v_c [m/min]	*f* [mm/rev]	F_c [N]	*S/N*
1	0	50	74	0.2	1375	-62.76
2	0	90	46	0.224	1450	-63.22
3	0	130	57	0.25	1320	-62.41
4	1.5	50	74	0.25	1250	-61.93
5	1.5	90	46	0.2	1275	-62.11
9	1.5	130	57	0.224	1275	-62.11
7	3	50	74	0.224	1187	-61.48
8	3	90	46	0.25	1160	-61.28
9	3	130	57	0.2	1450	-63.22

The study focused on investigating the influence of four independent variables — jet pressure (P), cutting speed (vc), feed rate (f), and distance between the point of impact of the jet and the cutting edge (d) — across three factor levels. We chose the orthogonal array L9 because it's particularly suitable for this purpose. We also assumed that there is no interaction between two factors. It's important to note that we applied the criterion "the smaller, the better" when evaluating the cutting forces.

3. RESULTS AND DISCUSSION

The test results and their conversion into signal-to-noise ratios are listed in Table 1. In this study, all analyzes performed using the Taguchi method were carried out using Minitab software. This facilitated the determination of the primary effects of the cutting parameters, enabled an analysis of variance (ANOVA) to be performed and helped to determine optimal conditions.
This table shows which control factors have a significant influence on the cutting force parameter Fc when turning with high pressure jet assistance (HPJA). The optimum cutting conditions for these factors can be easily read from the S/N curves.
Fig. 2 shows the response diagram of the cutting force parameter Fc for four factors. The optimum cutting force Fc can be recognized by the higher S/N values in the reaction diagrams. The influence of the parameters on the output process variable is shown by the angle of inclination of the line connecting the different parameter levels.

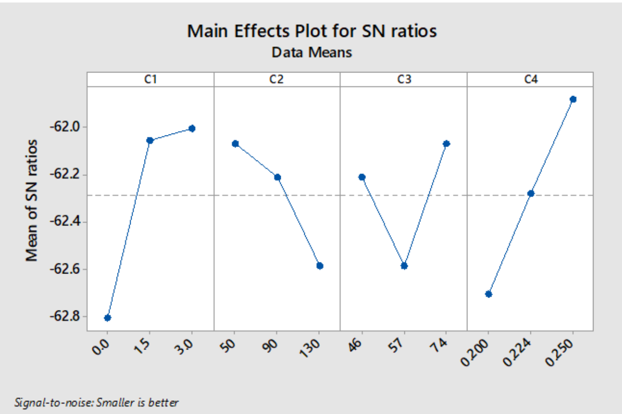

Fig. 2 *S/N response graphs for main cutting force: C1 - distance between the point of impact of the jet and the cutting edge; C2 - jet pressure (P), C3 - cutting speed (vc), C4 - feed rate (f).*

The diagrams show that the feed rate has the greatest influence on the main cutting force. The feed rate, which is crucial for advancing the cutting tool into the workpiece material, significantly determines the main cutting force due to several key factors.
Firstly, it has a direct influence on the material removal rate, as higher feed rates accelerate material removal and therefore increase the cutting force required. In addition, higher feed rates generally lead to larger contact surfaces between the tool and the workpiece, which increases resistance and increases the cutting forces. Higher feed rates also accelerate tool wear due to increased friction and heat generation, so more force is required to maintain cutting performance.
The distance between the point of impact of the jet and the cutting edge also has a major influence and takes second place. If the distance between the point of impact of the jet and the cutting edge is minimal, which indicates proximity to the machining zone, this will result in clogging of the jet. This is because the nozzle loses energy through repulsion in the immediate vicinity of the workpiece. Parameters such as the jet pressure (P) and the cutting speed (v_c) also have an effect on the main cutting force. Optimal cutting conditions for the main cutting force can be determined by analyzing combinations of control factors within the offered stages.
The response table (Table 2) for Signal-to-Noise (S/N) ratios serves as a valuable asset in Taguchi experimental design. It aids in pinpointing the optimal control factor settings that mitigate the variability induced by noise factors. Additionally, it offers a ranking of the influence of individual parameters, providing comprehensive insights into how various factor levels affect the response characteristics.

Table 2 – *Signal to Noise Ratios "Smaller is better".*

Level	C1	C2	C3	C4
1	-62.80	-62.06	-62.21	-62.70
2	-62.05	-62.21	-62.58	-62.28
3	-62.00	-62.58	-62.06	-61.88
Rank	2	3	4	1

Optimal cutting conditions for the cutting force parameter are outlined in Table 2. The process of optimizing cutting parameters within the designated factor levels, guided by the criterion " ", results in the combination of control factors: C1 = 3, C2 = 1, C3 = 3, C4 = 3. Subsequent to establishing the optimal settings for control factors, conducting a verification test is essential to validate the accuracy of the calculated value of the quality characteristic.
This analysis makes it possible to achieve the lowest cutting force parameter values. The difference between the calculated and determined values of the cutting force parameter is very small. Analysis of variance (ANOVA) can be useful to determine the influence of a particular input parameter from a set of experimental results obtained using the experimental design for the machining process and can be used to interpret experimental data. ANOVA is used to determine the factors that have a significant effect on the performance measures and is shown in Table 3.

Table 3 – *ANOVA results*

Source	DF	Adj SS	Adj MS	F-Value
C1	2	26682	13341	0.95
C2	2	9469	4734	0.34
C4	2	22819	11409	0.82
Error	2	27979	13989	
Total	8			

The percentage contribution of each parameter is determined by dividing the sum of squares for each parameter by the total sum of squares. C1, C2, and C4 represent distinct factors or treatments. A crucial parameter, the P-value, indicates the statistical significance of the F-value. Parameter C3 has been excluded from the analysis as it statistically insignificantly influences the cutting force.

4. CONCLUSIONS

The critical influence of the main cutting force by the feed rate in machining processes is underscored by our findings. A pivotal role is played by the feed rate in determining the material removal rate, contact surface area, and tool wear, thus significantly impacting cutting force dynamics. Additionally, variations in cutting force are also contributed to by factors such as the distance between the jet impact point and cutting edge, jet pressure, and cutting speed. By the optimization of control factors and the utilization of tools such as the response table for Signal-to-Noise ratios, the mitigation of variability induced by noise factors and the determination of optimal cutting conditions can be effectively achieved. The importance of conducting verification tests to validate the accuracy of calculated quality characteristics is highlighted, ultimately enabling the attainment of minimal cutting force parameter values. Furthermore, the interpretation of experimental data and the identification of factors with significant effects on performance measures are facilitated by techniques like ANOVA. Through meticulous analysis and optimization, machining efficiency and quality can be enhanced, while production costs are reduced, and statistical rigor is maintained in experimental design.

ACKNOWLEDGMENT

This research has been supported by the Ministry of Science, Technological Development and Innovation (Contract No. 451-03-65/2024-03/200156) and the Faculty of Technical Sciences, University of Novi Sad through project "Scientific and Artistic Research Work of Researchers in Teaching and Associate Positions at the Faculty of Technical Sciences, University of Novi Sad" (No. 01-3394/1).

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