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Taguchi DOE Analysis of Surface Integrity for High Pressure Jet Assisted Machining of Inconel 718

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Abstract

This paper presents the results of Taguchi DOE (Design of Experiment) investigation to determine the effects of High pressure jet assisted coolant on surface integrity in machining of Inconel 718 aerospace superalloys. Designed experiments were performed under conventional (0.6 MPa) and High pressure jet assisted cooling (15 MPa and 30 MPa) conditions using (Ti,Al)N+TiN coated carbide cutting tool. L_9 (3^4) Taguchi experimental techniques were used in the analyzing of the machined surface and subsurface: surface roughness measuring device for surface roughness, and X-ray diffraction (XRD) technique was used to determine residual stresses and phase changes induced by conventional and High pressure jet assisted machining coolant. The results show the benefits and the future potential of High pressure jet assisted cooling for surface integrity enhancement to achieve improved product's functional performance in superalloys machining.

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1. Introduction

Nickel based super alloy Inconel 718 is widely employed in the aerospace industry, in particular in the hot sections of gas turbine engines; this is due to their high temperature strength and high corrosion resistance. They are known as being among the most difficult-to-cut materials. In machining difficult-to-cut materials, the consumption of cooling fluids remains very important [1]. In order to improve machining productivity of nickel alloys and some other materials, some cooling techniques have been recently developed, which improve surface integrity, tool life and provide better dimensional accuracy of the produced parts to [2]. High pressure jet assisted cooling (HPJAC) is one of the main methods that aims to increase machinability of Inconel alloys by using high pressure jet water or emulsion injected into the cutting zone [3], [4]. Some studies have shown that the application of a high-pressure water jet to the tool-chip interface provides control of the chip shapes and better chip breakability, reduces temperatures in the cutting zone and improves chip removal, resulting in prolonged tool life (5-15

times) while machining nickel alloys [5]. It also High pressure jet assisted machining 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 [6]. Surface roughness, hardness, residual stresses, etc., characteristics are considered as surface integrity factors, determining functionality and fatigue life of the final product. As the surface integrity is one of the most relevant performance characteristic of the final product machined surface quality, particularly when critical structure components are machined, numerous studies have been conducted to determine the correlation between the machining conditions and residual stresses [7].

Residual stress is one of the most relevant practical parameters used for evaluating the quality of the machined surface, particularly when critical structural components are produced; with the objective to reach the higher reliability levels [8]. This is the case for the components made from Inconel alloys, largely used in aerospace industries. Residual stresses are an effect from both heat generated and mechanical work going into the surface and

subsurface [1]. The turning of Inconel 718 were performed, in three cooling pressures condition, using various cutting speeds and a (Ti, Al) N+TiN coated carbide tool. Residual stresses were measured using an X-ray diffraction technique from the surface to 150 microns depth. Finally, machining conditions used play a key role in deciding the surface quality. In view of this, statistically designed experiments were performed using Taguchi method with residual stress as response. Therefore, this paper presents a study of the influence of high pressure jet assisted machining process on surface integrity measures, aimed to evaluate the effect of varying cooling pressures conditions on the residual stress distribution in the machined layer on Inconel 718. Additionally, investigated Taguchi based optimization of high pressure jet assisted machinability of Inconel 718.

2. Experimental Procedures

The geometrical dimensions of the samples are shown in Fig. 1. All the experiments were carried out using the Inconel 718 alloy supplied as bars (65 mm diameter and 300 mm long). The standart chemical composition is 50-55% Ni, 17-21% Cr, 18% Fe, 1% Co, 2.8-3.3% Mo, 0.3-0.7% Al, 0.08% C, 0.35% Si, 4.8-5.5% Nb-Ta, 0.7-1.15%Ti. The mechanical properties of Inconel 718 are: tensile strength 1310 MPa, yield strength 1110 MPa, density 8.19 g/cm³ hardness 36-38 HRC. [3].

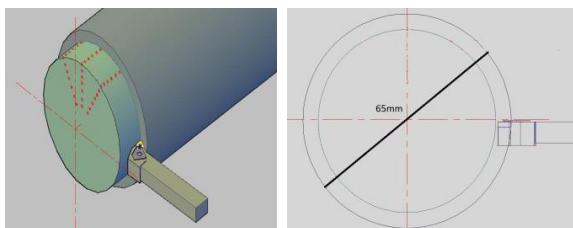


Fig. 1. The workpiece geometrical dimensions.

The experiments were conducted on ALEX ANL-75 CNC lathe machine that is equipped with variable spindle speed from 50 to 4000 rpm and a 15 kW motor drive that is equipped with the high-pressure plunger pump of maximum 35 MPa pressure and 21 l/min volumetric flow rate capacity. The cooling/ lubrication fluid (CLF) used in the experiments was the chemical-based 5% concentration water soluble oil (Swisslube Blaser BCool 650). The high pressure CLF was injected between the cutting tool and formed chip back surface, at a low angle (about 5 to 6° with the cutting tool rake angle. A schematic diagram of the High pressure jet assisted turning operation is shown in Fig. 2. [9].

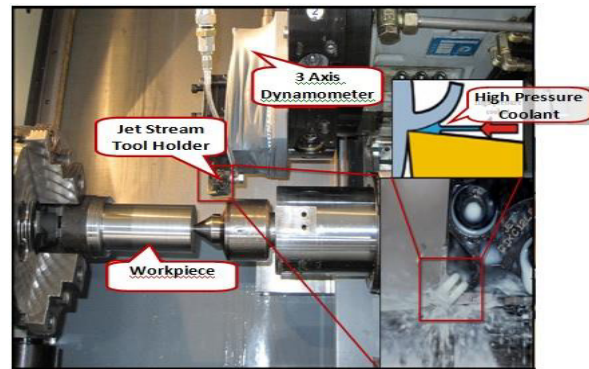


Fig. 2. Experimental set-up of the High pressure jet assisted

A (Ti,Al)N+TiN coated carbide cutting tool has been chosen for the experiments. The tool has $r_n = 0.8$ mm nose radius. It was mounted on a SECO Jet stream PCLNR tool holder, which results in cutting rake angle, $\gamma_a = -6^\circ$, back rake angle, $\gamma_b = -6^\circ$, approach angle, $K_r = 95^\circ$, and $d = 0.8$ mm nozzle diameter is shown in Fig. 3. Before each cutting experiment, a sharp insert was installed in order to eliminate the effect of creation texture.



Fig. 3. Coated carbide cutting tool and Jet stream PCLNR tool holder.

3. The machining of Inconel 718 experiment based on Taguchi method

Design of experiment (DoE) involves identifying the input factors and their levels, response variable, selection of work material, tooling, experimental setup and procedure used to analyze the experimental data. Design of experiment is a specially designed experimental method developed for evaluating the effects of process parameters on performance characteristics. It determines the process parameter conditions for optimum response variables. Application of robust design of experiment requires careful planning, accurate layout of the experiment, and analysis of results [1]. During experimentation, a large number of experiments have to be carried out as the number of machining parameters increases [10]. Taguchi's design of experiments involves proper selection of an orthogonal array to accommodate input variables (control factors) and their interactions. The use of statistically derived orthogonal arrays for

planning the experiments drastically reduces the number of experimental runs to be carried out without affecting the quality of the analysis [11].

The process parameters selected for the present investigation were cutting speed, feed rate, and jet cooling pressures. They were varied as V_c (50-70-90 m/min); f (0.1 - 0.15 - 0.2 mm/rev); P (0.6-15-30 MPa) and a constant depth of cut; 2 mm. The output response variable considered as the average residual stress. The experiments were planned using $L_9 (3^4)$ Taguchi's design of experiment. Nine experiments were performed to study the effects of three input variables on the response variable (residual stress) Table 1.

Table 1. Cutting parameters and their levels adopted in the experiments.

Symbol	Cutting parameters	Level 1	Level 2	Level 3
V_c (m/min)	Cutting speed	50	70	90
f (mm/rev)	Feed rate	0.1	0.15	0.2
P (MPa)	Cooling pressure	0.6	15	30

In this study, we adopt the Taguchi method, which was used by [12] to set turning parameters for each experiment and also for data analysis. An orthogonal array was employed to investigate the entire parameter space using a small number of experiments. The measured average stress for each test run was transformed into K_{ij} and R_i . K_{ij} , Eq. (1), is the average residual stresses for a specific level, j , of turning parameter, i . In this work, K_{ij} is evaluated as smaller-is-better to achieve the desired compressive residual stress. The optimum level of the process parameters is that with the lowest K_{ij} . R_i , Eq. (2) reveals the order of importance of cutting speed, feed rate, and cooling pressure on the residual stresses. Therefore, the optimal combination of turning parameters and their ranking effect on residual stress can be predicted by analysis of K_{ij} and R_i . [13].

$$K_{ij} = \frac{\sum R_a(k)}{3} \quad (1)$$

$$R_i = \max(K_{i1}, K_{i2}, K_{i3}) - \min(K_{i1}, K_{i2}, K_{i3}) \quad (2)$$

where $i = 1$ denotes cutting speed (V_c), $i = 2$ denotes feed rate (f), and $i = 3$ denotes cooling pressure (P), respectively; $j = 1, 2, 3$, denotes Levels 1, 2 and 3 respectively corresponding to the turning parameter setting; $k = 1, 2, \dots, 9$, is the experiment number; $R_a(k)$ denotes the average residual stresses over depth for the machined component in experiment k .

The feasible space for the cutting parameters was defined to be varying cutting speed in the range of 50-90 m/min, the cooling pressure in the range of 0.6-30 MPa, and the feed rate in the range of 0.1-0.2 mm/rev. A Taguchi orthogonal array, $L_9 (3^4)$, of turning parameters was adopted in this experiment. To cover the feasible space of cutting parameters, three levels for each turning parameter were selected, Table 2. The experimental layout for these three levels of turning parameters using the $L_9 (3^4)$ orthogonal array and experiment results are given in Table 3. [12].

Table 3. K_{ij} and R_i response table for average residual stress in the circumferential direction.

Symbol	Cutting parameters	K_{ij}			R_i
		Level 1	Level 2	Level 3	
V_c (m/min)	Cutting speed	-160	-245	-340	180
f (mm/rev)	Feed rate	-177.6	-197.3	-370	192.4
P (MPa)	Cooling pressure	-222.6	-242.3	-280	57.4

it can be concluded $R_{i_{circum.}} = R_2 > R_1 > R_3$ (3)

Table 4. K_{ij} and R_i response table for average residual stress in the radial direction.

Symbol	Cutting parameters	K_{ij}			R_i
		Level 1	Level 2	Level 3	
V_c (m/min)	Cutting speed	-233	-249	-142	107
f (mm/rev)	Feed rate	-170.3	-191.3	-262.3	92
P (MPa)	Cooling pressure	-178	-183	-263	85

it can be concluded $R_{i_{radial}} = R_1 > R_2 > R_3$ (4)

The average residual stress, R_a , for the ten locations along the depth was calculated both for the radial and for the circumferential direction, as shown in Table 2. This average residual stress was used as the experimental response to determine turning parameter effect on residual stresses [13].

Table 2. Cutting parameters and experiment results.

Exp. No.	Vc Cutting speed (m.min ⁻¹)	f Feed rate (mm rev ⁻¹)	P Cooling pressure (MPa)	$R_{aCIRCUM}$ Average circumferential residual stress (MPa)	$R_{aRADIAL}$ Average radial residual stress (MPa)
1	50	0.1	0.6	-94	-214
2	50	0.15	15	-107	-177
3	50	0.2	30	-279	-308
4	70	0.2	0.6	-345	-259
5	70	0.1	15	-134	-152
6	70	0.15	30	-256	-336
7	90	0.15	0.6	-229	-61
8	90	0.2	15	-486	-220
9	90	0.1	30	-305	-145

4. Residual stress measurement and analysis

Several experimental methods are available for determining residual stress which are classified as indirect methods and direct methods [14]. A widely accepted indirect method for practical application is the deflection method. The direct methods for residual stress analysis include X-ray and neutron diffraction, strain/curvature measurements, hole-drilling, layer removal, optical fluorescence, chemical etching, and others. Among these methods, the X-ray method is widely applied to superalloys turned components. Residual stress below the surface can also be measured using the X-ray method. Chemical etching is a common technique for material layer removal to acquire the residual stresses resulting from the high pressure jet assisted turning process. It has investigated the advances in residual stresses measurement methods by turning [15].

For this experiment, the residual stress measurements were done by means of X-ray diffraction. The $\sin^2\psi$ method used here was detailed by [15]. Two readings were taken for each layer of each specimen, both in the radial and the circumferential direction. Layers of approximately 15 μm were removed using electropolishing with a solution of phosphoric and sulphuric acid. Layers were removed until a depth of 15 μm under the machined subsurface was achieved. A majority of the experiments have a tendency to tensile residual stresses when the depth exceeds 150 μm . This observation lead to the conclusion that the residual stress distribution could be characterized by averaging stress over depth. The residual stress profiles for the nine experiments are shown in Figs. 4–6. In these three graphics, in a fixed cutting speed, the pressure effects of three different cooling pressures have been studied.

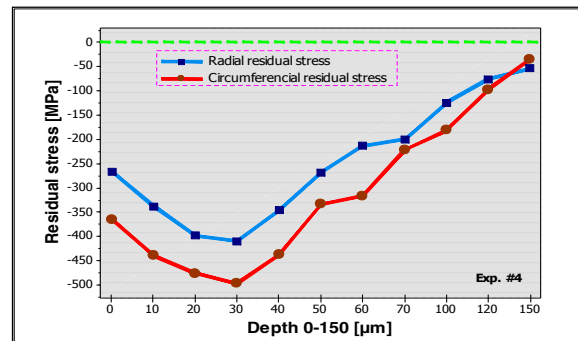


Fig. 4. The residual stress distribution of specimen in experiment #4 along subsurface depth.

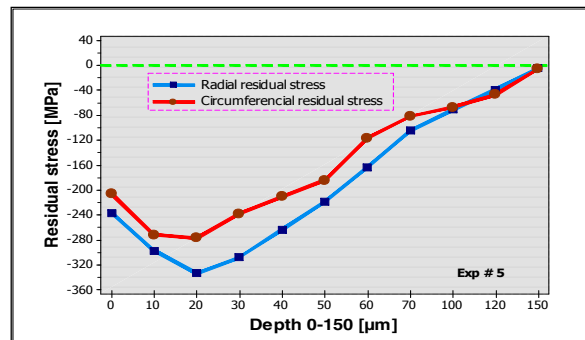


Fig. 5. The residual stress distribution of specimen in experiment #5 along subsurface depth.

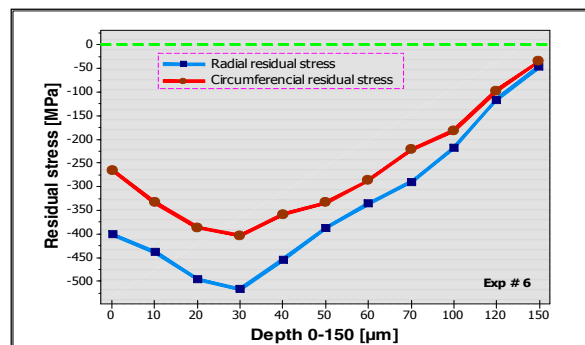


Fig. 6. The residual stress distribution of specimen in experiment #6 along subsurface depth.

5. Experiment analysis and validation

The results for average residual stresses, K_{ij} for both radial and the circumferential direction are shown in Tables 3 and 4, respectively.

$$K_{11} = (-94 - 107 - 279) / 3$$

$$K_{12} = (-345 - 134 - 256) / 3$$

$$K_{13} = (-229 - 486 - 305) / 3$$

$$\dots$$

$$K_{33} = (-279 - 256 - 305) / 3$$

Based on the Taguchi method, the optimal levels for turning parameters for radial and for circumferential compressive residual stress were determined as (50 m/min, 0.6 MPa, 0.1 mm/rev) and (90 m/min, 0.6 MPa and 0.15 mm/rev), respectively, using the smaller-is-better principle for K_{ij} . This result indicates that optimal cutting speed is common for circumferential compressive residual stress. But feed rate is effect on radial residual stress. R_i is used to determine the ranking of process parameters effect on the residual stresses. The R_i values shown in Tables 3 and 4 suggest that feed rate has the more effect on the residual stresses for circumferential directions. For radial residual stress, cutting speed more effect on the residual stress. It also feed rate is the second most influential factor, and finally cooling pressure. However, for circumferential residual stress, cutting speed is the second most influential factor and cooling pressure the last.

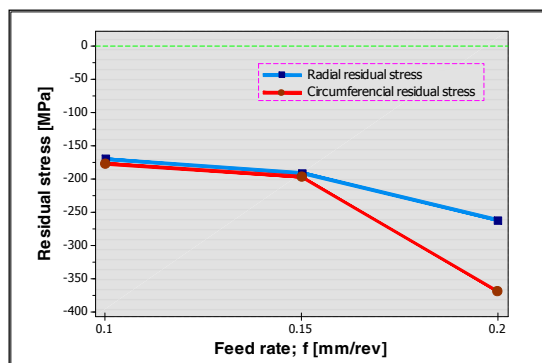


Fig. 7. K_{ij} value for each level of feed rate.

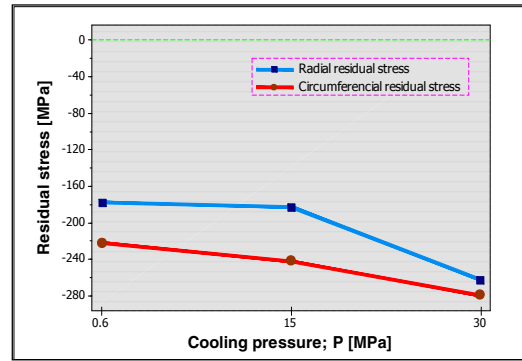


Fig. 8. K_{ij} value for each level of cooling pressure

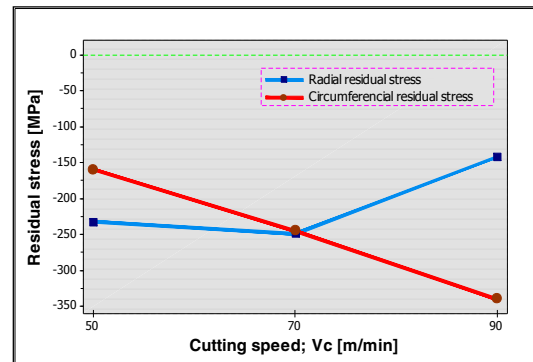


Fig. 9. K_{ij} value for each level of cutting speed

6. Conclusion

From this analysis, we conclude that the turning parameters bear different effect on residual stress for the radial and the circumferential directions. By plotting the K_{ij} values for each level of each parameter, Figs. 7–9, we can better visualize the experiment results. Feed rate of the lowest average stress occurs at level 3 for both radial and circumferential directions. Also feed rate level 1 is the maximum average stresses for both directions. Similarly, cooling pressure of the lowest average stress occurs at level 3. And the maximum average stresses at level 1 for both directions. However, cutting speed for the minimum average stress occurs at level 3 for circumferential direction and level 2 for the radial direction.

The residual stress distribution in a high pressure jet assisted machined Nickel alloys component has been experimentally investigated, and related to three turning parameters using the Taguchi method. The optimal turning parameter combination has been selected by evaluating the residual stress profile. The experiments show that;

- The overall effect for cooling pressure on both direction average stresses, R_3 , is very small and the average stress is only slightly larger at level 1 than at level 2 for radial and circumferential direction. Thus we can choose cooling pressure level 1 as a reasonable compromising for the optimal levels.
- For the average residual stress along the subsurface for radial direction, the feed rate has the most significant impact, followed by cutting speed, and finally cooling pressure. The optimal combination of feed rate, cutting speed and cooling pressure was found to be 0.2 mm/rev, 70 m/min, 30 MPa.
- In figure 4, residual stress under 0.6 MPa cooling pressure, has been measured as higher than 15 MPa cooling pressure.
- In the distance of 150 μ m depth from the surface in both directions the values of the residual stress have been figured 4-6. It is seen in figure 5 and 6, that cooling pressure is more effective in circumferential direction than in radial direction.

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References

- [1] Le Coz, G., Marinescu, M., Moufki, A., Dudzinski, D., 2010. "Residual Stresses After Dry Machining of Inconel 718, Experimental Results and Numerical Simulation."
- [2] Vishal S. Sharma a*, Manu Dogra b, N.M. Suri, C., 2009. "Cooling Techniques for Improved Productivity in Turning." 49(6), p 435–453.
- [3] Kramar, D., Sekulić, M., Jurković, Z., Kopač, J., 2013. "The Machinability of Nickel-Based Alloys in High-Pressure Jet Assisted (HPJA) Turning" Journal for Theory and Practice in Metallurgy. 52(4), p. 512-51.
- [4] Kıran, K., Çolak, O., 2013. "Optimization of Machining Performance in High Pressure Assisted Turning of Ti6Al4V Alloy" Journal of Mechanical Engineering.
- [5] Çolak O. (2012). "Investigation on Machining Performance of Inconel 718 under High Pressure Cooling Conditions." Strojniški vestnik - Journal of Mechanical Engineering, vol. 58, no.11, 683-690.
- [6] Sekulić, M., Kopač, J., Gostimirovic, M., Kramar, D., 2013. "Optimization of High-Pressure Jet Assisted Turning Process by Taguchi Method" Advances in Production Engineering and Management 8, p. 5-12.
- [7] Pusavec, F., Hamdi, H., Kopač, J., Jawahir, I. S., 2011. "Surface Integrity in Cryogenic Machining of Nickel Based Alloy-Inconel 718." Journal of Materials Processing Technology. 211, p. 773–783.
- [8] Mohd Hadzley, A B., Izamshah, R., Sarah, A. Siti. And Fatin, Nurul, M., 2013. "Finite Element Model of Machining with High Pressure Coolant for Ti-6Al-4V Alloy". Malaysian Technical Universities Conference on Engineering & Technology MUCET 2012. 53 p. 624-631.
- [9] Yünlü, L., Çolak, O., Kurbanoglu, C., 2013. "Chip Formation Analysis of High Pressure Jet Assisted Machining of Ti-6Al-4V" International Conference on Sustainable Life in Manufacturing, SLIM2013, 22nd – 24th September Slovenia.
- [10] Toprak, İ. B., Çağlar, M. F., Çolak, O., Kıran, K., Bayhan, M., 2012. "Optimization of Surface Roughness by Using Taguchi Method in Milling of Ti-6Al-4V Super- Alloy at High-Pressure Cooling Conditions". SDU International Technologic Science, Mechanical Technology, Vol. 4, No 2, p. 30-39.
- [11] Jadhav, P.V., Mankar, D.S., 2010. "Effect of Surface Roughness on Fatigue Life of Machined Component of Inconel 718" International Conference on Effect of Surface.
- [12] Yang, W.H., Tarng, Y.S., 1998. "Design optimization of cutting parameters for turning operations based on the Taguchi method." J. Mater. Process. Technol. 84, p. 122–129.
- [13] Xueping, Z., Erwei, G., Liu, C. R., 2009. "Optimization of Process Parameter of Residual Stresses for Hard Turned Surfaces" Journal of Materials Processing Technology 209, p. 4286–4291.
- [14] Brinksmeier, E., Hannnover, J.T., König, W., et al., 1982. "Residual Stresses Measurement and Causes in Machining Processes." Ann. CIRP 31, 491–510.
- [15] Zhang, X. P., Liu, C.R., Yao, Z. Q., 2004. "Investigational advances in residual stresses by hard turning." Master Science Forum Adv. Mater. Manufacturing Science Technology 471(472), 523–527.