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Investigation on Machining Performance of Inconel 718 under High Pressure Cooling Conditions

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The paper deals with experimental investigation on machinability of Inconel 718 in conventional and alternative high pressure cooling conditions. The experiments are designed according to Taguchi L18 orthogonal array based on three levels of cutting speed, feed rate and fluid pressure and two levels of depth of cut. The cutting forces and tool flank wear were measured, while turning Inconel 718 workpieces, using (Ti, Al)N+TiN coated CNMG0812 carbide cutting tools. In order to determine the importance of cutting parameters on tool flank wear and cutting forces, ANOVA (Analysis of variance) was employed. Moreover, with multi regression analysis, empirical equations that indicate relation between tool flank wear and cutting forces with machining parameters were defined. The experiment results have proven that the tool flank wear and cutting forces considerably decrease with the delivery of high pressure coolant to the cutting zone. Moreover, ANOVA results also indicate that high pressure cooling has a significant beneficial effect on cutting tool life.
Keywords: High pressure assisted machining, ANOVA, Taguchi

0 INTRODUCTION

Nickel-based alloys are the most widely used superalloys, accounting for about 50 wt.% of materials used in an aerospace engines, mainly in the gas turbine compartment (combustion part of the jet engine). They provide higher strength to weight ratio compared to steels. The use of nickel-based alloys in such aggressive environments hinges on the face that it maintains high resistance to corrosion, mechanical and thermal fatigue, mechanical and thermal shock, creep and erosion, at elevated temperatures [1] and [2].

Contrary to those superb properties, machining of nickel-based alloys generate high temperatures at the cutting tool edge, impairing their performance as they are subjected to high compressive stresses acting on the tool tip. This leads to the plastic deformation of the tool edge, severe notching and flank wear [3] to [5]. The poor thermal conductivity of nickel-based alloys, raises temperature at the tool–workpiece interface during machining, thus, it accelerates the undesired tool wear and results in the shortening of cutting tool life [6] and [7].

In order to keep increasing the machining performance, different assistance methods have been recently developed to replace the "conventional process" [8] and [9]. One of them presents high-pressure jet assistance (HPJA), which aims at upgrading conventional machining, using the thermal and mechanical properties of a high-pressure jet of water or emulsion directed into the cutting zone [10] to [12].

By applying a high-pressure fluid jet to the cutting zone, it is possible to achieve advantages such as significantly decreased temperature in the cutting zone, prolonged tool life (5 to 15 times), lower forces due to better frictional conditions between the tool face and the chip, and lower levels of vibration [12] to [14]. These results have also shown improved surface integrity and better dimensional accuracy of the produced parts [15] and [16]. HPJA also decreases the contact length between the chip and rake face [10]. The shorter contact length and lower friction force cause a larger shear plane angle, and thus reduce the chip-compression factor [17].

Currently, a major problem associated with conventional machining of super-alloys is the accelerated tool wear, resulting from generated high-temperature in the cutting zone. The use of high-pressure jet-assisted cooling technology during the machining of super-alloys, provides temperature reduction at the cutting zone. This can be understood as a consequence of improved access of coolant closer to the cutting tool edge. This can significantly improve the tool life due to lower tool wear rates. Additionally, cutting speeds can be increased for up to 50% with the added advantage of effective chip breakability [1], [6] and [10].

Courbon et al. [10] studied machining performance of Inconel 718 under high pressure jet cooling conditions. They used coolant pressure in the range 50 to 130 MPa and three nozzle diameters (0.25, 0.3 and 0.4 mm). The experiments were conducted by using PVD TiAlN-coated carbide tools at various cutting speeds and feed rates, and at constant depth of cut (a_p = 2 mm). They found that high pressure jet cooling provides better chip breakability and lower cutting forces. It can also improve surface finish and

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productivity for optimal pressure/ nozzle diameter/ cutting speed combination.

Palanisamy et al. [18] investigated the effect of coolant pressure on chip formation and tool life, while turning Ti6Al4V alloy with uncoated straight tungsten carbide inserts. The investigation showed that the application of high pressure coolant directly between the chip back face and the tool results generally in smaller chips and average chip thickness compared to conventional pressure (0.6 MPa). They also found that the application of high pressure coolant prolongs tool life by nearly three times.

This study mainly focuses on the evaluation of the cutting tool wear and wear characteristics, cutting force components and chip shape, while machining Inconel 718 under the high pressure and conventional cooling conditions. Therefore, a number of machining tests with Inconel 718 were conducted in conventional and various high pressure levels of cooling/lubrication fluid. The experiments were designed according to the plan of experiments methodologies and Taguchi L18 orthogonal array [19], at three different cutting speed (V_c), feed rate (f) and pressure (p) levels, and two different depth of cut (a_p) levels. Experimental results, namely cutting forces (F_c, F_r, F_f) and the average tool flank wear (V_b) were analyzed by using ANOVA and regression analysis. As a result of ANOVA, the effects of test parameters (V_c, f, p, a_p) on average tool flank wear and cutting forces were statistically determined. Finally, multi regression equations that indicate the relation between cutting forces, tool flank wear and test parameters were obtained and used as a model for the HPJA machining process.

1 EXPREMENTAL PROCEDURE

1.1 Design of Experiments

The experiments designed based on Taguchi L18 orthogonal array at three different cutting speed, feed rate and pressure levels and two different depth of cuts are performed, while each one has been performed with a new cutting edge for the ease of direct comparability of results. Cutting parameters and their levels are shown in Table 1.

Table 1. *The levels of machining parameters*

Level	I	II	III
V_c [m/min]	50	70	90
f [mm/rev]	0.05	0.10	0.15
p [MPa]	Conv. (0.6)	10	30
a_p [mm]	0.5	1	-

1.2 Experimental Set-Up and Equipment

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 (Fig. 1). 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), as is shown in Fig. 1.

A (Ti,Al)N+TiN coated carbide cutting tool CNMG0812 has been chosen for the experiments. The tool has r_ε = 0.8 mm nose radius. It was mounted on a SECO Jet stream PCLNR tool holder, which results in cutting rake angle, γ_a =-6°, back rake angle, γ_b = –6°, approach angle, K_r = 95°, and d = 0.8 mm nozzle diameter. All experiments were performed on machining nickel-based alloy Inconel 718 bar (63.5 mm diameter and 300 mm long). The standard chemical composition and mechanical properties of the workpiece are given in Tables 2 and 3, respectively [6]. The volume of totally removed material during each individual experiment was set to V = 57650.4 mm^3 (according to the machining parameters and workpiece diameter, the cutting length was defined), and was kept constant for the sake of consistent tool wear comparison. In this way the wear can be directly related to the volume of cut material.

2 RESULTS AND DISCUSSIONS

2.1 Cutting Forces

The results of experiments (cutting force components and average flank wear) are shown in Table 4. The influences of pressure and feed rate on cutting forces are illustrated in Figs. 2 to 4. The cutting forces generally increase with an increase in feed rate as expected. It can be also noticed that all the cutting force components decrease significantly with an increase in fluid pressure. This can be explained by the mechanical effect of the jet, which tends to lift up the chip, away from the tool rake face and reduces the contact area that is consistent with reference [10]. This has also been reported in [6], where a reduction in cutting forces when machining with assistance of high coolant pressure relates to the fact that high-pressure coolant is able to penetrate deeper into the cutting interface, thus, providing more efficient cooling as

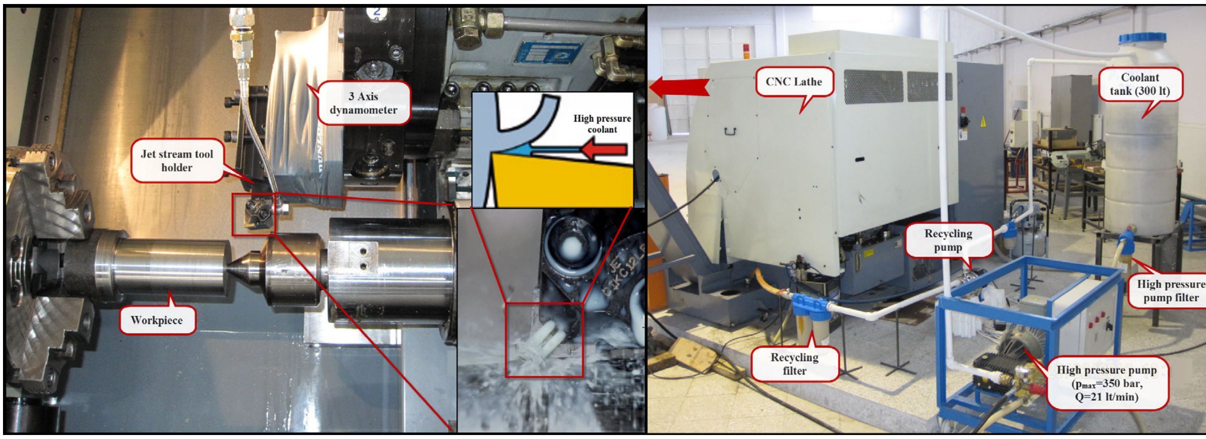


Fig. 1. *Experimental set-up, with the detailed view of high-pressure injection system*

Table 2. *Chemical composition of Inconel 718 (wt.%)*

C	Mn	Si	S	Cr	Fe	Mo	Nb&Ta	Ti	Al	Cu	Ni
0.08	0.35	0.35	0.15	18.6	17.8	3.1	5.0	0.9	0.5	0.3	balance

Table 3. *Mechanical properties of Inconel 718*

Tensile strength [MPa]	Yield strength [MPa]	Elastic modulus [GPa]	Hardness [HV150]	Density [g/cm³]	Melting point [°C]	Thermal conductivity [W/(mK)]
1310	1110	206	370	8.19	1300	11.2

Table 4. *The experiment results*

No	a_p [mm]	V_c [m/min]	f [mm/rev]	p [MPa]	F_c [N]	F_f [N]	F_r [N]	V_b [μm]
1	0.5	90	0.15	0.6	305.3	137.9	162.2	145
2	0.5	50	0.05	0.6	215	113.6	141	158.14
3	1	70	0.15	0.6	520.6	287.2	181	157.32
4	1	90	0.10	0.6	455.3	375.4	133.7	409.42
5	0.5	70	0.05	0.6	199.6	149.6	200.3	143
6	1	50	0.10	0.6	468.9	370	161	135.5
7	0.5	70	0.10	10	267	138.4	166.9	75
8	0.5	90	0.05	10	217	171.25	236.48	113.82
9	0.5	50	0.10	10	266	134.1	129.1	76.02
10	1	90	0.15	10	577.9	379.5	84.5	378.65
11	1	70	0.05	10	277.08	218.1	125	61.58
12	1	50	0.15	10	604.6	362.8	165.1	183.39
13	0.5	90	0.10	30	230	109.62	152.53	94.03
14	0.5	50	0.15	30	304.6	128.2	152	65.9
15	1	70	0.10	30	433	288.1	143.8	102.31
16	1	50	0.05	30	258.2	159.14	97.05	131.62
17	0.5	70	0.15	30	307.3	124.6	161.5	53.12
18	1	90	0.05	30	271.6	214.77	105.3	108.41

well as lubrication. The coolant water wedge created at the tool-chip interface reduces tool-chip contact length and forces, which can be also connected to benefits in friction conditions. According to the experiment results no significant effect of cutting speed V_c has been observed on the cutting force which is in agreement with experiments of Devillez et al. [20].

2.2 Chip Formation

After each experiment, the chips were collected and analyzed. Fig. 7 shows chip formation in various cutting conditions. It can be seen that turning of Inconel 718 with lower coolant pressure (p = 0.6 and 10 MPa) produced long continuous spiral chips, while smaller segmented chips were produced when machining with higher coolant pressure (30 MPa). What can be observed from those results Ezugwu and Bonney [6] also reported. Actually, the coolant supply at high-pressure tends to lift up the chip after passing through the deformation zone, resulting in a reduction in the tool-chip contact length/area. This tends to enhance chip fragmentation, as the chip curl radius is reduced significantly, hence, maximum coolant pressure is restricted only to a smaller area on the chip.

2.3 Tool Wear

Tool wear normally negatively influences cutting power, machining quality, tool life and machining cost. When tool wear reaches a certain value, it significantly increases the cutting force, causing vibration and rising cutting temperature, which can cause surface integrity deterioration and dimensional error greater than tolerance [21]. The distribution of the wear along the flank face was non-uniform as can be seen in Fig. 8. Additionally, Fig. 5 shows the effect of the cutting speed and feed rate on average tool flank wear (combination of abrasive and depth of cut notch wear) under the high pressure cooling conditions. It can be seen that average tool flank wear increases with an increase in cutting speed and feed rate as is expected. Tool wear rate reaches its maximum value with the upper value of cutting speed and feed rate. Fig. 6 shows the tool flank wear trend in relation to pressure and feed rate. It can be clearly seen that the pressure of delivered coolant strongly affects the tool flank wear. An increase in coolant pressure has a decreasing effect on the tool flank wear. Ezugwu and Bonney [6] have stated that a major cause of tool rejection when machining Inconel 718 are generated high temperatures in the tool-chip and tool-workpiece interfaces. The temperature is significantly reduced by administering coolant under high pressure directly to the cutting interface. This could, therefore, minimize and/or completely eliminate thermally related wear mechanisms. Therefore, tool performance tends to be primarily dependent on mechanical wear phenomena. This means that tool life can be dominantly prolonged when machining Inconel 718 under high pressure cooling conditions in comparison to conventional cooling. Figs. 8 and 9 show flank and crater wear on cutting tool after constant removal of material volume. It can be seen that during the experiments also crater wear on cutting tool appeared on the rake face. Dahlman and Escursell [22] have reported that crater wear normally appears due to the abrasive and diffusion wear mechanisms. On the one hand,

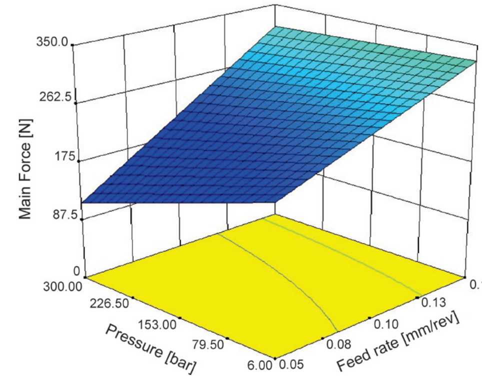


Fig. 2. *Effect of pressure and feed rate on the main force F_c (a_p = 0.5 mm, V_c = 50 m/min)*

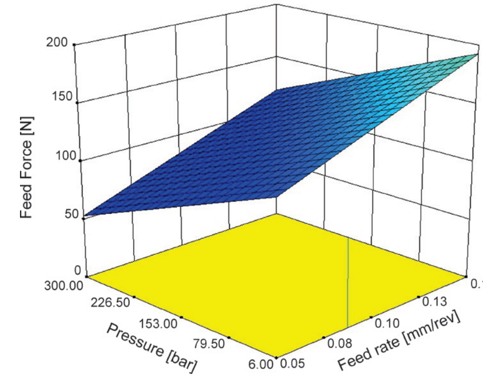


Fig. 3. *Effect of pressure and feed rate on the feed force F_f (a_p = 0.5 mm, V_c = 50 m/min)*

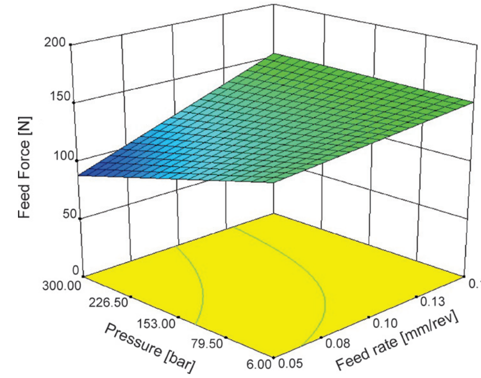


Fig. 4. *Effect of pressure and feed rate on the passive force F_r (a_p = 0.5 mm, V_c = 50 m/min)*

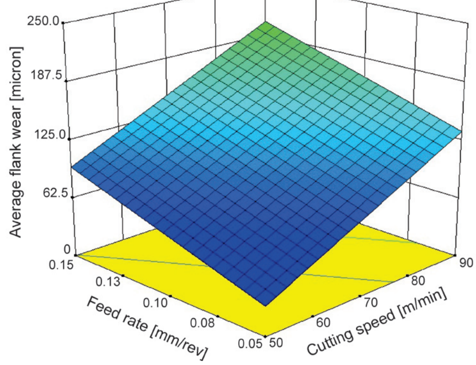


Fig. 5. *Effect of cutting speed and feed rate on average tool flank wear (a_p = 1 mm, p = 300 bar)*

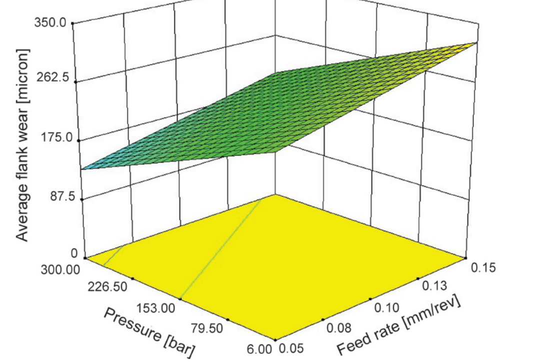
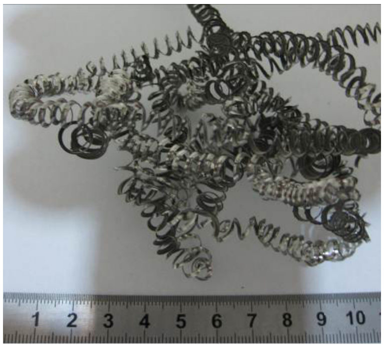
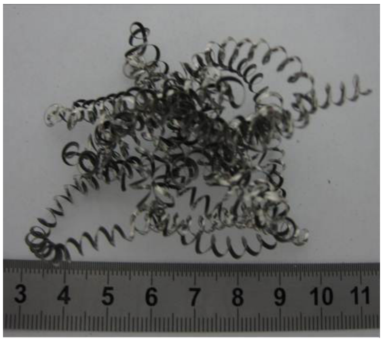


Fig. 6. *Effect of coolant pressure and feed rate on average tool flank wear (a_p = 1 mm, V_c = 90 m/min)*



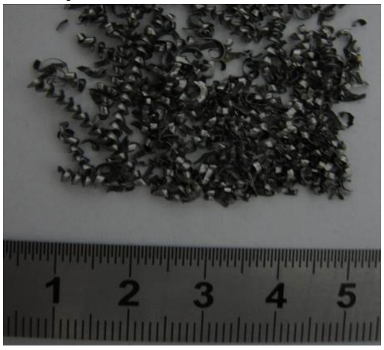
P = 6 bar, a = 1 mm, V_c = 70 m/min, f = 0.15 mm/rev



P = 6 bar, a = 0.5 mm, V_c = 70 m/min, f = 0.05 mm/rev

P = 100 bar, a = 1 mm, V_c = 50 m/min, f = 0.15 mm/rev

P = 100 bar, a = 0.5 mm, V_c = 50 m/min, f = 0.10 mm/rev



P = 300 bar, a = 0.5 mm, V_c = 50 m/min, f = 0.15 mm/rev

P = 300 bar, a = 1 mm, V_c = 50 m/min, f = 0.05 mm/rev

Fig. 7. *Chip formation at various pressure levels*

excessive crater wear can lead to deterioration in chip formation because the chip breaker geometry is destroyed; on the other hand, high pressure coolant reduces the contact length between chip and tool. As a consequence, the tool is less worn on the rake face.

2.4 ANOVA Results

In order to observe the influence of the experiment parameters on cutting force components and average tool flank wear, ANOVA was employed. Statistical significance of the fitted model and terms was evaluated by the P-values of ANOVA. Values are given in Tables 5 to 8 for F_c, F_f, F_r and V_b, respectively. When P-values are less than 0.05 (or 95% confidence), the obtained models/parameters are considered to be statistically significant [23]. This demonstrates that the terms chosen in the model have significant effects on the responses.

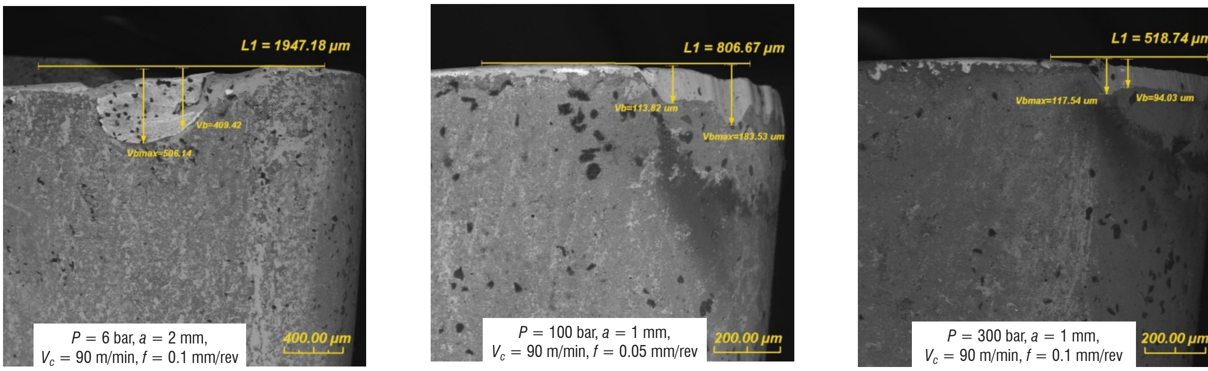


Fig. 8. *Maximum and average flank wear on cutting tool at various cutting conditions (volume of material removed is kept constant V = 57650.4 mm³)*

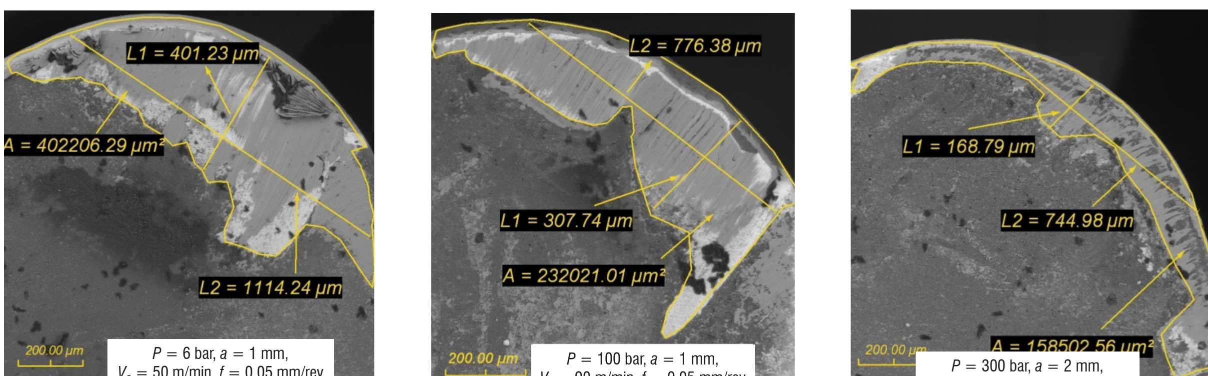


Fig. 9. *Crater wear on cutting tool at various cutting conditions (volume of material removed is kept constant V = 57650.4 mm³)*

Table 5. *ANOVA results for main cutting force*

	Sum of squares	Degree of freedom	Mean square	*F* value	*P*
Model	284214.600	10	28421.456	40.507	0.0001
a_p	80002.160	1	80002.162	114.022	0.0001
V_c	0.513	1	0.513	0.001	0.9792
F	64510.420	1	64510.417	91.943	0.0001
P	1303.922	1	1303.922	1.858	0.2150
a_p x V_c	181.055	1	181.055	0.258	0.6271
a_p x f	10881.860	1	10881.858	15.509	0.0056
a_p x p	602.878	1	602.878	0.859	0.3848
V_c x f	482.380	1	482.380	0.687	0.4344
V_c x p	126.812	1	126.812	0.181	0.6835
f x p	1459.077	1	1459.077	2.079	0.1925
Error	4911.447	7	701.635		
Total	289126.000	17			

Table 6. *ANOVA results for passive force*

	Sum of squares	Degree of freedom	Mean square	*F* value	*P*
Model	19393.120	10	1939.312	4.463	0.0297
a_p	1243.507	1	1243.507	2.862	0.1345
V_c	189.365	1	189.365	0.436	0.5303
F	26.534	1	26.534	0.061	0.8119
P	1504.486	1	1504.486	3.462	0.1051
a_p x V_c	4799.427	1	4799.427	11.045	0.0127
a_p x f	574.266	1	574.266	1.322	0.2881
a_p x p	69.866	1	69.866	0.161	0.7004
V_c x f	4504.463	1	4504.463	10.366	0.0147
V_c x p	259.656	1	259.655	0.597	0.4648
f x p	476.420	1	476.420	1.096	0.3299
Error	3041.725	7	434.5321		
Total	22434.840	17			

Table 5 shows ANOVA results for the main cutting force. It can be seen that depth of cut (a_p) and feed rate (f) are the most significant terms influencing the main cutting force (P = 0.0001). Their interaction ($a_p \times f$) exhibits significant effect on main cutting force as well (P = 0.0056).

Table 6 shows ANOVA results for passive force. It can be seen that the interaction between depth of cut and cutting speed ($a_p \times V_c$, P = 0.0127), and interaction between cutting speed and feed rate ($V_c \times f$, P = 0.0147) have significant effect on passive force. The other terms and their interaction have no effect on passive force. Further, as seen in Table 7 depth of cut has the most significant effect on feed force (P = 0.0001). Feed rate (P = 0.0272) and pressure (P = 0.0153) do not have as a significant effect as the depth of cut on passive force component. Table 8 exhibits ANOVA results for average tool flank wear. It can be seen that fluid pressure has the most significant effect on tool flank wear (P = 0.0134).

Table 7. *ANOVA results for feed force*

	Sum of squares	Degree of freedom	Mean square	F value	P
Model	146844.700	4	36711.165	17.586	0.0001
a_p	116441.700	1	116441.730	55.779	0.0001
V_c	1212.030	1	1212.030	0.581	0.4597
F	12919.270	1	12919.266	6.189	0.0272
P	16271.640	1	16271.635	7.795	0.0153
Error	27138.040	13	2087.541		
Total	173982.700	17			

Table 8. *ANOVA results for tool flank wear*

	Sum of squares	Degree of freedom	Mean square	F value	P
Model	107830.800	4	26957.701	5.030	0.0113
a_p	16210.200	1	16210.202	3.025	0.1056
V_c	34022.490	1	34022.490	6.349	0.0256
F	13804.760	1	13804.762	2.576	0.1325
P	43793.350	1	43793.349	8.172	0.0134
Error	69665.970	13	5358.921		
Total	177496.800	17			

Cutting speed (P = 0.0256) also has a significant effect on tool wear as expected. As a result of regression analysis, empirical equations have been obtained with R^2 = 0.98, 0.86, 0.84 and 0.60, respectively. Equations are presented in Eq. 1.

$$\begin{aligned} F_c &= 81.25 + 77.20\,a_p + 1.28\,V_c - 93.55\,f - \\ &\quad -0.70\,p - 0.84\,a_pV_c + 3211.19\,a_pf + \\ &\quad +0.28\,a_pp - 8.70\,V_cf + 0.001\,V_cp + 2.94\,fp, \\ F_r &= 166.87 + 168.71\,a_p + 6.47\,V_c - 1095.00\,f - \\ &\quad -0.18\,p - 4.35\,a_pV_c + .737.68\,a_pf + \\ &\quad +0.09\,a_pp - 26.60\,V_cf + 0.002\,V_cp + 1.68\,fp, \\ F_f &= -94.32 + 321.72\,a_p + 0.5\,V_c - 656.23\,f - 0.24\,p, \\ V_b &= -134.43 + 120.03\,a_p + 2.66\,V_c - 678.35\,f - 0.40\,p. \end{aligned} \quad (1)$$

3 CONCLUSIONS

In this study, machinability of Inconel 718 was experimentally investigated, comparing conventional with various high pressure cooling conditions on CNC lathe. The experiments are designed based on Taguchi L18 orthogonal array at three different levels of cutting speed, feed rate and pressure and two levels of depth of cut. During the experiments, cutting force components and tool flank wear were recorded. The results were analyzed by using ANOVA. Regression modeling was also used to investigate the relationships between process parameters and machining responses.

The following conclusions can be drawn from this work:

1. The application of high pressure cooling/lubrication fluid to the tool-chip interface decreases cutting force components on account of mechanical effect of high pressure coolant.
2. High pressure cooling improves and provides desirable chip breakability, which tends to improve the quality of machined surface.
3. Cutting tool wear, especially flank face wear, reduce with applying high pressure coolant to the tool-chip interface. This can be attributed to the fact that high pressure coolant provides better lubrication and cooling than conventional cooling. In addition, HPJA also helps to reduce tool-chip contact length and so helps in prolongation of tool life.
4. The high pressure coolant technique supports the sustainability directions in manufacturing, especially hard-to-cut materials, by increasing tool life and reducing the cutting forces resulting in higher productivity and lower energy consumption.
5. Sustainability can be supported even by the possibility of using less concentrated emulsions in HPJA machining (more water based CLF), which cause fewer health and environmental problems.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

[1] Ezugwu, E.O., Bonney, J., Yamane, Y. (2003). An overview of the machinability of aeroengine alloys. *Journal of Materials Processing Technology*, vol. 134, no. 2, p. 233-253; DOI:10.1016/S0924-0136(02)01042-7.

[2] Pušavec, F., Krajnik, P., Kopač, J. (2006). High-speed cutting of soft materials. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 52, no. 11, p. 706-722.

[3] Župerl, U., Čuš, F. (2004). A determination of the characteristic technological and economic parameters during metal cutting. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 50, no. 5, p. 252-266.

[4] Župerl, U., Čuš, F., Gečevska, V. (2007). Optimization of the characteristic parameters in milling using the pso evaluation technique. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 53, no. 6, p. 354-368.

[5] Čuš, F., Župerl, U., Kiker, E. (2007). A model-based system for the dynamic adjustment of cutting parameters during a milling process. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 53, no. 9, p. 524-540.

[6] Ezugwu, E.O., Bonney, J. (2004). Effect of high-pressure coolant supply when machining nickel-base, Inconel 718, alloy with coated carbide tools. *Journal of Materials Processing Technology*, vol. 153-154, p. 1045-1050, DOI:10.1016/j.jmatprotec.2004.04.329.

[7] Pušavec, F., Kramar, D., Krajnik, P., Kopač, J. (2010). Transition to sustainable production - part ii: Evaluation of sustainable machining technologies. *Journal of Cleaner Production*, vol. 18, no. 12, p. 1211-1221, DOI:10.1016/j.jclepro.2010.01.015.

[8] Pušavec, F., Krajnik, P., Kopač, J. (2010). Transition to sustainable production – Part I: Application on machining technologies. *Journal of Cleaner Production*, vol. 18, no. 2, p. 174-184, DOI:10.1016/j.jclepro.2009.08.010.

[9] Sharma, V.S., Dogra, M., Suri, N.M. (2009). Cooling techniques for improved productivity in turning. *International Journal of Machine Tools & Manufacture*, vol. 49, no. 6, p. 435-453, DOI:10.1016/j.ijmachtools.2008.12.010.

[10] Courbon, C., Kramar, D., Krajnik, P., Pušavec, F., Rech, J., Kopač, J. (2009). Investigation of machining performance in high-pressure jet assisted turning of Inconel 718: An experimental study. *International Journal of Machine Tools & Manufacture*, vol. 49, no. 11, p. 1114-1125, DOI:10.1016/j.ijmachtools.2009.07.010.

[11] Kramar, D., Krajnik, P., Kopač, J. (2010). Capability of high pressure cooling in the turning of surface hardened piston rods. *Journal of Materials Processing Technology*, vol. 210, no. 2, p. 212-218, DOI:10.1016/j.jmatprotec.2009.09.002.

[12] Nandy, A.K., Gowrishankar, M.C., Paul, S. (2009). Some studies on high-pressure cooling in turning of Ti–6Al–4V. *International Journal of Machine Tools & Manufacture*, vol. 49, no. 2, p. 182-198, DOI:10.1016/j.ijmachtools.2008.08.008.

[13] Klocke, F., Sangermann, H., Krtamer, A., Lung, D. (2011). Influence of a high pressure lubricoolant supply on thermo-mechanical tool load and tool wear behaviour in the turning of aerospace materials. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 225, no. 1, p. 52-61.

[14] Pušavec, F., Kopač, J. (2011). Sustainability assessment: Cryogenic machining of Inconel 718. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 57, no. 9, p. 637-647, DOI:10.5545/sv-jme.2010.249.

[15] Ezugwu, E.O., Bonney, J., Da Silva, R.B., Çakir, O. (2007). Surface integrity of finished turned Ti6Al4V alloy with PCD tools using conventional and high pressure coolant supplies. *International Journal of Machine Tools & Manufacture*, vol. 47, no. 6, p. 884-891, DOI:10.1016/j.ijmachtools.2006.08.005.

[16] Adamczak, S., Čuš, F., Miko, E. (2009). A model of surface roughness constitution in the metal cutting process applying tools with defined stereometry. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 55, no. 1, p. 45-54.

[17] Kaminski, J., Alvelid, B. (2000). Temperature reduction in the cutting zone in water-jet assisted turning. *Journal of Materials Processing Technology*, vol. 106, no. 1-3, p. 68-73, DOI:10.1016/S0924-0136(00)00640-3.

[18] Palanisamy, S., McDonald, S.D., Dargusch, M.S. (2009). Effects of coolant pressure on chip formation while turning Ti6Al4V alloy. *International Journal of Machine Tools & Manufacture*, vol. 49, no. 9, p. 739-743, DOI:10.1016/j.ijmachtools.2009.02.010.

[19] Krajnik, P., Kopač, J., Sluga, A. (2005). Design of grinding factors based on response surface methodology. *Journal of Materials Processing Technology*, vol. 162-163, p. 629-636, DOI:10.1016/j.jmatprotec.2005.02.187.

[20] Devillez, A., Schneider, F., Dominiak, S., Dudzinski, D., Larrouquere D. (2007). Cutting forces and wear in dry machining of Inconel 718 with coated carbide tools. *Wear*, vol. 262, no. 7-8, p. 931-942, DOI:10.1016/j.wear.2006.10.009.

[21] Kamruzzaman, M., Dhar, N.R. (2009). The influence of high pressure coolant on temperature tool wear and surface finish in turning 17CrNiMo6 and 42CrMo4 steels. *Journal of Engineering and Applied Sciences*, vol. 4, no. 6, p. 93-103.

[22] Dahlman, P., Escursell, M. (2004). High-pressure jet-assisted cooling: a new possibility for near net shape turning of decarburized steel. *International Journal of Machine Tools & Manufacture*, vol. 44, no. 1, p. 109-115, DOI:10.1016/S0890-6955(03)00058-0.

[23] Stamatis, D.H. (2003). Six Sigma and Beyond. *ST. Lucie Press*, New York.