Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 30 (2019) 253–260

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

14th Global Congress on Manufacturing and Management (GCMM-2018)

Evaluating the Machinability of Inconel 718 under Different Machining Conditions

Jeyapandiarajan.P[a] and Anthony Xavior M[b*]

[a, b] Manufacturing Department, School of Mechanical Engineering, VIT, India.

Abstract

Machining of Inconel 718 (In718) remains a challenging task for researchers and practising engineers in the shop floor for quite a long period. In the past decades, many researchers have explored various options with an objective to improve the tool life during machining of In 718. In this research work an attempt has been made to evaluate the machinability of In 718 under various machining conditions. Machining experiments has been conducted under dry, MQL and Flood cooling conditions with selected cutting parameters. Design of experiments has been done using Taguchi's orthogonal array and machining experiments were conducted on an ACE Micromatic CNC Lathe with spindle speed range of 50 - 4000 rpm. Three levels of each cutting parameters namely, cutting speed (50, 75 and 100 m/min), feed rate (0.06, 0.08 and 0.10 mm/rev) and depth of cut (0.2, 0.5 and 0.8 mm) were considered for the experimentation. Subsequent to the experimentation Analysis of Variance was performed on the experimental data to identify the significance of the cutting parameters on the tool performance. The performance of PVD TiAlN coated carbide, whisker reinforced ceramic and cubic boron nitride cBN inserts had been evaluated in terms of cutting force encountered during machining, flank wear developed on the tool and surface roughness on the machined component.

Keywords: Inconel 718; Machinability; Cutting force; Surface roughness; Flank wear:

1. Introduction

Heat-resistant super alloys or high-temperature alloys, are materials that results in development of high temperatures exceeding 1200˚ C during machining. Amongst the high-temperature alloys, nickel-based alloys are the most widely used and can be found in applications like aircraft engine, turbocharger rotor, gas-turbine engine, cryogenic fuel tank, high pressure vessel, nuclear water reactors, steam generator boilers, exhaust systems of high powered rotary engine and exhaust system of formula one cars. Almost all base parts of aerospace components are

* Corresponding author. Tel.: +919443687391
E-mail address: manthonyxavior@vit.ac.in

10.1016/j.promfg.2019.02.037

made of nickel based alloys because these superalloys have high oxidation resistant, wear resistant, high tensile strength and high fatigue strength. Even though the super alloys possess many positive characteristics they are very well known as difficult to cut materials because of their high strength, low thermal conductivity and work hardening effect. Devillez et al [1] aimed to economize the cost and ensure environmental safety while machining and opted for dry cutting of Inconel with coated carbide insert at higher cutting speeds. The objective was to understand the surface integrity and stress induced in the sub-surface layer (residual stresses) while cutting under wet and dry condition. Subsequently it was concluded that coated carbide under dry machining leads to acceptable finish with almost equal hardness value and residual stress. Devillez et al [2] made an attempt to cut down the cost of production by excluding cutting fluid and experimentation was conducted in dry machining condition with coated carbide tool and uncoated carbide. Bushlya et al [3] reported that Inconel 718 is a competent superalloy when machining with cemented carbide tools at a low cutting speed of Vc = 60 m/min because of its good thermal and mechanical properties. It was observed that 20% of tool life is improved by the protective coating available on the tool. Grzesik et al., [4] investigated on the tool wear during turning of Inconel 718 in terms of productivity enhancement and process performance. An empirical model was developed incorporating the cutting speed and the volume of the metal removed in order to predict the productivity of the turning operation. Hamid et al., [5] have reported about the influence of surface residual stresses on the fatigue life and crack propagation behaviour of Inconel 718 which was subjected to turning operation. It was reported that axial surface residual stress is the most influencing factor that affects the fatigue life of machined Inconel 718 specimen. Mohsan et al., [6] have determined the influence of cutting fluid conditions and cutting parameters on the surface integrity during high pressure jet assisted machining of Inconel 718. It was concluded that a higher cutting speed of 140 m/min. and a coolant pressure of 150 to 200 bar are the optimum levels to produce a satisfactory surface quality. Hua and Liu [7] have investigated on the effects of cutting parameters and tool nose radius on surface roughness and work hardening during dry turning of Inconel 718. It was mentioned that feed rate and tool nose radius have dominant effect on surface roughness whereas; the degree of work hardening is strengthened as the cutting speed and feed rate increases. Zeilmann et al., [8] have discussed about the wear mechanisms during dry and wet turning of Inconel 718 material using ceramic tools and have reported that the predominant wears were notch wear and flank wear. Tebaldo et al. [9] turned Inconel 718 in dry condition aiming at the environmental needs. They studied two different lubrication methods and made economic analyses. They could reach similar results as wet machining, but the lowest cost was obtained by the use of a cutting fluid. Cantero et al. [10] have investigated wear patterns produced on the TiAlN/TiN multilayer coated carbide tools in both dry and wet modes of finish turning (vc=50-70 m/min, f=0.1 mm/rev, ap=0.5 mm). It is concluded that cutting edges deteriorate mostly due to notching and chipping phenomena. In addition, the adhesion which causes the BUE (built-up edge) layer to be formed on the flank face of the tool inserts is developed. It is worth noticing that all these wear phenomena are not independent but closely interrelated. For instance, the breakage of the cutting edge due to chipping occurred for dry and wet machining but appropriate tool-life for the cutting speed of 70 m/min increases from 2 min to 5 min. The suitability of three cutting tool materials- PVD-TiAlN coated carbides, Al2O3-TiC ceramic and CBN to the turning of Inconel 718 was verified by Xavior et al.[11].

From the literature, it is understood that quite a few work on machining of Inconel 718 has been reported. The objective of this work is to determine the machining capability of three inserts (PVD coated TiAlN carbide, whisker reinforced ceramic and cBN) in terms of surface roughness, cutting forces and the flank wear. Further it is also aimed to investigate the work hardening effect induced by high temperature plastic deformation. The details of the tool material used, experimental work and the observation, micro-hardness analysis, ANOVA performed on the responses and the micro-structural analysis of the cutting inserts are presented in the subsequent sections.

2. WORK AND TOOL MATERIAL

The work material used in this research for experimentation is nickel chromium based super alloy, INCONEL 718 bar of 42mm diameter and 250mm long. The experiment is carried out with constant cutting length under dry, flood and MQL condition. Table 1 and 2 shows the chemical composition and physical properties of Inconel 718 respectively. The cutting tool inserts used in this work are PVD TiAlN coated carbide, whisker reinforced ceramic and cubic boron nitride cBN inserts. The PVD insert used is CNMG120408MS KCU25 grade with TiAlN coating. The new and superior edge coating strengthens the edge stability with wide range of speed and feed capabilities. The ceramic insert used is of CNGA120408T01020 KY4300 grade with ceramic matrix of Al_2O_3 and SiC whiskers. The SiC whiskers embedded inside the tool micro structure give this ceramic insert excellent stiffness for cutting high strength alloys and cast materials with high HRC. The third insert used here is cBN which has the highest hardness of all inserts and its specification is CNGA120408S01025MT KB1630grade.

Table 1 - Chemical Composition of Inconel 718

Inconel 718	Ni	Cr	Fe	Mo	Nb	Co	Mn	Cu	Al	Ti	Si	C
	50-55	17-21	balance	2.8-3.3	4.75-5.5	1.0	0.35	0.2-0.8	0.65-1.15	0.3	0.35	0.08

Table 2 - Physical properties of Inconel 718

Property	Metric
Density	8.19 g/cm^3
Melting point	1336 °C
Co-Efficient of Expansion	13.0 µm/m.°C (20-100 °C)
Modulus of rigidity	77.2 kN/mm^2
Modulus of elasticity	204.9 kN/mm
Hardness	38 HRC

Table 3 – Machining parameter and levels

Parameters	Level 1	Level 2	Level 3
Cutting speed - V_c (m/min)	50	75	100
Depth of cut - d (mm)	0.20	0.50	0.80
Feed rate - f (mm/rev)	0.06	0.08	0.10
Cutting insert	PVD –TiAlN carbide	Al_2O_3-TiC ceramic (SiC whisker reinforced)	cBN
Cutting condition	Dry cutting	MQL cutting	Flood cooling

3. EXPERIMENTATION

Table 4 - Design of experiments as per L27 Orthogonal Array

Exp. No	Vc	d	f	Insert	Cutting condition	Fz	Ra	Vb
1	50	0.2	0.06	Carbide	Dry	116.40	0.7527	67.66
2	50	0.2	0.08	Ceramic	MQL	143.10	1.5303	52.78
3	50	0.2	0.10	cBN	Flood	120.47	0.9781	24.78
4	50	0.5	0.06	Ceramic	Flood	169.90	1.1630	51.23
5	50	0.5	0.08	cBN	Dry	184.20	0.9171	78.85
6	50	0.5	0.10	Carbide	MQL	186.15	1.210	27.75
7	50	0.8	0.06	cBN	MQL	256.40	0.8210	69.45
8	50	0.8	0.08	Carbide	Flood	238.30	0.8629	30.61
9	50	0.8	0.10	Ceramic	Dry	246.80	1.3120	21.75
10	75	0.2	0.06	Ceramic	Flood	120.40	0.6885	77.42
11	75	0.2	0.08	cBN	Dry	128.50	0.8739	89.16
12	75	0.2	0.10	Carbide	MQL	132.83	1.5330	112.64
13	75	0.5	0.06	cBN	MQL	199.10	0.8920	110.96
14	75	0.5	0.08	Carbide	Flood	188.60	0.9830	108.44
15	75	0.5	0.10	Ceramic	Dry	187.30	1.7160	113.37
16	75	0.8	0.06	Carbide	Dry	231.40	1.1961	66.82
17	75	0.8	0.08	Ceramic	MQL	227.60	1.2330	74.62
18	75	0.8	0.10	cBN	Flood	243.60	0.9262	123.58
19	100	0.2	0.06	cBN	MQL	125.32	0.6550	80.03
20	100	0.2	0.08	Carbide	Flood	134.37	0.998	93.69
21	100	0.2	0.10	Ceramic	Dry	131.60	1.5701	109.75
22	100	0.5	0.06	Carbide	Dry	178.40	1.3280	122.75
23	100	0.5	0.08	Ceramic	MQL	171.10	1.2840	132.65
24	100	0.5	0.10	cBN	Flood	197.50	1.4531	144.52
25	100	0.8	0.06	Ceramic	Flood	211.50	1.4144	166.33
26	100	0.8	0.08	cBN	Dry	230.60	1.3780	174.2
27	100	0.8	0.10	Carbide	MQL	232.70	1.6400	188.85

Legend: Fz - Cutting Force in Newtons, Ra - Surface Roughness in microns and Vb - Flank wear in microns

Experiments were designed as per Taguchi's L27 orthogonal array considering five parameters each with three levels. Table - 3 shows the parameters and their levels considered for the experimentation. Table - 4 shows the Design of Experiment (DoE) as per L27 orthogonal array. The experiments were conducted in a CNC semi-automatic lathe and the CNC program for turning of Inconel bar is programmed and fed into the Fanuc operator. Three type of cutting conditions namely dry, MQL, flood coolant setup were used in the same machine. For flood coolant, water soluble oil is used in the ratio of 1:10. MQL (maximum flow rate is 80 ml/hour) is a separate setup, which is being attached to the CNC lathe and the nozzle is placed in such a way that the lubricant is sprayed towards the two sides of the workpiece, one by top side and the other by the flank side of the tool. The Mahr surface profilometer is used to measure the surface roughness of the machined workpiece. TESA image profiler and optical microscope are used to measure the tool wear occurred while machining. Cutting forces were measured (online measurement) during the machining process using Kistler dynamometer.

4. RESULTS AND DISCUSSION

Analysis of variances (ANOVA) was performed using MINITAB software to determine the significant parameter affecting the performance of the machining processes.

4.1. Analysis of Variances (ANOVA)

Experiments were performed as per L27 Taguchi orthogonal array, observations were analysed for cutting force and the response table for signal to noise ratio are recorded. Taguchi analysis for cutting force has been tabulated in table 5.

4.2. Cutting Force Response Analysis

Observation reveals depth of cut and feed has higher influence on cutting force as shown in table and the same has been observed in the main effect plot of S/N ratio for cutting force in shown in fig. 1. ANOVA was performed with experimentally observed data and the values are tabulated as in table 6. Depth of cut has the major contribution value as 75%. ANOVA is done to find out the influencing parameter and their percentage contribution for cutting force. The analysis were done at confidence level of 95% and the insignificant values are removed by eliminating terms below $\alpha = 0.05$. As shown in the S/N ratio rank the percentage contribution for depth of cut is high and considered as significant parameter. The coefficient of determination R^2 value is above 90% which is acceptable and the regression equation is developed for cutting force.

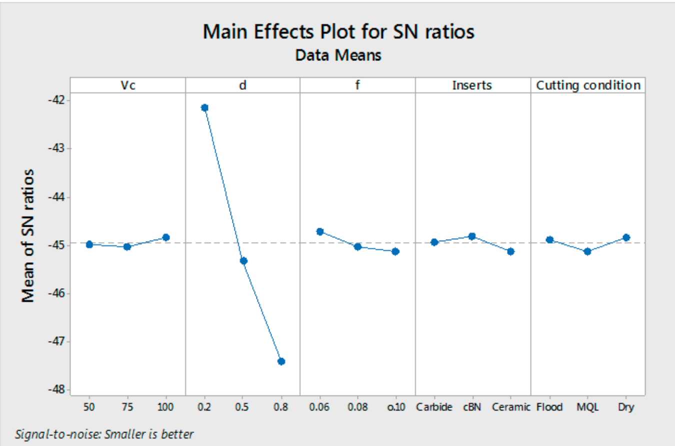

Fig.1. S/N ratio graph for cutting force Fz

Table 5: Taguchi Analysis Fx versus Vc, DOC, FEED, INSERT, COND

Level	Vc	d	f	Inserts	Cutting condition
1	-44.99	-42.14	-44.72	-44.94	-44.9
2	-45.04	-45.32	-45.03	-44.81	-45.14
3	-44.85	-47.43	-45.13	-45.12	-44.84
Delta	0.19	5.29	0.41	0.31	0.29
Rank	5	1	2	3	4

Contour Plots shown in figure reveals highest contribution factor for cutting force comes as the depth of cut. Cutting velocity and feed has minimum contribution to cutting force and the same has been given in surface Plot of cutting force in fig. 2. Contour plot shows minimum cutting force at depth of cut as 0.2 irrespective of the speed and feed.

Surface plot is a 3D plot showing the relation between results cutting force and two input parameter DOC and feed are shown in fig. 3. The plot shows the optimum parameter in which we can get low cutting force. While machining at low DOC 0.2 mm, cutting velocity 50-100 m/min and feed 0.08-0.06mm/rev we can expect low cutting force during dry condition by using carbide insert.

4.3. Surface Roughness Response Analysis

Table 6 - ANOVA for cutting force

Source	DF	Adj SS	Adj MS	F-Value	P-Value	P%
Vc	1	12.6	12.6	0.65	0.45	0.023
D	1	41427	41427	2137.32	0	75.861
F	1	273.2	273.2	14.1	0.009	0.500
Insert	3	315.8	105.3	5.43	0.038	0.578
Cutting condition	2	15.1	7.5	0.39	0.694	0.028
Vc*Vc	1	93.9	93.9	4.84	0.07	0.172
d*d	1	117.1	117.1	6.04	0.049	0.214
f*f	1	42.3	42.3	2.18	0.19	0.077
Vc*d	1	147.5	147.5	7.61	0.033	0.270
Vc*f	1	78.3	78.3	4.04	0.091	0.143
Vc*Cutting condition	2	97.5	48.8	2.52	0.161	0.179
d*f	1	10.1	10.1	0.52	0.498	0.018
d*Cutting condition	2	49.9	24.9	1.29	0.343	0.091
f*Cutting condition	2	113.2	56.6	2.92	0.13	0.207
Error	6	116.3	19.4			
Total	26	54609				
Summary		S = 4.40258	R-sq(adj) = 99.79 %	R-sq (pred) =99.08%		

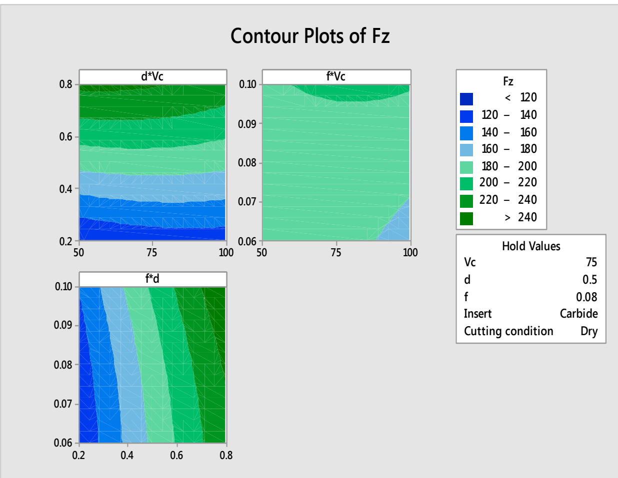

Fig. 2. Contour plot for cutting force

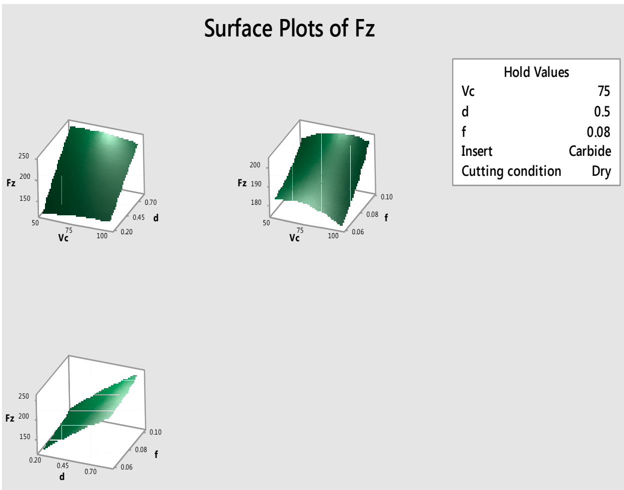

Fig. 3. Surface plot for cutting force

All the 27 experiments are carried out and the results are defined and analysed by Minitab software to determine the response graph for signal to noise ratio is developed and ranked. From the table 7 it clear that feed rate is the most influencing parameter then feed and Inserts. The rank is given based on smaller is better outcome. Main effect plot for SN ratios for surface roughness shown in fig. 4. The experiments were analysed in ANOVA to get the percentage contribution of each input parameter it also gives the square interaction and 2 way interaction p value as shown in table 8. The contribution showing p value above 0.05 is declared as insignificant. The feed, cutting speed and inserts are considered as significant values their p values are less than 0.05 for surface roughness as they show high percent contribution of 26.510, 12.710 and 11.725.

Table 7. Taguchi Analysis Ra versus speed, DOC, FEED, TOOL, COND

Level	Vc	d	f	Inserts	Cutting condition
1	-0.29067	-0.0622	0.41646	-1.08534	-1.48687
2	-0.61729	-1.51617	-0.78906	-2.19275	-1.21872
3	-2.02227	-1.35186	-2.55763	0.34787	-0.22463
Delta	1.7316	1.45397	2.97409	2.54062	1.26224
Rank	3	4	1	2	5

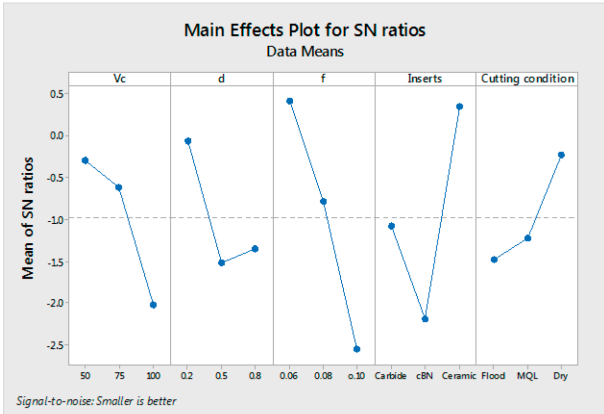

Fig. 4. S/N ratio graph for surface roughness

Insignificant parameter are DOC, cutting condition and the two way interactions shows p values greater than 0.05. The analysis was performed for 95% confidence level. The R^2 coefficient determination for surface roughness is 95.62% which is above the acceptable level 90%.

The contour plot shows the optimum machinable area were we can get good output result. Surface roughness will be good while machining at speeds in the range 50 -80 m/min depth of cut 0.2 mm and feed in the range 0.06 - 0.08 mm/rev. Fig. 5 shows the contour plot for surface roughness. The surface plot otherwise called as 3D plot shown in fig. 6 the graph in 3D for three parameters. Optimum surface roughness value can be achieved by machining at speed 50-80 m/min DOC 0.2 mm and feed 0.06 mm/rev.

4.4. Flank wear Response Analysis

The S/N ratio for flank wear was defined and analysed with smaller the better outcome. The rank for the parameters is distributed based on the response to signal to noise ratio are tabulated in table 9. The most influencing parameter for flank wear is cutting speed and DOC.

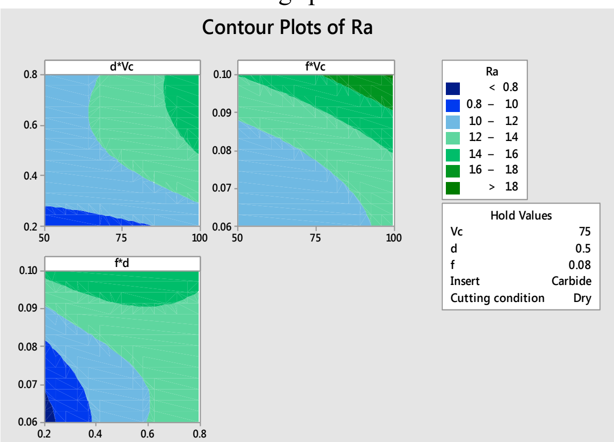

Fig. 5. – contour plot for surface roughness

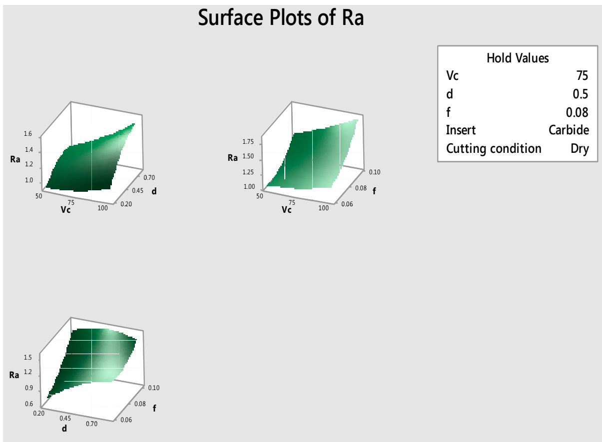

Fig. 6. Surface plot for Ra

Table. 8. ANOVA for Surface Roughness

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**P%**
Vc	1	0.31297	0.312965	17.42	0.006	12.710
D	1	0.13071	0.130707	7.28	0.036	5.308
F	1	0.65277	0.652767	36.33	0.001	26.510
Insert	3	0.28872	0.096241	5.36	0.039	11.725
Cutting condition	2	0.13814	0.06907	3.84	0.084	5.610
Vc*Vc	1	0.00635	0.006348	0.35	0.574	0.258
d*d	1	0.07324	0.073245	4.08	0.09	2.974
f*f	1	0.06566	0.065662	3.65	0.104	2.667
Vc*d	1	0.02548	0.025481	1.42	0.279	1.035
Vc*f	1	0.03156	0.031562	1.76	0.233	1.282
Vc*Cutting condition	2	0.00068	0.00034	0.02	0.981	0.028
d*f	1	0.13341	0.133414	7.43	0.034	5.418
d*Cutting condition	2	0.01303	0.006515	0.36	0.71	0.529
f*Cutting condition	2	0.02129	0.010644	0.59	0.582	0.865
Error	6	0.10779	0.017966			
Total	26	2.46238				
S = 0.134036 R-sq = 95.62% R-sq(adj) = 81.03%						

Fig.7 shows the main effect plot for SN ratios for surface roughness. Flank wear analysis were defined and analysed for all 27 experiments and the percentage contribution is calculated for a confidence level of 95% by following backward elimination α = 0.05. From the p value we can classify the significant and insignificant values which does not influence the flank wear. The most significant parameter is cutting velocity with 49.453% contribution for flank wear. The R2 value is above 90% which mean we will get 90% correct value for any variability as shown in table 10. The contour plot shown in fig. 8 the possible machining area were we can get our expected results. The expected flank wear can be achieved at speed 75 m/min at feed 0.03 - 0.08 mm/rev and also at speeds 50-75 m/min with DOC 0.2 mm/rev.

Table 9 - Taguchi Analysis WEAR versus Vc, DOC, FEED, TOOL, COND

Level	Vc	d	f	Inserts	Cutting condition
1	-32.58	-37.23	-38.56	-37.8	-38.37
2	-39.59	-39.01	-38.44	-37.71	-38.4
3	-42.28	-38.21	-37.44	-38.94	-37.68
Delta	9.7	1.78	1.12	1.23	0.71
Rank	1	2	4	3	5

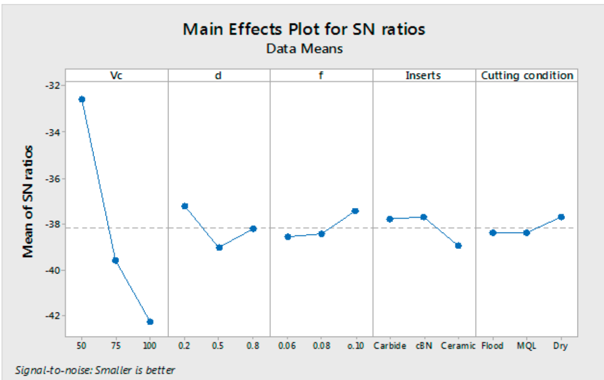

Fig 7 – Signal to noise ratio for flank wear

Table 10: ANOVA for Flank Wear

Source	DF	Adj SS	Adj MS	F-Value	P-Value	P%
Vc	1	26178.3	26178.3	58.09	0	49.453
D	1	1890.9	1890.9	4.2	0.086	3.572
F	1	164	164	0.36	0.568	0.310
Insert	3	1905.2	635.1	1.41	0.329	3.599
Cutting condition	2	39.3	19.7	0.04	0.958	0.074
Vc*Vc	1	244.5	244.5	0.54	0.489	0.462
d*d	1	435.5	435.5	0.97	0.364	0.823
f*f	1	4.7	4.7	0.01	0.922	0.009
Vc*d	1	3179.7	3179.7	7.06	0.038	6.007
Vc*f	1	1868.5	1868.5	4.15	0.088	3.530
Vc*Cutting condition	2	297	148.5	0.33	0.731	0.561
d*f	1	0	0	0	0.993	0.000
d*Cutting condition	2	660.1	330	0.73	0.519	1.247
f*Cutting condition	2	1602.8	801.4	1.78	0.247	3.028
Error	6	2703.8	450.6			
Total	26	52935.6				

S = 21.2281 R-sq = 94.89% R-sq(adj) = 77.87%

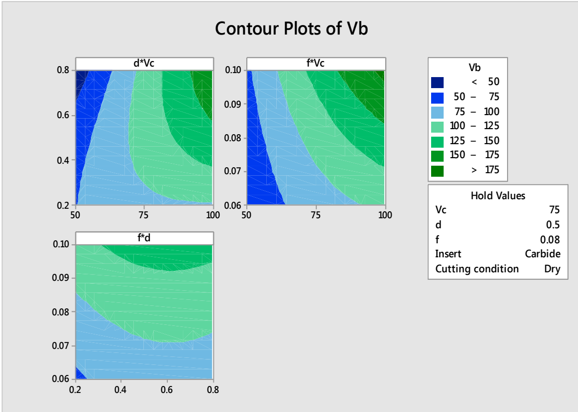

Fig. 8. Contour plot for wear

5. CONCLUSION

Machining experiments were conducted on Inconel 718 using different cutting tools, cutting conditions and cutting parameters by using Taguchi's design of experiments. Subsequent to experimentation ANOVA was performed to determine the influence of various cutting conditions, tools and parameters on the surface roughness generated on the machined surface, cutting force generated during the machining process and quantum of wear encountered on the flank face of the tool. A detailed analysis using surface plots, contour plots and interaction plots were presented to understand the variation in responses for a change in cutting conditions / cutting tool / cutting parameters.

REFERENCES

[1] Devillez, A., Coz, G. Le., Dominiak, S., and Dudzinski, D., "Dry Machining of Inconel 718, Workpiece Surface Integrity,"; Journal of Materials Processing Technology, Vol. 211, pp. 1590–1598 (2011).
[2] Devillez, A., Schneider, F., Dominiak, S., Dudzinski, D., and Larrouquere, D., "Cutting forces and wear in dry machining of Inconel 718 with coated carbide tools,"; Wear, Vol. 262, pp. 931–942 (2007).
[3] Bushlya, V., Zhoua, J., and Stahl, J.E., "Effect of Cutting Conditions on Machinability of Superalloy Inconel 718 during high speed turning with coated and uncoated PCBN Tools,"; Procedia CIRP, Vol. 3, pp. 370–375 (2012).
[4] Grzesik W., Nieslony P., Habrat W., Sieniawski J. and Laskowski P., "Investigation of tool wear in the turning of Inconel 718 super alloy in terms of process performance and productivity enhancement", Tribology International, doi: 10.1016/j.triboint.2017.10.005 (2017).
[5] Hamid J., Walid J., Elvi D., Myriam B. and Philippe B., "Influence of surface residual stresses on the fatigue life and crack propagation behaviour of turned Inconel 718 super-alloy" MATEC Web of Conferences 165, 18004 (2018).
[6] Mohsan AUH, Liu Z, Ren X., Liu W. "Influences of cutting fluid conditions and cutting parameters on surface integrity of Inconel 718 under high- pressure jet–assisted machining (HPJAM)", Lubrication Science. DOI: 10.1002/ls.1418 (2018).
[7] Hua Y. and Liu Z. "Effects of cutting parameters and tool nose radius on surface roughness and work hardening during dry turning Inconel 718" The International Journal of Advanced Manufacturing Technology, https://doi.org/10.1007/s00170-018-1721-7 (2018).
[8] Rodrigo P. Zeilmann, Fernanda Fontanive and Rafael M. Soares., "Wear mechanisms during dry and wet turning of Inconel 718 with ceramic tools". The International Journal of Advanced Manufacturing Technology, Vol. 92, pp. 2705 - 2714 (2017).
[9] V. Tebaldo, G.G. di Confiengo, M.G. Faga, Sustainability in machining: ―Eco - friendly turning of Inconel 718. Surface characterisation and economic analysis, Journal of Cleaner Production, Vol. 140, Part 3 1567 - 1577 (2017).
[10] Cantero JL, Diaz-Alvarez J, Miguelez MH, Martin NC. Analysis of tool wear patterns in finishing turning of Inconel 718, Wear, Vol. 297, pp. 885-894 (2013).
[11] Xavior MA, Monohar M, Jeyapandiarajan P, Patil MM. Tool wear assessment during machining of Inconel 718, Procedia Engineering, Vol. 174, pp. 1000-1008 (2017).