Performance of Cold Coolant for Machining of Inconel 718 using Carbide Cutting Tool

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Abstract: ***Inconel 718 machining is challenging and difficult task in the aspect of good surface quality and minimum tool cost by machining process with low tool wear rate. In this contest, cold coolant machining tries to find the solutions by reducing the tool wear significantly in turning processes. The usage of the cutting fluids and its machining conditions are critically significant in order to completely utilized in the machining process. Usually, the maximum heat generation at chip-tool interface as critical cutting zone, and friction between the tool face and work surface is always the crucial factor on the surface quality. A good understanding of the methods to apply the coldcutting fluid at the cutting zone may significantly reduce the heat generation in machining and thus reduce the tool wear then the surface roughness also improved. Surface roughness and tool wear are always used as a quality indicator of machined job. In this research frizzed ice placed near to the coolant pump to convert the coolant in cold condition. During turning of Inconel 718 flooded cold coolant were drastically removed heat from the chip tool interface. As result, the cold coolant allows a tool life better than the conventional cutting fluid, moreover longevity of the cooling fluid also maintained.***

Keywords: Cold Coolant;Design of experiments; Inconel 718 machining; Flank wear; Surface roughness; Taguchi Optimization

1. Introduction

The heat resistant super alloy material Inconel 718 is widely used in aerospace, nuclear and gas turbine industries due to excellent characteristics of the material, namely high strength-weight ratio at elevated temperature, exceptional corrosion resistance, and longer service life [1]. In machining Inconel 718 alloy, it is well known that the tool temperature rises easily due to its poor thermal properties. Micro-welding at tool-tip and chip interface takes place leading to the formation of built-up edge (BUE). The excellent material toughness results in difficulty in chip breaking during the process. In addition, precipitate hardening of secondary phase (Ni3Nb) together with work-hardening during machining makes the cutting condition even worse. As a result, increase in the cutting temperature leads to rapid tool wear, less material removel rate (MRR) and poor surface finish [2,3]. The manufacture of aerospace components involves a variety of machining operations such as turning, facing, milling and drilling. Any machining process does not allow achieving the theoretical surface roughness due to defects appearing on machined surfaces due to rapid tool wear and imbalances in the process [4]. This requires measuring surface quality of manufactured parts with accuracy. Aslan et al 2007 and Hascalik et al 2007 quoted in their research an optimum selection of process condition is extremely important as this one determine surface quality and flank wear phenomena of the manufactured parts [5,6]. The cost of machining is very strongly dependent on metal removal rate, but it affects tool life adversely due to friction and heat generation at the tool cutting zone. Many of the techno-economic problems of machining are caused by this heat generation. High cutting temperatures in machining always result in aggressive tool wear at the tool cutting point. The most practical way of effectiveness of machining for difficult-to-cut material can be achieved by reducing the cutting temperature of chip-tool interfaces. Several technologies have been developed for controlling the temperature in the chip-tool interface to increase the overall effectiveness of the process like high-pressure coolant, compressed air/gases, cryogenic cooling. High pressure jet cooling technique is one of an effective method to reduce cutting temperature. And it gives longer tool life, but inferior surface roughness was observed when machining of Ti-6Al-4V alloy. Machining of Inconel 718 with whisker reinforced ceramic tools gave better performance in terms of tool life under high-pressure coolant supplies compared to conventional coolants [7]. Tool life was found to increase with increase of coolant supply pressure. It was reported that the high-pressure coolant injection technique not only reduces cutting forces and cutting temperature, but also reduces the consumption of cutting fluid by 50%. Though high-pressure coolant supply exhibits a significant improvement in tool life and surface finish, it has many drawbacks like more floor space, separation of particles, affects operator's health, increases the operating cost etc.

Cryogenic cooling is the efficient and environmentally safe way of maintaining the cutting tool temperature in low. Reduction in tool temperature during cryogenic cooling is by lubrication and cooling the hottest spot that in turn reduces the tool wear. The benefit of cryogenic cooling has been more predominant at lower cutting velocity expectedly because at lower velocity a large portion of the chip-tool contact remains elastic in nature, which is likely to allow a more effective penetration of cryogen at the interface [8]. In comparison to dry cutting and conventional cooling, the most considerable characteristic of the cryogenic cooling application is control of machining temperature desirably at the cutting zone, thus reduction in tool wear and improved surface finish along with higher machining cost [9].

Water vapor and air are cheap, pollution-free and eco-friendly alternatives in cooling. Current industrial advice from tool manufactures is to use compressed air as cutting fluid during high-speed cutting operations. However, it is still not clear whether this environment assists the cutting process or if its popularity is due to the convenient availability of compressed air in the workshop and its ability to remove cutting chips from the work zone [10,11]. The effectiveness of water vapors as coolant was high as compare to that of O_2, CO_2 and mixture of gas, at the same time all these are act as green alternative in cooling. Compressed cold nitrogen gas and oil mist is the optimal cooling/lubrication condition to improve the tool life, provided proper filtration is used to minimize the hazards of oil mist to operator's health. Hence providing compressed air/gas and shielding process increases the cost of machining. Alternatively, cold water soluble oil coolant can be directed at the tool and work piece to dissipate the heat produced by the cutting process.

In any of the machining operations an improper selection of cutting parameters will cause undesired surface roughness and high tooling cost. In order to decide the surface quality and tool wear the statistical design of experiments is used quite extensively [12-14]. The design of experiments refers to the process of planning the experiment, so that the appropriate data can be analyzed by statistical methods, resulting in a valid and objective conclusion [15, 16]. In this paper, full factorial design of experiments was conducted by varying the machining parameters such as speed, feed and depth of cut for measuring the surface roughness and flank wear by using uncoated carbide inserts grade H13A. This paper describes the finish turning operations were done in dry, wet and cold coolant applied cutting conditions to fulfill the requirements and making it possible to minimize the objective functions.

2. Design of Experiments

Design of experiments is a powerful tool for modelling and analysis of process variables over some specific variable which is an unknown function of these process variables [17]. Taguchi design of experiments is a simple robust technique for analysing and optimizing the process parameters. In this method, main parameters which are assumed to have influence on process results are located at different columns in a designed orthogonal array. In general surface roughness and flank wear are mainly depends on the manufacturing conditions employed, such as cutting speed, feed, depth of cut machine tool, cutting tool rigidity and geometry etc. Among these parameters cutting speed, feed and depth of cut are controlled by the operator at the time of machining process. In the Taguchi design of experiments the signal to noise ratio (η) representing quality characteristics for the observed data [12, 14]. Depending on the experimental response, there are several quality characteristics. In the case of surface roughness and flank wear, lower values of them are desirable [15,19]. There are three S/N ratios that are available, which will be selected based on the response function and its characteristics. In turning operations, desired responses are minimum surface roughness and minimum flank wear so, smaller the better "SB" ratio were selected. The S/N ratio for minimum responses type of characteristic can be calculated as follows:

$$\eta = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (1)$$

where yi is the observed data at i^{th} trial and n is the number of trails. From the S/N ratio, the effective parameters having influence on process results can be seen and the optimal sets of process parameters can be determined.

3. Experimental procedure

Single-pass finish turning operations were conducted in dry, wet and cold conditions in order to investigate the performance and to study the wear mechanism of uncoated carbide tools on In conel 718 in the form of cylindrical bar stock of diameter 38 mm. The experiments were conducted on the L16ACE designer lathe with following specifications: power, 7.5 kW motor drive; speed range, 0–3,500 rpm, and feed range, 0.01–1,000 mm/rev with constant speed capabilities.

3.1 Work material

Inconel 718 material is used as the work material in the present investigation. The test specimens were prepared from the 38-mm cylindrical bar stock. Each specimen having 38 mm in diameter and 75 mm in length were used for turning and facing tests. The chemical composition and mechanical properties are given in Tables 1 and 2, respectively.

Table 1: Chemical compositions of Inconel 718 (%weight basis)

C	Si	Cu	Fe	Mn	Ti	Al	Cr	Mo	Ni	Co	Nb+Ta
0.034	0.07	0.04	Bal	0.09	0.98	0.48	17.40	2.98	50.80	0.04	5.294

Table 2: Mechanical properties of Inconel 718

Tensile strength (MPa)	Yield strength (MPa)	Young modulus (MPa)	Density (kg/m3)	Melting point(˚C)	Hardness (HRC)	Thermal conductivity (W/mK)
1280	1090	208×103	819	1285	18	12.23

3.2 Cutting tool material

The cutting materials are K10 type uncoated carbide inserts, and as per ISO specification, inserts are designated as SNMG 120408-QM H13A, which are having the following tool geometry: inclination angle, −6°; orthogonal rake angle, −6°; orthogonal clearance angle, 6°; auxiliary cutting edge angle, 15°; principal cutting edge angle, 75°; and nose radius, 0.8 mm. Cutting tool inserts were clamped onto a tool holder with a designation of DBSNR 2020K 12 for turning process.

3.3 Machining parameters and levels

Three levels were specified for each process parameter as given in the Table 3. The parameter levels were chosen within the intervals based on the recommendations by the cutting tool manufacturer. Three process parameters at three levels led to a total of 27 tests for finish turning processes. The machining operations were carried out on a 7.5-kW LT16 CNC lathe with a maximum spindle speed of 3,500 rpm. Three levels were specified for each process parameter as given in the Table 3. The parameter levels were chosen within the intervals recommended by the cutting tool manufacturer. A constant cutting length of 19 mm from the work piece for turning was carried out for each experiment. During wet and cold coolant machining processes nozzles of 1.5mm diameter were used to supply these coolants at a pressure of 2 bar and 0.05 Litre per Second to the cutting zone. Surface roughness was measured by Mittoyo-surftest 211 with sampling length of 0.25 mm. The flank wear was measured by Olympus Toolmakers microscope with 10× magnification and 1-μm resolution coupled with image processing software.

Table 3: Levels of machining parameters for orthogonal array

Machining parameters	Level 1	Level 2	Level 3
Cutting speed ‘V’ (m/min)	25	35	45
Feed ‘f’ (mm/rev)	0.1	0.15	0.2
Depth of cut ‘a’ (mm)	1.0	1.25	1.5

As mentioned earlier, three levels were specified for each of the factors as machining parameters (cutting speed, feed, and depth of cut). General full factorial design was chosen, which has 27 rows corresponding to the number of parameter combinations and first, second, and third columns were assigned to cutting speed (V), feed (f), and depth of cut, (a) respectively. Three tests are performed for each combination and process, resulting in a total of 81 tests for turning process which allows analysis of variance of the results. New cutting edge was used for each trial of experiments. The surface roughness was measured by positioning the stylus perpendicular to the feed marks on the machined surface towards the end of cutting. The surface roughness measurement was taken at four locations (90° apart) and repeated twice at each location on the face of the machined surface, and the average values were reported. Flank wear was measured at the end of the machining processes.

4. Results and Discussion

The plan of tests was developed with the aim of relating the influence of the cutting speed (V), feed (f) and depth of cut (a), with the flank wear (VB), and the surface roughness (Ra) on workpiece. The statistical treatment of the data was made in two phases. The first phase was concerned with the ANOVA and the effect of the factors and of the interactions. The second phase allowed us to obtain the correlations between the parameters. Afterwards, the optimal parameters results were through confirmation tests.

4.1 ANOVA and effects of factors on Surface roughness and Flank wear of turning process

An ANOVA of the data with the surface roughness (Ra) and the flank wear (VB) in workpiece, with the objective of analysing the influence of the cutting speed (V), of feed (f) and depth of cut (a) on the total variance of the results. Based on the ANOVA, the relative importance of the machining parameters with respect to surface roughness and flank wear was investigated to determine the optimum combination of the machining parameters. Tables 6 and 7 show the results of the ANOVA analysis for the surface roughness and flank wear of dry turning, Table 8, 9 and Table 10, 11 for wet and cold coolant turning processes respectively. These analysis were carried out for a significance level of α= 0.05, i.e., for confidence level of 95%. Table 5-10 shows that the probability levels are the realized significance levels, associated with the F tests for each source of variation and symbol *indicates that factors are physically significant . The sources with a probability level less than 0.05 are considered to have a statistically significant contribution to the performance measures.

Table 4: Full factorial design and experimental results for turning process

Machining parameters				Dry machining		Wet machining		Cold coolant machining	
Trail No.	Cutting speed ‘V’ (m/min)	Feed ‘f’ (mm/rev)	Depth of cut ‘a’ (mm)	Surface roughness ‘Ra’ (μ m)	Flank wear ‘VB’ (mm)	Surface roughness ‘Ra’ (μ m)	Flank wear ‘VB’ (mm)	Surface roughness ‘Ra’ (μ m)	Flank wear ‘VB’ (mm)
1	35	0.2	1.5	0.7	0.104	0.57	0.072	0.45	0.047
2	25	0.2	1	0.69	0.075	0.56	0.07	0.44	0.046
3	25	0.15	1	0.59	0.092	0.48	0.068	0.38	0.044
4	35	0.1	1	0.49	0.116	0.4	0.08	0.31	0.052
5	25	0.1	1	0.55	0.087	0.45	0.087	0.35	0.057
6	35	0.15	1	0.6	0.130	0.49	0.098	0.39	0.064
7	35	0.2	1.25	0.72	0.156	0.59	0.132	0.46	0.086
8	45	0.15	1	0.54	0.189	0.44	0.124	0.35	0.081
9	45	0.1	1	0.45	0.142	0.37	0.143	0.29	0.093
10	25	0.15	1.25	0.54	0.082	0.44	0.065	0.35	0.042
11	25	0.2	1.5	0.78	0.078	0.63	0.069	0.5	0.045
12	35	0.1	1.25	0.42	0.133	0.34	0.094	0.27	0.061
13	25	0.1	1.25	0.52	0.077	0.42	0.061	0.33	0.040
14	25	0.2	1.25	0.69	0.085	0.56	0.064	0.44	0.042
15	45	0.2	1.25	0.66	0.140	0.54	0.132	0.42	0.086
16	45	0.1	1.25	0.48	0.128	0.39	0.126	0.31	0.082
17	45	0.2	1	0.68	0.156	0.55	0.137	0.43	0.089
18	25	0.15	1.5	0.68	0.074	0.55	0.058	0.43	0.038

19	25	0.1	1.5	0.55	0.070	0.45	0.063	0.35	0.039
20	35	0.2	1	0.58	0.127	0.47	0.125	0.37	0.081
21	45	0.2	1.5	0.69	0.128	0.56	0.112	0.44	0.073
22	45	0.1	1.5	0.4	0.117	0.33	0.116	0.26	0.075
23	35	0.15	1.5	0.55	0.100	0.45	0.098	0.35	0.064
24	45	0.15	1.5	0.5	0.123	0.41	0.116	0.32	0.075
25	35	0.15	1.25	0.55	0.109	0.45	0.103	0.35	0.067
26	45	0.15	1.25	0.5	0.135	0.41	0.132	0.32	0.086
27	35	0.1	1.5	0.45	0.094	0.37	0.089	0.46	0.058

Table 5: ANOVA for surface roughness of dry turning process

Source term	Degree of freedom	Sum of squares	Mean square	F- ratio	Probability level	% of Contribution
V	2	0.028985	0.014493	9.51	0.008*	10.74
f	2	0.199319	0.099659	65.43	0.000*	73.86
a	2	0.002719	0.001359	0.89	0.447	1.01
V×f	4	0.005081	0.001270	0.83	0.540	1.88
V×a	4	0.010348	0.002587	1.70	0.243	3.83
f×a	4	0.011215	0.002804	1.84	0.214	4.16
Error	8	0.012185	0.001523			4.52
Total	26	0.269852				100.00

Also, last columns of Table 5-10 show the percentage of contribution of each source to the total variation, indicating the degree of influence on the result. According to Table 5, feed and cutting speed parameters are the most significant factors and their interactions have insignificant effect on the surface roughness generation in dry turning process. Table 5 shows the significant factors and their contribution for the surface roughness of the dry turning process which are cutting speed V (10.74%) , feed f (73.86%), depth of cut and parameters interactions have very low percentage of contribution and also insignificant of the total variation. From the analysis of Table 7, it is inferred that the most significant factor for surface roughness in the dry turning process is feed f which explains 73.86% of the total varia

Table 6: ANOVA for flank wear of dry turning process

Source term	Degree of freedom	Sum of squares	Mean square	F- ratio	Probability level	% of Contribution
V	2	0.016554	0.008277	109.42	0.000*	69.52
f	2	0.000457	0.000229	3.02	0.105	1.92
a	2	0.002981	0.001490	19.70	0.001*	12.52
V×f	4	0.000661	0.000165	2.18	0.161	2.78
V×a	4	0.001497	0.000374	4.95	0.026*	6.29
f×a	4	0.001056	0.000264	3.49	0.062	4.43
Error	8	0.000605	0.000076			2.54
Total	26	0.023811				100.00

Whilst in the ANOVA for flank wear in Table 6, the cutting speed V (69.52%), depth of cut a(12.52%) factors are having physically significant of total variation, feed and other factors interactions do not have any statistical significance. Notice that the errors associated to the ANOVA table for the surface roughness were 4.52% and the flank wear were 2.54%, which inferred that factors and interactions contributing the major role than other miscellaneous or noise factor. After analysing Table 7, for wet machining it may be observed that the feed factors (74.08%) and cutting speed factors (10.18%) have great influence on the obtained surface roughness. Analysing Table 8, it may be observed that the cutting speed factors have 78.15% contribution and also highly significant on the flank wear. Neither depth of cut nor feed factors and interactions do not present significant percentages of contribution on the obtained flank wear. It should be noticed that the error associated to the ANOVA table for wet turning process for the Ra was 4.63% and 6.88% for VB.

Table 7: ANOVA for surface roughness of wet turning process

Source term	Degree of freedom	Sum of squares	Mean square	F- ratio	Probability level	% of Contribution
V	2	0.017652	0.008826	8.7900	0.010*	10.18
F	2	0.128452	0.064226	63.9900	0.000*	74.08
A	2	0.001830	0.000915	0.9100	0.440	1.06
V×f	4	0.003415	0.000854	0.8500	0.532	1.97
V×a	4	0.006570	0.001643	1.6400	0.256	3.79
f×a	4	0.007437	0.001859	1.8500	0.212	4.29
Error	8	0.008030	0.001000			4.63
Total	26	0.173385				100.00

Table 8: ANOVA for flank wear of wet turning process

Source term	Degree of freedom	Sum of squares	Mean square	F- ratio	Probability level	% of Contribution
V	2	0.016239	0.008120	45.450	0.000*	78.15
F	2	0.000238	0.000119	0.6700	0.540	1.15
A	2	0.001369	0.000685	3.8300	0.068	6.59
V×f	4	0.000555	0.000139	0.7800	0.571	2.67
V×a	4	0.000460	0.000115	0.6400	0.647	2.21
f×a	4	0.000490	0.000122	0.6900	0.622	2.36
Error	8	0.001429	0.000179			6.88
Total	26	0.020780				100.00

Table 9: ANOVA for surface roughness of cold coolant turning process

Source term	Degree of freedom	Sum of squares	Mean square	F- ratio	Probability level	% of Contribution
V	2	0.010496	0.005248	2.43	0.149	9.68
F	2	0.060763	0.030381	14.09	0.002*	56.02
A	2	0.006007	0.003004	1.39	0.303	5.54
V×f	4	0.003215	0.000804	0.37	0.822	2.96
V×a	4	0.006504	0.001626	0.75	0.583	6.00
f×a	4	0.004237	0.001059	0.49	0.743	3.91
Error	8	0.017252	0.002156			15.90
Total	26	0.108474	0.005248			100.00

Table 10: ANOVA for flank wear of cold coolant turning process

Source term	Degree of freedom	Sum of squares	Mean square	F- ratio	Probability level	% of Contribution
V	2	0.006822	0.003411	45.0500	0.000*	77.91
F	2	0.000107	0.000053	0.7100	0.522	1.22
A	2	0.000593	0.000296	3.9100	0.065	6.77
V×f	4	0.000232	0.000058	0.7700	0.576	2.65
V×a	4	0.000194	0.000048	0.6400	0.649	2.22
f×a	4	0.000202	0.000051	0.6700	0.632	2.31
Error	8	0.000606	0.000076			6.92
Total	26	0.008756	0.003411			100.00

From the analysis of Table 9, it can be observed that the feed factors (56.02%) alone have statistical and physical significance on the surface roughness obtained by the cold coolant turning process. Other factors cutting speed (9.68%), depth of cut (5.54%) and interactions cutting speed/depth of cut (6%) and feed/depth of cut (3.91%) do not present percentages of physical significance of contribution on the surface roughness. From the analysis of Table 10, it can be observe that the cutting speed factors (77.91%) have statistical and physical significances on the flank wear obtained to perform the cold coolant turning operation. The interactions cutting speed/ feed (2.65%), cutting speed/depth of cut (2.22%) and feed/depth of cut (2.31%) do not present percentages of physical significance of contribution on the flank wear generated to perform the cold coolant turning process. In this study, the factors alone present a statistical significance the probability level is < 0.05.Notice that the error associated to the table ANOVA for surface roughness was approximately 15.9% and for flank wear was 6.92% in the cold coolant turning process.

4.2 Correlations

The correlations between the factors (cutting speed, feed and depth of cut) and the measured flank wear and surface roughness in the workpiece were obtained by multiple linear regression. The equations obtained were as follows:

Surface roughness in dry machining
$$\text{'Ra'} = 0.361 - 0.00383\times V + 2.09\times f + 0.0289\times a \quad (2)$$
R-Squared value is 82.9% for equation (2).

Surface roughness in wet machining
$$\text{'Ra'} = 0.292 - 0.0030\times V + 1.68\times f + 0.0244\times a \quad (3)$$
R- Squared value is 82.8% for equation (3).

Surface roughness in cold coolant machining
$$\text{'Ra'} = 0.219 - 0.00239\times V + 1.13\times f + 0.0556\times a \quad (4)$$
R- Squared value is 81.6% for equation (4).

Flank wear in dry machining
$$\text{'VB'} = 0.0569 + 0.00299\times V + 0.0944\times f - 0.0502\times a \quad (5)$$
R-Sq. =81.1%

Flank wear in wet machining
$$\text{'VB'} = 0.0227 + 0.0030\times V + 0.0678\times f - 0.0324\times a \quad (6)$$
R-Squared value is 84.7% for equation (6).

Flank wear in cold coolant machining
$$\text{'VB'} = 0.0151 + 0.00194\times V + 0.0456\times f - 0.0213\times a \quad (7)$$
R-Squared value is 84.6% for equation (7).

Ra the arithmetic average roughness in μm, VB the flank wear in mm, V the cutting speed in m/min, f the feed in mm/rev and a the depth of cut in mm. The R-squared value of the model is always greater than 0 and less than 1 ($0<$R-sq. <1). If the value closes to 1, the developed model gives the reliable estimation of performance measure.

4.3 Taguchi optimization analysis for minimum surface roughness

The data in Table 4 can be analysed using informal and statistical methods. This begins with determining the effects of each treatment level on the response and S/N ratio. The effects are merely the data means of the response at each level for each factor, which are shown in the Table 11and among the machining parameters feed has top rank in all of three cutting conditions. These values can then be graphically analysed, to look for relative effects on the response. A steeper slope in the graphed response effect indicates a greater effect of the parameter on the response. Figure 1; indicate a much stronger effect on Ra for feed rate than the other two parameters irrespective of cutting conditions. Based on the Taguchi's optimization process for minimizing the surface roughness the optimal parameters were obtained at V (25m/min), f (0.2mm/rev), and a (1.25mm) for dry machining, V (45m/min), f (0.1mm/rev) and a (1.25mm) for wet and cold coolant machining. It indicates that high level cutting speed can be employed for wet and cold coolant machining process which generates better surface roughness than the dry machining process.

Table 11: Surface Roughness at each level and its effects

Dry Machining				Wet Machining				Cold coolant Machining			
Level	V	f	a	Level	V	f	a	Level	V	f	a
1	0.6211	0.4789	0.5744	1	0.5044	0.3911	0.4678	1	0.3967	0.3256	0.3678
2	0.5622	0.5611	0.5644	2	0.4589	0.4578	0.4600	2	0.3789	0.3600	0.3611
3	0.5444	0.6878	0.5889	3	0.4444	0.5589	0.4800	3	0.3489	0.4389	0.3956
Delta	0.0767	0.2089	0.0244	Delta	0.0600	0.1678	0.0200	Delta	0.0478	0.1133	0.0344
Rank	2	1	3	Rank	2	1	3	Rank	2	1	3

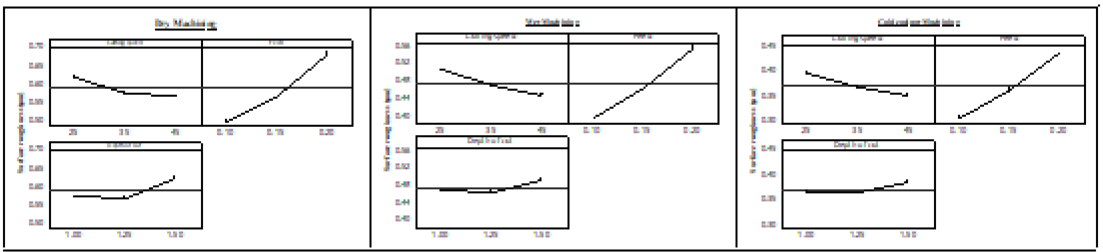

Figure 1: Main Effects Plots for Surface roughness against parameters under various conditions

Table 12: Flank Wear at each level and its effects

Dry Machining				Wet Machining				Cold coolant Machining			
Level	V	f	a	Level	V	f	a	Level	V	f	a
1	0.08000	0.10711	0.12378	1	0.06644	0.09467	0.10356	1	0.04333	0.06156	0.06744
2	0.11878	0.11489	0.11611	2	0.09900	0.09578	0.10100	2	0.06444	0.06233	0.06578
3	0.13978	0.11656	0.09867	3	0.12644	0.10144	0.08733	3	0.08222	0.06611	0.05678
Delta	0.05978	0.00944	0.02511	Delta	0.06000	0.00678	0.01622	Delta	0.03889	0.00456	0.01067
Rank	1	3	2	Rank	1	3	2	Rank	1	3	2

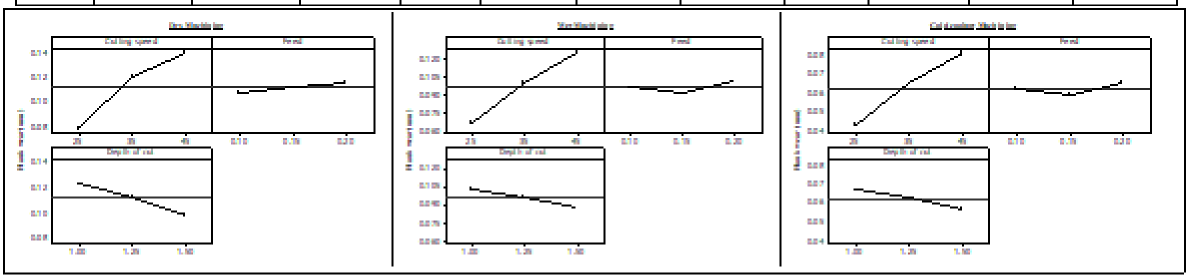

Figure 2: Main Effect Plots for Flank wear against parameters under various conditions

4.5 Confirmation Tests

The optimum machining parameters for turning confirmation tests were obtained based on the Taguchi technique and presented in Table 13 and Table 14 shows that the results were obtained as a comparison done between the foreseen values from the model developed in the present work with values obtained experimentally. From the analysis of Table 14, it can be observed that the maximum error for surface roughness and comparatively lower error in flank wear for the machining processes. The confirmation experimentsexhibit a good correlation between the predicted and the experimental responses. It can be observed that the lower surface roughness obtained by using the cold coolant machining than the other two conditions which are shown in the Figure 3. From the Figure 4 cold coolant yields the minimum flank wear than the other machining conditions. It can be observed that flank wear was severely damaged the tool face in dry and wet conditions whereas betterment in cold coolant conditions. From the confirmation experiments for the optimal machining parameters, it proves that the cold coolant drastically reduced the flank wear hence tool life has been increased. The effectiveness of the cold coolant in finish turning of Inconel 718 have been proved and presented in the Figure 5.

Table 13: Predicted Optimum Machining Parameters

Test	Machining Conditions	Optimal parameters for minimum Surface roughness	Optimal parameters for minimum Flank wear
1.	Dry machining	V 45, f 0.1, a 1.25	V 25, f 0.1, a 1.5
2.	Wet machining	V 45, f 0.1, a 1.25	V 25, f 0.1,a 1.5
3.	Cold coolant machining	V 45, f 0.1, a 1.25	V 25, f 0.1, a 1.5

Table 14: Confirmation tests and comparison with the experimental results

Test	Machining Condition	Surface roughness 'Ra' (µm)			Flank wear 'VB' (mm)		
		Predicted	Experimental	Error (%)	Predicted	Experimental	Error (%)
1.	Dry machining	0.70	0.69	1.43	0.073	0.071	2.74
2.	Wet machining	0.37	0.39	5.13	0.065	0.063	3.07
3.	Cold coolant machining	0.28	0.31	9.68	0.042	0.039	7.14

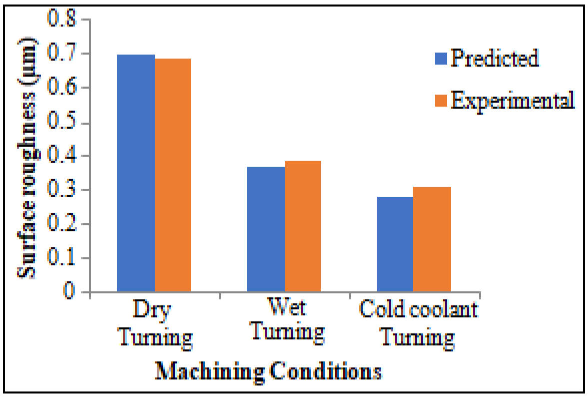

Figure 3: Experimental validation for minimum surface roughness

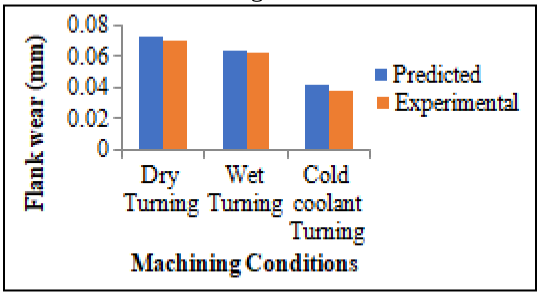

Figure 4: Experimental validation for minimum flank wear

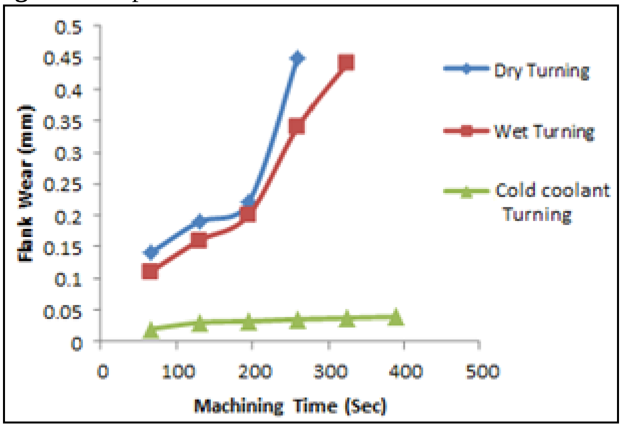

Figure 5: Optimal machining conditions machining time verses flank wear

5. Conclusion

In this study, surface roughness and tool flank wear have been investigated in finish turning of Inconel 718 using uncoated carbide inserts. Linear regression models are developed for predicting surface roughness and tool flank wear. The following conclusions are drawn from this work:

Feed rate is the cutting condition that has highest physical as well statistical influence on the surface roughness, cutting speed had a moderate effect, and depth of cut had an insignificant effect in all of the cutting conditions. This would indicate that feed rate and cutting speed might be included alone in future studies, although the literature review would caution against ruling out depth of cut altogether.

Cutting speed is the cutting condition that has highest physical as well statistical influence on the flank wear, depth of cut had a moderate effect, and feed had low effect in all of the cutting conditions.

Optimal machining parameters for minimum surface roughness were determined. The percentage error between experimental and predicted results are 1.43%, 5.13%, and 9.68% in turning process under dry, wet and cold coolant respectively.

Optimal machining parameters for minimum flank wear, the percentage error between experimental and predicted result are 2.74%, 3.07%, 7.14% for turning process under dry, flooded and cold coolant respectively.

Based on the Taguchi's optimization analysis the higher cutting speed is the optimal value for minimization of surface roughness in wet and cold coolant machining whereas low cutting speed is the optimal value for minimization of flank wear in all the cutting conditions.

Experimental result indicates that among the conditions use of cold coolant is encouraging in respect of finish turning performance parameters shown in figure 5.

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Nomenclature

V	: Cutting speed (m/min)
f	:feed (mm/rev)
a	: depth of cut (mm)
Ra	*:* Surface roughness (µm)
VB	*:* Flank wear (mm)
S/N	: Signal to Noise ratio