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Effect of Cooling Environment on Grinding Performance of Nickel Based Superalloy Inconel 718

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Abstract: The study presents the experimental investigation of surface grinding of superalloy Inconel 718. The grinding performance in terms of grinding force, surface roughness and surface topography were examined by conducting statistical experiments. The parameters that have been chosen as control factors are: table speed, infeed, grit size and the type of lubricant. An L_{27} orthogonal array experiments were conducted. The results show that the grit size and infeed are the most significant parameters on surface roughness Ra measured across the table feed direction. The interaction effect between lubricant and grit size is relatively important as compared to the individual effect of the latter variable. As far as the grinding forces are concerned, the grit size and table speed have largest contribution among the chosen parameters. SEM (Semester) examination revealed the flaws such as abrasion marks, smeared layers and micro-particle deposits on the surfaces produced in grinding.

Key words: Surface grinding, inconel 718, Taguchi design, grinding forces, surface roughness, SEM

INTRODUCTION

Nickel based superalloy Inconel 718 finds extensive applications in missile, aerospace, gas turbines, chemical, petrochemical and nuclear plants due to their competitive characteristics such as high specific strength, corrosion resistance, wear resistance and high temperature properties compared with other alloys. Despite of these good mechanical properties, they have serious issues of poor machinability and hence regarded as a difficult-to-cut material (Pawade *et al.*, 2007). There will be a greater demand to establish process parameters that produce surfaces with high precision and reliability longevity in product performance. Surface grinding is extensively used operation in finishing of flat shaped components. Being a secondary and last in the manufacturing cycle, a care is vital while selecting the process parameters to induce minimum damage to the surfaces. It was reported that the higher grinding speed and the temperature gradients developed during grinding operation could lead to thermal damage on the work surfaces. A number of researchers have described relationships between process factors affecting the performance of the grinding fluid. Some of the relevant findings are as follows.

Osterle and Li (1997) conducted experimental investigation on grinding of superalloy IN738. They reported that the local melting at contact spot leading to formation of white layers. It is found that the grinding wheel characteristics have a significant effect on surface topography of the machined surfaces. Jae-Seob (2004) studied the effect of grinding parameters on geometric error using Taguchi and response surface methodologies. They concluded that the depth of cut was dominant parameter influencing geometric error. Hwa-Soo (1996) found that the higher surface speed of grinding wheel results in lower grinding forces when CBN (Christian Broadcasting Network) wheel was used. Further higher peripheral speed of CBN wheel results in lower grinding forces. Xu *et al.* (2002) conducted experimental investigation in surface grinding of a cast nickel based superalloy with alumina abrasives wheels to assess the surface integrity. Shaji and Radhakrishnan (2003) conducted experimental investigation on effect of coolant on the workpiece quality in surface grinding process. They reported that the application of graphite reduces the heat generated in grinding zone and thus found that the tangential force and normal force is higher as compared to those in conventional grinding. Di Ilio and Paoletti (1999) found that the decrease in grindability is mainly caused by clogging of the active surface on the wheel due to chip adhesion rather than by flattening of grits caused by the abrasion of hard reinforcement. It is reported that the alumina/SiC grinding wheels produce lower grinding forces and better surface finish than those with super abrasive wheels. Venugopal and Rao (2005) reported an improvement in surface finish under the graphite assisted

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grinding. Besides, a considerable reduction of tangential force and specific grinding energy causes reduction in surface damages. Yin *et al*. (2005) found that the grinding at conventional as well as high speed do not have much difference on the grinding characteristics and surface damages. Both normal and tangential grinding force ratios at high speed were lower than those at the conventional speed. At higher grinding speed, due to increased metal removal rate, the normal forces are 4-6 times higher than the pure normal grinding forces. Kwak *et al*. (2007) optimized the grinding parameters in surface grinding of MMC using surface roughness and grinding force with Taguchi and response surface methods. It is observed during grinding of MMC that the normal grinding force changes very rapidly with the increase in the number of passes due to the wheel clogging. The tangential and normal forces found to be increased moderately with an increase in the depth of cut. It is reported that the surface roughness increases with an increase in the depth of cut and work speed during surface grinding Di Ilio *et al*. (1996).

As far as the superalloy Inconel 718 is concerned, very few studies have been reported till date. These include investigation of grinding mechanism and surface integrity. Manufacturers of nickel-based and cobalt-based turbine engine components often use plated CBN wheels in various grinding steps due to their capability of supporting high removal rates and their ability to hold consistent form without the need for in-line dressing steps (Harpster, 1991). However, they are costly and thus not commercialized in the shop floors. Pei-Lum (1994) studied the grinding of Inconel 718 in which he examined the surface finish, grinding force, wheel wear using different grinding wheels; He found that the CBN grinding wheel gives better performance as compared to WA and GC grinding wheels.

In the view of the above, the study reports the analysis of the grinding parameters on the surface roughness and the grinding force and determining the optimal sets of grinding parameters to be able to improve the grinding performance.

MATERIALS AND METHODS

Taguchi design of experiments: The Taguchi method is a traditional approach for robust experimental design that seeks to obtain a best parametric combination and the levels with the lowest cost and higher quality to achieve customer satisfaction. In the Taguchi design, the factors that can be controlled by designers called as control parameters and noise factors (factors that cannot be controlled by designers, such as environmental factors) are considered to be influential on process output. Therefore, the Taguchi design selects the levels of process parameters and reduces the effects of noise factors. That is parameter setting should be determined with the intention that the product response (quality characteristic) has minimum variation, while its mean is close to the desired target (Box GEP, 1985). Taguchi recommends the following step-by-step procedure for designing the experiments and analysis:

- Determining the quality characteristics (response variables) to be optimized
- Identifying the noise factors and test conditions
- Identifying the control factors and their alternative levels
- Selecting orthogonal matrix
- Selecting performance characteristics, S/N ratio
- Conducting the matrix experiment
- Analysing the data and determine optimum levels for control factors
- Predicting the performance at these levels

Determining the quality characteristics to be optimized: In this study, two types of response variables were used. These are: (i) in-process variables and (ii) post-process variables.

Grinding forces: Cutting forces in grinding influence surface and sub-surface quality. Therefore, magnitudes of the cutting force components during grinding, viz. Tangential-F_t and normal-F_n were selected as in process response variables.

Surface roughness: It is a geometrical feature of the machined surface that significantly influences the machined surface integrity. Therefore, the arithmetic average (R_a) (centerline average of peak to valley) surface roughness was selected as the post process response variables.

Identifying the control factors and their levels: Taguchi classified the factors in an experiment as control factors and noise factors. The factors which can be controlled by the designer or operator, are called as control factors. On the other hand, the noise factors cannot be controlled in the actual process (Phadke, 1989). The noise factors can be humidity, dust, temperature of the environment, material property variation, machine vibration, etc. In surface grinding, process, wheel and work material related parameters influence the quality of the ground surfaces. As far as the scope of this investigation is concerned, a few of them have been selected with consideration to

Table 1: Selection of control factors and their levels

Process parameters symbol	Process Parameters	Levels 1	2	3
A	Lubricant	Coconut oil	SAE+graphite	Liquid nitrogen
B	Grit size	60	120	220
C	Table speed, m min^{-1}	8	10	12
D	Infeed, mm	0.05	0.10	0.15

Table 2: Standard L_{27} (3^{13}) orthogonal matrix

	Column			
Expt. No.	1	2	5	9
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	2
5	1	2	2	3
6	1	2	3	1
7	1	3	1	3
8	1	3	2	1
9	1	3	3	2
10	2	1	1	2
11	2	1	2	3
12	2	1	3	1
13	2	2	1	3
14	2	2	2	1
15	2	2	3	2
16	2	3	1	1
17	2	3	2	2
18	2	3	3	3
19	3	1	1	3
20	3	1	2	1
21	3	1	3	2
22	3	2	1	1
23	3	2	2	2
24	3	2	3	3
25	3	3	1	2
26	3	3	2	3
27	3	3	3	1

Table 3: Experimental matrix with assigned parameters and response values

	Matrix column				Force, N		
Run	A	B	C	D	F_t	F_n	Ra (μm)
01	CO	60	8	0.05	67.8	118	0.96
02	CO	60	10	0.1	71.9	121.6	0.88
03	CO	60	12	0.15	70.5	120	1.09
04	CO	120	8	0.1	66.9	115.8	0.50
05	CO	120	10	0.15	66.6	214	0.53
06	CO	120	12	0.05	67.9	126	0.59
07	CO	220	8	0.15	66.8	113.9	0.42
08	CO	220	10	0.05	66.3	154	0.16
09	CO	220	12	0.1	67.5	113.8	0.18
10	SG	60	8	0.1	70	119.5	1.20
11	SG	60	10	0.15	70.1	120.3	1.30
12	SG	60	12	0.05	69.9	120	1.17
13	SG	120	8	0.15	68	112	0.47
14	SG	120	10	0.05	67	155	0.39
15	SG	120	12	0.1	65	137	0.45
16	SG	220	8	0.05	64.7	113	0.19
17	SG	220	10	0.1	66	115.7	0.24
18	SG	220	12	0.15	68	119	0.33
19	LN	60	8	0.15	68.5	115	1.50
20	LN	60	10	0.05	67	154	1.25
21	LN	60	12	0.1	67.3	109	1.07
22	LN	120	8	0.05	68	152	0.51
23	LN	120	10	0.1	67	112.9	0.50
24	LN	120	12	0.15	66	117	0.54
25	LN	220	8	0.1	66.3	166	0.20
26	LN	220	10	0.15	67.6	124	0.37
27	LN	220	12	0.05	66	111.3	0.26

A: Lubricant, B: Grit size, C: Table speed, D: Infeed, F_t: Tangential force, F_n: Normal force, R_a: Surface roughness

constraints on availability of machine, grinding wheel and the work material. The machining parameters were selected on the basis of the knowledge available in the literature and the past experience. It is believed that the table speed, infeed, grit size and the type of lubricant employed during grinding influences the forces and the mechanism of surface generation. As a result, it alters the nature of machining deformation and consequently nature of the surface generated. Therefore, the three parameters that have been chosen as control factors are: table speed, infeed, grit size and the type of lubricant (Table 1). Further, three two-factor interactions such as-lubricant and grit size, lubricant and table speed and grit size and table speed were chosen. The higher order interactions are generally not significant in engineering applications and hence were neglected (Ross, 1996).

Selecting orthogonal matrix: Taguchi's orthogonal matrix provides an alternative to standard factorial designs (Phadke, 1989). In the present study, four grinding parameters were considered as independent variables: table speed, infeed, grit size and the type of lubricant. Each of them has three different levels. Further, some interactions between them were selected. Thus total 20° of freedom are needed to calculate main effects of the factors and their interactions. Therefore, an L_{27} orthogonal matrix was selected (Table 2) because it has 26° of freedom which is greater than the required 20° of freedom. The experimental design matrix with assigned parameters is shown in Table 3.

Selecting performance characteristics: In Taguchi's methodology it is the "signal-to-noise" ratio which is used as a measure of performance. Here, the term 'signal' represents the desirable value (mean) and the 'noise' represents the undesirable value standard deviation). Thus, the S/N ratio represents the amount of variation present in the performance characteristic. As every process performance characteristic would have a target or nominal value. The robust design reduces the variability around this target or nominal value and models the departures from the target value as a loss function. Depending upon the objective of the performance characteristic, there are three types of S/N ratios. Here, the desirable objectives are to minimize the values of

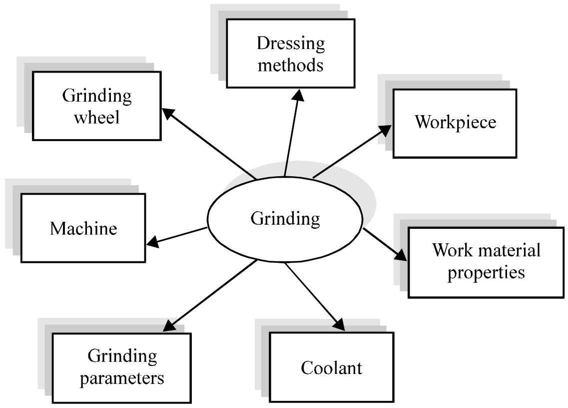

Fig. 1: Factors affecting grinding performance in Inconel 718

Table 4: Chemical composition of received Inconel 718

Element	Weight (%)	Element	Weight (%)
Ni	53.039	Cu	0.047
Cr	17.13	W	0.208
Fe	19.36	C	0.031
Mo	2.869	Al	0.315
Ti	1.119	Si	0.038
Nb	4.769	Mn	0.082
Co	0.957		

tangential and normal forces. Hence, the Lower-the-Better (LB) type S/N ratio, as defined below was applied for transforming the raw data (Ross, 1996).

$$S/N\,ratio(\eta) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

where, y_i is the value of the characteristic in an observation i and n is the number of observations or number of repetitions in a trial.

CONDUCTING THE EXPERIMENTS

Work material, grinding wheel and equipment: The work material used for the investigation was superalloy Inconel 718. The chemical composition of work material is shown in Table 4. These are prepared as a square shaped specimen with dimensions 20×20×5 mm. Annealing of the work specimen was carried out at temperature 995-1065°C over 30-60 min duration. It was performed in a salt bath furnace. After annealing the work specimen were cooled in the air. The purpose of annealing was to relieve induced stresses from previous machining operation used for sample preparation to the required size. The Al_2O_3 grinding wheel was used for the grinding tests. Factors affecting grinding performance in Inconel 718 are shown in Fig. 1.

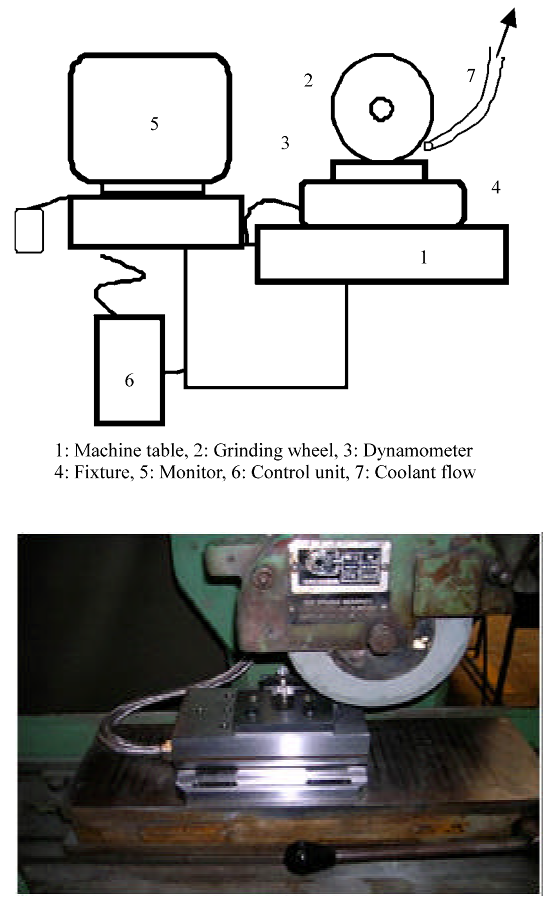

Fig. 2: Schematic of experimental set up and photograph of surface grinding

Experimental procedure: A photograph of detailed set up and close view of grinding operation is shown in Fig. 2. A PRAGA make 451 AP model surface grinder was used for the experimental work. The specimens are clamped to the fixture on grinding chuck. A kistler dynamometer model 9257A was fitted on grinding table for measurement of grinding force. A suitable arrangement was made to supply the coconut oil and SAE+graphite to the grinding zone. Liquid nitrogen was supplied to the grinding wheel and work piece interface from the cryocan. The grinding wheel was mounted on machine spindle and properly balanced. Machine is adjusted to required stroke and desired table speed is set for the experiment. Dial probe was touched on work piece and desired depth of cut is set. As per the design matrix 27 experiments were performed. The grinding wheels were dressed with a commercial single point diamond dresser after every two tests to keep the cutting edges sharp during grinding.

The grinding force magnitude and pattern were acquired through cutting force dynamometer. Surface roughness of the ground specimen along cross-feed direction was measured at three locations on the specimen's surface using a portable surface roughness tester (Make-Mitutoyo, Model-Surftest SJ301). The cut-off and sampling length for each measurement were kept as 0.8 and 4.8 mm, respectively. Surface topography of the ground specimens was examined using scanning electron microscopy (Make-JEOL-JSM) at various magnifications.

EXPERIMENTAL RESULTS AND DISCUSSION

Statistical Analysis of Surface Roughness R_a: It is observed from Fig. 3 that the lubricant used and the grit size of grinding wheel have shown linear trend, however infeed and table speed show nonlinear effect on the surface roughness. Further, it was seen that the grit size of grinding wheel used for experiments in this study has larger effect on the surface roughness compared to the other parameters. It is seen that the use of coconut oil leads to efficient cooling effects and thus suppressed the effect of grinding temperature on the work surface.

Therefore, the surfaces show lower values of the surface roughness. However, the highest surface roughness is observed when liquid nitrogen coolant was used while grinding. In the case of effect of grit size, the higher grit size results into lower surface roughness of the ground specimen. On the contrary, the smaller grit size wheels produced the higher surface roughness during grinding. It is found that the smaller chip thickness produced on account of smaller grain size of the grinding wheel abrasives. This will lead to generation of smaller peak to valley height during grinding. Hence higher grit wheels produce lower surface roughness.

The percentage contribution of various input factors on the selected performance characteristic can be estimated by performing ANOVA. The total variation in the result is the sum of variation due to various controlled factors and their interactions and variation due to experimental error. The ANOVA for S/N ratio have been performed to identify the significant parameters and to quantify their effect on the performance characteristic.

It is observed from analysis of variance (Table 5) that the grit size, followed by the infeed and the interaction between lubricant type and grit size show statistical significance at 95% confidence level on the surface roughness. The higher value of the coefficient of correlation, R^2 = 99.3 shows that the model developed is adequate to fit actual values with the predicted values of the surface roughness.

Figure 4 and 5 shows the normal probability plots of residual. A residual is the difference between the actual and predicted values of response variable. It is observed

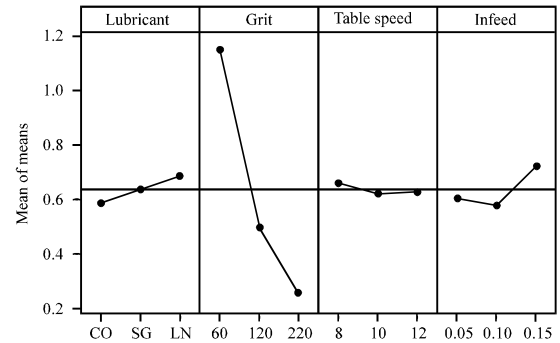

Fig. 3: Main effects plots of surface roughness (R_a) along cross-feed direction

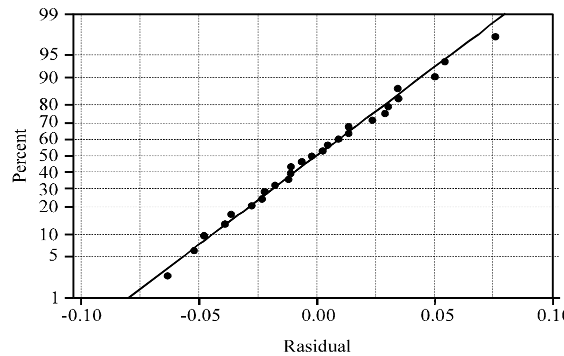

Fig. 4: Normal probability plot for R_a across the table feed

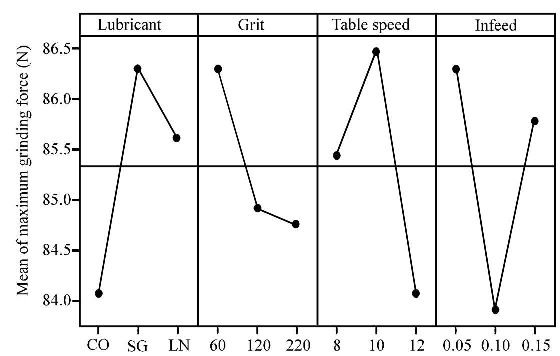

Fig. 5: Main effects plot of tangential grinding force

that almost all the residuals lies along the straight line. It indicates the best fit of the model and is adequate.

Statistical analysis of tangential grinding force: It is seen that the parameter grit size of grinding wheel has linear trend, however table speed, type of lubricant and infeed have nonlinear trend on the tangential force. It is seen that the use of coconut oil leads to efficient cooling effects due higher heat removal capacity and thus

Table 5: Analysis of variance for means (R_a Across)

Source	df	SS	V	F-ratio	F-tab	p (%)
A	2	0.04402	0.02201	4.30	4.10	1.03
B*	2	3.88687	1.94343	379.41	4.10	91.30
C	2	0.00687	0.00343	0.67	4.10	0.16
D*	2	0.11042	0.05521	10.78	4.10	2.59
A×B*	4	0.12604	0.03151	6.15	3.48	2.96
A×C	4	0.03538	0.00884	1.73	3.48	0.83
B×C	4	0.01693	0.83	0.554	3.48	0.40
Error	31	0.03073	0.00512			
Total	53	4.25726				

S = 0.07157, R^2 = 99.3%, R^2 (adj) = 96.9% , *Significant at 95% confidence level, SS: Sum of squares, SS': Adjusted sum of squares, DF: Degrees of freedom, V: Variance, A: Lubricant, B: Grit size, C: Table speed, D: Infeed

Table 6: Analysis of variance for tangential force (F_x)

Source	df	SS	V	F-ratio	F-tab	Contribution (%)
A	2	22.94	11.469	0.68	4.10	5.30
B	2	12.59	6.295	0.37	4.10	2.91
C	2	25.52	12.762	0.75	4.10	5.89
D	2	28.11	14.056	0.83	4.10	6.49
A×B	4	15.35	3.837	0.23	3.48	3.54
A×C	4	31.91	7.977	0.47	3.48	7.37
B×C*	4	296.81	74.204	4.37	3.48	68.51
Error	31	101.93	16.988			
Total	53	535.16				

S = 12.10, R^2 = 79.0% R^2 (adj) = 8.8%, *Significant at 95% confidence level, SS: Sum of squares, SS': Adjusted sum of squares, DF: Degrees of freedom, V: Variance, A: Lubricant, B: Grit size, C: Table speed, D: Infeed

suppressed the effect of grinding temperature on the work surface. This in turn facilitates the deformation and thus the lower magnitude of forces is required for removal of material during grinding. However, the highest forces are observed when SAE+graphite were used as a coolant while grinding. In the case of grit size effect, the higher grit size results into lower forces. On the contrary, the smaller grit size wheels produced the higher magnitude of forces during grinding. It is found that the area of metal removed per unit chip thickness would be higher, thus higher forces are required for removal of material. It is seen that the forces generated during grinding were of lower magnitude when the table speed was at its highest level of 12 m min^{-1}. However, the grinding forces are of larger magnitude when the table speed was 10 m min^{-1}. A change of table speed from 10 to 12 m min^{-1} resulted into drastic reduction in the grinding forces. It is observed that the increase in infeed from 0.05 to 0.10 mm reduces the magnitude of grinding force by a significant amount. Further increase in the infeed to 0.15 mm causes an increase in the magnitude of grinding force. This increasing trend of force is due to increase in the deformation area involved during the grinding process.

It is observed from analysis of variance (Table 6) that the interaction between grit size and table speed (BC) shows statistical significance at 95% confidence level on the grinding force. The value of the coefficient of correlation, R^2 = 79% shows that the model developed is adequate to fit actual values with the predicted values of the grinding force. It is noted that the interaction BC has the largest share of 68.51% on the variability of grinding force magnitude. Among the independent factors, only infeed has shown maximum share on the grinding force variability determined using ANOVA.

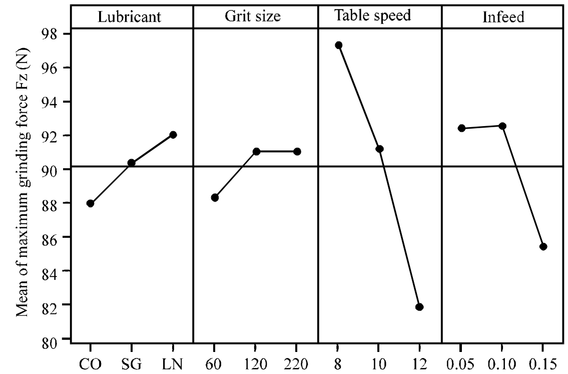

Fig. 6: Main effects plot of maximum normal grinding force

Statistical analysis of normal grinding force : Effects of grinding process parameters on the normal grinding force are discussed using main effects plots as shown in Fig. 6. It is observed that all the selected grinding parameters show linear trend on the force produced during grinding. It is seen that the use of coconut oil is more effective in reducing the heat generated during grinding. Therefore, the lower magnitude of forces is required for removal of material during grinding when coconut oil is used. However, significantly higher forces are observed when liquid nitrogen was used as a coolant while grinding. It is observed that the forces produce at 60 grit size wheel is smaller. But increase in the grit size to either 120 or 220 causes increase in the magnitude of forces. It is found that the area of metal removed per unit chip thickness would be less, thus lower forces are required for removal of material for lower grit grinding wheel. Table speed has significant effect on the generation of grinding forces. It is seen that the forces generated during grinding were of lower magnitude when the table speed was at its highest level of 12 m min^{-1}. higher grinding forces are seen when the table speed was at its lowest level of 8 m min^{-1}. It is observed that the increase in infeed from 0.10 to 0.15 mm decreases the magnitude of grinding force by a significant amount. However, a negligible change in the force magnitude is observed when the infeed increases from 0.05 to 0.10 mm.

It is observed from analysis of variance (Table 7) that none of the main factors and their interaction show statistical significance on grinding force at 95% confidence level. The value of the coefficient of

Table 7: Analysis of variance for normal grinding force (F_z)

Source	df	SS	V	F-ratio	F-tab	P (%)
A	2	75.19	37.60	0.26	4.10	2.28
B	2	44.15	22.08	0.15	4.10	1.34
C	2	1086.72	543.36	3.71	4.10	32.95
D	2	297.17	148.58	1.01	4.10	9.01
A×B	4	943.57	235.89	1.61	3.48	28.61
A×C	4	102.79	25.70	0.18	3.48	3.12
B×C	4	748.51	187.13	1.28	3.48	22.70
Error	31	878.57	146.43			
Total	53	4176.67				

S = 0.1964, R^2 = 82.1%, R^2 (adj) = 22.5%, *Significant at 95% confidence level, SS: Sum of squares, SS': Adjusted sum of squares, DF: Degrees of freedom, V: Variance, A: Lubricant, B: Grit size, C: Table speed, D: Infeed

Table 8: Optimal sets of grinding parameters to improve grinding performance

Performance measures	Lubricant, (Type) A	Grit size (#)B	Table speed ($m\ min^{-1}$) C	Infeed (mm) D
Surface roughness	CO (A1)	220 (B3)	10 (C2)	0.10 (D2)
Tangential force	CO (A1)	220 (B3)	12 (C3)	0.10 (D2)
Normal force	CO (A1)	60 (B1)	12 (C3)	0.15 (D3)

correlation, R^2 = 82.1% shows that the model developed is adequate to fit actual values with the predicted values of the grinding force.

OPTIMIZED GRINDING PARAMETERS

The grinding performance of the superalloy Inconel 718 was evaluated during surface grinding process. The optimal sets to improve the surface roughness and to reduce the grinding force were determined and are presented below. It may be noted that except table speed, all grinding parameters having the same value were applicable to achieve good surface finish and to reduce the tangential grinding force (Table 8). It was very difficult for the same grit size to satisfy both the good surface finish and the lower value of tangential grinding force. The medium value of the table speed is better for the surface finish but worst for the tangential grinding force. Further, the parameter levels that produce the smaller normal grinding force are different than the parameters satisfying the lower surface roughness. Hence, it is necessary to select the grinding parameters sacrificing one of them. From the above results, it follows that, if the criterion for selection of coolant for the smaller magnitude of forces and good surface finish, the best choice will be the use of coconut oil as a coolant during grinding.

SURFACE TOPOGRAPHY OBSERVATIONS

Surface topography reveals the surface features of an object or "how it looks", its texture; detectable features limited to a few micrometers. Surface topography of few ground samples was examined using Scanning Electron Microscope (SEM). Scanning electron micrographs of these samples are presented in Fig. 7. The surface

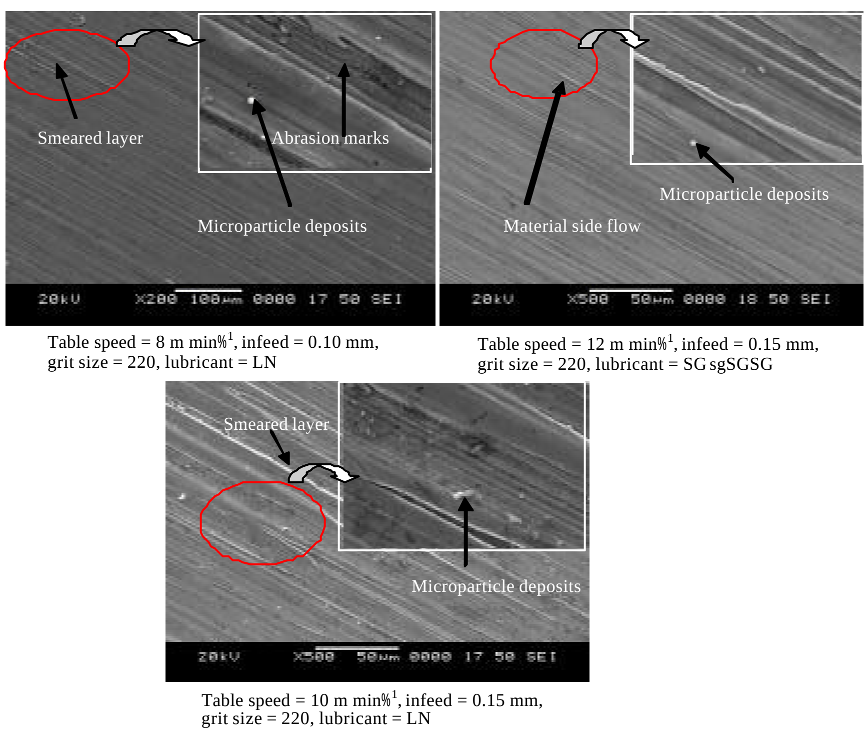

Fig. 7: SEM micrographs of ground surfaces

presents discrete streaks of grinding lay (grinding marks) The surface texture also presents different flaws such as abrasion marks, smeared layers and microparticle deposits. Smeared layers seen on the ground surfaces are the indication of higher grinding temperature and thus show the intensity of plastic deformation. Microparticle deposits are shown spread over the surfaces are due to localized pull out of the surface. The number of microparticles seen on the surface is more due to increase in the infeed. Abrasion marks are the result of interaction of abrasive cutting point with the work material. In the case of surfaces produced when SAE+graphite coolant was used, the microparticles and the material flow was less due to presence of graphite.

CONCLUSIONS

Surface grinding of Inconel 718 reported in this article is an important finishing process for machining of precision components. Within the range of test parameters used, the following conclusions can be drawn:

- The grit size of grinding wheel shows dominant effect on surface roughness Ra measured across the grinding direction
- In the case of lubricant, the coconut oil is more effective in reducing the surface roughness/
- The grit size, infeed and interaction between lubricant type and grit size shows statistical significant on surface roughness at 95°/CI
- In the case of grinding forces use of coconut oil leads to efficient cooling effects and lower tangential and normal forces are produced
- Table speed shows dominant effect in reduction of grinding forces
- The ground surfaces show the alterations such as abrasion marks, micro particle deposits and smeared layers

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