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Application of Taguchi Method to Study the Influence of Cutting Parameters on the Surface Hardness in Turning Inconel 718

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Abstract— In this study, the Taguchi method is used to investigate the relation between changes in hardness caused on the material surface due the turning operation with respect to different machining parameters. The orthogonal array, the signal-to-noise ratio, and analysis of variance are employed to study the performance characteristics in turning operations of Inconel 718 bars using TiCN – Al_2O_3 coated cemented carbide insert tools. Three cutting parameters namely, speed, feed rate, and depth of cut are used to find the optimum combination of the cutting parameters to minimize the surface hardness using Taguchi method. Experimental results are provided to illustrate the effectiveness of this approach.

Index Terms— Turning, Taguchi, Inconel 718, Vickers surface hardness, S/N ratio.

1 INTRODUCTION

IN modern industry the goal is to manufacture low cost, high quality products in short time. Automated and flexible manufacturing systems are employed for that purpose along with computerized numerical control (CNC) machines that are capable of achieving high accuracy and very low processing time. Turning is the first most common method for cutting and especially for the finishing machined parts. In a turning operation, it is important task to select cutting parameters for achieving high cutting performance. Usually, the desired cutting parameters are determined based on experience or by use of a handbook.

Hardness is generally considered as resistance to penetration. The harder the material, the greater is the resistance to penetration. Hardness is directly related to the mechanical properties of the material. Factors influencing hardness include microstructure, grain size, strain hardening, etc. The most popular methods are brinell, vickers and rockwell hardness tests for metals and alloys. Always researchers have tried to investigated the relation of surface roughness with different process parameters of different machining operations like drilling, milling etc. But there is a gap in determining of the exact affect of speed, feed and depth of cut on hardness of work piece in turning operation. Therefore this aspect has been selected for study in this research paper.

To select the cutting parameters properly, several mathematical models [1–5] based on statistical regression or neural network techniques have been constructed to establish the relationship between the cutting performance and cutting parameters. Then, an objective function with constraints is formulated to solve the optimal cutting parameters using optimization techniques. Therefore, considerable knowledge and experience are required for this approach. In this study, an alternative approach based on the taguchi method [6–8] is used to determine the desired cutting parameters more efficiency.

2 TAGUCHI METHOD

Taguchi has developed a methodology for the application of designed experiments, including a practitioner's handbook [1]. This methodology has taken the design of experiments from the exclusive world of the statistician and brought it more fully into the world of manufacturing. His contributions have also made the practitioner work simpler by advocating the use of fewer experimental designs, and providing a clearer understanding of the variation nature and the economic consequences of quality engineering in the world of manufacturing [1,2].

In Taguchi method, the word "optimization" implies "determination of best levels of control factors". In turn, the best levels of control factors are those that maximize the signal-to-noise ratios. The signal-to-noise ratios are log functions of desired output characteristics. The experiments, that are conducted to determine the best levels are based on "orthogonal arrays", are balanced with respect to all control factors and yet minimum in number. This in turn implies that the resources (materials and time) required for the experiments are also minimum.

The use of the parameter design of the taguchi method to optimize a process with multiple performance characteristics includes the following steps [11]:

1. Identify the performance characteristics and select process parameters to be evaluated.
2. Determine the number of levels for the process parameters and possible interactions between the process parameters.
3. Select the appropriate orthogonal array and assignment of process parameters to the orthogonal array.
4. Conduct the experiments based on the arrangement

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of the orthogonal array.

5. calculate the total loss function and the s/n ratio.
6. Analyze the experimental results using the s/n ratio and anova.
7. Select the optimal levels of process parameters.
8. Verify the optimal process parameters through the confirmation experiment.

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2.1 Selection of cutting parameters and their levels inal Stage

The cutting experiments were carried out on an Johnford T35 CNC lathe using TiN coated tools with the grade of P-20 for the machining of AISI 1030 steel bars. In the tests used inserts were TNMG160404-MA,TNMG160408-MA and TNMG160412-MA.. The initial cutting parameters were as follows: insert radius of 0.8 mm, a feed rate of 0.25 mm/rev, and a depth of cut of 1.5 mm. The feasible range for the cutting parameters was recommended by a machining handbook, i.e., insert radius in the range 0.4–1.2 mm, feed rate in the range 0.15–0.35 mm/rev, and depth of cut in the range 0.5–2.5 mm. Therefore, three levels of the cutting parameters were selected as shown in Table 3.

Inconel 718 is Gamma Prime (Ni_3Nb) strengthened alloy with excellent mechanical properties at elevated temperatures, as well as cryogenic temperatures. The chemical composition of Inconel 718 is given in Table 1. The properties of Inconel 718 are given in Table 2.

Table 1 Chemical composition of Inconel 718

Element	**% by mass**
Nickel + Cobalt	50.0 – 55.0
Chromium	17.0 – 21.0
Niobium + Tantalum	4.75 – 5.5
Molybdenum	2.8 – 3.3
Cobalt	1.0
Carbon	0.08
Aluminium	0.65 – 1.15
Silicon	0.35
Manganese	0.35
Titanium	0.3
Copper	0.2 – 0.8
Boron	0.006
Phosphorus	0.015
Sulphur	0.015
Iron	Remaining

Inconel 718 is used in any environment that requires resistance to heat and corrosion but where the mechanical properties of the metal must be retained.

Table 2 Properties of Inconel 718

Property	**Metric value**
Density (annealed & aged)	8190 kg/m^3
Melting range	1260-1335 °C
Curie temperature (annealed & aged)	-113 ^{o}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^2
Specific heat	435 J/kg °C (at 21°C)

High-speed machining to cut nickel-based super alloy Inconel 718 has long been researched to increase cutting process productivity [13]. The challenge and difficulty to machine Inconel 718 is due to its profound characteristics such as high shear strength, tendency to weld and form build-up edge, low thermal conductivity [12], and high chemical affinity. Inconel 718 also has the tendency to work harder and retain major part of its strength during machining. Due to these characteristics, Inconel 718 is not easy to cut and thus has been regarded as a difficult-to-cut material. Inconel 718 being a difficult-to-machine material requires hard cutting tool

3 Methodology

A methodology was developed to study the influence of cutting parameters on the surface hardness developed after turning of Inconel 718 with TiCN – Al_2O_3 coated cemented carbide insert.

3.1 Cutting conditions

The workpiece considered for the experiment was Inconel 718 and cemented carbide insert with TiCN – Al_2O_3 coating was used as cutting tool which were shown in Figures 3.1 and 3.2 respectively. The ISO designation of the cutting tool insert is TNMG 160408–MT. Turning tests were carried out on a Computer Numerically Controlled (CNC) lathe machine under wet condition using ISO VG68 cutting fluid. The CNC lathe machine, located in "M. Govind & Sons", Perecharla, Guntur, used for the experimental purpose was of Simple Turn type by ACE Designers Limited and was shown in Figure 3. Three cutting parameters (speed, feed rate and depth of cut) were considered with three levels for each cutting parameter. The cutting speeds were 300, 400 and 500 rpm. The feed rates used were 0.05, 0.1 and 0.15 mm/rev. The depths of cut of 0.1, 0.3 and 0.5 mm were used. The cutting parameters and their levels were summarised in Table 3.

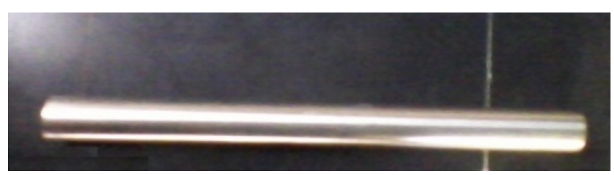

Figure 1 Workpiece: Inconel 718

Figure 2 Cutting tool: TiCN−Al_2O_3 coated cemented carbide insert

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Figure 3 CNC lathe machine

Table 3 Experimental factors and their levels

Levels of the experimental factors	Factors		
	Speed -N (rpm)	**Feed rate-f (mm/rev)**	**Depth of cut -d (mm)**
1	300	0.05	0.1
2	400	0.10	0.3
3	500	0.15	0.5

3.2 Orthogonal array selection

Three experimental factors and three levels for each factor are considered. So, L9 orthogonal array was taken and the experimental combinations were shown in Table 4.

Table 4 L9 orthogonal array for 3 factors and 3 levels

Experiment	Factor A	Factor B	Factor C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

3.3 Experimental procedure

The workpiece was initially of about 32 mm diameter and 345 mm length. It was first center-drilled on one side as shown in Figure 4. The workpiece was then set up on the CNC lathe machine as shown in Figure 5. Turning operation was first performed on the workpiece using CNC lathe to reduce the diameter to 30.9 mm for a length of 160 mm in order to minimize any effect of non-homogeneity on the experimental results. The nine experimental runs are performed based on the combinations from Table 4 with each experiment carried for a length of 15 mm.

Figure 4 Center drilling of workpiece

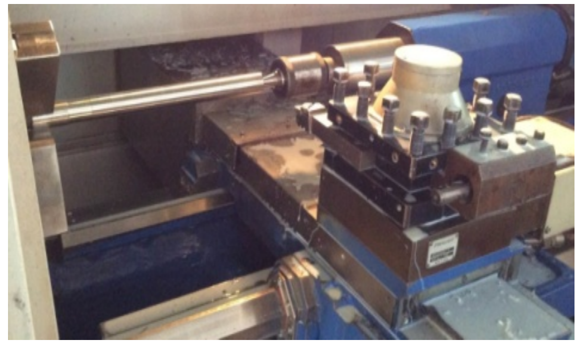

Figure 5 Workpiece setup on CNC

Figure 6 Vickers Hardness Tester

After machining, the surface hardness was measured using Vickers Hardness Tester of model VM – 50 which was shown in Figure 6. The Vickers hardness test uses a diamond indenter which is a pyramid with square base. The angle between the faces of pyramid is 136^o as shown in Figure 7. The test load selected was 10 kg. The length of diagonals (d_1 and d_2) of the indentation was measured to calculate the hardness. The Vickers Hardness Number (HRV) of materials is obtained by dividing the applied force P, in kg, by the surface of the pyramidal depression which yiels the relationship,

$$HRV = 1.854 * p/d^2 \quad (1)$$

Where,
HRV = Vickers hardness number
P = applied force in kg
d = average length of the diagonals in mm

$$d = (d_1+d_2) / 2 \quad (2)$$

The lengths of the diagonals d1 and d2 along with the average diagonal length (d) and the Vickers hardness number calculated using equations 1 and 2 were shown in Table 5.

Table 5 HRV values

Sl. No.	d_1 (mm)	d_2 (mm)	d (mm)	HRV
Initial	0.192	0.188	0.190	513.57
1	0.182	0.178	0.180	572.22
2	0.178	0.167	0.1725	623.06
3	0.177	0.174	0.1755	601.94
4	0.179	0.171	0.175	605.39

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5	0.171	0.169	0.170	641.52
6	0.162	0.187	0.1745	608.86
7	0.178	0.155	0.1665	668.78
8	0.100	0.194	0.147	857.97
9	0.181	0.182	0.1815	562.80

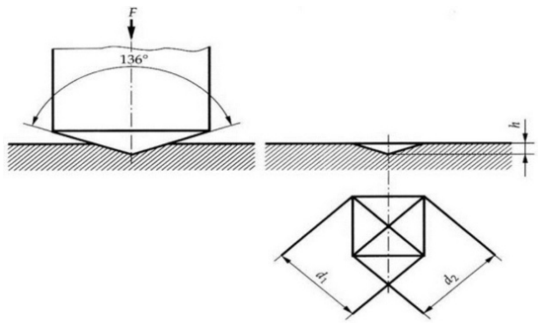

Figure 7 Principle of the Vickers hardness test

Table 6 shows the selected design matrix based on Taguchi L9 orthogonal array consisting of machining conditions and the experimental results of the response − surface hardness (HRV). All these data were utilised for the analysis and evaluation of the optimal parameter combination.

3.4 Evaluation of signal-to-noise ratio

To determine the effect each variable has on the output, the signal-to-noise (S/N) ratio needs to be calculated for each experiment conducted. The SN ratio formulae are given below:
Smaller-the better (minimize):

$$S/N_S = -10 * \log\left(\frac{1}{r}\sum_{i=1}^{r} y_i^2\right) \quad (3)$$

y = average of the observed data
r = number of replications

S/N_S ratio is used if the system is to be optimized when the response is as small as possible. Factor levels that maximize the appropriate S/N ratio are optimal. To obtain optimal machining performance smaller-the-better performance is considered as the characteristic for surface hardness
Table 6 shows the experimental results for surface hardness and the corresponding S/N ratio using the equation (3). Since the experimental design is orthogonal, it is then possible to separate out the effect of each cutting parameter at different levels. For example, the mean response for the speed at levels 1, 2 and 3 can be calculated by averaging the responses for the experiments 1–3, 4–6 and 7–9 respectively. The mean responses for each level of the other cutting parameters were computed in the similar manner and shown in Table 7. The delta values represent the algebraic difference between the maximum and minimum mean values of the levels for each factor.. In the similar manner, the mean S/N ratios for each factor at each level and also the total mean S/N ratio of the nine experiments were calculated and shown in Table 8 In addition, the total mean S/N ratio for the nine experiments was also calculated and listed in Table 8. The variation of responses of the S/N ratios and the means for each factor was shown in Figures 8 and 9 respectively. The graphs were obtained using the software *Minitab 15.*

***Table 6** Machining conditions and responses*

Run no.	*Cutting parameters*			*Output response*	*S/N ratio*
	Speed N (rpm)	*Feed rate f (mm/rev)*	*Depth of cut d (mm)*	*Hardness (HRV)*	
1	*300*	*0.05*	*0.1*	*572.22*	*-55.1513*
2	*300*	*0.10*	*0.3*	*623.06*	*-55.8906*
3	*300*	*0.15*	*0.5*	*601.94*	*-55.5911*
4	*400*	*0.05*	*0.3*	*605.39*	*-55.6407*
5	*400*	*0.10*	*0.5*	*641.52*	*-56.1442*
6	*400*	*0.15*	*0.1*	*608.86*	*-55.6903*
7	*500*	*0.05*	*0.5*	*668.78*	*-56.5057*
8	*500*	*0.10*	*0.1*	*857.97*	*-58.6694*
9	*500*	*0.15*	*0.3*	*562.80*	*-55.0071*

Table 7 Response table for means

Levels	**Factors**		
	Speed, N (rpm)	**Feed rate, f (mm/rev)**	**Depth of cut, d (mm)**
1	599.7	615.5	679.7
2	618.6	707.5	597.1
3	696.5	591.2	637.4
Delta	97.4	116.3	82.6
Rank	2	1	3

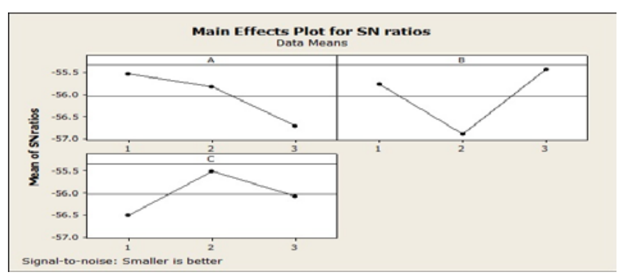

Figure 8 Response graph for S/N ratio

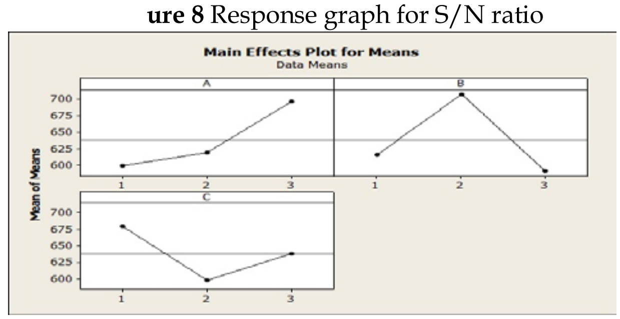

Figure 9 Response graph for means

Table 8 Response table for S/N ratios

Levels	**Factors**

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	Speed, N (rpm)	Feed rate, f (mm/rev)	Depth of cut, d (mm)
1	***-55.54***	-55.77	-56.50
2	-55.83	-56.90	***-55.51***
3	-56.73	***-55.43***	-56.08
Delta	1.18	1.47	0.99
Rank	2	1	3
Mean S/N ratio **= *-56.03***			

3.5 Optimal combination

Regardless of the category of the performance characteristics, a greater S/N value corresponds to a better performance. Therefore, the optimal level of the machining parameters is the level with the greatest S/N value. Based on the analysis of the S/N ratio from Table 8 and Figure 8, the S/N ratio was maximum at 1st level of speed, 3rd level of feed rate and 2nd level of depth of cut. Hence, the optimal combination for minimising the surface hardness is 300 rpm speed, 0.10 mm/rev feed rate and 0.3 mm depth of cut.

4 Results and Discussions itations

4.1 Analysis of Variance

The purpose of ANOVA is to determine which cutting parameters significantly affect the quality characteristic (here, HRV). ANOVA tests the *null hypothesis* that the population means of each level are equal, versus the *alternative hypothesis* that at least one of the level means are not all equal. This is accomplished by separating the total variability of the S/N ratio, which is measured by the sum of squared deviations from the total mean S/N ratio, into contributions from each of the turning parameters and error. The sums of squared deviations are calculated by using the following

$SS_T = SS_F + SS_e$ (4)

$SS_T = \sum_{i=1}^{n}(\gamma_i - \gamma^{2}$ (5)

SS_T = Total sum of the squared deviations about the mean S/N ratio

γ_j = S/N ratio for the j^{th} experimental run

γ_m = Mean S/N ratio

In addition, the F-test was used to determine which turning parameters have a significant effect on the output responses. The ANOVA for the S/N ratios was shown in Table 9. The following formulae are used for ANOVA calculations:

MSS = SS/DOF

F = MSS/MSE

Contribution % = SS/SS_T (6)

Where, MSS = Mean sum of squares

SS = Sum of squares

DOF = Degrees of freedom of factors

MSE = Mean sum of squares of error

Table 9 Results of ANOVA

Machining parameter	Degrees of freedom (DOF)	Sum of square (SS)	Mean sum of square s(MSS)	F	P	Contribution (%)
N	2	2.293	1.146	1.06	0.485	24.13
f	2	3.569	1.785	1.65	0.377	37.55
d	2	1.483	0.742	0.69	0.593	15.61
Error (e)	2	2.158	1.079			22.71
Total (T)	8	9.503				100

4.1 Confirmation test

For the optimal combination, $N_1f_3d_2$, a confirmation experiment was performed for 300 rpm speed, 0.15 mm/rev feed rate and 0.3 depth of cut. The predicted S/N ratio for the optimal combination was -54.42 and the surface hardness for the predicted S/N ratio was 526.02. HRV Surface hardness test when performed on the workpiece for this optimal combination was found to be 530.18 HRV. The S/N ratio for this value of surface hardness was -54.48 which was in close proximity with the predicted value. The results show that using the optimal parameter settings ($N_1f_3d_2$) causes a lower surface hardness.

Table 10 Results of confirmation test

	Reference value	Optimal cutting condition	
		Prediction	**Experiment**
Factor combinations	$N_1f_1d_1$	$N_1f_3d_2$	$N_1f_3d_2$
HRV	572.22	526.02	530.18
S/N ratio	-55.1513	-54.42	-54.48

ccording to this analysis, the most effective parameters with respect to surface hardness are feed rate, speed and depth of cut. The percentage contribution calculated by equation (6) indicates the relative power of a factor to reduce the variation. For a factor with a high percentage contribution, there is a greater influence on the performance.

5 Conclusion

IThis paper presents the optimisation of the surface hardness during the turning of Inconel 718 with TiCN – Al_2O_3 coated cemented carbide insert by using Taguchi method of DOE. The surface hardness was optimised for minimum and the factors accountable for it were 300 rpm speed, 0.15 mm/rev feed rate and 0.3 mm depth of cut. The effectiveness of this approach was verified by the confirmation test and analysis of variance (ANOVA). The predicted and the experimental S/N ratios and Vickers surface hardness of the optimal combination were in close proximity.

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