Design Optimization of Cutting Parameters when Turning Inconel 718 with Cermet Inserts

M. Aruna and V. Dhanalaksmi

Abstract**—**Inconel 718, a nickel based super-alloy is an extensively used alloy, accounting for about 50% by weight of materials used in an aerospace engine, mainly in the gas turbine compartment. This is owing to their outstanding strength and oxidation resistance at elevated temperatures in excess of 550^0 C. Machining is a requisite operation in the aircraft industries for the manufacture of the components especially for gas turbines. This paper is concerned with optimization of the surface roughness when turning Inconel 718 with cermet inserts. Optimization of turning operation is very useful to reduce cost and time for machining. The approach is based on Response Surface Method (RSM). In this work, second-order quadratic models are developed for surface roughness, considering the cutting speed, feed rate and depth of cut as the cutting parameters, using central composite design. The developed models are used to determine the optimum machining parameters. These optimized machining parameters are validated experimentally, and it is observed that the response values are in reasonable agreement with the predicted values.

Keywords**—**Inconel 718, Optimization, Response Surface Methodology (RSM), Surface roughness

I. INTRODUCTION

SURFACE roughness is an important task in determining how a real entity will intermingle with the environment. Rough surfaces generally wear more hastily and have higher friction coefficients than smooth surfaces. Roughness is the performance of a mechanical component, since irregularities in the surface may form nucleation resulting in cracks or corrosion [1]. Even though roughness is usually detrimental, it is complex and exclusive to control in manufacturing. Decreasing the roughness of a surface will usually exponentially increase its manufacturing costs. This often results in a trade-off between the manufacturing cost of a component and its performance in an application.

With time, as convolution in dynamics of cutting processes increased considerably, researchers and practitioners have focused on mathematical modeling techniques to conclude the optimal or near-optimal cutting condition(s) with respect to various objective criteria. Despite copious studies on process optimization problems; there exists no universal input – output and in-process parameters relationship model, which is applicable to all kinds of metal cutting processes [2]. Design and methods such as factorial design, response surface methodology (RSM) and Taguchi methods are now widely used in place of one-factor-at-a-time experimental approach which is time consuming and exorbitant in cost [3]. Taramen used a contour plot technique to simultaneously optimize tool wear, surface finish, and tool force for finished turning operations [4]. Alauddin applied response surface methodology to optimize the surface finish in end milling Inconel 718. They suggested that it is possible to select a combination of cutting speed and feed that reduces machining times without increasing the surface roughness [5]. Choudhury and El-Baradie used response surface methodology for assessing machinability of inconel 718. They found that the dual response contours of tool life and surface roughness are very useful in assessing the maximum attainable tool life for the same surface finish [6]. Mansour and Abdalla developed a surface roughness model for end milling of semi-free cutting carbon case hardened steel [7]. They investigated a first-order equation covering the speed range 30 – 35 m/min and a second order generation equation covering the speed range 24 – 38 m/min. They suggest that an increase in either the feed or the axial depth of cut increases the surface roughness, whilst an increase in the cutting speed decreases the surface roughness [8]. Response surface methodology is used with a developed genetic algorithm (GA) in the optimization of cutting conditions for surface roughness. Sharif used factorial design coupled with response surface methodology in developing the surface roughness model in relation to the primary machining variables such as cutting speed, feed, and radial rake angle [9].

The main objective of this work is to develop a model for surface roughness based on cutting speed, feed and depth of cut using response surface methodology. Surface roughness contour for cutting speed – depth of cut is developed to describe the values resulting from the cutting parameters selected. RSM is used to identify the factors which influence the surface roughness. Additionally this relationship is quantified using mathematical modeling. As a consequence, manufacturers can progress the quality and productivity of the product with minimum cost and time.

II. METHODOLOGY

The experiment is performed by using a PMT –TNS-25 CNC lathe and is shown in Fig. 1. Inconel 718 cylindrical rod is considered as the work piece material. Titanium carbide based cermet inserts (Triangular) are used as the cutting tool. Cermets are one of the best kept secrets in the cutting tool industry. They provide the user with improved productivity and profitability through higher cutting speeds and extended tool life. Cermets have small, well controlled grain structures. Hence, they show higher wear resistance. In addition, cermets maintain a sharp edge longer than carbide. Cermets have superior resistance to built-up edge. Less affinity with the study piece results in superior micro-finishes. Turning

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operation is carried out for the above cutting conditions using soluble oil as the cutting fluid. Surface roughness is measured in terms of roughness average (R_a) using Taly surf coder. Observations are carried out at three locations for each cutting conditions and the mean value is reported.

Fig. 1 PMT –TNS-25 CNC lathe

TABLE I
MACHINING PARAMETERS AND THEIR LEVELS

Factors	Levels		
	Low	Intermediate	High
Cutting speed, V (m/min)	100	150	200
Feed, f (mm/rev)	0.1	0.15	0.2
Depth of cut, a (mm)	0.3	0.4	0.5

The levels of machining parameters to be studied and the attribution of the levels are indicated in Table I.

A. Response Surface Methodology

There are many situations where the quality engineers run into several correlated responses concurrently. In such cases decision making on optimum set of parameters is a complicated mathematical problem. In the realistic application of RSM, it is necessary to extend an approximating model for the true response surface. The underlying true response surface is typically driven by some unidentified physical mechanism. The approximating model is based on the observed data from the process or system and is an empirical model. Multiple regression as a collection of statistical techniques is useful for building the types of empirical models requisite in RSM.

The central composite design is used, since it gives a comparatively accurate prediction of all response variable averages and the results from the machining trials performed is shown in Table II.

B. Empirical model

Examination of the fit summary output reveals that the Quadratic model is statistically significant for surface roughness. An ANOVA table is commonly used to summarize the tests performed. Table III shows the ANOVA table for response surface quadratic model for surface roughness. It is obvious from the results of ANOVA that the speed rate is the dominant factor affecting surface finish. The contribution of feed and depth of cut is 8.95 and 3.42 respectively. The interactions A×B, A×C and B×C are not significant. Respectively, their contributions are 12.04, 1.00 and 1.25. To understand the hard turning process in terms of surface

TABLE II
RESPONSES FOR CERMET INSERTS

Exp. No.	Cutting speed m/min	Feed mm/rev	Depth of cut mm	Surface roughness R_a μm
1	100.00	0.10	0.40	1.00
2	200.00	0.10	0.40	0.45
3	100.00	0.20	0.40	0.90
4	200.00	0.20	0.40	0.40
5	100.00	0.10	0.50	1.10
6	200.00	0.10	0.50	0.46
7	100.00	0.20	0.50	1.20
8	200.00	0.20	0.50	0.50
9	65.91	0.15	0.45	1.50
10	234.09	0.15	0.45	0.30
11	150.00	0.07	0.45	0.80
12	150.00	0.23	0.45	0.79
13	150.00	0.15	0.37	0.74
14	150.00	0.15	0.53	0.90
15	150.00	0.15	0.45	0.82
16	150.00	0.15	0.45	0.70
17	150.00	0.15	0.45	0.70
18	150.00	0.15	0.45	0.85
19	150.00	0.15	0.45	0.80
20	150.00	0.15	0.45	0.99

roughness R_a, mathematical model is developed using multiple regression method, R_a model refer to "(1)". Its coefficient of correlation R^2 is 99.20%.

$$\begin{aligned}\text{Surface roughness} = &+5.71931-(0.027172*\text{Cutting speed})-(0.05276*\text{Feed})\\ &-(11.8754*\text{Depth of cut})-\begin{pmatrix}0.029500*\text{Cutting speed}\\ *\text{Feed}\end{pmatrix}\\ &-(8.50000\text{E-}003*\text{Cutting speed}*\text{Depth of cut})\\ &-(9.50000*\text{Feed}*\text{Depth of cut})+\begin{pmatrix}8.33316\text{E-}005\\ *\text{Cutting speed}^2\end{pmatrix}\\ &+(32.41989*\text{Feed}^2)+(16.86354*\text{Depth of cut}^2)\end{aligned} \quad (1)$$

C. Model Validation

Fig. 2 shows the 3D graphs of the effect of cutting speed and feed on the surface roughness. It has a curvilinear shape in accordance to the model fitted. The contour plot for the response, surface roughness is shown in Fig. 3. The surface roughness increases with increase in depth of cut.

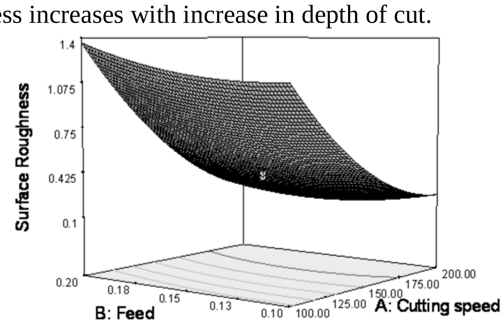

Fig. 2 3D surface graph for R_a data

TABLE III
ANOVA TABLE

Source	Sum of squares	df	Mean Square	F value	p-value prob>F	
Model	4.49	9	0.50	138.0	< 0.0001	Significant
A-Cutting speed	3.71	1	3.71	1026.5	< 0.0001	
B-Feed	0.032	1	0.032	8.95	0.0135	
C-Depth of cut	0.012	1	0.012	3.42	0.0941	
AB	0.044	1	0.044	12.04	0.0060	
AC	3.613E-003	1	3.613E-003	1.00	0.3409	Not Significant
BC	4.512E-003	1	4.512E-003	1.25	0.2899	
A2	0.63	1	0.63	173.11	< 0.0001	
B2	0.095	1	0.095	26.20	0.0005	
C2	0.026	1	0.026	7.09	0.0238	
Lack of fit	0.023	5	4.600E-003	1.75	0.2768	Not Significant
Pure error	0.013	5	2.627E-003			
Cor Total	4.52	19				
R-Squared = 0.9920			Pred R-Squared = 0.9541			
Adj R-Squared= 0.9848			Adeq.precision = 41.241			

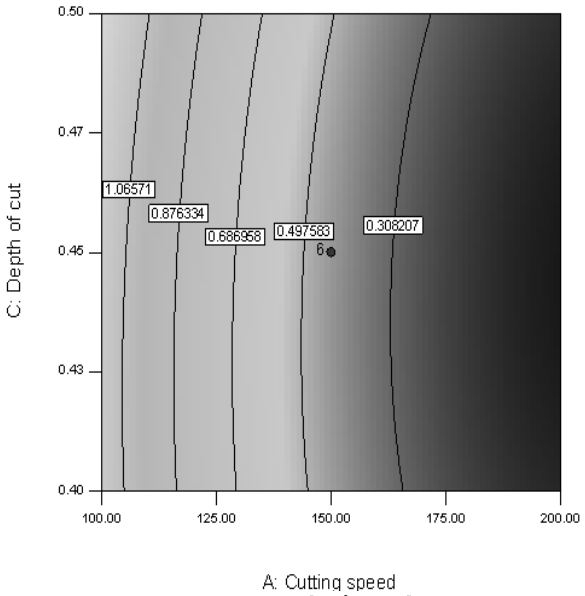

Fig. 3 Contour plot for R_a data

The improvement of surface roughness (average) with different cutting speeds is shown in the Fig. 5. In general, the surface roughness decreased with increase in the cutting speed.

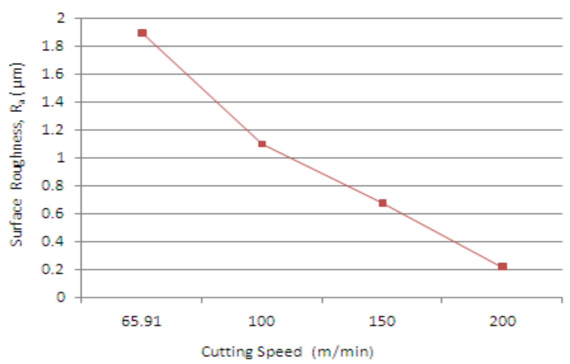

Fig. 4 Effect of cutting speed on surface roughness

II. CONFIRMATION EXPERIMENTS

To verify the fitness of the model developed, three confirmation run experiments are performed (Table IV). The test conditions are within the range of the levels defined before. The model developed is based on the prior predicted values and the associated prediction interval. The percentage error is calculated based on the difference between the predicted value and the actual experimental value. The percentage error range between the actual and predicted value for R_a is as follows: $R_a \approx 4.356$ to 9.032%. The experimental model developed for R_a is practically accurate. All the actual values for the confirmation runs are within the 95% prediction interval.

TABLE IV
CONFIRMATION RUNS

Sl. No	Surface roughness (R_a) µm		
	Experimental Value	Predicted value	Error %
1	0.732	0.71	9.032
2	0.297	0.2674	9.966
3	0.294	0.25044	4.356

III. CONCLUSION

The consequences of the experimental data is used for predicting the outcome of assorted input machining parameters such as cutting speed, feed and depth of cut on the surface roughness when machining Inconel 718 using cermet inserts. A non-linear regression equation is developed and projected. Cutting speed has the strongest effect on the surface roughness among the selected parameters; it is inversely proportional to the response. It is found that the surface roughness could be controlled in the design stage which is the most effective and inexpensive way.

ACKNOWLEDGMENT

The authors thank Scientist S. Mohan, Head / Technical Division for his guidance regarding tool wear analysis and B. Palanivel, Technical assistant for lending a hand in machining the Inconel 718 samples. The authors are grateful to CECRI – Karaikudi-India, for granting permission to conduct the Experiments.

REFERENCES

[1] M. Rahman, W. K. H. Seah and T.T. Teo 1997 “The machinability of Inconel 718”, Journal of Material Processing Technology, vol. 63, pp.199-204, 1997.

[2] G. A Hassan, S. M. A. Suliman, “Experimental modelling and optimization of turning medium carbon steel”, International Journal of Production Research, vol. 28 (2), pp. 1057 – 1065, 1998.

[3] M. Y. Noordin, V. C. Venkatesh, S. Sharif, S. Elting and A. Abdullah, “Application of response surface methodology in describing the performance of coated carbide tools when turning AISI 1045 steel” Journal of Materials Processing Technology, vol. 145, pp. 46–58, 2004.

[4] K. Taramen, “Multi-machining output multi independent variable turning research by response surface methodology”, International Journal of Production Research, vol. 12 (2), pp. 233 – 245, 1974.

[5] M. Alauddin, M. A. El Baradie, M. S. J. Hashmi, “Optimization of surface finish in end milling Inconel 718”, Journal of Material Processing and Technology, vol. 56, pp. 54 – 65, 1996.

[6] I. A. Choudhury, M. A. El-Baradie, “Machinability assessment of Inconel 718 by factorial design of experiment coupled with response surface methodology”, Journal of Material Processing and Technology 95, pp. 30 – 39, 1999.

[7] Mansour, H. Abdalla, “Surface roughness model for end milling: a semi-free cutting carbon case hardening steel (EN32) in dry condition”, Journal of Materials Processing Technology, vol. 124, pp. 183 – 191, 2002.

[8] H. Oktem, T. Erzurumlu and H. Kurtaran, “Application of response surface methodology in the optimization of cutting conditions for surface roughness”, Journal of Material Processing and Technology, vol. 170, pp. 11 – 16, 2005.

[9] S. Sharif, A. S. Mohruni, M. Y. Noordin, V. C. Venkatesh, “Optimization of surface roughness prediction model in end milling titanium alloy (Ti-6Al-4V)”, Proceeding of ICOMAST, 2006, pp.55-59.

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