Intelligent machining parameters selection for high speed finish turning of Inconel 718*

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ABSTRACT

The machinability assessment is the critical and challenging task for machining of heat resistant super alloy material like Inconel 718. In finish turning operations are very important in order assemble the component made of such difficult to machining materials. The high speed finish turning process has been carried out with uncoated carbide inserts are used with cold coolant machining conditions. This paper describes an intelligent interactive model development using the machining responses like tool life, surface roughness, and cutting force for high speed finish turning Inconel 718 by using response surface methodology. Based on the design of experiments finish turning trials are conducted at three levels of cutting parameters cutting speed, feed and depth of cut in low, medium and high. Tool life and surface roughness, and cutting force, which are the major aspects of machinability, have been discussed in this investigation. The interactive response optimizer has been developed for intelligent decision making also demonstrated the selection of process parameters against the multi response requirements.

1. Introduction

Inconel 718 is the nickel based super-alloy, widely used in the high resistant to heat application industries like aerospace, nuclear, gas turbine and marine engineering. It has exceptional mechanical resistances to high temperature and corrosion. Due to strange physical characteristics such as lower thermal conductivity, work hardening, presence of abrasive carbide particles, hardness, affinity to react with tool material etc. makes it difficult to machine. Cost effective machining with generation of good surface finish on the Inconel 718 components during finish turning operation is a challenge to the industrialist in practice [1–2].

Carbide tools have poor thermo-chemical stability and encounter pronounced dissolution/diffusion of tool materials at the tool-chip interface into the underside of the chip as it traverses the tool face causing tool when machining at speeds in excess of 30 m/min [3-4]. Based on the economic consideration, uncoated carbide tools are attracted and they give a better performance with respect to different cutting speeds and feed rates. In the speed range of 26-48 m/min, no significant difference in tool life was observed for the coated and uncoated tools [5]. Sharman, et al., (2006) conducted series of experiments for evaluating the generation of residual stress when turning Inconel 718 using uncoated and coated carbide tools [6]. They found tensile stresses formed in the surface layer when cutting with a coated tool, but uncoated tool at the same operating parameters produced deep compressive stresses beneath a reduced tensile layer. Uncoated carbide tools are better than the coated tools for machining Inconel 718. Apparently, the coating does not improve the performance of coated tools [5,7].

The Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques that are useful for modelling and analyzing problems in which response of interest is influenced by several variables, and the objective is to obtain the desired response [8]. Choudhury

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and El-baradie [5,9] also emphasised the use of RSM in developing machinability assessment model for turning Inconel 718 using uncoated and coated carbide tools. Musfirah et al. [10] developed a cryogenic cooling unit using liquid N2 to cool the combined tool-workpiece. Test results showed that the application of the cryogenic coolant not only reduced tool wear and cutting force, but also reduced the surface roughness of the machined workpiece compared with that obtained under dry cutting conditions. Kadirgama et al. [11] analyzed the wear behavior of carbide inserts coated with TiAlN and a triple layer of TiN/TiCN/TiN by physical vapor deposition (PVD), and those coated with a triple layer of TiN/TiCN/Al2O3 and TiN/TiCN/TiN by chemical vapor deposition (CVD) during the high-speed cutting of Hastelloy C-22HS. Adhesive and oxidation wear were found to be the primary wear mechanisms, and it was concluded that cutting speeds should be less than 100 m/min to extend tool life [11,12]. Bhatt et al. [13] evaluated the wear behaviour obtained for three different cemented WC inserts while machining Inconel 718 with different cutting parameters. According to the results, the uncoated WC tool exhibited a better wear resistance than the other inserts at an intermediate feed rate and low cutting speed, the WC tool coated with a single layer of TiAlN by PVD had a better wear resistance than the other inserts at a medium cutting speed, and the wear resistance of the WC tool coated with a triple layer of TiCN/Al2O3/TiN by CVD was better than the other inserts at a low feed rate and high cutting speed. Many researches were established the machinability model by the functional relationship between the input machining parameters (cutting speed, feed, and depth of cut) and the output responses (tool life, surface roughness, and cutting force) for turning of Inconel 718 using coated and uncoated carbide tools [14-16].

This paper focuses on the development of intelligent interactive model for elegant way of decision making based on the analysis of maximum tool life, minimum cutting force and minimum surface roughness when finish turning of Inconel 718 under cold coolant machining.

2. Experimental Setup

High rigidity CNC lathe used for machinability assessment in turning of Inconel 718 with following specifications: Continuous power: 15kW motor drive; speed range: 0-3500 rpm and feed range: 0.01-100 mm/rev. Dynamometer system consisting of Kistler piezoelectric dynamometer, charge amplifiers and chart recorder was used for recording the forces. The experimental setup used for on-line cutting force measurement is shown in the Figure 1 & Tool maker's microscope with digital read out device; used to observe tool wear and record it. Surface roughness tester (Mittoyo-surftest 211); the laboratory based system is used for the measurement of surface roughness. During the machining process the chilled coolant provided which decreasing the tool wear appreciably by removing the heat from the chip tool interface. Externally attached coolant tank made as experimental setup to conduct the experiments, coolant within the chilled condition 8°to 10°C is maintained. In this research water with nano powder of paraffin wax is packed with copper container and frizzed externally then positioned into the coolant tank closer to the suction valve of the coolant pump.

The work material used as test specimen is Inconel 718 for machinability assessment. A cylindrical bar of test specimen 50mm diameter and 1000mm length has been used for the turning tests. The Inconel 718 material is pre-processed in the fully-heat treated condition. By fully heat treated condition is meant that the specimen has been solution treated at 980°C for two hours followed by oil quenching and then ageing at 720°C for eight hours, furnace cooling to 620°C, holding for eight hours, followed by air cooling. The chemical compositions by percentage of weight basis and mechanical properties of Inconel 718 are given in Tables 1 and 2 respectively.

Uncoated cemented carbide cutting tool inserts as per ISO specification CNMG 120408-QM, grade H13A have been used for the turning tests to assess machinability of the heat treated Inconel 718. The inserts are rigidly attached to a

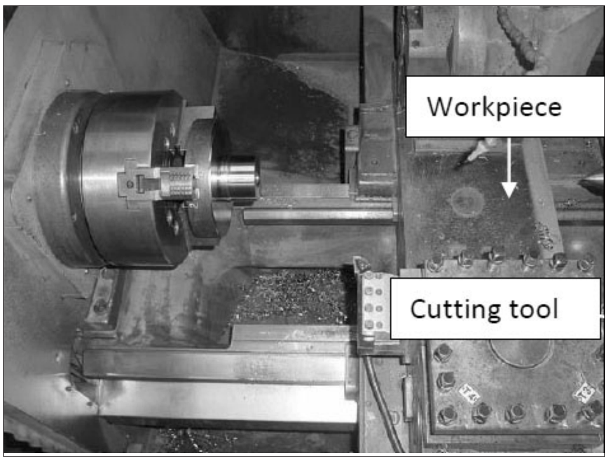

Fig. 1. Experimental setup for online force measurement.

Table 1
Chemical compositions of heat treated 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 heat treated Inconel 718.

Tensile strength (MPa)	Yield strength (MPa)	Young modulus (MPa)	Density (kg/m^3)	Melting point (˚C)	Hardness (HRC)	Thermal conductivity (W/mK)
1419	1248	212×10^3	819	1298	35	11.20

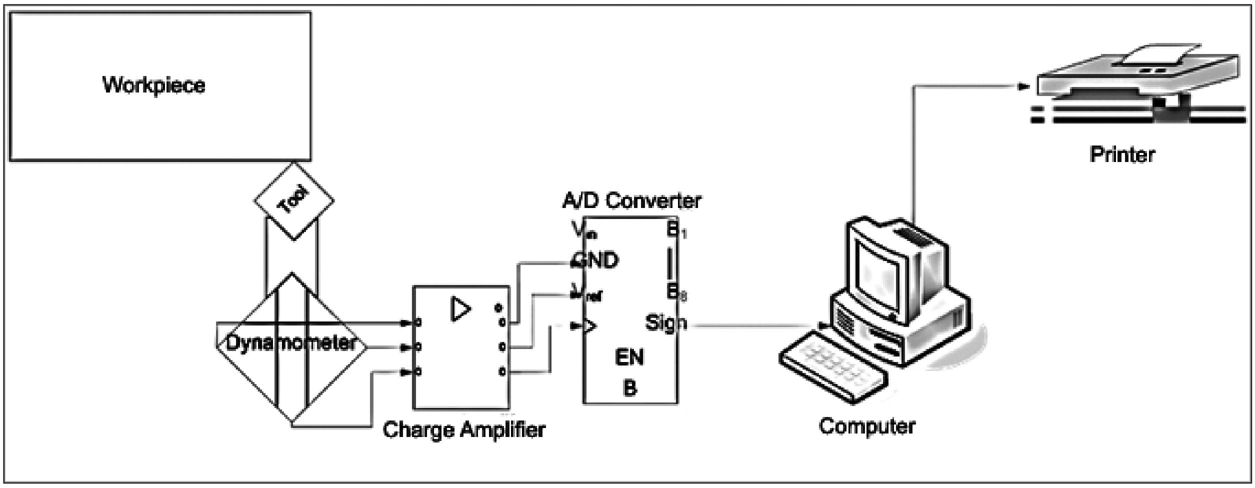

Fig. 2. Schematic experimental setup.

tool holder (PCLNR25M12).

The turning tests are performed on the high rigidity CNC lathe shown in the Figure 1. Orthogonal array is applied for the execution of the plan of experiment, for three levels, as per the levels taken by the factors. The levels of machining parameters factors to be studied and the attribution of the levels are indicated in Table 3.

3. Design of Experiments and Responses

Three levels are specified for each of the factors as machining parameters (cutting speed, feed and depth of cut) as indicated in Table 3. One test is performed for each combination resulting in a total of 27 tests for full factorial design of experiment and additionally few tests are replicated for RSM design. New cutting edge is used for each trial of experiment and cutting forces are in tandem recorded. Based on the experimental results, the major tangential cutting force is considered only for the development force model. Tool wear values are further recorded as per the ISO 3685 tool wear criterion. The criteria most commonly used for sintered carbide tools are as the maximum width of the flank wear land VBmax. = 0.3 mm if the flank wear land is considered to be regularly worn in zone B. Each test is started with a new cutting edge and machining is stopped and insert is removed to measure its wear at different intervals of time ranging from one to two minutes. Further insert

Table 3
Machining parameters and its levels.

Factors	**Levels**		
	Low	**Medium**	**High**
Cutting speed ‘V’ (m/min)	45	60	75
Feed ‘f’ (mm/rev)	0.1	0.2	0.3
Depth of cut ‘a’ (mm)	1.0	1.5	2.0

is rejected when average wear exceeds 0.3mm. The surface roughness has been measured by positioning the stylus perpendicular to the feed marks on the machined surface towards the end of cutting. The surface roughness has been taken at four locations (90°apart) and repeated twice at each point on the face of the machined surface and the average values reported. Based on the research interest and researcher recommendations, all the turning tests have been conducted under cold coolant supplied in all cutting conditions. Every experiment has been conducted three times to conformation and the results of the average values are recorded.

4. Results and Discussion

The interactive decision making for selection of machining parameters has been carried out by using response optimizer in MINITAB software. In this process based on the requirements the responses are fixed as maximizing the tool life; material removal rate and minimizing surface roughness; cutting force are the important objectives in the machining process. To establish the response optimizer the settings given in the figure 3 are keyed into the program. As per the optimization requirements the surface roughness and the tool life are having more importance than the cutting force and material removal rate. Minitab's response optimizer searches for combination of input variables that jointly optimize a set of responses by satisfying the requirements for each response in the experimental data. The response optimizer drives the optimization is accomplished by:

Obtaining the individual desirability (d) for each response

Combining the individual desirability to obtain the combined desirability (D)

Maximizing the composite desirability and identifying the optimal input parameter settings. The useful approach to optimization of multiple responses is to use the simultaneous optimization technique based on the desirability functions [17]. The general approach is to first convert each response yi into an individual desirability function di that varies over the range $0 \le di \le 1$ where if the response yi is at its goal or target, then di = 1, and response is outside an acceptable region, di = 0. Then the design variables are chosen to maximize the overall desirability

D = (d1 ×d2 ×......dm)1/m

Where there are m responses here m = 3. The response optimizer generated the optimization plot based on the individual and composite desirability value.

Response surface methodology is a modelling and optimization technique by creating the relationship between machining parameters and responses. A second order polynomial model has been developed to correlate the responses (surface roughness, tool life, cutting force) and the machining parameters. Based on the models developed, analysis has been carried out to investigate the interactive effects and the individual effects. Analysis of variance has been made to find out the significance of parameters on the responses. Using MINITAB software the response optimizer optimizes the multiple responses based on the desirability functions for the Box-Behnken design. The result of the optimization plot is shown in the Figure 3. Response surface methodology is a modelling and optimization technique by creating the relationship between machining parameters and responses. A polynomial model has been developed to correlate the responses (surface roughness, tool life, cutting force) and the machining parameters. Based on the models developed, operator can selected the machining parameters and other analysis has been carried out to investigate the interactive effects on the responses. Analysis of variance has been made to find out the significance of parameters on the responses. Using MINITAB software the response optimizer optimizes the multiple responses based on the desirability functions for the Box-Behnken design. The result of the optimization plot is shown in the Figure 3. An individual desirability function di value for the surface roughness with 1, tool life 1 and cutting force 1 are taken to indicate that the responses are reached to the goal. In the present study,

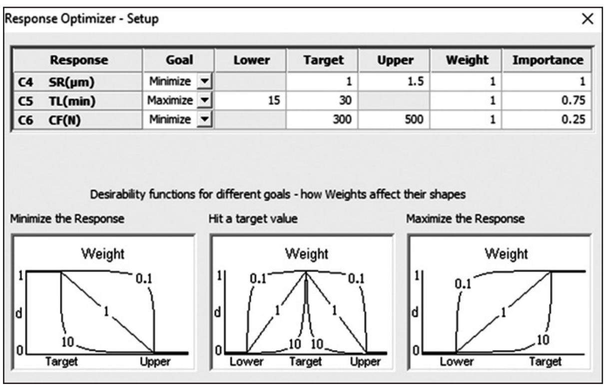

Fig. 3. Settings for optimization process.

Table 4
Experimental validation.

Sl. No.	Cutting Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Surface Roughness(μm)		Tool Life (min)		Cutting force (N)	
				Predicted	Experimental	Predicted	Experi-mental	Predic-ted	Experi-mental
1	55	0.125	1.12	0.7	0.74	31	30.6	141	147
				Error = 5.4%		Error = 1.3%		Error = 4.1%	

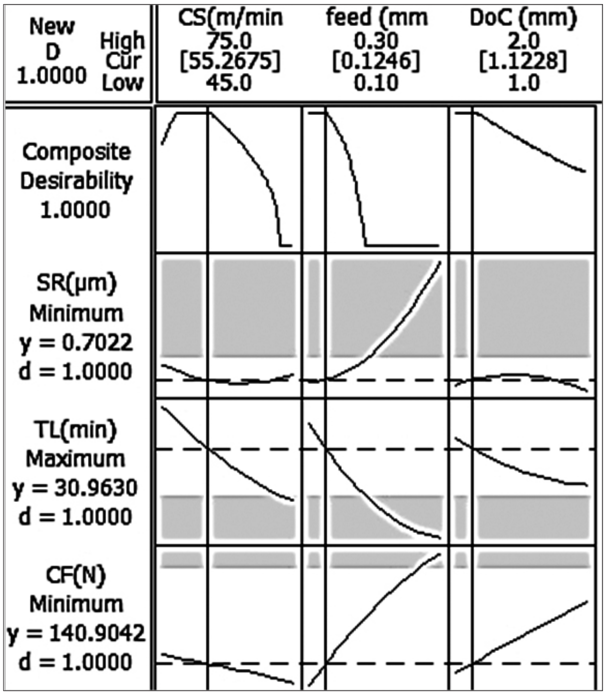

Fig. 4. Interactive response optimizer.

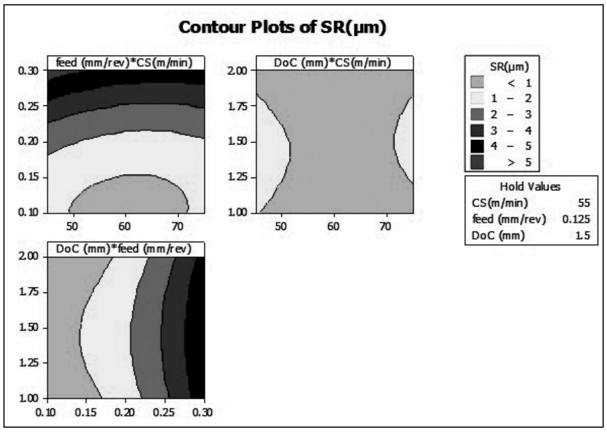

Fig. 5. Contour plot for surface roughness.

the goal is to minimize the surface roughness, maximum tool life and minimum cutting force at particular optimum cutting parameters for the operators' requirements. The optimum and selected cutting parameters are found to be cutting speed of 55.27 m/min, feed rate 0.125 mm/rev and depth of cut 1.12 mm with optimized surface roughness is 0.7 μm, tool life is 30.96 min and cutting force is 140.9 N as shown in Figure 3.

Form this response optimizer plot operator can select the cutting parameters based on the requirement. Contour plots have been plotted to analyse the influence of finish turning parameters on surface roughness as shown in Figure 4. This graph shows that with the increase of cutting speed with low feed rate the surface roughness was increased, whereas an increase of feed rate reduced the surface roughness there was nothing influenced with depth of cut.

The confirmation test was conducted for the optimum parameters to verify the accuracy of the developed model. The percentage of the error was within the permissible limits and also tabulated in Table 4.

5. Conclusions

An interactive model for surface roughness, tool life and cutting force was obtained from the surface response methodology technique for high speed finish turning of Inconel 718 has been discussed in this article. The influences of the machining parameters on surface roughness have been analysed based on the developed response surface methodology. The following conclusions are drawn based on this study.

1. The surface roughness increased with the increase of cutting speed and decreased with increase feed rate whereas depth of cut was not influenced with the surface roughness.
2. The tool life decreases with increase of the cutting speed, the feed and the depth of cut. Among the machining parameters cutting speed has the most dominant effect on tool life.
3. The cutting force almost linearly varying

with feed. At low cutting speed the cutting force is higher and the interactions of cutting speed with feed and depth of cut with feed dominantly affects the cutting force.

Later from cold coolant assessment, it can be concluded that machining under cold coolant environment seems to be one of the best cost effective practice towards high speed machining with better performance. It may be adopted as a practice by machining industries wants to achieve cost effective machining in their quality machining operations.

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