Modeling and Optimisation of Cutting and Feed Forces in Turning Inconel 718

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***Abstract*—Inconel 718, is a nickel based super alloy which is a difficult to machine material but has extensive application in high temperature and highly corrosive environment like aerospace and petrochemical industries respectively. This study investigates the significance of influence of cutting parameters namely speed, feed, and depth of cut on cutting force and feed force while turning inconel 718 using coated tungsten based cemented carbide insert tool. Taguchi's method of robust design is used to design the experiments. Taguch's L9 orthogonal array with 3 levels and 3 factors were used to conduct the nine experiments. Analysis of variance was done using design expert software. The analysis showed that the model is significant and also the feed rate has significant effect on cutting force and feed force in the range of experiments. Speed and depth of cut has no significance on cutting force and feed force in the range of the experiments. Regression models are also developed to predict the cutting force and feed force. Numerical optimization using desirability function approach was done using design expert software and the optimum value of cutting force and feed force along with the corresponding values of speed, feed and depth of cut were found. Optimization of cutting force and feed force were also done in Mat Lab software using genetic algorithm tool box. The values received in this method were in agreement with the values received in desirability function approach. These optimized machining parameters are validated experimentally and are in reasonable agreement with the predicted values.**

Keywords*— Inconel 718; Taguchi method; Anova; Desirabilitiy function; Genetic algorithm; Optimization;

I. INTRODUCTION

Super alloys are normally Nickel based, even though cobalt and iron based super alloys have also been developed. These alloys are named super alloys because their service conditions in critical applications usually require very high strength at high temperatures of the order of 500 to 600^0c. Inconel 718 is one of the most commonly used nickel based super alloy due to its high resistance to corrosion, mechanical and thermal fatigue, mechanical and thermal shock, creep and erosion at elevated temperature. It has wide applications in aircraft gas turbines, reciprocating engines, turbo chargers, exhaust valves, nuclear power plants, and petro chemical industries.

In spite of these superb qualities inconel 718 is difficult to machine due to its high shear strength, work hardening tendency, low thermal conductivity, low elastic modulus, presence of hard abrasive carbide particle in its microstructure and tendency to weld and form built up edge. Success of machining inconel 718 depends on overcoming these adverse characteristics. Optimization of cutting parameters in turning inconel 718 is very essential to avoid waste of costly raw material, man power, electricity, cutting tool, cutting fluid etc and also to increase productivity and product quality.

Turning is a machining process which generates external surface of revolution. The economics of turning consists in the determination of the process parameters namely cutting speed, feed, and depth of cut etc to optimize the cutting force (tangential force), feed force (axial force) etc within the limits of constraints in machining. Tangential (cutting) force acts downward on the tool tip allowing deflection of work piece upward and provides the required energy for cutting operation. The feed force acts in the longitudinal direction. It is called feed force since it acts in the feed direction of the tool and tends to push the tool away from the chuck. Speed expressed in revolutions per minute (rpm) is the rotating speed of the work piece past the cutting tool. It is also expressed in meters/minute as the surface speed of the work piece and is the product of rpm and circumference of the work piece. Feed is expressed in millimeter/ revolution and is the rate at which the tool advances into the work. Depth of cut is expressed in millimeters and is the thickness of material removed as the work revolves about its axis. The reduction in diameter of the work piece is twice the depth of cut. This paper aims at finding the optimum values of turning parameters, speed, feed and depth of cut, so that cutting force and feed force are the lowest.

Taguchi method is extensively used for optimizing different machining operations like turning, drilling etc by researchers. The various steps in this method are (1) selection of proper orthogonal array (OA), (2) running experiments based on (OA), (3) analyzing data and finding optimum conditions and (4) conducting confirmation tests. Here L9 (3^3) orthogonal array is selected for conducting the experiments. The three factors are speed, feed and depth of cut and the responses are cutting force and feed force.

In this paper genetic algorithm toolbox is also used to find the optimum values based on the experimental results. Genetic algorithm is a population-based search and optimization tool. It works equally well in either continuous or discrete search space. It is a heuristic technique inspired by the natural biological evolutionary process comprising of selection, crossover, mutation, etc. The evolution starts with a population of randomly generated individuals in first generation. In each generation, the fitness of every individual in the population is evaluated, compared with the best value, and modified (recombined and possibly randomly

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mutated) if required, to form a new population. The new population is then used in the next iteration of the algorithm. The algorithm terminates, when either a maximum number of generations has been produced or a satisfactory fitness level has been reached for the population. The fitness function of a GA is defined first. Thereafter, the GA proceeds to initialize a population of solutions randomly and then improves it through repetitive application of selection, crossover and mutation operators. This generational process is repeated until a termination condition is reached.

A lot of Literature is available on turning operation because of its importance in metal cutting. Speed, feed and depth of cut are the main parameters investigated in these researches. Dr. CJ Rao et al studied the importance of influence of speed, feed and depth of cut on cutting force and surface roughness when working with tool made of ceramic with an Al2O3+TiC matrix (KY1615) and the work material of AISI 1050 steel (hardness of 484 HV). Hamdi Aouici et al investigated the effects of cutting speed, feed rate, work piece hardness and depth of cut on surface roughness and cutting force components in the hard turning of AISI H11 steel which was hardened to (40; 45 and 50) HRC. Satish Chinchanikar et al studied the performance of coated carbide tool considering the effect of work material hardness and cutting parameters during turning of hardened AISI 4340 steel at different levels of hardness. The correlations between the cutting parameters and performance measures like cutting forces, surface roughness and tool life were established by multiple linear regression models. H.Joardar et al focused on the effect of certain cutting variables on cutting forces in straight turning of aluminum metal matrix composites under dry cutting condition. Cutting speed, depth of cut and weight percentage of SiCP are selected as the influencing parameters. Response surface methodology and face centered composite design were applied for modeling, optimization, and analysis.

D Philip Selvaraj et al optimized the dry turning parameters of two different grades of nitrogen alloyed duplex stainless steel using Taguchi method. The turning operations were carried out with TiC and TiCN coated carbide cutting tool inserts. A.K. Sahoo et al applied Taguchi's design of experiment methodology and regression analysis for optimization of process parameters in turning AISI 1040 steel using coated carbide insert under dry environment. G. Akhyar, et al applied Taguchi optimization methodology to optimize cutting parameters in turning Ti-6%Al-4%V extra low interstitial with coated and uncoated cemented carbide tools under dry cutting condition and high cutting speed. Taramen used a contour plot technique to simultaneously optimize tool wear, surface finish, and tool force for finished turning operations. 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.

II. EXPERIMENTAL DETAILS

A. *Workpiece Material*

Inconel 718 rods of 40mm diameter are used as work piece. This material is a nickel based super alloy with composition as given in Table I. Inconel 718 is famous for its high strength at high temperature. It has a high strength to weight ratio compared to steel. It is used in aggressive environments because it maintains resistance to corrosion, erosion, fatigue and creep at temperature up to 600^0c. Contrary to these highly advantageous qualities, it is a very difficult to machine material with a machinability percentage as low as below 15% due to its high shear strength, presence of hard abrasive carbide particle in its micro structure, work hardening tendency, tendency to weld and form built up edge and low thermal conductivity and low elastic modulus. The properties of inconel 718 are given in Table II. Application of Inconel 718 is in steam turbines, liquid fuel rockets, cryogenic engineering, acid environment, nuclear engineering etc.

B. *Cutting Inserts*

Commercially available coated tungsten based cemented carbide inserts were used to do the experiments. The grade of the inserts is Kennametal KC9110 (cvd with TiCN/Al2o3/Tin coating layer sequence) is an ISO class P10 grade with three main layers and several more sub layers of coating with a total thickness of 18 microns. A tool holder designated by ISO as PCBNR 2020K12 was used for mounting the insert.

C. *Design of experiments and procedure*

Taguchi method of orthogonal array was selected for conducting the experiments. L9 orthogonal array for three factors with three levels are selected for this experiment. The three factors and their three levels are shown in Table III.The nine experiments as per L9 (3^3) OA is conducted in a random order and the results tabulated in Table IV. A centre lathe with step variable spindle speed and feed was utilized for conducting the experiments. Oil in water emulsion was used as cutting fluid. Tool height, its overhang, and tool geometry were kept constant while conducting the experiment.

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TABLE I. COMPOSITION OF INCONEL718

Ni %	Cr %	Fe %	Mo %	Nb %	Co %	Mn %	Cu %	Al %	Ti %	Si %	C %	S %	P %	B %
50-55	17-21	Bal.	2.8-3.3	4.7-5.5	1	0.35	0.2-0.8	0.6-1.2	0.3	0.35	0.8	0.05	0.015	0.06

TABLE II. PROPERTIES OF INCONEL718

Density	Melting point	Tensile strength	Modulus of elasticity	Modulus of rigidity	Coefficient of expansion	Brinell hardness number
8.2 g/cc	1260-1340 ^{0}c	965 n/mm^2	204.9 KN/mm^2	77.2 KN/mm^2	13µm/m ^{0}c (20-100^{0}c)	≤ 363

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TABLE III. THREE FACTORS AND THEIR THREE LEVELS

Factor	Level 1	Level 2	Level 3
A : Speed (rpm)	325	550	930
B : Feed (mm/rev)	0.05	0.2	0.52
C : Depth of cut (mm)	0.5	0.64	0.8

TABLE IV. EXPERIMENT RESULTS

Run order	Standard order	Speed (rpm)	Feed (mm/rev)	Depth of cut (mm)	Cutting force (Newton)	Feed force (Newton)
1	4	550	0.05	0.64	186	67.6
2	1	325	0.05	0.5	184	67.2
3	3	325	0.52	0.8	371	219.6
4	2	325	0.2	0.64	256	127.2
5	9	930	0.52	0.64	332	214
6	8	930	0.2	0.5	256	136.8
7	6	550	0.52	0.5	378	236
8	5	550	0.2	0.8	262	136.4
9	7	930	0.05	0.8	181	64.4

TABLE V. ANOVA FACTORS FOR CUTTING FORCE

Standard deviation	17.34	R – squared	0.9690
Mean	267.33	Adj. R – squared	0.9504
C V %	6.49	Pred.R – squared	0.8873
PRESS	5462.79	Adqe. Precision	16.279

III. RESULTS AND DISCUSSION

A. Analysis of variance for cutting force (ANOVA

In order to evaluate the influence of speed, feed and depth of cut on the response variable –cutting force, ANOVA was carried out.

From the ANOVA table in Table V for cutting force we can see that the F value for the model is 52.05 and P value 0.0003 proving that the model is significant. F value of 1.26 and P value of 0.3132 for speed and F value of 0.002518 and P value of 0.9619 for depth of cut shows that these two parameters have no significant effect on the response variable namely cutting force where as an F value of 154.89 and P value of 0.001 for feed shows that it has significant effect on cutting force. Standard deviation, Mean, C V %, R – squared, Adj. R – squared, PRESS, Pred.R – squared, Adqe. Precision are given in Table VI. The R-square and Adj R-square values above 90% indicate that the model fit is on the higher side of the acceptable limit. The adjusted R-square and predicted R-square values are within 0.02 of each other and hence are in reasonable agreement.

The adequate precision is a measure of the range in predicted response about its associated error or in other words a signal to noise ratio and its value above 4 or more indicate reasonable adequacy and here the value is more than 4.

Regression equation for cutting force in terms of coded value is as follows.

Cutting force = 277.05 – 7.85 * speed + 86.26 * feed – 0.36 * depth of cut

Regression equation for cutting force in terms of actual values is as follows.

Cutting force = 190.27077 – 0.025960 * speed + 367.06189 * feed - 2.36686 * depth of cut

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TABLE VI. ANOVA TABLE FOR CUTTING FORCE

Source	Sum of squares	Degrees of freedom	Mean sum of squares	F value	P Value	
Model	46970.03	3	15656.68	52.05	0.0003	significant
A-speed	378.11	1	378.11	1.26	0.3132	
B -Feed	46591.17	1	46591.17	154.89	0.0001	significant
C-Depth of cut	0.76	1	0.76	0.002518	0.9619	
Residual	1503.97	5	300.79			
Cor. total	48474	8	6059.25			

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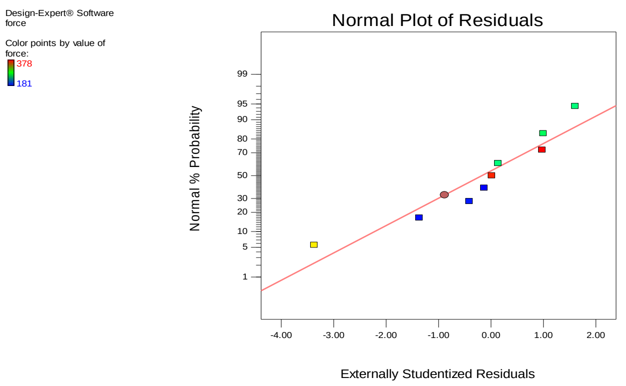

Fig. 1. Normal plot of residuals for Cutting force

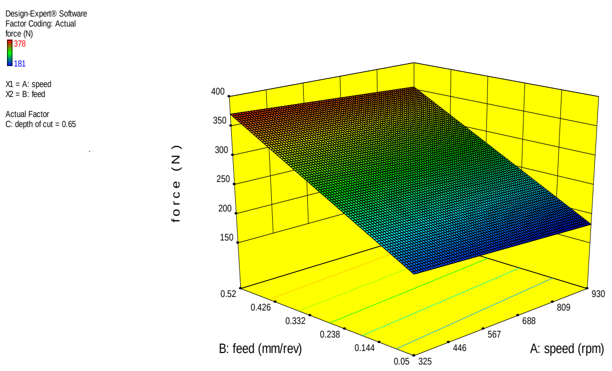

Fig. 2. 3D plot. Speed and Feed vs. Cutting force

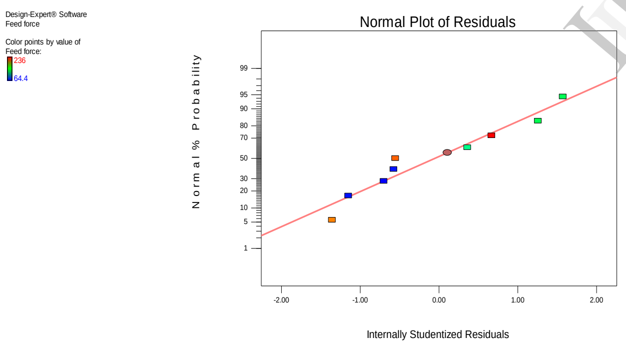

Fig. 3. Normal plot for feed force

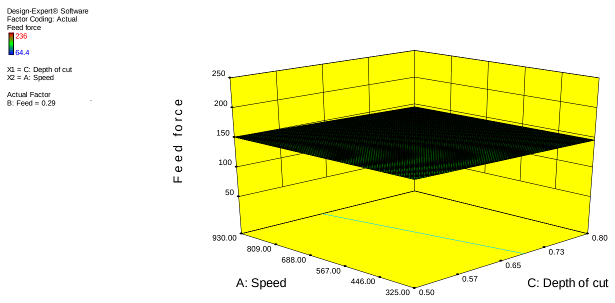

Fig. 4. 3D plot. Speed and depth of cut Vs Feed force

B. Analusis of Variance for Feed Force

In order to evaluate the influence of speed, feed and depth of cut on the response variable – feed force, ANOVA was carried out. From the ANOVA table (Table 3.3) for feed force we can see that the F value for the model is 72.45 and P value 0.0001 proving that the model is significant. F value of 0.009766 and P value of 0.9251 for speed and F value of 0.35 and P value of 0.5789 for depth of cut shows that these two parameters have no significant effect on the response variable namely feed force where as an F value of 222.39 and P value of 0.0001 for feed shows that it has significant effect on feed force. Standard deviation, Mean, C V %, R – squared, Adj. R – squared, PRESS, Pred.R – squared, Adqe. Precision are given in table 3.4.The R-square and Adj R-square values above 90% indicates that the model fit is on the higher side of the acceptable limit. The adjusted R-square and predicted R-square values are within 0.02 of each other and hence are in reasonable agreement. The adequate precision is a measure of the range in predicted response about its associated error or in other words a signal to noise ratio and its value above 4 or more indicate reasonable adequacy and here the value is more than 4.

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Regression equation in terms of coded values. Feed force = 150.12 – 0.51 * speed + 76.43 * feed – 3.10 * depth of cut

Regression equation in terms of actual values. Feed force = 71.93978 – 1.69207 * speed + 325.24773 * feed - 20.69034 * depth of cut

TABLE VII. ANOVA FACTRORS FOR FEED FORCE

Standard deviation	12.83	R – squared	0.9780
Mean	141.02	Adj. R – squared	0.9649
C V %	9.09	Pred.R – squared	0.9273
PRESS	2723.12	Adqe. Precision	18.680

TABLE VIII. ANOVA TABLE FOR FEED FORCE

Source	Sum of squares	Degrees of freedom	Mean sum of squares	F value	P Value	
Model	36640.31	3	12213.44	72.45	0.0001	significant
A-speed	1.61	1	1.61	0.009766	0.9251	
B -Feed	36580.83	1	36580.83	222.39	<0.0001	significant
C – Depth of cut	57.88	1	57.88	0.35	0.5789	
Residual	822.44	5	164.49			
Cor. total	37462.76	8	4682.85			

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C. Optimization Of Cutting And Feed Force Using Desirability Function Approach

Based on the experimental values, the cutting force and feed force were optimized using numerical optimization using design expert software based on desirability function approach. The optimum values obtained are given in table IX.Optimization Of Cutting And Feed Force Using Genetic Algorithm

The cutting force and feed force were optimized using genetic algorithm based on the mathematical models developed with the variables speed, feed and depth of cut. Matlab R2010a software was utilized for performing the optimization. The optimum values obtained are given in table X and XI

TABLE IX. OPTIMUM VALUES IN DESIRABILITY FUNCTION APPROACH

Cutting force	182.587
Feed Force	70.0763
Speed	930
Feed	0.05
Depth of cut	0.8
Desirability	0.979

TABLE X. OPTIMUM CUTTING FORCE USING GA

Cutting force (N)	182.6484
Speed (rpm)	929.541
Feed (mm/rev)	0.05013
Depth of cut (mm)	0.7999

TABLE XI. OPTIMUM FEED FORCE USING GA

Feed force (N)	70.08963
Speed (rpm)	929.98628
Feed (mm/rev)	0.05003
Depth of cut (mm)	0.7998

TABLE XII. CONFIRMATION TEST FOR CUTTING FORCE (N)

SI NO.	Speed (rpm)	Feed (mm/rev)	Depth of cut (mm)	Experimental value of cutting force	Predicted value of cutting force	Error %
1	930	0.05	0.8	71.9	70.1	2.5
2	550	0.2	0.64	120.1	122.8	2.24
3	325	0.52	0.5	227.4	230.2	1.23

TABLE XIII. CONFIRMATION TEST FOR FEED FORCE (N)

SI NO.	Speed (rpm)	Feed (mm/rev)	Depth of cut (mm)	Experimental value of feed force	Predicted value of feed force	Error %
1	930	0.05	0.8	187.2	182.6	2.56
2	550	0.2	0.64	242.3	247.9	2.30
3	325	0.52	0.5	363.7	371.5	2.14

IV. CONCLUSION

In this study, the effect of cutting parameters like speed, feed and depth of cut on the response functions cutting force and feed force while turning Inconel 718, a super alloy and difficult to machine material was investigated. The methodology of Taguchi's robust design was used for the design of experiments. Taguch's L_9 (3^3) orthogonal array was used to conduct the experiments.

The ANOVA study based on the experimental results revealed the following. The model is significant since the P value less than 0.05. Feed is the significant factor for cutting force and feed force in the range used in the experiment. Speed and depth of cut are insignificant for cutting force and feed force in the range used in the experiment. The regression models are statistically significant and adequate because of higher R^2 values. The normal plot of residuals showed that the residuals lie close to a straight line indicating that the residuals are independent and normally distributed and the terms in the model are significant. Optimization based on desirability function approach provided the optimum values for speed, feed and depth of cut for minimum cutting force and feed force within the range of the experiment. Optimization based on genetic algorithm also yielded the same results.

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