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Optimization of Cutting Parameters for Cutting Force Minimization in Helical Ball End Milling of Inconel 718 by Using Genetic Algorithm

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Abstract

Inconel 718 presents great opportunities in aerospace, space exploration, automobile and chemical industries due to their specific mechanical and thermal properties are superior to conventional materials. Despite their outstanding properties, their use is limited due to the machining difficulties. It is therefore necessary to determine the appropriate machining process window. Ball end milling is a rapidly growing process used for manufacturing of mechanical structural components of Inconel 718. The selection of optimal cutting conditions play an important role in reduction of cutting forces during ball end milling which governs the power consumption, machine stability, product quality and hence productivity. The paper mainly deals with the development of genetic algorithm to obtain optimum cutting conditions for minimization of cutting forces in helical ball end milling of Inconel 718 by using recorded cutting forces and regression model. The experiments were conducted using Taguchi *L*8 orthogonal array to analyze the effect of machining environment, cutting speed, feed, axial depth of cut and number of passes on cutting force magnitude. The obtained results show that the developed model fits very well with the experimental data. The developed model can be used for the prediction and estimation of cutting forces, optimization of cutting parameters in helical ball end milling of Inconel 718**.** The integration of the proposed method will lead to ensure machine stability, reduction in power consumption and cost along with flexibility in machining parameter selection.

Keywords: inconel 718; helical ball end milling; cutting forces; optimization; genetic algorithm

1. Introduction

The curved surface geometries found in turboreactors, gas turbine engines, rocket engines, cryogenic tanks, nickel-hydrogen batteries of space station and automobile structural components are complex in nature. These components are usually subjected to tremendous mechanical stresses and strains in challenging conditions while providing protection from corrosion and creep. High-performance materials like Inconel 718 which can withstand above conditions are used for producing these components [1] [4]. Around 50% of produced Inconel 718 is only used in manufacturing aircraft engines in their essential parts including blades, sheets and discs. But precipitation strengthened Inconel 718 possessing high temperature strength and poor thermal conductivity making itself difficult to machine [1] [6]. Ball end milling is the one of the effective machining process used to obtain three-dimensional contoured shapes. The toughness and durability of the cutting edge is very high in ball end mills because of the rounded edge design. Another benefit of the way the ball end mill is designed is that it can handle very high feed rates, thus it can mill the material very quickly on

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today's milling machines. The smooth geometry of the cutting tip also translates into lower cutting forces, giving the cutter added strength under pressure. Since it is less likely to break under normal forces, the ball end mill is also highly cost-effective for the applications to which it is suited [1-6]. While generating the curved and complex surfaces, the generated cutting forces directly or indirectly influence the machining process, power consumption and stability of the machine tool. Thus minimization of cutting force is an essential step to ensure machining system stability [3].

The success of the machining operation depends on the selection of proper machining parameters. In dry helical ball end milling of Inconel 718, milling cutter orientation and cutting speed have significant impact on magnitude of thrust force while number of passes shows larger significance on axial force and larger workpiece inclination which produces minimum cutting forces. High cutting speed, two pass cutting, moderate depth of cut, down milling & dry machining environment offers improved machined surface quality and integrity in ball end milling of Inconel 718 [1] [2]. Axial depth of cut is dominant cutting parameter among speed, feed per tooth and radial depth of cut that affects the three cutting force component [3].In case of helical ball end milling, the significant parameters that needs to optimize are cutting speed, radial and axial depths of cut, feed, number of passes and cutting environment. However, the optimization problems related to milling are usually complex in nature and characterized by mixed continuous-discrete variables and discontinuous and non-convex design spaces. The traditional optimization methods fail to give global optimum solution, as they are usually trapped at the local optimum and these are usually slow in convergence. Thus, researchers have studied application of non-traditional methods for optimization of process parameters of various manufacturing processes such as genetic algorithms (GAs) [7-9], particle swarm optimization and simulated annealing for milling operations. GAs makes use of population-type search. It can handle complex, continuous as well as discontinuous objective function and variables. GAs use probabilistic transition rules to find new design points for exploration rather than using deterministic rules based on gradient information to find these new points. In this work GA is implemented for estimating the best combination of cutting parameters for minimizing the cutting forces in ball end milling of Inconel 718 to reduce the cutting force (power consumption).

Based on the literature review, it is clear that most of the researchers have determined the effects of speed feed, depth of cut and tool material on cutting forces in the ball end milling process but very few studies are available on effect of machining environment during milling of Inconel 718. A large amount of work has been carried out on force modelling and chip analysis using experimental and numerical techniques [1] [4-6]. Moreover few attempts have been made by some researchers to study the machinability by employing chilled air and number of passes in ball end milling process. It is also noted that use of genetic algorithm technique for optimization of ball end milling process parameters for minimizing the cutting forces is very limited. Though the optimization of process parameters by using genetic algorithm is an effective, efficient and economic technique, a very little knowledge about the process parameter optimization in ball end milling of Inconel 718 using genetic algorithm is found. So, the assumption could be that this work gives a new contribution to the machining of Inconel 718 with optimized cutting parameters to reduce cutting forces and power consumption to improve productivity during manufacturing of free form surfaces.

2. Experimental work

The experiments were conducted using Taguchi *L*8 orthogonal array. A CNC milling machine (MAKE –HASS, Model-TM2) was used for conducting experiments on Inconel 718 plate (160 mm length, 70 mm width and 8 mm thickness). The chemical composition of work material is 51.3% Ni, 20.14% Fe, 18.17% Cr, 4.8% Nb, 3.25% Mo, and balance C. A PVD TiAlN coated carbide ball end mill (ICT 890 Grade) with two flutes, 10 mm diameter and 30° helix and 10° rake angle was used for the experiments. The cutting force components were measured with Kistler 3-component dynamometer with 5322 Al control unit having built in low pass filter, cut off frequency ~200Hz and output signal in the range of ±5Volt. The cutting force signals are acquired from dynamometer to amplifier at 200 Hz frequency thus the sampling rate was kept as 0.005. Based on the recorded experimental data regression equation was developed to determine the important machining variables influencing the cutting force magnitudes. The obtained regression model is chosen as the objective function for locating optimum machining conditions using genetic algorithm. The input parameters namely cutting speed (*m/min*), feed (*mm/tooth*), depth of cut (mm), no. of passes (1 - 2) and environment (dry and chilled air) were considered in this model. The optimal set value of independent variables are obtained using MATLAB software which gives minimum value of cutting force magnitudes using genetic algorithms. The results obtained with genetic algorithm are used for validation. Results of confirmation test compared with experimental sample data and regression model. The close up view of experimentation set up is presented in Fig.1.

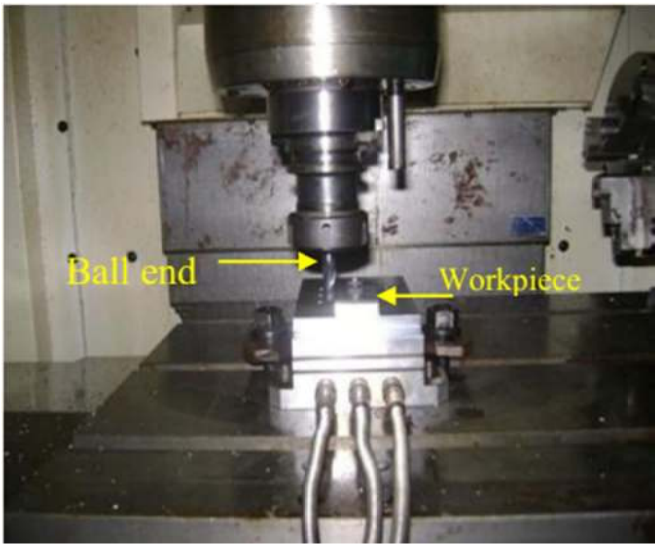


Fig. 1 (a) Experimentation Setup (b) Cutting forces, V_c (75m/min), f (0.4 mm/tooth), a_p 1.0 mm, NP 1, ENV chilled air

Table 1 presents the magnitude of cutting force components recorded during ball end milling. As far as the cutting force magnitude is concerned, it is higher at higher feed rate 0.08 mm/tooth and 1 mm depth of cut. In order to understand the most influencing machining parameters having largest contribution on the cutting force magnitude, analysis of variance was performed. The cutting speed, feed and depth of cut show statistically significant effect on the cutting force components at 95% confidence interval.

Table 1 Experimental observation of cutting forces in helical ball milling of Inconel 718

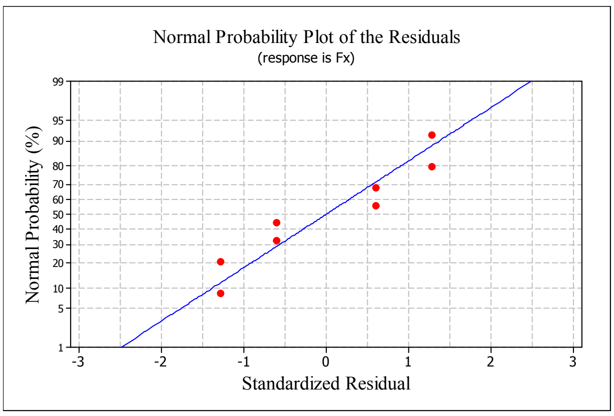
	Input Parameters				Output Parameters		
ENV	V_c (*m/min*)	f (*mm/tooth*)	a_p (*mm*)	NP	Fx	Fy	Fz
Room temp	25	0.04	0.5	1	144	181	73
Room temp	25	0.04	1.0	2	294	362	90
Room temp	75	0.08	0.5	2	365	451	78
Room temp	75	0.08	1.0	1	313	334	108
Chilled air	25	0.08	0.5	1	556	576	71
Chilled air	25	0.08	1.0	2	685	652	98
Chilled air	75	0.0	0.5	2	217	143	66
Chilled air	75	0.04	1.0	1	120	98	88

2. Results and Discussion

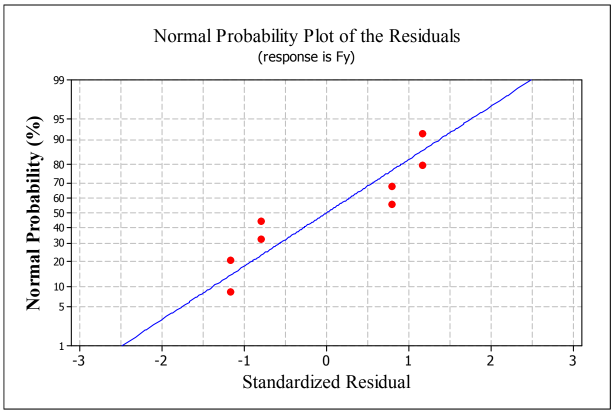
An analytical (regression) model for predicting cutting force components in F_x, F_y and F_z direction has been developed by using MINITAB 15 software. Table 2 represents the statistical significance of obtained model for force component. The desired level of confidence was considered to be 95%.

Table 2 Analysis of variance for cutting force components

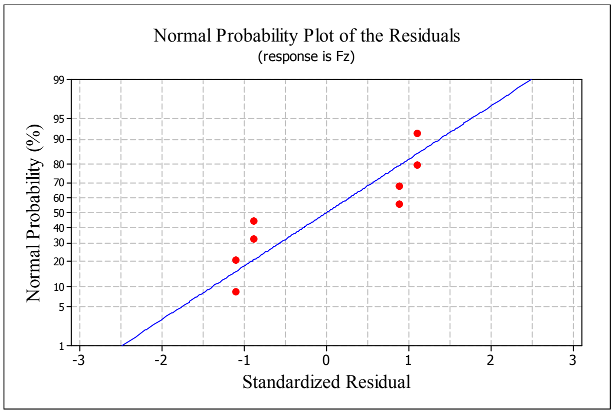
Cutting Force Component	F- value	P-value	R^2	R^2 (adj)
Fx	175.44	0.006	99.8	99.2
Fy	28.10	0.035	98.6	95.1
Fz	13.98	0.068	97.2	90.3



(a)



(b)



(c)

Fig. 2 Normal probability plot of residuals (a) F_x, (b) F_y, (c) F_z

The difference between R2 and R2 (adj.) is reasonably low which indicate the absence of insignificant terms in model. The normal probability plot of the residuals for cutting force components F_x, F_y, and F_z are shown in the Fig.2 (a-c). The regression equation for cutting force components are as follow:

$$F_x(N) = -72.9-4.81ENV-3.32V_c(m/min)+7150f(mm/tooth) +65.0a_p\,(mm) +107NP \quad (1)$$

$$F_y(N) = -98.7-1.47ENV-3.73V_c(m/min)+7681f\,(mm/tooth) +47.5a_p\,(mm) +105NP \quad (2)$$

$$F_z(N) = 31.2+0.271ENV+0.0400V_c(m/min)+238f\,(mm/tooth) +48.0a_p\,(mm)-2.00\,NP \quad (3)$$

4. Genetic Algorithm Optimization

For minimization of cutting force components in helical ball end milling of Inconel 718, cutting speed, feed, axial depth of cut, cutting environment and number of passes were selected as the input variable. The equation of response variable is obtained by regression analysis using MINITAB 15 software. Eqn (1), (2) and (3) are the best suited fitness function in the minimization of force components.

The optimization model is expressed as:

Find: V_c, f, a_p, NP, ENV, Minimize: F_x (V_c, f, a_p, NP, ENV), F_y (V_c, f, a_p, NP, ENV) and F_z (V_c, f, a_p, NP, ENV).

Variable bounds used were Feed = $0.04 \leq f \geq 0.08$ mm/ tooth, Doc= $0.5 \leq doc \geq 1$ mm, Speed = $25 \leq V \geq 75$ *m/min*, Temp= $1^oC \leq T \geq 25^oC$, No of passes = $1 \leq$ *no. of passes* ≥ 2. A binary string was used as solution string to represent real values of a variable. The length of the string depends on the precision required. In optimization procedure, set of parameter values is selected randomly from experimental data. The population size is 16, number of generations 100, number of bits in each parameter is 8, cross over fraction 0.5 and mutation rate is 0.15. 20 iterations of the GA program was performed in Matlab software which employed 20 optimized conditions of input variables that are required for minimizing the cutting force. The best obtained condition was V_c = 72 m/min, f = 0.05, a_p = 0.7, Temp. = 11^o*C,* number of passes = 1 is tested for confirmation of results by substituting in objective function and performing experiments. The maximum error obtained between the predicted and experimental values of process responses is around 3 %.

Table 3 Confirmations and Validation of Optimal Set of Process Parameters

Cutting force Components	Predicted force	Measured force	% error
F_x (N)	145.15	147	-1.27
F_y (N)	138.87	135	2.78
F_z (N)	80.56	83	-3.02

These results illustrate that the proposed procedure can be efficiently used to determine optimal parameters for any desired output value in helical ball end milling process and the optimal setting of the process parameters can be implemented for the process improvement. Confirmation of predicted and experimental force components are in well agreement is mentioned in Table 3.

5. Conclusions

The lower values of cutting speed (25*m/min*), higher depth of cut (1.0 *mm*) and feed rate (0.08mm/tooth) with chilled air produces cutting forces of higher magnitude. Cutting edge engagement with the workpiece material increases with increase in feed per tooth and axial depth of cut, thus more material will be available at cutting edge leads to increase in chip thickness which results into increase in cutting force. High speed ball milling of Inconel 718 results in highly localized temperature, stress and strain rate. An increase in temperature in the machining region could promote thermal softening causing ductility of the work material to increase and allows greater deformation. As a result, lower forces are required to shear the material during machining. It has been confirmed from the optimal value of cutting condition recommended by GA and real experiments. The optimized condition that gives better performance are – 11-12^{o}C temperature, high cutting speed (72 *m/min*), low feed (0.05 *mm/tooth*), moderate axial depth of cut (0.7*mm*), and one pass milling operation for considered variable bound.

6. Acknowledgement

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