Optimization of Cutting Parameters for Cutting Force in Shoulder Milling of Al7075-T6 Using Response Surface Methodology and Genetic Algorithm

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Abstract

This paper aims at developing a statistical model to predict cutting force in terms of machining parameters such as cutting speed, cutting feed rate and axial depth of cut. Response surface methodology experimental design was used for conducting experiments. The work piece material was Aluminum (Al 7075-T6) and the tool was a shoulder mill with two carbide insert. The cutting forces were measured using three axis milling tool dynamometer. The second order mathematical model in terms of machining parameters was developed for predicting cutting force. The adequacy of the predictive models was tested by analysis of variance and found to be adequate. The direct and interaction effect was graphically plotted which helps to study the significance of these parameters with cutting force. The optimization of shoulder mill machining parameters to acquire minimum cutting force was done by genetic algorithms (GA). A Matlab genetic algorithm solver was used to do the optimization.

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Keywords: Cutting force;Shoulder Mill;Response Surface Methodology;Genetic Algorithm;Optimization

1. Introduction

Shoulder mill is one of the most vital practices for shaping metal, nonmetallic components and a curved profile. It is one of the most widely used metal removal processes because of its ability to remove material faster with a good surface quality in industry and milled surfaces are largely used to mate with other in die, aerospace, automobile, biomedical products and machinery design as well as in manufacturing industries.

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Nomenclature

\begin{itemize}
\item $V_c$ Cutting speed (m/min)
\item $f_z$ Cutting feed rate (mm/tooth)
\item $ap$ Axial depth of cut (mm)
\item $F$ Cutting force (N)
\item $F_x$ Infeed force (N)
\item $F_y$ Crossfeed force (N)
\item $F_z$ Thrust force (N)
\item $X_i$ Required coded value of variable
\item $X_{\text{min}}$ Lower limit of the variable
\item $X_{\text{max}}$ Upper limit of the variable
\item $\phi$ Response surface
\item $e_u$ Residual
\item $u$ Number of observation
\item $b_0$ Constant
\item $b_i$ Linear term coefficient
\item $b_{ij}$ Quadratic term coefficient
\item $b_{ij}$ Interaction term coefficient
\item GA Genetic algorithm
\end{itemize}

During machining, the cutting tool uses a force on the workpiece as it removes the machining allowance in the form of chips. A correct estimation of such force could avoid quality problem related to the tool deflection, chatter or fixture improving also the productivity. The optimization of a machining process necessitates accurate measurement of the cutting force by a special device called a machine tool dynamometer, which is capable of measuring the components of the cutting force in a given coordinate system. It is a useful and powerful tool employed in a variety of applications in engineering research and manufacturing. The determination of optimal cutting parameter such as cutting speed, Axial depth cut, and feed, which are applicable for assigned cutting tools, is one of the vital modules in process planning of metal parts, since the economy of machining operations plays an important role in increasing productivity and competitiveness.

In the present work, an investigation on cutting forces is undertaken in order to study its effect on stability in end milling process together with its predictive model from machining parameters by way of response surface methodology and genetic algorithm. The literature survey pertaining to the work done by other researchers is given below.

Aladdin [1] used response surface method to predict tool life in end milling. The author found that the speed was the dominant factor in both the first and the second order models, followed by the feed and the axial depth of cut. Kovacic et al, [2] developed a genetic programming to predict cutting forces in milling. Baskar et al. [3] established a genetic algorithm (GA), hill climbing algorithm and memetic algorithm to optimize machining parameters for milling operations. The author considered the three objective functions namely minimum production cost, minimum production time and maximum profit rate for both single tool and multi-tool operations. Omar et al. [4] proposed a method to predict the cutting forces and 3D surface topography during side milling. The model incorporated the effects of tool runout, tool deflection, system dynamics, flank face wear, and the tool tilting on the surface roughness. Brezocnik et al. [5] introduced a genetic programming to predict surface roughness in end milling and established that the surface roughness was most influenced by the feed rate, whereas the vibrations increase the prediction accuracy. Ganesh babu et al. [6] carried out the effects of machining parameters on the variations of cutting forces during end milling operation of Al SiC metal matrix composite material. They showed the cutting force in tangential direction increases when the depth of cut increases. Ginting and Nouari [7] optimized the cutting coditions for end milling of aeroengine material Ti–6242S under dry condition. They also
used the FEM simulation, the chip morphology, contact length at the tool–chip interface and the tribological aspects (temperature, pressure) in machining to predict the optimum cutting condition. Peng et al. [8] investigated the characteristics of high speed machining dynamic milling forces of Titanium alloy by use of polycrystalline diamond tools. They found that amplitudes increase with the increase of cutting speed and tool wear. Ghani et al. [9] discussed the dynamic cutting force model for end milling which is developed to predict the tangential cutting force and the thrust force. They concluded that the cutting forces increase with increase in axial depths of cut. Li Zeng et al. [11] presented an experimental study of the tool wear propagation and cutting force variations in the end milling of Inconel 718 with coated carbide inserts. The tool flank wear propagation in the up milling operations was more rapid than that in the down milling operations. Soo Kang et al. [12] studied an analytical cutting force model for micro end milling was proposed for predicting the cutting forces. The cutting force model, which considered the edge radius of the micro end mill, was simulated. They found that the increasing of thrust force affects the feed direction cutting force in micro end milling with a very small feed per tooth. Okttem et al. [13] both response surface methodology and Genetic algorithm utilized to optimization of cutting conditions for surface roughness. The author concluded that GA decreases the surface roughness value in the mold cavity from 0.412 μm to 0.375μm corresponding to about 10%. Campatelli et al. [14] analysed the effect of feed per tooth and cutting speed on the cutting coefficients in order to create a model to predict reliably the cutting force with different process parameters. The experimental tests showed that the shearing cutting coefficient is influenced not only by the instantaneous chip thickness, or the feed per tooth, but also by the cutting speed, this contribution have a smaller effect respect to feed per tooth. Milfelner et al. [15] developed a genetic equation to predict the cutting force for ball end milling process. The authors indicated that intelligent production system will lead to decrease in manufacture cost and manufacture time, flexibility in machining parameter selection, and development of product quality. Zhang et al. [16] analyzed the tool wear and the cutting forces variation during high-speed end-milling Ti-6Al-4V alloy. The experimental results showed that the major tool wear mechanisms in high-speed end-milling Ti-6Al-4V alloy with uncoated cemented tungsten carbide tools are adhesion and diffusion at the crater wear along with adhesion and abrasion at the flank wear. Fnides et al. [17] developed a mathematical model for cutting forces and surface roughness in turning of hot work steel. The authors pointed that tangential cutting force was very sensitive to the variation of cutting depth what affects the cutting forces, surface roughness was very sensitive to the variation of feed rate and that flank wear has a great influence on the evolution of cutting force components and on the criteria of surface roughness. Yung Kuang Yang et al. [18] used a design of experiments to optimize parameters of a computer numerical control in end milling for high-purity graphite under dry machining. The author concluded that the feed rate was found to be the most significant factor affecting the groove difference and the roughness average in end milling. The literature showed above exposes that not much work has been stated on prediction and optimization of cutting force in shoulder mill. In this work, the main objective is to develop a model based on response surface methodology to the cutting force in terms of machining parameters such as cutting speed, cutting feed rate, and axial depth of cut. The mathematical model aided us to study the direct and interaction effect of each parameter. Additionally, the statistical model developed was utilized to optimize the machining parameters to obtain minimum cutting force using genetic algorithm.

2. Experimental design

Response surface method is the most effective method to study the result obtained from factorial experiments. It is an effective tool for modelling and studying the manufacturing problems. It delivers more information with fewer numbers of investigations. It is an investigation strategy for exploring the limits of the input parameters and emerging experiential statistical model for the measured response, by approximating the relationship existing between the response and input process parameters. The limit of the process parameters has to be defined in response surface method and the first experimentation was done to recognize the machining parameters that affect the cutting force and to discover the range of the selected cutting parameters. In the present study, cutting speed, cutting feed rate and axial depth of cut has been considered as the cutting parameters. The
response cutting force $F$ equation (1) can be expressed as a function of machining parameters cutting speed ($V_c$), cutting feed rate ($f_z$) and axial depth of cut ($a_p$),

$$F = \phi(V_c, f_z, a_p) + e_u$$

Where $\phi$ is the response surface, $e_u$ is the residual, $u$ is the Number of observations in the factorial experiment and $i_u$ represents level of the $i^{th}$ factor in the $u^{th}$ observation. When the mathematical form of $\phi$ is unknown, this function can be approximated acceptably within the experimental region by polynomials in terms of the machining parameter variable. Box and Hunter [25, 26] proposed the central composite rotatable design for fitting a second-order response surface based on the criterion of rotatability. The selected design plan chosen consists of 20 experiments. It has three factors-five levels central composite design consisting of 20 sets of coded condition (Table 1).

Table 1. Parameters and Levels in Shoulder Milling

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Notation</th>
<th>Units</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed</td>
<td>$V_c$</td>
<td>m/min</td>
<td>100 130 160 190 220</td>
</tr>
<tr>
<td>Cutting Feed</td>
<td>$f_z$</td>
<td>mm/tooth</td>
<td>0.06 0.07 0.08 0.09 0.10</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>$a_p$</td>
<td>mm</td>
<td>0.5 1 1.5 2 2.5</td>
</tr>
</tbody>
</table>

The design for the above experiment comprises of a full replication of $2^3(=8)$ factorial design plus six center points and six star points. These correspond to first 8 rows, the last six rows, and rows from 9 to 14, respectively. For Full replicate, the extra point included to form a central composite design, $\alpha$ becomes $2^3(=8)$. The upper limit of the parameter is coded as 1.682; lower limit, as $-1.682$. In this matrix, twenty experimental runs provide ten estimates for the effect of three parameters. One estimate for the mean effect of all the three parameters, three linear estimates for main effects, three quadratic estimates due to main effects, and three estimates for the two factor interactions are included. Thus the design matrix has allowed the estimation of linear, quadratic and two-way interactive effects of the selected machining parameter variables on cutting force. In the present work, shoulder mill of cutting tool insert, cutting speed, feed rate, and depth of cut have been considered as the machining parameters for cutting condition monitoring, and the cutting force is measured as a response variable (Table 2). In conducting the experiment, the upper limit of a factor was coded as $+1.682$ and the lower limit as $-1.682$. The coded values for intermediate values were calculated from the following relationship

$$X_j = \frac{1.682(2X - (X_{max} + X_{min}))}{(X_{max} - X_{min})}$$

Where $X_j$ is the required coded value of a variable $X$, $X$ is any value of the variable from $X_{min}$ to $X_{max}$, $X_{min}$ is the lower limit of the variable and $X_{max}$ is the upper limit of the variable. The intermediate values are coded as $-1$, 0, and 1. The coded values for intermediate condition have been calculated using Eq. 2.

Table 2. Experimental Design—Central Composite Design Matrix and Measured Value of Response
3. Experimental details

The experiments were conducted on a HAAS CNC vertical machining center with two carbide insert of shoulder mill cutter under dry condition. The work piece material was Aluminium 7075-T6 material was chosen in this study is usually employed in the aerospace industry to manufacture components that demand: lighter, harder, stronger, tougher, stiffer, more corrosion- and erosion-resistant properties. The dimension of the work piece specimen was 50 mm × 25 mm in cross section and 100 mm in length was used in this study. The cutting forces: infeed force, crossfeed force and thrust force are measured by using syscon instruments; three axis milling tool dynamometer. The data is acquired in the data acquisition software and observations are tabulated to obtain the mathematical model. The experimental setup used for conducting the experiments is shown in Fig.1a-1b.

4. Development of mathematical model

The general form of a quadratic polynomial which provides the relation between response surface $y$ and the cutting variable $x$ under study is given by Eq. 3.

$$ y = b_0 + \sum_{j=1}^{k} b_j x_j + \sum_{j=1}^{k} b_{jj} x_j^2 + \sum_{i<j}^{k} b_{ij} x_i x_j $$  \hspace{1cm} (3)

Where $b_0$ is a constant, $b_j$ is the linear term coefficient, $b_{jj}$ is the quadratic term coefficient and $b_{ij}$ is the interaction term coefficient.

The values of the coefficients of the polynomials were calculated by the multiple regression method. A statistical software Minitab14 and QA Six Sigma DOE PC IV was used to calculate the values of these coefficients.
The second-order mathematical model was established by neglecting the insignificant coefficients of the cutting force (F) Eq 4.

\[
\begin{align*}
\text{Infeed force } F_x &= 464.959 - 91.705V + 70.461f + 111.256a - 28.759f - 37.006a - 47.58Vf + 67.011fa \\
\text{Crossfeed force } F_y &= 646.517 - 76.674V + 149.781f + 195.58a - 62.23Vf + 69.63fa \\
\text{Thrust force } F_z &= 43.5316 - 16.6556V + 2.7161a + 6.2074V + 4.827f - 6.131Vf - 6.3813Va
\end{align*}
\]

The adequacy of the model was verified using the analysis of variance (ANOVA) technique (Table 3). The calculated F ratio of the model does not exceed the standard value for a desired 95% level of confidence. Table 3 shows that the model is acceptable, and that the error between the experimental and predicted values is less than 5%.

<table>
<thead>
<tr>
<th>Response</th>
<th>Factors Df</th>
<th>Lack of fit-df</th>
<th>Pure error</th>
<th>F-ratio</th>
<th>Whether Model is adequate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infeed force (F_x)</td>
<td>9</td>
<td>5</td>
<td>5</td>
<td>2.80</td>
<td>Adequate</td>
</tr>
<tr>
<td>Crossfeed force (F_y)</td>
<td>9</td>
<td>5</td>
<td>5</td>
<td>2.09</td>
<td>Adequate</td>
</tr>
<tr>
<td>Thrust force (F_z)</td>
<td>9</td>
<td>5</td>
<td>5</td>
<td>0.66</td>
<td>Adequate</td>
</tr>
</tbody>
</table>

5. Results and Discussion

The mathematical model was used to predict cutting force by substituting the respective values of the machining parameters. The influence of the machining parameters of cutting force was studied using the developed model.

5.1 Main effect of machining parameter on cutting force

The direct effect of machining parameters was studied by keeping all the machining parameters at the middle level except the parameter whose direct effect was studied. Fig. 2a-2c shows the effect of cutting speed, cutting feed and axial depth of cut on cutting force.
From the Fig.2a, it can be inferred that when cutting speed ranges from 100 m/min to 220 m/min the cutting force decreases with the increase of cutting speed due to the thermal softening which changes the shear angle and thus the necessary plastic deformation. This is due to due to an increase in strain and strain rate [19]. From the Fig.2b, it can be inferred that when cutting feed ranges from 0.06 mm/tooth to 0.1 mm/tooth the cutting force increases with the increase of cutting speed due to that more material will have to be cut per tooth per revolution, as a consequence more energy is required [19]. Fig.2c, it can be inferred that increase in axial depth resulted in an increase of in cutting force on all levels. Higher the axial depth of more length of the flute will get engaged which results in more cutting force. Increase in axial depth of cut, the length of the contact area in the axial cutting length in the rotating direction is increased, which resulted in increased cutting force [21].

5.2. Interactive effects of machining parameters on cutting force

The change in effect of one variable when the second variable is changed from one level to another is known as interaction effect. The interaction effects of the process variables are useful in understanding the machining behaviour. In this study, the two-way interactive effects of the process variables which have strong interaction with cutting force are discussed below.
Fig. 3. Interaction plot for response (cutting force)

Fig. 3a-3f shows the interactive effect of cutting speed, cutting feed and axial depth of cut on cutting force. Fig. 3a-3c shows the interactive effect of cutting speed and cutting feed on infeed force, cross feed force and thrust force. It has been inferred from the direct effect analysis that cutting speed has the negative effect and cutting feed has a positive effect on infeed force, cross feed force and thrust force. From Fig. 3a-3c, it is observed that the cutting force (infeed, crossfeed, thrust force) increases for cutting speed at 100 m/min and 220 m/min as the feed is increased from 0.06 mm/tooth to 0.1 mm/tooth. The resultant effect is due to the instantaneous accelerating in chip thickness with the increase in the feed rate and there is an amplified in the cutting forces as the forces are in proportion with the chip area. The reason is that more material will have to be cut per tooth per rotation as the feed is raised as a consequence more energy is required [19]. Therefore, it may be concluded here that cutting speed in the range of 160 m/min to 220 m/min and the cutting feed in the range of 0.06 mm/tooth to 0.08 mm/tooth would give minimum infeed force. Fig. 3d-3e shows the interactive effect of cutting feed and axial depth of cut on infeed force and cross feed force. From Fig. 3d-3e, it is observed that the cutting force (infeed, crossfeed) increases for cutting feed at 0.06 mm/tooth and 0.1 mm/tooth as the axial depth of cut is increased from 0.5 mm to 2.5 mm. This is because when the axial depth of cut increases, the average chip thickness increases which in turn increases the load on the ship resulting in decreased wedge strength of the tool [21]. Therefore, it may be concluded here that cutting feed rate in the range of 0.06 mm/tooth to 0.09 mm/tooth and the axial depth of cut in the range of 0.5 mm to 1.5 mm would give minimum cutting force.

Fig. 3f. shows the interactive effect of cutting speed and axial depth of cut on thrust force. It has been inferred from the direct effect analysis that cutting speed has the negative effect and axial depth of cut has a
positive effect on thrust. From Fig. 3f, it is observed that the infeed decreases for cutting speed at 100m/min, 130m/min and 160m/min as the axial depth of cut is increased from 1.5mm to 3.5mm. The trend changes in other two levels of cutting speed 190m/min and 220m/min. The thrust force increases for these two cutting speeds. By increasing the cutting speeds, the tendency of chatter decreases, but only up to a certain threshold value. After a certain limit, the tool will tend to deflect more, which induces vibration. Increase in axial depth of cut, the length of the contact area in the axial cutting length in the rotating direction is increased, which resulted in increased cutting force. Therefore, it may be concluded here that cutting speed in the range of 100m/min to 160m/min and the axial depth of cut in the range of 0.5mm to 1.5mm would give minimum cutting force.

6. Optimization procedure

The optimal selection of shoulder mill machining parameters should rise not only the function of cutting economics, however also the creative quality to a great magnitude by minimizing the cutting force. In this work, optimum values of end mill machining parameters are determined by an optimization method. Therefore, the machining parameters of end milling are distinct in the normal optimization method that is resolved by a numerical optimization algorithm. An objective function to be minimized is essential to describe the normal optimization problem. In end milling with different cutting condition cutting force, optimization problem can be expressed in the following:

\[ \text{Find: } V_c, f_z, a_p, \quad \text{Minimize: } F_w(V_c, f_z, a_p) \]

With ranges of cutting parameters:

\[
0.5 \text{mm} \leq a_p \leq 2.5 \text{mm}
\]

Genetic algorithm (GA) solver, an international optimization technique, is developed to solve the optimization problem conveyed by Eq. (5). Genetic algorithm simulates the biological progression method. The result of an optimization problem with genetic algorithm instigates with a set of possible solutions or chromosomes that are randomly selected [28]. The entire set of these chromosomes comprises a population. The chromosomes progress through numerous iterations or generations. New generations are produced employing the crossover and mutation method. Crossover comprises splitting two chromosomes and then joining one-half of each chromosome with the additional pair. Mutation includes tossing a sole bit of a chromosome. The chromosomes are then gauged using definite fitness criteria and the best ones are reserved while the others are rejected. This procedure recaps till one chromosome has the best fitness and is taken solution of the problem as the optimum [23, 28]. In this work, population size of 20, Elit count 2, crossover fraction 0.8, mutation rate of 0.01, lower bound \([-1.682 -1.682 -1.682\] and 100 generation are used. Optimization history only up to 51 iterations is illustrated in Fig. 4.

![Optimization history](image)
7. Conclusions

In this work, response surface methodology and genetic algorithm have been utilized for establishing optimum end mill process parameter guiding to minimum cutting force during shoulder mill Aluminium 7075-T6 with different cutting condition. Shoulder mill cutting parameters cutting speed, cutting feed, axial depth of cut used to conducting experiments. A response surface methodology was developed to regression model cutting force by manipulating experimental measurements found from these cutting forces. The established RSM model was further coupled with an established genetic algorithm to novelty the optimum end mill cutting parameter prominent to the minimum cutting force value.

In addition to the results discussed above, the following conclusions can be summarized:

The cutting force of AL7075-T6 aluminium alloy can be computed efficiently through the second-order quadratic model developed in this work. The direct and interactive effects of machining parameters on cutting force within the range of investigation can be studied with ease from the central composite design. The machining parameters for accomplishing the desired cutting force can be obtained from the mathematical model. A comparison is made between the predicted results and the experimental results and has been found that the deviation is well within the limit of 95% confidence level. We found that the cutting speed was the dominant factor in the second order models, followed by the cutting feed rate and the axial depth of cut. We also identified that high cutting speed, low cutting feed rate and low axial depth of cut leads to better low cutting force.

From this work, it is understood that it is possible to control the machining parameters and achieve the desired cutting force in AL7075-T6 aluminium alloy. Prior knowledge about the cutting force model acting on the system may help the operator in choosing the suitable machining parameters and the optimization of the machining parameters may help the manufacturer of machining tools in designing of cutting tools and to estimate the power.
requirement. This work will provide an engineer who designs a machining center with a tool to predict the cutting force and also provide a guideline for industrial engineers to estimate the cutting performance of high speed spindles during the design stage.

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