Paper ID: IE-34

Optimization of Turning Parameters for Cutting Force and Chip Thickness Ratio in Dry Turning Process: An Experimental Investigation

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Abstract

The aim of this paper is to determine the best turning process parameters that give the optimal magnitude of chip thickness ratio and cutting forces of cylindrical mild steel bar under turning operation. There were total 27 experimental combinations for the three machining parameters i.e. Spindle speed, Feed rate and Depth of cut in three levels. From the obtained experimental data, two separate general equations were developed for both chip thickness ratio and generated force, where chip thickness ratio and force are the responses of the three considered cutting parameters. In developing equations, the theory of multiple regression analysis was used. The Analysis of Variance Approach (ANOVA) was employed to verify the significance of the equations in practical implementation and the developed equations were found to be significant physically and statistically. Finally Genetic Algorithm (GA) was adopted to determine the best level of the parameters.

Keywords: Turning process parameters, optimization, cutting force, ANOVA, GA.

1. Introduction

Turning, Milling, and Drilling is the most common secondary metal shaping technology [1]. Turning is a form of machining or a material removal process, which is used to create rotational parts by cutting away unwanted material. The turning process requires a turning machine or lathe, work piece, fixture, and cutting tool. The work piece is a piece of re-shaped material that is attached to the fixture, which itself is attached to the turning machine, and allowed to rotate at high speed. The cutter is typically a single-point cutting tool that is also attached in the machine. The cutting tool feeds into the rotating work piece and cuts away material in the form of small chips to create the desired shape. In turning process, the speed and motion of the cutting tool and rotating work piece are specified through several parameters. These parameters are selected for each operation based upon the workpiece material, tool material, tool size and more. The most important turning parameters that can affect the process are cutting speed, depth of cut, feed rate etc.

The forces acting on a single point cutting tool are of fundamental importance in the design and of cutting and machine tools. The resultant cutting force P acting on the tool is considered to be as vector sum of three components of forces mutually at right angles. Feed force (F_x) acts in a horizontal plane but in the direction opposite to the feed. Thrust force (F_y) acting in the direction perpendicular to the generated surface. Cutting forces (F_z) is in the direction of the main cutting motion. The relationships among these forces depend upon cutting variables. Resultant force, P $=\sqrt{(F_x^2 + F_y^2 + F_z^2)}$. Power consumption is directly proportional to the resultant force generated.

During the turning process, when force is applied by cutting tool against the workpiece, the uncut layer deforms first elastically followed by plastic deformation due to the shearing action near the cutting edge of the tool. Shearing takes place along a shear zone and shear is highest at the shear plane. After passing out the shear plane, the deformed material slides along the tool face as chip as cutting progresses. Chip thickness ratio, $r = t_1/t_2$; where t_1= chip thickness before cutting and t_2= chip thickness after cutting. The value of chip thickness ratio is always less than 1. If the ratio r is larger i.e. close to 1, the cutting action is good defined by good surface finish. The ratio is affected by process parameters.

The high tech industries require, generally, high dimensional accuracy and good surface integrity of the fabricated parts, being the machining an essential manufacturing process for reaching these requirements [2]. There are several strategies which have been used with some success in the development of machinability of different materials, namely the optimization of cutting parameters [3, 4], chip breaking [5, 6], tool vibration [7,

8], cryogenic cooling [9], high pressure coolant [10], and others for meeting the demand of high tech industries. Chip thickness ratio is the important index of machinability [11] which is usually judged by cutting temperature; pattern and mode of chip formation; surface finish; tool wear and tool life [12]. Another researcher also said that Machinability of both materials and tools can be evaluated in terms of roughness, flank wear, cutting force, chip thickness ratio, and shear angle [13]. During the turning of the hard martensitic stainless steel it was found that it produced saw tooth chips in all operating parameters which increased the cutting forces [14] which is another great important machinability index. During the conduction of study on cutting AISI 420 steel using PCBN tool, it was observed that the tool wear was found due to abrasion and cutting temperature [15].
Environment awareness and the cost pressure on business organization have led to a rethinking of conventional flood cooling [16]. The last few decades, different cooling systems during machining process have been developed such as cryogenic cooling, solid lubricants, minimum quantity lubrication, high pressure coolant and also dry cooling [17]. After handsome amount of literature review, authors have selected two machinability indices which are the cutting force and the chip thickness ratio. These two machinability indices then have been optimized by selecting appropriate level of the turning process parameters such as depth of cut, feed rate, and spindle speed in dry condition.
When the chip thickness ratio is large, the cutting condition defined by surface finish is good and when the generated force is less, energy consumption is less. The chip thickness ratio depends on the turning parameters like depth of cut, spindle speed, feed rate etc. For obtaining good cutting conditions, the important affecting parameters need to be designed optimally. An investigation is made for searching the optimum and efficient combination of the affecting parameters of chip thickness ratio and force generated.

2. Experimental design

The experimental investigations were conducted to determine the optimal combination of the turning process parameters (Depth of cut, feed rate and spindle speed) on basis of the two response parameters (generated force and Chip thickness ratio). All the experimental tests were performed in a lathe machine whose specifications are demonstrated in table1. HSS single point cutting tool, widely used for machining carbon steel alloy, whose specifications are tabulated in the table 2 were used to perform the experiment in dry condition on the work piece whose specifications are demonstrated in the table 3. The most prominent turning process parameters which are depth of cut, feed rate and spindle speed were selected as control parameters, and each parameter was designed to have three levels, denoted as level 1, 2, and 3, mentioned in table 4. The experiments were designed by considering three control parameters and its levels. By this experimental design total 27 experimental runs were obtained and those are shown in table 5.

Table 1. Machine specifications

Characteristics	Size	Characteristics	Size
Bed Length	8.5 ft.	Spindle hollow	90 mm
Width of Bed	450 mm	Metric threads	1-14 mm
Height of center	400 mm	Number of feed rate	30
Swing over Bed	800 mm	Range of feed rate	0.033-0.5 mm
Swing over cross slide	530 mm	Number of spindle speed	9
Swing in gap	1200 mm	Spindle speed range	30-720 RPM
Admit between centers	1500 mm	Electric motor	5 Hp, 1440 RPM

Table 2. Cutting tool specifications

Characteristics	Size	Characteristics	Size
Tool material	High Speed Steel (HSS)	Side relief angle	6 degree
Tool type	Single point cutting tool	End cutting edge angle	8 degree
Back rack angle	10 degree	Side cutting edge angle	8 degree
Side rack angle	10 degree	Nose radius	2 mm
End relief angle	6 degree	Major cutting edge angle	71 degree

Table 3. Work piece specifications

Characteristics	Type	Characteristics	Size
Material	Mild Steel (MS)	Diameter	40 mm
Shape	Cylindrical	Length	1.5 ft.

Table 4. Parameters and its levels

Parameters	Level 1	Level 2	Level 3
Depth of cut (mm)	0.415	0.56	0.68
Feed Rate (mm/rev.)	0.08	0.14	0.28
Spindle speed (RPM)	245	490	650

3. Experimental results and decisions

The turning tests in dry condition were performed on a lathe machine according to the experimental design. During the turning process, the generated force and the chip thickness were measured with digital dynamometer and digital slide calipers respectively for each experimental run and those were also recorded for the further analysis. All data were recorded in the table 5.

Table 5.Experimental data table

No. of experiment	**Depth of Cut (mm)** x_{ai}	**Feed rate (mm/revolution)** x_{bi}	**Spindle speed (rpm)** x_{ci}	**Force Generated (KN)** y_{ai}	**Chip thickness Ratio** y_{bi}
01	0.415	0.08	245	0.16	0.860
02			490	0.15	0.880
03			650	0.13	0.915
04		0.14	245	0.19	0.875
05			490	0.18	0.900
06			650	0.17	0.930
07		0.28	245	0.24	0.880
08			490	0.22	0.905
09			650	0.21	0.910
10	0.56	0.08	245	0.29	0.790
11			490	0.27	0.813
12			650	0.25	0.821
13		0.14	245	0.28	0.844
14			490	0.27	0.861
15			650	0.25	0.870
16		0.28	245	0.30	0.820
17			490	0.29	0.830
18			650	0.28	0.850
19	0.68	0.08	245	0.34	0.653
20			490	0.32	0.671
21			650	0.31	0.690
22		0.14	245	0.43	0.674
23			490	0.41	0.692
24			650	0.38	0.710
25		0.28	245	0.52	0.722
26			490	0.49	0.740
27			650	0.44	0.763

Multiple regression analysis

The complexity of most scientific mechanics is such that in order to be able to predict an important response, a multiple regression model is needed. When this model is linear in the coefficient, it is called a multiple linear regression model. The depth of cut (mm), feed rate (mm/rev), and spindle speed (rpm) as turning process parameters were considered in the development of the mathematical models for the responses i.e. chip thickness ratio and the generated force. The coefficients of determination between the turning process parameters and the responses for the mild steel bar turning process performed by the lathe machine were also obtained by the multiple linear regression analysis.

The estimated response is obtained from the equation, $\hat{y} = b_0 + b_a x_a + b_b x_b + b_c x_c + \dots\dots\dots\dots + b_k x_k$; where,$\hat{y}$ is the estimate of the response variable, $x_a, x_b, x_c \dots\dots x_k$are the explanatory variables

and $b_0, b_a, b_b \dots\dots\; b_k$ are estimates of the explanatory variables. The mathematical model for the generated force during turning process is as follows: $\widehat{y_a} = b_0 + b_a x_a + b_b x_b + b_c x_c$; where, $\widehat{y_a}$ is the estimate of the generated force, x_a, x_b, x_c are the explanatory variables i.e. depth of cut (mm), feed rate (mm/rev), and spindle speed (rpm) respectively and b_0, b_a, b_b, b_c are estimates of the explanatory variables.The mathematical model for the chip thickness ratio during turning process is as follows: $\widehat{y_b} = b_0 + b_a x_a + b_b x_b + b_c x_c$; where, $\widehat{y_b}$ is the estimate of the chip thickness ratio and all other terms are same as the previous definition.
By using the most popularly used statistical analysis software package MINITAB, the following equations were obtained on the basis of the data table 5:
$\widehat{y_a} = -0.1071776379595 + 0.79320020501288x_a + 0.16164457721730x_b - 0.00014941495564x_c$..**(1)**
$\widehat{y_b} = 1.10907107499039 - 0.62732429036086x_a + 0.01444122008191x_b + 0.00009551097505x_c$…**(2)**
Sum square regression, SSR = $\sum_{i=1}^{27}(\widehat{y_i} - \bar{y})^2$
Sum square error, SSE = $\sum_{i=1}^{27}(y_i - \widehat{y_i})^2$
Sum square total, SST = SSR + SSE
Mean square regression, MSR = SSR/k
Mean square error, MSE = SSE/n-(k+1)
n = total number of experiments, k = number of parameters considered.
Coefficient of multiple determinations,
In response to generated force i.e. equation 1, R^2 = SSR/SST = 80.053%
In response to chip thickness ratio i.e. equation 2, R^2 = SSR/SST = 82.9898%
The quantity of R^2 indicates the measure of the proportion of variability explained by the fitted model. Both the fitted model in response of force generated and chip thickness ratio is acceptable, since R^2>80% for both the cases respectively.

Analysis of variance approach (ANOVA)

The problem of analyzing the quality of the estimated regression line is handled by an analysis of variance (ANOVA) approach. In this approach, the total variation in the dependent variable is subdivided into meaningful components that are then observed and treated in a systematic fashion. The general table of the different parameters of ANOVA is given in table 6.

Table 6. General parameters of ANOVA

Source	Sum of Squares	Degree of freedom	Mean Squares	*F-value*
Regression	SSR	k	MSR=SSR/k	MSR/MSE
Error	SSE	n-(k+1)	MSE=SSE/n-(k+1)	
Total	SST	n-1		

Table 7. Analysis of variance in response of force

Source	Sum of Squares	Degrees of freedom	Mean Squares	*F- value*
Regression	0.209688437	k=3	0.069896	30.76
Error	0.052247	n-(k+1) = 27-4	0.00227161	
Total	0.261935437	n-1 = 27-1		

Table 8.Analysis of variance in response of chip thickness ratio

Source	Sum of Squares	Degree of freedom	Mean Squares	*F-value*
Regression	0.13226	k=3	0.053123	7.66
Error	0.027109	n-(k+1)=27-4	0.0069291	
Total	0.159369	n-1=27-1		

For degrees of freedom n-(k+1) = 23 and k = 3, the critical value of the *F*-Distribution is 3.03 at 95% confidence interval. In above models, both the obtained *F*-values from experimental data in response of force generated and chip thickness ratio are greater than the critical value obtained from *F*-Distribution. Therefore the models present statistical and physical significance for the turning parameters of generated force and chip thickness ratio respectively.
The relationship of the process parameters on the response are demonstrated in the fig 1. Some parameters have the strong relationship with the response and it is indicated by the rate of change of curve. From the fig 1, it is clear that depth of cut has the strong relationship with the generated force and the chip thickness ratio. The mean generated force is increased with increase of the depth of cut. On the other hand, the chip thickness ratio is decreased with increase of depth of cut. All other factors have the moderate relationship with the generated force and the chip thickness ratio.

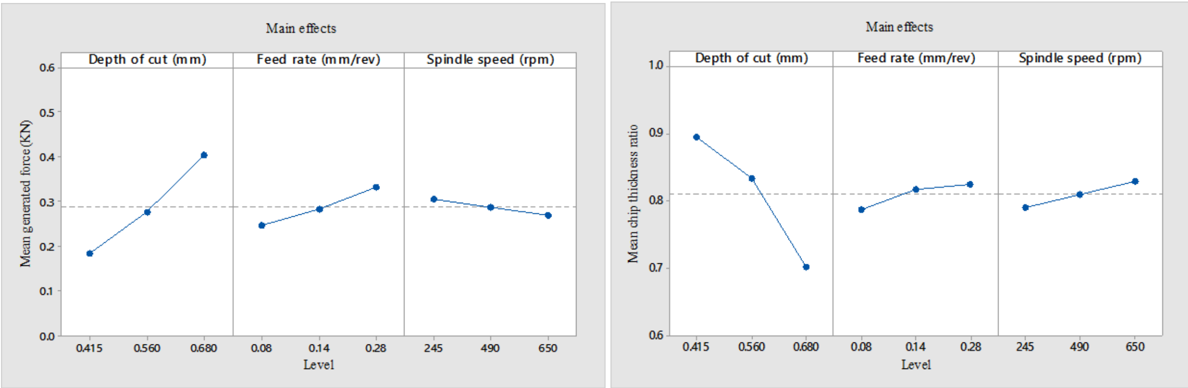

Fig 1: Main effects of process parameters

Genetic algorithm

Genetic algorithm (GA) is a method for solving both constrained and unconstrained optimization problems based on a natural selection process that mimics biological evolution. GA is a very effective way of quickly finding a reasonable solution to a complex problem. The GA repeatedly modifies a population of individual solutions. At each step, the GA selects individuals at random from the current population to be parents and uses the parents to generate the children for the next generation. Over successive generations, the population evolves toward an optimal solution.

In above modeled equations, the number of decision variable is three at each equation and each variable has the defined upper and lower limit i.e. level 1 and level 3. So the search space is known but very large and complex. In this situation, the GA can be used to find out the optimal solutions for the above models.

The less the force generated the less is the power consumption, so equation of $\widehat{y_a}$ is a minimization problem. Solving with Genetic Algorithm (GA), the following results are obtained, $\widehat{y_a}$= 0.13781427538676855 KN, x_a= 0.415 mm, x_b= 0.08 mm/rev., x_c = 650 RPM.

The more the chip thickness ratio the better the surface finish, so equation of $\widehat{y_b}$ is a maximization problem. Solving with Genetic Algorithm (GA), the following results are obtained, $\widehat{y_b}$= 0.9148564934304552, x_a= 0.415 mm, x_b= 0.28 mm/rev., x_c = 650 RPM.

4. Conclusion and recommendation

The chip thickness ratio and the cutting force are the important index of machinability measure. How are these indices of machinability measure influenced by the turning process parameters and what is the optimal combination of the turning process parameters for getting desired machinability were the main objectives in this research. It has been observed that the chip thickness ratio and the cutting force are strongly correlated with the turning process parameters, depth of cut, feed rate and spindle speed. From the experimental data, it has been also observed that (i) the generated force is increasing with the increase in depth of cut and this change is strongly significant whereas the chip thickness ratio is decreasing with the increase in depth of cut and this change is also strongly significant;(ii) the generated force is increasing with the increase in feed rate and this change is moderately significant whereas the chip thickness ratio is increasing with the increase in feed rate and this change is weakly significant; (iii) the generated force is decreasing with the increase of spindle speed and this change is moderately significant whereas the chip thickness ratio is increasing with the increase in spindle speed and this change is weakly significant.

To know about the effect of turning process parameters on the machinability indices is vital important for the manufacturing engineers to set the optimal level of process parameters in order to get the desired quality of the machined products along with lower power consumption. Finally, optimal combination of the process parameters has been also determined for both generated force and chip thickness ratio by adopting genetic algorithm. The optimal combination for low generated force is depth of cut (0.415 mm), feed rate (0.08 mm/rev) and spindle speed (650 RPM) and for high chip thickness ratio is depth of cut (0.415 mm), feed rate (0.28 mm/rev) and spindle speed (650 RPM).

The obtained equation 1 and equation 2 can be used to predict the turning process parameters to generate desired surface finish and energy consumption, since fitness (R^2) and physical significance (F-value) of both equations are acceptable. This methodology is very simple and systematic for identifying the optimal combination of process parameters and the output of the research can be used in practical purpose for better performance of the manufacturing process.

5. References

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