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Experimental Investigation for Cutting Force by Optimizing Machining Parameters with Taguchi Method in Turning of AISI 4340 Steel

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Abstract- To increase the productivity in machining industries demand for minimum cutting force, better surface finish and accuracy has been increasing rapidly in recent years. Therefore, this paper focuses on an effective approach for the optimization of process parameters. This paper investigate the effect of cutting parameters such as cutting speed, feed and depth of cut on the performance characteristics cutting force in turning of AISI 4340 steel with brazed tungsten carbide turning tools. The effects of the process parameters on performance characteristics cutting force are investigated by using Taguchi's L9 orthogonal array and analysis of variance (ANOVA). The results show that the depth of cut is majorly affecting the cutting force, followed by feed rate. The experimental data were further analyzed and to correlate with cutting parameters using linear regression analysis. Finally machined surface of the workpiece were examined under optimal cutting conditions such as CV = 75 m/min, FR = 0.4 mm/rev and DOC = 0.5 mm) and found the minimum force is equal to 5.09kg.

Keywords- AISI 4340 steel, Cutting force, Lathe Tool Dynamometer

INTRODUCTION

Nowadays, modern machining industries are trying to achieve high quality, dimensional accuracy, surface finish, high production rate and cost saving along with reduced environmental impact [1]. Turning is the most important operation in the machining process. It can be carried out on different machines like CNC Lathe, conventional lathe, Capston and Turret Lathe and special purpose lathe machine etc. [2]. The quality of turning is measured in terms of accuracy and surface finish. In turning operation, parameters such as cutting speed, depth of cut, feed rate have great impact on the cutting force. The turning operation seems very simple; through high speed turning of steel inherently generates high cutting zone temperature. Such high temperature causes dimensional deviation and premature failure of cutting tools. [3]. The study of cutting forces is critically important in turning operations because cutting forces give effect on cutting performance such as surface accuracy, cutting temperature self excited tool wear, tool breakage, and forced vibrations, etc. Knowledge of the cutting forces is needed for estimation of power requirements, tool geometry and for the design of machine tool elements. In turning, there are many factors affecting the cutting process behavior such as tool variables, work piece variables and cutting conditions. Tool variables consist of tool material, cutting edge geometry etc., while work piece variables comprise material, mechanical properties (hardness), chemicals and physicals properties, etc. Furthermore, cutting conditions include cutting speed, feed rate and depth of cut. The selection of optimal process parameters is usually a difficult work, however, is a very important issue for the machining process control in order to achieve improved product quality, high productivity and low cost. Ozel et al. conducted a set of analysis of variance (ANOVA) and performed a detailed experimental investigation on the surface roughness and cutting forces in the finish hard turning of AISI H13 steel. Their results indicated that the effects of work piece hardness, cutting edge geometry, feed rate and cutting speed on cutting forces are statistically significant. They reported that especially, small edge radius and lower work piece hardness increased surface roughness in their experiments.[4] Sachin Ohder, Debabrata P, Bhisal Khatau, Santosh T. concluded that Taguchi method of experimental design has been applied for optimizing the process parameters for turning Al-SiC alloy. Results obtained from Taguchi method closely matched with ANOVA. Best parameters

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found for lesser tool force are: Cutting Speed (100 RPM), Feed (0.125 mm/rev) and Depth of Cut (0.5mm) for machining on a high speed lathe and the result indicated by prediction model of regression equation was found to be almost confirming with the actual values obtained from experimental analysis[5].

Sanjeev Sharma , Rajdeep singh , Sandeep Jindal, investigated that the cutting forces and feed forces is directly proportional to depth of cut and feed rate of tool & inversely proportional to feed/rev. Natural frequency & stress produced in tool of dynamometer has been formulated to give the permissible limits of the safe designs[6].

Maheshwari Patil , Dr. R. J. Patil studied the effect of HSS single point cutting tool nose radius on cutting edge strength and tool wear in machining of EN9. This paper presents a survey on variation in tool geometry that is tool nose radius , rake angle, variable edge geometry and their effect on tool wear and cutting edge integrity in the turning operation of components from EN9 plain carbon steel. In their study they have carried out the experimental study of HSS tool or material EN9 with this objective to study the effect of rake angle and nose radius on tool edge integrity and stress produced in the tool material leading to tool edge failure [7].

In the present study, an attempt has been made to investigate the effect of cutting parameters cutting speed, feed rate and depth of cut on the cutting force in finish hard turning of AISI 4340 with brazed tungsten carbide turning tools. In this research, a L9 Taguchi standard orthogonal array is adopted as the experimental design. The combined effects of the cutting parameters on performance characteristics are investigated while employing the analysis of variance (ANOVA). The relationship between cutting parameters and performance characteristics through the linear regression analysis are developed.

TAGUCHI METHOD AND DESIGN OF EXPERIMENT

Traditional experimental design methods are very complicated and difficult to use. Additionally, these methods require a large number of experiments when the number of process parameters increases [8, 9, 10]. In order to minimize the number of tests required, Taguchi experimental design method, a powerful tool for designing high-quality system, was developed by Taguchi. This method uses a design of orthogonal arrays to study the entire parameter space with small number of experiments only. Taguchi recommends analyzing the mean response for each run in the inner array, and he also suggests to analyze variation using an appropriately chosen signal-to-noise ratio (S/N). There are 3 Signal-to-Noise ratios of common interest for optimization of static problems:

Table 1: Goal & S/N Ratio Formula

GOAL	S/N RATIO FORMULA
Nominal is better	S/Ni = $10 \log \frac{\bar{y}_i^2}{s_i^2}$
Smaller is better	S/Ni = $-10 \log \sum_{u=1}^{N_i} \frac{y_u^2}{s_i^2}$
Larger is better	S/Ni = $-10 \log \left[\frac{1}{N_i} \sum_{u=1}^{N_i} \frac{1}{\bar{y}_u^2}\right]$

In this study, three machining parameters were selected as control factors, and each parameter was designed to have three levels, denoted 1, 2, and 3 (Table 2). The experimental design was according to an L'9 array based on Taguchi method, while using the Taguchi orthogonal array would markedly reduce the number of experiments. A set of experiments designed using the Taguchi method was conducted to investigate the relation between the process parameters and response factor. Minitab 16 software is used to optimization and graphical analysis of obtained data.

Table 2: Process Parameter with Levels

S.No	Factors	Unit	Levels		
			1	2	3
1	Spindle Speed	m/min	45	75	115
2	Feed Rate	mm/Rev	0.4	0.8	1.27
3	Depth of Cut	mm	0.5	1.0	1.5

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In the Taguchi method, most all of the observed values are calculated based on 'the higher the better' and 'the smaller the better'. Thus in this paper, the observed values of Cutting Force and SR were set to minimum. Each experimental trial was performed with three simple replications at each set value. Next, the optimization of the observed values was determined by comparing the standard analysis and analysis of variance (ANOVA) which was based on the Taguchi method.

EXPERIMENTAL DETAILS

High Tensile Steel (AISI 4340) of Ø: 20 mm, length: 25 mm were used for the turning experiments in the present study. The chemical composition of AISI 4340 can be seen in Tables 3. The turning tests were carried out to determine the cutting force under various turning parameters. MAXCUT High Precision SUPER MODEL Lathe Machine MD 212S used for experimental investigations.

Table 3: Chemical Properties of AISI 4340

Element	Carbon	Silicon	Manganese	Nickel	Chromium	Molybdenum
Percentage	0.40%	0.25%	0.70%	1.85%	0.80%	0.25%

The machining performance (ANOVA-significant factor) for each experiment of the L9 can be calculated by taking the observed values of the as table 4.

Table 4: Taguchi L9 orthogonal array for Cutting Force

S.No	Spindle Speed(m/min)	Feed Rate (mm/Rev)	Depth of Cut (mm)	Thrust Force (kg)	Feed Force (kg)	Resultant Force (kg)
1	45	0.4	0.5	10	1	10.05
2	45	0.8	1.0	29	5	29.43
3	45	1.27	1.5	45	10	46.10
4	75	0.4	1.0	15	2	15.13
5	75	0.8	1.5	35	8	35.90
6	75	1.27	0.5	17	2	17.12
7	115	0.4	1.5	20	6	20.88
8	115	0.8	0.5	16	3	16.28
9	115	1.27	1.0	38	8	38.83

RESULT & DISCUSSION

The cutting velocity, feed rate and depth of cut were used for development of mathematical models for the cutting force. The mathematical relation between factors (CV, FR, and DoC) and response cutting force on high speed turning on AISI 4340 were obtained by multiple linear regressions. A commercial statistical software MINITAB was used to derive the models of the form. The regression equation is

Cutting Force = - 8.67 - 0.0397 * CV + 21.3*FR + 19.8*DoC

The Proportion of Variance Explained (R2) is 89.2% and Adjusted coefficient of multiple determination (Ra2) = 98.75% which indicates that the model gives an approximate result. In multiple linear regression analysis, if R2 (regression coefficient) is more than 82.8% for the models, then it is indicate that the fit of the experimental data is agreeable.

Table 5: Proportion of Variance for S/N ratio

Predictor	Coef	SE Coef	T	P
Constant	-8.675	7.693	-1.13	0.311
CV	0.039	0.0602	-0.66	0.539
FR	21.251	4.859	4.37	0.007
DOC	19.81	4.232	4.68	0.005
S = 5.18328 R-Sq = 89.2% R-Sq(adj) = 82.8%				

TAGUCHI ANALYSIS

Taguchi method is used to studying the response variation using the signal – to – noise (S/N) ratio. The S/N ration study is minimized the quality characteristic variation by controlling uncontrollable parameters. In this analysis material removal rate is taken as quality characteristic with the model of “Smaller is the Better".

In any case of the performance characteristics, a smaller S/N value belongs to a better performance. Therefore, the optimal level of the machining parameters is the level with the smallest S/N value. According to the analysis of the S/N ratio, the optimal machining performance for the cutting force was obtained at 45m/min (level 1), 1.27 feed rate (level 2) and 1.5mm depth of cut (level 3). Fig. 3 shows the effect of the process parameters on the cutting force.

Table 6: S/N value for cutting force by factor level

Response Table for Signal to Noise Ratios			
Smaller is better			
Level	CV	FR	DOC
1	-27.56	**-23.34**	**-22.98**
2	**-26.46**	-28.24	-28.25
3	-27.47	-29.91	-30.26
Delta	**1.11**	**6.56**	**7.27**
Rank	**3**	**2**	**1**

EFFECT OF CUTTING VELOCITY

The cutting force varies with increase in cutting speed. It will be noted that the cutting forces first decreased with increase in cutting speed and on further increase in speed reach a minimum value and then again increasing and become fairly stabilized at higher speed ranges. The initial reduction in cutting force up to about 75 m/min is due to the effect of built-up edge which does not occur at high speeds and at high speeds beyond 75 m/min increased because of strain hardening.

EFFECT OF FEED RATE

The cutting force is greatly influenced by the feed rate. It has been observed that cutting force changes linearly with feed rate at higher speeds, but at slower speeds the change is exponential. If the feed rate increases the section of the sheared chip increases because the metal resists the rupture more and requires larger efforts for chip removal. Hence the cutting force increases as the feed rate increases.

DEPTH OF CUT

The tangential component of cutting force is greatly influenced by the depth of cut. With the increase in Depth of cut the chip thickness becomes significant which causes the growth of volume deformed and that requires enormous cutting forces to cut the chip. Hence cutting force increases as the Depth of cut increases.

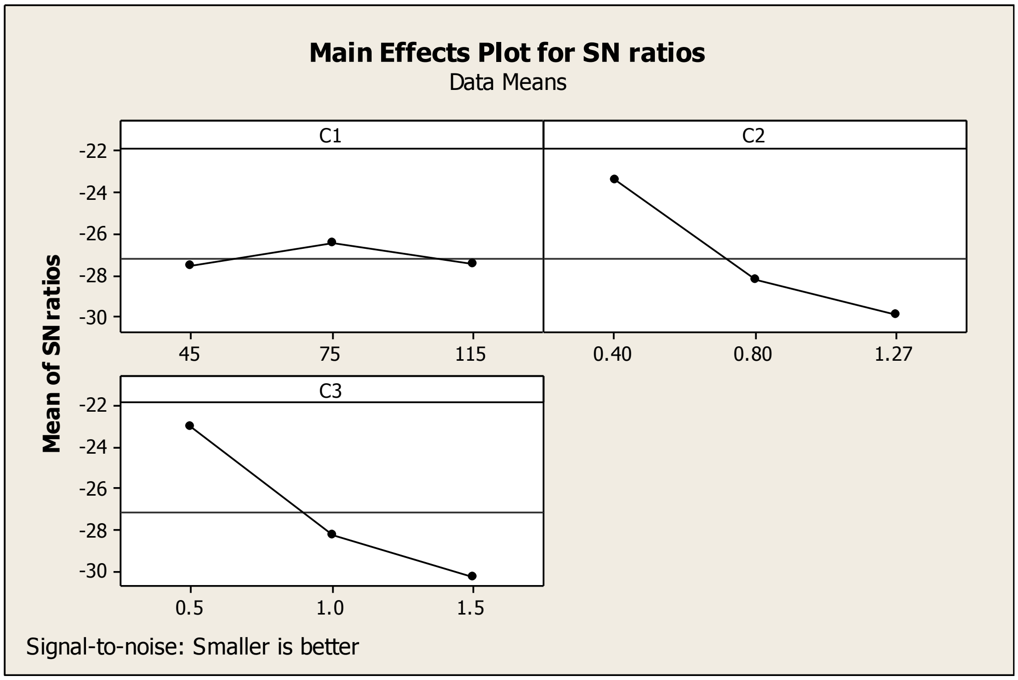

Fig 1: Effect of Cutting Velocity, Feed Rate and Depth of Cut on Cutting Force

Table 7: Analysis of Variance for Means

Analysis of Variance for Means						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
CV	2	50.8	50.8	25.4	1	0.499
FR	2	535.16	535.16	267.58	10.57	0.086
DOC	2	611.89	611.89	305.94	12.09	0.076
Residual Error	2	50.61	50.61	25.3		
Total	8	1248.47				

The P-value reports the significance level (suitable and unsuitable) in Table 7. Percentage is defined as the significance rate of the process parameters on the cutting force. The percent numbers show that the CV, FR and DoC have significant effects on the cutting force.

CONCLUSION

1. From the above results we can conclude that cutting force increases as the feed rate and depth of cut increases. The percentage of error is in the acceptable range hence the developed application can be readily used for the estimation of cutting forces and to know the effect of various cutting parameters on cutting forces in turning.
2. The cutting forces increase with the increase in feed rate.

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3. The cutting forces increase with the increase in depth of cut.
4. From ANOVA analysis, parameters making significant effect on cutting force are feed rate and depth of cut.
5. The parameters taken in the experiments are optimized to obtain the minimum cutting force possible. The optimum setting of cutting parameters for high quality turned parts is as :

   i) Cutting speed i.e. 75 m/min.

   ii) Feed rate i.e. 0.4 mm/rev.

   iii) Depth of cut should be 0.5 mm.

   The minimum cutting force for this parameter is 5.09kg.

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