ABSTRACT

With passage of time technologically advanced machines have been developed. But the problem of the tool wear and cutting force for a particular machining process remains to be improved. So, to avoid or to cope-up with this problem it is necessary to find the best combination of machining parameters for obtaining optimum cutting force. In this work the optimization of cutting force for a given combination is done in a useful and easy way. Three factors are selected that affect the optimizing parameters in case of turning. These factors are optimized to get the optimum cutting force. This is achieved by employing response surface methodology and signal to noise ratio calculation. One factor is varied by keeping the other two constant at same range. Through the response surface methodology 2D and 3D graphs are obtained and optimization is achieved. The S/N ratio is done to find out which factor has the most influence on the output that is cutting force.

Keywords: Cutting Force; Depth of cut; Spindle speed; Feed; RSM; DOE; S/N ratio; ANNOVA

I. INTRODUCTION

Turning is the most effective method for forming any work piece, because through turning we can easily remove unwanted material. It is used to remove rust, improve shape near to tolerance limit, improve surface finish, and many more. Turning encloses different metals for machining such as alloy steel, carbon steel, cast iron, stainless steel, aluminum, copper, magnesium, zinc. Machining process involves some parameters which affects machining. These are spindle speed, depth of cut, feed etc. these parameters are called independent factors whereas some dependent factors are cutting force, surface finish, tool wear, tool life etc. which are needed to be minimized or maximized depending on the type of factors. Here cutting force is optimized with respect to the independent factors within a given range.

In this research work the optimization of cutting force is done theoretically using response surface methodology. The S/N ratio calculation is done for finding out the most effective parameters for cutting force.

II. DESIGN & ANALYSIS

This method is designed by taking a given range of independent parameters from a HMT 22 lathe. The parameters are spindle speed, depth of cut, and feed. Here, three levels are taken for each parameter and Design of Experiments (DOE) is applied on it. This is a structured method which is used to identify various relationships between input and output. One of the DOE methods is RSM. The three levels obtained are fed into factorial combination in which we obtain 27 combinations of the parameters. Here optimization is done using AISI 1018 mild carbon steel.
Table-1: Attribution levels of cutting parameters for cutting force-

| Control parameters | Unit | Symbol | Level1 (low) | Level2 (medium) | Level3 (high) |
|--------------------|------|--------|--------------|-----------------|--------------|
| Spindle speed      | rpm  | N      | 40           | 102             | 192          |
| Feed rate          | mm/rev| f      | 0.04         | 0.05            | 0.06         |
| Depth of cut       | mm   | d      | 0.5          | 1               | 1.5          |

(A) RESPONSE SURFACE METHODOLOGY

RSM is a method developed by Box and Wilson in the early 1950’s. It is used for establishing relationships between various input and output variables. For n number of measurable input variables, the response surface can be given as –

\[ Y = f(x_1, x_2, x_3, x_4...x_n) + \varepsilon \]  

Where, \( x_1 \) … \( x_n \) are the independent input parameters and \( \varepsilon \) is the random error.

Y is the output or response variable which has to be optimized.

In a turning operation with three input variables, the response function can be written as –

\[ Y = f(x_1, x_2, x_3) + \varepsilon \]  

The second order or quadratic regression model includes the square terms in addition to the terms above –

\[ Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \varepsilon \]  

In this case equation 5 is used to have the response surfaces in the design expert software.

(B) SUMMARY OF TURNING PARAMETERS AND FORMULAS

N= rotational speed of the work piece in rpm
f= feed in mm/rev or in/rev
\( \nu_C \)= cutting speed of work piece in m/min or ft/min
\( \omega = \frac{2\pi N}{60} \) \[ \text{[Since, } \omega = 2\pi N/60 \]
D= diameter of work piece in mm
R = radius of the job
\( \omega = \) angular velocity rev/sec or rad/sec
\( R = \) radius of the job
\( d = \) depth of cut in mm or in
MRR = Material removal rate in mm\(^3\)/sec or in\(^3\)/min
\( P = \) Power in hp or in lb/min or joule/sec or watt
\( T = \) Torque in lb-in or N-m
\( F_C = \) Cutting force in N or lb

Table -2: Approximate range of energy requirements in cutting operations at the drive motor of the machine tool (for dull tools multiply by 1.25) –

| Material                | Specific energy (E) |
|-------------------------|---------------------|
|                         | w-s/mm\(^3\)        | hp-min/in\(^3\) |
| Aluminum alloys         | 0.4 - 1             | 0.15-0.4        |
| Cast irons              | 1.1-5.4             | 0.4-2           |
| Copper alloys           | 1.4-3.2             | 0.5-1.2         |
| High-temperature alloys | 3.2-8               | 1.2-3           |
(C) Calculation of Cutting Force ($F_C$)

Cutting force is the tangential force exerted by the tool. Here specific energy ($E$) of steels ranges from 0.7 - 3.4 hp min/in$^3$ as per table 4 so an approx medium value is selected of about 1.47 from the range. It is easier to calculate power in hp that’s why the values are transferred from mm$^3$/sec to in$^3$/min.

SET 1:

$N_1 = 40$ rpm
$f_1 = 0.04$ mm/rev
$d_1 = 0.5$ mm

Cutting speed = $V_{C1} = \omega_1 R = [(40*2\pi)/60]*7.5 = 31.4$ mm/sec

$MRR_1 = V_{C1} * f_1 * d_1$
$= (\pi * D * N_1) * f_1 * d_1$
$= 31.4 * 0.04 * 0.5$
$= 0.628$ mm$^3$/sec
$= 0.0023$ in$^3$/min

Power ($P_1$) = $E * MRR_1 = 1.47 * 0.0023 = 0.0034$ hp

Torque ($T_1$) = $P_1/2\pi N_1 = (1346.4)/(2*\pi*40) = 5.36$ lb-min

Cutting Force ($F_{C1}$) = $T_1/R = 5.36/0.2953 = 18.1510$ lb

Other sets can similarly be calculated following this process. The calculated cutting force for different combinations is shown in table 3.

Table- 3: Calculated cutting forces for the respective combination-

| Serial no. | Factorial combination | Spindle speed (N) | Feed(f) | Depth of cut (d) | Cutting forces ($F_C$) |
|------------|-----------------------|------------------|---------|-----------------|-----------------------|
| 1          |                       | 40               | 0.04    | 0.5             | 80.7358 N            |
| 2          |                       | 102              | 0.04    | 0.5             | 80.8262 N            |
| 3          |                       | 192              | 0.04    | 0.5             | 81.3383 N            |
| 4          |                       | 40               | 0.05    | 0.5             | 101.371 N            |
| 5          |                       | 102              | 0.05    | 0.5             | 101.368 N            |
| 6          |                       | 192              | 0.05    | 0.5             | 101.385 N            |
| 7          |                       | 40               | 0.06    | 0.5             | 122.120 N            |
| 8          |                       | 102              | 0.06    | 0.5             | 121.645 N            |
| 9          |                       | 192              | 0.06    | 0.5             | 121.661 N            |
| 10         |                       | 40               | 0.04    | 1               | 162.134 N            |
| 11         |                       | 102              | 0.04    | 1               | 162.224 N            |
| 12         |                       | 192              | 0.04    | 1               | 162.217 N            |
| 13         |                       | 40               | 0.05    | 1               | 202.682 N            |
(D) SIGNAL-TO-NOISE RATIO(S/N)

The S/N ratio calculation is done for finding out the most effective parameters for cutting force.

Calculating S/N ratio for smaller is better for cutting force, the equation is,

\[ S/N (Y_i) = -10 \log \left( \frac{\sum (X_i^2)}{n} \right) \]

Where \( Y_i \) = S/N ration for respective result

\( X_i \) = Cutting force for each combination = 1 to 27

\( n \) = No. of results for each combination for combination no. i

Table- 4: Calculated S/N ratio for the respective combination-

| Serial no. | Factorial combination | Cutting forces (F_C) | S/N ratio (Y_i) |
|------------|------------------------|----------------------|-----------------|
|            | Spindle speed (N) | Feed (f) | Depth of cut (d) |                     |                  |
| 1          | 40 | 0.04 | 0.5 | 80.7358 N | -38.141 |
| 2          | 102 | 0.04 | 0.5 | 80.8262 N | -38.15 |
| 3          | 192 | 0.04 | 0.5 | 81.3383 N | -38.20 |
| 4          | 40 | 0.05 | 0.5 | 101.3710N | -40.11 |
| 5          | 102 | 0.05 | 0.5 | 101.3686N | -40.11 |
| 6          | 192 | 0.05 | 0.5 | 101.3852N | -40.11 |
| 7          | 40 | 0.06 | 0.5 | 122.1204N | -41.73 |
| 8          | 102 | 0.06 | 0.5 | 121.6459N | -41.70 |
| 9          | 192 | 0.06 | 0.5 | 121.6610N | -41.70 |
| Level    | Average S/N ratio by factor level | Overall mean of S/N ratio (Y₀) |
|----------|----------------------------------|-------------------------------|
| Low      | Feed (f) Depth of cut (d) Spindle speed (N) | -45.1875                     |
|          | -43.3627 -39.9993 -45.1853          |                               |
| Medium   | -45.3058 -46.0213 -45.1856         |                               |
| High     | -46.8941 -49.5419 -45.1917         |                               |
| Delta = larger – smaller | 3.5314 9.5426 0.0064 |                               |
| Rank     | 2 1 3                             |                               |

Here rank 1, 2, 3 indicates that depth of cut is the most influencing factor for cutting force followed by feed and spindle speed.

III. RESULTS & DISCUSSIONS
Analysis of the effects of parameters on cutting force is done in design expert software, using response surface methodology by the theoretical and results obtained earlier.
(A) ANOVA

The analysis of variance (ANOVA) was used to study the significance and effect of the cutting parameters on the response variables i.e. cutting force.

**Table- 6: ANOVA for cutting force-**

| Source          | Sum of squares | df | Mean square | c     | p-value       |
|-----------------|---------------|----|-------------|-------|---------------|
| Model           | 2.195E+05     | 6  | 36582.49    | 2.225E+06 | < 0.0001     |
| A-depth of cut  | 1.839E+05     | 1  | 1.839E+05   | 1.119E+07 | < 0.0001     |
| B-feed          | 29512.58      | 1  | 29512.58    | 1.795E+06 | < 0.0001     |
| C-spindle speed | 0.0411        | 1  | 0.0411      | 2.50    | 0.1295        |
| AB              | 4897.71       | 1  | 4897.71     | 2.979E+05 | < 0.0001     |
| AC              | 0.0032        | 1  | 0.0032      | 0.1917  | 0.6662        |
| BC              | 0.0889        | 1  | 0.0889      | 5.41    | 0.0307        |
| Residual        | 0.3288        | 20 | 0.0164      |         |               |
| Cor Total       | 2.195E+05     | 26 |             |         |               |

From Table 6, we can see that the P-Value for the model is 0.0001 which is lesser than the significance value of 0.05. Hence, the model is significant. Feed and depth of cut is found to be the most influential parameters affecting the cutting force with low P-value among all three parameters.

**Table-7: Estimated Coded Regression Coefficients for cutting force-**

| Factor       | Co-efficient estimate | df | Standard error | 95% CI low | 95% CI high | VIF |
|--------------|-----------------------|----|----------------|------------|-------------|-----|
| Intercept    | 202.75                | 1  | 0.0247         | 202.70     | 202.80      |     |
| A-depth of cut | 101.36               | 1  | 0.0303         | 101.29     | 101.42      | 1.01|
| B-feed       | 40.60                 | 1  | 0.0303         | 40.54      | 40.67       | 1.01|
| C-spindle speed | 0.0475              | 1  | 0.0301         | -0.0152    | 0.1102      | 1.0000|
| AB           | 20.20                 | 1  | 0.0370         | 20.13      | 20.28       | 1.0000|
| AC           | 0.0161                | 1  | 0.0368         | -0.0607    | 0.0929      | 1.01|
| BC           | -0.0856               | 1  | 0.0368         | -0.1624    | -0.0088     | 1.01|

Table-8: Fit statistics of cutting force

| Std. Dev. | 0.1282 | R² | 1.0000 |
|-----------|--------|----|--------|
| Mean      | 202.75 | Adjusted R² | 1.0000 |
| C.V. %    | 0.0632 | Predicted R² | 1.0000 |

| Adeq Precision | 4351.0264 |

Regression Equation in Un-coded Units for cutting force:

cutting force = -1.63891 + 0.637870 depth of cut + 33.04753 feed + 0.005833 spindle speed + 4040.50667 depth of cut * feed + 0.000424 depth of cut * spindle speed – 0.112632 feed * spindle speed.
EFFECTS OF DEPTH OF CUT, FEED AND SPINDLE SPEED ON CUTTING FORCE

Fig-1  Variation of cutting force with depth of cut

Fig-2  Variation of cutting force with spindle speed

Fig-3  Variation of cutting force with feed

The graphs show that the most effective parameter is depth of cut.

VARIATION S/N RATIO WITH DEPTH OF CUT, FEED AND SPINDLE SPEED FOR CUTTING FORCE

Fig-4  Variation of mean S/N ratio with depth of cut
Fig-5  Variation of mean S/N ratio with spindle speed

Fig-6  Variation of mean S/N ratio with feed

The above graphs show the validation of the S/N ratio calculation and prove that the most effective parameter is depth of cut.

(E) RESPONSE SURFACES ANALYSIS

Fig-7  Effect of depth of cut and feed rate on cutting force

Fig-8  Effect of spindle speed and feed rate on cutting force

Fig-9  Effect of depth of cut and spindle speed on cutting force

The graphs interpret that cutting force increases with increasing depth of cut and varies approx linearly with feed. It is also clear from the S/N ratio calculation that the main parameter which effect cutting force is depth of cut.

(F) OPTIMIZATION

The desirability function is used as a decision support tool which is to identify the process parameters that are resulting in the near-optimum settings for process responses. The optimization is done in design expert software version 11.
Table- 9: Constraints for optimization of machining parameters –

| Condition       | Goal       | Upperlimit | Lower limit |
|-----------------|------------|------------|-------------|
| Depth of cut(mm) | In range   | 0.5        | 1.5         |
| Feed (mm/rev)   | In range   | 0.04       | 0.06        |
| Spindle speed (rpm) | In range | 40         | 192         |
| Cutting force (N) | Minimize   | 80.7358    | 364.9875    |
| Machining time (T_C) | Minimize | 1.21       | 10.49       |

Table- 10: Response optimization for cutting force –

| Number | depth of cut | Feed | spindle speed | cutting force | Desirability |
|--------|--------------|------|---------------|---------------|--------------|
| 1      | 0.500        | 0.040| 40.000        | 80.874        | 1.000        |
| 2      | 0.500        | 0.040| 41.296        | 80.876        | 1.000        |
| 3      | 0.500        | 0.040| 43.217        | 80.880        | 0.999        |
| 4      | 0.500        | 0.040| 45.653        | 80.882        | 0.999        |
| 5      | 0.500        | 0.040| 46.998        | 80.885        | 0.999        |
| 6      | 0.500        | 0.040| 48.706        | 80.887        | 0.999        |
| 7      | 0.500        | 0.040| 50.577        | 80.890        | 0.999        |

The optimum cutting parameters obtained in table 10 are as follows:
1) Spindle speed = 41.296 rpm
2) Feed rate = 0.04 mm/rev
3) Depth of cut = 0.5 mm

The optimized cutting force ($F_c$) = 80.876, with a Composite Desirability = 1.000

IV. CONCLUSION

From the above research work it can be concluded that the cutting force in case of turning can be improved when operated under optimum combination of the influencing parameters. Here the optimum combinations of the parameters for best cutting force are given above. Regression equation obtained here by software can be used to find one parameter when the other two are known so as to get the best cutting force within the range and is also used to obtain graphs. ANNOVA is also done to check the accuracy by R² value. From the S/N ratio the importance of one factor with respect to others can be obtained.

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