Optimization of cutting parameters and prediction of surface roughness during hard turning of H13 steel with minimal vegetable oil based cutting fluid application using response surface methodology

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Abstract. The manufacturing industries in modern era are competing to reduce cost of production by employing innovative techniques, one being hard turning. In hard turning process, the work piece is heat treated to the required hardness in the initial stage itself and near net shape is arrived directly by hard turning process. Hard turning reduces manufacturing lead time by excluding the normal cost incurring processes such as, turning, heat treatment, finish grinding etc. In this experimental investigation hard turning process is assisted with minimal cutting fluid application technique, which reduces cutting fluid usage to a minimum of 6-8 ml/min. Soya bean oil based emulsion was used to make the hard turning environment friendly. The oil was prepared by adding additives, which will enhance the desirable properties of the oil for hard turning. Response surface methodology was used for optimization of cutting parameters and for the prediction of surface roughness. A central composite design was implemented to estimate the second-degree polynomial model. The cutting parameters considered for experimentation were cutting speed, feed rate and depth of cut. The surface roughness was considered parameter for prediction. Surface roughness predicted by the response Surface Methodology matched well with the experimental results.

1. Introduction
The manufacturing industries adopt newer methods to reduce cost of production and manufacturing lead time. The technique of hard turning was developed long back which helps to attain the above objectives. This process led to the use of enormous quantities of cutting fluid to reduce friction and heat developed during machining.

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Cutting fluid’s use, storage and disposal was found to be a non-cost effective process. Industries spend 7% to 17% of the production cost on lubricants alone [1]. Oil mist content in the shop floor environment will increase that have to be limited by 0.5 mg/m³, according to national institute of occupational safety and health administration (NIOSH) and occupational safety and health administration [2]. Usage of cutting fluid in large quantity will cause environmental pollution and also possess great health hazard. Dry machining is a viable option but it requires machine tools and cutting tools that can take enormous cutting forces. Near dry machining came into being a decade ago, which promises usage of less cutting fluid and decent machined surfaces [3]. The process mixes cutting fluid emulsion with compressed air and sprays it at the precise area which needs to be lubricated. This process also leaves a lot of mist in the shop floor environment. Alternative to this problem was already mentioned by Varadarajan et.al, in 2002 [4], by excluding the role of compressed air from the system. Cutting fluid was compressed at higher pressure and was pumped directly to the cutting zone with the help of an injector in a pulsating manner, this process created very less oil mist [5].

In most of the research documented in MCFA was related to hard machining of AISI 4340 steel of 45 HRC. The researchers found that surface roughness and tool wear rate were considerably reduced by using MCFA assisted hard turning [6 & 7]. They used Taguchi’s orthogonal array to optimize their results. Experimental evaluation using vegetable based cutting fluids was conducted using MCFA to prove its effectiveness in hard turning by various researchers [8 & 9]. Response surface methodology (RSM) based experimental design was used since it offers more advantages than other design methods. RSM provides a systematic procedure to determine a relationship between independent input process parameters and output (process response). Many researchers have used RSM in their research pertaining to hard turning [12]. Although, coated tools are playing a key role in reducing the cutting temperatures and improving surface finish, the frictional resistance is high between cutting tool and work during machining. RSM was developed by Box and draper in 1987, to model experimental responses and then migrated into modeling of numerical experiments. In RSM, the errors are assumed to be random. The response can be represented graphically, either in the three-dimensional space or as contour plots that help visualize the shape of the response surface. The construction of response surface models is an iterative process. Once an approximate model is obtained, the goodness-of-fit determines if the solution is satisfactory. Through RSM, an equation (i.e., response surface) representing the approximate relationship between a single response and control factors can be obtained based on experimental data. The contour plot is used to characterize the response surface graphically and determine the optimal parameter-setting. When multiple responses are considered, the optimal parameter-setting is obtained by observing overlay contour plots [15]. These approaches for optimizing multiple responses consists of constructing equations for each response. Optimizing numerous equations simultaneously is difficult. Thus, determining an optimal parameter-setting for a multi-response problem is complex when numerous responses must be considered simultaneously.

In this research, hard turning of H13 tool steel having hardness of 45 HRC was used. RSM based design treated and blended with ethylene glycol, oleic acid and triethanol amine and other additives to improve its lubricity and was used to conduct cutting experiment. Cutting speed, Feed rate and depth of cut were varied according to RSM design by keeping fluid application parameters constant. Soya bean based cutting fluid was formulated and used for experimentation with MFA. The rate of cutting fluid application was maintained as 8 ml/min which was supplied at a pressure of 100 bar and with a pulsing frequency of 300 pulses/min. Surface roughness was measured and cutting parameters were optimized. The prediction model derived out of RSM method was found to be highly accurate with more than 90% accuracy.

2. Selection of work piece and cutting tool
The workpiece material that was used for this experiment was H13 tool steel of hardness 45 HRC. A Bar of 70 mm diameter and 360 mm length was used in the present experimental work. The chemical composition of the workpiece is tabulated in the table 1. The tool used for hard turning was SNMG
120408 (MT TT 5100) hard metal inserts and tool holder used was PSBNR 2525 M12 supplied by Taegu Tec India Pvt Ltd.

Table 1. Chemical composition of H13 steel (weight %)

| Element | C  | Cr  | Mo | V  | Si  | Mn  | Fe     |
|---------|----|-----|----|----|-----|-----|--------|
| Weight %| 0.39 | 5.15 | 1.25 | 1.1 | 1.0 | 0.5 | Balance |

3. Selection of cutting fluid
Manufacturing industries use mineral oil based emulsions as cutting fluid during hard turning. These oils are highly toxic and non-biodegradable. Vegetable based cutting fluid emulsions were tried by different authors during their investigations. During this investigation soyabean based cutting fluid emulsion was incorporated. Soyabean oil was emulsified with petroleum sulfonate, ethylene glycol, oleic acid and other ingredients to improve base oil’s characteristic to adapt it as a cutting fluid. The soyabean oil emulsion was tested for its stability, viscosity, pH value and thermal conductivity before experimentation.

3.1 Experimental set up
Experimental set-up consisted of an all geared Kriloskar Trunmaster-35 lathe which can facilitate infinite speed and feed variation. Mitutoyo surface roughness tester SJ-210 was used for measuring surface roughness. The experimental set-up is shown in Figure 1.

$$X_i = \frac{2X - (X_{\text{max}} + X_{\text{min}})}{X_{\text{max}} - X_{\text{min}}}$$ (1)

4. Design of Experiment
The experimental design was carried out using Response surface methodology. A central composite design was implemented to optimize the input parameters [14]. Preliminary experiments were carried out to find out the lower and upper limits of these factors. Accordingly, spindle speed of the lathe was fixed between 77 and 115 rpm. In line with this factor, the depth of cut was fixed between 0.5 and 1 mm and the feed rate of the lathe were fixed between 0.05 and 0.1 m/rev. The upper limit of the 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:
Where $X_i$ is the required coded value of a variable $X_i$; and $X$ is any value of the variable from $X_{\text{min}}$ to $X_{\text{max}}$. The selected process parameters with their limits, units and notations are given in table 2. The fluid application parameters were kept constant as, Pressure of cutting fluid as 100 bar, frequency of pulsing as 600 pulses/min, rate of application as 8 ml/min and composition of cutting fluid as 20% of oil in water.

Table 2. Parameters under investigation during MCFA turning

| Parameters               | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|--------------------------|---------|---------|---------|---------|---------|
| Cutting speed (m/min) (v)| 77      | 85      | 96      | 107     | 115     |
| Depth of cut (mm) (d)    | 0.5     | 0.6     | 0.75    | 0.88    | 1       |
| Feed (mm/rev) (f)        | 0.05    | 0.06    | 0.07    | 0.09    | 0.1     |

The experiment was carried out according to design matrix obtained from MINITAB 16 software is shown in table 3. Surface roughness was measured with the help of Mitutoyo Surface Roughness Tester – SJ210 after each run.

Table 3. Design matrix with both input values and output

| Std order | Run order | Pt Type | Blocks | v | f | d | Cutting speed (m/min) | Feed Rate (mm/rev) | Depth of cut (mm) | Surface roughness $R_s$ |
|-----------|-----------|---------|--------|---|---|---|----------------------|--------------------|---------------------|------------------------|
| 1         | 8         | 1       | 1      | -1 | -1 | -1 | 85                   | 0.06               | 0.6                 | 1.09                   |
| 2         | 15        | 1       | 1      | -1 | -1 | -1 | 107                  | 0.06               | 0.6                 | 0.92                   |
| 3         | 1         | 1       | 1      | -1 | 1  | -1 | 85                   | 0.09               | 0.6                 | 1.12                   |
| 4         | 18        | 1       | 1      | 1   | 1  | -1 | 107                  | 0.09               | 0.6                 | 1.34                   |
| 5         | 14        | 1       | 1      | -1 | 1  | 1  | 85                   | 0.06               | 0.88                | 1.38                   |
| 6         | 3         | 1       | 1      | -1 | 1  | 1  | 107                  | 0.06               | 0.88                | 2.2                    |
| 7         | 11        | 1       | 1      | -1 | 1  | 1  | 85                   | 0.09               | 0.88                | 1.23                   |
| 8         | 17        | 1       | 1      | 1   | 1  | 1  | 107                  | 0.09               | 0.88                | 2.5                    |
| 9         | 13        | -1      | 1      | 1.682 | 0  | 0  | 77                   | 0.07               | 0.75                | 1.35                   |
| 10        | 19        | -1      | 1      | 1.682 | 0  | 0  | 115                  | 0.07               | 0.75                | 2.1                    |
| 11        | 16        | -1      | 1      | 0   | 1.682 | 0  | 96                   | 0.05               | 0.75                | 1.19                   |
| 12        | 12        | -1      | 1      | 1.682 | 0  | 0  | 96                   | 0.1                | 0.75                | 1.24                   |
| 13        | 7         | -1      | 1      | 0   | 0  | -1.682 | 96                  | 0.07               | 0.5                 | 1.05                   |
| 14        | 10        | -1      | 1      | 0   | 0  | 1.682 | 96                   | 0.07               | 1                   | 2.3                    |
| 15        | 2         | 0       | 1      | 0   | 0  | 0  | 96                   | 0.07               | 0.75                | 1.33                   |
| 16        | 6         | 0       | 1      | 0   | 0  | 0  | 96                   | 0.07               | 0.75                | 1.26                   |
| 17        | 9         | 0       | 1      | 0   | 0  | 0  | 96                   | 0.07               | 0.75                | 1.25                   |
| 18        | 5         | 0       | 1      | 0   | 0  | 0  | 96                   | 0.07               | 0.75                | 1.28                   |
| 19        | 4         | 0       | 1      | 0   | 0  | 0  | 96                   | 0.07               | 0.75                | 1.27                   |
| 20        | 20        | 0       | 1      | 0   | 0  | 0  | 96                   | 0.07               | 0.75                | 1.29                   |

Central composite design (CCD) was adapted for RSM. CCD has three groups of design points a) Three-level factorial or fractional factorial design points b) Axial points or star points, c) Center points. CCD's were designed to estimate the coefficients of a quadratic model. MINITAB-16 was used for regression, which will help to generate a regression equation that can be used for optimization and prediction.
5. Results and discussion

A 20 run experiment was conducted in a Kriloskar turn master lathe by giving the input parameters varied at five levels maximum and minimum coded value and the three levels (-1, 0, 1). The output parameter (surface roughness) was measured by using surface roughness tester and the values are noted down. The results are shown in table 4 and then the regression and residual plot were generated by using the MINITAB software.

5.1 Regression Analysis:

Surface roughness (Ra) as a function of Cutting Speed (v), Depth of Cut (d), Feed Rate (f)

Surface roughness Ra = 1.28263 +0.24906*v +0.05009*f +0.36189*d +0.14013*v^2 -0.04018*f^2 +0.12245 *d^2 +0.105*v*f +0.255*d*v ……..(2)

Table 4. Results from regression analysis with interactions

| Term                          | Coef   | SE Coef | T     | p     |
|-------------------------------|--------|---------|-------|-------|
| Constant                      | 1.28263| 0.02740 | 46.812| 0.000 |
| Cutting speed (v)             | 0.24906| 0.01818 | 13.700| 0.000 |
| Feed Rate (f)                | 0.05009| 0.01818 | 2.755 | 0.020 |
| Depth of Cut (d)             | 0.36189| 0.01818 | 19.907| 0.000 |
| Cutting speed × Cutting speed (v^2) | 0.14013| 0.01770 | 7.918 | 0.000 |
| Feed Rate × Feed Rate (f^2)  | -0.04018| 0.01770 | -2.270| 0.047 |
| Depth of Cut × Depth of Cut (d^2) | 0.12245| 0.01770 | 6.920 | 0.000 |
| Cutting speed × Feed Rate (v * f) | 0.10500| 0.02375 | 4.421 | 0.001 |
| Depth of Cut × Cutting speed (d * v) | 0.25500| 0.02375 | 10.736| 0.000 |
| Feed Rate × Depth of Cut (d * f) | -0.03750| 0.02375 | -1.579| 0.145 |

The term T is the distribution and corresponding values along with the estimated input parameters. p value is used to check the significance of each coefficient, if p value is less than 0.05 there is less than 5% chance the equation is incorrect. The multiple regression coefficient R^2 = 98.83% and R^2 adjusted is 97.77%, which pre tell that the ratio of viability of explained by the model is viable and it is a measure if goodness fit. If R^2 approaches to unity, the better the model fits the experimental data. In other words, it is the proportion of variation in the dependent variable (response) that can be explained by the predictors (factor) in the model. The residual plots after regression analysis are shown in Figure 2.
Residual is the difference between observed value of the dependent variable (y) and predicted value (ŷ). Normal probability plots are used to assess whether data come from the normal distribution. The statistical procedure makes the assumption that an underlying distribution is normal. Thus normal probability plots can provide assurance that the assumption is justified, or else provide a warning of problems with the assumption. Histogram is the graphical representation of data distribution.
probability distribution of a continuous variable. Figure 3 shows the 3D surface plot establishing response values and operating condition.

The 3D contour plot figure 3(A) shows relation of surface roughness with feed rate and cutting speed, figure 3(B) shows relation of surface roughness with depth of cut and cutting speed and figure 3(C) shows relation of surface roughness with depth of cut and feed rate. In the above graphs, as the colour gets darker response increases. In graph figure 3(A) surface roughness increases as cutting speed and feed rate increases. The minimum value is 0.936 and maximum is 2.3. Here depth of cut is kept constant. In graph figure 3(B) surface roughness increases as cutting speed and the depth of cut increases. Minimum value of response is 0.97 and maximum is 3.5. Here feed rate is kept constant. In graph C surface roughness increased as feed rate and depth of cut increases. Minimum value is 0.57 and maximum is 2.3. Here cutting speed is kept constant. Result validation is done using Design Expert 9©, which uses its own internal programming to solve the regression model. The solution arrived had 0.93 desirability.

The optimum input for the above outputs were found to be cutting speed at 90.477 m/min, feed rate at 0.05 mm/rev and depth of cut at 0.50 mm. Above three graphs shows that the observed values are in relation with the optimum value. The optimum Ra value arrived from this above condition after prediction is 0.941 microns. Table 5 shows comparison with the optimum results arrived from RSM method and results from the two confirmatory tests. Confirmatory tests were conducted to validate the accuracy of the developed model and it was found that the experimental results very well matches with predicted results. The average error from both confirmatory tests revealed only 11% error.

| Parameters          | Optimum | Observed 1 | Observed 2 | Average | Error % |
|---------------------|---------|------------|------------|---------|---------|
| Surface Roughness   | 0.941   | 1.09       | 1.02       | 1.055   | 11      |

6. Conclusion
The model developed using the response surface methodology was used to predict surface roughness and the predictions matched well with the experimental values with 89 % percent accuracy. Such models can be used for predicting surface finish and the timing of tool change and setting of cutting speed and feed rate based on the tolerance limits on surface finish.

7. References
[1] Attanasio, A., Gelfi, M, Giardini, C., Remino, C.: Minimal quantity lubrication in turning: effect on tool wear. Wear. 260(3), 333-338 (2006).
[2] Marano, R. S., Smolinski, J. M., Esingulari, C. W. M.: Polymer additives as mist suppressant in metal cutting fluid. J. Soc. Tribol. Lubr. Eng. 25-32 (1997).
[3] Dhar, N. R., Ahamed, M. T., Islam S.: An experimental investigation on effect of minimum quantity lubrication in machining AISI 1040 steel. International Journal of Machine tools and Manufacture, 47(5), 748-753 (2007).
[4] Varadarajan, A. S., Philip, P. K., Ramamoorthy, B.: Investigations on hard turning with minimal cutting fluid application (HTMF) and its comparison with dry and wet turning. International Journal of Machine tools and Manufacture, 42, 132-200 (2002).
[5] Robinson Ganadurai, R., Varadarajan, A. S.: Investigation on the effect of an auxiliary pulsing jet of cutting fluid on the top side of the chip during hard turning with minimal fluid application. International Journal of machining and machinability of materials, 12, 321-336 (2012).
[6] Ram Kumar, P., Leo Dev Wins, K., Robinson Ganadurai, R., Varadarajan, A. S.: Investigations on hard turning with minimal multiple jet of cutting fluid. Proceedings of the International Conference on Frontiers in Design and Manufacturing Engineering, 188-191 (2008).

[7] Vikram Kumar, CH. R., Ramamoorthy, B.: Performance of coated tools during hard turning under minimum fluid application. Journal of Materials Processing Technology, 185, 210-216 (2007).

[8] Varadarajan, A. S., Robinson Ganadurai, R., John Thomas, E.: Investigations on the effect of an environment friendly coconut oil based cutting fluid on cutting performance during hard turning with minimal fluid application. Proceedings of 24th Kerala Science congress, 400-403 (2012).

[9] Anil Raj, Leo Dev Wins, K., Kiran Easow George, Varadarajan, A. S.: Experimental investigation of soyabean oil based cutting fluid during turning of hardened AISI 4340 steel with minimal fluid application. Applied mechanics and materials, 813-814, 337-341 (2015).

[10] Maleque, Masjuki, H. M., Sapuan, S. M.: Vegetable- based biodegradable lubricating oil additives. Industrial Lubrication and Tribology, 55(3), 137-143 (2003).

[11] Anil Raj, Leo Dev Wins, K., Varadarajan, A. S.: Review on hard machining with minimal cutting fluid application. International journal of current engineering and technology, 5(6), 3717-3722 (2015).

[12] Bouacha, K., Yallese, M. A., Mabrouki, T., Rigal, J. F.: Statistical analysis of surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel with CBN tool. Journal of Refract Met Hard Mater, 28(3), 349–361 (2010).

[13] Varadarajan, A. S., Ramamoorthy, B, Philip, P. K.: Formulation of a cutting fluid for hard turning with minimal fluid application. Proceedings 20th AIMTDR Conference at Birla Institute of Technology Ranchy India, 89-95 (2000).

[14] Myer, R. H., Khuri, A.I.: Response surface methodology: 1966-1988. Technometrics, 31,137-157, (1987)

[15] Box, G. E. P., Draper, N. R.: Empirical Model Building and Response Surfaces. John Wiley & Sons, New York, NY, (1987).

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