Optimization of Surface Roughness and Material Removal Rate in Turning of AISI D3 Steel with Coated Carbide Inserts

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Abstract. The aim of this paper is to optimize the metal removal rate and surface roughness through turning on AISI D3 Steel with coated carbide inserts. As per the current market scenario, for the metal cutting industries the most important challenge in the turning process is to satisfy both requirements quality as well as high productivity in less time in order to remain competitive. Among all the different cutting processes, the turning process is one of the most applied and fundamental metal removal operations in the real manufacturing environment. This work examines the impact of machining factors like speed, depth of cut & feed on roughness and MRR of AISI D3 steel which have a hardness value of 60 HRC with coated carbide inserts. At high speed and feed rate optimum MRR was achieved and opposite to that at low feed and depth of cut optimum surface roughness was obtained. Taguchi L9 (3)3 OA has been applied for experimental design. ANOVA analysis is performed just after DOE to identify the significant factor which influences MRR and surface roughness. Among the three machining factors, depth of cut and speed has more influencing effect on roughness and the feed influences MRR. Effort was made to find optimum solution to minimize the roughness and maximize the MRR by Taguchi and ANOVA technique.

Keywords: ANOVA, MRR, AISI D3 Steel, Surface Roughness, manufacturing.

1. Introduction

In the current scenario, all machining industry has its main focus in achieving high quality surface finish, dimensional accuracy, minimum tool wear, high-production rate and improving performance of product with less effort. Turning plays a very important role in the machining process, however with the turning other processes may also require several tools and for finishing several setup is required [1,2].

In this research, there are three processing parameters used which are cutting speed, depth of cut & feed. The roughness is dependent on these three parameters and tool geometry as well. In this work Taguchi L9 is used as an orthogonal array for experimental design followed by ANOVA analysis is performed on D3 steel to find out the significant factor on MRR and surface roughness.

Turning operation: Turning process is widely used for metal cutting in manufacturing companies. The primary function of turning is to remove metal from the outside diameter of the cylindrical shape work piece. Turning is used for reducing work piece diameter to get the desired dimensions and produces good surface finishing of metal [7].

Cutting speed: The cutting speed refers to what speed the tool cuts the work piece. Speed of cutting varies from metal to metal. All different materials have their optimum cutting speed. It may be defined
as the speed at which cutting tools move with respect to a workpiece. It is mainly expressed in m/min. Cutting speed represented as:

\[ V = \frac{\pi DN}{1000} \]

Hence, \( D \) = initial work piece diameter (mm), \( V \) = cutting speed (m/min), \( N \) = speed of spindle (rpm)

Depth of cut: Depth of cut mainly known to be layer thickness which is get removed by machining on work piece or it is the distance between the new surface obtained to original workpiece surface. It is expressed by mm. Depth of cut mathematically given as:

\[ d = \frac{(D1 - D2)}{2} \]

Where, \( D1 \) is work piece initial diameter (mm), \( D2 \) is work piece final diameter (mm)

Feed: It is basically stated that the distance of the tool moves a single or per revolution of the work piece. For better finish a finer feed is required. Feed is direct proportional to speed of spindle & is express by mm/rev [8,9].

It is given as: \( F_m = f \times N \)

Hence, \( F_m \) = speed of feed per min. (mm/min), \( F \) = feed (mm/rev), \( N \) = spindle speed (rpm)

2. Literature search methodology

Basically the term turning process has its own reputation in the metal cutting industry. It is mainly used in workshop practice for the purpose of performing conventional machine tools as well as CNC and NC machine tools, manufacturing system and machining centres. Turning process basically involves the lathe machine in its operation and its main function is to produce cylindrical and conical parts. Hence it is important to improve the tool life, reduce cutting force, increase surface finish & feed force and reduce temperature of machining zone in turning operation by optimization study. For minimizing the friction & wear, improving tool life & surface finish we mainly take use of cutting fluids [10,11,12]. Result signifies that the cutting speed has most influences on surface roughness and on MRR the feed rate gives more impact than other factors. At last for knowing the influence of input variables on MRR and surface roughness the normal probability plot, main effects plot and contour plot is to be found [13]. Grinding is a slow process with a low amount of material removal rate so it needs some replacement to increase MRR. Therefore the hard turning process is the new solution to that and it comes in early ninety [3]. There are 3 machining parameters like speed, feed & depth of cut but there are many other factors that may affect the work material. It was found out the impacting of these three factors on MRR & surface roughness. From this we get to know which parameter has more or less impact on roughness and MRR [4, 5]. Calculation method & DOE is used to examine the quality of surface. After that for achieving the main objective the DOE method is further executed with appropriate values and data. DOE table has been created to use Taguchi method and ANOVA method is used for finding the parameter which affects the roughness and MRR [6, 14, 15].

3. Objective & Approach:

- In turning process, the main objective is to examine the impact of processing factors on MRR and roughness through using cutting tool on steel AISI D3 when performing these experiments.
- To examine result of optimal values for MRR and roughness then the operation is executed in D3 steel for CI level at 95%.
- To create an experiment setup with different input parameters and then execute the process to find the response.
- To create DOE, Taguchi L9 orthogonal array which use to examine effect of processing variables.
- ANOVA technique was used for analysing contribution of percentage & to get the significant factor from machining factors.
4. Experimental Detail

Work Materials: In this study, the use of D3 steel as a workpiece material in the shape of a cylinder has its dimension i.e. diameter of 30 mm and length of 80 mm. Since the metal has very large application in metal cutting industry. It possesses different properties like wear resistance, high strength and good hardenability. Typical applications for D3 steel: Punching tools, drawing & deep drawing tools, shear blades, dies drawing, blanking, shear blades, cold die punches, trimming dies, etc.

4.1 Experiment procedure

In this section, we are performing the experiments basically to find out the main effects of different processing parameter on the value of (Ra & Rz) & material removal rate (MRR). Then the experiments with the three machining parameters were performed to three different levels, which is mention in Table 1. Taguchi L9 (3^3) OA in Minitab 18 software has 8 degree of freedom. Before executing the Taguchi process, turning operation was performed on different 9 work pieces in wet condition on a CNC lathe machine, it has 350 rpm spindle speed & have 16 KW max power. Before going to process main work, first removed the rust layer from 9 work pieces by cutting insert mainly for minimize the effects on experiment values. Then after performing turning operation on different work piece, following parameters were found out.

Table 1. OA L9 of Taguchi’s experimental design and experiment result

| Run No. | v (m/min) | f (mm/rev) | d (mm) | Ra (µm) | Rz (µm) | MRR (gm/sec) |
|---------|-----------|------------|--------|---------|---------|--------------|
| 1       | 200       | 0.05       | 0.20   | 0.86    | 7.12    | 0.12613      |
| 2       | 200       | 0.09       | 0.30   | 0.98    | 8.14    | 0.21510      |
| 3       | 200       | 0.13       | 0.40   | 1.25    | 10.09   | 0.27686      |
| 4       | 230       | 0.05       | 0.30   | 1.15    | 10.01   | 0.15690      |
| 5       | 230       | 0.09       | 0.40   | 0.90    | 8.01    | 0.24616      |
| 6       | 230       | 0.13       | 0.20   | 0.87    | 7.20    | 0.22107      |
| 7       | 260       | 0.05       | 0.40   | 0.81    | 6.90    | 0.19672      |
| 8       | 260       | 0.09       | 0.20   | 0.74    | 6.02    | 0.25674      |
| 9       | 260       | 0.13       | 0.30   | 0.80    | 6.81    | 0.32981      |

After completing the experiment, there are developed experiment data which were used for distinguishing the effects of processing parameters cutting speed (v), feed (f) and depth of cut (d) on our output variables, that is roughness (Ra & Rz) & MRR. All machining process completed, to get the results of roughness & MRR which are shown in tabulated form in Table 5. At run no. 8, finally achieved the minimum value of surface roughness (Ra & Rz) at v = 260 m/min, d = 0.20 mm & f = 0.09 mm/rev and at run no. 3, It is get the highest value of surface roughness Ra & Rz at d = 0.40 mm, v = 200 m/min & f = 0.13 mm/rev. At last the highest value of MRR was achieved at run no. 9 when d = 0.30 mm, f = 0.13 mm/rev & v = 260 m/min.
5. Results and Discussion

Results of ANOVA: By using the MINITAB software, ANOVA method gives final experimental and evaluates result. ANOVA result for MRR & surface roughness (Ra & Rz) are tabulated below (in Table 2, Table 3 & Table 4). At confidence interval (CI) 95% following analysis was done at $\alpha = 0.050$ as acceptance level. Below tabulated table give the idea for percentage contribution of main parameters and that shows the impact value on result obtained.

### Table 2 ANOVA for Ra

| Source | DOF | Seq SS  | Contribution (%) | Adj SS  | Adj MS   | F-value | P-value |
|--------|-----|---------|------------------|---------|----------|---------|---------|
| v      | 2   | 0.134274| 68.04%           | 0.134274| 0.067137 | 24.09   | 0.040   |
| f      | 2   | 0.010877| 5.51%            | 0.010877| 0.005438 | 1.95    | 0.339   |
| d      | 2   | 0.046614| 23.62%           | 0.046614| 0.023307 | 8.36    | 0.0107  |
| Error  | 2   | 0.005574| 2.82%            | 0.005574| 0.002787 |         |         |
| Total  | 8   | 0.197339|                  |         |          |         |         |

$S = 0.0527904$  
R-sq = 99.38%  
R-sq(adj) = 88.70%

### Table 3. ANOVA for Rz

| Source | DOF | Seq SS  | Contribution (%) | Adj SS  | Adj MS   | F-value | P-value |
|--------|-----|---------|------------------|---------|----------|---------|---------|
| v      | 2   | 10.7710 | 58.71%           | 10.7710 | 5.38549  | 366.11  | 0.003   |
| f      | 2   | 1.2066  | 6.58%            | 1.2066  | 0.60330  | 41.01   | 0.024   |
| d      | 2   | 6.3382  | 34.55%           | 6.3382  | 3.16912  | 215.44  | 0.005   |
| Error  | 2   | 0.0294  | 0.16%            | 0.0294  | 0.01471  |         |         |
| Total  | 8   | 18.3453 |                  |         |          |         |         |

$S = 0.121285$  
R-sq = 99.84%  
R-sq (adj) = 99.36%

After applying ANOVA, we get the table Ra, Rz & MRR. In Table 2, from this table we can see that which for Ra, our 1st main factor cutting speed mainly have 68.04% of contribution followed by depth of cut which have 23.62 % of contribution and last is the feed with 5.51% contribution.

In Table 3, in this table we see Rz is mainly affected by cutting speed which has a contribution of 58.71%, second factor is depth of cut with 34.55% contribution and the third parameter is feed with minimum 6.58% of contribution. In Table 4, the first most important factor which affects the MRR was feed with 71.19% of contribution and the 2nd factor that effect the MRR is our cutting speed which has mainly 17.15% of contribution & the last one factor was our depth of cut with 11.01% of contribution. Last contribution we see for roughness (Ra & Rz) & MRR is error. For MRR, Ra & Rz, the error contribution is 2.02%, 2.82% and 0.65% respectively. From this we can say that error contribution has negligible effect, then it may be guided that important parameter is not forgotten and no involvement of measurement error.

Interpretation of Plots: We have use the MINITAB 18 software for different interpretation plots, with the help of it we show the probability graph & main effect plot for Ra, Rz & MRR in Fig.1 and Fig. 2.
From these graphs our all 3 machining parameter i.e. depth of cut, feed & cutting speed and will show deviation of response.

Table 4. ANOVA for MRR

| Source | DOF | Seq SS  | Contribution (%) | Adj SS  | Adj MS  | F-value | P-value |
|--------|-----|---------|------------------|---------|---------|---------|---------|
| v      | 2   | 0.149324| 17.15%           | 0.149324| 0.074662| 26.47   | 0.036   |
| f      | 2   | 0.619868| 71.19%           | 0.619868| 0.309934| 109.89  | 0.009   |
| d      | 2   | 0.095894| 11.01%           | 0.095894| 0.047947| 17.00   | 0.056   |
| Error  | 2   | 0.005641| 0.65%            | 0.005641| 0.002820|         |         |
| Total  | 8   | 0.870727| 100.00%          |         |         |         |         |

S = 0.0531082 R-sq = 99.35% R-sq(adj) = 97.41%

Table 5. Ra & Rz Mean Value

| Criteria Ra (µm) | Criteria Rz (µm) |
|------------------|------------------|
|                  | v | f | d | v | f | d |
| Level            |   |   |   |   |   |   |
| 1                | 1.0300 | 0.9400 | **0.8233** | 8.450 | 8.010 | **6.780** |
| 2                | 0.9733 | 0.8733 | 0.9767 | 8.407 | 7.390 | 8.320   |
| 3                | **0.7833** | 0.9733 | 0.9867 | **6.577** | 8.033 | 8.333   |
| Delta            | 0.2467 | 0.1000 | 0.1633 | 1.873 | 0.643 | 1.553   |
| Rank             | 1 | 3 | 2 | 1 | 3 | 2 |
| Level | V  | f  | d  |
|------|----|----|----|
| 1    | 0.2060 | 0.1599 | 0.2013 |
| 2    | 0.2080 | 0.2393 | 0.2339 |
| 3    | 0.2611 | 0.2759 | 0.2399 |
| Delta | 0.0551 | 0.1160 | 0.0386 |
| Rank | 2   | 1   | 3   |

We made the inspection for diagnostic plot of model to test its statistical validity. Normal probability plot is plotted in between the residuals and predicted response for the surface roughness (Ra & Rz) & MRR which is shown in figure 1. The residuals are following the straight line closely. From the figures we made a conclusion that these values are in range of 95% CI level.
For Ra & Rz, from the graph, the outcome result shows that if we increase depth of cut then roughness value get increases. Whereas when we see the graph for cutting speed, if we increase the value of speed then roughness value get decreases. In feed graph, when we increase feed rate then roughness value first decreases and then start increasing. From main effects graph, the optimum condition for roughness is achieved at feed is 0.09 mm/rev, depth of cut is 0.20 mm & cutting speed is 260 m/min.

For MRR, It can say that by increasing the value of cutting speed, feed and depth of cut then the value of MRR is also increases. From the graph, it visible to us that we obtain highest value of MRR for all machining parameters when feed is 0.13 mm/rev, depth of cut is 0.40 mm & cutting speed is 260 m/min.

**Optimal Design:**
From these above figures of main effects plot of MRR & surface roughness (Ra & Rz), we can see speed and depth of cut are most influencing variables on Ra & Rz and cutting speed & feed are most
influencing variables for MRR. We achieve a smaller values of surface roughness at level 3 when cutting speed 260 m/min and at level 1 when depth of cut 0.20 mm and for MRR, we achieve a higher value at level 3 when cutting speed 260 m/min & at level 3 when feed 0.13 mm/rev.

From Table 5, for roughness (Ra) our approximate mean value solved as:

\[
\mu_{Ra} = \overline{V}_3 + \overline{d}_1 - \overline{T}_{Ra} \quad \text{(from Table 2 & 6, } \overline{T}_{Ra} = 0.9289) \\
\mu_{Ra} = (0.7833 + 0.8233) - 0.9289 \\
\mu_{Ra} = 0.6777
\]

At C.I. level 95% roughness is given mathematically:

\[
\text{C.I.} = \sqrt{\frac{F_{95\%}(1,2) \times \text{error}}{\eta_{\text{eff}}}}
\]

where, \( \eta_{\text{eff}} = \frac{N}{1 + \text{DOF associated to that level}} = \frac{9}{1 + 2 + 2} = 1.8 \)

\( F_{95\%(1,2)} = 18.51 \) & \( \text{V}_{\text{error}} = 0.002787 \) \quad \text{(from Table 3)}

Hence, \( \text{C.I.}_{Ra} = \sqrt{\frac{18.51 \times 0.002787}{1.8}} = 0.2271 \)

C.I. 95% approximate range for Ra = [ \( \mu_{Ra} - \text{C.I.}_{Ra} \leq \mu_{Ra} \leq \mu_{Ra} + \text{C.I.}_{Ra} \)]

That is, \( (0.6777 - 0.2271) \leq \mu_{Ra} \leq (0.6777 + 0.2271) \)

\( 0.4506 \leq \mu_{Ra} \leq 0.9048 \mu m. \)

For roughness (Rz), approximate mean value solved as:

\[
\mu_{Rz} = \overline{V}_3 + \overline{d}_1 - \overline{T}_{Rz} \quad \text{(from Table 2 & 6, } \overline{T}_{Rz} = 7.8111) \\
\mu_{Rz} = 6.577 + 6.780 - 7.8111 \\
\mu_{Rz} = 5.5459
\]

where, \( \eta_{\text{eff}} = \frac{9}{1 + 2 + 2} = 1.8 \)

\( F_{95\%(1,2)} = 18.51 \) & \( \text{V}_{\text{error}} = 0.01471 \) \quad \text{(from Table 4)}

Hence, \( \text{C.I.}_{Rz} = \sqrt{\frac{18.51 \times 0.01471}{1.8}} = 0.3889 \)

C.I 95% approximate limit for Rz = [ \( \mu_{Rz} - \text{C.I.}_{Rz} \leq \mu_{Rz} \leq \mu_{Rz} + \text{C.I.}_{Rz} \)]

That is, \( (5.5459 - 0.3889) \leq \mu_{Rz} \leq (5.5459 + 0.3889) \)

\( 5.1570 \leq \mu_{Rz} \leq 5.9348 \mu m. \)

For MRR, approximate mean value determined as:
\[ \mu_{\text{MRR}} = \bar{T}_{MRR} (\text{from Table 2 & 7}, \bar{T}_{MRR} = 0.2250) \]
\[ = 0.2759 + 0.2611 - 0.2250 = 0.3120 \]
Where, \( n_{\text{eff}} = \frac{9}{1+2^2+2} = 1.8 \)

\[ F_{95\% (1,2)} = 18.51 \text{ & } V_{\text{error}} = 0.00282 \]
\[ \text{(from Table 5)} \]

Hence, \[ \text{CI}_{\text{MRR}} = \sqrt{\frac{18.51 \times 0.00282}{1.8}} = 0.1702 \]

CI 95% approximate limit for MRR = \([ \mu_{\text{MRR}} - \text{CI}_{\text{MRR}} ] \leq \mu_{\text{MRR}} \leq [\mu_{\text{MRR}} + \text{CI}_{\text{MRR}}] \]
That is, \((0.3120 - 0.1702) \leq \mu_{\text{MRR}} \leq (0.3120 + 0.1720)\)

\[ 0.1418 \leq \mu_{\text{MRR}} \leq 0.4822 \text{ gm/sec} \]

6. Conclusion
In present work, test of turning has being performed on AISI D3 steel which have hardness of 60 HRC machined with coated carbide tool to find the effects of processing parameter on roughness (Ra & Rz) & MRR.

1. In MINITAB 18 software, we create DOE, Taguchi L\(_9\) OA and ANOVA method for evaluating the influence of processing parameter on roughness and MRR. We found the optimal values of maximum MRR and least roughness.

2. After this experiments we got a clear image in this cutting speed is the most influencing factor on Ra & Rz with % contribution of 68.04% & 58.71% respectively. Depth of cut was 2\(^{nd}\) affecting variable on Ra & Rz that have contribution of % with 23.62% &34.55% respectively. Feed is last parameter which affects Ra & Rz which has the percentage contribution 5.51% & 6.58% respectively.

3. For MRR, first influencing factor is feed with contribution of 71.19% following factor is speed with 17.15% & the last is depth of cut with % contribution of 11.01%.

4. In turning process, the value of roughness Ra is given in some limit of lower than 1.60 \( \mu \) m. This optimum calculation shows our value for Ra is in given range.
We get the minimum roughness value for Ra & Rz at feed (0.09 mm/rev), depth of cut (0.20 mm) & cutting speed (260 m/min). For MRR, we get maximum value at feed (0.13 mm/rev), depth of cut (0.40 mm) & cutting speed (260 m/min).

5. The calculated optimum range for Ra & Rz value is \[ 0.4506 \leq \mu_{\text{Ra}} \leq 0.9048 \text{ & } 5.1570 \leq \mu_{\text{Rz}} \leq 5.9348 \text{ resp.} \] & for MRR is \[ 0.1418 \leq \mu_{\text{MRR}} \leq 0.4822 \text{ gm/sec.} \]

Through this review, we try to reveal various confounding factors that have become barriers to the prevention of musculoskeletal diseases, and try to systematically solve these barriers. Various factors that have a significant impact on causing musculoskeletal diseases have been discovered, such as posture, strength, frequency, and working hours.

Conflict of Interest
None to report.
References
[1] M. Kumara Swamy, B.PadmaRaju and B.RaviTeja, “Modeling and Simulation of Turning Operation”, Journal of Mechanical and Civil Engineering, vol. 3, Issue 6, pp. 19-26, 2012
[2] SaurabhSinghvi, M. S. Khidiya, S. Jindal and M.A. Saloda, “Experimental Investigation of Cutting Force in Turning Operation”, International Journal of Advance Engineering and Research Development, vol. 3, Issue 3, 2016
[3] S.R. Das, D. Dhupal, and A. Kumar, “Study of surface roughness and flank wear in hard turning of AISI 4140 steel with coated ceramic inserts”, Journal of Mechanical Science and Technology, vol. 29, No. 10, pp. 4329-4340, 2015
[4] D.I. Lalwani, N.K. Mehta, and P.K. Jain, “Experimental investigations of cutting parameters influence on cutting forces and surface roughness in finish hard turning of MDN250 steel”, Journal of Materials Processing Technology, vol. 206, pp. 167-179, 2008
[5] Ravi K. Goyal, “Production Engineering - II”, Ashirwad Publication, 2006
[6] Douglas C. Montgomery, “Design and Analysis of Experiments”, Arizona state university, John Wiley & Sons, Inc., 2012
[7] Jitendra Sharma, Ajay Kumar Aggrawal, “Literature Review on Optimization of Surface Roughness during Turning Operation”, International Journal of Innovative Research in Science, Engineering and Technology, vol. 6, Issue 2, February 2017
[8] A. Rohit, B. Naga Raju, M. Raja Roy, “Optimization of Tool Temperature and Surface Roughness in Wet and Dry Conditions During Turning of Mild Steel Using Response Surface Method”, International Journal of Engineering Research in Management & Technology, vol. 4, Issue-5, 2015
[9] Mohd. Arif. I. Upletawala, Prof. TusharKatratwar, “A literature Review on various factors affecting Turning operation”, International Journal of Engineering Technology, Management and Applied Sciences, vol. 4, Issue 4, April 2016
[10] Dr. Osama Khayal, “Literature Review on Turning operations”, Researchgate, August 2019
[11] Ranganath M S, Vipin, “Effect of machining parameters on surface roughness with turning process – Literature Review”, International Journal of Advance Research and Innovation, vol. 2, Issue 2, 2014
[12] M. Kaladhar, K. Venkata Subbaiah, Ch. Shrinivasa Rao and K.Narayana Rao, “Optimization of process parameters in turning of AISI 202 austenitic stainless steel”, ARPN Journal of Engineering and Applied Sciences, vol. 5, No. 9, 2010
[13] Arshad Qureshi, Prof. Madhukar Sorte, Prof. S.N. Teli, “A literature review on optimization of cutting parameters for surface roughness in turning process”, International Journal of Engineering Research and Development, vol. 11, Issue 5, May 2015
[14] A Joshi, AK Saraf, RK Goyal, “EDM machining of die steel EN8 and testing of surface roughness with varying parameters”, https://doi.org/10.1016/j.matpr.2020.05.277 Materials Today: Proceedings Vol 28,Part 4, PP 2557-2560, May 2020.
[15] Singh, Ajay Pal and Samad, Abdul and Saraf, Amit Kumar, Enhancement of Surface Finish by Optimization Technique Employed for Al 6061 Considering Different Parameters Using RSM (October 12, 2019). Proceedings of International Conference on Advancements in Computing & Management (ICACM) 2019, SSRN: https://ssrn.com/abstract=3468726 or http://dx.doi.org/10.2139/ssrn.3468726.