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Optimization of Dimensional Tolerances and Material Removal Rate in the Orthogonal Turning of AISI 4340 Steel

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Abstract

Turning is one of the most used metal removal operations in the industry. It can remove material faster, giving reasonably good surface quality apart from geometrical requirements. Conformity of geometry is one of the most significant requirements of turned components to perform their intended functions. Apart from dimensional requirements, the important geometrical necessities are Circularity, Straightness, Cylindricity, Perpendicularity, etc. Since they have a direct influence on the functioning of the components, the effect of the cutting parameters on them has greater significance. In this paper experiments are carried out to examine the effect of turning parameters such as cutting speed, feed rate, and depth of cut on responses like; straightness, roundness, surface roughness, and material removal rate during turning of AISI 4340 steel. Analysis of Variance (ANOVA) is performed and the influence of parameters on each response is studied. The optimal values of parameters obtained from the study are further confirmed by conducting experiments.

Keywords

circularity, cylindricity, perpendicularity, straightness, RSM

1 Introduction

More prominent consideration is given to geometrical tolerances and surface finish of items by the industries nowadays. When a part has been made with measurements that are out of tolerances, it winds up unusable as the main qualities and functions of that part isn't as indicated by design.

Metal cutting is one of the most important processes and broadly used manufacturing processes in mechanical industries. Among various metal removing operations, turning is one of the main rudimentary and commonly applied machining processes in a real production environment. Turning could machine materials at a faster rate without compromising the surface quality. Turning is used in a diversified production industry, where quality is a prime factor in the production of dies, slots, precision molds, and pockets, including aerospace and automotive sectors.

Conformity of geometry is one of the most significant requirements of turned components to perform their intended functions. The geometrical requirements, apart from dimensional requirements are roundness, straightness, etc. Since they have a direct influence on the functioning of the components, the effect of the cutting parameters on them has greater significance. This study focuses on developing an optimization model, which eliminates the necessity of extensive experimentation process currently used in the industry to understand the relationship between machining parameters and performance characteristics.

The development of optimization models is the cost-effective and accurate prediction of optimum machining parameters that leads to minimum deviation in roundness and straightness. Examination of the material removal rate contains vast parameters embracing machining parameters, the geometry of the tool, workpiece material, vibrations, and coolants. Achieving optimum cutting or machining parameters, keeping in mind the reduction in machining time, improving productivity, and quality plays an indispensable role in the competitive market. In this study Response Surface Methodology (RSM) is used for the optimization. Advanced deep learning optimization techniques such as Classic Neural Networks, Convolutional Neural Networks, Recurrent Neural Networks, etc require substantial computing power and large amounts of data for optimization. Hence not considered for this study.

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Cutting speed, depth of cut, and feed play a vital role in machining the workpiece to the recommended shape, dimensions, and finish. These parameters have a significant influence on the tool-life/tool wear, part accuracy, surface roughness, power consumption, etc. in addition to time and cost. The judicious selection of these parameters is significant. The selected machining parameters should give the desired quality on the machined surface with the minimum environmental impact. Jena et al. [1] modeled and optimized surface finish in dry hard turning of AISI 4340 steel. Using Taguchi L16 orthogonal array (OA) the experimental design matrix is developed. A correlation of cutting parameters with the surface roughness of the machined workpiece is found using the Response Surface Methodology (RSM). Panda et al. [2] modeled and optimized surface finish while dry hard turning of AISI 4340 steel with a coated ceramic tool. Using Taguchi L27 orthogonal array (OA) the experimental design matrix is developed. The desirability function approach of RSM is proposed to find optimal cutting conditions. Singh et al. [3] studied and optimized chip formation processes and surface integrity while machining AISI 4340 steel. The central composite design (CCD) of RSM is used for optimization. Recently Singh et al. [4] investigated the influence of turning parameters on tool flank wear and machined surface quality of AIS 304 steel. CCD of RSM is used to generate the design matrix. Multi-response desirability methodology is used for the optimization of process parameters. Manav et al. [5] optimized process parameters for tool life, surface finish, and cutting force. The Particle Swarm Optimization approach is used for optimization. Panda et al. [6] investigated machinability of AISI 4340 steel on economic analysis, surface roughness, and tool wear. The design of experiments having full factorial is conducted. Multiple regression methods, ANOVA, and the Taguchi method are employed for parametric study. Zahia et al. [7] optimized the cutting force and surface roughness during turning of AISI 4140 steel. ANOVA and Response Surface Methodology techniques are used for the optimization process.

Panda et al. [8] examined the influence of machining factors on tool wear, chip morphology, surface finish, and economic analysis while dry turning of AISI 4340 steel. The full factorial design of experiments with 27 trials was performed. Agrawal et al. [9] considered the effect of machining parameters in influencing the machined surface finish during hard turning of AIS 4340 steel. Patole and Kulkarni [10] studied the influence of process parameters on the machinability of AISI 4340 steel with minimum quantity lubrication mode. Using the full factorial design matrix in RSM, the connection between response variables and the process parameters was determined. Azam et al. [11] developed an average surface roughness model for turning of light strength low alloy steel. Adarsha Kumar et al. [12] proposed an optimization method using grey relational analysis. Mia and Dhar [13] evaluated the effects of the material hardness and high-pressure coolant jet during dry machining. Taguchi L36 OA is used to generate the experimental design matrix. Sumesh and Ramesh [14] studied the influence of machining parameters on surface integrity while turning of Al 6061 – T6 alloy. CCD in RSM is used for optimization. Saidi et al. [15] identified the influence of various cutting parameters on the machinability of cobalt-based alloy. Predictive models are established using the experimental design matrix obtained using the experimental approach.

Debnath et al. [16] experimentally investigated the influence of several cutting fluid levels and machining parameters on surface finish and flank wear of the tool. Raghuram et al. [17] characterized the energy consumption by varying the machining parameters during turning operations using a thermodynamic framework. Radhika et al. [18] designed a new hybrid composite to analyze the optimum turning conditions using ANOVA. Krishnakumar et al. [19] developed a finite element model to predict the residual stresses developed in the machined workpiece during multi-pass operation. Rashid et al. [20] experimentally examined the consequence of machining parameters on surface roughness. A full factorial based Taguchi matrix is developed for the trials. Zheng et al. [21] investigated the relationships of machining parameters and tool wear, force, and surface finish are carried out for high-speed dry milling of steel. SEM micrograph and EDS are used for revealing the wear mechanism. Sohrabpoor et al. [22] experimentally investigated the effect of various machining parameters and lubrication on surface roughness and tool wear. Aouici et al. [23] compared the machining forces and flank wear on the ceramic cutting tool in dry hard turning of cold work steel AISI 4140 steel. RSM and ANOVA are used in the study.

Das et al. [24] investigated the machined surface characterization, tool wear mechanism, and chip morphology. Developed mathematical models for surface roughness and flank wear and optimize the results. Benlahmidi et al. [25] experimentally investigated the effect of machining parameters on surface roughness, tool-chip interface temperature, and cutting forces. A L9 OA is selected for Taguchi's design of experiments. Manohar et al. [26] compared and validated different analytical models while machining Inconel 718. Ukamanal et al. [27] investigated the spray-assisted turning performance of AISI 316 stainless under different environments. Taguchi based L16 orthogonal array is used for optimization. Asiltürk [28] proposes an interface based on artificial intelligence for predicting the surface roughness of AISI 1040 steel material. Several experiments were carried out and the data thus obtained is used for the training and testing of an artificial neural network. Ribeiro Filho et al. [29] used an acoustic emission sensor for online monitoring of the micro turning process. Babu et al. [30] presented the usage of copper nanofluids with minimum quantity lubrication (MQL) in turning on EN24 steel. Experiments are conducted based on L18 OA by changing the cutting speed, feed rate, and environment with MQL.

2 Experimental procedure

2.1 Machining details

In this work, the experiments are carried out on AISI 4340 steel. The initial diameter and length of the workpiece are 50 mm and 300 mm respectively. The composition of the material is presented in Table 1. HSS tool used for machining operation is shown in Fig. 1. After each cutting operation, the tool is re-grinded to maintain the sharpness of the tool tip. All turning operations are performed on a conventional lathe, shown in Fig. 2.

2.2 Roundness of workpiece

Roundness is the measure of how closely the shape of the object approaches that of a mathematically perfect circle. Sudjatmiko et al. [31] investigated the effect of nose radius, spindle speed, feed rate, and depth of cut on surface roughness and roundness during the turning process of Aluminium alloy. Patod and Sharma [32] studied the influence of machining parameters on output size precision, circularity, taper, concentricity, and better surface finish. Saglam et al. [33] studied the effect of cutting parameters on roundness error and surface roughness in cylindrical grinding. Jayaraman and Kumar [34] studied the effect of turning parameters on surface finish, roundness, and material removal rate during turning of aluminum alloy using grey relational analysis. A dial gauge is placed over the workpiece and the workpiece is rotated after keeping the dial gauge reading zero. Thus, the error in roundness can be directly measured by taking the maximum deviation shown in the dial gauge. This procedure is repeated at two more locations to check for the repeatability of the reading and an average value was taken. Roundness Error of the machined surface must be low for optimum condition.

Table 1 % composition of AISI 4340 steel

P	Ni	Mn	Cr	C	Mo	Si	S	Fe
0.03	1.8	0.7	0.8	0.4	0.3	0.23	0.04	95.7

Fig. 1 HSS tool used in this work

Fig. 2 Conventional lathe used in this work

2.3 Straightness of workpiece

Perfect straightness is one of the important geometrical parameters of many of the surfaces on a part of the machine in order to serve its intended function. Straightness can be defined as one of the qualitative representations of a surface in terms of variation of its geometry from a predefined straight line. Sheth and George [35] investigated the effect of machining parameters spindle speed, feed, and depth of cut on surface roughness and flatness, a form control of Geometric Dimensioning & Tolerancing (GD&T). A dial gauge is placed over the workpiece and moved over the entire length of the machined workpiece, after keeping the dial gauge reading zero. Thus, the error in straightness can be directly measured by taking the maximum deviation shown in the dial gauge. This procedure is also, repeated at two more locations to check for the repeatability of the reading and an average value was taken. Straightness Error of the machined surface must be low for optimum condition.

2.4 Metal Removal Rate (MRR) in turning operation

MRR in metal cutting is a volume of chips removed in one minute, and it is measured in a three-dimensional quantity. MRR (m^3/sec) is determined by taking the difference of weight of workpiece before and after machining with the help of a precision weighing machine (max. capacity = 2 kg, least count = 0.2 g). The given Eq. (1) is used for finding MRR [36],

$$\text{MRR} = \left(W_f - W_i\right)/\rho t\ , \tag{1}$$

where W_i and W_f are the weight of workpiece before and after machining in kg, ρ is the density of material (7850 kg/m^3) and t is the time taken to machine in sec.

Various instruments like dial gauge and weighing machine used for the experimental investigation are shown in Fig. 3(a) and (b).

2.5 Identification of process parameters

In this work, Cutting Speed (taken as the rotation of workpiece), Feed Rate, and Depth of Cut were taken as the machining parameters. The three levels of selected machining parameters are shown in Table 2. The range of cutting parameters was selected based on ISO 3685:1993E [37].

3 Response Surface Methodology (RSM)

Significant parameters in this optimization study can be identified by using Design of Experiments (DoE) software MINITAB. In the present work, the effect of machining parameters on the responses - roundness error, straightness error, and MRR are investigated during the turning of AISI 4340 steel. Using CCD of RSM for the levels shown in Table 2, experimental runs are generated. Experiments are performed for these experimental runs, different combinations of machining parameters. Table 3 shows the experimental runs and measured values of roundness error, straightness error, surface roughness, and MRR corresponds to each run.

4 Results and discussions

4.1 Influence of parameters on surface roughness

ANOVA is performed for Surface Roughness with a 95 % confidence interval. In the ANOVA table, P values are checked and found that square terms of CS and interaction between FR and DoC are insignificant, which means P-value greater than 0.05. Hence these terms are ignored and ANOVA is done again. The regression equation thus obtained is given by Eq. (2).

$$\begin{aligned}\text{Ra} = {} & 0.001665 - 0.000002 * \text{CS} + 0.001642 * \text{FR} \\ & + 0.003391 * \text{DoC} - 0.000712 * \text{FR} * \text{FR} \\ & - 0.00125 * \text{DoC} * \text{DoC} + 0.000001 * \text{CS} * \text{FR} \\ & - 0.000001 * \text{CS} * \text{DoC}\end{aligned} \tag{2}$$

(a)

(b)

Fig. 3 (a) Dial gauge used; (b) weighing machine

Table 2 Machining parameters and the three levels

Machining Parameter	Units	Low	Medium	High
Cutting Speed	RPM	135	280	427
Feed Rate	mm/sec	0.3	0.57	0.83
Depth of Cut	mm	0.6	0.8	1.0

Table 3 Possible combinations and values of response variables

Trial #	CS (rpm)	FR mm/sec.)	DoC (mm)	Roundness Error (mm)	Straightness Error (mm)	Surface Roughness (mm)	MRR (mm^3/sec.)
1	281	0.83	0.8	0.0029	0.0017	0.0042	457.9
2	427	0.83	1	0.0035	0.0016	0.0041	903.2
3	281	0.3	0.8	0.0027	0.0023	0.0036	159.8
4	427	0.3	0.6	0.0029	0.0028	0.0034	176.5
5	281	0.565	0.8	0.0028	0.002	0.0039	282.4
6	281	0.565	0.8	0.0028	0.002	0.0039	282.4
7	427	0.83	0.6	0.002	0.0022	0.0040	457.38
8	135	0.565	0.8	0.0025	0.0018	0.0036	126.77
9	135	0.83	1	0.0029	0.0011	0.0041	222.24
10	135	0.3	0.6	0.0023	0.0022	0.0040	46.163
11	427	0.3	1	0.0033	0.0022	0.0035	232.62
12	281	0.565	0.8	0.0028	0.002	0.0039	282.49
13	135	0.3	1	0.0027	0.0016	0.0035	69.308
14	281	0.565	1	0.0031	0.0016	0.0041	255.07
15	281	0.565	0.8	0.0028	0.002	0.0039	282.49
16	281	0.565	0.6	0.0025	0.0022	0.0040	145.07
17	135	0.83	0.6	0.0024	0.0017	0.0040	98.163
18	281	0.565	0.8	0.0028	0.002	0.0039	282.49
19	427	0.565	0.8	0.0031	0.0023	0.0036	176.14
20	281	0.565	0.8	0.0028	0.002	0.0039	282.49

The main effect of Ra is plotted in Fig. 4. It is observed from the plot that, all the parameters have a significant influence on surface roughness. Also from this plot, an increase in cutting speed decreases surface roughness and surface roughness has an increasing trend with an increase in depth of cut and feed rate. The reason for these variations is; when cutting speed increases, the volume of workpiece material comes in contact with the tool in unit time decreases. Hence to remove the material, the less cutting force is required. This leads to a decrease in the surface roughness of the finished workpiece. Similarly, at low values of feed rate and depth of cut, less volume of the material comes in contact with the tool, so less force is necessary and hence better surface finish.

Figs. 5(a) and (b) demonstrates the contour and surface plots for surface roughness. These figures show the interaction of two parameters, simultaneously on surface roughness. From the contour plot of feed rate and cutting speed on surface roughness at low values of feed rate and high values of cutting speed, surface roughness is low. Similarly, from the interaction plot of the depth of cut and cutting speed on surface roughness at low values of depth of cut and high values of cutting speed, surface roughness is minimum. Also, from the interaction plot of feed rate

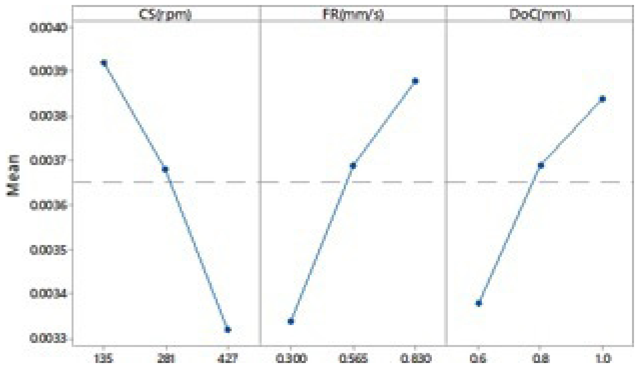
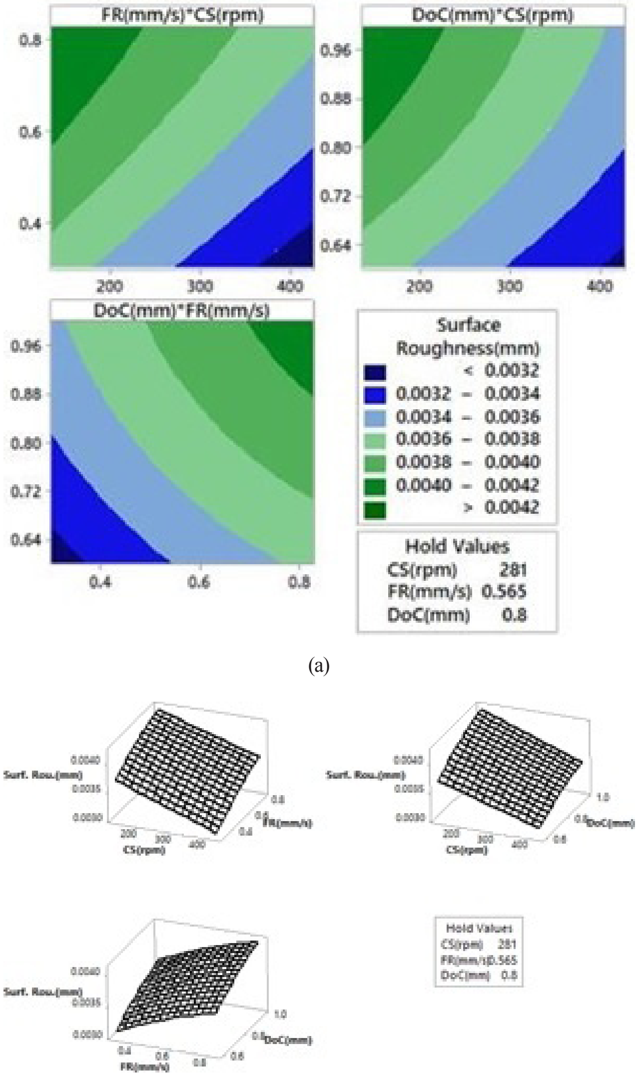


Fig. 4 Main effect plot for surface roughness



(a)

(b)

Fig. 5 (a) 2D or contour plots for surface roughness; (b) 3D or Surface plots for surface roughness and depth of cut on surface roughness at low values of feed rate and depth of cut, surface finish is better. The same combination of cutting parameters is obtained from the 3D surface plots also.

4.2 Influence of parameters on Material Removal Rate (MRR)

ANOVA for MRR is done, in the same way as discussed earlier and the corresponding values are shown in the Appendix (Tables 5 to 8).

The regression equation thus obtained is given by Eq. (3).

$$\begin{aligned} MRR &= -283 - 0.415 * CS - 129 * FR \\ &\quad + 380 * DoC + 2.412 * CS * FR \end{aligned} \quad (3)$$

The main effect of MRR is plotted in Fig. 6. It can be observed that all the parameters have an increasing trend with MRR. At high values of depth of cut, more amount of workpiece material comes in contact with the tool, which increases the Material Removal Rate (MRR). The same reason can be applied to feed rate and cutting speed.

Fig. 7(a) and (b) show the contour and surface plots for MRR. These figures show the interaction of two parameters, simultaneously on MRR. From the interaction plot of feed rate and cutting speed, at high values of cutting speed and feed rate, MRR is high. Similarly, from the interaction plot of the depth of cut and cutting speed, at high values cutting speed and DoC, MRR is maximum. Also, from the interaction plot of feed rate and depth of cut, it is found that, at high values of feed rate and depth of cut, maximum workpiece material is removed. The same combination of cutting parameters is obtained from the 3D surface plots also.

4.3 Influence of parameters on straightness error

Similarly, ANOVA is performed for Straightness Error (St. Err.). The regression equation thus obtained is given by Eq. (4).

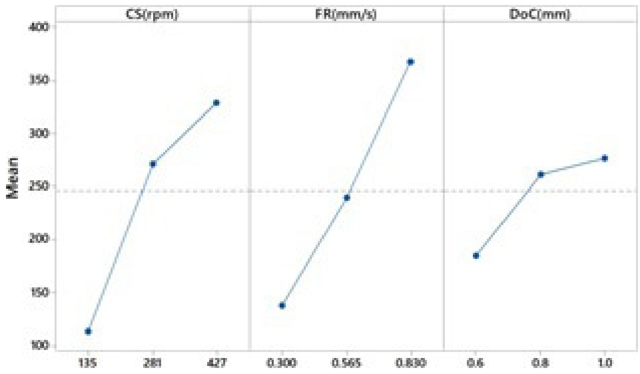
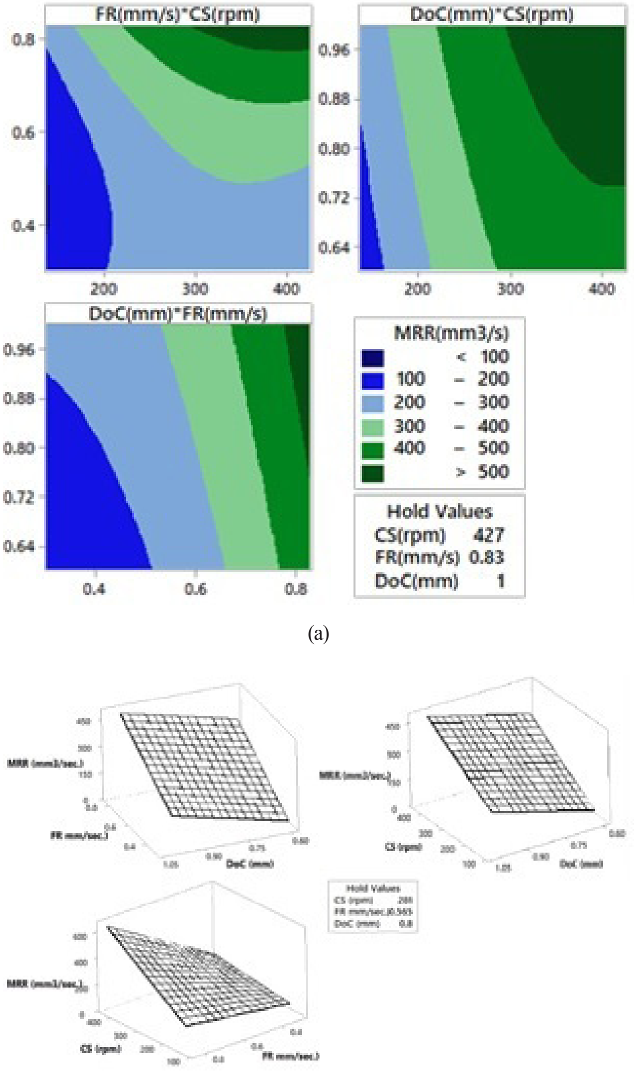


Fig. 6 Mean effect plot for MRR



(a)

(b)

Fig. 7 (a) 2D or contour plots for MRR; (b) 3D or Surface plots for MRR

$$\begin{aligned} &\text{Straightness Error} = 0.001516 + 0.000001 * CS \\ &-0.000875 * FR + 0.003 * DoC - 0.002813 * DoC * DoC \\ &-0.000001 * FR * DoC \end{aligned} \quad (4)$$

The main effect of Straightness Error is plotted in Fig. 8. It is observed from the plot that, all the parameters have a major influence on Straightness Error, and the variation in parameters is having the same trend as in Surface Roughness. Hence the reasons mentioned in Subsection 4.1 can be applied here as well.

Fig. 9(a) and (b) show the contour and surface plots for Straightness Error. From the interaction plot of feed rate and cutting speed on Straightness Error at high values of cutting speed and low values of feed rate, Straightness Error is low. Similarly, from the interaction plot of the depth of

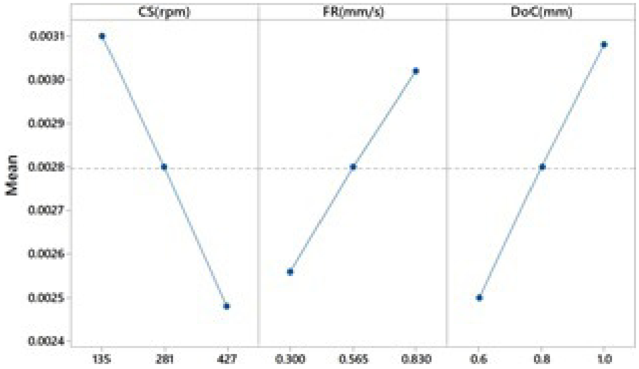
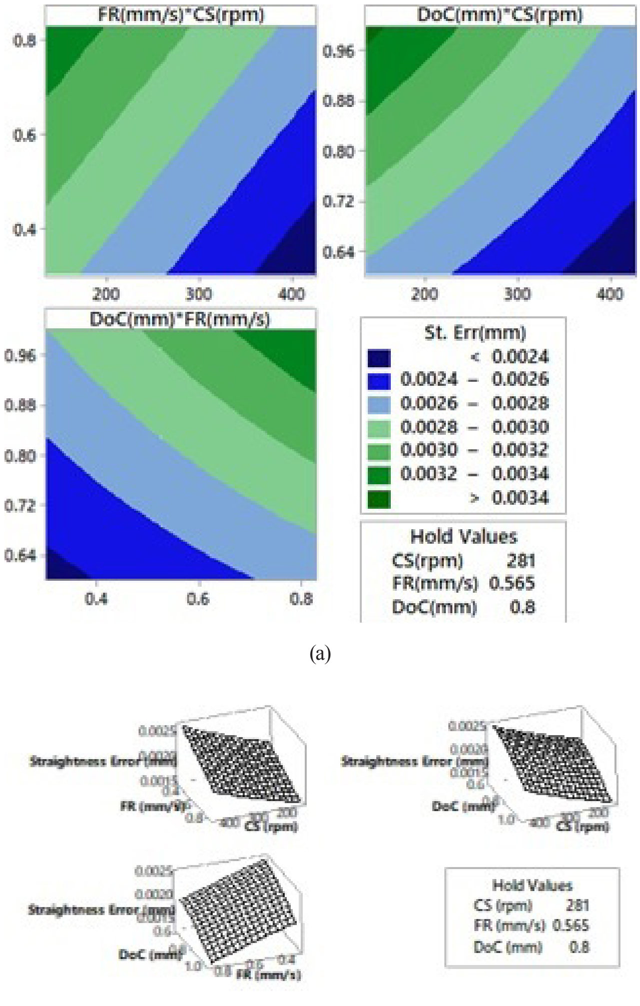


Fig. 8 Mean Effect Plot for Straightness Error



(a)

(b)

Fig. 9 (a) 2D or contour plots for straightness error; (b) 3D or surface plots for straightness error

cut and cutting speed at high values cutting speed and low values of DoC, Straightness Error is minimum. Also, from the interaction plot of feed rate and depth of cut, it is found that, at low values of feed rate and depth of cut, Straightness Error is at its lowest value. The same combination of cutting parameters is obtained from the 3D surface plots also.

4.4 Influence of parameters on roundness error

ANOVA is performed for roundness error using the same procedure discussed earlier. The regression equation thus obtained is given by Eq. (5).

$$\begin{aligned}\text{Roundness Error} &= 0.002806 - 0.001432 * \text{FR} \\ &- 0.001102 * \text{DoC} - 0.000003 * \text{CS} * \text{FR} \\ &+ 0.000004 * \text{CS} * \text{DoC} + 0.002830 * \text{FR} * \text{DoC}\end{aligned} \tag{5}$$

The main effect of Roundness Error is plotted in Fig. 10. It is observed from the plot that, all the parameters have a major influence on roundness error. Moreover, the CS/FR/DoC is observed from the plot that, all the parameters have a major influence on Roundness Error. Moreover, the variation in parameters is having the same trend as in Surface Roughness. Hence the reasons mentioned in Subsection 4.1 can be applied here as well.

Fig. 11(a) and (b) show the contour and surface plots for Roundness Error. These figures show the interaction of two parameters, simultaneously on Roundness Error. From the interaction plot of feed rate and cutting speed on Roundness Error at high values of cutting speed and low values of feed rate, Roundness Error is low. Similarly, from the interaction plot of the depth of cut and cutting speed at high values cutting speed and low values of DoC, Roundness Error is minimum. Also, from the interaction plot of feed rate and depth of cut, it is found that, at low values of feed rate and depth of cut, Roundness Error is at its lowest value. The same combination of cutting parameters is obtained from the 3D surface plots also.

4.5 Multiple objective optimization using RSM

Multi-objective optimization is the process of determining the best combination of process parameters to optimize responses simultaneously. The desirability of individual parameters combined to get composite desirability D.

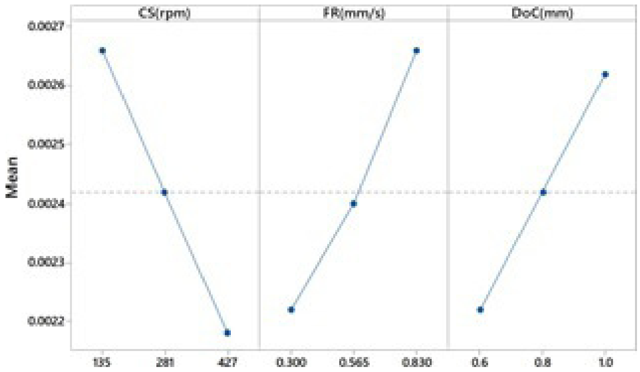
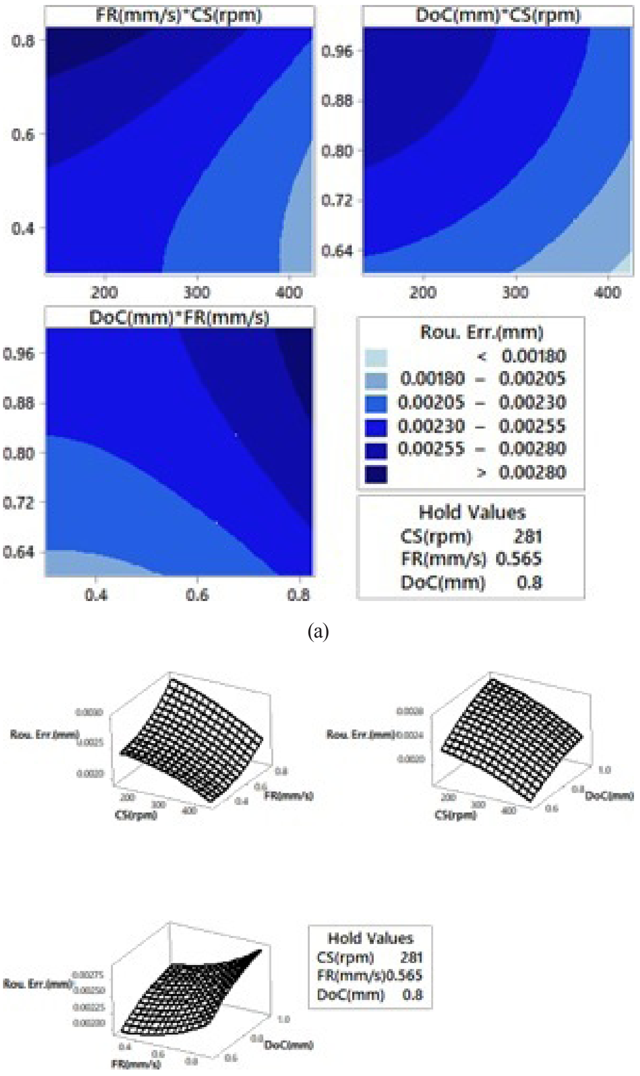


Fig. 10 Mean Effect Plot for Roundness Error



(a)

(b)

Fig. 11 (a) 2D or Contour plots for roundness error; (b) 3D or Surface plots for roundness error

Optimized values of parameters are indicated in the square bracket and optimized values of responses are given by y-values in Fig. 12. The composite desirability obtained is D = 0.7125, which is close to one, implies the significance of responses.

4.6 Validation of results

Results are confirmed by conducting further experiments (three times) for optimized cutting conditions i.e.

Cutting speed = 427 rpm, Feed rate = 0.83 mm/sec, and depth of cut = 0.6 mm. Mean value of responses, Straightness Error, Roundness Error, Surface roughness, and MRR are measured. Table 4 shows the confirmation results.

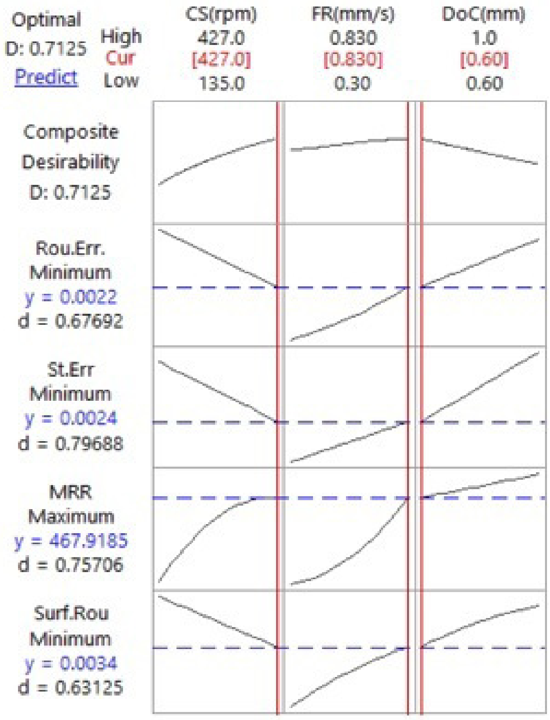


Fig. 12 Optimization plot

Table 4 Confirmation of results

	Roundness Error	Straightness Error	MRR	Surface Roughness
Optimized Values	0.0022	0.0024	467.9	0.0034
Experimental Values	0.0020	0.0022	457.3	0.0033
% Error	9.09	8.33	2.25	2.94

5 Conclusions

In this work, the effect of turning parameters like depth of cut, cutting speed, and feed rate on responses such as straightness error, roundness error, Surface roughness, and MRR while turning of AISI 4340 steel was studied. The CCD in RSM is used for the optimization study. The multiple objective optimizations of turning was performed using concepts of composite desirability functions. The major findings of this work are given below:

1. The regression equations developed during ANOVA can predict the responses effectively during the dry turning of AISI 4340 steel.
2. Based on percentage contributions from the ANOVA tables (Tables 5 to 8):
    - for MRR, the feed rate is the most influencing factor followed by cutting speed and depth of cut,

  - for Surface roughness and Straightness Error, all the parameters are equally significant and
  - for Roundness Error, cutting speed is the most significant factor. Feed rate and Depth of cut have no significant influence on roundness error.
3. 3D surface plots are useful in determining the optimum condition to obtain the values of all responses.
4. For multi objective optimization of responses, the optimal values are Feed rate = 0.83 mm/sec, depth of cut = 0.6 mm and Cutting speed = 427 rpm.
5. To validate the optimized results, confirmation experiments are carried out. The results obtained are in close agreement.
6. The developed optimization model can be used to predict the responses accurately.

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Appendix

Table 5 ANOVA Table for Surface Roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	0.000002	0.000000	2134.60	0.000
Linear	3	0.000002	0.000001	4182.53	0.000
CS (rpm)	1	0.000001	0.000001	3790.80	0.000
FR (mm/s)	1	0.000001	0.000001	4076.80	0.000
DoC (mm)	1	0.000001	0.000001	4680.00	0.000
Square	2	0.000000	0.000000	117.00	0.000
CS (rpm)* CS (rpm)	1	0.000000	0.000000	23.40	0.000
DoC (mm)* DoC (mm)	1	0.000000	0.000000	210.60	0.000
2-Way Interaction	1	0.000000	0.000000	26.00	0.000
CS (rpm)* FR (mm/s)	1	0.000000	0.000000	26.00	0.000
Error	13	0.000000	0.000000		
Lack of Fit	8	0.000000	0.000000	*	*
Pure Error	5	0.000000	0.000000		
Total	19	0.000002			

Table 6 ANOVA Table for Material Removal Rate (MRR)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	530174	132543	15.28	0.000
Linear	3	460511	153504	17.69	0.000
CS (rpm)	1	191323	191323	22.05	0.000
FR (mm/s)	1	211555	211555	24.38	0.000
DoC (mm)	1	57633	57633	6.64	0.021
CS (rpm)* FR (mm/s)	1	69663	69663	8.03	0.013
Error	15	130145	8676		
Lack of Fit	10	130145	13015	6025236.63	0.000
Pure Error	5	0	0		
Total	19	660319			

Table 7 ANOVA Table for Straightness Error

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	0.000001	0.000000	17.49	0.000
Linear	3	0.000001	0.000000	29.38	0.000
CS (rpm)	1	0.000000	0.000000	5.18	0.044
FR (mm/s)	1	0.000001	0.000001	82.82	0.000
DoC (mm)	1	0.000000	0.000000	0.14	0.712
Square	2	0.000000	0.000000	16.18	0.001
CS (rpm)* CS (rpm)	1	0.000000	0.000000	31.71	0.000
DoC (mm)* DoC (mm)	1	0.000000	0.000000	16.18	0.002
2-Way Interaction	3	0.00000	0.000000	6.47	0.009
CS (rpm)* FR (mm/s)	1	0.000000	0.000000	6.47	0.027
CS (rpm)* DoC (mm)	1	0.000000	0.000000	6.47	0.027
FR (mm/s)* DoC (mm)	1	0.000000	0.000000	6.47	0.027
Error	11	0.000000	0.000000		
Lack of Fit	6	0.000000	0.000000	*	*
Pure Error	5	0.000000	0.000000		
Total	19	0.000001	0.000000		

Table 8 ANOVA Table for Roundness Error

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	0.000002	0.000000	21.34	0.000
Linear	3	0.000002	0.000001	33.47	0.000
CS (rpm)	1	0.000000	0.000000	25.74	0.000
FR (mm/s)	1	0.000000	0.000000	0.26	0.620
DoC (mm)	1	0.000001	0.000001	74.40	0.000
2-Way Interaction	3	0.000000	0.000000	9.22	0.002
CS (rpm)* FR (mm/s)	1	0.000000	0.000000	8.04	0.014
CS (rpm)* DoC (mm)	1	0.000000	0.000000	8.04	0.014
FR (mm/s)DoC (mm)	1	0.000000	0.000000	11.58	0.005
Error	13	0.000000	0.000000		
Lack of Fit	8	0.000000	0.000000	*	*
Pure Error	5	0.000000	0.000000		
Total	19	0.000002			