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OPTIMIZATION OF DRILLING PARAMETERS

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Abstract

Optimization of drilling parameters considering multiple responses thrust force and torque simultaneously are performed using response surface methodology (rsm). The workpiece material chosen for turning is AISI 1045, medium carbon steel with High speed steel drill bit. Twenty experiments are designed based on face-centred composite design for three numerical parameters such as rotational speed, feed rate and drill bit diameter. In this work, both the thrust force and torque should be minimized. Desirability function is applied to optimize multiple responses simultaneously and to obtain the optimized condition. ANOVA is performed to understand the significance of input parameters over the output responses.

Introduction

The workpiece material chosen for analysis in this work is AISI 1045, medium carbon steel. This material is used when greater strength and hardness and other physical properties is desired. The applications of AISI 1045 steel includes component parts for vehicles, shafts, bushings, crankshafts, connecting rods and parts for the machine building industry and steel for axes, knives, hammers, etc. The Brinell hardness value is 280 BHN. The cutting tool inserts chosen for analysis are DNMG160608WIDIA—THMgrade, which is an uncoated cementedcarbide cutting insert grade. The tool holder used for holding the cuttingtool inserts during turning operation is PDJNR 2525 M15.The scanning electron microscope (SEM) photomicrographof the cemented carbide tool is shown in Fig. 1. Themicrograph shows the particles of predominant tungsten carbide(WC), which appear as light gray particles. Some voidsare present during compacting, which appear as black areas.The structure is the variable composition of solid solutionphases of WC and TiC. The inter-granular areas in betweenthe grains are cobalt solid solution. The marginal dendriticsolid solution of cobalt is seen at the extreme right.Figure 1shows the dimensions of the cutting tool insert chosen in this analysis with an included angle of 55◦andnose radius 0.8mm along with other dimensions.

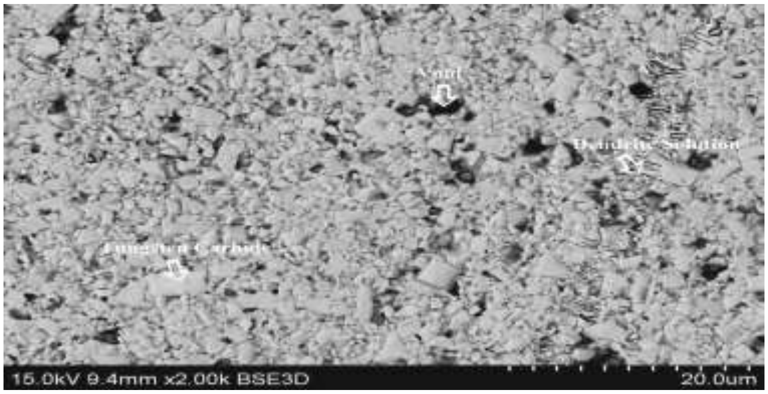

Fig.1.2SEM image of cemented carbide cutting insert

Literature Review

Manufacturing industries are more concerned about producing high-quality products at low cost due to the competitiveglobal market prevailing today. One of the most importantfactors that affect the quality of the machined component is the tool wear, since it drastically influences the surfacefinish of the machined surface and dimensional accuracy offinished component and lowers the life of the cutting tooland increases the tool changing cost. At the same time, theamount of material to be removed has to be higher in orderto achieve higher production rate. Hence, a combination ofproduction rate and good quality along with longer tool lifehas to be achieved. Neseli [1] investigated the influence of tool geometry on surface finish using RSM and indicated that nose radius contributes much to the surface roughness. Asilturk and Neseli [2] presented a new method of Taguchi method-based response surface analysis of machining parameters over surface roughness and found that the feed rate contributes much to roughness. Makadia and Nanavati [3] studied the effects of turning parameters and nose radius on the surface roughness using Taguchi's technique, and the effect of those chosen parameters is investigated using RSM. Noordin et al. [4] described the performance of multilayered tungsten carbide tool during turning AISI 1045 steel over tangential force and surface roughness and found that the feed rate is themost significant parameter contributing toward the responses. Hornget al. [5] investigated the machinability evaluation of Hadfield steel using uncoated Al_2O_3/TiC mixed ceramics and the found that the flank wear is influenced by cutting speed and surface roughness by corner radius and cutting speed. Fnideset al. [6] developed a statistical model for cutting force during hard turning of AISI H11 steel using mixed ceramic tool using RSM and conclude that the depth of cut is the dominant factor that affects the cutting force. Aouici et al. [7] investigated the effect of cutting parameters in turning AISI H11 steel with cubic boron nitride (CBN) tool on flank wear and surface roughness and observed that cutting speed influences flank wear and feed rate influences surface roughness. Saini et al. [8] developed a model to predict the surface roughness and tool wear in finish hard turning and found that with lower feed rate and higher cutting speed, a significant increase in surface quality is achieved using RSM Box–Behnken method. Mandal et al. [9] investigated the effect of cutting parameters on machining forces during finishing hard turning of AISI 4340 steel with zirconia toughened alumina (ZTA) insert using RSM and obtained 76.51% desirability level. Senthilkumar andTamizharasan [10] studied the performances of cutting tool inserts of varying tool geometry considering multiple responses simultaneously using Taguchi's technique and confirmed it using FEM analysis. Yildiz [11] implemented artificial bee colony algorithm for multipass turning operation, which is used to optimize the cutting parameters, and the effectiveness of the algorithm shows that it can also be used for solving other nonlinear optimization problems. Population-based optimization technique, cuckoo search algorithm, can be used for solving manufacturing optimization problems, which is effectively used for milling operation, and the results demonstrate the effectiveness of the algorithm [12]. Yildiz [13] developed a hybrid optimization algorithm by combining Taguchi's technique with differential evolution algorithm for minimizing productioncost in multipass turning operation. In turning process, the cutting tool, workpiece material, machining parameters and cutting conditions have a direct and indirect influences on the output responses achieved. Suhail et al. [14] presented a method for surface roughness identification based on the measurement of root mean square for feed vibration of the cutting tool and workpiece surface temperature for machining mild steel in turning operation and applied gray relational analysis method for combining effects of tool vibration and workpiece surface temperature.Ganesan and Mohankumar [15] presented amultiobjective optimization technique, non-dominated sorting genetic algorithm, for optimizing the cutting parameters in turning processes for minimum operating time and minimum production cost and minimum tool wear. Tharik [16] compared two nature-inspired metaheuristic algorithms, firefly algorithm and cuckoo search algorithm, for optimizationmachining parameters in turning operations for minimizing production cost considering surface finish and power as constraint. Raja et al. [17] implemented firefly algorithm for optimizing machining parameters during electric discharge machining of die steel considering surface finish as constraint and concluded that firefly algorithm is suitable for solvingmachining optimization problems. Raja et al. [18] applied firefly algorithm for selecting the optimal machining parameters cutting speed, feed and depth of cut in minimum possible production time, and production cost on single-pass turning process and compared it with other optimization techniques. Relationship between flank wear and cutting zone temperature is studied [19] to correlate the relationship between them when considering both machining parameters and geometrical parameters.

In this work, the effect of machining parameters such as cutting speed, feed rate, and depth of cut is analyzed overflank wear at the cutting tool face, surface roughness at the machined surface, and the amount of material removed using RSM during turning AISI 1045 steel with uncoated carbide cutting tool inserts. These chosen parameters are the basic turning parameters that are to be altered to achieve better output in order to obtain increased productivity, lower production cost, and longer tool life. The output responses are predicted using the empirical models that are developed using RSM. With the help of a non-traditional evolutionary optimization technique [20–21], firefly algorithm, themachining parameters are optimized for lower flank wear and higher MRR considering surface roughness as the constraint. This algorithm is based on the flashing light of fireflies produced by a process of bioluminescence, which is used to attract mating partners and to potential prey and also serves as a protectivewarning mechanism to remind potential predators [22].

Experimental Setup

The experiments are conducted on a CNC turning center,Lokesh make 2 axis CNC TL-20, swing diameter 350mm, between center 600mm, spindle speed 4,500 rpm, mainmotor power of 11kW. After performing the machiningprocess, the flank wear is measured and recorded by using aMitutoyo digital tool makers microscope of specifications,eyepiece 15X, view field diameter 13mm, objective 2X,working distance 67mm, total magnification 30X. Surfaceroughness values of the machined surfaces are recorded byusing a Kosaka Laboratory Ltd make Surfcorder SE1200, with a vertical measuring range of 520 μm, horizontal measuringrange of 25mm, vertical resolution of 0.008μm, cutoffvalue of 0.8mm with Gaussian filter. MRR is determinedby the loss ofweight duringmachining and by noting the timetaken for machining. Figure shows the machine and instrumentsused for conducting the experiment and to measurethe output quality characteristics.The dimension of the workpiece materials chosen isof 30mm diameter and of length 150mm. The machiningprocess is a dry turning process, which eliminates the usageof cutting fluids. Before performing the turning process,the workpiece is weighed. Three passes are considered formachining so that a considerable amount of wear takes placein the flank face of the cutting tool since carbide tools havevery high hardness even at elevated temperatures. Duringthe turning operation, a separate workpiece and cutting toolinsert is used in every experiment. The machining is performedfor a total length of 100mm out of 150mm length ofworkpiece. This machining length is kept constant throughoutthe analysis. For everyworkpiece, the time taken for turningis noted down using a stopwatch. After performing theturning operation, the workpiece is removed from the turningcenter and weighed. Flank wear is measured using digitaltool makers microscope, and surface roughness is measuredusing Surfcorder. The MRR is the rate at which the materialis removed from the unfinished workpiece, which is the ratioof difference in weight before and aftermachining to the timeperiod of machining, given by the formula:

$$\text{Material removal rate} = \frac{\text{Workpiece weight before turning-weight after turning}}{\text{Time taken for turning}} \quad (1)$$

(a) CNC Turning Center (b) Tool Maker's Microscope (c) Surfcorder SE1200

Fig 2 CNC machining setup

Table 1 Control parameters and its level

Sl. No	Parameter/level	Low Level	High Level
1	Rotational Speed (m/min)	20	60
2	Feed rate (mm/rev)	0.3	0.9
3	Drill bit diameter (mm)	6	12

Box–Behnken designs are experimental designs for response surface methodology, devised by George E. P. Box and Donald Behnken in 1960. Each design can be thought of as a combination of a two-level (full or fractional) factorial design with an incomplete block design. In each block, a certain number of factors are put through all combinations for the factorial design, while the other factors are kept at the central values. For instance, the Box–Behnken design for 3 factors involves three blocks, in each of which 2 factors are varied through the 4 possible combinations of high and low.

Table 2 Box Behnken Design of RSM

Std. No	Rotational Speed (m/min)	Feed Rate (mm/rev)	Drill Diameter (mm)
1	20.00	0.30	9.00
2	60.00	0.30	9.00
3	20.00	0.90	9.00
4	60.00	0.90	9.00
5	20.00	0.60	6.00
6	60.00	0.60	6.00
7	20.00	0.60	12.00
8	60.00	0.60	12.00
9	40.00	0.30	6.00
10	40.00	0.90	6.00
11	40.00	0.30	12.00
12	40.00	0.90	12.00
13	40.00	0.60	9.00
14	40.00	0.60	9.00
15	40.00	0.60	9.00

Optimization Using Firefly Algorithm

The responses are analyzed, optimized, and predicted usingthe RSM. For predicting each response, a quadratic model isgenerated. These empirical models are used to optimize the

machining parameters to achieve minimum flank wear and maximize MRR within a specific range of surface roughnessvalue. The non-traditional evolutionary technique, fireflyalgorithm, is utilized for this. The surface roughness ischosen as constraint, which is set to be within 3µm. Thefirefly parameters chosen are number of fireflies n = 100,number of iterations N = 100,alpha= 0.5, βmin = 0.2,and γ = 1. The purpose of α was to reduce randomness andto increase the convergence, because of which the value ischosen as 0.5. βmin is the minimum value of β chosen as0.2, which varies with the absorption coefficient and sourcedistance, which is the attractiveness of fireflies, and γ is the absorption coefficient, which varies between 0 to ∞, whichdepends mainly on the light intensity of fireflies. The problem is formulated as, Objective 1: Minimize Flank wear ,Objective 2: Maximize MRR.
Combined Objective: Minimize Flank wear + MaximizeMRR.
Constraint: Surface roughness ≤3µm.
Lower and upper bounds of input parameters: 227<cutting speed<285, 0.203<feed rate<0.432, 0.30<depth of cut <0.60.

These parametric values are fed into the firefly algorithm coding written in MATLAB and the output is analyzed. Figureshows the combined objective obtained during minimization of flank wear and maximization of MRR for all iterations. It is observed that initially the combined objective is at a higher value and as the iteration progresses, the combined objective converges quickly and it gets settled for the further iterations. Figureshows the plot between the input parameter cutting speed and number of iterations. It is observed that throughout the optimization process, for obtaining better results, the cutting speed has to be moderate. Initially, the cutting speed is around 256 m/min, and as the iteration progresses,it settles down to a moderate level of 253.29 m/min.

Table 3 Experimental values of responses for firefly output

Responses	Experimental value
Flank wear	0.131
Surface roughness	2.96
Material removal rate	169.82

RESULTS AND DISCUSSION

During the drilling process, cutting forces were measured by kistler dynamometer. The measured output characteristics, thrust force and torque is shown in Table,

Table 4 Measured Thrust force and Torque

Std. order	Thrust Force (N)	Torque (N-m)
1	52.47	0.687
2	142.87	4.054
3	85.68	2.612
4	154.67	4.389
5	56.17	1.83
6	135.19	4.271
7	67.21	1.268
8	139.68	4.683
9	104.62	3.125
10	120.45	3.872
11	113.08	3.683
12	130.69	4.163
13	122.84	3.571
14	120.31	3.607
15	120.68	3.612

ANALYSIS OF THRUST FORCE

The thrust force measured during drilling AISI 1045 steel with HSS drill bit is analyzed and the Table shows the ANOVA model generated. It is observed that the model is significant and a quadratic model is suggested for the measured values. The Model F-value of 372.80 implies the model is significant. There is onlya 0.01% chance that a "Model F-Value" this large could occur due to noise.Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, A^2, B^2, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Lack of Fit F-value" of 8.40 implies the Lack of Fit is significant. There is only a3.35% chance that a "Lack of Fit F-value" this large could occur due to noise.Significant lack of fit is bad -- we want the model to fit.

Table4.3.1 ANOVA Table for Thrust force

	Sum of		Mean	F	p-value	
Source	Squares	Df	Square	Value	Prob > F	
Model	14323.75	9	1591.528	372.7957	< 0.0001	significant
A-Rotational Speed	12080.8	1	12080.8	2829.776	< 0.0001	
B-Feed Rate	769.3003	1	769.3003	180.199	< 0.0001	
C-Drill Diameter	146.4616	1	146.4616	34.30681	0.0006	
AB	114.597	1	114.597	26.84292	0.0013	
AC	10.72563	1	10.72563	2.512344	0.1570	
BC	0.7921	1	0.7921	0.18554	0.6796	
A^2	952.4911	1	952.4911	223.1092	< 0.0001	
B^2	28.61663	1	28.61663	6.703088	0.0360	
C^2	192.0127	1	192.0127	44.97657	0.0003	
Residual	29.8842	7	4.269171			
Lack of Fit	25.79048	3	8.596825	8.400013	0.0335	Not significant
Pure Error	4.09372	4	1.02343			

The R-square value and R-square adjusted values obtained during ANOVA is given in Table

Table4.3.2 R-square values for Thrust force analysis

Std. Dev.	2.066197		R-Squared	0.997918
Mean	112.3271		Adj R-Squared	0.995241
C.V. %	1.839447		Pred R-Squared	0.970806
PRESS	419.044		Adeq Precision	61.49425

The "Pred R-Squared" of 0.9708 is in reasonable agreement with the "Adj R-Squared" of 0.9952."Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 61.494 indicates an adequate signal. This model can be used to navigate the design space.The second order quadratic model developed during the analysis of thrust force is given below,Influence of input parameters over the measured output is studied by means of surface plots.

The second order quadratic model developed during the analysis of thrust force is given below,

Thrust Force	=
-127.889	*Rotational speed
5.731975	* Rotational Speed
29.16083	* Feed Rate
15.72725	* Drill Diameter
-0.89208	* Rotational Speed * Feed Rate
-0.02729	* Rotational Speed * Drill Diameter
0.494444	* Feed Rate * Drill Diameter
-0.0376	* Rotational Speed^2

28.96667	* Feed Rate^2
-0.75033	* Drill Diameter^2

Analysis of Torque

The torque measured during drilling AISI 1045 steel with HSS drill bit is analyzed and the Table 4 shows the ANOVA model generated. It is observed that the model is significant and a quadratic model is suggested for the measured values.

Table 4.4.1 ANOVA Table for Torque

	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob > F	
Model	19.48793	9	2.165325	45.45545	< 0.0001	Significant
A-Rotational Speed	15.125	1	15.125	317.5106	< 0.0001	
B-Feed Rate	1.519896	1	1.519896	31.90632	0.0008	
C-Drill Diameter	0.061075	1	0.061075	1.282116	0.2948	
AB	0.632025	1	0.632025	13.26774	0.0083	
AC	0.237169	1	0.237169	4.978755	0.0609	
BC	0.017822	1	0.017822	0.374132	0.5601	
A^2	1.872234	1	1.872234	39.30275	0.0004	
B^2	0.004027	1	0.004027	0.084532	0.7797	

C^2	0.049499	1	0.049499	1.039102	0.3420	
Residual	0.333453	7	0.047636			
Lack of Fit	0.321504	3	0.107168	35.87456	0.0024	Not significant
Pure Error	0.011949	4	0.002987			
Cor Total	19.82138	16				

The Model F-value of 45.46 implies the model is significant. There is onlya 0.01% chance that a "Model F-Value" this large could occur due to noise.Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, AB, A^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Lack of Fit F-value" of 35.87 implies the Lack of Fit is significant. There is only a0.24% chance that a "Lack of Fit F-value" this large could occur due to noise.Significant lack of fit is bad -- we want the model to fit. The R-square value and R-square adjusted values obtained during ANOVA is given in Table 5.

Table4.4.2 R-square values during Torque analysis

Std. Dev.	0.218257		R-Squared	0.983177
Mean	3.323176		Adj R-Squared	0.961548
C.V. %	6.567728		Pred R-Squared	0.739537
PRESS	5.162739		Adeq Precision	23.8462

The "Pred R-Squared" of 0.7395 is not as close to the "Adj R-Squared" of 0.9615 as one mightnormally expect. This may indicate a large block effect or a possible problem with your modeland/or data. Things to consider are model reduction, response tranformation, outliers, etc."Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 23.846 indicates an adequate signal. This model can be used to navigate the design space. The second order quadratic model developed as suggested for predicting the torque is given below.

Table 4.4.3 Torque values

Torque	=
-2.40975	
0.20534	* Rotational Speed
4.358083	* Feed Rate
-0.30556	* Drill Diameter
-0.06625	* Rotational Speed * Feed Rate
0.004058	* Rotational Speed * Drill Diameter
-0.07417	* Feed Rate * Drill Diameter
-0.00167	* Rotational Speed^2
0.343611	* Feed Rate^2
0.012047	* Drill Diameter^2

The ramp plot showing the optimum values in the range of input parameters and the predicted output responses is given in Fig. The optimum input parameters for multiresponse optimization is rotational speed of 20 m/min, feed rate of 0.3mm/rev, and drill bit diameter of 8 mm. The predicted output responses are thrust force of 52.47 kN and torque of 0.77 N-m.

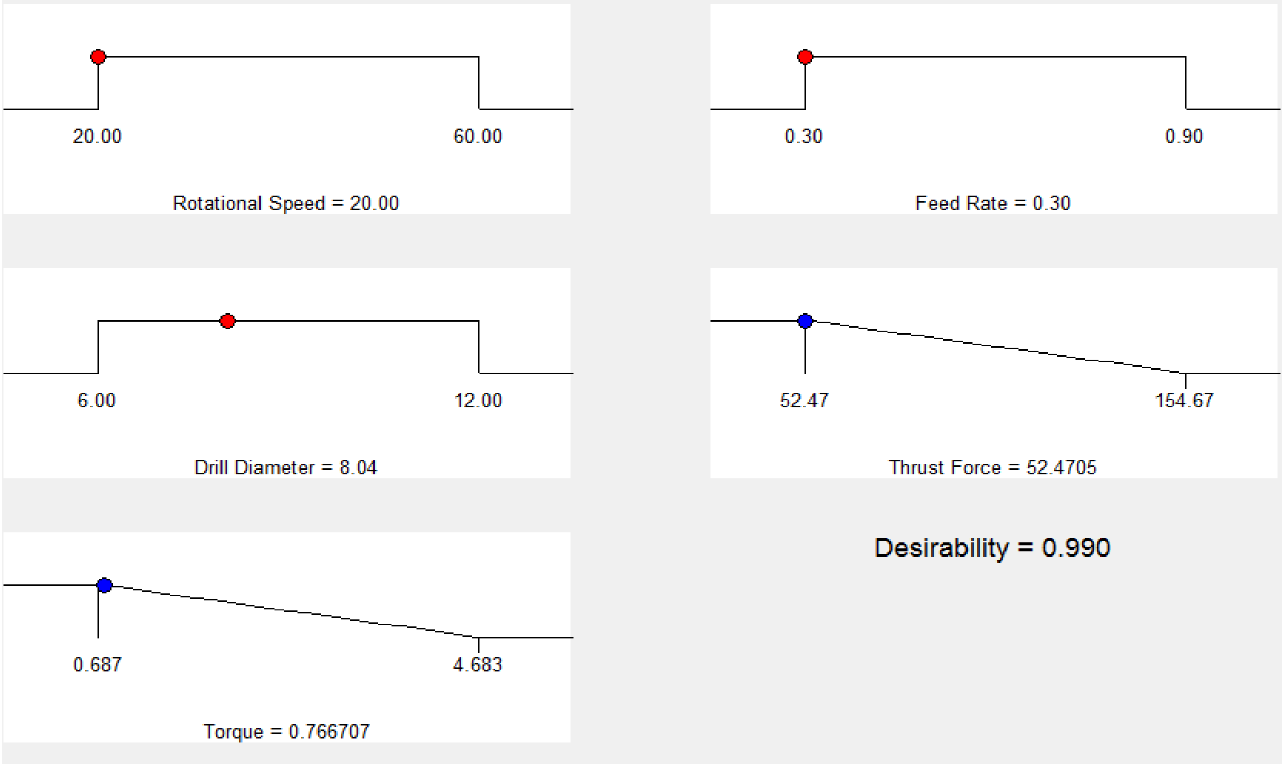

Fig4.5.1 Ramp plot for combined objective

CONCLUSION

The selection of best combination of drilling parameters for optimizing rotational speed, feed rate and drill bit diameter over the responses thrust force and torque is performed in this work. The following inferences are obtained from this analysis.

1. The optimized condition evolved is rotational speed of 20 m/min, feed rate of 0.3mm/rev, and drill bit diameter of 8 mm. The predicted output responses are thrust force of 52.47 kN and torque of 0.77 N-m.
2. The quadratic mathematical models for thrust force and torque are designed to correlate the dominant machining parameters. The developed mathematical models are well fitted with experimental values with a 95% interval.

3. The main significant factor that affects the thrust force is rotational speed and feed rate, whereas for torque, it is only the rotational speed. The optimum values obtained are all within the given constraints.

The results obtained would be useful and serve as a technical database for automotive industries for achieving betterquality and higher productivity.

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