



GRA & DFA Based Multi Objective Optimization during Turning of AISI D3 Steel Using CNMG Insert

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ABSTRACT

In the present day scenario of manufacturing industry, quality and productivity play a significant role. Surface roughness and material removal rate are indicators of quality and productivity as also interface temperature and flank wear are the indicators of tool life. Hence surface roughness, material removal rate, interface temperature and flank wear are considered as response characteristics. This article focuses on an approach based on Grey relational analysis and Desirability function analysis for optimizing the process parameters during turning of AISI D3 steel with CVD coated tool with multiple performance characteristics. Experimentation were carried out on a Conventional lathe using L9 orthogonal array based on Taguchi design of experiments. The influence of spindle speed, feed and depth of cut were analyzed on the performance of surface roughness, material removal rate, interface temperature and flank wear. The optimal turning parameters are determined by composite desirability index and grey relational grade. Analysis of variance (ANOVA) is used to determine the influence of parameters which significantly affect the responses simultaneously. From the study, it is concluded that machining performance is significantly improved.

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Introduction

The important goal in the modern industries is to manufacture the product with lower cost and with high quality in short span of time. There are two main practical problems that engineers face in a manufacturing process, the first is to determine the product quality (meet technical specifications) and the second is to maximize manufacturing system performance using the available resources. The challenge of modern machining industry is mainly focused on achievement of high quality, in terms of work piece dimensional accuracy, surface finish, high production rate, less wear on the cutting tools, economy of machining in terms of cost saving and increase the performance of the product with reduced environmental impact. Today metal cutting process places major portion of all manufacturing processes. Within these metal cutting processes the turning operation is the most fundamental metal removal operation in the manufacturing industry. Increase in productivity and the quality of the machined parts are the main challenges of metal based industry. There has been increased interest in monitoring all aspects of machining process. Surface finish and material removal rate are two important parameters are need to be considered in manufacturing industry to ensure aesthetic appeal to the product as well as improved productivity. Surface roughness has become the most significant technical requirement and is an index of product quality in order to improve the tribological properties, fatigue strength, corrosion resistance and aesthetic appeal of the product reasonably good surface finish is required. Now a day's manufacturing industries especially concerned to dimensional accuracy and surface finish. In order to obtain better surface finish and increased material removal rate, proper setting of cutting parameters is crucial before the process takes place factors such as spindle speed, feed

rate, depth of cut that control the cutting operation can be set up in advance. values of process parameters that will yield the desire In the present work, AISI D3 steel was selected as work material which finds applications in the manufacture of Blanking & Forming dies, press tools, punches, bushes, forming rolls and many more. For the purpose of experimentation, factorial design experiments are considered as per Taguchi DOE. By advocating Taguchi design, a clear understanding of the nature of variation and economical consequences of quality engineering in the world of manufacturing can be clearly got through. In the present study, Desirability function analysis and Grey relational analysis were performed to combine the multiple performance characteristics in to one numerical score which is an indicative of the optimal process parameter setting. Analysis of variance (ANOVA) is also performed to investigate the most influencing parameters on the surface roughness and material removal rate.

Literature review

W.H.Yang & Y.S Tang [1] envisages that the Taguchi method is a powerful tool to design optimization for quality and is used to find the optimal cutting parameters for turning operations. An orthogonal array, the signal to noise ratios and ANOVA are employed to investigate the cutting characteristics of S45C steel bars using Tungsten carbide cutting tools. Through this study, not only optimal cutting parameters for turning operations obtained, but also the main cutting parameters that affect the cutting performance in turning operations are found.

M.P. Jenarathanan & R. Jeyapaul[2] presents a new approach for optimizing machining parameters on milling glass-fibre reinforced plastic (GFRP) composites. Optimization of parameters was done by an analysis called desirability function

analysis(DFA) which is a useful tool for optimizing multi response problems. A composite desirability value is obtained for multi- responses viz., surface roughness. Delamination factor and machining force using individual desirability values from DFA. Based on composite desirability value, the optimum levels of parameters have been identified and significant contribution of parameters is determined by analysis of variance.

T.Saravanan & R. Udaykumar[3] presents the machining of hybrid metal matrix using a medium duty lathe. The optimum machining parameters have been identified by a composite desirability value obtained from desirability function analysis as the performance index and significant contribution of parameters can then be determined by analysis of variance.

P.S. Kao & H.Hocheng[4] explains the usefulness of Grey relational analysis for multi-input, discrete data and experimental study. Developed an application of grey relational analysis for optimizing the electro polishing of 316L stainless steel with multiple performance characteristics. The processing parameters(temperature, current density and electrolyte composition) are optimized with consideration of the multiple performance characteristics(surface roughness and passivation strength). The conducted experiments approve the effectiveness of the grey relational analysis.

S.Khalilpourazary etal[5] depicts the influencing parameters such as cutting speed, feed rate, depth of cut and tool rake angle on surface roughness and tool life. ST37 steel and M1 high speed steel (HSS) were selected as work piece material and tool respectively. Grey relational analysis was performed to elicit the optimal values for the mentioned data. To achieve this, grey relational generating, grey relational coefficient and grey relational grade are calculated step by step. Finally it was shown that ST37 led to high surface quality and tool life.

R.K.Suresh, P.Venkataramaiah and G.Krishnaiah[6] envisages an experimental investigation on turning of AISI 8620 alloy steel using PVD coated cemented carbide CNMG inset. Nine experimental runs based on Taguchi factorial design were performed to find out optimal cutting level condition. The main focus of present experimentation is to optimize the process parameters namely spindle speed, feed and depth of cut for desired response characteristics i.e. surface roughness, VMRR and interface temperature. To study the performance characteristics in this work orthogonal array(OA), analysis of means(ANOM) and analysis of variance(ANOVA) were employed. The experimental results showed that the spindle speed affects more on surface roughness, feed affects more on VMRR and feed affects more on interface temperature. Confirmation tests also been performed to predict and verify the adequacy of models for determining optimal values of response characteristics.

M.Y Wang & T.S. Lan[7] presents Orthogonal array of Taguchi experiment where in four parameters like cutting speed, feed rate, tool nose run off with three levels in optimizing the multi-objective such as surface roughness, tool wear and material removal rate in precision turning on CNC lathe. For the purpose of multi response optimization, Grey relational analysis was employed.

Bala Murugan Gopalsamy, etal[8] deals with experimental investigations carried out for machinability study of hardened steel and to obtain optimum process parameters by Grey relational analysis. An orthogonal array, grey relations, grey relational coefficients and analysis of variance are applied to study the performance characteristics of machining process parameters such as cutting speed, feed, depth of cut and width of

cut with consideration of multiple responses i.e., volume of material removed, tool wear and tool life.

Thaman Balgassim etal[9] conducted experimentation on EDM machine using AISI D3 tool steel. An L9 orthogonal array based on Taguchi method is used to conduct a series of experiments to optimize the EDM parameters. Experimental data were evaluated statistically by analysis of Variance(ANOVA). The experimental results have given optimal combination of input parameters which give the optimum surface finish of EDMed surface From the literature survey, it is evident that little work has been reported on AISI D3 steel work with combination of CVD coated cemented carbide tool. Also little work has been reported on Desirability function Analysis and Grey relational analysis simultaneously on various machining operations. Hence the experimentation is done on above said combination of work piece and tool and optimization method-Desirability function analysis and Grey relational analysis are put forth.

Experimentation

In the present study, three turning parameters were selected with three levels as shown in Table.1. The experimentation was carried out using L9 orthogonal array based on Taguchi design of experiments. The work material selected for this experiment is AISI D3 steel of 40 mm diameter, length 100 mm. The chemical composition of AISI D3 steel is given in Table.2

The turning tests were carried out on Kirloskar model centre lathe machine to determine the responses characteristics for various runs of experiment. Surface roughness is measured using "SVC 4500" surface roughness measuring instrument. The material removal rate (mm³/min) is calculated using formula:

$$MRR = [\pi/4(D_1^2 - D_2^2)L]/t \text{ mm}^3/\text{min}$$

Where, D_1 = Diameter of the work piece before turning,mm

D_2 = Diameter of the work piece after turning,mm

L = Length of turning, mm

t = Machining time, min

The tool-work interface temperature is read from Infrared pyrometer. The flank wear is calculated from Image measuring reader

Methods used

Desirability Function Analysis

Desirability function analysis is widely accepted method used in manufacturing industry. Desirability function analysis is used to convert multi response characteristics in to single response characteristic. Derringer and suich[10] popularized the concept of DFA as a simultaneous optimization technique which proved to be useful in solving multi response optimization problems. In view of this, complicated multi response characteristics can be converted in to single response characteristic which is termed as composite desirability. In the present study, multi responded such as surface roughness and material removal rate are combined as composite desirability using desirability function analysis

The steps involved in the optimization process are detailed as follows

Step 1: The first step is to calculate desirability index(d_i) for each of the process parameters i.e surface roughness and material removal rate. The desirability index values are tabulated. It is calculated based on the desirability function shown in equations (1) and (2) respectively for the cases smaller is better and larger is better. In this study, surface roughness need to be minimized and material removal rate need to be maximized.

Table 1

Element	carbon	silicon	Mn	Ni	Cr	Mo	S	P	Al	B
% composition	2.179	0.511	0.511	0.05	12.634	0.178	0.021	0.025	0.178	0.065

Table 2

Turning parameters	Level 1	Level 2	Level 3
Spindle speed, S(rpm)	450	710	1120
Feed, F(mm/rev)	0.05	0.071	0.09
Depth of cut, D(mm)	1.0	1.5	2.0

Table 3. Experimental data and results for 3 parameters, corresponding Ra and MRR for CVD tool

Expt No	Spindle speed(rpm)	Feed (mm/rev)	Doc(mm)	Surface roughness(μm)	Material removal rate(mm^3/min)	Interface temperature	Flank wear(mm)
1	450	0.05	1.0	0.44	1118.50	32.44	0.029
2	450	0.071	1.5	1.31	2942.97	39.46	0.015
3	450	0.09	2.0	0.84	4947.18	39.82	0.032
4	710	0.05	1.5	0.56	3074.13	33.66	0.017
5	710	0.071	2.0	1.65	4584.33	35.66	0.034
6	710	0.09	1.0	0.77	6037.10	38.12	0.007
7	1120	0.05	2.0	3.56	7608.05	36.82	0.019
8	1120	0.071	1.0	0.64	5422.40	36.12	0.120
9	1120	0.09	1.5	0.61	9643.32	40.54	0.250

Tables 4,5,6,7,8 and 9 depicts the results related with Desirability function analysis and Grey relational analysis

Table 4. Evaluated results of composite desirability

Expt No	Normalized values				Weighted desirable index				Composite desirability	Rank
	Surface Roughness	MRR	Temp	Flank wear	Surface roughness	MRR	Temp	Flank wear		
1	1.0000	0.0000	1.0000	0.9095	1.0000	0.0000	1.0000	0.9812	0.0000	7
2	0.7212	0.2140	0.1333	0.9671	0.9066	0.6296	0.6683	0.9933	0.3789	6
3	0.8718	0.4491	0.0889	0.8971	0.9596	0.7865	0.6163	0.9785	0.4551	5
4	0.9615	0.2294	0.8494	0.9588	0.9882	0.6429	0.9679	0.9916	0.6096	3
5	0.6122	0.4066	0.6025	0.8889	0.8631	0.7634	0.9036	0.9767	0.5815	4
6	0.8942	0.5769	0.2988	1.0000	0.9670	0.8479	0.7854	1.0000	0.6439	1
7	0.0000	0.7613	0.4593	0.9506	0.0000	0.9214	0.8559	0.9899	0.0000	8
8	0.9359	0.5049	0.5457	0.5349	0.9803	0.8146	0.8859	0.8824	0.6242	2
9	0.9455	1.0000	0.0000	0.0000	0.9833	1.0000	0.0000	0.0000	0.0000	9

Table 5. Response table for composite desirability

Process parameters	Average composite desirability				
	Level 1	Level2	Level3	Max-Min	Rank
Spindle speed(S)	0.2780	0.6116*	0.2081	0.4035	1
Feed(F)	0.2032	0.5282*	0.0.3663	0.3850	2
Depth of cut(D)	0.4227*	0.3295	0.3455	0.0932	3
Total mean value of the composite desirability = 0.3659					
*Optimum levels					

Table 6 . ANOVA based on Composite desirability

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F-ratio	Percent contribution
Spindle speed	2	0.2791	0.13955	1.34	42.31
Feed	2	0.1584	0.0792	0.76	24.01
Depth of cut	2	0.01491	0.00745	0.0720	2.26
Error	2	0.20719	0.1035		31.41
∑	8				100.000

Table 7. Grey relational analysis for surface roughness and material removal rate

Expt No	Normalized values				Grey relational coefficient				GRG	Rank
	SR	MRR	Temp	Flank wear	SR	MRR	Temp	Flank wear		
1	1.0000	0.0000	1.0000	0.9095	1.0000	0.3333	1.0000	0.8467	0.7950	2
2	0.7212	0.2139	0.1333	0.9671	0.6420	0.3887	0.3658	0.9383	0.5837	9
3	0.8718	0.4491	0.0889	0.8971	0.7959	0.4758	0.3543	0.8293	0.6138	5
4	0.9615	0.2294	0.8494	0.9588	0.9285	0.3935	0.7685	0.9239	0.7536	3
5	0.6122	0.4066	0.6025	0.8889	0.5632	0.4573	0.5571	0.8182	0.5989	8
6	0.8942	0.5769	0.2988	1.0000	0.8254	0.5417	0.4163	1.0000	0.6959	4
7	0.0000	0.7613	0.4593	0.9506	0.3333	0.6769	0.4804	0.9101	0.6002	7
8	0.9359	0.5049	0.5457	0.5350	0.8864	0.5025	0.5239	0.5181	0.6077	6
9	0.9455	1.0000	0.0000	0.0000	0.9017	1.0000	0.3333	1.0000	0.8088	1

Table 8. Response table for Grey relational grade

Process parameters	Average relational grade				
	Level 1	Level2	Level3	Max-Min	Rank
Spindle speed(S)	0.6642	0.6828*	0.6722	0.0186	3
Feed (F)	0.7163*	0.5968	0.7062	0.1195	1
Depth of cut(D)	0.6995	0.7154*	0.6043	0.1111	2
Total mean value of the Grey relational grade = 0.6731					
*Optimum levels					

Table 9. ANOVA based on Grey relational grade

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F-ratio	Percent contribution
Spindle speed	2	0.00049	0.00024	0.00265	0.7329
Feed	2	0.0263	0.01315	1.425	39.342
Depth of cut	2	0.0216	0.0108	1.170	32.311
Error	2	0.0185	0.00923		27.614
∑	8				100.000

Table 10. Comparison of predicted and Experimental results using GRA and DFA

GRA	Optimum process parameters		
	Initial process parameters	Predicted values	Experimental values
Level of parameters setting	S1-F1-D1	S2-F1-D2	S2-F1-D2
Surface roughness (µm)	0.44	1.033	0.56
MRR (mm ³ /min)	1118.50	3634.892	3074.13
Temperature(0c)	32.44	34.07	33.66
Flank wear(mm)	0.029	0.0187	0.017
Grey relational grade	0.7950	0.7683	0.7536
DFA			
Level of parameters setting	S1-F1-D1	S2-F2-D1	S2-F2-D1
Surface roughness (µm)	0.44	0.50337	0.52
MRR (mm ³ /min)	1118.50	2990.425	3140.89
Temperature(0C)	32.44	34.53	32.97
Flank wear(mm)	0.029	0.01139	0.0108
Composite desirability	-	0.8308	0.6337

Step 2: The second step is to evaluate the composite desirability based on equation (3)

Step 3: The third step is to determine optimality condition based on highest composite desirability index. Also the ranking of process parameters is estimated.

Step 4: The next step is to perform ANOVA by which contribution made by each parameter influencing the combined objective is estimated

Step 5: The last stage is to calculate the values from conformity test based on optimum level of parameters is found out.

For smaller is better,

$$d_i = \frac{y_i - y_{max}}{y_{min} - y_{max}} \tag{1}$$

For larger is better,

$$d_i = \frac{y_i - y_{min}}{y_{max} - y_{min}} \tag{2}$$

where d_i is desirability index for a particular level

y_i is i^{th} normalized value

y_{min} is minimum of particular column values(response characteristic)

y_{max} is maximum of particular column values(response characteristic)

$$dc = \sqrt[w_1]{d_1^{w_1}} \sqrt[w_2]{d_2^{w_2}} \sqrt[w_3]{d_3^{w_3}} \dots \dots \dots \sqrt[w_n]{d_n^{w_n}} \tag{3}$$

where w_1 and w_2 are the weights assigned. Since both surface roughness and material removal rate plays a significant role in improving productivity and quality of the product during machining operation, more weightages are assigned to surface roughness and material removal rate. The weights assigned are : for surface roughness, $w_1=0.3$, for MRR, $w_2=0.3$, for temperature $w_3=0.2$, for flank wear $w_4=0.2$

Grey relational analysis

In the procedure of GRA, the experimental result of surface

roughness, material removal rate, interface temperature and flank wear are normalized at first in the range between zeros to one due to different measurement units. This data pre-processing step is termed as ‘grey relational generating’. Based on the normalized experimental data, grey relational coefficient is calculated to correlate the desired and actual experimental data using equation (4). The overall Grey Relational Grade (GRG) is determined by averaging the grey relational coefficient corresponding to selected responses using equation (5). This approach converts a multiple response process optimization problem into a single response optimization by calculating overall grey relational grade. The normalized experimental results can be expressed as follows.

For larger is better,

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}$$

For smaller is better,

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$$

Where $\max y_i(k)$ and $\min y_i(k)$ are the largest and smallest values of $y_i(k)$ respectively

The Grey relational coefficient $\xi(k)$ for $y_i(k)$ is calculated as

$$\xi(k) = \frac{\Delta \min + \psi \Delta \max}{\Delta o_i(k) + \psi \Delta \max} \dots \dots \dots \tag{4}$$

where $\Delta o_i(k)$ is reference sequence deviation which is equal to $\text{mod}(\max y_i(k) - y_i(k))$

ψ is a distinguishing coefficient which varies from 0 to 1, the value of ψ is set as 0.5 to maintain equal weightage of surface roughness and material removal rate.

Grey relational grade, $\gamma_i =$

$$\frac{1}{n} \sum_{i=1}^n \xi_i(k) \dots \dots \dots \tag{5}$$

Results

A series of turning tests were conducted to assess the effect of turning parameters on surface roughness and material removal rate and the results of experimentation are shown in table(3)

Prediction at optimum levels

The objective of the prediction at optimum levels is to validate the conclusions drawn during the analysis phase. Once the optimal level of process parameters is selected, the next step is to verify the improvement in response characteristics using optimum level of parameters. A conformity test is conducted using the following equation:

$\gamma = \gamma_m + \sum_{i=1}^n \gamma_i - \gamma_m$, where γ_m is total mean of the required responses

γ_j is the mean of the required responses at optimum level

n is the number of process parameters that significantly affects the multiple performance characteristics

Conclusions

Grey relational analysis

1. The optimal parameters setting with Grey relational analysis lies at 710 rpm spindle speed, 0.05 mm/rev feed and 1.5 mm depth of cut. The optimum predicted value for surface roughness is 1.033 μ m, MRR 3634.892 mm³/min, interface temperature 34.07^oC, flank wear 0.0187 mm and grey relational grade is 0.7683. Also the experimental value for surface roughness is 0.56 μ m, MRR is 3074.13 mm³/min, interface temperature 33.66^oC, flank wear 0.017 mm and grey relational grade is 0.8912.

2. In case of Grey relational analysis, it is found that both predicted and experimental response characteristics are better as compared to initial machining parameters. To be specific predicted surface roughness(1.033 μ m) and experimental surface roughness (0.56 μ m) are slightly higher than surface roughness at initial setting level which is undesirable which are combated by other responses. Also predicted MRR (3634.892 mm³/min) and experimental MRR(3074.13 mm³/min) are much higher as compared to MRR at initial setting level. Also predicted flank wear (0.0187 mm) and experimental flank wear (0.017 mm) are lower than the initial setting level which signifies tool wear is minimized which substantially increases tool life. It may be noted that there is a good agreement between the predicted GRG (0.7683) and experimental GRG(0.7536) and therefore the condition S2-F1-D2 of process parameters combination was tested as optimal. Further significant improvement in machinability is observed and measured that there is substantial improvement in material removal rate(Experimental value), 42% improvement in flank wear (Experimental value) as compared with initial machining parameters. This encourages applying Grey relational analysis for optimizing multi response problems.

3. Further, from Analysis of variance (ANOVA) depicts that feed is the most significant parameter followed by depth of cut affecting multi response characteristics with feed 39.342%, depth of cut 32.311% and speed almost negligible.

Desirability function analysis

4. The optimal parameters setting with Desirability function analysis lies at 710 rpm spindle speed, 0.071 mm/rev feed and 1.0 mm depth of cut. The optimum predicted value for surface roughness is 0.50337 μ m, MRR 2990.425 mm³/min, interface temperature 34.53^oC, flank wear 0.01139 mm and composite desirability is 0.8308. Also the experimental value for surface roughness is 0.52 μ m, MRR is 3140.89 mm³/min, interface temperature 32.97^oC, flank wear 0.01139 mm.

5. In case of Desirability function analysis, it is found that both predicted and experimental response characteristics are better as

compared to initial machining parameters. To be specific predicted surface roughness(0.50337 μ m) and experimental surface roughness (0.52 μ m) are slightly higher than surface roughness at initial setting level which is undesirable which are combated by other responses. Also predicted MRR (2990.425 mm³/min) and experimental MRR(3140.89 mm³/min) are much higher as compared to MRR at initial setting level which is highly desirable to productivity. It may be noted that there is a good agreement between the predicted Composite desirability (0.8308) and experimental Composite desirability(0.6337) and therefore the condition S2-F2-D1 of process parameters combination was tested as optimal. Further significant improvement in machinability is observed and measured that, there is substantial improvement in material removal rate(Experimental value as well as predicted values) as compared with initial machining parameters and at the same time there is a 62% improvement in flank wear (Experimental value) and 60% improvement in flank wear (Predicted value)as compared with initial setting. This encourages applying Composite desirability analysis for optimizing multi response problems.

6. Further, from Analysis of variance(ANOVA) depicts that speed signifies the most followed by feed affecting multi response characteristics with speed 42.31%, feed 24.01% and depth of cut 2.26% respectively

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