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Application of RSM with Grey Relational analysis in metal cutting for Multi-response quality characteristics

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Abstract- Application of RSM with grey relational analysis for modeling and optimizing the machining parameters with considerations of the multi-response (chip-tool interface temperature, main cutting force and tool wear rate) is introduced. Various machining parameters, such as the cutting speed, feed rate, and depth of cut and effective tool nose radius are considered. Composite factorial design (2^4+8) is used for the experimentation. Multiple response values are obtained using actual experimentation. Optimal machining parameters are determined by the grey relational grade obtained from the grey relational analysis for multi-performance characteristics. Analysis of variance (ANOVA) for the grey relational grade is implemented. The results showed good agreement with the experimental result.

Keywords – Metal cutting, Response surface methodology, Grey relational analysis, Multiple-optimization

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I. INTRODUCTION

Metal cutting operations (Turning) are widely used in workshop practice for applications carried out in conventional machine tools, as well as in NC and CNC machine tools, machining centers and related manufacturing systems in many industries, especially in automotive industry. In order to improve process efficiency, reduce the machining cost, and improve the quality of processed parts, it is necessary to select the most appropriate machining conditions. Therefore, it is valuable to increase tool life, to improve surface accuracy, to reduce main cutting force, tool wear rate, and machining zone temperatures (chip-tool interface temperature) in turning operations through an optimization study.

Usually, in metal cutting operation the main cutting force is the largest force as compared to feed force and radial force [1]. When cutting speed increases both cutting force and feed force are tend to decrease, for most of the metallic parts cut with carbide tools. Trent [2] attributes such behavior partly to the softening effect of the work piece material, due to temperature increase, and partly to the decreasing of the chip-tool contact length.

One of the most important phenomenons occurring during the machining process is that heat generation in the machining zone. Many researchers, Shaw [3], Komanduri Hou [4] and Stephenson [5,6], among them, agree that most of the energy applied to the cutting process is converted into heat in the machining zone of plastic deformation. The cutting temperature is a key factor which directly affects cutting tool wear, workpiece surface integrity, main cutting force and machining precision according to the relative motion between the tool and workpiece. RSM is a dynamic and foremost important tool of design of experiment (DOE), wherein the relationship between responses of a process with its input decision variable is mapped to achieve the objective of maximization or minimization of the response properties [7]. Many machining researchers have used response surface methodology to obtain their experiments and asses results. Kopac et al. [8],

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Abhang et al. [9] investigated the use of response surface methodology (RSM) in developing a surface roughness prediction model. Paulo [10] studied the influence of cutting conditions on the surface finish obtained by turning, using the Taguchi techniques. Hari Singh et al [11] developed the mathematical models for predicting surface roughness and tool life of En-24 steel during turning operation using coated tungsten carbide tool. The parameters considered were cutting speed, feed rate and depth of cut. Nihat Tosun [12] used the grey relational analysis technique and determined the optimum drilling process parameters. Kao et al [13] obtained grey relational grade using grey relational analysis while electrochemical polishing of the stainless steel. The grey relational analysis based on grey system theory can be used for solving the complicated interrelationships among the multi-responses [14, 15, 16]. A grey relational grade is obtained to evaluate the multiple responses. As a result, optimization of the multiple responses can be converted into optimization of a single relational grade. To the best of knowledge of the authors, there is no published work evaluating the optimization and the effect of metal cutting parameters on the multi-performance characteristics in turning process by using grey relational analysis.

II. EXPERIMENTAL PROCEDURE

In this investigation, a commercial alloy steel work piece (EN-31 steel alloy) is machined on heavy duty lathe machine (LTM-20) with tungsten carbide tools under flooded lubricant machining. The work piece material used has a dimension of 400 mm in length and 50 mm in diameter. This material is suitable for a wide variety of automotive type applications. The cutting tools used for experimentation were CNMA 120404, CNMA 120408, CNMA 120412 and diamond shape carbide. The tool holder used for experimentation was WIDAX SCLCR 12, Fo9 (ISO-designated). A detailed survey has been carried out to find out the metal cutting parameters, namely cutting speed, feed rate, depth of cut, and tool nose radius of the single point cutting tool were selected for experimentation. The range of each parameter is set at three different levels, namely low, middle and high based on industrial practice as shown in Table1. Factorial design with eight added centre points (2^4+ 8) used in this work is a composite design. The complete design consists of 24 experiments.

The cutting temperature is measured using tool-work thermocouple designed, fabricated and calibrated in the Mechanical Engineering lab, AMU, ALIGARH [6]. On line measurement of cutting forces and chip-tool interface temperature are carried out using lathe tool dynamometer and tool work thermocouple respectively. Tool wear weight 'W' is measured on a sensitive single pan balance (maximum) 300 gram and minimum scale is 0.01 milligram). Tool inserts were properly cleaned before weighing so that dust or any other adhered particles are removed. Experimental design values of process parameters along with average values of chip-tool interface temperature, main cutting force and tool wear rate are measured and used for analysis.

Table 1. Levels of the independent variables And coding identification

Levels	V (m/min)	F (Mm/rev.)	D (mm)	R (mm)	Code
High	189	0.15	0.6	1.2	+1
Middle	112	0.10	0.4	0.8	0
Low	39	0.06	0.2	0.4	-1

III. RESULTS AND ANALYSIS

A statistical software program, Mini-Tab-15 and Microsoft excel (MS Office-2007) were employed in models training [14]. The analysis of variance is used to check the adequacy of the predictive model. It is to be noted from the final equations that some of the coefficients are not considered. Only significant parameters and their coefficients are included in the final

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equation. The remaining insignificant parameters are omitted. The final forms of these models are shown in equation(1-3).

$$T = 31.779 + 2.033\,v + 766\,f + 253.783d - 57.083\,r - 0.003\,v^2 + 0.444\,vf - 0.717\,vd + 0.104\,vr - 305.556fd + 201.389fr - 4.688dr \quad (1)$$

$$Fc = 98.822 - 0.141\,v + 558.428\,f + 134.651d + 5.192\,r - 0.507vf - 0.089vd + 0.092vr + 261.806fd + 106.250fr + 15.938dr \quad (2)$$

$$Tw = -0.13081 + 0.00084\,v + 0.96250f + 0.19223\,d + 0.01513r + 0.00001v^2 + 0.01620vf + 0.00042\,v\,d - 0.00055\,vr - 1.40972\,fd + 0.09375fr - 0.02422dr \quad (3)$$

3.1. Multi-objective optimization by grey relational analysis

The multiple performance characteristics were evaluated using grey relational analysis [15]. In this study the optimization of multiple performance parameters can be converted into optimization of single grey relational grade. The following procedures were used for grey relational analysis [14].
[a] Identify and evaluate the machining parameters, [b] to determine the number of levels of machining parameters, [c] selecting factorial design and assign the machining parameters, [d] conducting the experiment based on factorial design, [e] Normalize the experimental results of cutting temperature, cutting force and tool wear rate, [f] Perform the grey relational analysis and determine the grey relational coefficient, [g] analyzing the experimental data by using the grey relational grade, and [h] selecting the optimal levels of machining parameters.

The grey relational coefficients of cutting temperature, main cutting force and tool wear rate which are determined by using grey relation analysis are shown in Table 2. The grey relational grades were calculated as shown in Table 2. Thus, the optimal design was performed with respect to a single grey relational grade rather than the complicated performance characteristics. The higher the grey relational grade represents that the experimental result is closer to the ideally normalized value. In this work experiment 2 has the best multi-response characteristics among the 24 experiments conducted (Table 2). The larger the value of the grey relational grade, the better is the multi-response characteristics. The average grey relational grade for each level of the machining parameters is.
Level1 (cutting speed) = 1/8 (0.8697 + 0.9083 + 0.6963 + 0.7163 + 0.664 + 0.647 + 0.5387 + 0.5393 = 0.69745

Figure1 shows the grey relational grade obtained for different turning parameters. Thus, larger grey relational grade is desired for optimum performance. Therefore, the optimal level of machining parameters setting for controlling cutting temperature, main cutting force and tool wear is (V1, F_1, D1, and R1) as shows in figure.1. Optimal level of the turning parameters is the level with the highest grey relational grade. Therefore, experiment 2, as shown in table 2 may be considered as very close to fit the optimal process conditions.

Table 2. Grey relational coefficients with grey relational grades

Exp No	Temp-erature	Cutting force	Tool wear	Grade relational grade
1	0.826	0.801	0.982	0.8697
2	1.00	0.737	0.988	0.9083
3	0.573	0.534	0.982	0.6963
4	0.686	0.463	1.000	0.7163
5	0.617	0.549	0.826	0.6640
6	0.642	0.468	0.832	0.6470

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7	0.478	0.366	0.772	0.5387
8	0.506	0.333	0.779	0.5393
9	0.429	1.000	0.466	0.6316
10	0.448	0.755	0.523	0.5753
11	0.388	0.586	0.424	0.4660
12	0.403	0.489	0.449	0.4470
13	0.347	0.611	0.335	0.4310
14	0.363	0.498	0.343	0.4013
15	0.333	0.425	0.333	0.3636
16	0.338	0.355	0.357	0.3500
17	0.465	0.512	0.577	0.5180
18	0.466	0.501	0.597	0.5213
19	0.460	0.552	0.606	0.5393
20	0.455	0.523	0.543	0.5070
21	0.439	0.545	0.643	0.5423
22	0.450	0.530	0.592	0.5240
23	0.477	0.535	0.593	0.5350
24	0.446	0.522	0.593	0.5203

Table 3. Analysis of variance for machining parameters

Source	Df	SS	MS	F - value	P- value
Model	11	0.439028	0.039912	213.61	0.000 s
Linear	4	0.403600	0.020666	110.61	0.000 s
Square	01	0.022215	0.022244	119.05	0.000s
Interact	06	0.013212	0.002202	11.79	0.000s
Residual error	12	0.002242	0.000187	-	-
Lack-of fit	05	0.001235	0.000247	1.72	0.249 ns
Error	07	0.001007	0.000144	-	-
Total	23	0.441270	-	--	-

(Df- degree of freedom, SS- sum of square, Ms- Mean square, S -significant and ns- not significant)

Table 4. ***Results of cutting performance using initial And optimal cutting parameters***

Design condition	Best combination	Chip-tool interface temperature(0c)	cutting force (N)	Tool wear rate
Initial design	$V_0F_0D_0R_0$	322.00	219.98	0.335
Optimal design	$V^- F^- D^- R^-$	180.00	166.78	0.054
Final gain	-	142.00	53.20	0.281

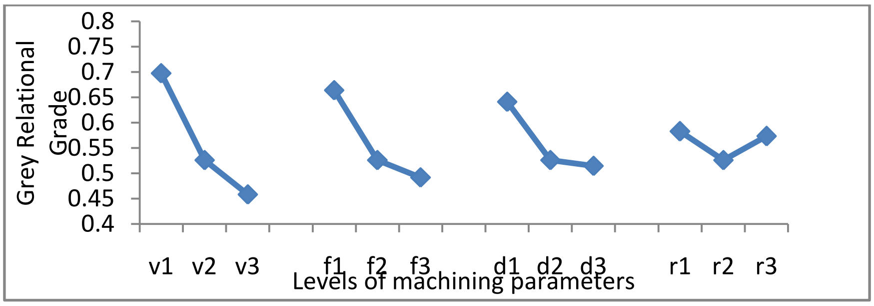

Figure 1. Effect of turning parameters on grey relational grade (1, corresponds low level factors, 2, corresponds middle level factors and 3 corresponds higher level factors)

3.2 Analysis of variance

From figure (1) of the grey relational grade for various levels, it can be visually understood about to be significance of each parameter. It can visually understood that the p-value of quadratic model

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(Table 3) is less than 0.05, which means model is significant at 95% confidence level. All interaction terms are significant since its p-value is less than 0.05. From statistical analysis it known that p-value less than 0.05 shows that specific parameter has significant effect on process and also p-value between 0.05 and 0.1 shows the low significant parameter. If the p-value is more than 0.1 it understood that the specific parameter has not significant effect on machining process. The analysis of variance result for this study indicates that cutting speed, feed rate depth of cut and nose radius are significant, while two other main machining parameters means feed rate and depth of cut as well as interaction effect of speed and feed, feed and depth of cut and square of speed are most significant affecting the multi-performance process response. As it can be seen from Table 3, the conceptual approach for grey relational analysis is confirmed by the analysis of variance analysis.

IV. CONFIRMATION TEST

The conformation results are shown in Table 4. From the Table 4 it is evident that the optimum combination of machining parameters obtained by the grey relational multi-performance optimization technique (using grey relational analysis coupled with response surface method) gives much improvement in all the machining characteristics compared to the initial design experiments, the chip-tool interface temperature decreases from 322^0c to 180^0c, main cutting force decreases from 219.98 N to 166.78 N and tool wear rate decreases from 0.335mg/min to 0.054 mg/min. From confirmation test it is observed that the proposed algorithm for solving the optimal combinations of the turning parameters control the chip-tool interface temperature, main cutting force and tool wear during turning of En-31 steel alloy.

V. CONCLUSIONS

Emprical models were developed for chip-tool interface temperature, main cutting force and tool wear rate in machining of En-31 steel material. The turning parameters were selected for the models were cutting speed, feed rate, depth of cut, and tool nose radius. The constants and coefficients in these models were determined by using the results of designed experiments. In addition, a multi-objective performance characteristic was calculated called as grey relational grade by using grey relational analysis.The study of grey relational graph for turning parameters shows that the cutting speed, feed rate , depth of cut and nose radius are significant, while two other main machining parameters means feed rate and depth of cut as well as interaction effect of speed and feed, feed and depth of cut and square of speed are most significant affecting the multi-performance process response. While the greater grey relational grade is the best, so level 1(low) for cutting speed, level 1 (low) for feed rate, level1 (low) depth of cut,and tool nose radius (low) is proposed. It means selecting these levels for turning parameters, it result the minimum tool wear rate, main cutting force and chip-tool interface temperature. It is shown that the performance characteristics of the turning are improved together by using the method proposed by this study. Grey relational grade was found to be significantly affected by cutting speed, feed rtae, depth of cut and tool nose radius during steel turning process.

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