Off-line Multicritera Optimization of Creep Feed Ceramic Grinding Process

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ABSTRACT

The objective of this study is to optimize the responses of the creep feed ceramic grinding process simultaneously by an off-line multicriteria optimization methodology. The responses considered as objectives are material removal rate, flexural strength, normal grinding force, workpiece surface roughness and grinder power. Alumina material was ground by the creep feed grinding mode using superabrasive grinding wheels. The process variables optimized for the above objectives include grinding wheel specification, such as bond type, mesh size, and grit concentration, and grinding process parameters, such as depth of cut and feed rate. A weighting method transforms the multi-objective problem into a single-objective programming format and then, by parametric variation of weights, the set of non-dominated optimum solutions are obtained. Finally, the multi-objective optimization methodology was tested by a sensitivity analysis to check the stability of the model.

I. Introduction

Due to extraordinary characteristics, such as high hardness, high compressive strength, high temperature resistance, high wear and corrosion resistance, lower specific weight, superior electrical properties, high magnetic permeability, specific optical and conductive properties, advanced ceramics are one of the materials that have received the greatest amount of attention from automotive, aerospace, and electric industries [1-3].

Creep feed grinding deals with large depth of cut and lower work feed, while in the conventional grinding mode, the workpieces are ground by small depth of cut and high feed rate. Little previous research has utilized the creep feed grinding process to successfully machine ceramics for mass production [4-5]. Konig and Wemhoner [6] have compared the performances between conventional grinding and creep feed grinding for ceramic material. From the results reported in [6], it appears that creep feed grinding is better than conventional grinding. The reason is: since the major difference between these two processes is the size of the contact area between the grinding wheel and workpiece, the chip thickness of the individual grain is generally smaller in the creep feed grinding process, which results in material removal without brittle cracking. From the concept of indentation fracture mechanics [7], this characteristic feature is very important for ceramic grinding.

As Liao and Sathyanarayanan [8] pointed out, the diamond is the best abrasive material to be used to grind ceramics because of its unique properties: it is inert to react with or dissolve in the ionically bonded constituents founds in ceramics; and it possesses the highest hardness and wear resistance among abrasive materials, and higher thermal conductivity. Therefore, the creep feed grinding mode with diamond grinding wheels is the candidate for optimizing the ceramic grinding process.

Figure 1 shows the inputs and outputs of a creep feed ceramic grinding process. For the process engineers, they usually face the following problems: how to select the optimum specifications of grinding wheel and process parameters so that the workpiece can have maximum flexural strength and material removal rate, minimum grinding force, grinder power, and surface roughness. But these objectives conflict since improving one may require sacrificing at least another, for example, improving the flexural strength requires lower normal grinding force which will decrease the material removal rate. Hence, the compromise among a set of conflicting objectives has to be achieved.

From the previous research, the multi-objective optimization methodology was applied to optimize the different machining processes. Sundaram [9] has showed the use of the goal programming technique in selecting the levels of machining parameters for a fine single point turning operation on AISI 4140 steel using cemented tungsten carbide tools. Ghiassi et al [10] provided a multi-criteria decision model to formulate the problem of machining 390 die cast aluminum alloy. Srinivas et al [11] have applied the non-linear goal programming technique to optimize the process parameters of Electrical Discharge Machining (EDM). Ilhan et al [12] have formed a non-linear integer multi-objective model to optimize the Electrochemocal Grinding (ECG) process.

As the above discussion and survey pointed out, since all the research focused on metal cutting and nontraditional process, such as EDM and ECG, and not on the ceramic grinding, and since all sectors of the industry have been attracted to ceramics. These developments motivate the need to undertake this optimization study for ceramic grinding. In this paper, by incorporating the multiple regression technique to obtain the empirical model for each objective, the creep feed ceramic grinding process was formed by multi-objective techniques in order to compromise among five objectives. Then, based on a weighting method, the set of non-dominated optimum operation parameters was obtained. Finally, a sensitivity analysis of the multi-objective model was undertaken to check the effectiveness of this model.

II. Experimental Design and Procedures

A creep feed grinding experiment was performed in a down grinding mode on the JUNG JF 520 surface-grinding machine. The experimental setup is shown in Figure 2. Grinding conditions are given in Table 1. In this study, the related variables were considered and the evaluations of the effect and interaction of these variables are included in order to optimize the ceramic grinding process. Three grinding wheel specifications: bond type (B), mesh size (M) and grit concentration (C), and two grinding process parameters: feed rate (F) and depth of cut (D) were selected. A 2^{5-1} fractional factorial experimental design with two replicates was applied to screen the effects of these variables and their interactions. The experimental conditions are shown in Table 2.

The experiment was sequentially executed as follows: 1. The wheels were trued to ensure the concentricity of the wheel with a brake truing device; a silicon carbide truing wheel was used for this purpose; 2. The wheel was then dressed with aluminum oxide in order to open it up; 3. The wheel was stabilized by grinding two layers of alumina block to a thickness of 0.12 inch; 4. The force data was collected with a Norland Spectrum Analyzer, and power was noted from the Ampere Meter attached to the grinder while grinding the specimen; 5. The roughness of ground workpieces were measured by a Perthern SP5 profilometer; 6. The flexural strengths were obtained by conducting a four-point bending test on an Instron Universal Test Machine, Model 1011, at a crosshead speed of 0.1 mm/min. Breaking loads were automatically recorded by a microcomputer.

III. Multi-objective Models

(a) Empirical Models

The significant variables and their interactions were determined by the analysis of variance (ANOVA) tests for each response of the creep feed grinding process. The significant values for the above ANOVA test were set to 0.05. The significant effects on the response models were considered and modeled into empirical models by multiple regression analysis at 95% confidence intervals. These models form the basis for the optimization of the ceramic creep feed grinding process. The physical explanation for these models has been discussed in the previous research [13-14]. The regression empirical models of the grinding system are:

Flexural Strength [Kpsi] = 43.994 - 1.09*B + 0.173*F + 2.19E-4*M*C - 3.01E-3*M*F-6.46E-4*C*F + 2.538E-1*M*D - 3.333E-1*C*D

Normal Grinding Force [lb/in] = 1.505*M + 1.97*C - 1.658E-2*M*C - 9.83*F - 918.97*D - 3.92E-2*M*F + 1.276E-1*C*F + 285.777*F*D -1.117*C*B - 0.343*M*B + 60.936*B

Surface Roughness [m] = 5.706 - 1.347E-3*M - 1.54E-3*C + 1E-5*M*C + 1.268E-3*F - 3.374E-3*C*D + 3.4E-2*F*D + 7.1E-5*C*B

Grinding Power [Hp/in] = 6.78E-2*M + 1.623E-2*C - 5.4E4*M*C - 4.7E-1*F + 3.742E-3*C*F + 28.085*D*B - 28.491*D - 4.05E-1*M*D +2.077E-1*F*B + 6.252*F*D - 4.138*B

The material removal rate is the product of feed rate and depth of cut, and its unit is in 3 /min-in.

(b) Objectives

From Figure 1, the outputs of the grinding system are material removal rate, flexural strength, normal grinding force, surface roughness, and grinder power. These five outputs form the objectives of the present study, and the importance of these objectives to the grinding system will be discussed.

Material Removal Rate: Productivity plays the most important role for competitive industry. A high material removal rate will achieve this goal. But an increase in normal grinding force, coarseness of surface roughness, and grinder power, and a decrease in flexural strength suffer from this high material removal rate.

Flexural Strength: Reliability is one of the main goal for ceramic products, since all kinds of machining processes will introduce the crack or subsurface crack into ceramic components. The high and dense distribution of the flexural strength is the optimum goal.

Normal Grinding Force: Based on the indentation fracture mechanisms [7] discussed later, the normal grinding force is a critical factor for ceramic workpieces, since it determines the type of material removal mechanism, namely, plastic deformation or brittle fracture.

Surface Roughness: The requirement of the surface roughness of a component must be met in engineering design for achieving a good performance between the components. A coarser surface roughness causes the deterioration in accuracy. But a too fine surface roughness increases the manufacturing cost. Hence, the optimum surface roughness should be specified in order to compromise this dilemma.

Grinder Power: The grinder power is constrained by the equipment capacity, which comes with a price. The more powerful the equipment, the more expensive it is going to be.

(c) Constraints

In this study, as Table 2 shows, the specifications of the superabrasive grinding wheels, such as bond type, mesh size, grit concentration, and the creep feed grinding process parameters, such as feed rate, depth of cut, should be constrained, and these three specifications of grinding wheel are integer. Besides, the limit for the surface roughness of ground workpiece provided from the design engineers and the power limitation should be offered.

There are two approaches to investigate the material removal mechanism of the ceramic grinding process, namely, the "machining" approach and the "indentation fracture mechanics" approach [7,15]. The detailed discussion is in [13]. Basically, this study totally follows the indentation fracture mechanics approach, which considers grinding operation as analogous to continuous indentation by a series of indenters. Two principal crack systems are introduced by a sharp indenter: medial/ radial cracks and lateral cracks, as shown in Figure 3. Lateral cracks are assumed to be mainly responsible for material removal due to interaction with abrasives, while medial/radial cracks are associated with strength degradation. The material removal mechanism is dependent on the normal force on each cutting edge: namely, when this normal force is less than a minimum threshold force, the material removal mechanism is due to plastic deformation. Otherwise, brittle fracture will dominate.

From the above analysis, the constraint, i.e. the normal grinding force associated with each cutting edge (unit load) being less than the minimum threshold load, is required. From [12], the minimum threshold load for alumina is 0.46 lb/in and the regression empirical model for unit load is:

$$\text{Unit Load [lb/edge-in]} = 3.796E\text{-}3*M + 7.646E\text{-}3*C + 8.287E\text{-}3*F + 1.868*D - 3.559E\text{-}1*B - 7.1E5*M*C + 3.415E\text{-}3*F*B$$

(d) Multiple Objective Function

As Figure 1 shows, there are five outputs from the grinding system. As the above section discussed, the maximum material removal rate and flexural strength, and minimum normal grinding force, surface roughness, and grinder power are the objectives of the present study. This multiple objective function (MOF) can be written as:

MOF = Max (Material Removal rate) + Max (Flexural Strength) + Min (Normal Grinding Force) + Min (Surface Roughness) + Min (Grinder Power)

Each objective has different value range. For example, the value of the normal grinding force is larger, and the value of the surface roughness is smaller, therefore, normalization is required to remove the scale effect [16-17]. Each single objective function is transformed into a [0,1] domain and the normalization variable (U) is defined as:

$$U = (R - min)/ Delta$$

Where: R is the output value; min is the minimum value of the empirical model; Delta is the different of the maximum and minimum of the empirical model. The normalization variable for each objective function is:

MRR = material Removal Rate - 0.3944 / 1.258

FLX = Flexural Strength - 37.35 / 11.40

NGF = Normal Grinding Force - 88 / 432

RA = Surface Roughness - 0.349 / 0.154

HP = Grinder Power - 1.54 / 11.9

(e) Multiple Objective Model

Based on the previous section, a mixed integer non-linear multi-objective model is formed as follows:

Objective function:

Max MOF = MRR + FLX - NGF - RA - HP

Constraints:

Process Constraints:

Depth of Cut (D) $0.058 \leq D \leq 0.102$ [in],

Feed Rate (F) $16.2 \leq F \leq 6.8$ [in/min],

Grinding Wheel Specification Constraints:

Bond type (B) B=0 (Resinoid Wheel), or B=1 (Vitrified Wheel)

Mesh size (M) $80 \leq M \leq 180$,

Concentration (C) $50 \leq C \leq 100$,

Surface Roughness Constraint:

Surface Roughness ≤ 0.40 [m],

Grinder Power Constraint:

Grinder Power ≤ 26.755 [Hp/in],

Minimum Threshold load Constraint:

Unit Load ≤ 0.46 [lb/in-edge],

B, M, and C are integer.

IV. Multi-objective Optimization Methodology

Multiple objective optimization problems can be solved with prior, progressive and no prior articulation of the preferences of a decision-maker. For the purpose of developing comparative ceramic grinding guidelines and for a broad base of widely varying industrial applications, the method of no prior articulation of the decision-maker's preferences was selected. The weighting method proposed by Zadeh [18] was applied in the present study. This is one of the many available methods which can be used to obtain non-dominated solutions when the objective functions and/or constraints are nonlinear. The multi-objective problem can be transformed into a single objective programming format, and then, by parametric variation of the parameters, the set of non-dominated solutions can be obtained. The assignment of weights discussed in [19] is also incorporated. The procedure of the optimization methodology is shown in Figure 4. This procedure starts to optimize each objective function individually. After each objective is optimized, a systematic variation of the weights is conducted, that is, the variation of each weight is from zero to some upper bound using a predetermined step size. Based on the weighting method [18], the multi-objective model can be transformed into a single objective programming format. For this study, the weighted multi-objective function is :

$$\text{Max} \quad MOF = W1*MRR + W2*FLX - W3*NGF - W4*RA - W5*HP$$

Where the W1, W2, W3, W4, W5, are the weights addressed to each single objective function. And then, by the variation of the weights, a set of nondominated solutions can be obtained. The method presented by Cohen [19] was utilized to check the inferiority of the alternative optimal which might occur when one or more weights are set at zero. The trade-off between the accuracy of the nondominated solutions obtained and the efficiency of the methodology are determined by the upper bound, and the step size is set for each objective. A branch and bound method was used to solve the single objective nonlinear mixed integer problem at each step. The most fractional integer variable is selected as a branching node. As Lasdon surveyed [20], there are three general purpose non-linear optimization algorithms: Generalized Reduced Gradient (GRG), Successive Linear Programming (SLP), and Successive Quadratic Programming (SQP). From a comparison of these three algorithms [20], the GRG is probably the most robust of these three methods. Hence, the GRG algorithm is used to solve the intermediate nonlinear problems.

GINO (General Interactive Optimizer) is designed by being based on the GRG algorithm and is a highly interactive system which runs on mainframe VAX 8530. In the present study, the multi-objective problems were solved by employing GINO and by applying the weighting method.

V. Results and Discussion

(a) Single-Objective Function Analysis

Based on the procedure of Figure 4, each objective was optimized individually at first. This single-objective function analysis provides the necessary settings for operating variables that are required to optimize (maximum or minimum) each objective function and is used as an upper bound (for maximum objective function) or lower bound (for minimum objective function) to achieve optimal values by the multi-objective optimization methodology.

Table 3 shows the optimal conditions and solutions for single-objective analysis. Three different sets of operation parameters are shown in Table 3. The objective to minimize normal grinding force will also minimize the grinder power. This reflects the strong relationship that exits between these two objectives as explained in [12]. The objective to maximize the flexural strength has the same optimal operation conditions as the objective to minimize the surface roughness. But from Spur and Tio [21] and Chen et al [14] research, these two objective seems to have a critical relationship, since the material removal mechanism of alumina is dominated by brittle fracture [13].

(b) Multi-objective Optimization

Based on the "indentation fracture mechanics" approach to explain the material removal mechanism of ceramics and the ultimate goal for ceramic products, namely, high flexural strength products, the flexural strength and normal grinding force are the important objectives. Hence, the weights for these two objectives, W2 and W3, were kept at 1.

For W1, W4, and W5, there are four classifications representing the relative importance among these four objectives: unimportant, necessary, important, and very important. W1, W4, and W5 are varied from 0 to nine in steps of three. There are 64 different weight sets. By using GINO, it was found that the total number of different non-dominated solutions is seven for 64 combinations of weight sets. The results of the non-dominated solutions are shown in Table 4 and the comparison of the solutions is presented in Figure 5.

These non-dominated solutions will play an important role to guide engineers faced with the multi-objective problems and furthermore, to offer them optimal solutions. Under the presumption that the flexural strength and the normal grinding force are important, the guidelines for creep feed grinding can be summarized as follows:

a) Optimization of material removal rate : as seen in Table 4 for set 2 and 3, total material removal rate is maximized. The vitrified wheels with 180 mesh size, 50 concentration, 15.3-16.2 in/min feed rate, and 0.091-0.102 in depth of cut are suggested. If smaller grinder power is desired, the lower bound of feed rate and depth of cut is applied.

b) Optimization of grinder power: as seen in Table 4 set 1, grinder power is minimized. The vitrified wheels with 180 mesh size, 100 concentration, the lowest bound of feed rate and depth of cut, namely, 6.8 in/min and 0.058 in, are suggested

c) Optimization of material removal rate and grinder power: as in Table 4 for set 4, the resinoid wheels with 180 mesh size, 100 concentration, 14.30 in/min feed rate, and 0.092 in depth of cut are recommended.

d) Optimization of material removal rate and surface roughness: as in Table 4 in set 5, the resinoid wheels with 180 mesh size, 100 concentration, 12.11 in/min in/min feed rate, and 0.102 depth of cut are suggested.

e) Optimization of all the objectives: as seen in Table 4 in set 6 and 7, the resinoid wheels with 180 mesh size, 100 concentration, 6.8-12.02 in/min feed rate, and 0.102 in depth of cut are suggested. If it is required to pay more attentions to the surface roughness, the lower feed rate is selected.

The above summaries are consistent with [13-14]. From [13-14], the vitrified wheels provide coarser surface profiles, which is good for material removal rate. However, the flexural strength is seriously deteriorated by using vitrified wheels, compared with resinoid wheels. The compromise between these two is dependent on the range of the wheel specifications and process parameters.

VI. Sensitivity Analysis

In this study, the multi-objective model was formed by the empirical regression models. The coefficients of the variables of the regression models were estimated with a standard error. The sensitivity analysis is necessary to check the stability of the multi-objective model and the results of the model changes as the estimated parameters change. Table 5 show the coefficients and standard error of the empirical models.

For analyzing the range of the variation of the multi-objective model, model parameters were perturbed by one standard error. By perturbing one unit of standard error, two strategies (shown in Table 6) are developed in order to find the maximum and minimum of the MOF. One unit of standard error, was added to or subtracted from each estimated parameter depending on the sign of the parameter (positive or negative) and the type of the single objective function (maximum or minimum). In the case of the maximum MOF, for the positive (negative) sign of the parameters of the model, such as normal grinding force, surface roughness, and grinder power, one is subtracted from (added to) each estimated parameter. For the positive (negative) sign of the parameters of the model, such as flexural strength, one is added to (subtracted from) each estimated parameter. In the case of the minimum MOF, it is just reversed.

Two extreme cases, namely, weight sets, (0,1,1,0,0) and (9,1,1,9,9), were applied to this sensitivity analysis. The optimal conditions and solutions are shown in Tables 7 and 8. Compared with the original study, the multi-objective function of the case (0,1,1,0,0) has a smaller variation than the case (9,1,1,9,9). The optimal conditions in these two cases do not change, which means that the multi-objective optimization methodology is insensitive to the changes in the estimated constant parameters.

VII. Conclusion

Basically, this study is a successive section of a systematic research of ceramic grinding from [13-14]. In these studies, the single objective was specified, such as *material removal mechanism and strength degradation of ceramics after the grinding* process. In [13], the observations found were: (1) the material removal mechanism of alumina is dominated by brittle fracture since it has low fracture toughness; (2) the vitrified wheels provide more active cutting edges since the surface topography of these wheels are coarser, and the normal grinding force associated with each cutting edge is smaller. In [14], the strength degradation becomes worse usually in a workpiece ground by vitrified wheels. But the determination of final strength of the ceramic workpiece is compromised by the material removal mechanism, tensile and compressive residual stresses, and material properties.

How to compromise these objectives is the main goal of this study. In this paper, the procedure to optimize the multi-objective problems was developed. The upper/lower bound of the single objectives and the non-dominated solutions of the multi-objective model are found, which can provide the process engineers with an effective guideline to optimize the ceramic grinding process. Finally, the sensitivity analysis is checked by perturbing one standard error. The results demonstrate that the model used in the present study is insensitive to the changes of this perturbation.

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Table 1 Grinding Conditions

Wheel Size: 7" x 1/4" x 1/8" Wheel Speed: 4400 ft/min (2400 rpm)
Coolant: Cincinnati CIMTECII GL 2015; diluted in water in 1:50 proportion
Truing: Silicon Carbide truing with 0.001 increment
Dressing: Constant feeding of Al_2O_3 stick at speed of 1000 ft/min (545 rpm)
Grinding Condition for Wheel Stabilization: Depth of Cut: 0.05 in
Table Feed Speed: 10 in/min

Table 2 2^{5-1} Fractional Factorial Experimental Design

Experimental Factors	Two-level
1. Wheel Bond Type	Resinoid, Vitrified
2. Wheel Mesh Size	80, 180
3. Wheel Concentration	50, 100
4. Feed Rate	6.8, 16.2 (inches/min)
5. Depth of Cut	0.058, 0.102 (inches)

Table 3 Optimal Conditions and Solutions for Single-objective Analysis

	WEIGHT SET				
Solution #	W1	W2	W3	W4	W5
1	1	0	0	0	0
2	0	1	0	0	0
3	0	0	1	0	0
4	0	0	0	1	0
5	0	0	0	0	1

	OPERATIONG CONDITIONS				
Solution #	Bond Type	Mesh Size	Concentration	Feed Rate	Dept of Cut
1	1	180	100	392.43	2.5908
2	0	180	100	172.72	2.5908
3	1	180	100	172.72	1.4732
4	0	180	100	172.72	2.5908
5	0	180	100	172.72	2.5908

	OPTIMAL SOLUTIONS					
Solution #	MRR	Strength	Grinding Force	Roughness	Power	MCF
1	1048.39	285.66	1555.78	0.4	281.06	1.022
2	273.55	291.38	1093.67	0.35	86.23	0.781
3	254.19	307.72	392.71	0.36	60.33	-0.001
4	273.55	318.96	1093.67	0.35	86.23	-0.019
5	273.55	291.38	1093.67	0.35	86.23	-0.117

Table 4 Weights, Non-dominated Optimal Conditions and Solutions

	WEIGHT		SET			
Solution #	W1	W2	W3	W4	W5	MCF
1	0	1	1	0	0	0.637
	0	1	1	0	3	0.508
2	9	1	1	0	0	7.641
3	6	1	1	0	3	3.852
4	9	1	1	3	3	5.703
	9	1	1	0	6	3.946
5	9	1	1	6	3	3.855
6	9	1	1	9	6	2.252
7	6	1	1	9	9	0.822
	9	1	1	6	9	1.381
	6	1	1	9	9	1.324
	9	1	1	9	9	0.651

	OPERATING	CONDITIONS			
Solution #	Bond Type	Mesh Size	Concentration	Feed Rate	Dept of Cut
1	1	180	100	172.72	1.4732
2	1	180	50	411.48	2.3114
3	1	180	50	388.62	2.5908
4	0	180	100	363.22	2.3368
5	0	180	100	307.34	2.5908
6	0	180	100	304.81	2.5908
7	1	180	100	172.72	2.5908

	OPTIMAL SOLUTIONS				
Solution #	MRP	Strength	Grinding Force	Roughness	Power
1	254.19	307.65	392.71	0.36	60.33
2	508.39	282.97	1472.55	0.40	229.26
3	762.58	287.59	1491.46	0.40	232.21
4	841.29	295.73	1786.01	0.39	193.36
5	794.19	303.11	1680.49	0.38	170.39
6	788.39	303.45	1674.72	0.38	169.52
7	273.56	311.45	593.19	0.35	90.35

Table 5 The Coefficient and Standard Error for Regression Model

(a) Normal Grinding Force

Variable	Coeff.	Std. Error
M	2.64E-01	1.23E-02
C	3.45E-01	1.35E-02
M*C	-2.9-0E-03	5.28E-04
F	-6.78E-02	1.35E-04
M*F	-2.70E-04	4.62E-05
D	-6.335	1.30E-01
C*F	2.23E-02	8.60E-05
F*D	7.76E-02	6.74E-03
C*B	-1.96E-01	5.84E-03
M*B	-6.01E-02	1.18E-02
B	1.07E+01	6.37E-01

(b) Grinder Power

Variable	Coeff.	Std.Error
M	2.00E+00	1.58E-01
C	4.78E-01	5.23E-02
M*C	-1.59E-02	1.50E-03
F	-5.45E-01	2.25E-02
C*F	4.34E-03	6.34E-04
D*B	3.25E+01	7.12E+00
D	-33	9.88E+00
M*D	4.69E-01	6.49E-02
C*D	6.25E-01	1.97E-02
F*B	2.41E+01	3.36E-02
F*D	7.24E+00	2.75E-02
B	1.22E+02	1.21E-01

(c) Surface Roughness

Variable	Coeff.	Std.Error
Const.	5.71E-01	3.20 E-02
M	-1.35 E-03	2.21 E-04
C	-1.54 E-03	2.17 E-04
M*C	1.00 E-05	2.80 E-06
F	4.99 E-05	1.05 E-05
C*D	1.33 E-04	1.65 E-05
F*D	5.27 E-05	1.09 E-05
C*B	7.10 E-05	9.00 E-06

(d) Flexural Strength

Variable	Coeff.	Std.Error
Const.	2.90 E+02	6.42 E-00
B	-7.51215	6.13 E-01
F	4.71 E-02	6.65 E-03
M*C	1.11 E-03	5.00 E-04
M*F	-8.16 E-04	1.65 E-04
C*F	1.75 E-04	1.85 E-05
M*D	6.89 E-02	1.94 E-02
C*D	9.05 E-02	1.83 E-01

Table 6 The Perturbation Strategy for Sensitivity Analysis

Max MOF		Sing of Parameter	
		-	+
Objective Function	MAX	$+\delta$	$-\delta$
	MIN	$-\delta$	$+\delta$

Min MOF		Sing of Parameter	
		-	+
Objective Function	MAX	$-\delta$	$+\delta$
	MIN	$+\delta$	$-\delta$

Table 7 Comparison of Optimal Conditions and Solutions for Max-original-min

Optimal Operating Conditions (Weight Set: (0,1,1,0,0)

	Bond Type	Mesh size	Concentration	Feed Rate	Depth of Cut
Max MOF	1	180	100	172.72	1.4732
Original	1	180	100	172.72	1.4732
Min MOF	1	180	100	172.72	1.4732

Optimal Solutions

	MRR	Strength	Grinding Force	Roughness	Power	MOF
Max MOF	254.19	322.75	556.13	0.34	52.68	0.743
Original	254.19	307.72	392.71	0.36	60.33	0.637
Min MOF	254.19	293.24	229.29	0.39	68.28	0.538

Optimal Operating Conditions (Weight Set: (9,1,1,9,9))

	Bond Type	Mesh size	Concentration	Feed Rate	Depth of Cut
Max MOF	0	180	100	305.31	2.5908
Original	0	180	100	172.72	2.5908
Min MOF	0	180	100	172.72	2.5908

Optimal Solutions

	MRR	Strength	Grinding Force	Roughness	Power	MOF
Max MOF	273.55	318.82	1696.82	0.35	179.23	2.781
Original	273.55	318.82	1093.67	0.35	86.23	1.381
Min MOF	273.55	300.76	1012.19	0.38	61.51	0.467