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OPTIMIZATION OF MULTIPLE PERFORMANCE CHARACTERSTICS IN ULTRASONIC MACHINING PROCESS USING GREY RELATIONAL ANALYSIS

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ABSTRACT

The present study points out a multi-objective optimization problem to determine the optimal process parameters in machining of soda lime glass in Ultrasonic machining process. In this study, the process parameters such as Concentration of slurry (C), Power (P) and Static load (F) have been considered. The response variables like material removal rate (MRR), dimensional tolerance i.e. hole over size (HOS) and circularity of holes i.e. out of roundness (OOR) have been established. Grey Relational Analysis has been coupled with Taguchi method in the present investigation. A grey relational grade obtained from the grey relational analysis is used as performance index to solve the optimization problem of process parameters. Taguchi orthogonal array, the signal-to-noise ratio, and the analysis of variance are used to investigate the optimal levels of process parameters. The confirmation tests are conducted to verify the results and it is observed that this approach is efficient in determining the optimal process parameters based on multiple performance characteristics.

Keywords: USM**,** ANOVA, DOE.

1. INTRODUCTION

Ultrasonic machining (USM) is a non conventional material removal process generally associated with low material removal rates; however its application is not limited by the electrical or chemical characteristics of the work piece materials. As the name implies the process operates at ultrasonic frequency range between 20 to 40 KHz. The equipment used is based upon a generator energizing a magnetostrictive or piezoelectric transducer which causes an attached tool to vibrate. The vibrating tool transfers energy to abrasive particles carried, within a slurry, underneath the tool tip. Many researchers have looked at the modification of steel, alumina based ceramics and carbide work piece, but few have examined the optimization of various responses related to soda lime glass. T.C Lee et al.(1997) pointed out that MRR decreases with decrease in amplitude of vibration & increase in static load and size of abrasive. R_a increases with increase in static load, size of abrasive and amplitude of vibration using K-type magnetic ferrite as work-piece using ultrasonic machining. Zoo Zhi Min et al.(1998) used stainless steel as the work piece & found that surface roughness (R_a) decreases with increase in amplitude & R_a increases with increase in tool feed, cutting depth & cutting speed using ultrasonic machining. R. Hahn et al.(1994) found that MRR detoriates, if critical vertical pressure is exceeded & the acceleration of the abrasive particle is inadequate using glass as work piece using USM. R.S Jadoun et al. pointed out that hole over size (HOS), out of roundness (OOR) increases with increases in grain size, power, and concentration taking alumina composites as the work -piece. J. Zhixin et al.(1995) analyzed on combined machining technology of ultrasonic machining and electrical discharge machining and proposed that it can be used to machine all conductive hard and brittle material with high efficiency and surface integrity. The results showed that the efficiency of it is over three times greater than that of ultrasonic machining, and the surface integrity was not significantly different.

Sing and Kumar (2006) studied on optimization of feed force through setting of optimal value of process parameters namely speed, feed and depth of cut in turning of EN24 steel with TiC coated tungsten carbide inserts. The authors used Taguchi's parameter design approach and concluded that the effect of depth of cut and feed in variation of feed force were affected more as compare to speed. Shuyu Lin (2005) studied the ultrasonic exponential horns in longitudinal and torsional composite vibration modes. He analyzed the propagation characteristics of the longitudinal and torsional vibration in ultrasonic exponential horns and had chosen the decay constant of the cross-section area of the ultrasonic exponential solid horn, the condition at which the longitudinal and torsional vibration resonate at the same resonance frequency was given and then the resonance frequency equation for the design of the longitudinal-torsional composite ultrasonic exponential horns derived. Jia Zhixin et al. (1997) analyzed combined machining technology of ultrasonic machining and electrical discharge machining and carried out combined advantage of both of them. Combined machining technology used to machine all conductive hard and brittle material with high efficiency and surface integrity and found that its efficiency was three times greater than that of ultrasonic machining, and surface integrity is not significantly different.

Kishore, Tiwari, Dvivedi, Singh et al.(1998) found that drilling in composite materials was often required to facilitate the assembly of the parts to get the final product. However they noticed that drilling induced damage drastically affects the residual tensile strength of the drilled components. They investigated and studied the effect of the cutting speed, the feed rate, and the drill point geometry on the residual tensile strength of the drilled unidirectional glass fiber reinforced epoxy composite using the Taguchi method and suggested the optimal conditions for maximum residual tensile strength.

Thamizhmanii et al. (2007) applied Taguchi method for finding out the optimal value of surface roughness under optimum cutting condition in turning SCM 440 alloy steel. The experiment was designed by using Taguchi method and experiments were conducted and results thereof were analyzed with the help of ANOVA (Analysis of Variance) method. The causes of poor surface finish as detected were machine tool vibrations, tool chattering whose effects were ignored for analyses. The authors concluded that the results obtained by this method would be useful to other researches for similar type of study on tool vibrations, cutting forces etc. The work concluded that depth of cut was the only significant factor which contributed to the surface roughness.

Liu et al. designed a force control system in a CNC grinding machine to reduce the grinding force variation and surface roughness. They conducted series of experiments using Taguchi method.

Wang and Lan (2008) used Orthogonal Array of Taguchi method coupled with grey relational analysis considering four parameters viz. speed, cutting depth, feed rate, tool nose run off etc. for optimizing three responses: surface roughness, tool wear and material removal rate in precision turning on an ECOCA-3807 CNC Lathe. The MINITAB software was explored to analyze the mean effect of Signal-to-Noise (S/N) ratio to achieve the multi-objective features. This study not only proposed an optimization approaches using Orthogonal Array and grey relational analysis but also contributed a satisfactory technique for improving the multiple machining performances in precision CNC turning with profound insight.

Z. J. Pei et al. (1998) investigated an experiment of the newly-developed rotary ultrasonic face milling machine (RUFM) process. A five-variable two-level fraction factorial design was used to conduct the experiment The purpose of these experiments was to reveal the main effects as well as the interaction effects of the process parameters on the process outputs such as Material Removal Rate (MRR), cutting force, material removal mode and surface roughness. He had drawn the following conclusions from the experiment: DOC (depth of cut) and feed rate affect the MRR.

In the present study, the responses are taken as material removal rate (MRR), dimensional tolerance i.e hole over size (HOS) and circularity of holes i.e. out of roundness (OOR). These can be optimized by a multi-objective optimization technique to solve the problem. This technique is used to find out best process environment for optimizing the responses. But the fact is that traditional Taguchi approach is insufficient to find a solution of this given problem. A grey relational grade obtained from the grey relational analysis is used as performance index to solve the optimization problem of process parameters. Taguchi orthogonal array, the signal-to-noise ratio, and the analysis of variance are used to investigate the optimal levels of process parameters.

2. EXPERIMENTAL DETAILS

2.1 Work Material

Soda lime glass (30×30×6 mm) is used as work material. Soda-lime glass, also called soda-lime-silica glass, is the most prevalent type of glass, used for windowpanes, and glass containers (bottles and jars) for beverages, food, and some commodity items. Glass bakeware is often made of tempered soda-lime glass. Soda-lime glass is prepared by melting the raw materials, such as sodium carbonate (soda), lime, dolomite, silicon dioxide (silica), aluminium oxide (alumina), and small quantities of fining agents (e.g., sodium sulfate, sodium chloride) in a glass furnace at temperatures locally up to 1675 °C.

2.2 Tool Material

For minimum tool wear, tools should be constructed from relatively ductile materials such as stainless steel, brass and mild steel. The harder the tool material, the faster will be its wear rate. The cutting tool have been used in this experiment is made of High Carbon Steel (D2).

2.3 Abrasive Slurry

The slurry used in ultrasonic machining process is a mixture of abrasive grains and a liquid media mainly water, kerosene, benzene, glycerol or thin oil. The ratio of abrasives to liquid can vary from 1:4 to 1:1 (by weight). Slurry can be fed externally or internally. In the case of external feeding, the slurry is pump fed by several jets covering the circumference of the tool or by a single jet. The abrasive used for an application should be harder than the material being machined. Otherwise, the usable life time of the abrasive will be reduced. The performance characteristics or responses of an ultrasonic machining process have investigated by using the boron carbide (B_4C) with different abrasive slurry concentrations. The slurry concentrations have been used during the experiments are of three different types which are given as follows:-2%,3% and 4% of B_4C in the volume of water.

2.4 Ultrasonic Machine

The Ultrasonic machine used during experiments is

Sonic-Mill 500 Watts (USA), model no. CN50061R in the Non-traditional machining lab at Manufacturing department of Veer Surendra Sai University of Technology (VSSUT), Burla.

Fig 1. Sonic-Mill 500 Watts (USA)

2.2 Responce

(a) Material Removal Rate (MRR)

It is expressed as penetration rate in mm/min for a given cross-section of the tool, or expressed as volume material removal rate in mm^3/min. Material removal rate(MRR) will be calculated by the weight difference of the sample before and after undergoing the USM process.The formula used for calculating MRR is-

Where $$MRR = \frac{W_1 - W_2}{\rho \times t}$$

W_1= Weight of the sample before experimant
W_2= Weight of the sample after experiment
ρ = Density of the work piece
t = Time of machining

(b) Dimensional Tolerance

The increase in the size of the hole produced with reference to the size of the tool is known as dimensional tolerance of hole. The diameter of the hole at the entry side will be measured by using Tool Maker's microscope. Here the diameter of the cutting tool is 2mm and three diameters are measured at different places of the entry side of the work piece. Then the difference between the average diameter to the cutting tool diameter is measured. It is otherwise also called as Hole over size (HOS).

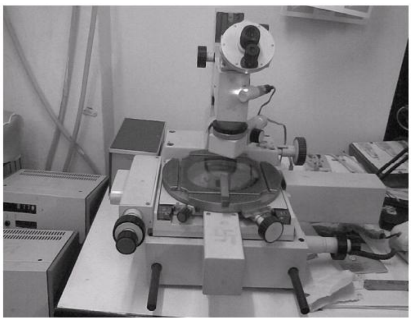

Fig. 2. Tool Maker's microscope

(c) Circularity of Hole

Circularity of hole refers to the errors of geometrical form of the circular holes that will be drilled. For this, diameters at three different places will be measured by the above instrument. It is calculated by finding the difference between highest and lowest diameters of the drilled hole. It is also otherwise called as out of roundness (OOR).

3. DESIGN OF EXPERIMENTS

Design of Experiments (DOE) is a powerful statistical technique introduced by R. A. Fisher in England in the 1920's to study the effect of multiple variables simultaneously. Experiments have been carried out using Taguchi's L_9 Orthogonal Array (OA). Experimental design which consists of 9 combinations of concentration of slurry, power and static load. It considers three process parameters (without interaction) to be varied in three different levels shown in table 1. The experimental design has been shown in Table 2 (all factors are in coded form). Here 1 represents low level, 2 represents medium level and 3 represents high level of each input parameters.The experimental value the three responses are shown in the Table 3.

Table 1: Process variables and their levels

Parameter	unit	Symbol	Factor levels		
			1	2	3
Conc-entration.	gm/m^3	C	2%	3%	4%
Power	Watt	P	70	80	90
Static load	gm	F	500	700	900

Table 2: Taguchi's L_9 orthogonal array

Factor	Conc. (C)	Power (P)	Static load(F)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

4. GREY RELATIONAL ANALYSIS

In the grey relational analysis, data preprocessing is first performed in order to normalize the raw data (Table 4) for analysis. In this study, a linear normalization of the experimental results for material removal rate (MRR), dimensional tolerance (HOS) and circularity of holes (OOR) were performed in the range between zero and one, which is also called the grey relational generation.

The normalized processing for MRR corresponding to larger-the-better criterion can be expressed as data

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max \ y_i(k) - \min \ y_i(k)} \quad (1)$$

Table 3: Experimental results

Expt. No	MRR (mm^3/sec)	HOS (mm)	OOR (mm)
1	0.4180	0.6666	0.1
2	0.7110	1.2000	0.4
3	0.6188	0.7000	0.2
4	0.6967	1.1000	0.2
5	0.1290	0.7333	0.1
6	0.6680	0.8333	0.3
7	0.7010	1.0333	0.1
8	0.2233	0.8333	0.1
9	0.1905	0.9000	0.2

In this grey relational analysis, the normalized data processing for hole oversize (HOS) and and circularity of holes (OOR) corresponding to lower- the-better criterion can be expressed as

$$x_i(k) = \frac{\max\ y_i(k) - y_i(k)}{\max\ y_i(k) - \min\ y_i(k)} \qquad (2)$$

where $x_i(k)$ is the value after the grey relational generation, min $y_i(k)$ is the smallest value of $y_i(k)$ for the kth response, and max $y_i(k)$ is the largest value of $y_i(k)$ for the kth response. An ideal sequence is $x_0(k)$ (k=1, 2 for *MRR, HOS & OOR* respectively). The grey relational generation has been shown in the Table 4. Basically, the larger normalized results correspond to the better performance and the best-normalized results should be equal to one. Next, the grey relational coefficient is calculated to express the relationship between the ideal (best) and actual normalized experimental results.

Table 4: Data processing of each performance characteristic (Grey relational generation)

Exp. No	MRR	HOS	OOR
Ideal Sequence	1	1	1
1	0.505235	1.00000	1.00000
2	1.000000	0.00000	0.00000
3	0.844309	0.93633	0.66666
4	0.975853	0.18726	0.66666
5	0.017224	0.87397	1.00000
6	0.927389	0.68670	0.33333
7	0.983114	0.31217	1.00000
8	0.176461	0.68670	1.00000
9	0.121074	0.56179	0.66666

Table 5 Evaluation of Δ_{oi} for each response

Exp. No	MRR	HOS	OOR
Ideal Sequence	1	1	1
1	0.49476	0.00000	0.00000
2	0.00000	1.00000	1.00000
3	0.15569	0.06367	0.33333
4	0.02414	0.81273	0.33333
5	0.98277	0.12603	0.00000
6	0.07261	0.31329	0.66666
7	0.01688	0.68782	0.00000
8	0.82353	0.31329	0.00000
9	0.87892	0.43820	0.333333

The grey relational coefficient $\xi_i(k)$ can be calculated as

$$\xi_i(k) = \frac{\Delta_{\min} + \psi\,\Delta_{\max}}{\Delta_{oi}(k) + \psi\,\Delta_{\max}} \qquad (3)$$

where $\Delta_{0i} = \left\| x_0(k) - x_i(k) \right\|$ = difference of the absolute value between $x_0(k)$ and $x_i(k)$, $\Delta_{\min}$ and $\Delta_{\max}$ are respectively the minimum and maximum values of the absolute differences (Δ_{0i} as shown in Table 5) of all comparing sequences. ψ is a distinguishing coefficient, $0 \le \psi \le 1$, the purpose of which is to weaken the effect of $\Delta_{\max}$ when it gets too big and thus enlarges the difference significance of the relational coefficient. In the present case, ψ = 0.5 is used. After averaging the grey relational coefficients (Table 6), the grey relational grade γ_i can be calculated as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \qquad (4)$$

where n = number of process responses. The higher value of grey relational grade is considered as the stronger relational degree between the ideal sequence $x_0(k)$ and the given sequence $x_i(k)$. It has already been mentioned that the ideal sequence $x_0(k)$ is the best process response in the experimental layout. Thus the higher relational grade implies that the corresponding parameter combination is closer to the optimal.

Table 6.: Grey relational coefficient of each performance characteristics (with ψ= 0.5)

Exp. No	MRR	HOS	OOR
Ideal Sequence	1	1	1
1	0.50263	1.00000	1.00000
2	1.00000	0.33333	0.33333
3	0.76255	0.88704	0.60000
4	0.95393	0.38088	0.60000
5	0.33720	0.79868	1.00000
6	0.87319	0.61478	0.42857
7	0.96733	0.42093	1.00000
8	0.37777	0.61478	1.00000
9	0.36260	0.53293	0.60000

Table 7: Grey relational grade of performance characteristic

Exp. No	Grade
1	0.834210
2	0.555556
3	0.749866
4	0.644938
5	0.711963
6	0.638849
7	0.796089
8	0.664186
9	0.498512

The higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value. In other words, optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade. The grey relational grade is shown in the Table 7. Since the experimental design is orthogonal, it is then possible to separate out the effect of each machining parameter on the grey relational grade at different levels. Basically, the larger the grey relational grade, the better is the multiple performance characteristics. However, the relative importance among the machining parameters for the multiple performance characteristics still needs to be known so that the optimal combinations of the machining parameter levels can be determined more accurately.

5. ANALYSIS OF VARIANCE

The purpose of the analysis of variance (ANOVA) is to investigate which machining parameters significantly affect the performance characteristic. This is accomplished by separating the total variability of the grey relational grades, which is measured by the sum of the squared deviations from the total mean of the grey relational grade, into contributions by each machining parameter and the error. In addition, the Fisher's *F*-test can also be used to determine which machining parameters have a significant effect on the performance characteristic. Usually, the change of the machining parameter has a significant effect on the performance characteristic when *F* is large is shown in Table 8. Its clearly shown in the table that P-value is less than 0.05 for power and static load which means that both the process parameters are significant at 95% confidence level.

Table 8: ANOVA for Grey relational grade

Source	DF	Seq SS	Adj MS	F	P
C	2	0.006086	0.003043	6.99	0.125
P	2	0.030061	0.01503	34.54	0.028
F	2	0.057667	0.028833	66.26	0.015
Error	2	0.00087	0.000435		
Total	8	0.094683			

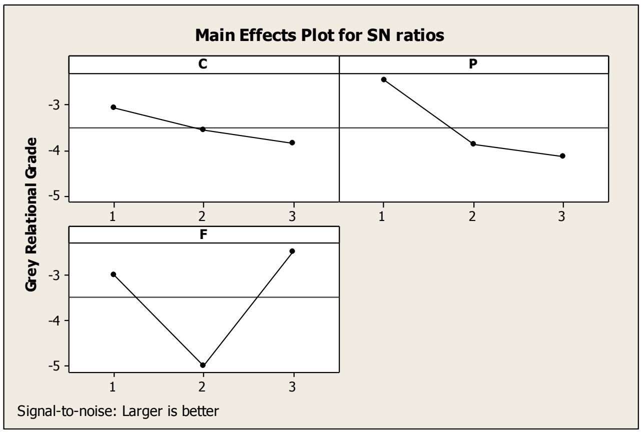

Fig 3. Grey relational grade graph of multiple performance characteristics

In the grey relational grade graph (Fig.3), it is clearly mentioned that first level of concentration, first level of power, third level of static load (C1P2F3) are the optimal combination of process parameters for multiple performance characteristics.

6. CONFIRMATION TEST

After the optimal level of machining parameters has been identified, a verification test needs to be carried out in order to check the accuracy of analysis. The estimated grey relational grade, $\hat{\gamma}$, using the optimal level of the process parameters can be calculated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{o} \left(\bar{\gamma}_i - \gamma_m\right) \quad (5)$$

where γ_m is the total mean grey relational grade, $\bar{\gamma}_i$ is the mean grey relational grade at the optimal level, and *o* is the number of the main design parameters that significantly affect the machining characteristics of ultrasonic machining process. Table 8 shows the comparison of the estimated grey relational grade (calculated using eqn. (4)) with the actual grey relational grade obtained in experiment using the optimal cutting parameters. It may be noted that there is good agreement between the estimated value (0.7862) and experimental value (0.9823). The improvement of grey relational grade from initial parameter combination (C1P1F1) to the optimal parameter combination (C1P1F3) is 0.1481.

Table 9: Confirmation test results

	Initial machining parameter	Optimal machining parameter	
		Prediction	Expt.
Level	C1P1F1	C1P1F3	C1P1F3
MRR	0.4180	-	0.7230
HOS	0.6666	-	0.3420
OOR	0.1000	-	0.1560
Grey Relational Grade	0.8342	0.7862	0.9823

7. CONCLUSION

Multi-response optimization problem has been solved by finding out an optimal sequence (favorable process environment), capable of producing high material removal rate machined the work piece in a relatively lesser time and at the same time it ensures reduction in dimensional tolerance (HOS) and circularity of holes (OOR). Decrease in HOS and OOR ensures good accuracy when the work sample will be machined under USM process. This study proposes a multi optimization approach using grey relational grade with the combination with Taguchi's robust design technique. As a result, optimization of the complicated multiple performance characteristics can be greatly simplified through this approach. It is shown that the performance characteristics of the USM process such as material removal rate, dimensional tolerance and circularity of holes are improved together by using this study.

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