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Experimental Analysis of Machining Zerodur Material in Rotary Ultrasonic Machine Using Taguchi Based Grey Relational Analysis

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ABSTRACT:

Rotary ultrasonic machining is one of the cost-effective machining processes available for machining advanced glass ceramics like Zerodur material using Rotary ultrasonic machine. In this research study, the experiments are conducted on a Rotary Ultrasonic Machine to study the effects of various parameter combinations during machining Zerodur glass ceramic material using diamond tool of 8mm diameter. Taguchi method is used for design of experiment. L27 orthogonal array is selected for design. The objective of the work is to analyse the effects of Rotary ultrasonic machining process parameters such as Cutting speed, Feed rate and Depth of cut on Material Removal Rate, surface finish & flatness are studied. The optimum level of parameters have been identified based on the values of Grey relational grade using Grey relational analysis (GRA) and also significant parameter are identified using ANOVA. A mathematical model of the relation connecting the input parameters and output responses using regression analysis using MINITAB software are developed. Confirmation test are also performed with optimum parameter combination and an improvement of machining parameter is obtained.

Keywords: *Rotary ultrasonic machining, Zerodur, Ultrasonic vibration, Taguchi technology, Grey Relational Analysis.*

INRODUCTION

The components used in aerospace applications calls for very precise & complex machining operations. Some of the materials used for aerospace applications are classified as difficult-to-cut materials. Zerodur is an inorganic, non-porous lithium alumino silicate glass ceramic material characterized by evenly-distributed nano-crystals within a residual glass phase. It is a low expansion glass ceramic and a brittle material, which delivers extremely high precision for many challenging high-tech applications such as laser gyroscopic sensor blocks in space applications.

Rotary ultrasonic machining is one of the cost-effective machining processes available for machining advanced ceramics using Rotary ultrasonic machine (RUM). It is a machining process in which a vibrating diamond tool oscillating at ultrasonic frequencies is used to remove material from the workpiece. Rotary ultrasonic machining is a hybrid machining process that combines the material removal mechanisms of diamond grinding and conventional Ultrasonic machine (USM), resulting in higher material removal rate (MRR) than that obtained by USM alone. It also gives superior surface finish, improved hole accuracy and low tool pressure. It is perfect for machining hard and brittle materials such as Zerodur and Suprasil glasses, ceramics, quartz, alumina etc. Also the combination of rotating and vibrating action of diamond tool makes Rotary Ultrasonic Machine ideal for milling the Zerodur and Suprasil glasses, ceramics that are difficult to machine with traditional process.

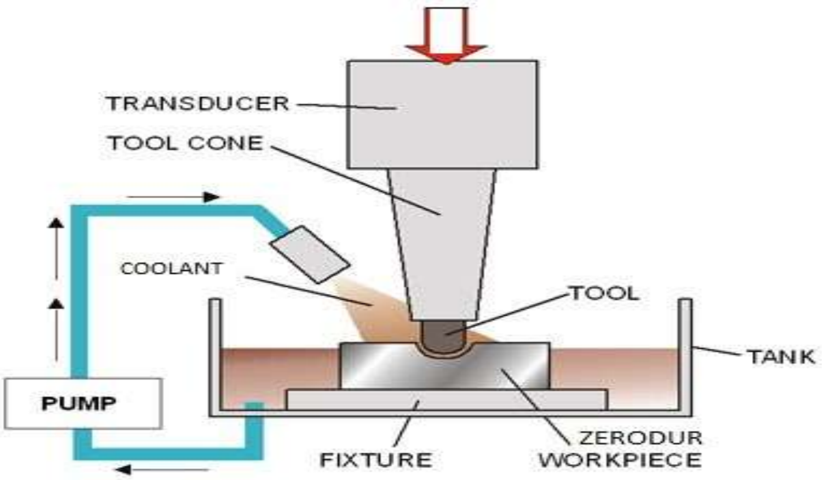

Figure 1: Schematic illustration of RUM

In this work, an experimental study is carried out for the simultaneous optimization of three responses and to study the effects of cutting parameters on the responses considered. Here Material removal rate, Surface finish, and Flatness are selected as responses. The study is carried out while machining Zerodur material in Rotary ultrasonic machine (RUM) using a diamond tool of 8mm. The surface roughness of the Zerodur material is tested by Talysurf roughness tester and flatness is tested by Co-ordinate Measuring Machine (CMM). The material removal rate (MRR) in milling operation is the volume of material removed by the tool per unit time. The effect of cutting parameters such as cutting speed, feed rate and depth of cut on the MRR, surface finish and flatness of machined workpiece were inspected and an optimization strategy is developed using Taguchi based Grey Relational analysis (GRA). L 27 Orthogonal Array is selected for design. The prediction or regression model for each of the output response were developed using MINITAB software. ANOVA is used to check the adequacy of the regression models and to find out the percentage of contribution of each parameter on various responses. Confirmation test are also performed with optimum parameter combination and an improvement of machining parameter is obtained.

EXPERIMENTAL DETAILS

The experiment is conducted on 5-axis Rotary Ultrasonic Machine and Zerodur glass ceramic material is machined using a diamond tool.

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Machining Conditions

Table 1: Machining Conditions

Machine	Ultrasonic 60 Sauer : 5 axis machine: X,Y,Z.B & C Maximum Spindle Speed:14000rpm Ultrasonic Frequency : 45KHz Tool Magazine: 30 pockets
Tool	Diamond tool (20mm) ---for Facing Diamond tool (8mm) ---for Milling
Workpiece	Zerodur (Glass Ceramic)- (90 x 34 x 6mm) - 4pieces
Fixture	Aluminium Block (210 x 160 x 40mm)
Coolant	Blazer (Soluble oil + Deionized water)
Binding material	Pitch (Tar + Pinewood resin)

5-axis Rotary ultrasonic 60 Sauer machine

A 5-axis Rotary ultrasonic machine is a non-traditional machine in which a vibrating and rotating diamond tool oscillating at ultrasonic frequencies is used to remove material from the workpiece. It comprises of a tool mounted on a rotary spindle attached to a piezo-electric transducer to produce the rotary and ultrasonic motion. The combination of rotating and vibrating action of diamond tool makes Rotary Ultrasonic Machine ideal for milling the Zerodur and Suprasil glasses, ceramics that are difficult to machine with traditional process.

Figure 2: 5-axis Rotary Ultrasonic 60 Sauer Machine

Zerodur material

Zerodur is a lithium alumino silicate glass ceramic material produced by Schott AG in 1968. Ceramics and glasses are inorganic, non-metallic materials consisting of metallic and nonmetallic elements bonded primarily with ionic and covalent bonds. These high strength bonds give rise to the special characteristics of these materials.

The distinguishing property of Zerodur, its ultra-low CTE, is the result of its glass-ceramic composite structure. This means that both amorphous and crystalline phases are present in the material. The amorphous phase has a positive CTE, but the crystalline phase has a negative CTE. Careful control during the manufacturing process adjusts the two phases to a ratio of 70% crystals 30 - 50 nm in diameter and 30% amorphous glass. At this ratio the net CTE of the material is essentially zero. The optical property of Zerodur is low transmittance relative to most glasses. This is due to the two-phase structure of Zerodur. The tight tolerance on Coefficient of thermal expansion, allows for highly accurate applications which require high-precision.

Figure 3: Zerodur material

Table 2: Properties of Zerodur

Properties	**Values**
Young's modulus, E @20°C	90.3 GPa
Density	2.53 g/cm^3
Poisson ratio, ν	0.24
Thermal conductivity @20°C	1.46 W/m.K
Maximum application temperature (melting point)	600°C
Cofficient of thermal expansion (20°C to 300°C)	0.05 ± 0.10 × 10^{-6}/K

Table 3: Chemical Composition of Zerodur (Wt %)

Materials	**% By Weight**
Silica	57.2
Aluminium Oxide	25.3
Phosphoric Pentoxide	6.5
Other Oxide s	3.4
Titanium Oxide	2.3
Zirconium Oxide	1.8
Zinc Oxide	1.4
Magnesium Oxide	1
Arsenic Trioxide	0.5
Potassium Oxide	0.4
Sodium Oxide	0.2

Diamond Tool

A diamond tool of 8mm is used for machining Zerodur material in Rotary ultrasonic machine. 20 mm diamond tool is used for facing operation in Zerodur material. Diamond is the hardest material. For machining a brittle material, the tool should be harder and must be ultrasonically vibration along with rotational motion.

Figure 4: Diamond tool

PLAN OF EXPERIMENTS

The design of experiment (DOE) is an efficient procedure for the purpose of planning experiments. In order to minimize the number of tests required, Taguchi experimental design method, a powerful tool for designing high-quality system, was developed by Taguchi. L 27 Orthogonal Array (3 factors each at three levels which gives a total of 3^3=27 experiments) is selected for design as shown in Table 5. The three RUM process parameters and levels of factors are listed in Table 4.

Table 4: RUM process parameters

Process Parameter	**Unit**	**Level 1**	**Level 2**	**Level 3**
Cutting Speed	rpm	8000	9000	10000
Feed Rate	mm/min	250	500	750
Depth Of Cut	mm	0.03	0.045	0.06

Experimental Analysis

Table 5: Results obtained from the experiments on Zerodur material

Exp No:	**Parameter Combinations**			**Machining Time** (min)	**MRR** (mm^3/min)	**Surface Roughness Ra** (microns)	**Flatness** (mm)
	Cuttin g Speed (rpm)	**Feedrate** (mm/min)	**Depth Of Cut** (mm)				
1	8000	250	0.03	0.136	60	0.974	0.0007
2	8000	250	0.045	0.136	90	0.971	0.0008
3	8000	250	0.06	0.136	120	0.935	0.0009
4	8000	500	0.03	0.068	120	1.104	0.0008

5	8000	500	0.045	0.068	180	1.055	0.001
6	8000	500	0.06	0.068	240	1.171	0.0011
7	8000	750	0.03	0.045	181	1.024	0.0012
8	8000	750	0.045	0.045	272	1.077	0.0013
9	8000	750	0.06	0.045	363	1.059	0.0015
10	9000	250	0.03	0.136	60	0.983	0.0006
11	9000	250	0.045	0.136	90	0.959	0.0007
12	9000	250	0.06	0.136	120	0.954	0.0012
13	9000	500	0.03	0.068	120	1.245	0.0015
14	9000	500	0.045	0.068	180	1.038	0.002
15	9000	500	0.06	0.068	240	1.117	0.0009
16	9000	750	0.03	0.045	181	1.028	0.0014
17	9000	750	0.045	0.045	272	1.234	0.0021
18	9000	750	0.06	0.045	363	1.097	0.0025
19	10000	250	0.03	0.136	60	0.927	0.0005
20	10000	250	0.045	0.136	90	0.965	0.0007
21	10000	250	0.06	0.136	120	0.93	0.0006
22	10000	500	0.03	0.068	120	1.106	0.0013
23	10000	500	0.045	0.068	180	1.013	0.0011
24	10000	500	0.06	0.068	240	1.078	0.0008
25	10000	750	0.03	0.045	181	1.067	0.0009
26	10000	750	0.045	0.045	272	1.131	0.0008
27	10000	750	0.06	0.045	363	1.021	0.0011

OPTIMIZATION OF MACHINING PARAMETERS

Grey Relational Analysis (GRA)

The grey relational analysis (GRA) is one of the powerful and effective soft-tool to analyse various processes having multiple performance characteristics.

Calculation of Normalized values

To avoid the effect of adopting different units and reduce the variability the response data obtained is pre-processed. For this purpose the experimental results are normalized in the range between zero and one. The normalization can be done in three different approaches.
If the target value of the original sequence is infinite, then it has characteristics of "larger-the-better". The original sequence can be normalized as follows.

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^o(k)}{\max x_i^0(k) - \min x_i^o(k)} \qquad (1)$$

If the expectancy is "smaller-the-better", then the original sequence is normalized as follows.

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^o(k)} \qquad (2)$$

If there is a definite target value to be achieved (nominal-the-better), the original sequence will be normalized in the form,

$$x_i^*(k) = 1 - \frac{|x_i^o(k) - x^o|}{\max x_i^0(k) - x_i^0} \quad (3)$$

Finding Grey Relational Coefficient (GRC)

Following data pre-processing, a grey relational coefficient (GRC or φ) is calculated to express the relationship between the ideal and actual normalized experimental results. The grey relational coefficient can be expressed as follows:

$$\varphi_i(k) = \frac{\Delta_{min} + \delta\Delta_{max}}{\Delta_{oi}(k) + \delta\Delta_{max}} \quad (4)$$

Where, δ is the weightage coefficient or is distinguishing or identification coefficient (δ or Є [0, 1] and is taken as 0.5 when both the response characteristics have the same weightage and Δ represents the deviation and is given as follows:

$$\Delta_{oi}(k) = |x_0^*(k) - x_i^*(k)| \quad (5)$$

$$\Delta_{max} = \max|x_0^*(k) - x_i^*(k)| \quad (6)$$

$$\Delta_{min} = \min|x_0^*(k) - x_i^*(k)| \quad (7)$$

Finding Grey Relational Grade

After obtaining the grey relational coefficient, the grey relational grade is obtained by taking the average of grey relational coefficients. The grey relational grade is defined as follows.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \varphi_i(k) \quad (8)$$

where,

γ_i = Grey Relational Grade

n = Number of response factors

Rank

Ranks are provided according to the decreasing order of grey grades for all experiments as shown in Table 6. 1st rank corresponds to highest value of grey grade among 27 values.

Table 6: Grey Relational Grade (GRG)

Exp No:	Normalized Values			Grey Relational Coefficients			GRG	
	MRR	Surface roughness	Flatness	MRR	Surface roughness	Flatness	Grey Grade	Rank
1	0	0.8522	0.9	0.3333	0.7718	0.8333	0.6461	9
2	0.0990	0.8616	0.85	0.3568	0.7832	0.7692	0.6364	10
3	0.1980	0.9748	0.8	0.3840	0.9520	0.7142	0.6834	4
4	0.1980	0.4433	0.85	0.3840	0.4732	0.7692	0.5421	21
5	0.3960	0.5974	0.75	0.4529	0.5540	0.6666	0.5578	19
6	0.5940	0.2327	0.7	0.5519	0.3945	0.625	0.5238	23
7	0.3993	0.6949	0.65	0.4542	0.6210	0.5882	0.5545	20
8	0.6996	0.5283	0.6	0.6247	0.5145	0.5555	0.5649	18
9	1	0.5849	0.5	1	0.5463	0.5	0.6821	5

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10	0	0.8238	0.95	0.3333	0.7395	0.9090	0.6606	8
11	0.0990	0.8993	0.9	0.3568	0.8324	0.8333	0.6742	6
12	0.1980	0.9150	0.65	0.3840	0.8548	0.5882	0.6090	13
13	0.1980	0	0.5	0.3840	0.3333	0.5	0.4057	27
14	0.3960	0.6509	0.25	0.4529	0.5888	0.4	0.4806	24
15	0.5940	0.4025	0.8	0.5519	0.4555	0.7142	0.5739	16
16	0.3993	0.6823	0.55	0.4542	0.6115	0.5263	0.5307	22
17	0.6996	0.0345	0.2	0.6247	0.3412	0.3846	0.4501	26
18	1	0.4654	0	1	0.4832	0.3333	0.6055	14
19	0	1	1	0.3333	1	1	0.7777	**1**
20	0.0990	0.8805	0.9	0.3568	0.8071	0.8333	0.6657	7
21	0.1980	0.9905	0.95	0.3840	0.9814	0.9090	0.7582	2
22	0.1980	0.4371	0.6	0.3840	0.4704	0.5555	0.47	25
23	0.3960	0.7295	0.7	0.4529	0.6489	0.625	0.575	15
24	0.5940	0.5251	0.85	0.5519	0.5129	0.7692	0.6113	11
25	0.3993	0.5597	0.8	0.4542	0.5317	0.7142	0.5667	17
26	0.6996	0.3584	0.85	0.6247	0.4380	0.7692	0.6106	12
27	1	0.7044	0.7	1	0.6284	0.625	0.7511	3

Table 7: Response table for grey relational grade

PROCESS PARAMETERS	GREY RELATIONAL GRADE				
	Level 1	**Level 2**	**Level 3**	**MAX-MIN**	**RANK**
Cutting speed	0.5990	0.5545	**0.6430***	0.0885	**2**
Feed rate	**0.6790***	0.5267	0.5907	0.1522	**1**
Depth of cut	0.5727	0.5795	**0.6442***	0.0715	**3**
Total mean value of grey grade = 0.5988					
***Optimum levels**					

The mean effect plots of machining parameters are shown in figure below.

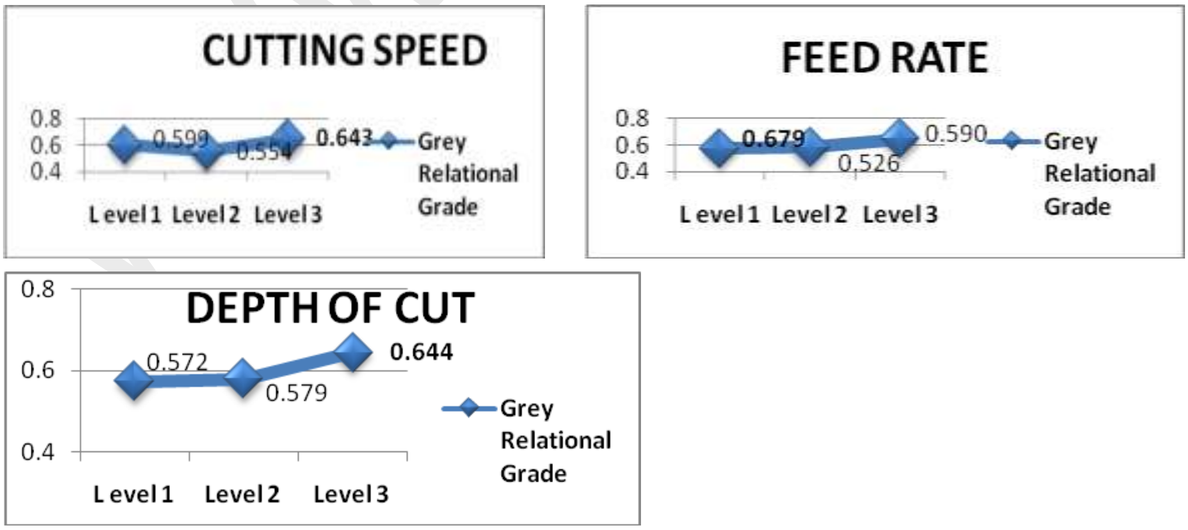

Figure 5: Mean effect plot for Grey relational grade

ANALYSIS OF VARIANCE (ANOVA)

The purpose of analysis of variance (ANOVA) is to investigate which of the tool parameters significantly affect the performance characteristics. The ANOVA test establishes the relative significance of the individual factors and their interaction effects.

Table 8: Results of ANOVA

Source	DOF	SS	MS	F	% Contribution
Cutting Speed	2	0.0117	0.0058	0.7037	16.1234
Feedrate	2	0.0350	0.0175	2.1008	**48.1336**
Depth of cut	2	0.0093	0.0046	0.5600	12.8317
Error	20	0.1670	0.0083	1	22.9111
Total	26	0.2232		4.3646	100

From the ANOVA test, feedrate is the most significant process parameter in machining Zerodur material using Rotary ultrasonic machine.

Mathematical model for prediction of optimal machining parameter

The regression equation for the prediction of optimal machining parameter is obtained from MINITAB software. The regression equations obtained are as follows:

The regression equation for MRR= -182 - 0.00000s + 0.364f + 4022d (9)

The regression equation for Surface Roughness = 1.00 - 0.000007s + 0.000253f - 0.36d (10)

The regression equation for Flatness = 0.000900 - 0.000000s + 0.000001f + 0.00630d (11)

CONFIRMATION TEST

After evaluating the optimal parameter settings, the next step is to predict and verify enhancement of the quality characteristics using optimal parametric combination. The estimated grey relational grade

$\gamma'' = \gamma m + \sum (\gamma i - \gamma m)$ (12)

where, γm = Total mean grey relational grade

γi = Mean grey relational grade at the optimum level

Table 9: Results of Confirmation experiment

	Initial machining parameter	Optimal machining parameters	
		Prediction	Experiment
Setting level	$s_1f_1d_1$	$s_3f_1d_3$	$s_3f_1d_3$
MRR	60	150.32	120
Surface Roughness	0.9740	0.9716	0.9726
Flatness	0.0007	0.0015	0.0005
Grey grade	0.6461	0.7686	
Improvement in GRG	**0.1224**		

RESULTS AND CONCLUSION

An experimental study to analyze the effects of RUM process parameters such as cutting speed, feed rate & depth of cut on machining parameters such as Material removal rate (MRR), Surface roughness and Flatness during machining Zerodur glass ceramic material using a diamond tool in 5-axis RUM are conducted and optimized using the Taguchi based GRA technology.

1. Optimum combination for MRR, Surface finish and Flatness are found using GRA and the values are obtained as Cutting speed 1000rpm (level 3), feed rate 250mm/min (level 1) and depth of cut 0.06mm (level 3).
2. The contribution of each parameter is obtained as cutting speed is 16.12%, feed rate is 48.13% and depth of cut is 12.83%. From the study, feedrate is the most significant process parameter in machining Zerodur material using Rotary ultrasonic machine.
3. The surface finish of machined work piece is mostly affected by feed rate and cutting speed. As the feedrate decreases, the surface roughness parameter Ra also decreases gradually.
4. A mathematical model of the relation connecting the input parameters and output responses using regression analysis using MINITAB software is obtained.
5. Comparing initial experiment and confirmation experiment, it is found that MRR is improved from $60mm^3$/min to $120mm^3$/min i.e. improvement is double, surface roughness reduces from 0.9740 microns to 0.9726 microns i.e. 0.14% reduction and also flatness is improved from 0..0007mm to 0.0005mm i.e. 28.57% improvement.

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