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Grey Relational Analysis Based Optimization of Process Parameters for Ultrasonic Slitting of Glass

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Abstract —*Ultrasonic machining is extremely popular for machining of brittle materials like glass, ceramics etc. Various optical and other applications require slitting of glass. In this work, a full factorial experiment is designed to study the effect of process parameters on ultrasonic slitting of glass. The control parameters selected include amplitude, pressure and thickness of the glass sheet being machined. Three levels of each of these parameters are selected giving* $3^3 = 27$ *trials. The material removal rate (MRR), overcut (OC) and taper produced on the glass while slitting are measured as response parameters. Ultrasonic machining is a complex process to control and get desired machining results. Grey relational analysis is applied to the experimental output data in order to determine the best combination of input parameters for different cutting requirements like roughing, semi-finishing and finishing. Parameter combinations are graded using grey relational analysis (GRA) process and the optimum combination is suggested for various requirements of machiningin terms of roughing, semi-finishing and finishing.*

Keywords-*Ultrasonic Slitting, Optimization, Grey Relational Analysis*

I. INTRODUCTION

Traditional ceramics and glasses are extensively used to manufacture many products. Advanced ceramics have been widely adopted as functional as well as structural engineering materials [1]. Ultrasonic machining offers a solution to the expanding need for machining brittle materials such as single crystals, glasses and polycrystalline ceramics, and for increasing complex operations to provide intricate shapes and workpiece profiles. This machining process is non-thermal, non-chemical, creates no change in the microstructure, chemical or physical properties of the workpiece and offers virtually stress-free machined surfaces. It is therefore used extensively in machining hard and brittle materials that are difficult to cut by other conventional methods [2]. Generation of slits in glass is required in variety of applications like optical microscopes, measurement optics etc. In order to produce these components, ultrasonic machining is a viable alternative. For machining to required dimensions, the setting of process parameters to appropriate value is extremely necessary.

Since, optimizing multiple output qualities of a process requires the calculation of a grey relational analysis (GRA) is used to integrate and optimize the multiple output qualities of a process [3–5]. Many papers have presented the effective method and proven its usefulness in various applications [6-8].

In this paper, the experimental data as an outcome of experiments on producing slits using ultrasonic process on common glass is analyzed using grey relational analysis to find the optimum process parameters.

II. ULTRASONIC SLITTING EXPERIMENTS

A full factorial design of experiment with replication is used with three control factors – amplitude, pressure and thickness of the glass sheet. The values selected for the low, medium and high level for each of the control parameters is mentioned in Table 1. The amplitude is varied in terms of percentage of amplitude delivered at full power by the converter.

Table 1. Parameters and their Levels

Amplitude	Pressure	Glass Thickness
A_1 = 70%	P_1 = 0.5 bar	t_1 =1.23 mm
A_2 = 80%	P_2 = 2 bar	t_2 =2.16 mm
A_3 = 90%	P_3 = 3.5 bar	t_3 = 3.12 mm

Material removal rate (MRR), overcut (OC) and taper generated during slitting are taken as response parameters representing process behaviour. Taper cylindrical sonotrode is designed and manufactured as amplitude of propagated sound wave is inversely proportional to the cross-sectional area in solids. The shape of the tool is designed integral at the end of the sonotrode. Sonotrode with and approximate gain of 3 is designed using CARD (Computer Aided Resonator Design) software. The cross-section of the tool and the amplitude variation along length is shown in Figure 1. The manufacturing drawing produced based on this design is shown in Figure 2.

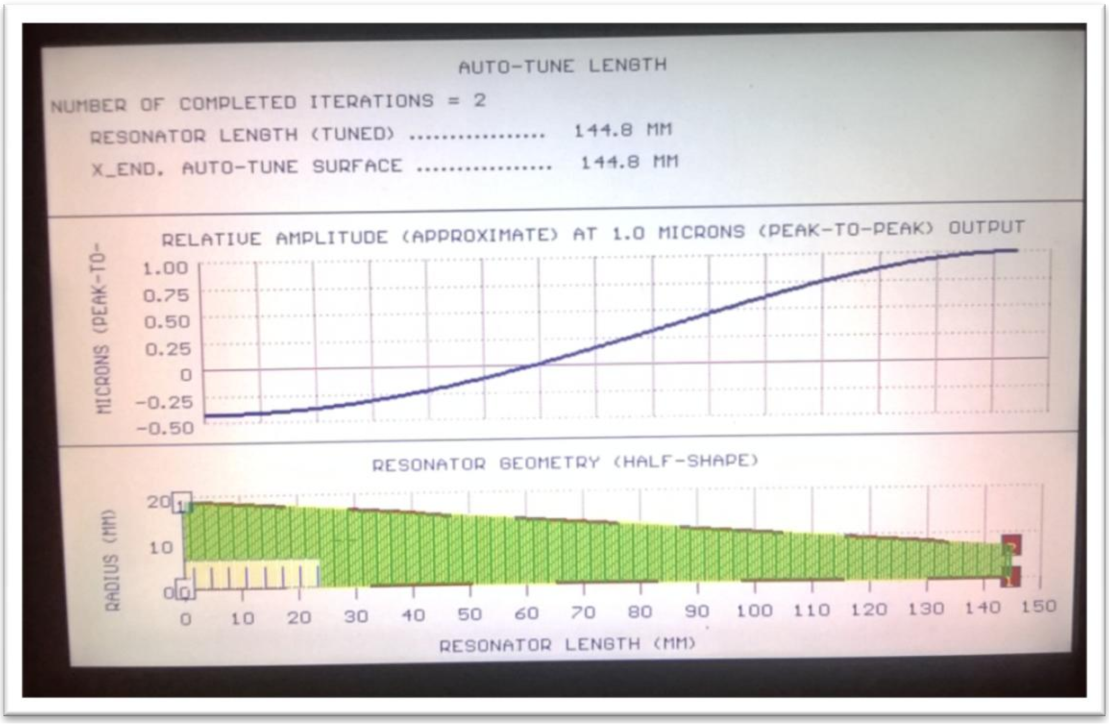

Figure 1. Blanking Sonotrode & Tool Shape with Amplitude Variation

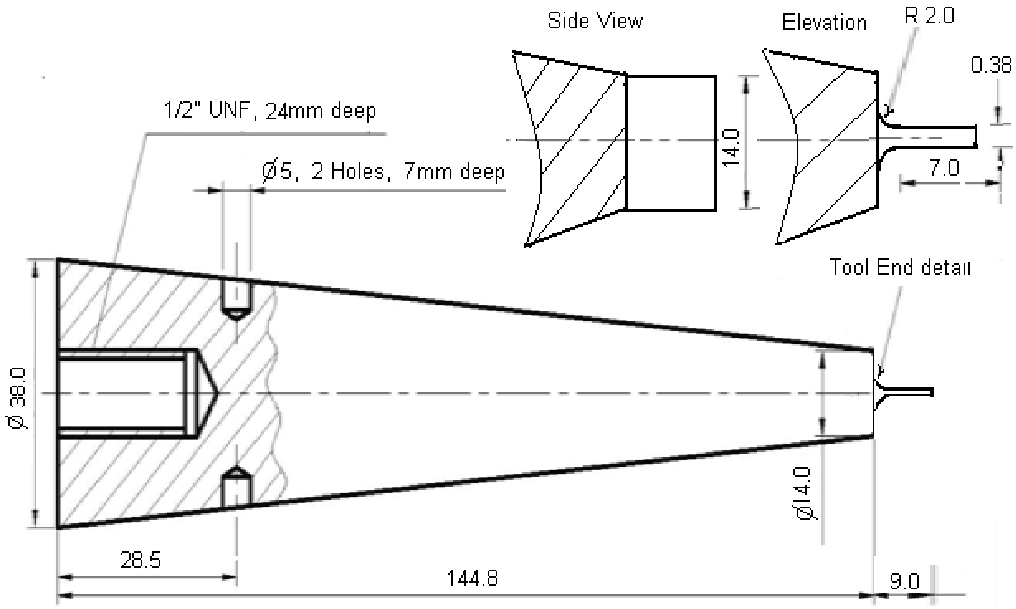

Figure 2. Production Drawing for Blanking Tool

The experimental procedure for producing slits in common glass using ultrasonic machining is described as under.

1) Measure the weight of glass sheet of thickness corresponding to the trial.
2) Mount the glass sheet in molten wax in petri-dish with aluminium foil at its bottom and allow wax to cure.
3) Start slurry circulation and adjust the flow.
4) Set the control parameters and start vibrations using foot operated switch.
5) Machining is completed when through cut is obtained.
6) Machining time is recorded using stop watch.
7) Switch off slurry pump and clean the workpiece using Acetone.
8) Remove workpiece from petri-dish by reheating wax.
9) Measure the weight of glass sheet with the slit.

The material removed during the slitting process is determined by subtracting the mass of glass sheet after machining from the mass of sheet before machining. The MRR is then obtained in terms of volumetric material removal rate considering density of common glass as 2.5 gms/cc. OC is calculated considering the tool thickness of 0.38 mm at the cutting edge as the ideal dimension required and evaluating half of the difference between the largest widths of slit and the ideal dimension. Taper is calculated as a ratio of the half of difference between the top and bottom width of the slit produced to the thickness of the glass sheet. The experimental results are listed in Table 2.

Table 2 Experimental Results

Sr.No	Thickness mm	Amplitude	Pressure bar	MRR mm^3/min	Overcut Mm	Taper
1	1.23	70%	0.5	0.04071	0.10148	0.04125
2	1.23	70%	2	0.0454	0.11873	0.04827
3	1.23	70%	3.5	0.04876	0.13825	0.0562
4	1.23	80%	0.5	0.05336	0.14405	0.05856
5	1.23	80%	2	0.06241	0.1459	0.05931
6	1.23	80%	3.5	0.07383	0.15535	0.06316
7	1.23	90%	0.5	0.07483	0.15618	0.06348
8	1.23	90%	2	0.08701	0.16358	0.06647
9	1.23	90%	3.5	0.09734	0.17268	0.07018
10	1.64	70%	0.5	0.0257	0.1365	0.04161
11	1.64	70%	2	0.02877	0.14545	0.04434
12	1.64	70%	3.5	0.03327	0.1532	0.04671
13	1.64	80%	0.5	0.03081	0.15628	0.04769
14	1.64	80%	2	0.03703	0.1691	0.05156
15	1.64	80%	3.5	0.04342	0.17683	0.05392
16	1.64	90%	0.5	0.05025	0.18463	0.0563
17	1.64	90%	2	0.05416	0.18575	0.05664
18	1.64	90%	3.5	0.05678	0.20065	0.06117
19	3.12	70%	0.5	0.02237	0.1483	0.02377
20	3.12	70%	2	0.02853	0.1585	0.0254
21	3.12	70%	3.5	0.03	0.15933	0.02554
22	3.12	80%	0.5	0.02	0.1712	0.02744
23	3.12	80%	2	0.03	0.18383	0.02947
24	3.12	80%	3.5	0.03	0.19255	0.03085
25	3.12	90%	0.5	0.02722	0.21778	0.0349
26	3.12	90%	2	0.03256	0.21843	0.03423
27	3.12	90%	3.5	0.04152	0.23498	0.03684

III. GRA OPTIMIZATION

3.1 GRA Procedure

GRA is an effective method for solving the complicated interrelationship among the multiple designated performance characteristics. It also provides an efficient and effective solution to multi-input and discrete data problems. In this method, the complex multiple response optimization problem can be simplified into optimization of single response grey relational grade. The procedure for determining the grey relational grade is shown in flow chart Figure 5 [9].

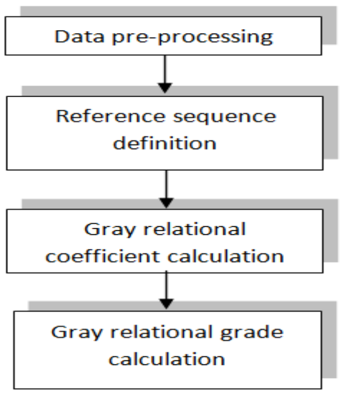

Figure 5. Steps to Determine GRG [9]

***Data pre-processing*:** If the number of experiments is "*m"* and the number of response (i.e. performance characteristics) is "*n* then the i^{th} experiment can be expressed as $Y_i = (y_{i1}, y_{i2}, \ldots, y_{ij}, \ldots, y_{in})$ in decision matrix form, where yij is the performance value (or measure of performance) of response j ($j = 1, 2, \ldots, n$) for experiment i ($i = 1, 2, \ldots, m$). The general form of decision matrix D is given as,

$$D = \begin{bmatrix} y_{1l} & \cdots & y_{1j} & \cdots & y_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ y_{il} & \cdots & y_{ij} & \cdots & y_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ y_{ml} & \cdots & y_{mj} & \cdots & y_{mn} \end{bmatrix}$$

The term Y_i can be translated into the comparability sequence $X_i = (x_{i1}, x_{i2} \ldots x_{ij} \ldots x_{in})$ where x_{ij} is the normalized value of y_{ij} for the response j ($j = 1, 2\ldots n$) of experiment i ($i = 1, 2\ldots m$). After normalization, decision matrix D becomes normalization matrix D' is given as follows.

$$D' = \begin{bmatrix} x_{1l} & \cdots & x_{1j} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{il} & \cdots & x_{ij} & \cdots & x_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{ml} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix}$$

The normalized values x_{ij} are determined by use of following equation. These are for beneficial type, non-beneficial type and target value type responses.

1. If the expectancy of the response is larger-the-better (i.e. beneficial response), then it is expressed by Equation 1.

$$Xij = \frac{(Yij - minYj)}{(maxYj - minYj)} \qquad (1)$$

2. If the expectancy of the response is smaller-the-better (i.e. non-beneficial response), then it si determined by using Equation 2.

$$Xij = \frac{(maxYj - Yij)}{(maxYj - minYj)} \qquad (2)$$

3. If the expectancy of the response is nominal-the-best (i.e. closer to the desired value or target value), then it is expressed by Equation 3.

$$Xij = 1 - [\frac{(Yj^{*} - Yij)}{(maxYij - minYij)}] \qquad (3)$$

where Yj^{*} is closer to the desired value of j^{th} response.

***Reference sequence*:** In comparability sequence all performance values are scaled to [0, 1]. For a response j of experiment i, if the value x_{ij} is equal to 1 or nearer to 1 then the value for any experiment, then the performance of experiment i is considered as best for the response j. The reference sequence X *is defined as* $(x_1, x_2, \ldots, x_j, \ldots, x_n) = (1, 1, \ldots, 1, \ldots, 1)$, where x_j is the reference value for j^{th} response and it aims to find the experiment whose comparability sequence is closest to the reference sequence.

***Grey relational coefficients*:** Grey relational coefficient is used for determining how close x_{ij} is to x_j. The larger the grey relational coefficient, the closer x_{ij} and x_j are. The grey relational coefficient can be calculated using Eq. 4-Eq. 7.

$$\gamma ij = \frac{(\Delta min + (\xi * \Delta max))}{(\Delta ij + (\xi * \Delta max))} \qquad (4)$$

For $i = 1, 2\ldots m$ and $j = 1, 2\ldots n$

Where, γ = the grey relational coefficient

$$\Delta min = min\, ij \,|Xj - Xij| \qquad (5)$$

$$\Delta max = max\, ij\, |Xj - Xij| \qquad (6)$$

$$\Delta ij = |Xj - Xij| \qquad (7)$$

$\xi = Distinguishing\ coefficient\ \xi \in (0,1)$

The purpose of distinguishing coefficient is to expand or compressed the range of the grey relational coefficient. Different distinguishing coefficient may lead to different solution results. Generally a value of 0.5 for distinguishing coefficient is preferred.

Grey relational grades: The measurement formula for quantification in grey relational space is called grey relational grade. A grey relational grade (grey relational degree) is a weighted sum of grey relational coefficients and it can be calculated using Equation 8.

$$\gamma i = \sum_{j=1}^{n} w_j . \gamma ij \quad i = 1, 2\ldots m \text{ and } j = 1, 2\ldots n \qquad (8)$$

where γ_i is the grey relational grade between comparability sequence X_i and reference sequence X_n. It represents correlation between the reference sequence and the comparability sequence, w_j is the weight of response j and depends on decision maker's judgment.

3.2 Optimization Using Grey Analysis

As discussed in section 3.1 step 1, an ideal sequence (X_{ij} = 1, j = 1, 2 . . . 9) for MRR, OC and taper is generated as shown in Table 2 which also shows the experimentally obtained values of these response parameters. Equation 1 is applied for MRR and Equation 2 for OC and taper both of which should be minimized. Grey relational coefficients are calculated taking value of distinguishing coefficient as 0.5 using Equation 4-Equation 7. Table 3 shows the grey relational coefficients for each of the measured responses for ultrasonic slitting of glass. Ultrasonic machining may be used for rough cutting where accuracy may not be as important as the MRR. It can also be used for semi-finishing where equal weight has to be given to all response parameters. USM can be used to obtain final component by finish cutting using small weights for MRR and relatively higher importance to dimensional accuracy in terms of OC and taper. Grey optimization is conducted for all the three cutting scenarios. In case of optimization for rough cutting, value of 0.65 is selected as weight for MRR and OC and taper are given weights of 0.20 and 0.15 respectively. OC being given larger weightage to identify the fact that dimensional accuracy also controls the taper on the feature produced. In case of semi-finish cutting, to balance between MRR and limit the ROC and taper simultaneously, MRR is assigned a weight of 0.34 and OC and taper are given weightage of 0.33 each. In case of finishing cuts, 80% weightage is given to limiting of OC and taper for dimensional accuracy with OC and taper being given weights of 0.5 & 0.3 respectively and MRR is given a low weight of 0.2. These weights are used to calculate grey relational grade using Equation 8 and its order as shown for roughing case in Table 3 for ultrasonic blanking. Similar to roughing case, grey relational grades are found for semi-finishing and finishing cases as well and given ranks in descending order of the grade. These results are listed in Table 4.

Table 2. Sequence of Performance Characteristics after Data Pre-Processing

SN	T	A	P	MRR	OC	Taper	xMRR	xOC	xTaper	ΔMRR	ΔOC	ΔTaper
	Ideal-->			**0.0973**	**0.1015**	**0.0238**	**1.0000**	**1.0000**	**1.0000**	**0.0000**	**0.0000**	**0.0000**
1	1.23	70%	0.5	**0.04071**	**0.10148**	**0.04125**	0.2446	1.0000	0.6234	0.7554	0.0000	0.3766
2	1.23	70%	2	**0.0454**	**0.11873**	**0.04827**	0.3072	0.8708	0.4721	0.6928	0.1292	0.5279
3	1.23	70%	3.5	**0.04876**	**0.13825**	**0.0562**	0.3519	0.7245	0.3011	0.6481	0.2755	0.6989
4	1.23	80%	0.5	**0.05336**	**0.14405**	**0.05856**	0.4133	0.6811	0.2504	0.5867	0.3189	0.7496
5	1.23	80%	2	**0.06241**	**0.1459**	**0.05931**	0.5341	0.6672	0.2343	0.4659	0.3328	0.7657
6	1.23	80%	3.5	**0.07383**	**0.15535**	**0.06316**	0.6864	0.5964	0.1513	0.3136	0.4036	0.8487
7	1.23	90%	0.5	**0.07483**	**0.15618**	**0.06348**	0.6996	0.5903	0.1443	0.3004	0.4097	0.8557
8	1.23	90%	2	**0.08701**	**0.16358**	**0.06647**	0.8621	0.5348	0.0799	0.1379	0.4652	0.9201
9	1.23	90%	3.5	**0.09734**	**0.17268**	**0.07018**	1.0000	0.4667	0.0000	0.0000	0.5333	1.0000
10	1.64	70%	0.5	**0.0257**	**0.1365**	**0.04161**	0.0444	0.7376	0.6156	0.9556	0.2624	0.3844
11	1.64	70%	2	**0.02877**	**0.14545**	**0.04434**	0.0853	0.6706	0.5567	0.9147	0.3294	0.4433
12	1.64	70%	3.5	**0.03327**	**0.1532**	**0.04671**	0.1454	0.6125	0.5058	0.8546	0.3875	0.4942
13	1.64	80%	0.5	**0.03081**	**0.15628**	**0.04769**	0.1125	0.5895	0.4846	0.8875	0.4105	0.5154
14	1.64	80%	2	**0.03703**	**0.1691**	**0.05156**	0.1955	0.4934	0.4011	0.8045	0.5066	0.5989
15	1.64	80%	3.5	**0.04342**	**0.17683**	**0.05392**	0.2807	0.4356	0.3504	0.7193	0.5644	0.6496
16	1.64	90%	0.5	**0.05025**	**0.18463**	**0.0563**	0.3718	0.3772	0.2991	0.6282	0.6228	0.7009
17	1.64	90%	2	**0.05416**	**0.18575**	**0.05664**	0.4239	0.3687	0.2917	0.5761	0.6313	0.7083
18	1.64	90%	3.5	**0.05678**	**0.20065**	**0.06117**	0.4589	0.2571	0.1942	0.5411	0.7429	0.8058
19	3.12	70%	0.5	**0.02237**	**0.1483**	**0.02377**	0.0000	0.6493	1.0000	1.0000	0.3507	0.0000
20	3.12	70%	2	**0.02853**	**0.1585**	**0.0254**	0.0821	0.5728	0.9647	0.9179	0.4272	0.0353
21	3.12	70%	3.5	**0.03**	**0.15933**	**0.02554**	0.1356	0.5667	0.9619	0.8644	0.4333	0.0381
22	3.12	80%	0.5	**0.02**	**0.1712**	**0.02744**	0.0129	0.4777	0.9208	0.9871	0.5223	0.0792
23	3.12	80%	2	**0.03**	**0.18383**	**0.02947**	0.0719	0.3831	0.8772	0.9281	0.6169	0.1228
24	3.12	80%	3.5	**0.03**	**0.19255**	**0.03085**	0.1501	0.3178	0.8473	0.8499	0.6822	0.1527
25	3.12	90%	0.5	**0.02722**	**0.21778**	**0.0349**	0.0646	0.1288	0.7601	0.9354	0.8712	0.2399
26	3.12	90%	2	**0.03256**	**0.21843**	**0.03423**	0.1359	0.1240	0.7746	0.8641	0.8760	0.2254
27	3.12	90%	3.5	**0.04152**	**0.23498**	**0.03684**	0.2554	0.0000	0.7182	0.7446	1.0000	0.2818
		Max.		0.097344	0.234975	0.070181	1.0000	0.0000	0.0000	0.0000	1.0000	1.0000
		Min.		**0.022375**	**0.101475**	**0.023765**	0.0000	1.0000	1.0000	1.0000	0.0000	0.0000
		Diff.		**0.074969**	**0.133500**	**0.046415**	0.7015	0.7601	0.5120	0.2985	0.2399	0.4880

Table 3. Grey Relational Coefficients & Grey Relational Grades for Roughing

Sr. No	γ_{MRR} 0.65	γ_{OC} 0.20	γ_T 0.15	Grade	Rank
1	0.3983	1.0000	0.5704	0.5444	5
2	0.4192	0.7946	0.4864	0.5044	7
3	0.4355	0.6448	0.4171	0.4746	12
4	0.4601	0.6106	0.4001	0.4812	10
5	0.5176	0.6004	0.3950	0.5158	6
6	0.6145	0.5534	0.3707	0.5657	4
7	0.6247	0.5496	0.3688	0.5713	3
8	0.7838	0.5180	0.3521	0.6659	2
9	1.0000	0.4839	0.3333	0.7968	1
10	0.3435	0.6559	0.5654	0.4393	18
11	0.3534	0.6028	0.5301	0.4298	20
12	0.3691	0.5634	0.5029	0.4280	21
13	0.3604	0.5492	0.4924	0.4179	24
14	0.3833	0.4967	0.4550	0.4167	25
15	0.4101	0.4697	0.4349	0.4257	22
16	0.4432	0.4453	0.4163	0.4396	17
17	0.4646	0.4420	0.4138	0.4525	13
18	0.4803	0.4023	0.3829	0.4501	14
19	0.3333	0.5877	1.0000	0.4842	9
20	0.3526	0.5393	0.9341	0.4772	11
21	0.3664	0.5357	0.9291	0.4847	8
22	0.3362	0.4891	0.8632	0.4459	15
23	0.3501	0.4477	0.8028	0.4375	19
24	0.3704	0.4229	0.7660	0.4402	16
25	0.3483	0.3647	0.6758	0.4007	27
26	0.3665	0.3634	0.6892	0.4143	26
27	0.4017	0.3333	0.6396	0.4237	23

Table 4. Grey Relational Grades for Various Ultrasonic Slitting Conditions

S. N.	Roughing		Semi-Finishing		Finishing	
	Grade	Rank	Grade	Rank	Grade	Rank
1	0.5444	5	**0.6562**	**1**	**0.7508**	**1**
2	0.5044	7	0.5668	6	0.6271	3
3	0.4746	12	0.4991	15	0.5346	10
4	0.4812	10	0.4903	17	0.5173	14
5	0.5158	6	0.5044	14	0.5222	12
6	0.5657	4	0.5129	13	0.5108	16
7	0.5713	3	0.5144	12	0.5104	17
8	0.6659	2	0.5513	8	0.5214	13
9	**0.7968**	**1**	0.6057	5	0.5419	8
10	0.4393	18	0.5216	10	0.5662	7
11	0.4298	20	0.4954	16	0.5311	11
12	0.4280	21	0.4785	18	0.5064	18
13	0.4179	24	0.4673	20	0.4944	19
14	0.4167	25	0.4450	23	0.4615	21
15	0.4257	22	0.4382	25	0.4474	23
16	0.4396	17	0.4349	26	0.4362	26
17	0.4525	13	0.4401	24	0.4381	25
18	0.4501	14	0.4218	27	0.4121	27
19	0.4842	9	0.6404	2	0.6605	2
20	0.4772	11	0.6087	4	0.6204	4
21	0.4847	8	0.6104	3	0.6199	5
22	0.4459	15	0.5629	7	0.5708	6
23	0.4375	19	0.5335	9	0.5347	9
24	0.4402	16	0.5198	11	0.5154	15
25	0.4007	27	0.4629	21	0.4547	22
26	0.4143	26	0.4730	19	0.4618	20
27	0.4237	23	0.4582	22	0.4389	24

IV. RESULTS & DISCUSSION

From the listing of grey relational grades in Table 4 it is observed that for ultrasonic slitting of common glass, in case of roughing the best rank is attributed to DOE serial 9 which relates to lowest thickness and maximum pressure and maximum amplitude. While in case of semi-finishing as well as finishing the best rank is attributed to DOE serial 1 which is the combination of lowest thickness, lowest pressure and lowest amplitude.

This is matching with the experimental findings and subsequent analysis showing that MRR is higher for lower thickness values and higher pressure and amplitude values. In case of semi-finishing and finishing operations the effective contribution of MRR to the grade is lower as compared to the combined effect of OC and taper which leads to the same combination being selected as the best for semi-finishing and finishing cases. These combinations are indicated in bold in Table 4.

IV. CONCLUSION

Following major conclusions can be drawn from the attempt to apply GRA to ultrasonic slitting of glass,

(1) GRA procedure converts decision making involving multiple performance characteristics into a decision regarding single performance indicator in terms of the grey relational grade using suitable weights.
(2) Weights should be carefully decided depending upon the machining performance required.
(3) The optimum combination of control variables can be selected by ranking the parameter combinations using GRA procedure.
(4) The combination of lowest thickness, highest pressure and highest amplitude is found optimum for roughing.
(5) The combination of lowest thickness, lowest pressure and lowest amplitude is found optimum for semi-finishing and finishing.

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