IJSRD - International Journal for Scientific Research & Development| Vol. 3, Issue 10, 2015 | ISSN (online): 2321-0613

Multi-Objective Optimization for Ultrasonic Drilling of GFRP using Grey Relational Analysis

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Abstract— For machining of brittle materials like glass, ceramics etc., ultrasonic machining has become very popular. Number of engineering and common applications require use of glass fiber reinforced plastic (GFRP) and it is essential to machine features in this material for use. In this work, full factorial design of experiments (DoE) based investigation is conducted to study the effect of process parameters on ultrasonic drilling of GFRP. The control parameters selected include amplitude, pressure and thickness of the GFRP sheet being machined. Three levels of each of these parameters are selected giving $3^3 = 27$ trials. The material removal rate (MRR), overcut (OC), taper, top delamination and bottom delamination produced on the GFRP while slitting are measured as response parameters. Ultrasonic machining has number of process parameters and is not a simple process to control and get desired machining results. Grey relational analysis is applied to the experimental data to obtain the best combination of input parameters for different cutting conditions like roughing, semi-finishing and finishing. Parameter combinations are given grades using grey relational analysis (GRA) process and the optimum combination is suggested for various requirements of machining in terms of roughing, semi-finishing and finishing.

Key words: GFRP, MRR, BDF

I. INTRODUCTION

Traditional ceramics and glasses are extensively used to manufacture many products. GFRP material has gained popularity in many applications too. GFRP has 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 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 holes in GFRP is required in number of applications in automobiles, aerospace, furniture etc. In order to produce these components, ultrasonic drilling is a good method. For machining to required dimensions, the setting of process parameters to appropriate value is very essential.

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

In this paper, the experimental data obtained by conducting experiments to produce holes using ultrasonic process on GFRP is analyzed using grey relational analysis to find the optimum process parameters.

II. ULTRASONIC DRILLING EXPERIMENTS

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

Amplitude	Pressure	GFRP Thickness
$A_1 = 70\%$	$P_1 = 1$ bar	$t_1 = 1.3$ mm
$A_2 = 80\%$	$P_2 = 2$ bar	$t_2 = 2$ mm
$A_3 = 90\%$	$P_3 = 3$ bar	$t_3 = 2.3$ mm

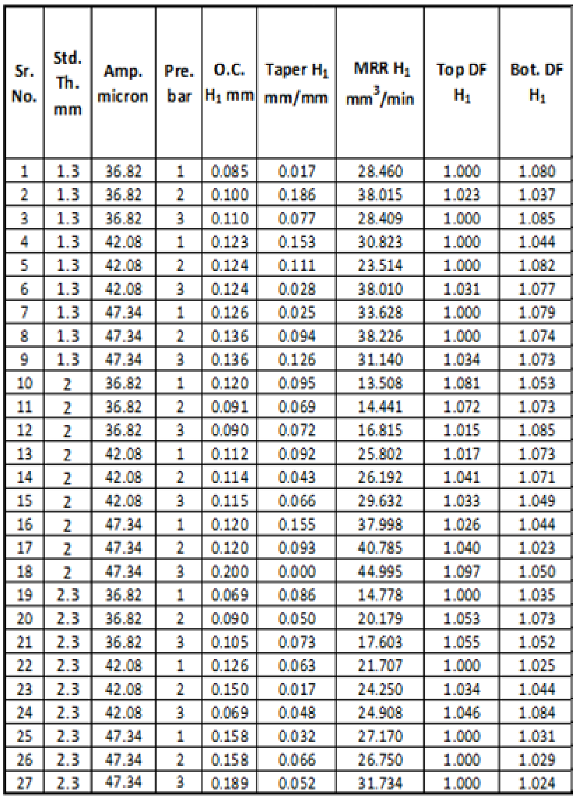
Table 1**:** Parameters and Their Levels

Material removal rate (MRR), overcut (OC), taper, top delamination factor (TDF) and bottom delamination factor (BDF) generated during ultrasonic drilling 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 experimental procedure for producing holes in GFRP using ultrasonic machining is described as under.

1) Measure the weight of GFRP sheet of thickness corresponding to the trial.
2) Mount the GFRP 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 of slurry.
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.
8) Remove workpiece from petri-dish by reheating wax.
9) Measure the weight of GFRP with the hole and the blank cut out during drilling.

The material removed on weight basis is obtained by subtracting the sum of mass of blank and mass of slug from the mass of GFRP sheet before machining. The MRR is then obtained in terms of volumetric material removal rate by taking density of GFRP. The top and bottom diameters of each drilled hole were measured using 0.1 micron accuracy travelling microscope four times by changing the position. Average of these values was taken as the value for top and bottom diameters.



Sr. No.	Std. Th. mm	Amp. micron	Pre. bar	O.C. H_1 mm	Taper H_1 mm/mm	MRR H_1 mm^3/min	Top DF H_1	Bot. DF H_1
1	1.3	36.82	1	0.085	0.017	28.460	1.000	1.080
2	1.3	36.82	2	0.100	0.186	38.015	1.023	1.037
3	1.3	36.82	3	0.110	0.077	28.409	1.000	1.085
4	1.3	42.08	1	0.123	0.153	30.823	1.000	1.044
5	1.3	42.08	2	0.124	0.111	23.514	1.000	1.082
6	1.3	42.08	3	0.124	0.028	38.010	1.031	1.077
7	1.3	47.34	1	0.126	0.025	33.628	1.000	1.079
8	1.3	47.34	2	0.136	0.094	38.226	1.000	1.074
9	1.3	47.34	3	0.136	0.126	31.140	1.034	1.073
10	2	36.82	1	0.120	0.095	13.508	1.081	1.053
11	2	36.82	2	0.091	0.069	14.441	1.072	1.073
12	2	36.82	3	0.090	0.072	16.815	1.015	1.085
13	2	42.08	1	0.112	0.092	25.802	1.017	1.073
14	2	42.08	2	0.114	0.043	26.192	1.041	1.071
15	2	42.08	3	0.115	0.066	29.632	1.033	1.049
16	2	47.34	1	0.120	0.155	37.998	1.026	1.044
17	2	47.34	2	0.120	0.093	40.785	1.040	1.023
18	2	47.34	3	0.200	0.000	44.995	1.097	1.050
19	2.3	36.82	1	0.069	0.086	14.778	1.000	1.035
20	2.3	36.82	2	0.090	0.050	20.179	1.053	1.073
21	2.3	36.82	3	0.105	0.073	17.603	1.055	1.052
22	2.3	42.08	1	0.126	0.063	21.707	1.000	1.025
23	2.3	42.08	2	0.150	0.017	24.250	1.034	1.044
24	2.3	42.08	3	0.069	0.048	24.908	1.046	1.084
25	2.3	47.34	1	0.158	0.032	27.170	1.000	1.031
26	2.3	47.34	2	0.158	0.066	26.750	1.000	1.029
27	2.3	47.34	3	0.189	0.052	31.734	1.000	1.024

Table 2**:** Experimental Results

The value of OC was determined by halving the difference between larger of the top and bottom hole diameters and the tool diameter which is 8 mm. Taper was obtained by dividing the difference between top and bottom diameters by the thickness. The delamination factor is measured by taking ratio of maximum diameter of hole to sum of the diameter of tool and abrasive particle size. The experimental results are listed in Table II.

III. GRA OPTIMIZATION

A. *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].

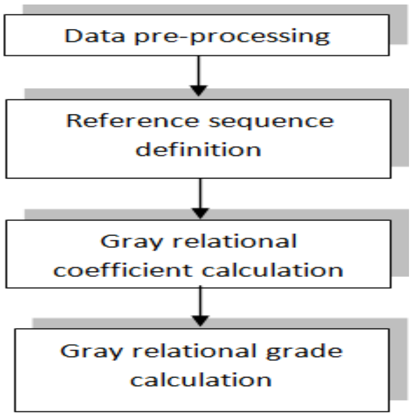


Fig. 1. Steps to Determine GRG

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.

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

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

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

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.

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

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

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 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.

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

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

Where, $\boldsymbol{\gamma}$ = the grey relational coefficient

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

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

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

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

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.

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.

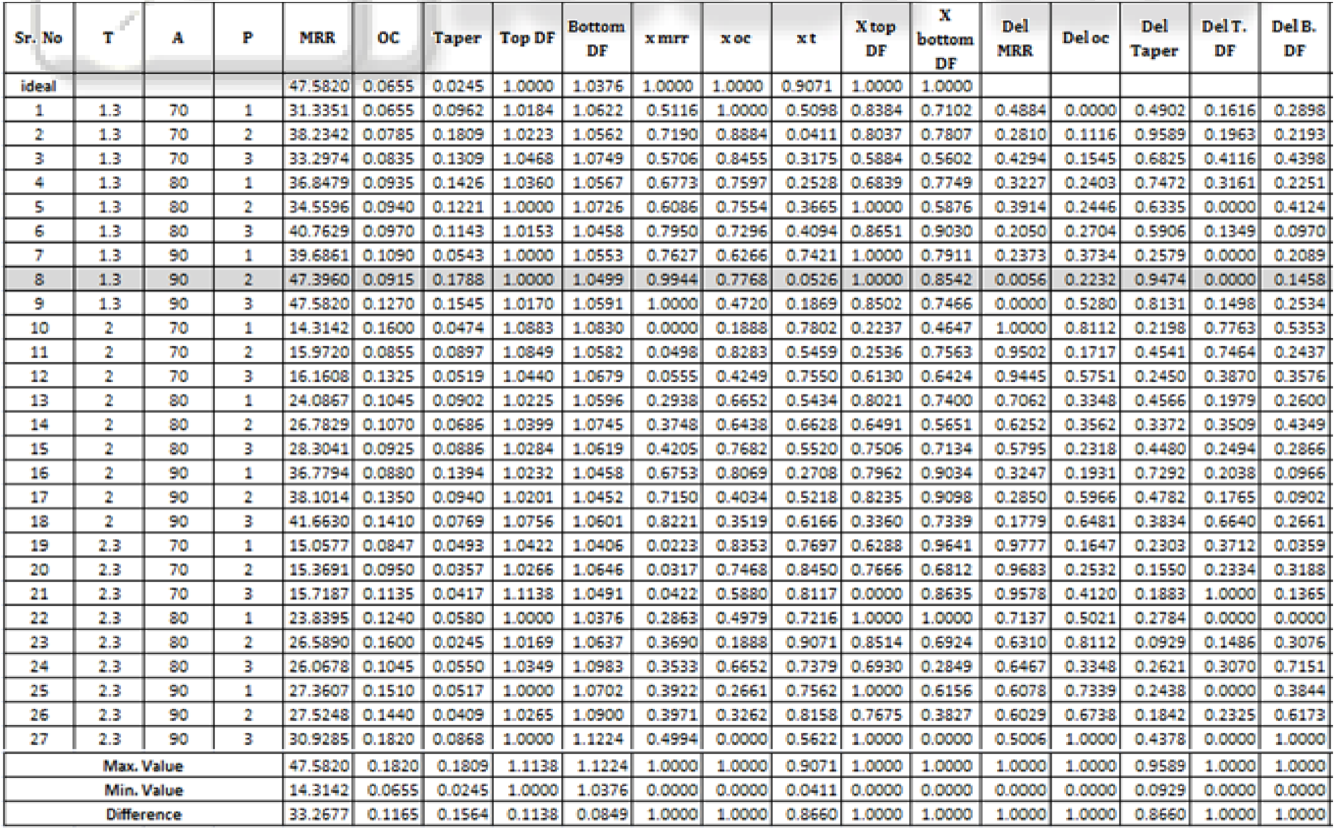
$$\gamma i = \sum_{j=1}^{n} w_j . \gamma ij \quad i = 1, 2\ldots m \text{ and } j = 1, 2\ldots n \qquad (8)$$

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.

B. *Optimization Using Grey Analysis*

As discussed in section A step 1, an ideal sequence (X_{ij} = 1, j = 1, 2 . . . 9) for MRR, OC, taper and delaminations are generated as shown in Table III 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 IV shows the grey relational coefficients for each of the measured responses for ultrasonic drilling of GFRP. 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, taper, top delamination factor and bottom delamination factor. Grey optimization is conducted for all the three cutting scenarios. In case of optimization for rough cutting, value of 0.40 is selected as weight for MRR and overcut, taper, top delamination factor and bottom delamination factor are given a weight of 0.15 each. In case of semi-finish cutting, to balance between MRR and overcut, taper, top delamination factor and bottom delamination factor simultaneously, MRR is assigned a weight of 0.2 and overcut, taper, top delamination factor and bottom delamination factor are given weightage of 0.2 each. In case of finishing cuts, for dimensional accuracy 30% weightage is given to overcut, 30% weightage is given to taper, 15% weightage is given to top delamination factor, 15% weightage is given to bottom delamination factor and only 10% weightage is given to MRR. These weights are used to calculate grey relational grade using Equation 8 and its order as shown for roughing case in Table IV for ultrasonic drilling of GFRP.

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 V.



Sr. No	T	A	P	MRR	OC	Taper	Top DF	Bottom DF	x mrr	x oc	x t	X top DF	X bottom DF	Del MRR	Del oc	Del Taper	Del T. DF	Del B. DF
ideal				47.5820	0.0655	0.0245	1.0000	1.0376	1.0000	1.0000	0.9071	1.0000	1.0000					
1	1.3	70	1	31.3351	0.0655	0.0962	1.0184	1.0622	0.5116	1.0000	0.5098	0.8384	0.7102	0.4884	0.0000	0.4902	0.1616	0.2898
2	1.3	70	2	38.2342	0.0785	0.1809	1.0223	1.0562	0.7190	0.8884	0.0411	0.8037	0.7807	0.2810	0.1116	0.9589	0.1963	0.2193
3	1.3	70	3	33.2974	0.0835	0.1309	1.0468	1.0749	0.5706	0.8455	0.3175	0.5884	0.5602	0.4294	0.1545	0.6825	0.4116	0.4398
4	1.3	80	1	36.8479	0.0935	0.1426	1.0360	1.0567	0.6773	0.7597	0.2528	0.6839	0.7749	0.3227	0.2403	0.7472	0.3161	0.2251
5	1.3	80	2	34.5596	0.0940	0.1221	1.0000	1.0726	0.6086	0.7554	0.3665	1.0000	0.5876	0.3914	0.2446	0.6335	0.0000	0.4124
6	1.3	80	3	40.7629	0.0970	0.1143	1.0153	1.0458	0.7950	0.7296	0.4094	0.8651	0.9030	0.2050	0.2704	0.5906	0.1349	0.0970
7	1.3	90	1	39.6861	0.1090	0.0543	1.0000	1.0553	0.7627	0.6266	0.7421	1.0000	0.7911	0.2373	0.3734	0.2579	0.0000	0.2089
8	1.3	90	2	47.3960	0.0915	0.1788	1.0000	1.0499	0.9944	0.7768	0.0526	1.0000	0.8542	0.0056	0.2232	0.9474	0.0000	0.1458
9	1.3	90	3	47.5820	0.1270	0.1545	1.0170	1.0591	1.0000	0.4720	0.1869	0.8502	0.7466	0.0000	0.5280	0.8131	0.1498	0.2534
10	2	70	1	14.3142	0.1600	0.0474	1.0883	1.0830	0.0000	0.1888	0.7802	0.2237	0.4647	1.0000	0.8112	0.2198	0.7763	0.5353
11	2	70	2	15.9720	0.0855	0.0897	1.0849	1.0582	0.0498	0.8283	0.5459	0.2536	0.7563	0.9502	0.1717	0.4541	0.7464	0.2437
12	2	70	3	16.1608	0.1325	0.0519	1.0440	1.0679	0.0555	0.4249	0.7550	0.6130	0.6424	0.9445	0.5751	0.2450	0.3870	0.3576
13	2	80	1	24.0867	0.1045	0.0902	1.0225	1.0596	0.2938	0.6652	0.5434	0.8021	0.7400	0.7062	0.3348	0.4566	0.1979	0.2600
14	2	80	2	26.7829	0.1070	0.0686	1.0399	1.0745	0.3748	0.6438	0.6628	0.6491	0.5651	0.6252	0.3562	0.3372	0.3509	0.4349
15	2	80	3	28.3041	0.0925	0.0886	1.0284	1.0619	0.4205	0.7682	0.5520	0.7506	0.7134	0.5795	0.2318	0.4480	0.2494	0.2866
16	2	90	1	36.7794	0.0880	0.1394	1.0232	1.0458	0.6753	0.8069	0.2708	0.7962	0.9034	0.3247	0.1931	0.7292	0.2038	0.0966
17	2	90	2	38.1014	0.1350	0.0940	1.0201	1.0452	0.7150	0.4034	0.5218	0.8235	0.9098	0.2850	0.5966	0.4782	0.1765	0.0902
18	2	90	3	41.6630	0.1410	0.0769	1.0756	1.0601	0.8221	0.3519	0.6166	0.3360	0.7339	0.1779	0.6481	0.3834	0.6640	0.2661
19	2.3	70	1	15.0577	0.0847	0.0493	1.0422	1.0406	0.0223	0.8353	0.7697	0.6288	0.9641	0.9777	0.1647	0.2303	0.3712	0.0359
20	2.3	70	2	15.3691	0.0950	0.0357	1.0266	1.0646	0.0317	0.7468	0.8450	0.7666	0.6812	0.9683	0.2532	0.1550	0.2334	0.3188
21	2.3	70	3	15.7187	0.1135	0.0417	1.1138	1.0491	0.0422	0.5880	0.8117	0.0000	0.8635	0.9578	0.4120	0.1883	1.0000	0.1365
22	2.3	80	1	23.8395	0.1240	0.0580	1.0000	1.0376	0.2863	0.4979	0.7216	1.0000	1.0000	0.7137	0.5021	0.2784	0.0000	0.0000
23	2.3	80	2	26.5890	0.1600	0.0245	1.0169	1.0637	0.3690	0.1888	0.9071	0.8514	0.6924	0.6310	0.8112	0.0929	0.1486	0.3076
24	2.3	80	3	26.0678	0.1045	0.0550	1.0349	1.0983	0.3533	0.6652	0.7379	0.6930	0.2849	0.6467	0.3348	0.2621	0.3070	0.7151
25	2.3	90	1	27.3607	0.1510	0.0517	1.0000	1.0702	0.3922	0.2661	0.7562	1.0000	0.6156	0.6078	0.7339	0.2438	0.0000	0.3844
26	2.3	90	2	27.5248	0.1440	0.0409	1.0265	1.0900	0.3971	0.3262	0.8158	0.7675	0.3827	0.6029	0.6738	0.1842	0.2325	0.6173
27	2.3	90	3	30.9285	0.1820	0.0868	1.0000	1.1224	0.4994	0.0000	0.5622	1.0000	0.0000	0.5006	1.0000	0.4378	0.0000	1.0000
Max. Value				47.5820	0.1820	0.1809	1.1138	1.1224	1.0000	1.0000	0.9071	1.0000	1.0000	1.0000	1.0000	0.9589	1.0000	1.0000
Min. Value				14.3142	0.0655	0.0245	1.0000	1.0376	0.0000	0.0000	0.0411	0.0000	0.0000	0.0000	0.0000	0.0929	0.0000	0.0000
Difference				33.2677	0.1165	0.1564	0.1138	0.0849	1.0000	1.0000	0.8660	1.0000	1.0000	1.0000	1.0000	0.8660	1.0000	1.0000

Table 3**:** Sequence of Performance Characteristics After Data Pre-Processing

IV. RESULTS & DISCUSSION

From the listing of grey relational grades in Table V it is observed that for ultrasonic drilling of GFRP, in case of roughing as well as semi-finishing the best rank is attributed to DOE serial 8 which relates to lowest thickness and intermediate pressure and maximum amplitude. While in case of finishing the best rank is attributed to DOE serial 1 which is the combination of lowest thickness, lowest pressure and lowest amplitude.

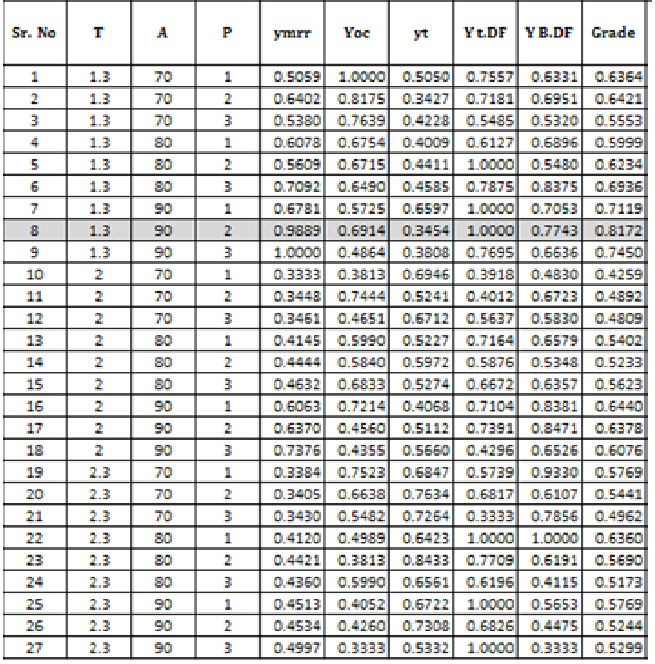
This is matching with the experimental findings and subsequent analysis showing that MRR is higher for lower thickness values and higher pressure and amplitude values. In case of finishing operations the effective contribution of MRR to the grade is lower as compared to the combined effect of OC and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

V. CONCLUSION

Following major conclusions can be drawn from the attempt to apply GRA to ultrasonic drilling of GFRP,

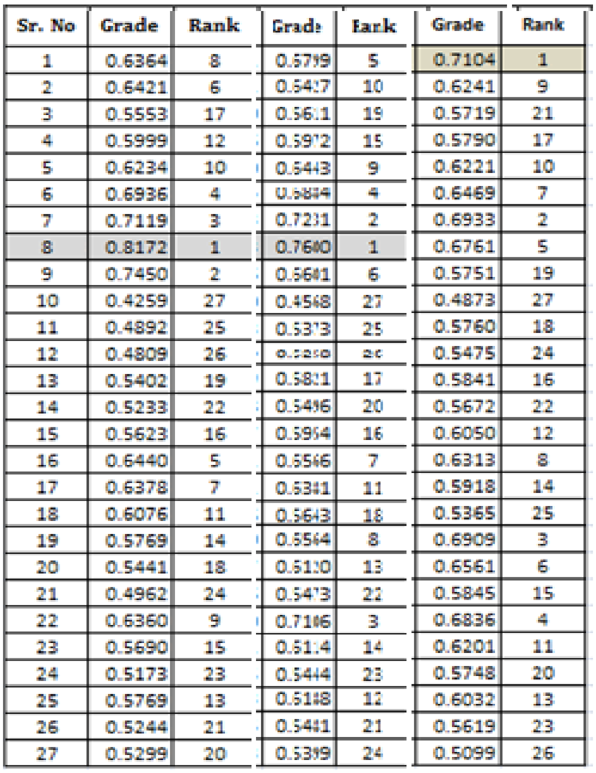
1) GRA transforms decision making involving multiple performance objectives into a decision regarding single performance indicator denoted by the grey relational grade using suitable weights.
2) Weights should be carefully decided based on the machining performance required.
3) The optimum combination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

The combination of lowest thickness, lowest pressure and lowest amplitude is found optimum for finishing.



Sr. No	T	A	P	ymrr	Yoc	yt	Y t.DF	Y B.DF	Grade
1	1.3	70	1	0.5059	1.0000	0.5050	0.7557	0.6331	0.6364
2	1.3	70	2	0.6402	0.8175	0.3427	0.7181	0.6951	0.6421
3	1.3	70	3	0.5380	0.7639	0.4228	0.5485	0.5320	0.5553
4	1.3	80	1	0.6078	0.6754	0.4009	0.6127	0.6896	0.5999
5	1.3	80	2	0.5609	0.6715	0.4411	1.0000	0.5480	0.6234
6	1.3	80	3	0.7092	0.6490	0.4585	0.7875	0.8375	0.6936
7	1.3	90	1	0.6781	0.5725	0.6597	1.0000	0.7053	0.7119
8	1.3	90	2	0.9889	0.6914	0.3454	1.0000	0.7743	0.8172
9	1.3	90	3	1.0000	0.4864	0.3808	0.7695	0.6636	0.7450
10	2	70	1	0.3333	0.3813	0.6946	0.3918	0.4830	0.4259
11	2	70	2	0.3448	0.7444	0.5241	0.4012	0.6723	0.4892
12	2	70	3	0.3461	0.4651	0.6712	0.5637	0.5830	0.4809
13	2	80	1	0.4145	0.5990	0.5227	0.7164	0.6579	0.5402
14	2	80	2	0.4444	0.5840	0.5972	0.5876	0.5348	0.5233
15	2	80	3	0.4632	0.6833	0.5274	0.6672	0.6357	0.5623
16	2	90	1	0.6063	0.7214	0.4068	0.7104	0.8381	0.6440
17	2	90	2	0.6370	0.4560	0.5112	0.7391	0.8471	0.6378
18	2	90	3	0.7376	0.4355	0.5660	0.4296	0.6526	0.6076
19	2.3	70	1	0.3384	0.7523	0.6847	0.5739	0.9330	0.5769
20	2.3	70	2	0.3405	0.6638	0.7634	0.6817	0.6107	0.5441
21	2.3	70	3	0.3430	0.5482	0.7264	0.3333	0.7856	0.4962
22	2.3	80	1	0.4120	0.4989	0.6423	1.0000	1.0000	0.6360
23	2.3	80	2	0.4421	0.3813	0.8433	0.7709	0.6191	0.5690
24	2.3	80	3	0.4360	0.5990	0.6561	0.6196	0.4115	0.5173
25	2.3	90	1	0.4513	0.4052	0.6722	1.0000	0.5653	0.5769
26	2.3	90	2	0.4534	0.4260	0.7308	0.6826	0.4475	0.5244
27	2.3	90	3	0.4997	0.3333	0.5332	1.0000	0.3333	0.5299

Table. 4: Grey Relational Coefficients & Grey Relational Grades for Roughing



Sr. No	Grade	Rank	Grade	Rank	Grade	Rank
1	0.6364	8	0.5719	5	0.7104	1
2	0.6421	6	0.5417	10	0.6241	9
3	0.5553	17	0.5611	19	0.5719	21
4	0.5999	12	0.5972	15	0.5790	17
5	0.6234	10	0.6443	9	0.6221	10
6	0.6936	4	0.6884	4	0.6469	7
7	0.7119	3	0.7231	2	0.6933	2
8	0.8172	1	0.7600	1	0.6761	5
9	0.7450	2	0.6641	6	0.5751	19
10	0.4259	27	0.4568	27	0.4873	27
11	0.4892	25	0.5373	25	0.5760	18
12	0.4809	26	[illegible]	[illegible]	0.5475	24
13	0.5402	19	0.5821	17	0.5841	16
14	0.5233	22	0.5496	20	0.5672	22
15	0.5623	16	0.5954	16	0.6050	12
16	0.6440	5	0.6566	7	0.6313	8
17	0.6378	7	0.6341	11	0.5918	14
18	0.6076	11	0.5643	18	0.5365	25
19	0.5769	14	0.6564	8	0.6909	3
20	0.5441	18	0.6130	13	0.6561	6
21	0.4962	24	0.5473	22	0.5845	15
22	0.6360	9	0.7186	3	0.6836	4
23	0.5690	15	0.6114	14	0.6201	11
24	0.5173	23	0.5444	23	0.5748	20
25	0.5769	13	0.6188	12	0.6032	13
26	0.5244	21	0.5441	21	0.5619	23
27	0.5299	20	0.5399	24	0.5099	26

Table 5: Grey Relational Grades for Various Ultrasonic Drilling Conditions

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