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An Exploratory Investigation and Optimization of Taper Cutting Operation with Wire Electro Discharge Machining

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Abstract

Taper cutting, a typical application of Wire Electro Discharge Machining process is widely used to produce parts with complex geometry such as cutting and extrusion dies, which finds wide application in tool and die making industry. Taper angle becomes a vital process parameter during taper cutting and is a critical performance measure for the tool and die making industry. The present investigation is initiated with a thought to optimize the different process parameters such as pulse on time (Ton), wire tension (WT), wire feed rate (WFR), taper angle (TA) on the performance measures namely taper error (TE), material removal rate (MRR) and surface roughness (SR) during taper cutting operation utilizing WEDM.
Experiments were conducted using Taguchi's L9 (34) orthogonal array on En-31 tool steel work material using brass wire of 0.25 mm diameter, as electrode material. The parametric multi-objective optimization of the experimental results has been carried out using Taguchi based Grey Relational Analysis (TGRA). The analyzed results uncovers that the pulse on time is the utmost prompting factor for MRR and SR while the taper angle cut on the work material turn out to be a significant factor for taper error.

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Keywords: WEDM; Tool steel; Taper cutting; Taguchi based grey relational; Material removal rate; Taper error; Surface roughness

1. Introduction

Recent technological changes in the manufacturing industries and the demand for hard and difficult to cut material have made wire electro discharge machining (WEDM) process a commonly recognized non-conventional machining process.

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Nomenclature

WEDM	wire electro discharge machining
Ton	pulse on time
WT	wire tension
WFR	wire feed rate
TA	taper angle
MRR	material removal rate
SR	surface roughness
TGRA	taguchi based grey relational analysis

WEDM uses a continuously moving conductive wire electrode to easily cut and shape advance material without distortion or burrs [1]. WEDM, an electro-thermal machining process erodes work material through electric discharges between the work material and the wire electrode that causes localized temperatures high enough to melt and vaporize the metal within the localised region [2-3]. WEDM is used to cut complicated contours and intricate shape in conductive difficult-to-cut materials, thus imparting high degree of accuracy and better surface finish. The only requirement for WEDM is that work material and wire electrode materials should be electrically conductive [4]. There is no contact between the wire and work material during machining. Proper flushing is essential to prevent formation of resolidified layers and give improved surface finish.

These days WEDM has become an effective solution for the machining of engineering materials such as tool and die steel, superalloys, ceramics and composites, which finds wide application in tool and die making, aerospace, nuclear and automobile industries [5].

The systematic study using design of experiment on the angular error during WEDM taking part thickness, pulse on time, taper angle, pulse energy and open circuit voltage as process parameter has been made on AISI D2 tool steel material using Coated Broncocut- W wire with diameter 0.2 mm. It was concluded that the most influencing factor for the angular error was the part thickness and the angle that is to be cut which decide wire mechanical behaviour also there was a small effect of EDM parameters on the angular error [6]. The modified Denavit–Hartenberg (DH) notation has been implemented to improve the precision and accuracy of the machined components. By developing the effective wire compensation to specify the location of the wire matrix for the machining using brass wire electrode of diameter 0.25mm. The results showed that the components that are machined using the proposed wire compensation method are very close to the designed value in comparison with the built-in wire compensation [7].

The WEDM has been utilized to improve the corner cutting accuracy of thin parts on the aluminum alloy using copper wire electrode of diameter 0.25 mm. The results showed that the magnitude of the machining error during the corner cutting is especially dependent on the corner angle, and the work material thickness and the outside corners are bent in the direction of wire electrode, but it was opposite in the diamagnetic work piece. The bending is caused due electromagnetic forces developed during the machining process. These forces occur due to the interaction between the electric current which pass through the wire and the workpiece during the electrical discharge [8].

The tapered parts of AISI D3 tool steel were produced by WEDM process using copper wire electrode of 0.25mm diameter. The process parameters namely pulse on time, peak current wire tension and taper angle were considered in the study. The results showed that cutting speed is mainly influenced by the pulse on time and peak current, and independent of taper angle [9]. The effect of pulse on time, wire feed rate and pulse off time was studied during the WEDM machining of AISI D7 using brass wire electrode of diameter 0.25 mm. It was found that for material removal rate the most influencing parameter is pulse on time and pulse off time, whereas the wire feed rate is least influencing [10]. The improvement in the contouring accuracy in case of stairs tapering by controlling the feed rate surge around the corners has been performed to maintain the accuracy of desired part [11]. The taper angle, peak current and dielectric flow rate was the most promoting factors for the taper error but in case of radius over cut the significant factors reported was the pulse on time, taper angle and peak current during the WEDM machining WC composite having 5.3% cobalt with zinc coated brass wire electrode of diameter 0.25mm [12].

Taper cutting is a unique capability of WEDM process by which any draft tapered parts with different cross-section and taper angles can be produced effectively. From the overview of past literature, it has been found that limited published work has been reported till date on the taper cutting operation using WEDM. All the dies are provided with taper to avoid possible part sticking and smooth ejection [9-13]. This study will investigate the influence of process parameter namely pulse on time, wire tension wire feed rate and taper angle in the taper cutting of En 31 using brass wire electrode of diameter 0.25mm by WEDM. En 31 is widely popular tool steel used in the manufacturing of tool and dies used as the work material in the study.

1.2 Experimentation

1.2.1 Materials

In the present investigation, a rectangular plate of En-31 tool steel was taken as work material with a dimension of 300×200×25 mm, shown in Fig 1. The tool steel En-31 (AISI 52100) have high carbon content which contributes in varying hardness in range of 59 - 65 HRC, which imparts wear resistance and make it an appropriate potential material for tool and die making and automobile industry. The En 31 tool steel was initially shaped using milling and grinding process for making it sides at right angle for the proper clamping on the WEDM work table. The chemical composition of En 31 tool steel is determined by the spectrographic analysis and is shown in the Table 1.

Table 1: En 31 tool steel chemical composition

Element	C	Mn	Si	P	S	Cr	Fe
wt.%	1.15	0.48	0.20	0.04	0.037	0.93	Balance

Table 2: Brass wire electrode chemical composition

Components	Copper (C)	Zinc (Zn)	Iron (Fe)	Lead (Pb)
Wt.%	63-67	Balance	0.05 max	0.05 max

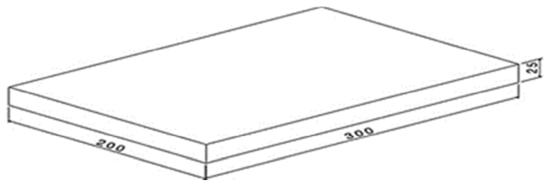

Fig 1: Dimensions of Work material En-31 tool steel (alldimensions in mm)

The wire electrode material used is brass having diameter of 0.25 mm (Make: Vertex Machinery Works Co., Ltd Taiwan). The brass wire (an alloy of copper consisting of zinc) is electrically and thermally conductive is typically alloyed in the range of 63-65% Cu and 35-37% Zn. The chemical composition of brass wire electrode is shown in Table 2.

1.2.2. Methodology

In the present study, L9 (34) Taguchi's orthogonal array has been chosen for performing experimental runs. Experiments was conducted as per the designed experimental plan and the performance were measured for each experimental run. The four process parameters chosen are Pulse on time (Ton), Wire tension (WT), Wire feed rate (WFR), Taper angle (TA) each having three levels. That makes a total degree of freedom 8 for the four process parameters. So, the selected array fulfills the criteria for working. The Taguchi's orthogonal array L9 (34) with factors and levels is shown in the Table 3. The levels were assigned to the four process parameters based on preliminary experiments.

The present work is focused on achieving the optimum parametric combination for maximum material removal rate (MRR) and minimum taper error (TE) and minimum surface roughness (SR). The multi-objective optimization of the parameters has been done by applying Taguchi based Grey Relational Analysis (TGRA).

Table 3: Process parameters with their levels

Factor	Process parameter	Symbol	Unit	Levels		
A	Pulse on time	T_{on}	nanosecond (ns)	250	500	750
B	Wire tension	WT	gram (g)	1000	1300	1600
C	Wire feed rate	WFR	meter/minute (m/min)	3	5	7
D	Taper angle	TA	degree (°)	2	3	5

1.2.3 *Experimental procedure*

The experimental investigation is performed on the 5 axes CNC WEDM machine (Model: EX 40, Make: Excetek Technologies Co., Ltd, Taiwan) for the taper cutting of tool steel En 31 (anode) using brass wire of diameter 0.25 mm as wire electrode (cathode). EXCETEK EX 40 machine is capable of cutting taper of ± 22°/80 mm. Taper angle is the only parameter goes with the part geometry and rest all are related with the WEDM system, to study the effect on the response parameters namely material removal rate, taper error and surface roughness. The work material is clamped on the WEDM is exhibit in Fig 2. The experimental conditions are displayed in Table 4. Each experimental run was repeated thrice, and the mean value of response was considered. Total 27 triangular wedge shape of side 20 mm at a different level of taper angle has been cut using WEDM, under different machining conditions (Fig 2).

Table 4: Experimental conditions (parameters kept constant during experimentation)

Parameters	**Symbol**	**Unit**	**Value**
Pulse off time	T_{off}	µs	19
Open circuit Voltage	OV	V	50
Servo Voltage	SV	V	40
Arc on time	A_{on}	ns	5
Arc off Time	A_{off}	µs	22
Dielectric fluid pressure	WP	Kgf/cm^2	7
Workpiece thickness		25mm	
Brass wire diameter		0.25mm	

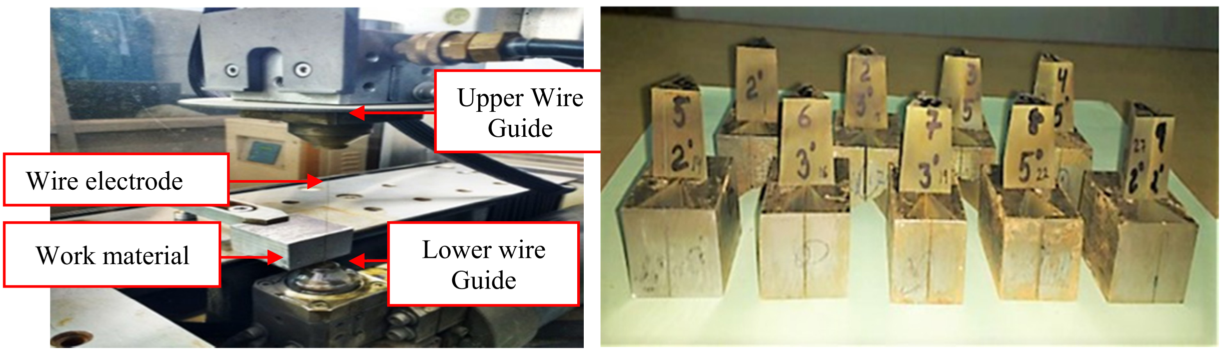

Fig 2: Work material mounted before the start of experimental run and the final work material after taper cutting using WEDM

1.2.4 *Measurement of Performance Measures*

The performance criteria namely material removal rate, taper error and surface roughness were calculated/ measured are discussed below:

1.2.4.1. Material Removal Rate (MRR)

The rate material removal in WEDM process is the total amount of material that's removed per unit time. Units for MRR are mm^3/min or g/min or mm^2/min and calculated by the using after equation 1 [14]:

$$MRR = \frac{W_i - W_f}{\rho t} \ (mm^3/min) \quad (1)$$

where,

W_i = Initial weight of work material (g)
W_f = Final weight of work material (g)
ρ = density of the work material (kg/mm^3)
t = machining time (min)

The weight was measured by using Electronic balance (Make: Shimadzu, Japan, Model: AUW 320), having least count of 10 mg.

1.2.4.2. Taper Error (TE)

Taper error (minute) is the deviation of taper angle from the programmed angle. Tapper error is influenced by theamount of taper to be cut on the work material during WEDM process, and calculated using the following equation2 [15]:

$$\text{Taper Error} = \text{Measured angle} - \text{Programmed angle} \quad (2)$$

In the present study, taper angle was measured using Coordinate Measuring Machine (CMM) (Make: Mitutoyo, Japan Model: BND-Crysta c7106) with resolution 0.0001mm.

1.2.4.3. Surface Roughness (SR)

Surface roughness(µm) is a measure of irregularities occurring due to the machining and these irregularities combine to forms surface texture. The measurement of the surface roughness has been done using Surtronic 25 (Make: Taylor Hobson) roughness tester with cut off length 16mm.

1.3 Results and Discussion

Table 5: Experimental results with mean and S/N ratio

Run	Mean MRR (mm^3/min)	Mean Taper Error (min)	Mean Surface roughness (µm)	S/N Ratio Material Removal Rate	S/N Ratio Taper Error	S/N Ratio Surface Roughness
1	8.8986	30.7899	0.3792	18.9864	-29.7682	8.4226
2	8.2825	21.2315	0.2231	18.3632	-26.5396	13.0300
3	7.5310	15.8847	1.8671	17.5371	-24.0196	-5.4234
4	13.6539	26.2620	1.9708	22.7051	-28.3866	-5.8929
5	14.9796	34.1667	1.8414	23.5100	-30.6721	-5.3030
6	15.8146	32.3222	1.5679	23.9812	-30.1900	-3.9064
7	14.3577	35.6526	1.9050	23.1417	-31.0418	-5.5974
8	14.4058	16.5509	2.0991	23.1707	-24.3764	-6.4407
9	19.2055	21.9401	2.2720	25.6685	-26.8248	-7.1282

The result obtained after WEDM of En-31 tool steel using brass wire electrode of 0.25mm diameter were analyzed using TGRA using MATLAB® software and MINITAB® 17 software. S/N Ratio for material removal rate (MRR) is calculated utilizing Larger the Better, whereas Smaller the Better for taper error (TE) and surface roughness (SR). The calculated values are shown in Table 5.

1.3.1. Analysis of MRR

As observed from the Table 6, pulse on time (Ton) has the highest value of main effects (delta), thus it is ranked 1 in the response table. The value of delta determines the levels of contribution made by the parameters. Pulse on time has the highest contribution in MRR with value of delta equals to 5.70. Taper angle (°) has been ranked as second most significant factor as the value of delta is 1.58 in the response table. Wire feed rate (WFR) with the value of delta 0.85 is the third most significant factor. Wire tension (WT) with the lowest value of delta which is 0.78 has least effect on MRR which makes it least significant factor. The sequence of process parameters in decreasing order are pulse on time (Ton), Taper angle (°), Wire feed rate (WFR) and Wire tension (WT). It is evident that value of MRR is higher when pulse on time increases from 250ns to 750ns. The reason for this being that at higher amount of energy being liberated per spark as spark period is elongated. The larger spark causes wider molten pool and hence high MRR. The Optimal parametric setting for MRR is A3B3C2D1.

Table 6: Response table for MRR (Larger the better)

Levels	T_{on} (ns)	WT (g)	WFR (m/min)	TA (°)
1	18.30	21.61	22.05	22.72*
2	23.40	21.68	22.25*	21.83
3	23.99*	22.40*	21.40	21.14
Delta	5.70	0.78	0.85	1.58
Rank	1	4	3	2

*Optimal parametric setting A3B3C2D1

1.3.2 Analysis of TE

Table 7 shows the response table for S/N Ratio for taper error. The highest value of delta is 3.66 in case of taper angle among all parameters. So, it is rank at number 1. Thus, TA contributes most in taper error. The second largest value of delta is for pulse on time is 2.97 which makes Ton the second significant factor. The rank of WT for significant factor is third with value of delta 2.72. WFR has the lowest value of delta that is 1.33 so it is the least significant factor among all other factor. The optimal parametric setting for TE is A2B1C3D2.
From the Table 7 it can be concluded that the TA depends on the part geometry rather than WEDM process. It comes out to be the promoting factor for the taper error and it is always desired to have low taper error.

Table 7: Response table for TE (Smaller is better)

Levels	T_{on} (ns)	WT (g)	WFR (m/min)	TA (°)
1	-26.78	-29.73*	-28.11	-29.09
2	-29.75*	-27.20	-27.25	-29.26*
3	-27.41	-27.01	-28.58*	-25.59
Delta	2.97	2.72	1.33	3.66
Rank	2	3	4	1

*optimal parametric setting **A2B1C3D2**

1.3.3. Analysis of SR

The S/N ratios for surface roughness is listed below in Table 8 and it can be observed that the pulse on time has a maximum value of delta equal to 11.73201, hence the first rank is given to it. Taper angle has the second rank because it has a second highest value of delta is 7.09420, which influence the surface roughness. The value of delta for wire tension is calculated to be 5.91476. Which is the third highest value. Wire feed rate has the lowest value of delta, therefore, it has been given rank four. The optimalparametric settings for SR is A1B2C2D1.

Table 8: Response table for SR (Smaller the better)

Levels	T_{on} (ns)	WT (g)	WFR (m/min)	TA (°)
1	5.34310*	-1.02271	-0.64147	-1.33617*
2	-5.03406	0.42879*	0.00300*	1.17525
3	-6.38891	-5.48596	-5.44140	-5.91896
Delta	11.73201	5.91476	5.44440	7.09420
Rank	1	3	4	2

*optimal parametric settings **A1B2C2D1**

1.3.4. Multi-response optimization using grey relational analysis

It has been concluded from the published work that Taguchi method concentrates on the optimization of single performance measure. The traditional Taguchi approach cannot solve multi- objective optimization problem [16]. GRA is a multi-objective optimization method and primary thought behind the present investigated work is to find out the ideal best combination for the process parameters that decrease taper error and surface roughness and at the same time increases the material removal rate during taper cutting operation utilizing WEDM process.

1.3.4.1 Grey Relational Generation

In grey relational generation normalization of signal to noise (S/N) ratio to bring the data in range of 0 and 1 and this will be raw data for the further calculation and the normalization is done using Larger the Better for material removal rate (MRR) and Smaller the Better for taper error (TE) and surface roughness (SR).
In Grey relational generation, normalized S/N Ratio result for MRR is done using Larger the better (LB), which is expressed as:

'Larger the better' (LB) value using the Equation 3[17]:

$$x_{ij} = \frac{y_{ij} - min_i y_{ij}}{max_i\, y_{ij} - \min y_{ij}} \quad (3)$$

In Grey relational generation, the normalized result for the surface roughness(SR) and taper error (TE) is done through Smaller thebetter (SB) which is expressed as:

'Smaller the better' (SB) value using the Equation 4 [17]:

$$x_{ij} = \frac{max_i\, y_{ij} - y_{ij}}{max_i\, y_{ij} - \min y_{ij}} \quad (4)$$

Where y_{ij} stands for j^{th}performance characteristic in i^{th} run and $max_i\, y_{ij}$ and $min_i y_{ij}$ definethe maximum andminimum value of j^{th} performance characteristic fori where Eq. 3 is used for the larger the better (LB) value, whereas Eq. 4 is used for smaller the better (SB) values.

1.3.4.2. Grey Relational Coefficient (GRC)

Grey relational coefficient (GRC) determines the relationship between the ideal and real normalized values by applying normalization, a matrix is created and from that matrix, a grey relational coefficient (GRC) is calculated, expressed as equation 5[18]:

$$\xi_{ij} = \frac{min_i min_j \left|x_j^0 - x_{ij}\right| + \xi\ max_i max_j \left|x_j^0 - x_{ij}\right|}{\left|x_j^0 - x_{ij}\right| + \xi\ max_i max_j \left|x_j^0 - x_{ij}\right|} \quad (5)$$

Where, x_j^0 is the ideal normalized result for the jth performance characteristic andx_j^0=1 is the idealsequence. GRC (ξ_{ij}) is calculated via selecting an appropriate di3stinguishing coefficient ζ (in general, ζ=1) by with Equation 5.

1.3.4.3 Grey Relational Grade (GRG)

Finally, GRG is obtained after averaging the GRC for each experiment corresponding to each performance measures.The Grey relational grade is calculated, expressed as [17]:

$$r_i = \frac{1}{m}\sum_{j=1}^{m} \xi_{ij} \quad (6)$$

1.3.4.4. Grey relational ordering

The GRG obtained from each experiment runs and the ranking order, is shown inTable 9. It is seen that experimental run 1 has the best multiple performance characteristicsamong the other 9 runs performed and having highest value of GRG and is optimal. It isfollowed by the run 2 and 7, being ranked second and third, respectively.

Table 9 GRG for each experimental run

Run order	GRG	Rank
1	0.8658	**1**
2	0.8293	**2**
3	0.6690	5
4	0.6024	7
5	0.6827	4
6	0.6622	6
7	0.7117	**3**
8	0.5887	8
9	0.5059	9

1.3.4.5. Grey Relational Grade (GRG)

The difference among the maximum and the minimum value of the Grey Relational Grade (GRG) are calculated and recorded inTable 8, followed by ranking accordingly based on the difference in the values for the averages. GRG of process parameters are follows 0.2059 for pulse on time, 0.1143 for wire tension, 0.0419 for wire feed rate and 0.1344 for taper angle. This result displays that pulse on time has the strongest effect among all other parameters. Further, as shown in Table10 the uppermost value of GRG gives the optimal parametric settings i.e. pulse on time at level 1, wire tension at level 1, wire feed rate at level 3 and taper angle at level 2.

Table 10 Response table for (GRG) taking Larger the better

Levels	T_{on} (ns)	WT (g)	WFR (m/min)	TA (°)
1	0.7880*	0.7266*	0.6856	0.6848
2	0.6491	0.6802	0.6459	0.7344*
3	0.5821	0.6124	0.6878*	0.6000
Delta	0.2059	0.1143	0.0419	0.1344
Rank	1	3	4	2

*Optimal parametric settings **A1B1C3D2**

To conclude, as per the findings the pulse on time (T_{on}) is most effective controllable factor having maximum having delta value 0.2059 among all the other process parameters considered in present investigation, followed by the taper angle, wire tension and wire feed rate. The increase in pulse on time and wire tension results in an increase in MRR but is also increasesthe surface roughness.Accordingly, A1B1C3D2 are an optimal setting to obtain better results of performance characteristics.

1.3.4.6. Main effect plot for Grey Relational Grade (GRG)

The main effect plot created on the basis of grey relational grade (GRG) is shown in Fig3 and themid-line indicates the value of total means forGRG and for the mean effect plot shows the best combination values forthe multiple performance characteristics that is 250 ns for Pulse on time (T_{on}), 1000 g for Wire tension (WT), 7 m/min for Wire feed rate (WFR) and finally 3° for Taper angle (TA).

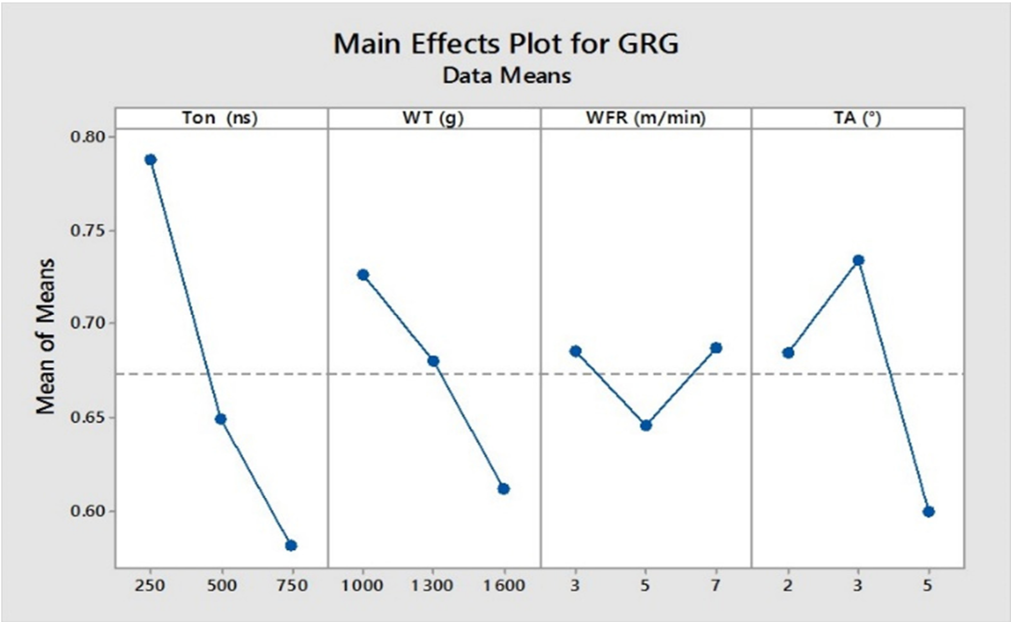

Fig 3: Main effect plot for grey relational grade (GRG)

1.3.4.7. Analysis of variance for GRG

Table 11 shows the ANOVA table for the GRA, it is evident from the table that pulse on time has highest contribution of 56.65 % among all the process parameters considered in the present investigation.

Table 11 ANOVA table for GRG (Larger the Better)

Factor	DOF	SS	MS	% contribution
T_{on} (ns)	2	0.066200	0.033100	56.5546
WT (g)	2	0.019816	0.009908	16.9288
WFR (m/min)	2	0.003339	0.001670	2.8525
TA (°)	2	0.027700	0.013850	23.6641
Error	0	0		
Total	8	0.117055		100.0000

CONCLUSION

Present experimental work has been carried out to determine the optimal parametric setting amid the taper cutting operation on the response characteristics especially material removal rate (MRR), taper error (TE) and surface roughness (SR).Moreover optimization of all the three responses using Taguchi Based Grey Relational Analysis (TGRA) is adopted to optimize and establish a connection among multi-performance characteristics and TGRA simplifies the multi-optimization, and it does not require any complex mathematical computations. The various conclusion which hasbeen observed from results and discussions are given below:

- From the present investigation, it can be concluded that among all other parameters considered in the investigation the pulse on time comes out to with the strongest effect followed by taper angle, wire tension and wire feed rate.
- It is found that asthe pulse on time increases higher MRR was achieved due to more energy being released per spark, as spark period is elongated.
- Taper error increases with increment in taper angle and the swaying factor in deciding the taper error is the taper angle that's to be cut on the workpiece.
- It is observed that surface roughness increase with the rise in the value of pulse on time and the surface finish isn't much affected with slight alter within the value of wire tension and wire feed rate.
- Wire tension plays a significant part in the improvement taper error.
- From Taguchi based grey analysis (TGRA) it is found that the optimal parameter combination for taper angle of 3°, pulse on time of 250 ns, wire pressure of 1000 g and wire feed rate of 7 m/min for accomplishing higher material removal rate enhanced surface finish and improved taper precision.

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