Multiple machining characteristics optimization of process parameters in wire electrical discharge machining process using Taguchi, Grey Relational and Entropy Methods

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Abstract: The objective of the present work is to investigate and optimize the multiple machining parameters of WEDM process viz. wire feed, peak current, pulse on time, pulse off time and servo voltage for machining characteristics viz. cutting speed and surface roughness of AISI D2 tool steel. Copper coated brass wire is used as electrode material for present experimental work. Taguchi method along with Grey relational analysis (GRA) and Entropy method has been used for optimizing the machining characteristics. The experimental results show that integrated methodology developed in this work has been successfully used to find optimal combination of WEDM parameters for multi-machining characteristics as compared to previous methods.

***Index Terms*:** Wire electrical discharge machining, optimization, Taguchi method, grey relational Analysis (GRA), entropy method, process parameters, D2 tool steel.

I. INTRODUCTION

Wire electrical discharge machining (WEDM) is non-traditional machining method in which thermal energy is used to vaporize the work material by concentrating by creating an electrical discharge between the wire or electrode, & the work piece. The material is eroded from the job by a series of discrete sparks occurring between the electrode wire and job, separated by a dielectric fluid, continuously fed at the point of liberation of thermal energy [1]. Figure 1 shows diagram of WEDM process.

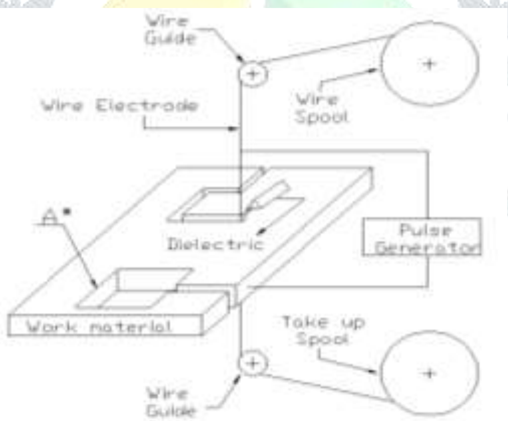


Figure 1: Wire electrical discharge machining process [1]

II. LITERATURE REVIEW

Lin and Lin [1] optimized the multiple performance characteristics in wire electrical discharge machining by combining the orthogonal array and grey relational analysis. Machining parameters such as work piece polarity, pulse on time, duty factor, open discharge voltage, discharge current, and dielectric fluid were optimized for improved material removal rate, surface roughness and electrode wear ratio. **Jangra and Grover** [2] used grey relational analysis along with Taguchi method to optimize material removal rate and surface roughness simultaneously for WEDM of WC-Co composite. Authors investigated the influence of taper angle, peak current, pulse-on time, pulse-off time, wire tension and dielectric flow rate on material removal rate and surface roughness. **Rao and Yadava** [3] applied a hybrid approach of Taguchi and grey relational analysis to optimize the multi-objective optimization of Nd-YAG laser cutting of thin supper alloy sheet. The significant parameters were obtained by performing analysis of variance (ANOVA) and optimized parameters for straight and curved laser cut profiles were compared. **Singh et. al** [4] employed orthogonal array with grey relational analysis to optimize the multiple performance characteristics of electrical discharge machining. The multi-response optimization of process parameters such as metal removal rate, tool wear rate, taper, radial overcut, and surface roughness on electric discharge machining of Al–10%SiC as cast metal matrix composites using orthogonal array with Grey relational analysis is reported. **Li and Tsai** [5] applied grey relational analysis to laser beam cutting for flash memory modules with special shapes. Analysis of the grey relational grade indicates that parameter significance and the optimal parameter combination for the laser cutting process are identified. **Gauri and Chakraborty** [6] used the principal component analysis (PCA) for the multi response optimization. In this paper, some modifications in the PCA based approach are suggested and two sets of experimental data published by past researchers are analyzed using modified procedure. **Mukherjee and Ray** [7] described different optimization technique, their advantages and drawbacks. The application potential of several modelling and optimization techniques in metal cutting process, classified under several criteria, has been critically appraised, and a general framework for parameter optimization in metal cutting processes is suggested for the benefits of selection of an appropriate approach. **Sarkar et. al** [8] studied the trim cutting operation in Wire EDM of γ-titanium aluminide. A second order mathematical model was developed for surface roughness, dimensional shift and cutting speed using response surface methodology (RSM).. **Kanagurajan et. al** [9] studied the influence of operating parameters of EDM such as pulse current, pulse on time, electrode rotation and flushing pressure on material removal rate and surface roughness with tungsten carbide and cobalt. **Aggarwal et. al** [10] optimized the multiple characteristics, in CNC turning of AISIP-20, such as tool life, cutting force, surface roughness and power consumption. Four controllable factors of the turning process viz. cutting speed, feed, depth of cut and nose radius were studied. **Mahapatra and Patnaik** [11] optimized metal removal rate (MRR), surface finish and cutting width for a rough cut. Genetic Algorithms and Taguchi's L_{27} is used to optimize the individual response characteristic. **Ho et. al** [12] reviewed the vast array of research work carried out from the spin-off from the EDM process to the development of the WEDM.

III. METHODOLOGY

All the experiments were performed on a 5-Axis sprint cut wire electrical discharge machine (ELPLUS-40) manufactured by Electronica Machine Tool Pvt. Ltd. AISI D2 high carbon high chromium die-steel is used as a work material. Total five process parameters were investigated. Table 1 lists the range, symbol & units and levels of the process parameters.

Table 1: Process parameters, symbols and their ranges

Sr	Factor	Process Parameters	Symbol	Units	Range	Level-1	Level-2	Level-3
1	A	Wire feed	(Wf)	m/min	4 – 8	4	8	—
2	B	Peak current	(Ip)	Amp	80 – 160	80	120	160
3	C	Pulse-on time	(Ton)	µs	106 – 118	106	112	118
4	D	Pulse-off time	(Toff)	µs	35 – 45	35	40	45
5	E	Servo voltage	(Sv)	V	20 – 40	20	30	40

The mean data analysis and S/N data analysis have been performed by conducting 18 experiments Taguchi's design methodology. The experimental results for cutting speed and surface roughness is given in table 2.

Table 2: Cutting speed, surface roughness and their respective S/N Ratio

Expt.	Trial	A	B	C	D	E	CS (mm/min)	SR (µm)	S/N ratio	
									CS	SR
1	1	4	80	106	35	20	0.78	1.19	-2.1581	-1.5109
2	2	4	80	112	40	30	0.90	1.37	-0.9151	-2.7344
3	3	4	80	118	45	40	1.28	2.1	2.1441	-6.4443
4	4	4	120	106	35	30	0.68	1.28	-3.3498	-2.1441
5	5	4	120	112	40	40	1.20	1.6	1.5836	-4.0823
6	6	4	120	118	45	20	1.48	2.6	3.4052	-8.2994
7	11	4	160	106	40	20	0.80	1.30	-1.9382	-2.2788
8	12	4	160	112	45	30	1.1	1.80	0.8278	-5.1054
9	7	4	160	118	35	40	1.65	2.89	4.3496	-9.2179
10	14	8	80	106	45	40	0.50	1.01	-6.0205	-0.0864
11	17	8	80	112	35	20	1.29	1.58	2.2117	-3.9731
12	18	8	80	118	40	30	1.42	2.5	3.0457	-7.9588
13	16	8	120	106	40	40	0.61	1.11	-4.2934	-0.9064
14	10	8	120	112	45	20	1.26	1.50	2.0074	-3.5218
15	13	8	120	118	35	30	1.67	2.67	4.4543	-8.5302
16	8	8	160	106	45	30	0.65	1.25	-3.7417	-1.9382
17	15	8	160	112	35	40	1.36	2.2	2.6707	-6.8484
18	9	8	160	118	40	20	1.70	2.3	4.6089	-7.2345
Mean							1.1294	1.7916		

GREY RELATIONAL METHOD

Step I: Normalization of results

It is the process of transforming the original sequence to a comparable sequence with range of zero. Three types of data normalization [4, 5] is done in the GRA, lower the better (LB), the higher the better (HB) and nominal the best (NB).

- Lower is better (LB) $X_i^*(k) = \frac{\max X_i(k) - X_i(k)}{\max X_i(k) - \min X_i(k)}$ … (1)
- Higher is Better (HB) $X_i^*(k) = \frac{X_i(k) - \min X_i(k)}{\max X_i(k) - \min X_i(k)}$ … (2)
- Nominal is best (NB) $X_i^*(k) = \frac{|X_i(k) - X_{ob}(k)|}{\max X_i(k) - X_{ob}(k)}$ … (3)

Let the original reference sequence is $X_0(k)$. $X_i^*(k)$ is normalized value of the k^{th} element in the i^{th} sequence, $X_{ob}(k)$ is desired value of the k^{th} quality characteristic, max $X_i^*(k)$ is the largest value of $X_i(k)$, and min $X_i^*(k)$ is the smallest value of $X_i(k)$, Where i = 1,2,……,n; k = 1,2,……,p; n(=18) is the no. of experiments and p(=2) is the no. of quality characteristics [4, 5].

Step II: Calculation of Grey Relational Coefficient (GRC)

Second step is to display the relationship between optimal and actual normalized value using grey relational coefficient. Deviation sequences of the normalized data are calculated. The grey relational coefficient can be expressed as [4, 5]

$$\xi_{0,i}(k) = \frac{\Delta \min - \zeta\Delta \max}{\Delta_{o,i}(k) + \zeta\Delta max} \quad \dots (4)$$

Where i = 1,… ,n; k = 1,…,p, $\xi_{0,i}(k)$ is the difference of kth element between comparative sequence X_i and the reference sequence X_0 , $\Delta_{o,i}(k)$ is the difference between $X_0(k)$ and $X_i(k)$. [$\Delta_{o,i}(k) = X_0(k) - Xi(k)$] ζ is a distinguishing or identification coefficient, and its value lie between zero and one. In general it is set to 0.5.

Step III: Calculation of Grey Relational Grade (GRG)

Grey relational grade is the weighting sum of grey relational coefficient. Highest grey relational grade gives the best multiple machining characteristics. The average of the grey relational co-efficient (GRG) is determined by eq 5 [4, 5].

$$GRG = \sum_{k=1}^{p} w_k \, \xi_{0,i}(k), \quad i = 1,2,\ldots\ldots,18 \quad \dots (5)$$

Entropy Measurement Method

As applying the concept of entropy to weight measurement, an attribute with a large entropy attribute has a more significant influence on the response [4, 5]. The mapping function f_i: [0, 1] [0, 1] used in entropy should satisfy three conditions [8]:

1. $f_i(0) = 0$
2. $f_i(x) = f_i(1 - x)$,
3. $f_i(x)$ is monotonic increasing in the range of $x \in (0, 0.5)$.

Thus, the function $w_e(x)$ can be used as the mapping function in entropy measurement

$$w_e(x) = xe^{(1-x)} + (1-x)e^{x} - 1 \quad \dots (6)$$

The maximum value of this function occurs at $x = 0.5$, and the value $e^{0.5} - 1 = 0.6487$. In order to let the mapping result in the range [0, 1], new entropy as:

$$W = \frac{1}{(e^{0.5}-1)\,n} \sum_{i=1}^{n} w_e(x) \quad \dots (7)$$

Step by Step procedure [4, 5]

The step by step procedure to calculate the weights of each characteristic [4, 5] is:

Sum of the Grey relational Coefficient [4, 5]in all sequences for each performance measure:

$$D_k = \sum_{i=1}^{n} \xi\, 0, i(k), \quad k = 1, \ldots, p \quad \dots (8)$$

Normalized coefficient [4, 5]:

$$K = \frac{1}{(e^{0.5}-1)\times n} = \frac{1}{0.6487 \times n} \quad \dots (9)$$

Entropy of each quality characteristic [4, 5]:

$$e_k = K \sum_{i=1}^{n} w_e \left[\frac{\xi_i(k)}{D_k}\right] \quad \dots (10)$$

Sum of entropy [4, 5]:

$$E_T = \sum_{k=1}^{n} e_k \quad \dots (11)$$

Weight of each quality characteristic [4, 5]:

$$w_k = \frac{\frac{1}{n-E_T}[1-e_k]}{\sum_{k=1}^{n} \frac{1}{n-E_T}[1-e_k]}, \quad k = 1, \ldots., p \quad \dots (12)$$

Where Dk = Sum of the grey relational coefficients of k^{th} quality characteristics, K = Normalized coefficient, e_k = Entropy of k^{th} quality characteristics, E_T = Sum of entropy, W_k = Weight of k^{th} quality characteristics

Multiple Machining Characteristics Optimization

Procedure for Experimentation [4, 5, 9]

- Conduct the experiments at different settings of parameters based on the orthogonal array.
- Convert the experimental data into S/N values.
- Normalize the S/N ratio.
- Perform the grey relational generating and calculate the grey relational coefficient.
- Calculate the grey relational grade by using the weighing factor for the performance characteristics. In this study, it is done with the help of entropy measurement method.

- Analyse the experimental results using the GRA and ANOVA
- Select the optimal levels of process parameters.
- Conduct the confirmation experiment to verify the optimal process parameter settings.

IV. RESULTS AND DISCUSSIONS

According to the first step of grey relational analysis, experimental data must be normalized to avert above said effect. In this investigation, a linear normalization of the experimental results (S/N data) for cutting rate and surface roughness were performed in the range of 0 and 1. Linear normalization of S/N data of machining characteristics was done using eq (2). Table 3 shows the normalization experimental result (S/N ratio).

Table 3: Normalized values for CR and SR

Sequence No.	CR	SR
Comparability sequence [x_i^*(k)]		
1	0.3633	0.8440
2	0.4803	0.7100
3	0.7681	0.3037
4	0.2512	0.7746
5	0.7153	0.5624
6	0.8867	0.1005
7	0.3840	0.7599
8	0.6442	0.4503
9	0.9756	0.0000
10	0.0000	1.0000
11	0.7744	0.5743
12	0.8529	0.1378
13	0.1624	0.9102
14	0.7552	0.6237
15	0.9854	0.0753
16	0.2143	0.7972
17	0.8176	0.2594
18	1.0000	0.2172
Reference Sequence [x_o^*(k)]	**1.0000**	**1.0000**

The value of the element in the reference sequence means the optimal value of the corresponding quality characteristic. x_i^*(k) and x_o^*(k) represent the numeric value of kth element in the reference sequence and comparative sequence. Then, the grey relational coefficients were calculated to express the relationship between the ideal and actual experimental results. Following the data pre-processing, a Grey relational coefficients were calculated using eq 4 taking of distinguishing coefficient ζ= 0.5. Table 4 shows the results for deviation sequence used to calculate the GRC.

Table 4: Deviation sequence

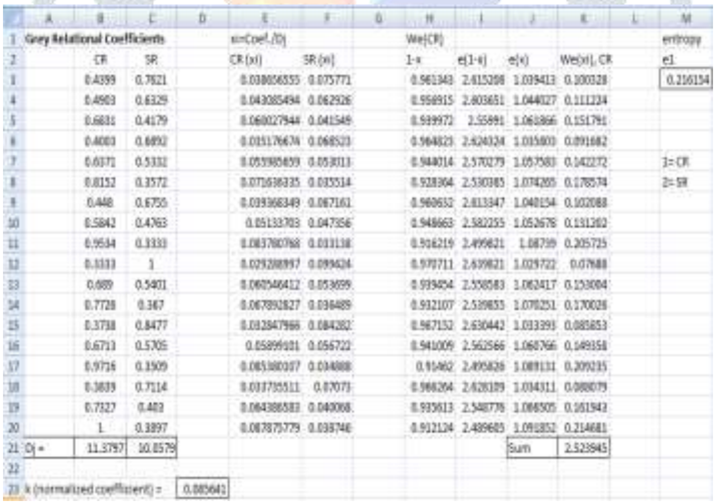
Deviation sequence No.	**Δ_{oi} (1)**	**Δ_{oi} (2)**
1	0.6366	0.1560
2	0.5197	0.2900
3	0.2319	0.6963
4	0.7488	0.2254
5	0.2847	0.4376
6	0.1133	0.8995
7	0.6160	0.2401
8	0.3558	0.5497
9	0.0244	1.0000
10	1.0000	0.0000
11	0.2256	0.4257
12	0.1471	0.8622
13	0.8376	0.0898
14	0.2448	0.3763
15	0.0146	0.9247
16	0.7857	0.2028
17	0.1824	0.7406
18	0.0000	0.7828

Table 5 shows the values of GRC for cutting speed and surface roughness. Next step is to calculate the grey relational grade for each comparability sequence. The overall evaluation is based on the grey relational grade. Thus, optimization of multiple characteristics is converted into a single optimization of grey relational grade [10].

Table 5: Grey relational coefficient and GRG

Comparability sequence	Cutting Speed **GRC$_i$ (1)**	Surface roughness **GRC$_i$ (2)**	Grey Relational Grade **(GRG$_i$)**
1	0.4399	0.7621	0.601003
2	0.4903	0.6329	0.561601
3	0.6831	0.4179	0.550497
4	0.4003	0.6892	0.544753
5	0.6371	0.5332	0.585149
6	0.8152	0.3572	0.586196
7	0.4480	0.6755	0.561752
8	0.5842	0.4763	0.530249
9	0.9534	0.3333	0.643344
10	0.3333	1.0000	0.666656
11	0.6890	0.5401	0.614549
12	0.7726	0.3670	0.569796
13	0.3738	0.8477	0.610755
14	0.6713	0.5705	0.620899
15	0.9716	0.3509	0.661244
16	0.3839	0.7114	0.547653
17	0.7327	0.4030	0.567847
18	1.0000	0.3897	**0.694844**

The obtained weight for the quality characteristics 1 is 0.49999044 and weight for the quality characteristics 2 is 0.50000956. After calculating the weight of each quality characteristics, Grey Relational Grades are calculated using eq 5. All the calculations regarding entropy measurement method were done using Microsoft excel. Figure 2, 3 & 4 shows the results of entropy method.



	A	B	C	E	F	H	I	J	K	M
1	Grey Relational Coefficients			xi=Coef./Dj		We(CR)				entropy
2		CR	SR	CR(xi)	SR(xi)	1-x	e(1-x)	e(x)	We(xi), CR	e1
3		0.4399	0.7621	0.038656555	0.075771	0.961343	2.615298	1.039413	0.100328	0.216154
4		0.4903	0.6329	0.043085494	0.062926	0.956915	2.603651	1.044027	0.111224	
5		0.6831	0.4179	0.060027944	0.041549	0.939972	2.55991	1.061866	0.151791	
6		0.4003	0.6892	0.035176674	0.068523	0.964823	2.624324	1.035803	0.091682	
7		0.6371	0.5332	0.055985659	0.053013	0.944014	2.570279	1.057583	0.142272	1=CR
8		0.8152	0.3572	0.071636335	0.035514	0.928364	2.530385	1.074265	0.178574	2=SR
9		0.448	0.6755	0.039368349	0.067161	0.960632	2.613347	1.040154	0.102088	
10		0.5842	0.4763	0.05133703	0.047356	0.948663	2.582255	1.052676	0.131202	
11		0.9534	0.3333	0.083780768	0.033138	0.916219	2.499621	1.08739	0.205725	
12		0.3333	1	0.029288997	0.099424	0.970711	2.639821	1.029722	0.07688	
13		0.689	0.5401	0.060546412	0.053699	0.939454	2.558583	1.062417	0.153004	
14		0.7726	0.367	0.067892827	0.036489	0.932107	2.539855	1.070251	0.170026	
15		0.3738	0.8477	0.032847966	0.084282	0.967152	2.630442	1.033393	0.085853	
16		0.6713	0.5705	0.05899101	0.056722	0.941009	2.562566	1.060766	0.149358	
17		0.9716	0.3509	0.085380107	0.034888	0.91462	2.495826	1.089131	0.209235	
18		0.3839	0.7114	0.033735511	0.07073	0.966264	2.628109	1.034311	0.088079	
19		0.7327	0.403	0.064386583	0.040068	0.935613	2.548776	1.066505	0.161943	
20		1	0.3897	0.087875779	0.038746	0.912124	2.489685	1.091852	0.214681	
21	Dj =	11.3797	10.0579					Sum	2.523945	
22										
23	k (normalized coefficient) =			0.085641						

Fig 2: Calculation of entropy for CR in Microsoft excel

	A	B	C	D	E	F	G	H	I	J
1	Coef./Dj (x)							entropy	entropy	
2	SR		1-x	e(1-x)	e(x)	We, SR		e2	e1	
3	0.075771		0.924229	2.519924	1.078716	0.187918		0.21612	0.21615	
4	0.062926		0.937074	2.552503	1.064948	0.158553				
5	0.041549		0.958451	2.607653	1.042425	0.107459				
6	0.068523		0.931477	2.538255	1.070926	0.171472				
7	0.053013		0.946987	2.577931	1.054443	0.135208		Sum of entropies =		0.43227
8	0.035514		0.964486	2.623438	1.036153	0.092524				
9	0.067161		0.932839	2.541715	1.069468	0.168346				
10	0.047356		0.952644	2.592556	1.048495	0.121615		weight	w1= 0.49999044	
11	0.033138		0.966862	2.629679	1.033693	0.086581			w2= 0.50000956	
12	0.099424		0.900576	2.461019	1.104535	0.239402				
13	0.053699		0.946301	2.576161	1.055167	0.136843				
14	0.036489		0.963511	2.620883	1.037163	0.094951				
15	0.084282		0.915718	2.498569	1.087936	0.206827				
16	0.056722		0.943278	2.568388	1.058361	0.144012				1= CR
17	0.034888		0.965112	2.625082	1.035504	0.090961				2= SR
18	0.07073		0.92927	2.532658	1.073292	0.176514				
19	0.040068		0.959932	2.611519	1.040882	0.103814				
20	0.038746		0.961254	2.614974	1.039506	0.100549				
21					Sum =	2.523548				
22										
23	k =	0.085641								

Figure 3: Calculation of entropy for SR in Microsoft excel

	A	B	C	D	E	F	G	H
1	**Coefficients**			1 = CR	2 = SR			
2	CR	SR		w1	w2	GRG (CRi*w1+Sri*w2)		
3	0.4399	0.7621		0.49999	0.50001		0.601003	
4	0.4903	0.6329		0.49999	0.50001		0.561601	
5	0.6831	0.4179		0.49999	0.50001		0.550497	
6	0.4003	0.6892		0.49999	0.50001		0.544753	
7	0.6371	0.5332		0.49999	0.50001		0.585149	
8	0.8152	0.3572		0.49999	0.50001		0.586196	
9	0.448	0.6755		0.49999	0.50001		0.561752	
10	0.5842	0.4763		0.49999	0.50001		0.530249	
11	0.9534	0.3333		0.49999	0.50001		0.643344	
12	0.3333	1		0.49999	0.50001		0.666656	
13	0.689	0.5401		0.49999	0.50001		0.614549	
14	0.7726	0.367		0.49999	0.50001		0.569796	
15	0.3738	0.8477		0.49999	0.50001		0.610755	
16	0.6713	0.5705		0.49999	0.50001		0.620899	
17	0.9716	0.3509		0.49999	0.50001		0.661244	
18	0.3839	0.7114		0.49999	0.50001		0.547653	
19	0.7327	0.403		0.49999	0.50001		0.567847	
20	1	0.3897		0.49999	0.50001		0.694844	
21								
22					Maximum Grade =		0.694844	

Figure 4: Calculation of Grey Relational Grade in Microsoft excel

Selection of Optimum Level

As explained earlier, Highest grey relational grade gives the best multiple machining characteristics, it is clear from table 5 the process parameter setting of experiment no. 18^{th} has the highest grey relational grade. Thus it gives best multiple machining characteristics using Taguchi method, in eighteen experiments. The main effects of each process parameter on grey relational grade were calculated as given in table 6.

Table 6: Response table for mean GRG

Level	A	B	C	D	E
1	0.573838	0.594017	0.588762	0.605457	0.613207
2	0.617138	0.601499	0.580049	0.597316	0.569216
3	---	0.590948	0.617654	0.583692	0.604041

The main effects of each process parameter on grey relational grade were calculated using Taguchi methodology e.g. average effect on GRG for parameter E at level 1 is calculated as follows:

$$E_1 = (0.601003 + 0.586196 + 0.561752 + 0.614549 + 0.620899 + 0.694844) / 6 \quad = \mathbf{0.613207}$$

Figure 5 shows the graphical representation of values which are tabulated in table 6.

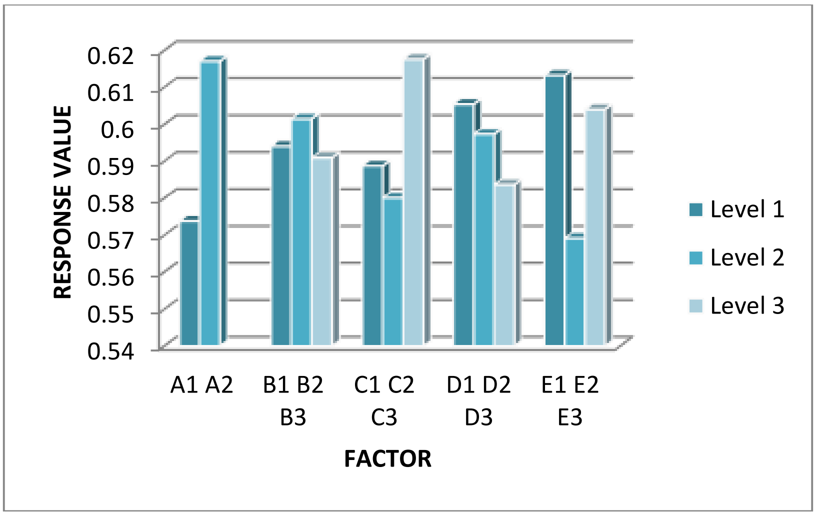


Figure 5: Response graph for grey relational grade

It can be seen from figure 5 that the second level of wire feed (A2), second level of peak current (B2), third level of pulse on time (C3), first level of pulse off time (D1) and first level of servo voltage have the maximum value of grey relational grade. Hence, the optimum input parameter level corresponds to maximum average grey relational grade is **A2 B2 C3 D1 E1**.

V. Conclusions

In present investigation, the effect of process parameters viz. wire feed, peak current, pulse on time, pulse off time and servo voltage of wire electrical discharge machining on performance measure such as cutting speed and surface roughness has been studied. Integrated approach of taguchi, Grey Relational Analysis and Entropy measurement method is used for optimization.

Following conclusions have been made from the present investigation are given below:

- The process parameters and their ranges are selected on the base of trial experiments and expert knowledge & experience.
- Taguchi design of experiment has utilised to optimize the single machining characteristic. An L_{18} orthogonal array was selected for conducting experimentation to analyse the influence of selected five process parameters.
- Grey Relational Analysis has been used to optimize the multiple performance characteristics.
- Entropy measurement method is used calculate the actual weight for each machining characteristics. The obtained weight for the quality characteristics 1 is **0.49999044** and weight for the quality characteristics 2 is **0.50000956**.
- Using Grey Relational Analysis, the optimal combination of WEDM parameters for multi-machining characteristics was set at **A2 B2 C3 D1 E1**.

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