Multi Objective Optimization Of Parameters For Wire Edm Using Grey Relational Based Taguchi's Approach

Shanky Sudan[1], Ashwani Verma[2], Manpreet Singh[3]
[1, 2, 3] Dept of Mechanical Engineering
[1, 2, 3] Ambala College of Engineering and Applied Research, Devsthali, Ambala, Haryana, India

Abstract- *In this study, an attempt has been made with wire electric discharge machining (WEDM) of M6 high speed steel (HSS) to investigate the influence of process parameters namely pulse on time (T_{on}), pulse off time (T_{off}), peak current (I_p) and servo voltage (S_v) on material removal rate (MRR) and surface roughness (SR). The experiment is designed and conducted as per Taguchi approach with L_{25} orthogonal array. The Grey Relational Analysis has been performed to convert multi response into single response. The investigation revealed that pulse on time (T_{on}) and peak current (I_p) are the most significant parameters affecting MRR. The optimal settings of process parameters obtained for maximum MRR and minimum SR number are A5-B5-C4-D2 (T_{on}= 120 µs, T_{off}= 60 µs, I_p= 140 amp and S_v= 30 V). The mean values obtained from the confirmatory experiments were found to be well within 5% error of the predicted optimal values.*

Keywords- M6 (HSS), Wire EDM, Material removal rate (MRR), Surface roughness (SR), Taguchi's approach, GRA.

I. INTRODUCTION

Machine tool technology is often regarded as "Mother Technology" as it provides indispensable tools that generate production in almost all regions of economy. Therefore it is of prime importance to both machine tool industries and the manufacturing industries utilizing machine tools in every form. Although the machine tool industry has made remarkable improvement, yet the metal cutting production houses deploying different machine tools continue to suffer from a main shortcoming of not using the machine tools at their packed capacity. This is due to fact that machine tools are not operated at their optimum running conditions. This has attracted the good number of researchers and engineers from a long time. It is very sad to say still the machine tool's operating conditions continue to be chosen exclusively on account of handbook standards and / or manufacturer's suggestions and / or operator's expertise. Therefore in today's fast changing world, optimization techniques usage in both conventional and non-conventional machining processes is vital to struggle for low machining cost and high quality of products. Non-conventional machining refers to removal of material in form of chips/debris having micro level size [V. K. Jain (2002)] **[1].** They are suitable for difficult to cut materials. Wire electric discharge machining (WEDM) process is variation of electric discharge machining (EDM) process coming under the family of non-conventional machining processes. M6 high speed steel (HSS) falls under the category of difficult to cut materials. It has wide application for the manufacturing of various metal cutting tools namely twist drills, milling cutters, thread dies, broaches, reamers, countersinks and thread chasers. In this study, M6 HSS material having composition as shown in table 1 has been selected to investigate the influence of process parameters on MRR and SR during WEDM using combination of Taguchi's approach and Grey relational analysis.

Table 1.1: Composition of M6 HSS

C %	Mn %	P %	Si %	CO %	W %	Cr %	V %	Mo %
0.914	0.246	0.011	0.214	11.95	3.84	4.12	1.912	5.21

Taguchi is a statistical method developed by Genichi Taguchi to improve the Quality of manufacturing goods.Taguchi's parameter design is key tool for robust design, offering a simple systematic approach for optimizing design for performance, quality and cost. The two tools used in this robust design are signal to noise (S/N) ratio and orthogonal array. S/N ratio measures quality with emphasis on variation, whereas orthogonal array accommodates many design factors simultaneously (Park, 1996; Unal and Dean, 1991; Phadke, 1989) [2-4]. Taguchi has built upon W.E. Deming's observation that 85% of poor quality is attributable to the manufacturing process and only 15% to the worker. When a significant quality characteristic deviates from the target value, then loss occurs (Unal and Dean, 1991) [3]. The continuous reduction of variability from the target value is the key to achieve high quality and reduce cost. By using this methodology we can not only significantly reduce the experimental investigation time, but can also study which factor has more influence and which has less (Singh and Kumar, 2003, 2005) [5-6].

Grey Relational Analysis (GRA)

The Grey theory was put forward by Dr. Deng includes Grey relational analysis, Grey modeling, prediction and decision making of a system in which the model is unsure or the information is incomplete (Deng, 1989) [7]. This methodology presents a best result to the uncertainty, multi-input and discrete data problem. The relation between machining process parameters and machining performance can be established with the help of the Grey relational analysis (Lin, 2004) [8].

II. METHODOLOGY

In this work, Taguchi's approach and Grey relational analysis has been used for the optimization of process parameters. The figure 2 shows the flow chart of the Grey based Taguchi method.

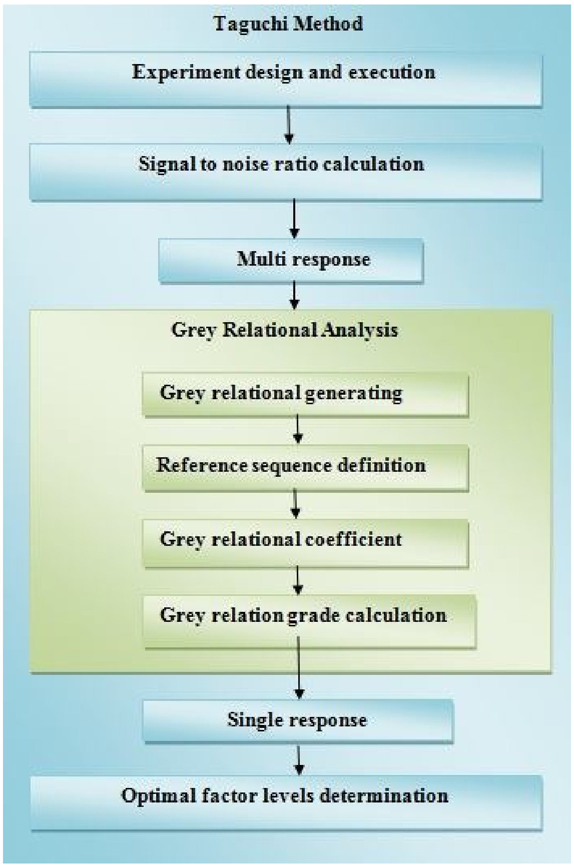

Figure 2.1 Flow chart of Grey based Taguchi method.

The first step in this method is to design and conduct the experiments as per Taguchi approach with L_{25} orthogonal array. The results of these experiments have to be presented in the tabulated form. Then the signal to noise (S/N) ratio has to be calculated using S/N ratio's formula. The purpose of Grey relational analysis is to convert multi response into single response. In this analysis, firstly Grey relations have to be generated using the multi responses, which further have to be converted into the reference sequence definition. Then Grey relational coefficients have to be worked out followed by calculation of Grey relation grade. This finally results in single response that is the single performance characteristic. Using this single response, then optimal factors levels have to be worked out which is the objective of present research work.

III. LITERATURE SURVEY

The study of few past years papers revealed that lot of research has been done on WEDM in terms of improving performance parameters, optimizing the process parameters, monitoring and controlling the sparking process and improving the sparking efficiency. The work done by different researchers are as listed below.

Kumar et al. (2017) [9] studied the influence of pulse on time, pulse off time and maximum current on process parameters namely machining time and material removal rate (MRR) while processing on wire electrical discharge machining (WEDM) of D2 steel. The experiment was designed using Taguchi's approach. They reported that better MRR can be obtained by deploying lower machining time. They used Grey relation analysis for multi-objective optimization of MRR and machining time. Their investigation revealed that with pulse on time =120µs, pulse off time = 55µs and maximum current = 210 ampere led to optimum MRR of 0.10905 mm^3/sec and Machining time of 825 seconds.

Garg et al. (2017) [10] studied the influence of pulse on time, pulse off time, spark gap voltage and wire feed on response parameters namely cutting speed, gap current, and surface roughness while processing on wire electrical discharge machining (WEDM) of Inconel 625. They employed Response surface methodology to build up the experimental models. They reported that pulse on time and pulse off time were observed to be significant, whereas spark gap voltage was the least significant, and wire feed as insignificant parameter. They performed multi-objective optimization involving desirability approach for getting the optimal setting of process parameters. Also pulse on time and pulse off time affected significantly the surface finish of the current material, producing deep, wide overlapped craters and debris globules.

Kumanan and Nair (2017) [11] investigated the influence of pulse on time, pulse off time, current, voltage, flushing pressure, wire tension, table feed and wire speed on surface roughness, material removal rate, wire wear rate and geometric tolerances while processing on wire EDM of Inconel 617. The experiment was designed as per Taguchi's approach with L_{18} orthogonal array. They used Grey relational Adaptive neuro fuzzy inference system (ANFIS) to optimise the multi objectives. The significant parameters were identified by employing the grey grades. Their investigation revealed that the values predicted by the developed ANFIS model were found to be in close agreement with the experimental values.

Dhakad and Vimal (2017) [12] studied the effect of open voltage (OV), servo voltage (SV), & wire feed (WF) on metal removal rate (MRR), machining time (MT) and gap voltage (GV) while processing on wire EDM of En45A Alloy Steel. The experiment was designed as per Taguchi's approach with L_9 orthogonal array. The principal component analysis approach has been used for the optimization of process parameters. They reported that the open voltage affected most significantly the multiple responses.

Goyal (2017) [13] investigated the effect of process parameters namely tool electrode, current density, pulse off time, pulse on time, wire tension and wire feed on response variables namely metal removal rate (MRR) and surface roughness (SR) during the WEDM of Inconel 625 alloy. The experiment was designed using L_{18} orthogonal array and analysis of variance (ANOVA) was carried out. Their investigation revealed that tool electrodes, current density and pulse on time were the significant parameters affecting response.

Chandrakanth et al. (2016) [14] investigated the influence of pulse on time (T_{on}), wire tension and spark gap voltage (SV) on the metal removal rate (MRR) of M42 high speed steel (HSS) with brass wire of 0.25 mm diameter as tool electrode. The experiment was performed in 8 runs using full factorial design. The analysis of variance (ANOVA) was carried out to determine the most significant factors. They obtained optimum settings of different input parameters using Genetic algorithm. The accuracy of mathematical model so obtained was verified using Response surface methodology technique. Their investigation revealed that the most significant factor for promoting MRR was pulse off time (T_{on}) and servo voltage (SV).

Mukhuti et al. (2016) [15] investigated inconel 600 using wire EDM. The experiment was designed as per Taguchi's approach with L_9 orthogonal array. The MOORA method was used to determine the signal to noise (S/N) ratio of responses namely material removal rate, machining time, surface roughness and overcut. They reported that different input process parameters have different affects on machining of work piece. They used multi-objective optimization for finding out the optimal setting of process parameters.

Nagaraja et al. (2015) [16] investigated the influence of process parameters namely pulse on time (T_{on}), pulse of time (T_{off}) and wire feed rate on MRR and SR while WEDM of bronze-alumina metal matrix composite (MMC). The experiment was designed as per Taguchi's approach with L_9 orthogonal array. Signal to noise ratio (S/N) and analysis of variance (ANOVA) were used to analyze the affect of the parameters on MRR and SR. Their investigation revealed that wire feed rate was the most significant parameter influencing SR.

Bobbili et al. (2015) [17] showed a multi response optimization technique based on Taguchi method used with Grey relational analysis is used for wire-EDM operations on ballistic grade aluminum alloy for different applications. They investigated the influence of pulse-on time, pulse-off time, peak current and spark voltage on material removal rate (MRR), surface roughness (SR) and gap current (GC). They reported that pulse-on time, peak current and spark voltage were the most significant variables to Grey relational grade. They performed confirmation tests to verify the results obtained by Grey relational analysis and 6% of error was reported.

Khanna et al. (2015) [18] investigated the influence of pulse on-time, pulse off-time and water pressure on tool wear rate (TWR) and MRR while electric discharge drill machining (EDDM) of Al-7075 using brass wire of 2 mm diameter. The experiment was designed as per Taguchi's approach with L_{18} orthogonal array. They revealed from the investigation that the combination of maximum pulse on-time and minimum pulse off-time gives maximum MRR.

Khan et al. (2014) [19] investigated the influence of on-time, pulse off-time, and current on process parameters namely surface roughness and microhardness while processing on wire electrical discharge machining (WEDM) of high strength low alloy steel (ASTM A572-grade 50). The experiment was designed as per Taguchi's approach with L_9 orthogonal array. The optimization was carried out using Grey relational analysis approach. They reported that pulse off time emerged as the most significant parameter affecting the surface roughness and the micro-hardness.

Joshi (2014) [20] investigated the influence of process parameters namely peak current, pulse off time, pulse on time, bed speed on material removal rate (MRR) and machining time while processing on wire EDM of En31 steel. They reported that pulse on time (T_{on}) and current were the most significant parameters affecting material removal rate (MRR).

Basil et al. (2013) [21] investigated the influence of voltage, dielectric pressure, pulse on-time and pulse off-time on spark gap of Ti6AL4V alloy. They reported that the pulse on time, pulse off time, the interaction of dielectric pressure and pulse off time, and interaction of pulse on time and pulse off time were significant parameters which affect the spark gap of WEDM. Minimum spark gap can be obtained by adopting a low value of pulse on time (20 µs), a high value of dielectric pressure (15 kgf/cm^2) high value of pulse off time (50 µs) and voltage of 50 V. They reported their research findings with the error of 6%.

Kumar and Narang (2013) [22] studied the influence of cutting speed, feed rate and depth of cut on MRR and SR while high speed turning of medium carbon steel AISI 1045 in dry conditions. The experiment was designed as per Taguchi's approach with L_9 orthogonal array. The optimization was carried out using Grey relational analysis approach. The optimum condition for combined effects was found with the optimal value of the surface roughness (Ra) of 1.007 (µm) and MRR of 465.08 (mm^3/sec) was reported.

Rajyalakshmi and Ramaiah (2013) [23] studied the effect of process parameters namely pulse on time, pulse off time, corner servo, flushing pressure, wire feed rate, wire tension, spark gap and servo feed on response variables namely material removal rate (MRR), surface roughness (SR), and spark gap (SG) during the WEDM of Inconel 825 alloy. The experiment was designed with L_{36} orthogonal array and grey relational grade was used for the analysis purpose. They reported that pulse on time, pulse off time**,** spark gap and corner servo influenced significantly for maximization of material removal rate (MRR), otherwise for minimization of surface roughness (SR), and spark gap (SG).

Dharmender et al. (2012) [24] studied the effect of peak current, pulse on time, pulse off time and wire tension on surface roughness (SR) while processing on wire EDM of En31 tool steel. Their investigation revealed that for surface roughness the error between the predicted and experimental values was found to be 5.67%.

Singh and Verma (2012) [25] investigated the influence of pulse on time (T_{on}), pulse off time (T_{off}), and water pressure on Material removal rate (MRR) while processing on electric discharge drill machine (EDDM) of Al-7075. The experiment was designed as per Taguchi's approach with L_{27} orthogonal array. They reported that the combination of maximum pulse on time (T_{on}) and minimum pulse off time (T_{off}) resulted in maximum MRR.

Sreenivasulu and Rao (2012) [26] investigated the effects of cutting speed, feed rate, drill diameter, point angle and cutting fluid mixture ratio on the surface roughness (SR) and roundness error (RE) while drilling AI6061 alloy with HSS twist drills. The experiment was designed as per Taguchi's approach with L_{18} orthogonal array and Grey relational analysis was applied so as to minimize the SR and RE. Their investigation revealed that with optimal settings of cutting speed at 25.13 m/min, feed rate at 0.3 mm/rev, 10mm drill diameter with 110 degrees point angle and 12% cutting fluid mixture ratio resulted in minimum SR and RE.

Kumar and Agarwal (2012) [27] studied the influence of peak current, pulse-on time, pulse-off time, wire feed, wire tension and flushing pressure on the material removal rate (MRR) and surface roughness (SR) while WEDM of M2 high speed steel (HSS). Taguchi's parametric design approach was adapted to conduct the experiments and analysis was done by employing multi-objective genetic algorithm. They reported that peak current, pulse-on time, pulse-off time and wire feed significantly influenced the MRR and SR.

Jangra et al. (2010) [28] studied the effect of process parameters peak current, pulse-on time, pulse-off time, wire feed, wire tension on cutting speed, surface roughness and dimensional lag during the WEDM of D3 die steel. The experimented was designed as per Taguchi's approach with L_{18} orthogonal array. Grey relational analysis was carried out to find optimal settings of process parameters. They observed from the investigation that cutting speed (3.80 mm/min) was obtained with a dimensional lag of 0.008 mm, which is suitable for rough cut. However the surface roughness was poor and can be enhanced by assigning high weightage in grey relational grade.

Singh and Garg (2009) [29] investigated the effect of pulse on time (TON), pulse off time (TOFF), gap voltage (SV), peak current (IP), wire feed (WF) and wire tension (WT) on material removal rate (MRR) while processing of Hot die steel (H-11) on WEDM. They reported that the WF and WT affected little to the response parameter. However, MRR directly increased with increase in TON and IP, while it reduced with increase in TOFF and SV.

Mahapatra and Patnaik (2007) [30] employed Taguchi's method for studying the effect of discharge current, pulse duration, pulse frequency, wire speed, wire tension, and dielectric flow on material removal rate (MRR) , surface finish (SF) and cutting width (CW) while processing of D2 die steel on WEDM. They established relationship between process parameters and responses using nonlinear regression analysis. Their research findings revealed that process parameters namely discharge current, pulse duration, and dielectric flow rate significantly affects towards maximization of MMR and minimization of both the SF and CW.

Ramakrishnan and Karunamoorthy (2006) [31] performed multi response optimization using Taguchi's parametric design approach. They investigated the effect of pulse on time, wire tension, delay time, wire feed speed, and ignition current intensity on responses namely material removal rate (MRR), surface roughness (SR) and wire wear ratio (WWR) while processing of heat treated tool steel on wire electrical discharge machining (WEDM) process. The experiment was designed as per L_{16} orthogonal array. They performed analysis of variance (ANOVA) for identifying the level of the process parameters affecting the multiple responses considered. They reported that pulse on time and ignition current intensity was the most significant parameters influencing material removal rate (MRR) and wire wear ratio.

IV. EXPERIMENTATION

The work material selected for the study was M6 high speed steel (HSS). The experimental work was carried out on Wire EDM machine of ELECTRONICA make (SPRINTCUT 734). A brass Wire with a diameter of 0.25 mm was used as an electrode for cutting a square of 5 mm x 5 mm dimensions in a flat plate as shown in figure 4.1. The non linear relationship among the input parameters, if it exists, can only be discovered if more than two levels of the parameters are considered (Byrne & Taguchi 1987) [32]. Thus each selected parameter was analyzed at five levels. The range of selected input parameters were determined by conducting the pilot experiments using one factor at a time (OFAT) approach. The process parameters and their values at five levels are given in Table 4.1.

Table 4.1: Levels for various process parameters

Designation	Process Parameter	Level 1	Level 2	Level 3	Level 4	Level 5
T_{on}	Pulse on Time (µs)	100	105	110	115	120
T_{off}	Pulse off time (µs)	20	30	40	50	60
I_p	Peak Current (A)	60	100	120	140	160
SV	Servo Voltage (V)	20	30	40	50	60

The Wire cut EDM process to be investigated corresponds to L_{25} orthogonal array consisting of twenty five trials, with each trial having three replications. The experiments have been conducted in completely randomized order. The pulse on time (T_{on}), pulse off time (T_{off}), peak current (IP) and servo voltage (SV) have been taken as input parameters. Material removal rate (MRR) and surface roughness (SR) have been taken as the response parameters. The experiments were conducted and collected data was analyzed using Taguchi based Grey Relational Analysis to know the optimal setting of process parameters for better SR and good MRR under different machining conditions.

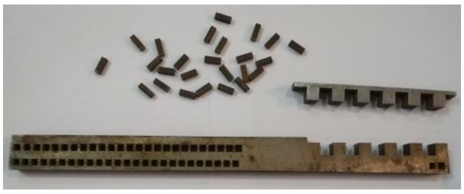

Figure 4.1 Square cut in a flat plate of M6 HSS.

The signal to noise (S/N) ratio for both MRR and SR were calculated using Minitab 17 and have been tabulated respectively in table 4.2 and 4.3.

Table 4.2 Signal to Noise ratio for mean MRR

S No.	T_{on}	T_{off}	I_p	SV	Mean MRR	S/N Ratio (dB)
1	100	20	60	20	147.162	43.35593
2	100	30	100	30	165.282	44.36449
3	100	40	120	40	165.491	44.37551
4	100	50	140	50	141.746	43.0302
5	100	60	160	60	117.775	41.42105
6	105	20	100	40	180.820	45.14492
7	105	30	120	50	173.368	44.77938

8	105	40	140	60	160.309	44.09917
9	105	50	160	20	167.944	44.50327
10	105	60	60	30	121.953	41.72385
11	110	20	120	60	181.927	45.19794
12	110	30	140	20	203.997	46.19248
13	110	40	160	30	194.133	45.76199
14	110	50	60	40	152.022	43.63813
15	110	60	100	50	156.839	43.90909
16	115	20	140	30	203.316	46.16341
17	115	30	160	40	204.151	46.19904
18	115	40	60	50	166.845	44.44626
19	115	50	100	60	160.175	44.09189
20	115	60	120	20	166.560	44.43142
21	120	20	160	50	196.032	45.84655
22	120	30	60	60	196.541	45.86905
23	120	40	100	20	220.885	46.88334
24	120	50	120	30	218.368	46.78377
25	120	60	140	40	206.181	46.28495

Table 4.3 Signal to Noise ratio for mean SR

S No.	T_{on}	T_{off}	I_p	SV	Mean SR(μm)	S/N Ratio(dB)
1	100	20	60	20	2.61	-8.344
2	100	30	100	30	8.32	-18.399
3	100	40	120	40	6.74	-16.581
4	100	50	140	50	2.34	-7.392
5	100	60	160	60	1.60	-4.083
6	105	20	100	40	11.69	-21.356
7	105	30	120	50	10.79	-20.658
8	105	40	140	60	3.74	-11.465
9	105	50	160	20	7.65	-17.677
10	105	60	60	30	1.66	-4.402
11	110	20	120	60	11.91	-21.521
12	110	30	140	20	12.97	-22.261
13	110	40	160	30	12.55	-21.975
14	110	50	60	40	2.95	-9.389
15	110	60	100	50	3.43	-10.709
16	115	20	140	30	12.90	-22.212
17	115	30	160	40	12.92	-22.228
18	115	40	60	50	6.67	-16.483
19	115	50	100	60	4.78	-13.597
20	115	60	120	20	8.27	-18.347
21	120	20	160	50	12.56	-21.554
22	120	30	60	60	12.67	-22.056
23	120	40	100	20	15.34	-23.719
24	120	50	120	30	14.88	-23.450
25	120	60	140	40	13.82	-22.811

The normalized S/N ratios for surface roughness (SR) and Material removal rate (MRR) have been tabulated in table 4.4.

Table 4.4 Normalized Signal to Noise Ratio for MRR and SR

S No.	T_{on}	T_{off}	I_p	SV	Normalized S/N Ratio	
					MRR	SR
1	100	20	60	20	0.3542	0.7829
2	100	30	100	30	0.5389	0.2709
3	100	40	120	40	0.5409	0.3634
4	100	50	140	50	0.2946	0.8314
5	100	60	160	60	0.0000	1
6	105	20	100	40	0.6817	0.1202
7	105	30	120	50	0.6148	0.1158
8	105	40	140	60	0.4903	0.624
9	105	50	160	20	0.5643	0.3076
10	105	60	60	30	0.0554	0.9837
11	110	20	120	60	0.6914	0.1119
12	110	30	140	20	0.8735	0.0742
13	110	40	160	30	0.7947	0.0887
14	110	50	60	40	0.4059	0.7297
15	110	60	100	50	0.4555	0.6625
16	115	20	140	30	0.8682	0.0767
17	115	30	160	40	0.8747	0.0759
18	115	40	60	50	0.5538	0.3684
19	115	50	100	60	0.4890	0.5154
20	115	60	120	20	0.5511	0.2735
21	120	20	160	50	0.8102	0.0885
22	120	30	60	60	0.8143	0.0846
23	120	40	100	20	1.0000	0
24	120	50	120	30	0.9818	0.0136
25	120	60	140	40	0.8905	0.0462

These normalized S/N ratios for SR and MRR has been calculated using the following relation:

$$\frac{Yij - \min(Yij, i=1,2,3,\ldots,n)}{\max(Yij, i=1,2,3,\ldots,n) - \min(Yij, i=1,2,3,\ldots,n)}$$

(For maximum MRR and minimum SR)

Thereafter grey relational coefficient is calculated to show relation between ideal and actual normalized result. Prior to calculation of the grey relational coefficient, the deviation sequence for both MRR and SR has to be worked out. These Deviation sequence for MRR and SR have been tabulated in table 4.5

Table 4.5 The Deviation sequences for MRR and SR

S No.	T_{on}	T_{off}	I_p	SV	Deviation Sequence	
					MRR	SR
1	100	20	60	20	0.6458	0.2171
2	100	30	100	30	0.4611	0.7291
3	100	40	120	40	0.4591	0.6366
4	100	50	140	50	0.7054	0.1686
5	100	60	160	60	1.0000	0
6	105	20	100	40	0.3183	0.8798
7	105	30	120	50	0.3852	0.8842
8	105	40	140	60	0.5097	0.376
9	105	50	160	20	0.4357	0.6924
10	105	60	60	30	0.9446	0.0163
11	110	20	120	60	0.3086	0.8881
12	110	30	140	20	0.1265	0.9258
13	110	40	160	30	0.2053	0.9113
14	110	50	60	40	0.5941	0.2703
15	110	60	100	50	0.5445	0.3375
16	115	20	140	30	0.1318	0.9233
17	115	30	160	40	0.1253	0.9241
18	115	40	60	50	0.4462	0.6316
19	115	50	100	60	0.5110	0.4846
20	115	60	120	20	0.4489	0.7265
21	120	20	160	50	0.1898	0.9115
22	120	30	60	60	0.1857	0.9154
23	120	40	100	20	0.0000	1
24	120	50	120	30	0.0182	0.9864
25	120	60	140	40	0.1095	0.9538

Once the deviation sequence has been found, then with the help of following relation,

$$\xi(k)=\frac{\Delta \min +\zeta\Delta max}{\Delta o +\zeta\Delta max}$$

the Grey Relational Coefficient is calculated and tabulated in table. 4.6. Here 'ζ' is identified coefficient and its value ζ= 0.5 is generally used.

Table 4.6 Grey Relation Coefficient

S No.	T_{on}	T_{off}	I_p	SV	GRC	
					MRR	SR
1	100	20	60	20	0.4364	0.6972
2	100	30	100	30	0.5202	0.4068
3	100	40	120	40	0.5213	0.4399
4	100	50	140	50	0.4148	0.7478
5	100	60	160	60	0.3333	1
6	105	20	100	40	0.6111	0.3623
7	105	30	120	50	0.5649	0.3612
8	105	40	140	60	0.4952	0.5705
9	105	50	160	20	0.5343	0.4193
10	105	60	60	30	0.3461	0.9684
11	110	20	120	60	0.6184	0.3599
12	110	30	140	20	0.7981	0.3506
13	110	40	160	30	0.7089	0.3542
14	110	50	60	40	0.4570	0.649
15	110	60	100	50	0.4787	0.597
16	115	20	140	30	0.7914	0.3512
17	115	30	160	40	0.7996	0.351
18	115	40	60	50	0.5284	0.4418
19	115	50	100	60	0.4945	0.5078
20	115	60	120	20	0.5269	0.4076
21	120	20	160	50	0.7248	0.3542
22	120	30	60	60	0.7292	0.3532
23	120	40	100	20	1.0000	0.3333
24	120	50	120	30	0.9648	0.3363
25	120	60	140	40	0.8203	0.3439

After finding out the Grey relational coefficient corresponding to each performance characteristic, the grey relation grade was calculated and ranked in table 4.7. The optimal parametric combination has been carried out to obtain highest Grey relational grade (GRG). The higher value of GRG corresponds to a relational degree between the reference sequence and the given sequence. The reference sequence shows the best process sequence. So a higher GRG means the corresponding parameter combination is closer to the optimal condition. In this grade ranking two trials have been kept at rank 1.

Table 4.7 Grey Relational Grades

S No.	T_{on}	T_{off}	I_p	SV	Grade	Rank
1	100	20	60	20	0.5668	9
2	100	30	100	30	0.4635	23
3	100	40	120	40	0.4806	20
4	100	50	140	50	0.5813	5
5	100	60	160	60	0.6667	1
6	105	20	100	40	0.4867	18
7	105	30	120	50	0.4630	24
8	105	40	140	60	0.5328	14
9	105	50	160	20	0.4768	22
10	105	60	60	30	0.6573	2
11	110	20	120	60	0.4891	17
12	110	30	140	20	0.5744	7
13	110	40	160	30	0.5316	15
14	110	50	60	40	0.5530	10
15	110	60	100	50	0.5378	13
16	115	20	140	30	0.5713	8
17	115	30	160	40	0.5753	6
18	115	40	60	50	0.4851	19
19	115	50	100	60	0.5012	16
20	115	60	120	20	0.4673	21
21	120	20	160	50	0.5395	12
22	120	30	60	60	0.5412	11
23	120	40	100	20	0.6667	1
24	120	50	120	30	0.6506	3
25	120	60	140	40	0.5821	4

The figure 4.2 shows the Grey relational grade for maximum MRR and minimum SR presented in table 4.7. The highest value of grey relational grade shows the stronger relational degree between the given sequence and reference sequence. The higher value of grey relational grade means the corresponding cutting parameter is closer to optimal solution. They reported from table 4.8 that pulse on time of level 5, Pulse of time of level 5 and peak current of level 4 and servo voltage of level 2 will be nearer to optimal solution for this study.

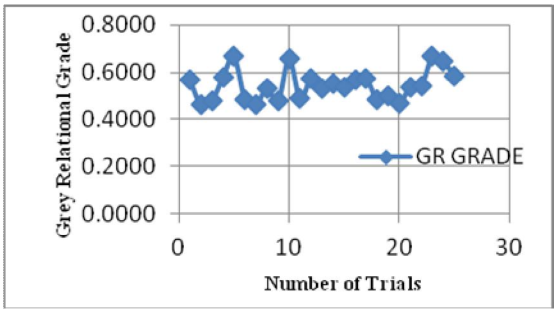

Figure 4.2 Grey relational grades for maximum MRR and SR.

The figure 4.2 shows the larger grey relational grade for the better performance characteristics. However, the multiple performance characteristics for the machining parameters are still need to be known. Therefore with the help of table 4.8 and figure 4.3 to 4.6, the optimal parameters have been determined for WEDM. Those parameters are T_{on} (5^{th} level, 120 µs), T_{off} (5^{th} level, 60 µs), IP (4^{th} level, 140 amp) and SV (2^{nd} level, 30 V).

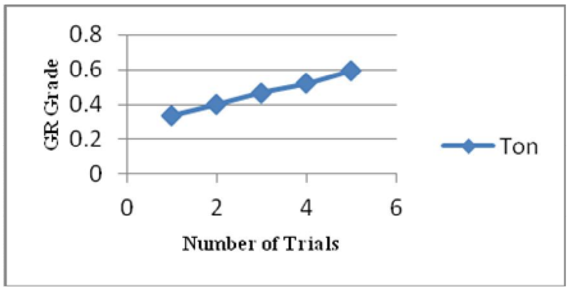

Figure 4.3 Grey relational grade with respect of Ton (Pulse on Time)

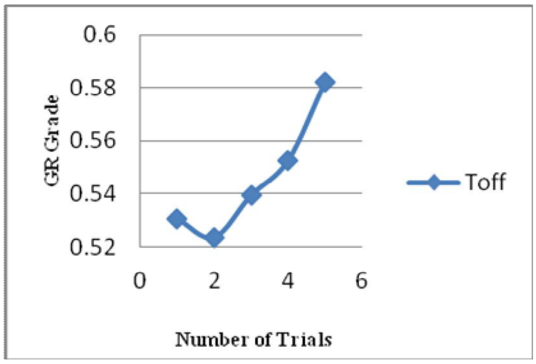

Figure 4.4 Grey relational grade with respect of Toff (Pulse off Time)

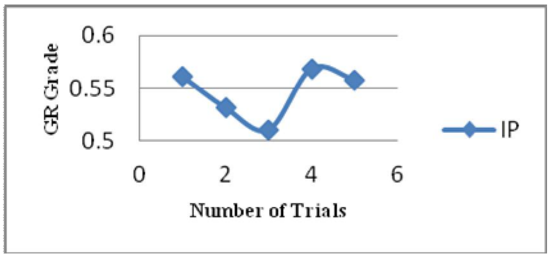

Figure 4.5 Grey relational grade with respect of IP (Peak Current)

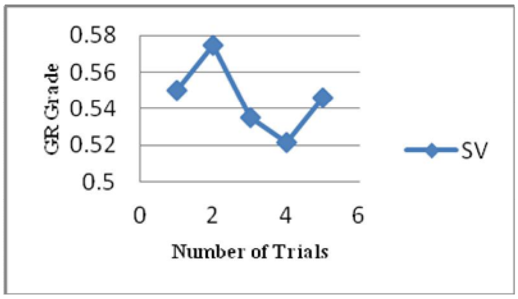

Figure 4.6 Grey relational grade with respect of SV (Servo Voltage)

Table 4.8 Levels of Optimum Factors

Parameters	Level 1	Level 2	Level 3	Level 4	Level 5	Rank
T_{on}	0.5517	0.5233	0.5371	0.5120	**0.5960***	1
Toff	0.5306	0.5234	0.5393	0.5525	**0.5822***	2
I_P	0.5608	0.5311	0.5101	**0.5683***	0.5579	3
SV	0.5504	**0.5748***	0.5355	0.5213	0.5462	4

The predicted value of Grey relation grade, Material removal rate (MRR) and Surface roughness (SR) has been calculated using following relation:

$$\mathbf{n = n_m + \sum_{i=1} (n_{im} - n_m)}$$

Where,

n is the predicted value of optimal setting
$\mathbf{n_m}$ is total mean value of quality characteristics.
$\mathbf{n_{im}}$ mean value of quality characteristics at optimum level of each parameter.

The expected mean at optimal setting (µ) is calculated by using relation:

µ= T_{on} (5th level, 120 µs) + T_{off} (5th level, 60 µs) + I_P (4th level, 140 amp) + SV (2nd level, 30 V) - 3 x T_{qq}.

Where, T_{qq} is the overall mean of Grey relational grade.

By using the optimal parameters, the optimum output response (Material removal rate and Surface roughness) are predicted by the given formula:

Predicted mean= Average of T_{on} (5th level, 120 µs) + Average of T_{off} (5th level, 60 µs) + Average of I_P (4th level, 140 amp) + Average of SV (2nd level, 30 V) – 3 x Mean of response.

Predicted Grey Relational Grade = 0.5960 + 0.5822 + 0.5683 + 0.5748 -3 x 0.5457 **= 0.6842**

Predicted mean MRR= 207.59 + 153.86 + 183.10 + 180.61 – 3 x 174.79 **= 200.80mm^3/min**

Predicted mean SR = 14.44 + 5.75 + 9.13 + 6.94 – 3 x 8.631 **= 12.90µm.**

V. CONFIRMATION EXPERIMENT

The confirmation experiment is the final step in verifying the conclusions drawn based on Taguchi's parameter design approach using Grey relational based analysis. The optimum settings are combinations of the significant process parameters and a selected number of experiments are run under these settings. The mean of the results of the confirmation experiment is compared with the predicted optimal values. The confirmation experiment is a decisive step and is deeply suggested by Taguchi to verify the experimental conclusions (Ross 1996) [33]. Three confirmation experiments were thus conducted at the optimal settings of the WEDM process parameters recommended by the study that is 5th level of T_{on} , 5th level of T_{off} , 4th level of I_P and 2nd level of SV. The average value of material removal rate (MRR) and surface roughness (SR) while WEDM M6 HSS with a brass wire of 0.25 mm diameter was found to be 195.75 mm^3/min and 12.48 µm respectively. These results were found to be within the 5% error of the predicted optimal value of the selected machining characteristics (MRR and SR). Hence the optimal settings of the process parameters, as predicted in the analysis, can be implemented. The predicted optimum value and the error for both material removal rate and surface roughness have been tabulated in Table 5.1.

Table 5.1 Comparison of predicted and experimental results

Response	Predicted mean value	Experimental value	Error interval (±5%)
Material removal rate (mm^3/min)	200.80	195.75	190.76 < MRR < 210.84
Surface roughness (µm)	12.90	13.29	12.255 < SR < 13.545

VI. CONCLUSION

The current investigation has successfully demonstrated the application of Taguchi based Grey relational analysis for multi response optimization of process parameters in WEDM of M6 HSS.

The following conclusions can be drawn from the current study:

1. From this experimental work it is observed that the pulse on time (Ton) emerged as the most significant factor which affects material removal rate (MRR).
2. Peak current (IP) is also an significant factor in the WEDM. As the peak current is increased, the MRR also increases.
2. When pulse of time (Toff) is increased in WEDM, the MRR also decreases.
3. When servo voltage (SV) is increased in WEDM, the MRR also decreases.
4. The optimal combination of WEDM process parameters obtained for maximizing material removal rate and minimizing surface roughness are pulse on time of 120 µs, pulse off time of 60 µs, peak current of 140 amp and servo voltage of 30 V.

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