MULTI-RESPONSE OPTIMIZATION OF AISI M42 HSS MATERIAL IN WIRE-CUT EDM USING GREY RELATIONAL ANALYSIS

Joshi Guruprasad R., Research Scholar, Dept. of Mechanical Engg., AMGOI, Kolhapur, Maharashtra, India

A. N. Chapgaon, Professor and H.O.D., Dept. of Mechanical Engg., AMGOI, Kolhapur, Maharashtra, India

Abstract: *Wire Electro-discharge machining (WEDM) process consists of large number of variables. The selection of optimal combination of process parameters helps to achieve the optimal performance but, large number of variables makes it difficult. WEDM needs the multi-response optimization technique to achieve this. The goal of current research work is multi-response optimization of AISI M42 HSS material using Grey relational analysis (GRA) in WEDM. The pulse on time (Ton), pulse off time (Toff) and wire feed rate (Wf) are selected as process parameters. The Grey relational grade was calculated by adopting four different weight systems. The study reveals that, the most significant factors for MRR, SR and kerf width are Ton followed by Toff. The obtained optimal combination for three weighted GRG is A2-B3-C1 i.e., wire feed rate 6m/min, pulse on time 114µs and pulse off time 50µs. At this level the MRR of 7.2020mm^3/min, SR of 3.29µm and KW of 0.317mm could be achieved. For average GRG, the optimum combination is A2-B3-C3. i.e., (wire feed rate – 6m/min, pulse on time – 114µs and pulse off time – 56µs). At this level the MRR of 5.2894mm^3/min, SR of 3.07µm and KW of 0.3028mm have been achieved.*

Keywords: *Grey relational analysis; Multi response optimization; Process parameters; Response variables; Wire electro-discharge machining (WEDM)*

1. INTRODUCTION

Wire Electro-discharge machining (WEDM) is a non-contact type electro-thermal non-conventional machining process. EDM has the capability of machining intricate features in hard and difficult-to- cut material with high dimensional accuracy, which has made EDM process the most popular and an inevitable non-conventional machining process [1]. Wire electro-discharge machining (WEDM) or wire-cut EDM utilizes electrically conductive workpiece and tool i.e., metal wire (usually brass wire of diameter 0.25mm). Servo-driven system controlled by microprocessor drives the electrode with extreme accuracy. Material removal takes place due to rapid and repetitive spark discharges (more than thousand times per second) between workpiece and tool electrode. Both EDM and micro-EDM processes in recent years were used extensively in the fields such as mould making, production of dies and cavities [1-2]. Depending on the geometry, for smaller batch sizes EDM was found to be a better choice, whereas for large scale production ECM is more suitable choice [2]. The WEDM has great scope for improvement in machining processes and equipment to achieve higher productivity, accuracy and reliability [2]. U. A. Dabade et al. [3] analyzed Inconel 718 using Taguchi L8 orthogonal array for material removal rate (MRR), surface roughness (SR), cutting width (kerf) and dimensional deviation in WEDM. The result of the study reveals that, pulse-on-time (Ton) is the most influential factor for all the response variables. It was also observed that, peak current is significant for kerf and dimensional deviation whereas, servo voltage is significant for MRR and SR.

Rupesh Chalisgaonkar et al. [4] investigated process capability for commercially pure titanium in WEDM using Taguchi method. Higher pulse on time releases higher spark energy which increases the melting and evaporation of work piece material that leads to higher MRR. The increase in pulse off time and spark gap voltage results in loss of effective pulse discharge energy. It was also observed that higher release of spark energy increases size of craters formed that leads to increase in the SR [3-4]. Feng Yerui et al. [5] examined EDM process parameters using TiC/Ni metal ceramic material and revealed that, SR and MRR increases with the increase of peak current and pulse duration. J. Deng [6] in 1982 proposed the Grey system theory also called as Grey relational analysis (GRA). The Taguchi method was developed by Genichi Taguchi in 1970's. It is the most important statistical tool used by industry for single output parameter optimization.

In Grey relational analysis, multi-response problem is converted into single output parameter problem by calculating grade [6-12]. Grey relational grade is weighted sum of Grey relational coefficient [7,11]. Shailesh Dewangan et al. [8] applied grey-fuzzy logic-based hybrid optimization technique to determine the optimal settings of EDM for AISI P20 tool steel to improve surface integrity aspect using Response surface methodology (RSM). The result of the study reveals that, pulse on time is the most contributing parameter followed by peak current. Vikas et al. [9] studied the effect of pulse on time, pulse off time, discharge current and voltage over the SR for an EN41 material in EDM using the Grey-Taguchi method. The result of the study reveals that, the current had larger impact over the SR value followed by the voltage.

Amitesh Goswami et al. [10] explained the effect of process parameters on surface integrity, MRR and wire wear ratio (WWR) for Nimonic 80A in WEDM using GRA and Taguchi method. The material removal rate (MRR) increases with increase in pulse on time, peak current and wire tension. The Increase in the pulse duration increases the WWR and increasing the wire speed decreases it. J. B. Saedon et al. [11] examined the effects of pulse-off time, peak current, wire feed and wire tension on different responses such as SR, cutting rate and MRR for Titanium alloy in WEDM using Taguchi method and GRA. The result of the study reveals that, pulse off time is the most significant machining parameter that affects the multiple performance characteristics, followed by peak current, wire feed and wire tension. Rajesh Purohit et al. [12] optimized MRR, electrode wear ratio (EWR) and over cut (OC) during EDM of M2 steel using GRA with L9 orthogonal array. The study revealed that, mainly electrode rotation speed affects the output parameters significantly followed by voltage and pulse on time.

Most of the researchers investigated the effect of a limited number of process parameters on the response variables in WEDM. Pulse on time followed by pulse off time is significant for MRR and SR. Wire feed rate along with pulse off time affects the Kerf width. The effect of machine process parameters on AISI M42 HSS material was not fully explored using WEDM with constant current and voltage parameter condition [13,14]. Due to a large number of variables and improper combination of process parameters, the optimal performance of WEDM processes is very difficult to achieve [3,13,14]. This goal can be achieved by using multi-response optimization technique such as Grey relational analysis (GRA) to determine the relationship between the process parameters and response variables in WEDM.

AISI M42 is premium cobalt high speed steel with a chemical composition designed for high hardness and superior hot hardness. The composition of AISI M42 HSS makes it excellent in wear resistance due to high heat-treated hardness (68 to 70 hrc), and the high cobalt content imparts the hot hardness. Therefore the investigation of effect of different process parameters on AISI M42 HSS using GRA is very important. The goal of current research work is to determine the optimum process parameters such as pulse on time (Ton), pulse off time (Toff), wire feed rate (Wf) for the response variables such as material removal rate (MRR), surface roughness (Ra), kerf width (KW) in WEDM for AISI M42 HSS material using Grey relational analysis (GRA) as a multi-response optimization technique.

2. EXPERIMENTAL PROCEDURE

2.1 Experimental set-up

The CNC Wirecut EDM Machine Electronica - Maxicut 734 was selected for current research work. For current research work experiments were performed on AISI M42 HSS material with a size of 10 x 10 x 200 mm. Taguchi L18 orthogonal array is used for the experimentation and analysis is performed by using Minitab-17 software. In each experimental run 6 mm x 6 mm square punch was cut from the work piece on the CNC Wirecut EDM Machine. Brass wire of 0.25mm diameter with deionized water as dielectric fluid has been used during machining process. Based upon pilot experiments and available literature, the process parameters with levels were selected to conduct the main (major) experiment and are arranged in Table 1. Current at 2A, voltage at 20V with other parameters were maintained at constant level. Fig. 1 shows the details of experimental setup.

Table 1. Process parameters with levels

Process parameters	Unit	Levels		
		1	2	3
A - wire feed rate (Wf)	m/min	4	6	----
B - pulse on time (Ton)	µs	108	111	114
C - pulse off time (Toff)	µs	50	53	56

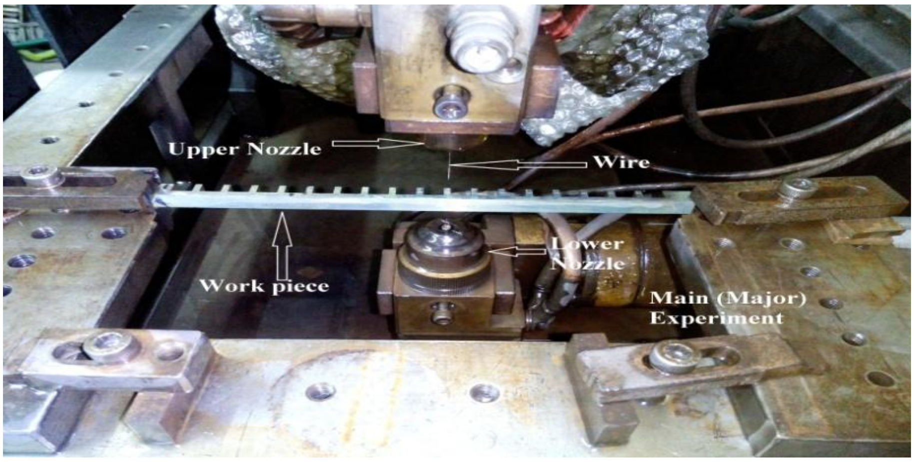

Fig. 1. Experimental setup with work piece

2.2 Measurement of responses

MRR was calculated by taking product of kerf width, cutting speed and thickness of material. Eq. (1) was utilized to calculate MRR. Heidenhain make electronic probe with DRO (L.C. - 0.0001mm) was used to measure the kerf width and thickness of material. The difference between dimensions (thickness) of workpiece before and after machining was observed to calculate the kerf width. The cutting speed was recorded directly from control panel of the WEDM machine. The surface roughness values were measured by using a Mitutoyo make SJ-201 surface roughness tester (L.C. - 0.01µm). For each test four values were recorded. After measurement, the arithmetic mean of data is calculated and used as an absolute value.

$$MRR = KW * Vc * Mt \qquad (1)$$

Where KW = Kerf Width in mm, Vc = Cutting Speed in mm/min, Mt = Thickness of material in mm [3].

3. GREY RELATIONAL ANALYSIS

In many cases single response optimization [9-10] is not possible as the objective would be to simultaneously minimizing some parameters and maximize the remaining one. Hence there is need for a multi-response (objective) optimization. In GRA, complicated multiple performance characteristics is converted into the single performance characteristics by calculating Grey relational grade [6-12]. This makes GRA a multi-response optimization technique. Step wise procedure for GRA is given below.

3.1 Data pre-processing

Data pre-processing involves transforming of original sequence of values (results of the parameters) to comparable sequence which is a dimensionless quantity. Experimental results are thus normalized in a range of 0 to 1. The original reference sequence and sequence for comparison is represented as $x_o(k)$ and $x_i(k)$, i = 1, 2, . . ., m; k =1, 2, . . ., n, respectively, where m is the total number of experiment to be considered, and n is the total number of observation data. In data pre-processing, depending upon characteristics of original sequence, the values are normalized by using respective equation as follows.

Smaller-the-better-

$$x_i^*(k) = \frac{\max x_i^o(k) - x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \qquad (2)$$

Larger-the-better-

$$x_i^*(k) = \frac{x_i^o(k) - \min x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \tag{3}$$

Nominal-the-better-

$$x_i^*(k) = 1 - \frac{\left| x_i^o(k) - OB \right|}{\max\{\max x_i^o(k) - OB; OB - \min x_i^o(k)\}} \tag{4}$$

Here, OB is the target value.

3.2 Deviation sequence

The absolute difference between the reference sequence $x_o^*(k)$ and the comparability sequence $x_i^*(k)$ after normalization is called as the deviation sequence $\Delta_{oi}(k)$.

$$\Delta_{oi}(k) = \left| x_o^*(k) - x_i^*(k) \right| \tag{5}$$

$$\Delta_{\max} = \max_{\forall j \in i} \max_{\forall k} \left| x_o^*(k) - x_j^*(k) \right|$$

$$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} \left| x_o^*(k) - x_j^*(k) \right|$$

3.3 Grey relational co-efficient and Grey relational grades

The Grey relational coefficient expresses the relationship between the ideal (best) and actual (current) normalized experimental results. The Grey relational co-efficient $\xi_i(k)$ [6,8] can be expressed by,

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta.\Delta_{\max}}{\Delta_{oi}(k) + \zeta.\Delta_{\max}} \tag{6}$$

Where ζ is the distinguishing co-efficient, $\zeta \in [0,1]$

Here ζ is considered as 0.5. The Grey relational grade (GRG) is an average sum of the Grey relational coefficients which represents the level of correlation between reference and comparability sequence. The overall evaluation of the multiple performance characteristics is based on the Grey relational grade γ_i, which is expressed as.

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \tag{7}$$

However, in a real engineering system, the importance of different factors to the system varies and these factors carry unequal weights (w_k) as per the real condition. Hence, Eq. (7) is extended and defined as weighted sum [7,11] of Grey relational coefficient. Here w_k represents the weighting value of factor k and if factors have the same weight i.e., $w_k = 1$, then Eq. (7) and Eq. (8) becomes one and the same.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} w_k . \xi_i(k) \qquad \sum_{k=1}^{n} w_k = 1 \tag{8}$$

Higher Grey relational grade (GRG) among all other relational grades shows the importance of particular comparability sequence to the reference sequence [7].

4. RESULT AND DISCUSSION

The experimental results of MRR, SR and KW obtained for the main (major) experiment are listed in Table 2. The 'larger-the-better' characteristic is selected for MRR, whereas for SR and KW 'smaller-the-better' is selected. Eq. (2) and Eq. (3) is used for data preprocessing, the results of which are tabulated in Table 3. Eq. (5) is employed for deviation sequence and Eq. (6) for Grey relational coefficient. The results are listed in Table 4. The overall evaluation of the multiple performance characteristics is based on the Grey relational grade. The Grey relational grade is a weighted sum of the Grey relational coefficients $\xi_i(k)$. In a real engineering system, the importance of different factors to the system varies and accordingly in the real condition unequal weightage or weight (w_k) is carried by these factors. Eq. (7) was utilized to determine the Grey relational grade by adopting four different weight systems. These weights were adopted based on industrial requirements. Results of Grey relational grades with four different weights are listed in Table 5. In Table 5, column 2 shows the weight of MRR (50%), SR (25%) and KW (25%) i.e., equal weight is allotted to surface roughness and kerf width. The Column 3 shows the weight of MRR (50%), SR (40%) and KW (10%). The column 4 shows the weight of MRR (45%), SR (45%) and KW (10%) i.e., equal weight is allotted to MRR and SR. The column 5 shows average GRG with equal weightage (33-33-33) to all the three response variables. Response tables for GRG were calculated by employing Taguchi method for four different weight systems. They are shown in Table 6, Table 7, Table 8 and Table 9. In response tables average of GRG was calculated for each factor at respective level in the orthogonal array. Analysis of response tables for weighted GRG and average GRG was conducted different.

Table 2. L18 Orthogonal Array (OA) with experiment results

Expt. No.	Wf	Ton	Toff	Vc (mm/min)	MRR mm^3/min)	SR (Ra in µm)	KW (mm)
1	4	108	50	1.38	4.1729	3.17	0.3204
2	4	108	53	1.18	3.5290	3.02	0.31703
3	4	108	56	0.99	2.7857	2.97	0.2981
4	4	111	50	1.88	5.2859	3.21	0.2983
5	4	111	53	1.61	4.3539	3.08	0.2866
6	4	111	56	1.37	3.6449	3.04	0.2821
7	4	114	50	2.48	6.8818	3.4	0.2943
8	4	114	53	2.05	5.6123	3.36	0.2899
9	4	114	56	1.81	4.8898	3.19	0.2862
10	6	108	50	1.36	3.8435	2.9	0.2999
11	6	108	53	1.15	3.2256	2.83	0.2977
12	6	108	56	0.97	2.6192	2.67	0.2855
13	6	111	50	1.91	5.5151	3.18	0.3063
14	6	111	53	1.58	4.4675	3.15	0.2992
15	6	111	56	1.36	3.8377	3.07	0.2989
16	6	114	50	2.41	7.2020	3.29	0.31701
17	6	114	53	2.13	6.0823	3.24	0.3029
18	6	114	56	1.85	5.2894	3.07	0.3028

Table 3. Data pre-processing – Normalization

Expt. No.	Normalization		
	MRR	SR	KW
1	0.3390	0.3151	0
2	0.1985	0.5206	0.0882
3	0.0363	0.5890	0.5818
4	0.5819	0.2603	0.5779
5	0.3785	0.4384	0.8813
6	0.2238	0.4932	1
7	0.9301	0	0.6809
8	0.6531	0.0548	0.7957
9	0.4955	0.2877	0.8936
10	0.2672	0.6849	0.5361
11	0.1323	0.7808	0.5930
12	0	1	0.9113
13	0.6319	0.3014	0.3673
14	0.4033	0.3425	0.5526
15	0.2659	0.4521	0.5604
16	1	0.1507	0.0887
17	0.7557	0.2192	0.4573
18	0.5826	0.4521	0.4587

Table 4. Deviation sequence and Grey relational coefficient

Expt. No.	Deviation Sequence			Grey Relational Co-efficient		
	MRR	SR	KW	MRR	SR	KW
1	0.6610	0.6849	1	0.4307	0.4220	0.3333
2	0.8015	0.4795	0.9118	0.3842	0.5105	0.3542
3	0.9637	0.4110	0.4182	0.3416	0.5489	0.5445
4	0.4181	0.7397	0.4221	0.5446	0.4033	0.5422
5	0.6215	0.5616	0.1187	0.4458	0.4710	0.8081
6	0.7762	0.5068	0	0.3918	0.4966	1
7	0.0699	1	0.3191	0.8774	0.3333	0.6104
8	0.3469	0.9452	0.2043	0.5904	0.3460	0.7099
9	0.5045	0.7123	0.1064	0.4977	0.4124	0.8245
10	0.7329	0.3151	0.4639	0.4056	0.6134	0.5187
11	0.8677	0.2192	0.4070	0.3656	0.6952	0.5513
12	1	0	0.0887	0.3333	1	0.8493
13	0.3681	0.6986	0.6327	0.5760	0.4171	0.4414
14	0.5967	0.6575	0.4474	0.4559	0.4320	0.5277
15	0.7341	0.5479	0.4396	0.4051	0.4771	0.5321
16	0	0.8493	0.9113	1	0.3706	0.3543
17	0.2443	0.7808	0.5427	0.6717	0.3904	0.4795
18	0.4174	0.5479	0.5414	0.5450	0.4771	0.4801

Since the Grey relational grade represents the level of correlation between the reference sequence and the comparability sequence, the larger GRG means the importance of particular comparability sequence to the reference sequence. Hence comparability sequence has larger value of GRG for MRR, SR and KW. Based on this premise, this study selects the level that provides largest average response. For three weighted GRG, the analysis of all the three response tables (* Optimal Level) shows that, A2-B3-C1 is an optimal combination for multi-response optimization i.e., (wire feed Rate 6m/min, pulse on time 114µs and pulse off time 50µs). At this level the values of response parameters are MRR 7.2020 mm^3/min, SR 3.29µm and KW 0.317mm. The study also reveals that, the most significant factors for MRR, SR and kerf width are Ton followed by Toff. The optimal combination A2-B3-C1 comes under Taguchi L18 Array. Confirmation Test was carried out for A2-B3-C1 by comparing experimental results with predicted results for validation. Eq. (9) [8,11] was employed to calculate the predicted GRG $(\hat{Y})$ using the respective response tables. The Table 9 shows the response table for Avg. GRG. Average Grey relational grade is calculated by adding Grey relational co-efficient of MRR, SR and KW and dividing it by three.

Table 5. Grey relational grade (GRG)

Expt. No.	Grey Relation Grade (GRG) (% Weightage)			Average GRG
	GREY GRADE (50-25-25)	GREY GRADE (50-40-10)	GREY GRADE (45-45-10)	Avg. GRG (33-33-33)
1	0.4042	0.4175	0.4170	0.3953
2	0.4083	0.4317	0.4380	0.4163
3	0.4442	0.4448	0.4558	0.4783
4	0.5087	0.4879	0.4808	0.4967
5	0.5427	0.4921	0.4934	0.5750
6	0.5700	0.4945	0.4998	0.6295
7	0.6746	0.6331	0.6059	0.6071
8	0.5592	0.5046	0.4924	0.5488
9	0.5581	0.4963	0.4920	0.5782
10	0.4858	0.5000	0.5104	0.5126
11	0.4944	0.5160	0.5325	0.5374
12	0.6290	0.6516	0.6849	0.7276
13	0.5026	0.4990	0.4911	0.4782
14	0.4679	0.4535	0.4523	0.4719
15	0.4549	0.4466	0.4502	0.4715
16	0.6812	0.6837	0.6522	0.5750
17	0.5534	0.5399	0.5259	0.5139
18	0.5118	0.5114	0.5079	0.5008

Table 6. Response Table for Grey relational grade (GRG) with 50-25-25% weight

Factors / Levels	GREY RELATIONAL GRADE (GRG)				Rank
	1	2	3	Delta	
Wf	0.5189	0.5312*	----	0.0124	3
Ton	0.4776	0.5078	0.5897*	0.1121	1
Toff	0.5429*	0.5043	0.528	0.0386	2

Table 7. Response table for Grey relational grade (GRG) with 50-40-10% weight

Factors / Levels	GREY RELATIONAL GRADE (GRG)				Rank
	1	2	3	Delta	
Wf	0.4892	0.5335*	----	0.0444	3
Ton	0.4936	0.4789	0.5615*	0.0826	1
Toff	0.5368*	0.4896	0.5075	0.0472	2

Table 8. Response table for Grey relational grade (GRG) with 45-45-10% weight

Factors / Levels	GREY RELATIONAL GRADE (GRG)				Rank
	1	2	3	Delta	
Wf	0.486	0.5342*	----	0.0481	2
Ton	0.5063	0.4779	0.5461*	0.0681	1
Toff	0.5262*	0.4891	0.515	0.0371	3
* Optimal level.					

Taking the Average gives the equal weightage (33-33-33) to all the three response variables i.e., MRR, SR and KW. The Grey-Taguchi analysis shows that, the optimum combination for average GRG is A2-B3-C3. i.e., (wire feed rate – 6m/min, pulse on time – 114µs and pulse off time – 56µs). It is experiment no. 18. At this level the MRR of 5.2894mm^3/min, SR of 3.07µm and KW of 0.3028mm have been achieved.

Table 9. Response table for Avg. GRG with 33-33-33% weight

Factors / Levels	GREY RELATIONAL GRADE (GRG)				Rank
	1	2	3	Delta	
Wf	0.5250	0.5321*	----	0.0071	3
Ton	0.5112	0.5204	0.5539*	0.0427	2
Toff	0.5108	0.5105	0.5643*	0.0538	1
* Optimal level.					

$$\hat{Y} = Y_m + \sum_{i=1}^{n}(Y_i - Y_m) \quad (9)$$

Where, Y_m is the total mean of GRG for all experiments and Y_i is the mean of GRG at the optimal level of i th parameter. Confirmation test shows an improvement in the experimental results when compared with predicted results for all three weight system as listed in Table 10 hence; these results have been confirmed and validated.

Table 10. Result of confirmation test

Initial combination A2-B3-C1		Weight (%)	Optimal combination A2-B3-C1		Improvement in GRG (%)
Responses			GRG		
			Predicted	Experimental	
MRR	7.2020 mm^3/ min	50-25-25	0.6136	0.6812	11.02
SR	3.29µm	50-40-10	0.6092	0.6837	12.22
KW	0.317 mm	45-45-10	0.5863	0.6522	11.24

5. CONCLUSIONS

In current research work, the effort have been taken to determine the optimum process parameters such as pulse on time (Ton), pulse off time (Toff), wire feed rate (Wf) for the response variables such as material removal rate (MRR), surface roughness (Ra), kerf width (KW) in WEDM for AISI M42 HSS material using Grey relational analysis as multi-response optimization technique. Based upon pilot experiment and available literature the parametric levels were selected to conduct the main (major) experiment. Taguchi L18 orthogonal array was used to conduct the main experiments. The Grey relational grade was calculated by adopting four different weight systems. The study reveals that, the most significant factors for MRR, SR and kerf width are Ton followed by Toff. For three weighted GRG, the Grey-Taguchi analysis shows that, the optimal combination is A2-B3-C1 i.e., wire feed rate 6m/min, pulse on time 114µs and pulse off time 50µs. At this level the MRR of 7.2020mm^3/min, SR of 3.29µm and KW of 0.317mm have been achieved. For average GRG, the Grey-Taguchi analysis shows that, the optimum combination is A2-B3-C3. i.e., (wire feed rate – 6m/min, pulse on time – 114µs and pulse off time – 56µs). At this level the MRR of 5.2894mm^3/min, SR of 3.07µm and KW of 0.3028mm have been achieved.

ACKNOWLEDGMENT

The authors would like to thank the management of Ashokrao Mane Group of Institutions and M/S RUTURAJ WIRECUT, Kolhapur for extending the help in preparation of this research paper.

REFERENCES

[1] M. P. Jahan, M. Rahman, Y. S. Wong, "A review on the conventional and micro-electrodischarge machining of tungsten carbide", International Journal of Machine Tools & Manufacture, 51 (2011), pp. 837–858.

[2] K. P. Rajurkar, M. M. Sundaram, A. P. Malshe, "Review of Electrochemical and Electrodischarge Machining", The Seventeenth CIRP Conference on Electro Physical and Chemical Machining, Procedia CIRP 6 (2013), pp. 13-26.

[3] U. A. Dabade, S. S. Karidkar, "Analysis of response variables in WEDM of Inconel 718 using Taguchi technique", 48th CIRP Conference on MANUFACTURING SYSTEMS, Procedia CIRP 41 (2016), pp. 886–891.

[4] Rupesh Chalisgaonkar, Jatinder Kumar, "Process capability analysis and optimization in WEDM of commercially pure titanium", 12th GLOBAL CONGRESS ON MANUFACTURING AND MANAGEMENT, Procedia Engineering 97 (2014), pp. 758–766.

[5] Feng Yerui, Guo Yongfeng, Li Zongfeng, "Experimental Investigation of EDM Parameters for TiC/Ni Cermet Machining", 18th CIRP Conference on Electro Physical and Chemical Machining, Procedia CIRP 42 (2016), pp. 18– 22.

[6] J. Deng, "Introduction to Grey system", J. of Grey System, 1 (1) (1989), pp. 1-24.

[7] Jong Hyuk Jung and Won Tae Kwon, "Optimization of EDM process for multiple performance characteristics using Taguchi method and Grey relational analysis", Journal of Mechanical Science and Technology, 24 (5) (2010), pp. 1083-1090.

[8] Shailesh Dewangan, Soumya Gangopadhyay, Chandan Kumar Biswas, "Multi-response optimization of surface integrity characteristics of EDM process using grey-fuzzy logic-based hybrid approach", Engineering Science and Technology, an International Journal, 18 (2015), pp. 361-368.

[9] Vikas, Apurba Kumar Roy, Kaushik Kumar, "Effect and Optimization of various Machine Process Parameters on the Surface Roughness in EDM for an EN41 Material using Grey-Taguchi", 3rd International Conference on Materials Processing and Characterization, Procedia Materials Science 6 (2014), pp. 383–390.

[10] Amitesh Goswami, Jatinder Kumar, "Investigation of surface integrity, material removal rate and wire wear ratio for WEDM of Nimonic 80A alloy using GRA and Taguchi method", Engineering Science and Technology, an International Journal, 17 (2014), pp. 173-184.

[11] J. B. Saedona, Norkamal Jaafarb, Mohd Azman Yahaya, NorHayati Saad and Mohd Shahir Kasim, "Multi-objective optimization of titanium alloy through orthogonal array and grey relational analysis in WEDM", 2nd International Conference on System-Integrated Intelligence: Challenges for Product and Production Engineering, Procedia Technology 15 (2014), pp. 832–840.

[12] Rajesh Purohit, R.S. Rana, R.K. Dwivedi, Deepen Banoriya, Swadesh Kumar Singh, "Optimization of electric discharge machining of M2 tool steel using grey relational analysis", 4th International Conference on Materials Processing and

Characterization, Materials Today: Proceedings 2 (2015), pp. 3378–3387.

[13] Joshi Guruprasad R., A. N. Chapgaon, “A Review on Recent Trends on Parametric Optimization in WEDM”, International Research Journal of Engineering and Technology (IRJET), Volume: 03, Issue: 08, Aug-2016, pp. 758-764.

[14] Joshi Guruprasad R., Dr. A. N. Chapgaon, “ Effect and Optimization of Process Parameters using Taguchi Method in WEDM for AISI M42 HSS Material”, International Journal of Science and Research, Volume 6 Issue 2, February 2017, pp. 2329-2335.

Dr. A. N. Chapgaon received his B.E. (Mech.) from Karnataka University, M.E. from Mangalore University, Ph.D. degree from Shivaji University in 1979, 1985 and 1996, respectively. Dr. A. N. Chapgaon is currently working in AMGOI, Kolhapur as Professor and Head of Mechanical engineering department. His research fields include Thermal and manufacturing engineering.

Joshi Guruprasad R. received his B.E. (Mech.) from Visvesvaraya Technological University (VTU), Belgaum in 2006. Joshi Guruprasad R. is a P.G. research scholar and pursuing his M.E. in Mechanical-Production Engineering from AMGOI, Kolhapur. He is currently an Assistant Professor in Dhanajay Mahadik Group of Institutions, Kolhapur. His research fields include production engineering.