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A COMPARATIVE STUDY ON THE PERFORMANCE OF WIRE EDM MACHINING OF D2 STEEL USING UNCOATED, COATED AND ANNEALED WIRE

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ABSTRACT: In the present work, a comparative study on the performance of Wire Electrical Discharge Machining of D2 Steel using Brass wire, Zinc coated Copper wire and Annealed Copper wire is carried out using Grey – Fuzzy Logic technique. The input parameters are Pulse ON time (T_{ON}), Pulse OFF time (T_{OFF}), Spark Voltage (SV), Peak Current (IP), Wire Feed (WF) and Wire Tension (WT).The output parameters like Material Removal Rate (MRR), Tool Wear Rate (TWR), Surface Roughness (SR) and Kerf Width are optimized. Using Taguchi's design of experiment, a set of 27 experiments is performed using each wire. The grey relational analysis followed by fuzzy logic is carried out to find Grey Fuzzy Relational Grade (GFRG) values. The optimal combination obtained using brass wire is T_{ON} = 110µs, T_{OFF} = 45µs, SV = 15volts, IP = 210amps, WF = 6m/min and WT = 6 grams. For zinc coated copper wire it is T_{ON} = 110µs, T_{OFF} = 60µs, SV = 21volts, IP = 210amps, WF = 6m/min and WT = 6 grams. Also, for annealed copper wire it is T_{ON} = 110µs, T_{OFF} = 30µs, SV = 21volts, IP = 210amps, WF = 6m/min and WT = 6 grams. It is found that the Material Removal Rate is higher using annealed copper wire compare to zinc coated copper wire and brass wire. Similarly, the Tool Wear Rate is found to be lower in annealed copper wire compared to other wires. Also it is observed that surface roughness and kerf width are nearly equal for all the wires.

KEYWORDS: Taguchi's design of experiment, Grey Relational Coefficient, Fuzzy Logic, Grey Fuzzy Relational Grade

I. INTRODUCTION

Wire Electrical Discharge Machining (WEDM) process is extensively used in industries as it is suitable for machining very hard and brittle materials with good finish. WEDM process works on the phenomena that the discharge electrons from the wire electrode collides the work piece surface leading to melting and vaporization. As the surface quality obtained is good in WEDM so researchers are working to improve the output performance. Gamage et. al. [1] performed the machining of Inconel 718 and Ti6Al4V composite using copper wire and brass wire electrodes and compared their machining performance. They conclude that lower pulse OFF time and higher voltage yields lower specific energy consumption and surface roughness for machining of Inconel. They also conclude that for Ti6Al4V composite also lower pulse OFF time is preferred with higher pulse ON time for the same optimization criteria. Dongre et. al. [2] investigated the machining of Silicon wafer using Molybdenum wire using multi response optimization based on Response Surface Method (RSM) technique. They concluded that WEDM process reduces the kerf width from 250µm to 50µm. They also found that the process improves the surface roughness to 2-3µm. Mohanty et. al. [3] performed the machining of Inconel 718 using copper, graphite and brass electrodes and compared using Utility concept and QPSO algorithm. It is found that MRR improves with the use of graphite tool but SR and radial overcut are seriously affected. Puhan et. al. [4] performed the machining of Aluminium Silicon Carbide composite and used a hybrid approach combining Principal Component Analysis (PCA) and Fuzzy Inference System (FIS) to optimize the machining parameters. They have found that the process parameters such as discharge current, pulse ON time, duty factor and flushing pressure have the significant effect on the multi performance characteristics. Saha et. al. [5] investigated the machining of Tubular coated nanocomposite based electrode (Nanocarb 110) using brass wire and zinc coated brass wire and utilized GRA-PCA hybrid technique to get the optimal results. It is observed that zinc coated brass wire is better compared to brass wire. Datta et. al. [6] performed the machining of D2 steel using zinc coated copper wire and used the RSM coupled with GRA technique to optimize the machining parameters. They utilized this technique to evaluate optimal parametric combination to achieve maximum MRR, minimum SR and minimum kerf width. Harish et.al. [7] performed the machining of D2 Steel in WEDM using brass wire and applied the TOPSIS approach to optimize the output performance. They also performed the machining of D2 Steel in WEDM using coated copper wire using the same approach [8]. Patro et.

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al. [9] developed a fuzzy model for selection of machining parameters in wire electrical discharge machining of D2 steel. They found that the MRR increases with the increase in pulse ON time and peak current. Also the WWR decreases with increase in peak current and decrease in wire feed. They also conclude that the surface roughness decreases with the decrease in spark voltage and peak current. Caydas et. al. [10] performed the WEDM machining of D5 tool steel and optimizes the machining parameters using Adaptive Neuro-Fuzzy Inference System (ANFIS) model. It was found that the ANFIS model greatly improves the process response such as surface roughness and white layer thickness in the WEDM process. Maji et. al. [11] investigated the machining of mild steel using copper tool electrode in EDM process and studied the input-output parameters relationships in both forward and reverse directions using ANFIS technique. They conclude that the ANFIS model with non-linear membership function distributions gives better performance compared to linear membership function distributions. Dewangan et. al. [12] performed the machining of P20 tool steel in EDM process and used the Grey-Fuzzy logic based hybrid optimization technique for optimal results. They found that pulse ON time is the most significant parameter followed by discharge current, whereas tool work time and tool lift time do not have significant effect. In the present work, a comparative study of the machining performance is carried out during the machining of D2 Steel in WEDM using Brass wire, Zinc coated Copper wire and Annealed Copper wire.

II. METHODOLOGY

2.1 Grey Relational Analysis

Grey Relational Analysis (GRA) technique is generally used to find the optimal results. Grey is a colour in between black and white. Here, white means the best result and black means the worst result. So, grey is a result in between the worst and the best [13]. This technique gives an intermediate result. The first step in GRA is to normalize the experimental data. During normalization all the responses are expressed in the range of zero to one.

For 'larger-the-better' type, the equation for normalization is given as:

$$x_i(k) = \frac{yi(k) - minyi(k)}{maxyi(k) - minyi(k)} \quad (1)$$

where i = Experiment Number

k = Response Number

$x_i(k)$ = Normalized value of k^{th} response for i^{th} experiment

$y_i(k)$ = value of k^{th} response for i^{th} experiment

max $y_i(k)$ = Maximum value of k^{th} response in the total set of experiments

min $y_i(k)$ = Minimum value of k^{th} response in the total set of experiments

For 'smaller-the-better' criteria, the normalization equation is given as:

$$x_i(k) = \frac{maxyi(k) - yi(k)}{maxyi(k) - minyi(k)} \quad (2)$$

Once normalization is over, the Grey Relational Coefficient (GRC) is found. GRC is calculated using the equation given as:

$$\xi_i(k) = \frac{\Delta min + \Psi \Delta max}{\Delta i(k) + \Psi \Delta max} \quad (3)$$

where $\Delta_i(k)$ is the absolute value of the difference between $x_o(k)$ and $x_i(k)$.

$$\Delta_i(k) = |xo(k) - xi(k)| \quad (4)$$

where $x_o(k)$ is the best normalized result and it is equal to 1. Δ_{max} and Δ_{min} are the global maximum and global minimum in the particular data set. Ψ is the distinguishing coefficient and is generally taken as 0.5.

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2.2 Grey-Fuzzy Logic

GRA technique gives the values which have some uncertainty. This uncertainty can be examined using Fuzzy Logic approach. So, in the present work hybrid Grey-Fuzzy Logic technique has been used to solve the optimization problem.

Fuzzy logic approach (Mamdani approach) consists of Fuzzifier, Membership Function, Fuzzy Rule Base, Fuzzy Inference Engine and Defuzzifier [14]. In this method, the fuzzifier uses membership functions to fuzzify the Grey Relational Coefficient (GRC). The fuzzy inference engine uses the fuzzy rules to convert fuzzified data into fuzzy values. Finally, the defuzzifier converts the fuzzified values into equivalent Grey Fuzzy Relational Grade (GFRG) values.

2.3 Procedure in Grey-Fuzzy Logic technique

The steps involve in Grey-Fuzzy Logic technique is shown in fig. 1 and is as follows:

1. Normalizing the experimental values of MRR, TWR, SR and kerf width in the range of 0 to 1.
2. Calculating the Grey Relational Coefficient (GRC) value of each response.
3. Applying Fuzzy logic technique. Expressing the GRC values as membership function using fuzzifier.
4. Firing the fuzzy rules and finally defuzzifing to converts fuzzy values into Grey Fuzzy Relational Grade (GFRG) values.
5. The optimal combination of machining parameters is obtained with the help of main effect plots for GFRG.

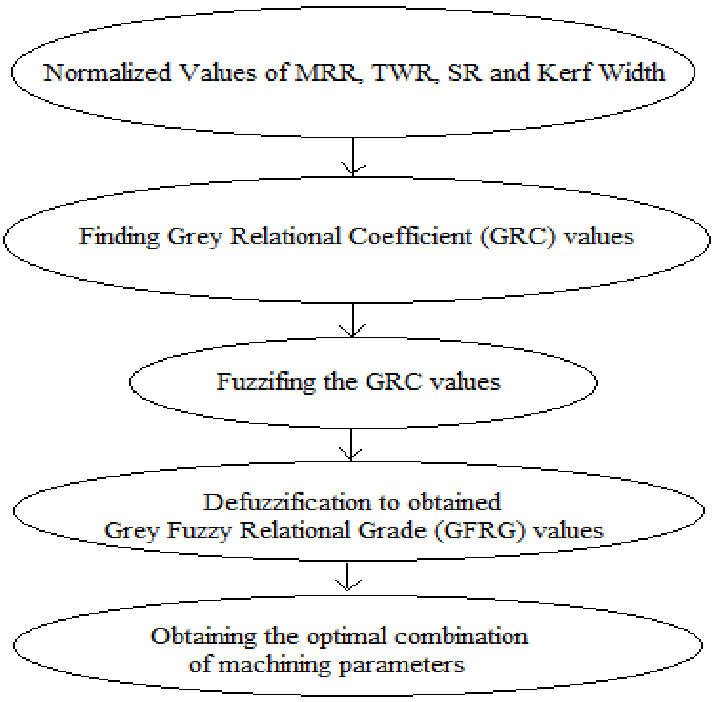

Fig. 1 Steps in Grey Fuzzy Logic Approach

III. EXPERIMENTAL DETAILS

Wire electrical discharge machine (ELECTRONICA) was used for carrying out the experiments. D2 Steel was taken as work piece material. The machining was carried using brass wire, zinc coated copper wire and annealed copper wire. A set of 27 experiments were performed using each wire. The composition of each wire is shown in table 1(a) to 1(c). Pulse ON time, pulse OFF time, spark voltage, peak current, wire feed and wire tension were the input parameters taken during the experiments. The details of input parameters with their

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levels are shown in table 2. Material Removal Rate (MRR), Tool Wear Rate (TWR), Surface Roughness (SR) and Kerf Width were the output parameters. Apart from the parameters mentioned above, few parameters were kept constant as shown in table 3. The work piece material was cut in a shape of cube of size 10 mm as shown in fig. 2. The set of experiments conducted using each wire and the values of MRR, TWR, SR and Kerf Width are shown in table 4(a) to 4(c).

Table 1(a) Composition of Brass wire

Compound	Si	P	Cl	Ca	Ti	Cr	Fe	Cu	Zn	Nb
% Conc.	1.652	2.042	0.665	1.142	0.024	0.022	0.251	58.757	34.924	0.211

Table 1(b) Composition of Zinc coated Copper wire

Compound	Si	P	S	Cl	Ca	Ti	Fe	Cu	Zn	Nb
% Conc.	2.170	2.616	1.212	0.963	1.501	0.037	0.289	50.869	40.291	0.038

Table 1(c) Composition of Annealed Copper wire

Compound	Si	P	S	Cl	Ca	Fe	Cu	Zn	Nb	Mo
% Conc.	1.107	1.854	0.000	0.674	1.043	0.161	64.577	30.271	0.233	0.079

Fig. 2 Work Piece

Table 2 Input Parameters

Process Parameters	Symbol	Unit	Levels		
			1	2	3
Pulse ON time	A	µs	110	115	120
Pulse OFF time	B	µs	30	45	60
Spark Voltage	C	volt	15	18	21

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Peak Current	D	amp	180	210	240
Wire Feed	E	m/min	2	4	6
Wire Tension	F	gram	6	8	10

Table 3 Constant Parameters

Parameters	Values
Peak Voltage	110 volts
Flushing Pressure	15 kgf/cm^2
Servo Feed	2100 units
Conductivity of Dielectric	20 mho
Work piece Height	10 mm

Table 4(a) Experimental Details using Brass wire

Exp. No.	A	B	C	D	E	F	MRR (mm^3/s)	TWR (mm^3/s)	SR (μm)	Kerf Width (mm)
1	1	1	1	1	2	3	0.058	0.020	1.60	0.264
2	1	1	2	2	3	1	0.058	0.080	1.60	0.270
3	1	1	3	3	1	2	0.056	0.008	1.73	0.277
4	1	2	1	2	3	1	0.086	0.016	2.32	0.252
5	1	2	2	3	1	2	0.099	0.036	2.69	0.262
6	1	2	3	1	2	3	0.096	0.040	2.81	0.266
7	1	3	1	3	1	2	0.046	0.020	1.72	0.260
8	1	3	2	1	2	3	0.044	0.028	1.77	0.258
9	1	3	3	2	3	1	0.043	0.072	1.71	0.264
10	2	1	1	1	2	3	0.098	0.048	3.22	0.284
11	2	1	2	2	3	1	0.089	0.056	3.17	0.262
12	2	1	3	3	1	2	0.082	0.048	2.49	0.248
13	2	2	1	2	3	1	0.100	0.032	3.12	0.216
14	2	2	2	3	1	2	0.063	0.036	2.21	0.241
15	2	2	3	1	2	3	0.116	0.040	2.84	0.222
16	2	3	1	3	1	2	0.061	0.032	2.78	0.238
17	2	3	2	1	2	3	0.057	0.040	2.36	0.233
18	2	3	3	2	3	1	0.055	0.076	1.87	0.232
19	3	1	1	1	2	3	0.135	0.080	4.07	0.330
20	3	1	2	2	3	1	0.121	0.036	3.64	0.312
21	3	1	3	3	1	2	0.135	0.084	3.64	0.337
22	3	2	1	2	3	1	0.127	0.036	4.19	0.280
23	3	2	2	3	1	2	0.141	0.120	5.01	0.289
24	3	2	3	1	2	3	0.154	0.120	4.76	0.289
25	3	3	1	3	1	2	0.106	0.120	3.76	0.290
26	3	3	2	1	2	3	0.095	0.100	3.59	0.297
27	3	3	3	2	3	1	0.100	0.120	3.02	0.291

Table 4(b) Experimental Details using Zinc coated Copper wire

Exp. No.	A	B	C	D	E	F	MRR (mm^3/s)	TWR (mm^3/s)	SR (μm)	Kerf Width (mm)
1	1	1	1	1	2	3	0.111	0.040	1.90	0.394
2	1	1	2	2	3	1	0.114	0.060	2.38	0.380
3	1	1	3	3	1	2	0.104	0.084	1.88	0.383
4	1	2	1	2	3	1	0.135	0.040	3.43	0.331
5	1	2	2	3	1	2	0.097	0.060	2.87	0.311
6	1	2	3	1	2	3	0.131	0.048	2.93	0.285
7	1	3	1	3	1	2	0.064	0.056	1.85	0.267

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8	1	3	2	1	2	3	0.055	0.020	1.68	0.230
9	1	3	3	2	3	1	0.051	0.016	1.72	0.208
10	2	1	1	1	2	3	0.161	0.100	2.97	0.429
11	2	1	2	2	3	1	0.191	0.020	3.32	0.410
12	2	1	3	3	1	2	0.150	0.100	2.66	0.390
13	2	2	1	2	3	1	0.172	0.060	3.89	0.352
14	2	2	2	3	1	2	0.168	0.080	3.81	0.307
15	2	2	3	1	2	3	0.179	0.060	3.29	0.286
16	2	3	1	3	1	2	0.108	0.048	2.81	0.302
17	2	3	2	1	2	3	0.101	0.040	2.41	0.294
18	2	3	3	2	3	1	0.096	0.040	2.29	0.280
19	3	1	1	1	2	3	0.196	0.088	4.27	0.391
20	3	1	2	2	3	1	0.154	0.076	4.10	0.388
21	3	1	3	3	1	2	0.196	0.120	3.91	0.382
22	3	2	1	2	3	1	0.178	0.040	3.46	0.370
23	3	2	2	3	1	2	0.207	0.080	3.24	0.349
24	3	2	3	1	2	3	0.181	0.100	3.46	0.347
25	3	3	1	3	1	2	0.164	0.080	3.33	0.341
26	3	3	2	1	2	3	0.172	0.072	3.07	0.347
27	3	3	3	2	3	1	0.169	0.060	2.99	0.352

Table 4(c) Experimental Details using Annealed Copper wire

Exp. No.	A	B	C	D	E	F	MRR (mm^3/s)	TWR (mm^3/s)	SR (μm)	Kerf Width (mm)
1	1	1	1	1	2	3	0.100	0.020	1.74	0.237
2	1	1	2	2	3	1	0.116	0.028	2.32	0.273
3	1	1	3	3	1	2	0.135	0.036	1.88	0.313
4	1	2	1	2	3	1	0.126	0.020	3.38	0.317
5	1	2	2	3	1	2	0.157	0.020	2.70	0.340
6	1	2	3	1	2	3	0.173	0.020	2.97	0.350
7	1	3	1	3	1	2	0.092	0.012	1.74	0.345
8	1	3	2	1	2	3	0.093	0.016	1.70	0.358
9	1	3	3	2	3	1	0.079	0.008	1.75	0.301
10	2	1	1	1	2	3	0.140	0.020	2.98	0.247
11	2	1	2	2	3	1	0.137	0.020	3.03	0.238
12	2	1	3	3	1	2	0.136	0.032	2.81	0.242
13	2	2	1	2	3	1	0.122	0.020	4.01	0.245
14	2	2	2	3	1	2	0.142	0.160	3.81	0.234
15	2	2	3	1	2	3	0.149	0.200	3.43	0.234
16	2	3	1	3	1	2	0.080	0.180	2.78	0.236
17	2	3	2	1	2	3	0.082	0.008	2.49	0.250
18	2	3	3	2	3	1	0.081	0.016	2.11	0.255
19	3	1	1	1	2	3	0.218	0.020	4.12	0.401
20	3	1	2	2	3	1	0.232	0.016	4.10	0.375
21	3	1	3	3	1	2	0.222	0.060	3.76	0.355
22	3	2	1	2	3	1	0.210	0.012	3.54	0.342
23	3	2	2	3	1	2	0.212	0.016	4.36	0.315
24	3	2	3	1	2	3	0.223	0.036	3.60	0.310
25	3	3	1	3	1	2	0.159	0.040	3.37	0.310
26	3	3	2	1	2	3	0.165	0.040	3.06	0.310
27	3	3	3	2	3	1	0.168	0.020	2.15	0.321

The MRR has been calculated using the expression:

$$MRR = \frac{wi-wf}{\rho t}, \ mm^3/s$$

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where w_i is the weight of work piece before machining in grams

w_f is the weight of work piece after machining in grams

ρ is the density of the work piece material in gram/mm^3

t is the machining time in seconds

The TWR has been calculated using the expression:

$$TWR = \frac{vi - vf}{t} \text{, } mm^3/s$$

where v_i is the volume of the wire before machining in mm^3

v_f is the volume of the wire after machining in mm^3

t is the machining time in seconds

The Surface Roughness is measured using Talysurf (Mitutoyo) and the R_a values are expressed in microns. The Kerf Width is measured by projecting the machined work piece in the profile projector. It is given as:

$$\text{Kerf Width} = \frac{OD - ID}{2} \text{, mm}$$

where OD is the outer dimension or dimension of the hole generated after removal of cube material in mm

ID is the inner dimension or dimension of the cube material in mm.

IV. RESULTS AND DISCUSSION

4.1 Calculation of Grey Relational Coefficient (GRC)

The GRA technique has been used to normalize the output response in the range of 0 to 1 using the eqn. 1 and 2. The Grey Relational Coefficient (GRC) values for each response were calculated using the eqn. 3. The details using each wire are shown in table 5(a) to 5(c). However, to obtain improved values of output performance and to reduce the uncertainty in the data, the Grey-Fuzzy logic technique is further used to find Grey Fuzzy Relational Grade (GFRG) values.

Table 5(a) Calculation of Grey Relational Coefficient (GRC) and Grey Fuzzy Relational Grade (GFRG) for Brass wire

Exp. No.	Normalized value				Grey Relational Coefficient (GRC)				GFRG	Ranking
	MRR	TWR	SR	Kerf Width	MRR	TWR	SR	Kerf Width		
1	0.1351	0.8928	1.0000	0.6033	0.3663	0.8234	1.0000	0.5576	0.6868	2
2	0.1351	0.3571	1.0000	0.5537	0.3663	0.4375	1.0000	0.5284	0.5830	13
3	0.1171	1.0000	0.9619	0.4959	0.3616	1.0000	0.9292	0.4979	0.6972	1
4	0.3874	0.9286	0.7888	0.7025	0.4494	0.8750	0.7030	0.6269	0.6636	6
5	0.5045	0.7500	0.6803	0.6198	0.5022	0.6667	0.6099	0.5680	0.5867	12
6	0.4775	0.7143	0.6452	0.5868	0.4889	0.6364	0.5849	0.5475	0.5644	16
7	0.0270	0.8928	0.9648	0.6364	0.3394	0.8234	0.9342	0.5789	0.6689	5
8	0.0090	0.8214	0.9501	0.6529	0.3353	0.7368	0.9092	0.5902	0.6428	7
9	0.0000	0.4286	0.9677	0.6033	0.3333	0.4667	0.9393	0.5576	0.5742	15

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10	0.4955	0.6428	0.5249	0.4380	0.4978	0.5833	0.5128	0.4708	0.5162	21
11	0.4144	0.5714	0.5396	0.6198	0.4606	0.5384	0.5206	0.5680	0.5219	20
12	0.3514	0.6428	0.7390	0.7355	0.4353	0.5833	0.6570	0.6540	0.5824	14
13	0.5135	0.7857	0.5542	1.0000	0.5068	0.6999	0.5286	1.0000	0.6838	3
14	0.1802	0.7500	0.8211	0.7934	0.3788	0.6667	0.7365	0.7076	0.6224	8
15	0.6576	0.7143	0.6364	0.9504	0.5935	0.6364	0.5790	0.9098	0.6797	4
16	0.1622	0.7857	0.6539	0.8182	0.3737	0.6999	0.5909	0.7334	0.5995	11
17	0.1261	0.7143	0.7771	0.8595	0.3639	0.6364	0.6916	0.7806	0.6181	9
18	0.1081	0.3928	0.9208	0.8678	0.3592	0.4516	0.8632	0.7909	0.6162	10
19	0.8288	0.3571	0.2756	0.0578	0.7449	0.4375	0.4084	0.3467	0.4844	23
20	0.7027	0.7500	0.4018	0.2066	0.6271	0.6667	0.4553	0.3866	0.5339	19
21	0.8288	0.3214	0.4018	0.0000	0.7449	0.4242	0.4553	0.3333	0.4894	22
22	0.7568	0.7500	0.2405	0.4710	0.6728	0.6667	0.3969	0.4859	0.5556	17
23	0.8288	0.0000	0.0000	0.3967	0.8101	0.3333	0.3333	0.4532	0.4825	24
24	1.0000	0.0000	0.0733	0.3967	1.0000	0.3333	0.3504	0.4532	0.5342	18
25	0.5676	0.0000	0.3666	0.3884	0.5362	0.3333	0.4411	0.4498	0.4401	26
26	0.4685	0.1786	0.4164	0.3306	0.4847	0.3784	0.4614	0.4276	0.4380	27
27	0.5135	0.0000	0.5836	0.3802	0.5068	0.3333	0.5456	0.4465	0.4580	25

Table 5(b) Calculation of Grey Relational Coefficient (GRC) and Grey Fuzzy Relational Grade (GFRG) for Zinc coated Copper wire

Exp. No.	Normalized value				Grey Relational Coefficient (GRC)				GFRG	Ranking
	MRR	TWR	SR	Kerf Width	MRR	TWR	SR	Kerf Width		
1	0.3846	0.7692	0.9150	0.1584	0.4483	0.6842	0.8547	0.3727	0.5899	6
2	0.4038	0.5769	0.7297	0.2217	0.4561	0.5416	0.6491	0.3911	0.5095	17
3	0.3397	0.3462	0.9228	0.2081	0.4309	0.4334	0.8662	0.3870	0.5294	14
4	0.5385	0.7692	0.3243	0.4434	0.5200	0.6842	0.4253	0.4732	0.5257	15
5	0.2949	0.5769	0.5405	0.5339	0.4149	0.5416	0.5211	0.5175	0.4988	22
6	0.5128	0.6923	0.5174	0.6516	0.5065	0.6190	0.5088	0.5893	0.5559	11
7	0.0833	0.6154	0.9344	0.7330	0.3529	0.5652	0.8840	0.6519	0.6135	4
8	0.0256	0.9615	1.0000	0.9004	0.3391	0.9285	1.0000	0.8339	0.7754	2
9	0.0000	1.0000	0.9846	1.0000	0.3333	1.0000	0.9701	1.0000	0.8258	1
10	0.7051	0.1923	0.5019	0.0000	0.6290	0.3824	0.5009	0.3333	0.4614	26
11	0.8974	0.9615	0.3668	0.0860	0.8297	0.9285	0.4412	0.3536	0.6382	3
12	0.6346	0.1923	0.6216	0.1765	0.5778	0.3824	0.5692	0.3778	0.4768	25
13	0.7756	0.5769	0.1467	0.3484	0.6902	0.5416	0.3695	0.4342	0.5089	18
14	0.7500	0.3846	0.1776	0.5520	0.6667	0.4483	0.3781	0.5274	0.5051	19
15	0.8205	0.5769	0.3784	0.6470	0.7358	0.5416	0.4458	0.5862	0.5774	9

16	0.3654	0.6923	0.5637	0.5747	0.4407	0.6190	0.5340	0.5404	0.5335	13
17	0.3205	0.7692	0.7181	0.6108	0.4239	0.6842	0.6395	0.5623	0.5775	8
18	0.2885	0.7692	0.7645	0.6742	0.4127	0.6842	0.6798	0.6055	0.5956	5
19	0.9295	0.3077	0.0000	0.1719	0.8764	0.4194	0.3333	0.3765	0.5014	20
20	0.6602	0.4231	0.0656	0.1855	0.5954	0.4643	0.3486	0.3804	0.4472	27
21	0.9295	0.0000	0.1390	0.2127	0.8764	0.3333	0.3674	0.3884	0.4914	24
22	0.8141	0.7692	0.3127	0.2670	0.7290	0.6842	0.4211	0.4055	0.5599	10
23	1.0000	0.3846	0.3977	0.3620	1.0000	0.4483	0.4536	0.4394	0.5853	7
24	0.8333	0.1923	0.3127	0.3710	0.7500	0.3824	0.4211	0.4429	0.4991	21
25	0.7244	0.3846	0.3629	0.3982	0.6447	0.4483	0.4397	0.4538	0.4966	23
26	0.7756	0.4615	0.4633	0.3710	0.6902	0.4815	0.4823	0.4429	0.5242	16
27	0.7564	0.5769	0.4942	0.3484	0.6724	0.5416	0.4971	0.4342	0.5363	12

Table 5(c) Calculation of Grey Relational Coefficient (GRC) and Grey Fuzzy Relational Grade (GFRG) for Annealed Copper wire

Exp. No.	Normalized value				Grey Relational Coefficient (GRC)				GFRG	Ranking
	MRR	TWR	SR	Kerf Width	MRR	TWR	SR	Kerf Width		
1	0.1372	0.9375	0.9850	0.9820	0.3669	0.8889	0.9709	0.9652	0.7980	1
2	0.2418	0.8958	0.7669	0.7665	0.3974	0.8275	0.6820	0.6817	0.6472	15
3	0.3660	0.8542	0.9323	0.5269	0.4409	0.7742	0.8807	0.5138	0.6524	12
4	0.3072	0.9375	0.3684	0.5030	0.4192	0.8889	0.4418	0.5015	0.5628	23
5	0.5098	0.9375	0.6241	0.3653	0.5049	0.8889	0.5708	0.4406	0.6013	19
6	0.6144	0.9375	0.5226	0.3054	0.5646	0.8889	0.5115	0.4186	0.5959	20
7	0.0850	0.9792	0.9850	0.3353	0.3534	0.9601	0.9709	0.4293	0.6784	7
8	0.0915	0.9583	1.0000	0.2575	0.3550	0.9230	1.0000	0.4024	0.6701	9
9	0.0000	1.0000	0.9812	0.5988	0.3333	1.0000	0.9638	0.5548	0.7130	2
10	0.3987	0.9375	0.5188	0.9222	0.4540	0.8889	0.5096	0.8654	0.6795	6
11	0.3791	0.9375	0.5000	0.9760	0.4461	0.8889	0.5000	0.9542	0.6973	5
12	0.3725	0.8750	0.5827	0.9521	0.4434	0.8000	0.5451	0.9126	0.6753	8
13	0.2810	0.9375	0.1316	0.9341	0.4102	0.8889	0.3654	0.8835	0.6370	17
14	0.4118	0.2083	0.2068	1.0000	0.4595	0.3871	0.3866	1.0000	0.5583	25
15	0.4575	0.0000	0.3496	1.0000	0.4796	0.3333	0.4346	1.0000	0.5619	24
16	0.0065	0.1042	0.5940	0.9880	0.3348	0.3582	0.5519	0.9766	0.5554	27
17	0.0196	1.0000	0.7030	0.9042	0.3377	1.0000	0.6274	0.8392	0.7011	4
18	0.0131	0.9583	0.8459	0.8742	0.3363	0.9230	0.7644	0.7990	0.7057	3
19	0.9085	0.9375	0.0902	0.0000	0.8453	0.8889	0.3547	0.3333	0.6056	18
20	1.0000	0.9583	0.0977	0.1557	1.0000	0.9230	0.3566	0.3719	0.6629	11
21	0.9346	0.7292	0.2256	0.2754	0.8843	0.6487	0.3923	0.4083	0.5834	21
22	0.8562	0.9792	0.3083	0.3533	0.7766	0.9601	0.4196	0.4360	0.6481	14
23	0.8693	0.9583	0.0000	0.5150	0.7928	0.9230	0.3333	0.5076	0.6392	16
24	0.9412	0.8542	0.2857	0.5449	0.8948	0.7742	0.4118	0.5235	0.6511	13
25	0.5229	0.8333	0.3722	0.5449	0.5117	0.7500	0.4433	0.5235	0.5571	26
26	0.5621	0.8333	0.4887	0.5449	0.5331	0.7500	0.4944	0.5235	0.5752	22
27	0.5817	0.9375	0.8308	0.4790	0.5445	0.8889	0.7472	0.4897	0.6676	10

4.2 Determination of Grey Fuzzy Relational Grade (GFRG)

The Grey Relational Coefficient (GRC) values of each response were modelled using fuzzy approach (Mamdani Approach) in Matlab 2007b software. The four responses, namely, MRR, TWR, SR and Kerf Width were taken as input parameters, each having six levels were expressed using triangular membership function. The levels were expressed using linguistic terms like Very Small (VS), Small (S), Medium (M), Large (L), Very Large (VL) and Very Very Large (VVL). Similarly, the output variable is also expressed in six levels using triangular membership function. The membership functions of input and output variables are shown in fig.3. The relationship between the inputs and output is expressed in the form of 'if-then' statements called as fuzzy rules. A total of 27 rules were fired in the modelling as shown in fig.4. The expression of a rule is as follows:

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Rule 1: If MRR is Very Small and TWR is Very Large and SR is Very Very Large and Kerf Width is Medium then GFRG is Very Very Large.

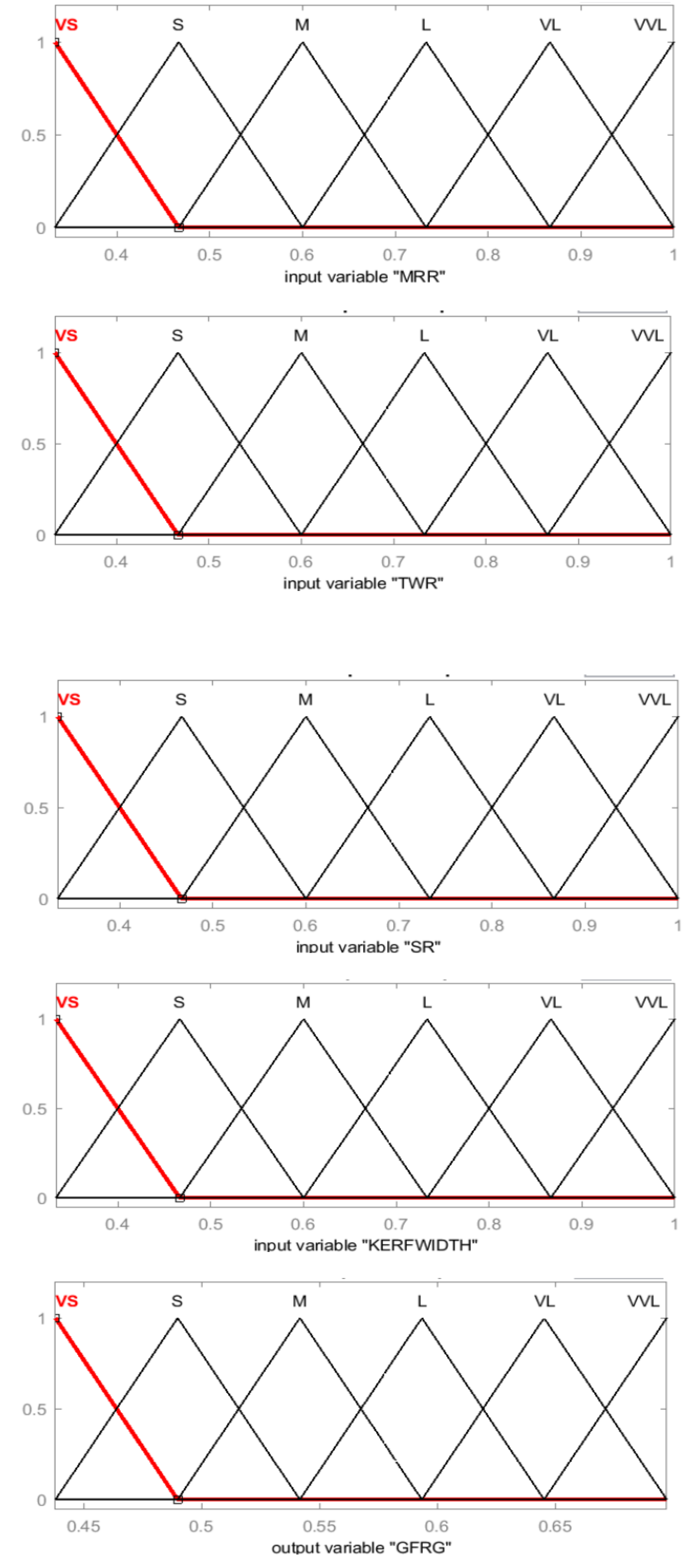

Fig. 3 Membership Function of Input and Output Variables

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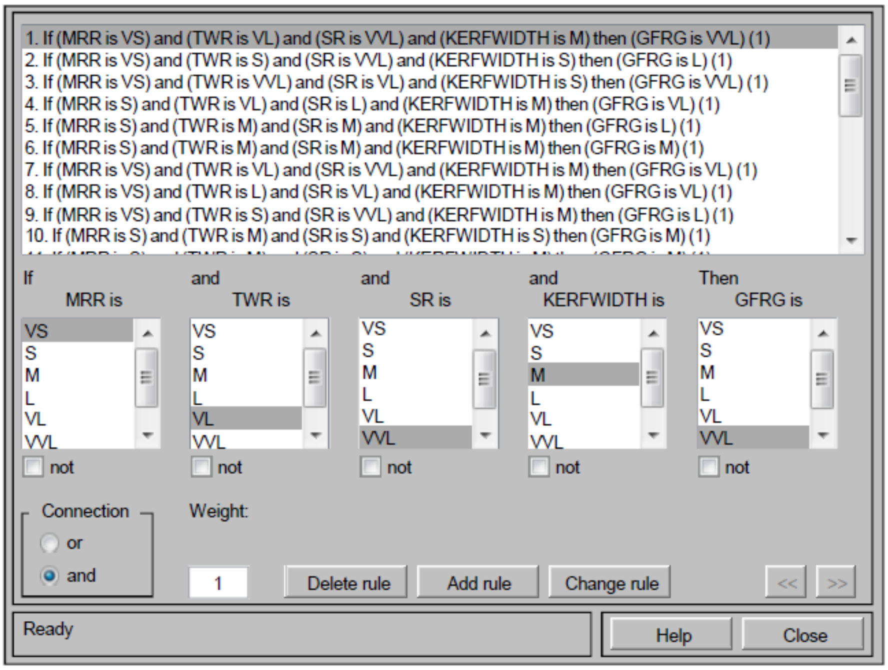

Fig. 4 Fuzzy Rules

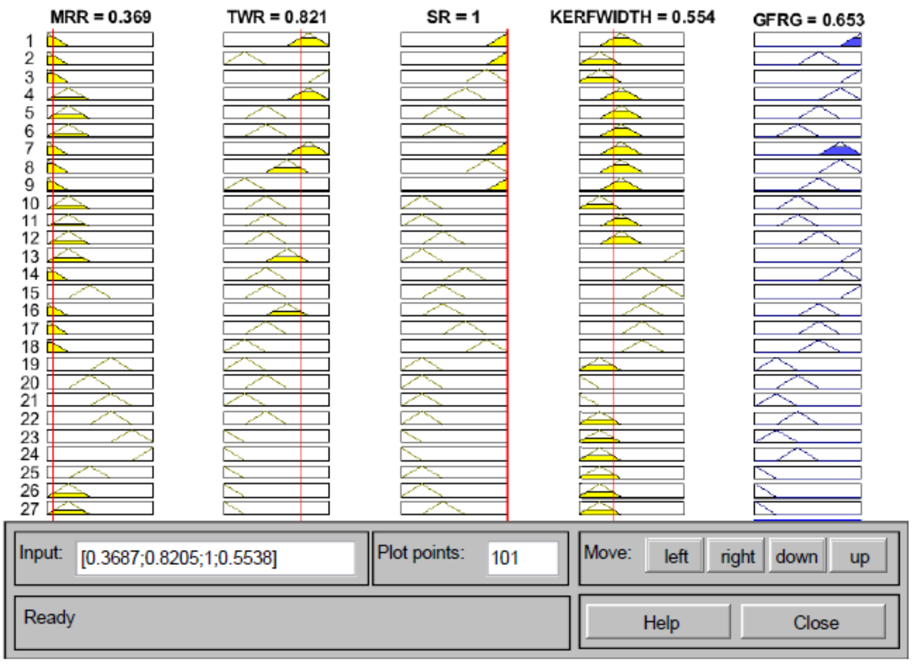

Fig. 5 Graphical Representation of Fuzzy Values

The graphical representation of the modelled values is shown in fig.5. The GFRG values were ranked from the highest value to the lowest value as shown in table 5(a) to 5(c). Based on the mean values of GFRG obtained for each level as shown in the table 6(a) to 6(c), the favourable level of each input parameter is selected. The higher value means the most favourable condition. The optimal combination of input parameters using brass wire is found to be Pulse ON time is 110µs, Pulse OFF time is 45µs, Spark Voltage is 15volts, Peak Current is 210Amps, Wire Feed is 6m/min and Wire Tension is 6grams. Similarly, the optimal combination using zinc coated copper wire is found to be Pulse ON time is 110µs, Pulse OFF time is 60µs, Spark Voltage is 21volts, Peak Current is 210Amps, Wire Feed is 6m/min and Wire Tension is 6grams. Also for the annealed copper

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wire, the optimal combination of the input parameters were found to be Pulse ON time is 110μs, Pulse OFF time is 30μs, Spark Voltage is 21volts, Peak Current is 210Amps, Wire Feed is 6m/min and Wire Tension is 6grams.

Table 6(a) Mean value of GFRG at different levels using Brass wire

Levels	Input Parameters					
	T_{ON}	T_{OFF}	SV	IP	WF	WT
1	**0.6297**	0.5661	**0.5888**	0.5738	0.5743	**0.5767**
2	0.6045	**0.5969**	0.5588	**0.5767**	0.5738	0.5743
3	0.4907	0.5618	0.5773	0.5743	**0.5767**	0.5738
Δ = Max-Min	0.1390	0.0351	0.0300	0.0029	0.0029	0.0029
Ranking	1	2	3	4	5	6

Table 6(b) Mean value of GFRG at different levels using Zinc coated Copper wire

Levels	Input Parameters					
	T_{ON}	T_{OFF}	SV	IP	WF	WT
1	**0.6026**	0.5161	0.5323	0.5625	0.5256	**0.5719**
2	0.5416	0.5351	0.5624	**0.5719**	0.5625	0.5256
3	0.5157	**0.6087**	**0.5650**	0.5256	**0.5719**	0.5625
Δ = Max-Min	0.0869	0.0926	0.0327	0.0463	0.0463	0.0463
Ranking	2	1	6	3	4	5

Table 6(c) Mean value of GFRG at different levels using Annealed Copper wire

Levels	Input Parameters					
	T_{ON}	T_{OFF}	SV	IP	WF	WT
1	**0.6577**	**0.6668**	0.6358	0.6487	0.6112	**0.6602**
2	0.6413	0.6062	0.6392	**0.6602**	0.6487	0.6112
3	0.6211	0.6471	**0.6451**	0.6112	**0.6602**	0.6487
Δ = Max-Min	0.0366	0.0606	0.0093	0.0490	0.0490	0.0490
Ranking	5	1	6	2	3	4

The variation of MRR, TWR, SR and Kerf Width using different wires are compared and is shown in fig. 6(a) to 6(d). It is found that the Material Removal Rate is higher using annealed copper wire compare to zinc coated copper wire and brass wire. Similarly, the Tool Wear Rate is found to be lower in annealed copper wire compared to other wires. Also it is observed that surface roughness and kerf width are nearly equal for all the wires.

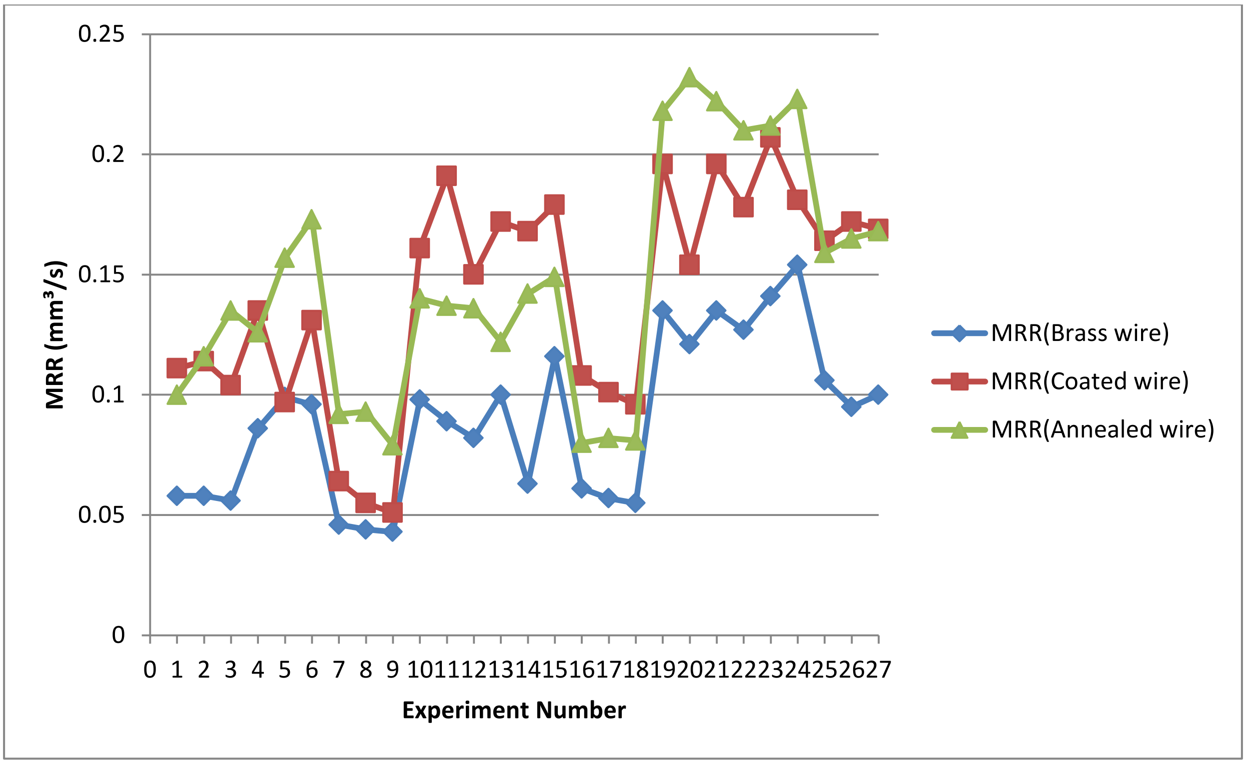

Fig. 6(a) Variation of MRR using different wires

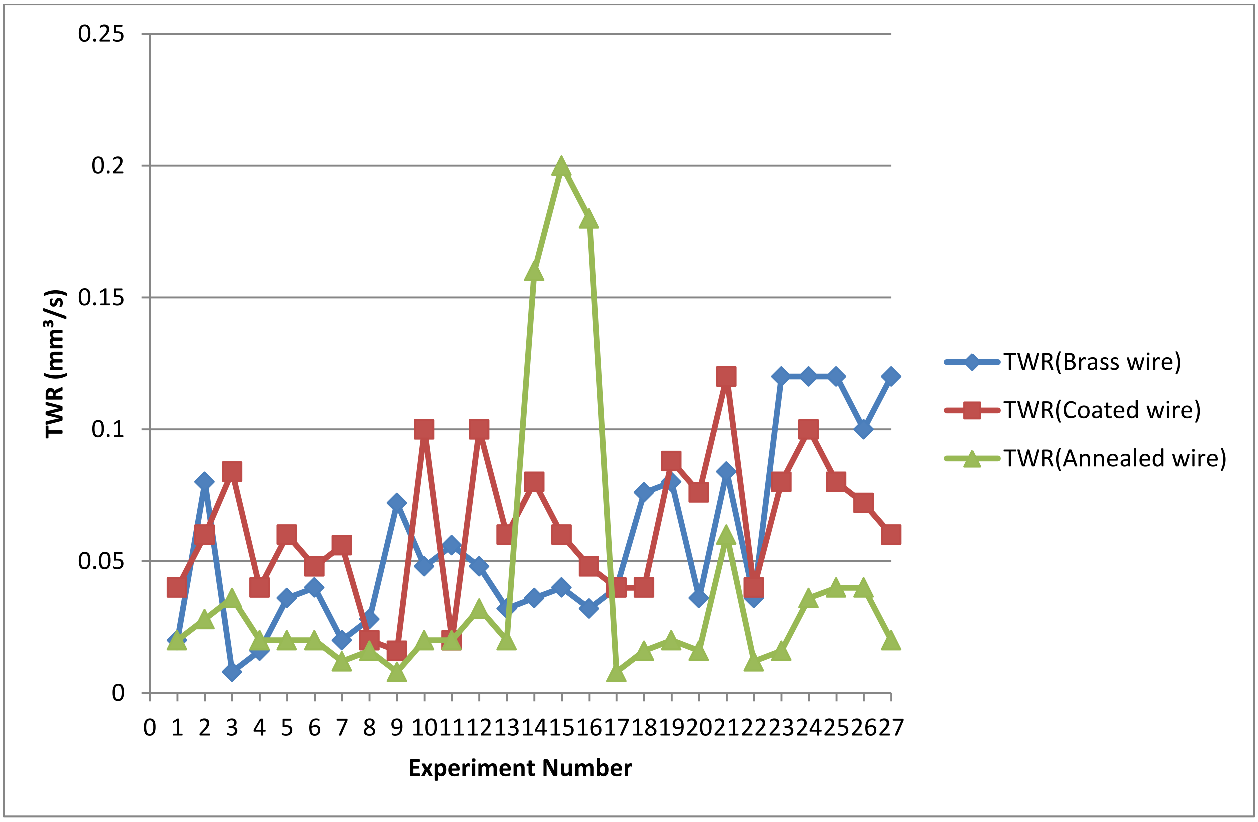

Fig. 6(b) Variation of TWR using different wires

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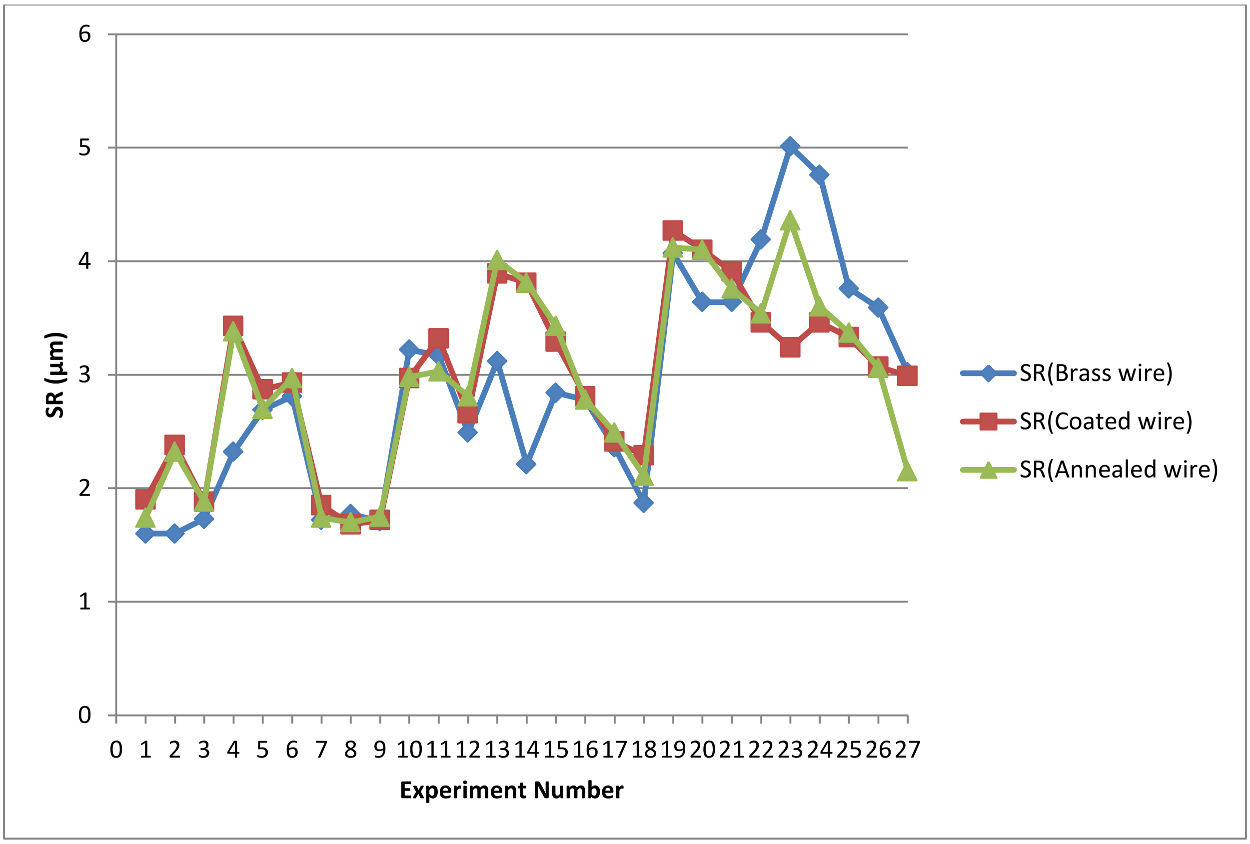

Fig. 6(c) Variation of SR using different wires

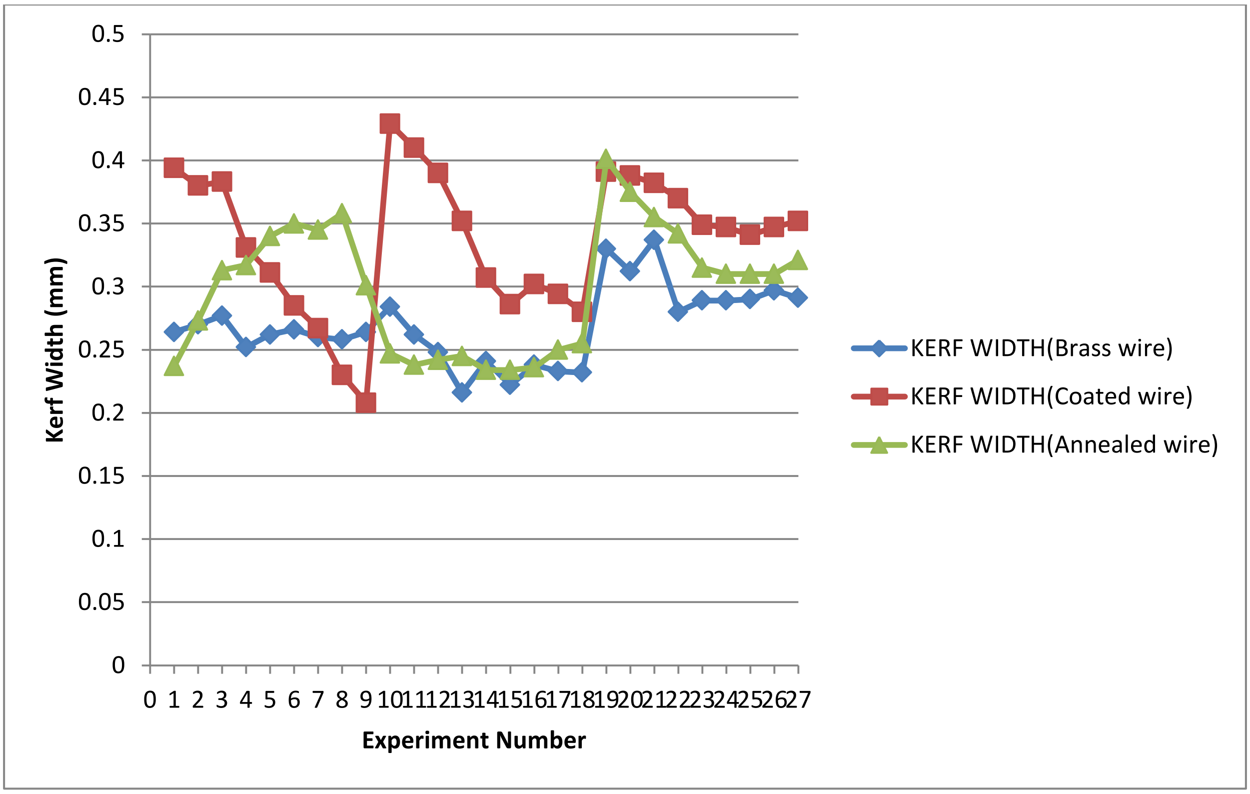

Fig. 6(d) Variation of Kerf Width using different wires

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V. CONCLUSIONS

The following conclusions were drawn from the present study:

1. The optimal combination obtained during machining using Brass wire is Pulse ON time = 110 μs, Pulse OFF time = 45 μs, Spark Voltage = 15 volt, Peak Current = 210 Amp, Wire Feed = 6 m/min and Wire Tension = 6 gram using Grey-Fuzzy logic technique.
2. Similarly, the optimal combination obtained during machining using Zinc coated Copper wire is Pulse ON time = 110 μs, Pulse OFF time = 60 μs, Spark Voltage = 21 volt, Peak Current = 210 Amp, Wire Feed = 6 m/min and Wire Tension = 6 gram using Grey-Fuzzy logic technique.
3. Also, the optimal combination obtained during machining using Annealed Copper wire is Pulse ON time = 110 μs, Pulse OFF time = 30 μs, Spark Voltage = 21 volt, Peak Current = 210 Amp, Wire Feed = 6 m/min and Wire Tension = 6 gram using Grey-Fuzzy logic technique.
4. It is found that the Material Removal Rate is higher using annealed copper wire compare to zinc coated copper wire and brass wire. Similarly, the Tool Wear Rate is found to be lower in annealed copper wire compared to other wires. Also it is observed that surface roughness and kerf width are nearly equal for all the wires.
5. The Grey-Fuzzy logic technique is having the good potential to give an optimal result in WEDM process.

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