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Effect of wire coating on the wire EDM performance characteristics during the machining of Inconel 718

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Abstract: The current work aims to investigate the effect of wire electrode coating, wire EDM process parameters like pulse on time, pulse off time, servo voltage and wire feed rate, on the performance characteristics like cutting speed, surface roughness and flatness error. Inconel 718 superalloy is chosen as the work material, the wire electrodes considered for the study are uncoated brass and zinc coated brass wires having a diameter of 0.25 mm. Grey relational analysis is performed to optimize the process parameters for maximizing machining performance and the results are verified by conducting confirmation experiments. L_{18} orthogonal array was considered to perform the experiments. The effects of wire coating was analyzed separately on each response. Wire coating was found to have a significant effect in improving the cutting speed and surface quality. Optimized process parameters improved surface roughness and profile accuracy by 6% and 37% respectively with an overall improvement of 8.6% in grey relational grade.

Keywords: *Wire electric discharge machining, Form Error, Flatness, wire electrode, Inconel, profile accuracy*

1. Introduction

Wire electric discharge machining (Wire-EDM) is a high precision advanced machining technique that finds its application in non-contact machining of conductive materials irrespective of their hardness. The mechanism that drives the process is material removal by controlled repetitive sparks between a wire electrode and workpiece material. An inter electrode gap of ~30-50 µm is maintained between the electrodes and the gap is flushed constantly by a di-electric fluid. When a suitable voltage is applied by the pulse generator, the dielectric will start to ionize in a very narrow discharge channel where the inter-electrode gap is minimum. At break down voltage, the dielectric allows the current to conduct through it in the form of a high energy spark. The specific energy of spark would be so high that it melts and vaporizes an extremely small localized area of both the electrodes creating micro craters. Then follows the pulse off time during which the molten debris are flushed away by the dielectric and the process repeats. The sparking happens at extremely high rate in the order of more than 20 kHz.

Wire-EDM is considered as one of the precision manufacturing process because of its ability to control the energy and frequency of the pulses to machine the components with utmost accuracy and precision. Also the wire is fed with respective to the workpiece through a predefined contour using CNC commands controlled by the integrated computer console. Since the collective effect of individual craters causes the material removal, there is need to understand the right combinations of machine process parameters which would give the best machining performance. However, such a selection of parameters is material dependent too. Apart from the pulse control parameters, another prominent factor affecting the machining performance is the choice of wire electrode. The wire electrode comes in different materials, diameters, cross sections and coatings. A good understanding of how each of these effect various performance measures are required to choose the right wire material according to application.

The machining performance is generally expressed in terms of productivity and surface quality. Cutting speed is a commonly considered criteria to represent the productivity. However, the machined surface quality can be judged based on various performance measures. Some of those are surface roughness, profile/geometric accuracy, dimensional accuracy, surface integrity etc. Average surface roughness (Ra) is a very commonly studied performance measure in manufacturing industries to judge the surface quality. But many a times the other parameters, especially the profile accuracy were found overlooked. The modern industries demands products with exceptional surface finish and profile accuracy. Also for the process to be economically viable, the productivity shall not be compromised either.

The wire EDM machining process is more relevant when the material is tough to be machined by conventional methods. Inconel 718 (IN718) is one such superalloy which can retain its superior mechanical properties at elevated temperatures. Such superalloys finds their applications in aerospace, gas turbine, medical implants and automobile components. Ni based superalloys including IN718 can perform well in the high temperature, extreme conditions since it can withstand creep and corrosion [1, 2]. However, the material is regarded "difficult to machine" by conventional techniques owing to its higher shear strength, low thermal conductivity, cold working nature, presence of hard carbides and the tendency to form build up edge [2]. Wire-EDM can be a suitable alternative to machine such superalloys due to its non-contact type material removal mechanism. The process is considered as an economic feasible solution to machine exotic materials compared to conventional methods like broaching or non- conventional methods like laser beam machining etc. Since the tool and workpiece doesn't come in contact, no mechanical residual stress and cutting forces are present. [3]

Quality of machining and productivity are the two important considerations especially during the machining the exotic materials having high temperature applications. Gas turbine industry demands exceptional surface finish and profile accuracy to which the WEDM process has to be optimized. The possibility of machining fir tree slots by WEDM were studied by Klocke et al. on an Inconel 718 alloy. The wire-EDMed part quality was found suitable for turbine manufacturing industry standards [4]. Anurag [5] reviewed the possibility of using WEDM machined gamma titanium aluminides in the future turbine engines. Such an idea is put forward by studying the minimum surface damage WEDM machining techniques and comparing those with the conventionally broached parts.

Parametric study of the process to improve the machining performance was attempted by many researchers in the past. Aggarwal et al., [6] developed the response surface methodology model of the WEDM process during the machining of Inconel 718 empirically. Pulse on time was found to affect the performance the most. Parametric optimization of Wire-EDM process for IN718 was conducted by Yang et al. [7]. Cutting rate and surface finish were optimized by combined Taguchi and grey relational analysis (GRA). The optimal conditions showed an improvement of 54.5 % in material removal rate. A RSM based particle swarm optimization was done by Sharma et al. [8]. Modeling was performed, considering material removal and surface finish as response by response surface methodology followed by backward elimination for the WEDM process of Inconel 706. ANOVA results showed that the voltage pulse duration and servo voltage effected cutting rate and surface quality the most.

Islam et al. [9] experimentally investigated the effect of six controllable input parameters on the linear dimensional errors and geometrical errors. Flatness and Perpendicularity errors were the geometrical errors considered for the study. Input current was the major contributor for flatness error. Kumanan and Nair [10] has done experimental study on Inconel 617 in optimizing the WEDM process considering Circularity, Cylindricity, Perpendicularity and Parallelism as the geometrical tolerance parameters using grey ANFIS. GRA was used for multi-attribute optimisation.

The capability of WEDM in manufacturing fir tree slots in turbine disks were explored by Klocke et al. by using different wire electrodes [11]. Ni coated wire was found to be more suitable for minimizing the contamination of work material surface, when compared to Zn and Cu coated wires. Coated wires were observed to decrease the machining time by 33%. Reolon et al. [12] had compared the process performance of wire-EDM of IN718 superalloy with zinc coated and brass wire electrodes. Ramamurthy et al. [13] analyzed the impact of different wire electrode types on the wire-EDM process performance. Diffused wire was found to perform better for machining Ti- 6Al-4V

Thus based on the existing literature, it could be inferred that there is a need to optimize the WEDM process to meet the growing industrial demands in terms machined part quality and productivity. Also, from the different choices of wire electrodes available, an investigation is needed to study the significance of wire coatings on the measurable machining performances. Therefore the current study is expected to add value to the existing limited database of experiments that deals with the process optimization for improving the productivity and geometrical accuracy simultaneously. Also the work aims to weigh the significance of coated wire electrodes in ensuring the superior performance of the WED-machining process.

2. Materials and Methods

2.1 Material selection

Nickel based superalloys finds its application in the mechanical components due to their sustained performance at elevated temperatures, ability to withstand corrosion and creep and good fatigue strength. Inconel 718 is one such alloy commonly chosen for gas turbine applications especially for the manufacturing of turbine blades. For such high temperature high performance applications, dimensional and profile accuracy of machined surface along with good surface integrity is mandatory. Table 1 lists the typical properties of the alloy.

Table 1. Properties of Inconel 718

Property	Value
Density	8.19 g/cm^3
Melting Point	1260 – 1336^{o}C
Specific Heat	435 J/kg K
Coefficient of thermal expansion	13 µm /m K
Thermal Conductivity	11.4 W/m K
Ultimate Tensile strength	1240 MPa

2.2 Experimental details

The machining was conducted on Electronica Eco-cut CNC wire EDM. The profile contour was programmed in ELCAM software and is fed to the machine. The machine axes are servo controlled and follows the path of programmed contour. The axes has minimum resolution of 1 µm. The wire electrodes used are of 0.25mm diameter with deionised water as the dielectric medium. The deionised water is continuously flushed to the inter electrode gap by top and bottom nozzles. It removes the machined debris from the spark gap and cools the workpiece.

The profile cut was a flat rectangular piece of 8 mm x 2mm x 10mm. The machined samples are shown in Fig. 1.

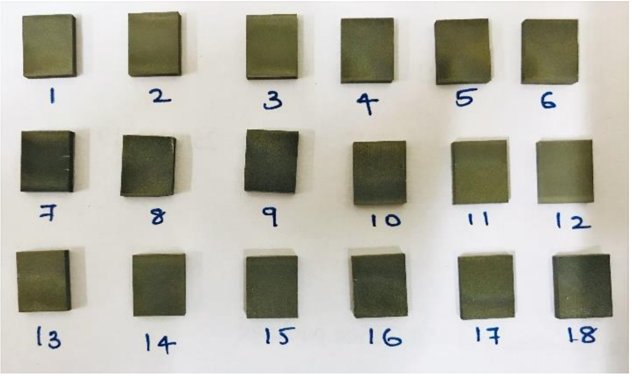


Fig. 1. Samples cut for 18 experimental runs

Accurate Tutor 5.5.4 coordinate measuring machine is used to measure the form errors in the profile. Surface roughness was measured using the Zeiss Surfcom flex 35-B surface profilometer. Zeiss GeminiSEM 300 – field emission scanning electron microscope (FESEM) was used for imaging the worn wire electrode samples.

2.2.1 Machining parameters and performance characteristics

Five process parameters selected for investigation are voltage pulse duration (T_{on}), pulse off time (T_{off}), servo voltage (SV), wire feed rate (WF) and the wire type. Selection of the range of machining parameters were done by referring the machining manual, literature and by conducting pilot experiments. The selection of parameter range is not only depended on machine specifications but also on the workpiece material. The selected range ensured stable machining without wire breakages, machined surface damages and reduced productivity. Four process parameters were varied in three different levels and two types of wire electrodes, namely coated and uncoated brass are chosen, as given in Table 2. L_{18} orthogonal array is chosen as the experimental design and the parameter combinations are as shown in Table 3.

The choice of wire material can influence the machining performance to a considerable extent. The coated wire is said to increase the cutting speed without compensating the surface finish [14]. Coating a wire electrode like copper or brass with a metal with lesser vapor pressure would protect the core wire from thermal shock. The usual thickness of the coating would be 20 to 30 µm. When the sparks are produced between workpiece and wire electrode, part of the energy is consumed in heating up the coating which will be evaporated as a result. This results in a heat sink effect and ultimately cools the wire core. Also the inter-electrode gap will increase due to vaporization of coating material and will result in improved flushing. The overall result is increased cutting speed while using coated wires. However the effects of wire electrode coatings on profile accuracy during the machining of superalloys is rarely explored and thus it has been included in the scope of the current experimental analysis.

Table 2. Experimental Settings of Control Parameters

Symbol	Parameters	Level 1	Level 2	Level 3
A	T_{on} (µs)	105	110	115
B	T_{off} (µs)	40	45	50
C	Servo voltage SV (V)	40	45	50
D	Wire feed WF (m/min)	3	5	7
E	Wire type	Type 1 (Zn coated brass wire)	Type 2 (Uncoated brass wire)	-

Table 3. Parameter Combinations

Sl. No.	Wire Type	T_{on}(µs)	T_{off}(µs)	Servo Voltage (V)	Wire Feed (mm/min)
1	1	105	40	40	3
2	1	105	45	45	5
3	1	105	50	50	7
4	1	110	40	40	5
5	1	110	45	45	7
6	1	110	50	50	3
7	1	115	40	45	3
8	1	115	45	50	5
9	1	115	50	40	7
10	2	105	40	50	7
11	2	105	45	40	3
12	2	105	50	45	5
13	2	110	40	45	7
14	2	110	45	50	3
15	2	110	50	40	5
16	2	115	40	50	5
17	2	115	45	40	7
18	2	115	50	45	3

Since the objective of the current experimental study is to analyze the effect of wire type and process parameters on the profile accuracy and productivity, the responses of interest in the current study are cutting speed (CS), surface roughness (R_a) and flatness error (FE) of machined surface.

Surface roughness and rate of material removal primarily depends on the size of crater produced by individual spark, which is again depended on the energy per spark. Higher the energy, greater would be the crater size, rougher would be the surface and more would be the cutting speed. However, relative size of the crater for a particular parametric setting and choice of wire electrode is material dependent. This is one of the reason why there is a need to optimize the parameters for machining different classes of materials.

The profile accuracy or geometrical accuracy of the machined surface is depended on the effectiveness of wire guidance along with choice of proper parametric settings. Ineffective wire guidance causes wire vibrations which can influence the machined part quality. Setting the proper wire tension partly eliminates the effect. However, apart from wire tension, proper setting of process parameters and choice of the wire material also plays a part in deciding the amplitude, frequency and character of the wire vibrations [15]. Proper selection of process parameters and wire type can affect profile accuracy and improves the overall machining performance. A schematic representation of the effect of wire vibrations on the flatness error is shown in Fig. 2.

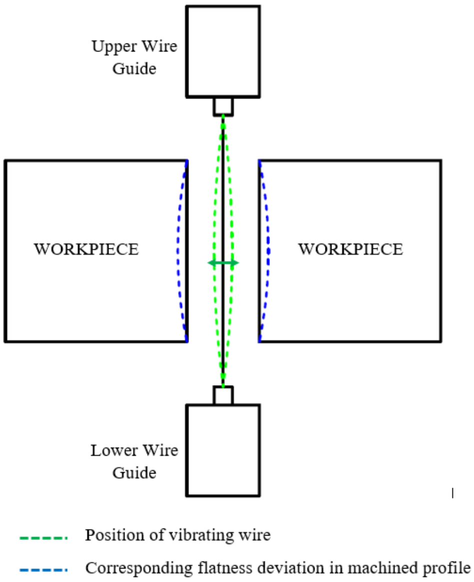


Fig. 2. Representation of geometrical inaccuracy (flatness error) caused due to wire vibrations

3. Results and Discussions

The results of the eighteen experimental runs are shown in Table 4. Each experimental run according to L_{18} orthogonal array was replicated thrice to check for outliers and the average response was considered.

Table 4. Measured Performance Characteristics

Sl. No.	Wire Type	T_{on} (µs)	T_{off} (µs)	SV (V)	WF (mm/min)	CS (mm/min)	Ra (µm)	FE (µm)
1	1	105	40	40	3	1.22	1.97	4.15
2	1	105	45	45	5	0.70	1.85	4.13
3	1	105	50	50	7	0.33	1.63	2.83
4	1	110	40	40	5	0.90	2.41	2.20
5	1	110	45	45	7	0.66	2.37	1.95
6	1	110	50	50	3	0.46	2.28	3.73
7	1	115	40	45	3	1.40	2.89	4.50
8	1	115	45	50	5	0.90	2.72	3.98
9	1	115	50	40	7	1.03	2.87	3.18
10	2	105	40	50	7	0.70	1.77	2.20
11	2	105	45	40	3	0.82	1.87	2.35
12	2	105	50	45	5	0.47	1.77	3.20
13	2	110	40	45	7	0.67	2.33	2.65
14	2	110	45	50	3	0.48	2.28	2.70
15	2	110	50	40	5	0.56	2.43	3.93
16	2	115	40	50	5	0.86	2.99	3.15
17	2	115	45	40	7	1.04	3.03	2.78
18	2	115	50	45	3	0.75	3.09	2.65

3.1 Grey relational analysis

GRA optimizes the parameter levels to maximize multiple machining performance characteristics. In the current study, three responses constitute the machining performance namely cutting speed, Surface roughness and flatness error. GRA is a multi-attribute decision making algorithm which requires normalized experimental responses.

Table 5. Grey Relational Grades and Ranking of Surface Roughness, Cutting Speed and Flatness Error

Sl. No.	Normalized Results			Grey relational Coefficient (GRC)			Grey relational grade (GRG)	RANK
	CS*	Ra*	FE*	GRC, CS	GRC, Ra	GRC, FE		
1	0.83	0.77	0.14	0.75	0.68	0.37	0.637	2
2	0.34	0.84	0.15	0.43	0.76	0.37	0.499	12
3	0.00	1.00	0.66	0.33	1.00	0.59	0.565	7
4	0.53	0.47	0.90	0.52	0.48	0.84	0.588	5
5	0.31	0.49	1.00	0.42	0.50	1.00	0.584	6
6	0.12	0.55	0.30	0.36	0.53	0.42	0.418	17
7	1.00	0.14	0.00	1.00	0.37	0.33	0.675	1
8	0.53	0.25	0.21	0.52	0.40	0.39	0.455	16
9	0.66	0.15	0.52	0.59	0.37	0.51	0.516	10
10	0.35	0.90	0.90	0.43	0.84	0.84	0.635	3
11	0.46	0.83	0.84	0.48	0.75	0.76	0.617	4
12	0.13	0.90	0.51	0.37	0.83	0.50	0.517	9
13	0.32	0.52	0.73	0.42	0.51	0.65	0.501	11
14	0.14	0.55	0.71	0.37	0.53	0.63	0.474	13
15	0.21	0.45	0.23	0.39	0.48	0.39	0.412	18
16	0.50	0.07	0.53	0.50	0.35	0.52	0.466	15
17	0.66	0.04	0.67	0.60	0.34	0.61	0.535	8
18	0.40	0.00	0.73	0.45	0.33	0.65	0.471	14

The cutting speed were normalized by higher the better formula and the surface roughness and flatness error were normalized by lower the better formula as shown in equations (1) and (2) respectively.

$$X_i^*(k) = \frac{X_i(k) - min\,[X_i(k)]}{max\,[X_i(k)] - min\,[X_i(k)]} \quad (1)$$

$$X_i^*(k) = \frac{max[X_i(k)] - X_i(k)}{max\,[X_i(k)] - min\,[X_i(k)]} \quad (2)$$

$X_i(k)$ is the value of response parameter k. Then GRC was found using the equation (3) and (4)

$$\gamma = \frac{\Delta min + \varepsilon \Delta max}{\Delta_{oi}(k) + \varepsilon \Delta max} \quad (3)$$

$$where\ \Delta_{oi}(k) = X_0^*(k) - X_i^*(k) \quad (4)$$

Δmax and Δmin are maximum and minimum values from normalized column and should be 1 and 0 respectively. ε is weightage factor normally taken as 0.5. Δ_{oi} (k) is absolute difference between $X_o^*(k)$ and $X_i^*(k)$. $X_o^*(k)$ is the ideal normalized value for the k^{th} response parameter. The ideal value of any normalized response is taken as 1. Once the gray relational grade is calculated for each response for every trial, ranks are then assigned to each experimental run based on the grey relational grade which is the weighted sum of all coefficients. Here cutting speed is provided with a weightage of 0.5 and other responses are given 0.25 each.

Table 5 shows the grey relational grades and corresponding ranks for all the 18 experimental runs. 7th experimental run is ranked first according to the table. Table 6 gives the factor response table showing the maximum variations in average grey relational grade values for various input variables.

According to the factor response table, pulse off time contributes the maximum to the response variations. 'Pulse on time' and 'wire feed' were also notable contributors. Each parameter is ranked based on the relative contribution in varying the responses. The effect is shown graphically in Fig. 3 in the effects plot for GRG. If the process parameters are considered separately, the levels for each parameter which gives the maximum GRG could be considered ideal. Maximizing GRG implies the overall better responses in terms of material removal, surface finish and profile accuracy.

Table 6. Factor Response Table for GRG

	Wire Type	T_{on}	T_{off}	SV	WF
Level 1	**0.5485**	**0.5784**	**0.5837**	**0.5508**	0.5485
Level 2	0.5142	0.496	0.5272	0.5414	0.4895
Level 3		0.5196	0.4832	0.5019	**0.556**
Delta	0.0343	0.0824	0.1005	0.0488	0.0665
Rank	5	2	1	4	3

Thus, from the main effects plot for GRG, $A_1B_1C_1D_1E_3$ can be inferred as the optimal level of machine parameters. Confirmation tests were conducted to verify the optimal process parameter obtained by grey relational analysis.

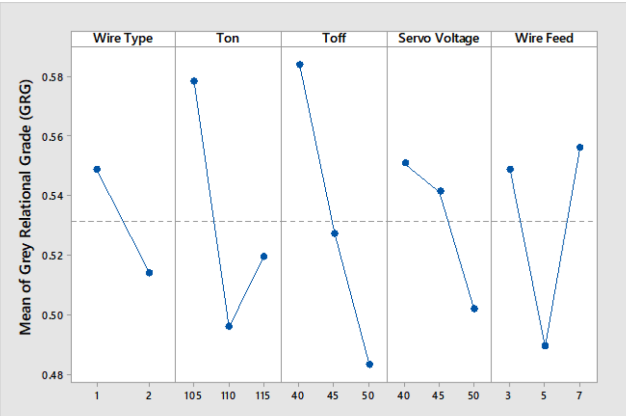
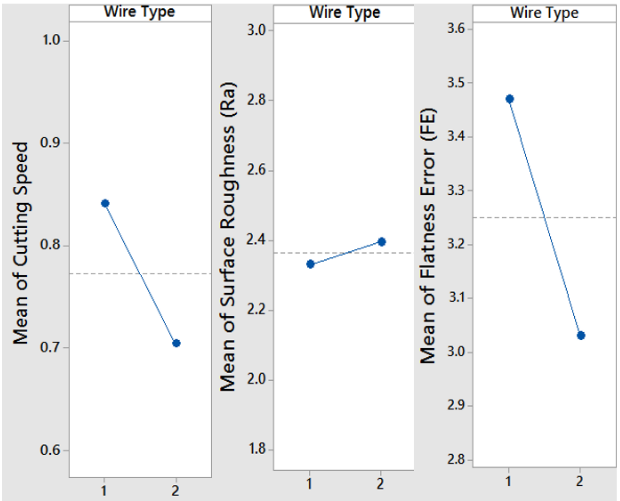


Fig. 3. Main effects plot for GRG

3.2 Effect of wire electrode coatings

Based on the current study, it could be inferred that the wire electrode coating does have an effect on the variations observed in all the responses. When all the five parameters are ranked based on their relative effect on responses, wire type is ranked 4th, 3rd and 2nd on cutting speed, surface roughness and flatness error respectively. However due to the inverse proportionality between cutting speed and surface quality (normally lesser the material removal, better will be the part quality), the effects of wire type is nullified when considering the overall performance improvement.



1. Zn Coated Brass wire
2. Uncoated Brass wire

Fig. 4. Effects of wire type on various responses

The effects of wire type on each of the performance measures are plotted separately in Fig. 4. From the figure it can be inferred that the zinc coated brass wire is found suitable for improving productivity compared to uncoated brass wire. Again when the surface finish is considered, zinc-coated brass wire performed better. Better surface finish is related to more stable machining. The coated wire electrodes promote improved flushing and thus keeps the inter electrode gap free from debris. Thus unstable arc and short circuit pulses are reduced resulting in better surface quality.

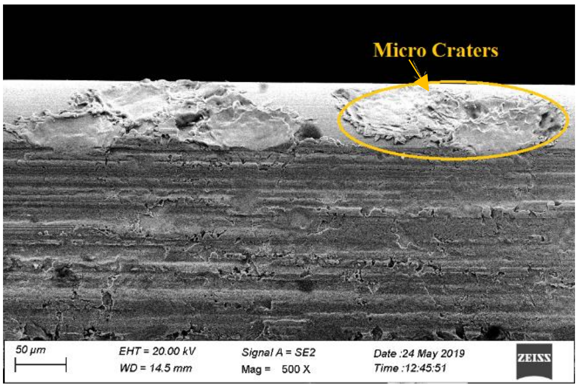


Fig. 5 a). SEM image of brass wire after machining

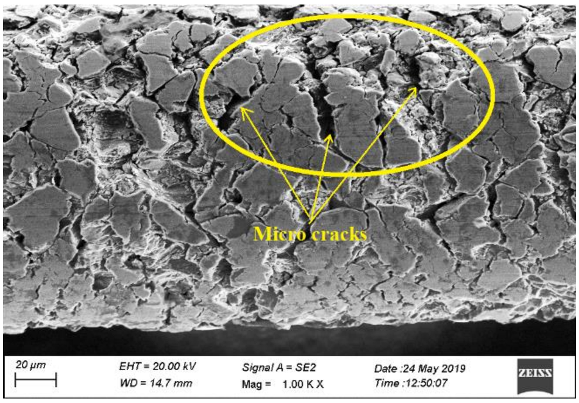


Fig. 5 b). SEM image of Zn coated brass wire after machining

Fig. 5 shows the scanning electron microscope (SEM) images of uncoated and Zn coated wire electrodes after machining. On comparing the wear pattern it is observed that extensive micro cracking of coated wire surface by excessive Zn vaporization during sparking was occurred. This could increase the instantaneous inter electrode gap and could promote improved flushing of debris resulting a better machining stability. On the contrary, such a phenomenon is absent in uncoated brass wire due to higher melting point of Brass. However craters due to individual sparks are seen.

In minimizing the flatness error, uncoated brass wire performed better than Zn coated brass wire electrode which could be related to the better tensile strength of uncoated wire resulting in lesser wire electrode vibrations. When the overall performance improvement is considered in grey relational grade, again the Zn coated wire electrode was recommended as the preferred choice, evident from Fig. 3.

3.3 Confirmation tests

Once the optimal process parameters for maximum machining performance are obtained, theoretical grey relational grade was calculated using equation (5).

$$\hat{\gamma} = \gamma_m + \sum_{k=1}^{q}(\gamma_i - \gamma_m) \quad (5)$$

Where γ_m is the mean GRG, γ_i is the average GRG at each optimal level of control parameters and q is the total number of significant input parameters under consideration. Table 7 shows the result comparison between the initial and optimum parametric conditions.

The optimal parametric combinations yielded 37.9% reduction in flatness error, 6% reduction in surface roughness and an 8.6% improvement in grey relational grade. The improvement in grey relational grade verifies that the overall performance is improved even though the cutting speed was reduced marginally.

Table 7. Confirmation test results

	Initial Parameter setting	Optimal condition	
		Prediction	Experiment
Level	$A_1B_1C_1D_1E_1$	$A_1B_1C_1D_1E_3$	$A_1B_1C_1D_1E_3$
Cutting speed	1.22		1.13
Surface roughness	1.97		1.85
Flatness error	4.15		2.575
GRG	0.637	0.654	0.692

The optimal processes parameters obtained by grey relational analysis improved the surface quality without effecting the productivity

4. Conclusions

The following are the conclusions from the experimental study.

1. Zinc coated brass wire electrode improved the overall machining performance compared to uncoated brass wire while machining Inconel 718.
2. Numerous micro cracks were observed in zinc coated brass wire resulting from localized vaporization of zinc, which leads to improved flushability and overall performance improvement.
3. Grey relational analysis is an effective tool in optimizing the process parameters to maximize the performance.
4. According to grey relational analysis, $A_1B_1C_1D_1E_3$ combination, i.e. Zn coated brass wire electrode, T_{on} of 105 µs, T_{off} of 40 µs, servo voltage of 40 V and wire feed rate of 7 mm/min would give the maximum machining performance while machining Inconel 718.

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