Multi-Response Optimization during Electro-Discharge Machining of Super Alloy Inconel 718: Application of PCA-TOPSIS

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Abstract

The present work aims to determine an appropriate setting of process parameters (viz. gap voltage, peak discharge current, pulse-on time, duty factor and flushing pressure) for achieving optimal machining performance during Electro-Discharge Machining (EDM) of super alloy Inconel 718 by using copper tool electrode. Experiments have been performed based on L_{25} Orthogonal Array (OA) design of experiment by varying each of the aforesaid process parameter at five different levels. The machining performances have been evaluated in terms of Material Removal Rate (MRR), Electrode Wear Rate (EWR), Surface Roughness (R_a), Surface Crack Density (SCD), White Layer Thickness (WLT), and Micro Hardness (MH) of the EDMed Inconel 718 end product.

In this paper, two different optimization routes have been explored. The proposed optimization routes have been (i) Principal Component Analysis (PCA) followed by TOPSIS (*Technique for Order Preference by Similarity to Ideal Solution*) and Taguchi method and (ii) PCA coupled with Combined Quality Loss (CQL) concept followed by Taguchi method. Application feasibility of aforementioned two optimization approaches has been compared herein through this case experimental research.

Keywords: Electro-Discharge Machining (EDM); Super Alloy; Inconel 718; Orthogonal Array (OA); Principal Component Analysis (PCA);

1. Research Background

Inconel 718 is age-hardened nickel-chromium based super alloy having high strength, high resistance to corrosion, high yield as well as creep-rupture strength. It also exhibits excellent weldability because of its unique property to resist post weld cracking. Inconel 718 is *Gamma Prime* strengthened alloy and it retains mechanical property even at elevated as well as cryogenic temperatures (-423° to 1300°F). Inconel 718 can easily be annealed and weld without any spontaneous hardening during heating and cooling.

Because of aforesaid properties and ease of fabrication, Inconel 718 is commonly used for jet and gas turbine engine, liquid fuelled rocket, space craft, cryogenic storage tanks, rocket motors and thrust reversers, nuclear reactors, pumps bodies and in making airframe parts like bucket, spacers and making high temperature bolts- fasteners and instrumentation parts.

Inconel 718 comes under the category of '*difficult-to-cut*' material because of its superior strength and high toughness, work hardening tendency; it provides high resistance in material removing because of its high shear strength. It has poor thermal conductivity which causes high tool-tip temperature. It also possesses hard abrasive compound and carbide which are detrimental for tool life. It has work hardening tendency which leads to tool notching and ultimately blur formation on the work material being used. The machining of Inconel alloy provides poor surface finish; so it requires post finishing operation. Due to the above mentioned difficulties, non-conventional machining such as Electro-Discharge Machining (EDM) is generally preferred for machining of Inconel 718.

Ay et al. [1] conducted micro-EDM drilling operation on Inconel 718 by considering taper ratio and hole dilation as responses. It was concluded that taper ratio, hole dilation and electrode wear assumed a direct relationship with discharge current and pulse duration. The authors also reported that cracks and damage could be reduced by decreasing the discharge current and reducing the pulse duration. Sengottuvel et al. [2] conducted EDM experiments on Inconel 718 using copper electrode to investigate the effect of input parameter and tool geometry on Material Removal Rate (MRR), Tool Wear Rate (TWR) and surface roughness. An optimal setting of the input parameters was obtained using Desirability Function (DF) approach. Analysis of Variance (ANOVA) concluded that peak current and pulse-on time appeared the most significant parameter affecting EDM performance. The authors recommended tool geometry of rectangular cross section for ensuring better output. Aggarwal et al. [3] used Response Surface Methodology (RSM) based Taguchi approach in conducting Wire-EDM experiments on Inconel 718 by considering pulse-on time, pulse-off time, peak current, spark gap voltage, wire feed rate and wire tension as process parameters. In addition to this, the authors obtained the optimized values of cutting rate as well as surface roughness. Kuppan et al. [4] conducted drilling operation using EDM on Inconel 718 and characterised the hole quality in terms of surface roughness value (R_a), depth averaged radial overcut (DAROC) and hole profile; the authors concluded that peak current and pulse-on time imposed significant effect on surface roughness; whereas, pulse-on time was found significantly effecting the DAROC.

Li et al. [5] investigated machining characteristics of Inconel 718 by conducting Wire-EDM and Sinking-EDM using Cu-SiC electrode, respectively. Machining performance was evaluated in terms of material removal efficiency, surface roughness, surface topography, surface alloying, and electrode wear. The authors concluded that Cu-SiC electrode was found to incur lower electrode wear than traditional Cu electrode. The authors revealed that absence of micro-cracks was due to high toughness of Inconel 718. Dabade and Karidkar [6] conducted Wire-EDM experiments on Inconel 718 based on orthogonal array and used Taguchi technique in optimising the responses such as MRR, SR, Kerf and dimensional deviation. The authors observed that pulse-on time followed by peak current was found remarkably significant on effecting Wire-EDM response.

There exists several controllable parameters viz. gap voltage, peak current, pulse-on time, duty factor, flushing pressure etc. on the EDM setup. Proper tuning of these parameters may result satisfactory machining yield. However, these parameters interact in a complicated manner and hence affect the machining responses (outputs). In this context, research interest has been evolved to search for a suitable machining environment (setting of controllable process parameters) to satisfy multi-requirements of process performance yields in terms of Material Removal Rate (MRR), Electrode Wear Rate (EWR), roughness average (R_a), Surface Crack Density (SCD) of the EDMed surface, While Layer Thickness (WLT) and micro-hardness of the white layer during EDM of Inconel 718.

Since controllable process parameters assumes a discrete domain of variation (as per specification and provision of the factorial adjustment in the EDM setup), application of Taguchi method seems fruitful in this context. However, traditional Taguchi approach [7, 8] fails to solve multi-response optimization problem. As the current problem is associated with multiple performance characteristics of EDM; it seems customary to aggregate multi-performance features into am equivalent single index; which can finally be optimized by Taguchi method. PCA-TOPSIS approach has been proposed herein in amalgamation with Taguchi method to optimize aforesaid performance features obtained in EDM of Inconel 718. The optimal setting thus obtained has been verified to that of obtained by Principal Component Analysis (PCA) and Combined Quality Loss (CQL) based Taguchi approach already highlighted in existing literature [9]. Optimal setting has been verified by confirmatory test.

Nomenclature

EDM	Electro-Discharge Machining
I_p	Peak Current
T_{on}	Pulse-on Time
τ	Duty Factor
R_a	Surface Roughness (Roughness Average)
PCA	Principal Component Analysis
TWR	Tool (Electrode) Wear Rate
MRR	Material Removal Rate
SCD	Surface Crack Density
WLT	White Layer Thickness

2. Experimental details

Inconel 718 plates of dimension have been used as work material. The chemical composition and mechanical properties of Inconel 718 could be retrieved from [10]. A pure copper rod of circular cross section $(\phi 20)$ has been used as tool electrode.

The experiments have been carried out on die sinking EDM setup (Make: Electronica ElektraPlusPS 50ZNC, India). Commercially available EDM oil with specific gravity of 0.763 has been used as dielectric fluid. Polarity has been kept positive (i.e. workpiece positive). In the present work, the selected process parameters have been open circuit voltage (OCV) (also called gap voltage), peak current (I_p), pulse-on time (T_{on}), duty factor (τ) and flushing pressure (F_p). Each process parameter has been varied at five discrete levels (Table 1) as per configuration of parametric setting available with the setup.

Table 1: Machining control parameters: Domain of variation

Parameters	Unit	Notation	Levels of variation				
			1	2	3	4	5
Gap voltage/ OCV (V_g)	[V]	A	50	60	70	80	90
Peak current (I_P)	[A]	B	3	5	7	9	11
Pulse-on-Time (T_{on})	[µs]	C	100	200	300	400	500
Duty Factor (τ)	[%]	D	65	70	75	80	85
Flushing Pressure (F_p)	[bar]	E	0.2	0.3	0.4	0.5	0.6

The Design of Experiment (DOE) has been selected based on 5-level-5-factor L_{25} Orthogonal Array (OA). Parametric interaction effect has been assumed negligible here. Experiments have been conducted as per 25 factorial settings (shown in Table 2); the EDM of Inconel 718 plates have been carried out with copper electrode. Both workpiece and tool have been immersed in dielectric fluid. The machining duration has been kept constant (10 minutes) for each experimental run. The responses studied have been Material Removal Rate (MRR), Electrode Wear Rate (EWR), Roughness average (R_a) of the machined surface, Surface Crack Density (SCD) on the machined surface, White Layer Thickness (WLT) and Micro-hardness (MH) at the mid-depth of the white layer. In this experimentation, weights losses of work and tool material have been were measured by electronic weighing balance (Shinko Denshi Co. Ltd, JAPAN, DJ 300S, Accuracy: 0.001 g). The measurement of surface roughness (R_a value) of the EDMed surface has been made with portable stylus type profilometer, Talysurf (Model: Taylor Hobson, Surtronic 3+). In order to measure surface crack density, the top surface morphology of the EDMed surface has been studied using Scanning Electron Microscopy (SEM) (Fig. 1). For a particular sample, SEM images have been captured in three different locations and corresponding surface crack densities have been collected. The average of these three has been considered for that particular specimen. For a particular sample area, the total crack length has been measured using PDF-X Change Viewer Software. The total crack length divided by the specimen area provides the measure of average/relative SCD.

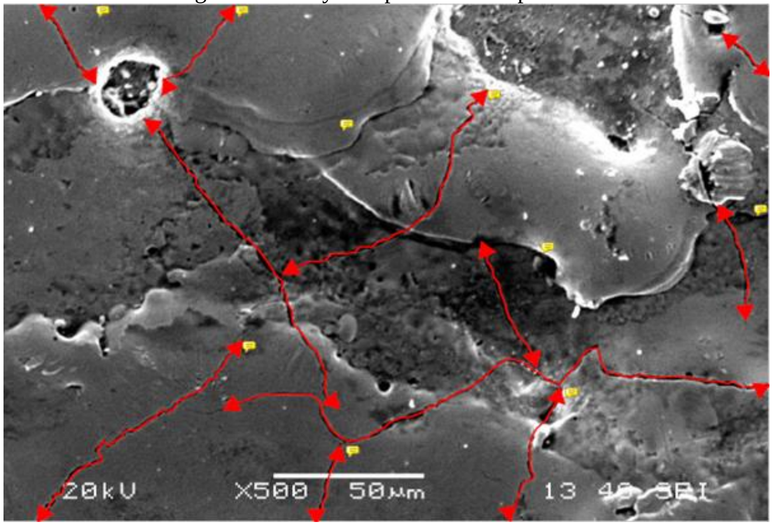

Fig. 1: Surface crack density measured by pdf-x change viewer software (for the specimen obtained at Run No. 6)

The image of white layer has then been viewed under SEM (Model: Joel JSM-6480LV; Japan) with a magnification of ×500 and ×1000 (Fig. 2). The thickness of the white layer has been measured by ImageJ Software at five different locations across each cross-sectioned specimen; and an average value has been considered for further analysis. The micro-hardness of white layers has been determined by Vicker’s micro-hardness tester (Make: LECO, USA; Model No. LM810).

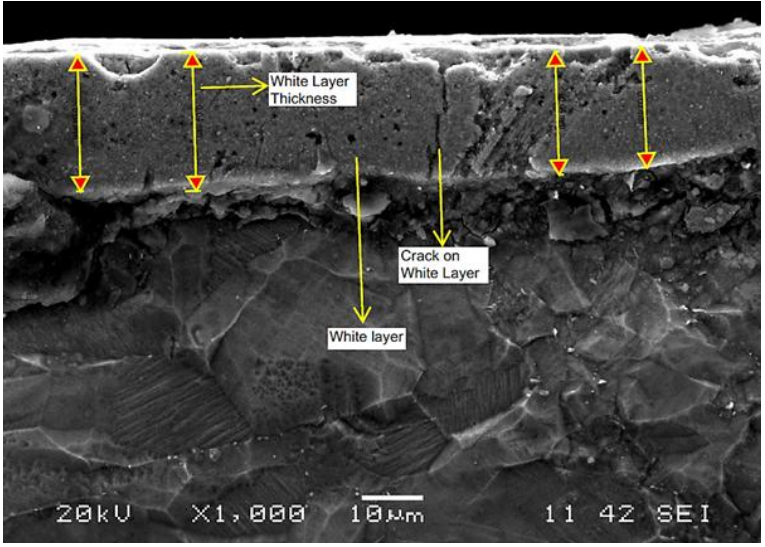

Fig. 2: Measurement of White Layer Thickness (WHT) (for the specimen obtained at Run No. 21)

3. Methodologies

PCA-TOPSIS approach has been attempted herein in conjugation with Taguchi’s philosophy for optimization of EDM performance features on Inconel 718. Principal Component Analysis (PCA) has been carried out to eliminate response-correlation and to transform correlated responses into lesser number of uncorrelated quality indices, called major principal components (PCs). Quality Loss (QL) concept has been introduced herein representing the absolute deviation of individual PCs with respect to the ideal values. Using TOPSIS concept, based on QL estimates of major PCs, ideal as well as anti-ideal solution have been determined. Next, separation measures of each alternative (parametric setting) with respect to ideal and anti-ideal solution both have been obtained. A closeness coefficient has been determined against each alternative. This has been optimized finally by Taguchi method. The concept of QL in course of PCA as well as procedural steps of TOPSIS philosophy could be well articulated from [9], [11], respectively.

The optimal parametric setting thus obtained has been compared to that of PCA and Combined Quality Loss (CQL) based Taguchi optimization approach [9]. The flow chart of aforesaid two optimization approaches has been depicted in Fig. 3.

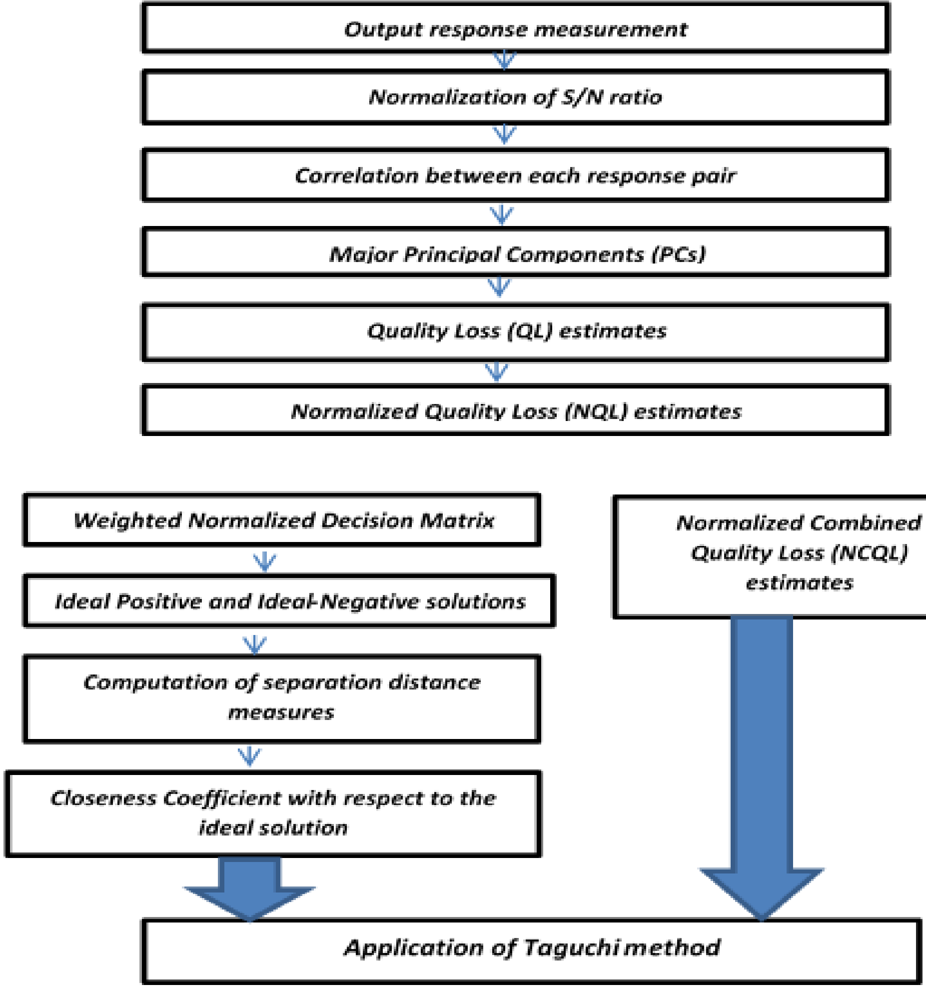

Fig. 3: Flow chart of the optimization approaches employed

4. Results and Discussion

In order to avoid dimensional effect and response conflict, response data have been normalized first. For data normalization, a Higher-is-Better (HB) criterion has been used for MRR; and a Lower-is-Better (LB) criterion has been considered for remaining responses. In order to check response correlation, Pearson's correlation coefficients for individual response pairs have been computed. In all cases, the non-zero value of correlation coefficient has exhibited that responses are correlated to each other. In order to eliminate response correlation and to convert correlated response into uncorrelated quality indices, PCA has been applied. Results of PCA have provided information regarding Eigen values, Eigen vectors, Accountability Proportion (AP) and cumulative accountability proportion (CAP). It has been found that only the first three Principal Components (PCs) have been found capable of capturing data variation by 31.8%, 30.4% and 16.0%, respectively (CAP 78.3%); hence, these have been treated as major Principal Components (PCs) and considered for further analysis. The remaining PCs correspond to very less accountability proportion and hence ignored. Next, values of the major PCs i.e. PC1, PC2, and PC3 have been computed in all experimental runs. Quality Loss (QL) estimates of major PCs have been computed next. These quality loss estimates have further been normalized considering Lower-is-Better (LB) criterion. Considering equal importance of individual major PCs (33.33%) weighted normalized decision matrix (in TOPSIS computation) has been obtained. The ideal and anti-ideal solutions have been computed next as retrieved from the concept of TOPSIS theory. Here, each of the parametric settings in the L_{25} orthogonal array has been considered as alternative solution. Next, separation measures for individual alternatives with respect to both ideal and anti-ideal solution have been computed. A closeness coefficient value has been computed against each of the alternatives; which have been optimized finally by Taguchi method. For optimizing closeness coefficient, a Higher-is-Better (HB) criterion has been considered. The predicted optimal setting as obtained from Fig. 4 appears $A_2B_3C_3D_2E_4$. From the mean response table (i.e. S/N ratio of closeness coefficient) it has been exhibited that factor B has appeared as the most significant parameter; whilst factor D has been found least significant.

The same problem has been solved through exploration of Combined Quality Loss (CQL) concept in the PCA theory (assuming equal importance of major PCs) (Refer to Table 2); the predicted optimal setting appears as $A_2B_1C_3D_4E_1$ (as shown in Fig. 5).

Table 2: Design of experiment (L_{25} OA), S/N Ratios and Predicted S/N Ratio of CQL

Sl. No.	L_{25} OA					S/N Ratios [dB] of CQL	Predicted S/N Ratio [dB] at optimal setting
	A	B	C	D	E		
1	1	1	1	1	1	-2.71928	-0.365981 $A_2B_1C_3D_4E_1$
2	1	2	2	2	2	-5.87853	
3	1	3	3	3	3	-5.87939	
4	1	4	4	4	4	-5.8422	
5	1	5	5	5	5	-8.33472	
6	2	1	2	3	4	-3.1777	
7	2	2	3	4	5	-2.27185	
8	2	3	4	5	1	-5.48013	
9	2	4	5	1	2	-7.03833	
10	2	5	1	2	3	-7.55162	
11	3	1	3	5	2	-5.7875	
12	3	2	4	1	3	-7.0289	
13	3	3	5	2	4	-6.80629	
14	3	4	1	3	5	-8.61069	
15	3	5	2	4	1	-8.03023	
16	4	1	4	2	5	-6.01709	
17	4	2	5	3	1	-5.621	
18	4	3	1	4	2	-7.21459	
19	4	4	2	5	3	-9.79718	
20	4	5	3	1	4	-8.13801	
21	5	1	5	4	3	-5.16088	
22	5	2	1	5	4	-7.15935	
23	5	3	2	1	5	-5.79177	
24	5	4	3	2	1	-6.5629	
25	5	5	4	3	2	-8.44126	

4. Conclusions

In the forgoing research, EDM on Inconel 718 has been carried out in order to determine an optimal setting of process control parameter towards achieving satisfactory machining performance in relation to Material Removal Rate (MRR), Electrode Wear Rate (EWR), Surface Roughness (R_a), Surface Crack Density (SCD), White Layer Thickness (WLT), and Micro Hardness (MH) of the EDMed end product. The following process parameters viz. gap voltage, peak discharge current, pulse-on time, duty factor and flushing pressure have been investigated to check its influence on overall machining performance. The work has proposed an integrated optimization route combining PCA, TOPSIS and Taguchi philosophy for solving correlating multi-response optimization for EDM on Inconel 718. The optimal setting, obtained thereof, has also been compared to that of obtained through optimization route 2 i.e. PCA and CQL based Taguchi approach. It has also been observed that peak current appeared as the most significant parameter; whilst flushing pressure has been found the least significant one.

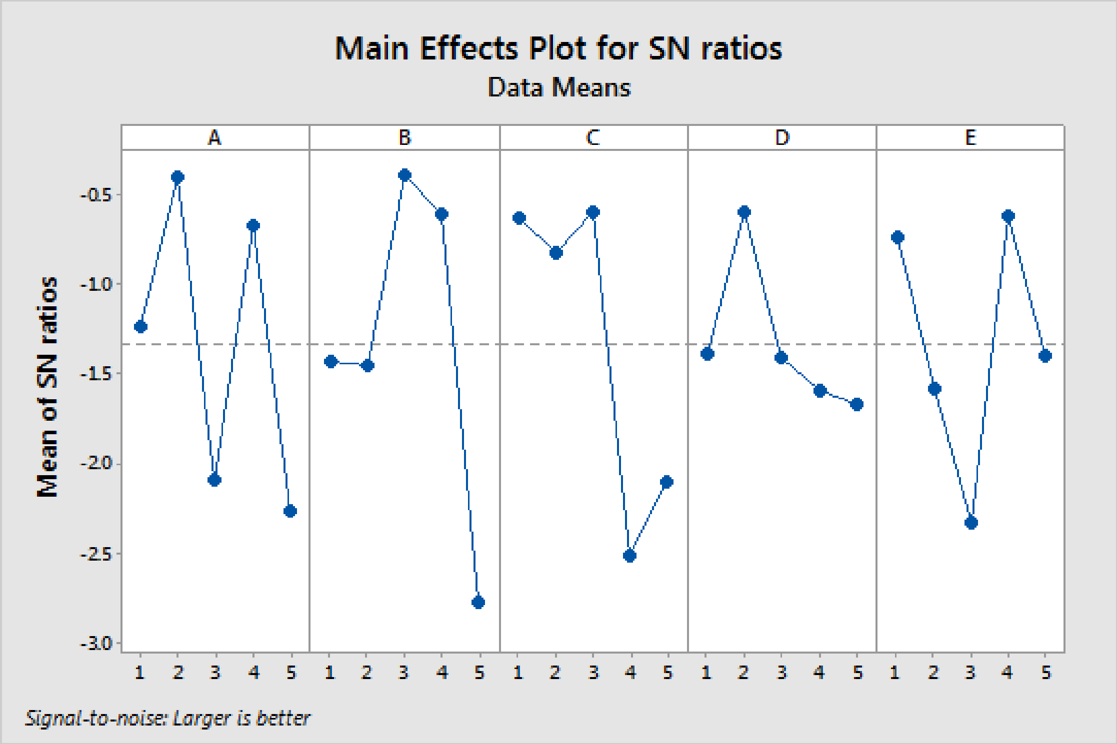

Fig. 4: S/N ratio plot: Evaluation of optimal setting (Route 1) [$A_2B_3C_3D_2E_4$]

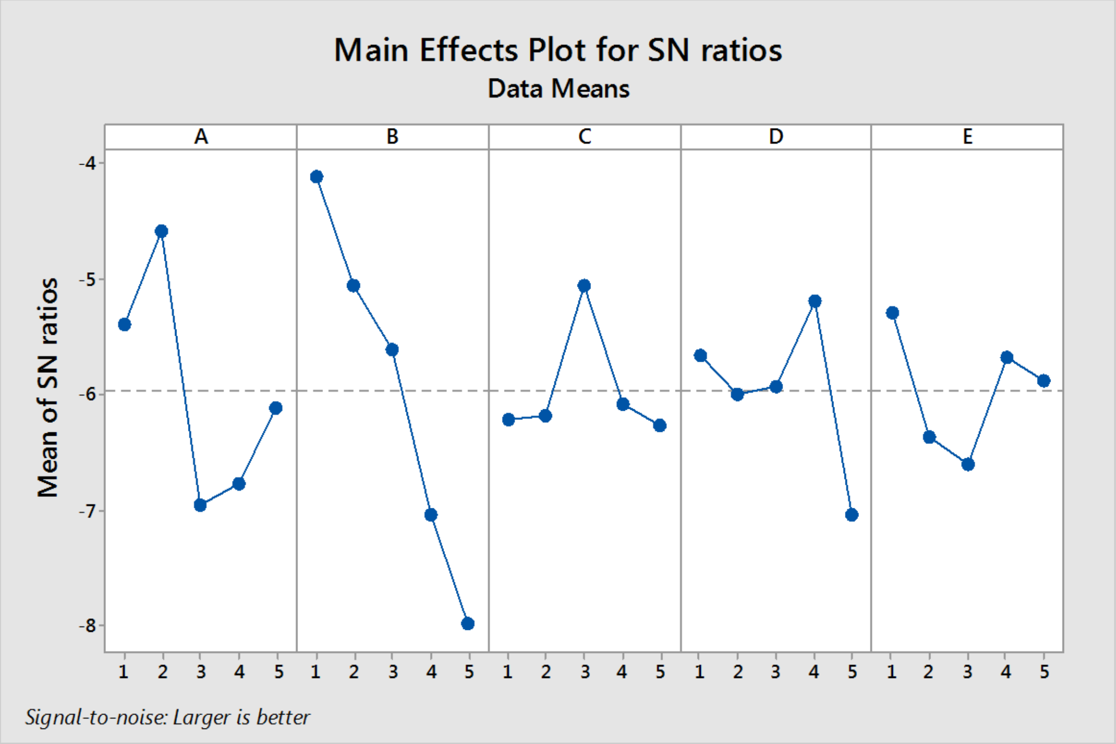

Fig. 5: S/N ratio plot: Evaluation of optimal setting (Route 2) [$A_2B_1C_3D_4E_1$]

References

[1] M. Ay, U. Çaydaş, A. Hasçalık, Optimization of micro-EDM drilling of Inconel 718 superalloy. The International Journal of Advanced Manufacturing Technology. 66(5-8) (2013) 1015-1023.

[2] P. Sengottuvel, S. Satishkumar, D. Dinakaran, Optimization of multiple characteristics of EDM parameters based on desirability approach and fuzzy modeling. Procedia Engineering. 64 (2013) 1069-1078.

[3] V. Aggarwal, S.S. Khangura, R.K. Garg, Parametric modeling and optimization for wire electrical discharge machining of Inconel 718 using response surface methodology. The International Journal of Advanced Manufacturing Technology. 79(1-4) (2015) 31-47.

[4] P. Kuppan, S. Narayanan, A. Rajadurai, M. Adithan, Effect of EDM parameters on hole quality characteristics in deep hole drilling of Inconel 718 superalloy. International Journal of Manufacturing Research. 10(1) (2015) 45-63.

[5] L. Li, Z.Y. Li, X.T. Wei, X. Cheng, Machining characteristics of Inconel 718 by sinking-EDM and wire-EDM. Materials and Manufacturing Processes. 30(8) (2015) 968-973.

[6] U.A. Dabade, S.S. Karidkar, Analysis of Response Variables in WEDM of Inconel 718 Using Taguchi Technique. Procedia CIRP. 41 (2016) 886-891.

[7] J.A. Ghani, I.A. Choudhury, H.H. Hassan, Application of Taguchi method in the optimization of end milling parameters. Journal of Materials Processing Technology. 145(1) (2004) 84-92.

[8] J.S. Pang, M.N.M. Ansari, O.S. Zaroog, M.H. Ali, S.M. Sapuan, Taguchi design optimization of machining parameters on the CNC end milling process of halloysite nanotube with aluminium reinforced epoxy matrix (HNT/Al/Ep) hybrid composite. HBRC Journal. 10(2) (2014) 138-144.

[9] B.C. Routara, S.D. Mohanty, S. Datta, A. Bandyopadhyay, S.S. Mahapatra, Combined quality loss (CQL) concept in WPCA-based Taguchi philosophy for optimization of multiple surface quality characteristics of UNS C34000 brass in cylindrical grinding. The International Journal of Advanced Manufacturing Technology. 51(1-4) (2010) 135-143.

[10] www.specialmetals.com

[11] L.I. Tong, C.H. Wang, H.C. Chen, Optimization of multiple responses using principal component analysis and technique for order preference by similarity to ideal solution. The International Journal of Advanced Manufacturing Technology. 27(3-4) (2005) 407-414.