Parametric optimization of wire-EDM machining of nimonic 80a using response surface methodology

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Wire electrical discharge machining (WEDM) can machine hard materials with ease. Nimonic 80A is hard and high temperature resistant material which is widely used in the power plant boiler tubes, gas turbines, exhaust valves. This work involves in developing a models for correlating the dependency of various WEDM process parameters of Nimonic 80A like gap voltage, duty factor and feed rate on response factors like rate of material removal (MRR), wire wear ratio and surface roughness (SR). This experiment was carried out on the basis of Response Surface Methodology (RSM) and Grey Relational Analysis (GRA). Using the design of experiments, 20 experiments were conducted. The duty factor of 0.8771, gap voltage 17V and wire feed rate of 17m/min was found to be the optimized process parameter while machining Nimonic 80A.

Keywords: Nimonic 80A, Wire EDM, RSM, MRR, Surface Roughness.

1. Introduction

Nimonic 80A, is a nickel-chromium superalloy with nickel more than 50% and chromium around 20%. It can be precipitate hardened by adding titanium, iron, cobalt and aluminium in small quantity as alloying element [1]. Nimonic possess good creep, fatigue, reduced surface oxidation and better corrosion resistance at high temperature (815°C). It also has better mechanical properties like higher tensile strength and hardness [2]. All these characteristics make Nimonic alloys an ideal material to be used in aerospace and automotive industries. Nimonic is used in manufacturing steam turbine components like turbine blades [3], jet engine’s exhaust nozzles for aerospace industries; exhaust valves for automotive industries; boiler tube supports, cores, inserts and bolts in nuclear power plants. Thus, Nimonic find its application where the parts or the component are subjected to high temperature and pressure [4]. Nimonic’s properties make the material very complicate for the processing purpose. It results in few drawbacks while performing conventional machining operation on nimonic
material as: (i) cutting nimonic alloy leads to burr formation and tool nose wear because of work hardening of the material [5]. (ii) Low thermal diffusivity of the material leads to the generation of high temperature at the tool tip. (iii) Resistance to continuous chip formation during the machining process, since nimonic has the ability to retain its properties at elevated temperature [6]. (iv) Chips have the tendency to stick to the cutting edge while machining at high temperature thereby it causes poor machined surface [7]. In order to find an alternative and a solution for these problems; Wire EDM, a non-conventional machining process is preferred to perform the cutting operation of the nimonic alloys. It can produce simple and complex shapes, can be CNC controlled, has high dimensional accuracy and minimal burr formation [8 & 9]. Even though a right machining operation is chosen, it is important to select the optimized parameter. Following are the literature survey done to investigate the outcome of the input parameter of wire EDM for nimonic and other materials.

Ashok Kumar et al. [10] observed the presence of Cu on the surface of Nimonic 75 alloy during the wire cut EDM process from the brass wire. They also observed the reduction in nickel and iron, as it was flushed with the dielectric fluid during the process. Renu K.shastri et al. [11] chose three electrodes namely copper, Tungsten and copper-tungsten electrode for machining Nimonic C263 alloy using wire EDM. Authors suggested the use of copper electrode in industries because of its high MRR and tungsten electrode for precise machining work, as it provides smooth surface finish. Maninder singh et al. [12] applied Teaching Learning Based Optimization (TLBO) algorithm for optimizing multiple objective for machining Nimonic 75 in EDM process. They found the optimized parameter for the copper and brass tool electrode. Subrahmanyam et al. [13] did optimization of parameters for MRR and surface roughness using Taguchi method and ANOVA. They concluded that pulse off time contributes more for MRR while pulse-ON-time contributes for SR. Sachin ashok sonawane et al. [14] used PCA based utility theory for transforming multi-objective response to single response for WEDM of Nimonic 75. Authors conducted L27 orthogonal array to find the optimized parameter. Sreenivasa Rao et al. [15] experimented the process parameter outcomes of WEDM-ed Nimonic 236. ANOVA was done to find the relevance of the parameters, also RSM and PSO algorithm were compared and concluded that PSO is better than RSM.

From the research works, it can be said that there isn’t much work carried out in Nimonic 80A using response surface methodology. Hence an attempt has been made in this work to achieve the optimized parameters by response surface methodology and grey relation analysis.

2. Materials and Methods

Nimonic 80A material with a thickness of 10mm was taken for the wire EDM process. The experiment was performed in Ezeecut wire EDM machine. A conductive electrode, molybdenum having 0.25mm dia was used a tool wire material and de-ionized water as dielectric fluid. Constant peak current of 4A was maintained throughout the process. Ezeecut wire-EDM machine was given in the Figure 1 and the machine specification was given in Table 1.
Figure 1. Ezeecut wire-EDM machine.  

Figure 2. Machined Work piece.

Duty factor, Wire feed rate and gap voltage were considered as input parameters with two levels. Input parameter and their level are represented in Table 2. Duty factor from 0.8108 to 0.9434, gap voltage from 15V to 20V and Wire feed rate from 65mm/min to 100mm/min was considered. The values for the levels were taken from the literature survey.

Table 1. Machine Specifications.

| Specifications               | Size                              |
|-----------------------------|----------------------------------|
| Worktable size:             | 680*500 mm                       |
| XY table traverse:          | 300x400 mm                       |
| Max Z height:               | 480mm                            |
| Max workpiece weight:       | 300kgs                           |
| Max taper cutting angle:    | 3” at 100 mm job height          |
| Maximum tool weight:        | 1400kg                           |
| Wire diameter:              | 0.12 to 0.25 mm                  |
| Best surface finish:        | 1-15 microns                     |
| Maximum cutting speed:      | 60 mm/min                        |

Central composite method of “Response surface method” has been selected for the experiments design in MINITAB 17 and it is given in Table 3.

Table 2. Input factor with their levels.

| Input factors     | Low       | High      |
|-------------------|-----------|-----------|
| Duty Factor       | 0.8108    | 0.94340   |
| Gap Voltage       | 15.0      | 20.0      |
| Wire Feed Rate    | 65.0      | 100.0     |

The experiment was conducted for 20 runs and the machining characteristics like surface roughness (SR), Material Removal Rate (MRR) and Wire Wear Rate (WWR) was measured. Surface roughness values of the processed work piece were measured using the Surfcom 1400g machine. The mechanical stylus of the Surfcom instrument was allowed to drag gently over the machined surface at a speed of 0.3mm/s for a distance of 4mm. The output, surface roughness value Ra is obtained from the digital display unit of the Surfcom instrument.
MRR was found by equation 1 and specimen weights were measured using the digital weighing machine.

\[
MRR = \frac{I - (A + x)}{T}
\]  
(1)

Where ‘I’ refers to initial weight of the workpiece in grams, ‘A’ refers to specimen weight post the machining process, ‘x’ refers to the weight of the cut specimen and ‘T’ refers the machining time in mins.

Wire wear rate was found by calculating the difference in weights of wire prior and post machining to the ratio the initial wire weight. All the response values are tabulated in Table 3.

| Ex.No | Duty Factor | Gap Voltage (v) | Wire Feed Rate (m/min) | MRR (g/min) | SR (Ra) | WWR (g) |
|-------|-------------|----------------|------------------------|-------------|---------|---------|
| 1.    | 0.916666    | 16             | 72                     | 0.0520938   | 3.4078  | 0.135135|
| 2.    | 0.943400    | 17             | 82                     | 0.0501800   | 4.4299  | 0.171300|
| 3.    | 0.877193    | 17             | 100                    | 0.0108200   | 4.4033  | 0.112186|
| 4.    | 0.916666    | 16             | 93                     | 0.0161278   | 4.1148  | 0.136898|
| 5.    | 0.837837    | 16             | 72                     | 0.0241013   | 3.0490  | 0.127649|
| 6.    | 0.837837    | 16             | 93                     | 0.0380114   | 3.8301  | 0.154142|
| 7.    | 0.877193    | 15             | 82                     | 0.0403139   | 3.7684  | 0.123014|
| 8.    | 0.837837    | 19             | 93                     | 0.0471560   | 5.0777  | 0.141493|
| 9.    | 0.916666    | 19             | 82                     | 0.0304467   | 4.0333  | 0.163471|
| 10.   | 0.877193    | 17             | 82                     | 0.0087045   | 4.4542  | 0.169894|
| 11.   | 0.877193    | 17             | 82                     | 0.0139529   | 4.3245  | 0.145479|
| 12.   | 0.877193    | 17             | 82                     | 0.0179812   | 4.4208  | 0.169572|
| 13.   | 0.916666    | 19             | 93                     | 0.0088131   | 3.9968  | 0.094578|
| 14.   | 0.877193    | 17             | 82                     | 0.0251214   | 4.0454  | 0.144232|
| 15.   | 0.877193    | 17             | 82                     | 0.0309462   | 4.5976  | 0.148821|
| 16.   | 0.877193    | 20             | 82                     | 0.0190711   | 4.3816  | 0.176200|
| 17.   | 0.877193    | 17             | 82                     | 0.0076690   | 4.4910  | 0.149598|
| 18.   | 0.810810    | 17             | 82                     | 0.0271270   | 3.4990  | 0.162991|
| 19.   | 0.877193    | 17             | 65                     | 0.0085374   | 2.7896  | 0.132405|
| 20.   | 0.837837    | 19             | 72                     | 0.0128415   | 3.9129  | 0.175879|

3. Results and Discussion

3.1 Contour plots for MRR

**Figure 3.** Contour plot MRR vs Gap voltage, duty factor.

**Figure 4.** Contour plot MRR vs feed rate, Gap voltage.

The above-mentioned contour plot (Figure 3) presents the outcomes of the interaction between voltage and duty factor on the MRR. We can see from the plot that as we increase
the duty factor value, MRR increases. As we increase the gap voltage there is decrease for first few values and then there is increase in the value of MRR. The contour plot is basically a 3-d surface plot converted into 2-d the surface which shows the blue patch has the minimum MRR that means the interaction points that of Gap voltage and duty factors that lie in the blue patch will provide minimum MRR.

Figure 4 indicates the feed rate and the Gap voltage’s effect on MRR. We can see from the plot that as we increase the feed rate value there is increase in the MRR. And as we increase the gap voltage there is decrease value of MRR.

Figure 5 presents the outcomes of the feed rate and duty factor on MRR. We can see from the plot that as we increase the feed rate value there is increase in the MRR. And as we increase the duty factor there is increased value of MRR.

3.2 Contour plots for WWR

Figure 6 indicates feed rate and the voltage’s effect on WWR. It can be observed from the plot that as we increase the feed rate value there is increase in the WWR. And as the increase the Gap voltage there is increased value of WWR.

Figure 7 presents the outcomes of the feed rate and duty factor on WWR. From the plot, it can be observed that as we increase the feed rate value there is increase in the WWR. And as the increase the duty factor, WWR value increase.
Figure 8. Contour plot of WWR vs Gap voltage, Duty factor.

Figure 8 presents the outcomes of the voltage and the Duty factor on the WWR. We can see from the plot that as we increase the gap voltage value there is increase in the WWR. And as we increase the duty factor there is increased value of WWR.

3.3 Contour plots for SR

Figure 9. Contour plot of surface roughness vs Gap voltage, Duty factor.

Figure 9 shows the effect of the interaction of the Gap voltage and the feed rate on SR. From the plot, it can be observed that as we increase the gap voltage value, SR increases. And as we increase feed rate there is increased value of surface roughness.

Figure 10. Contour plot of surface roughness vs feed rate, Duty factor.

Figure 10 shows the effect of the interaction of the duty factor and the feed rate on SR. It can be observed from the plot that as we increase the feed rate value there is increase in the surface roughness. And as we increase the duty factor there is increased value of surface roughness.

Figure 11. Contour plot of surface roughness vs gap voltage, Duty factor.
Figure 11 shows the effect of the interaction of the duty factor and the gap voltage on the surface roughness. We can see from the plot that as we increase the gap voltage value, SR increases. And as we increase duty factor there is increased value of surface roughness.

3.4 Result Optimizer:

Figure 12 shows the responses optimizer the tool which is used to optimize the parameters as per our requirement. Here we want the MRR to be maximum and surface roughness and WWR to be minimum; hence optimizer with such response requirement has been set. Figure 13 shows the optimized response for the given response now the Graph shows the individual outcomes of each input parameters, as well as it also shows the interaction of the all the three parameters which are suitable to find the optimum solution and to get the minimum WWR, surface roughness and maximum MRR at the same time.

3.5 Grey Relation based multi response optimization

In wire-EDM process, the main aim is to have less surface Roughness, WWR and high MRR. So, ‘Larger the better’ for MRR and ‘smaller the better’ for SR and WWR is applied. Following are the steps used to find the optimal parameter.

Step 1: Determination of S/N ratio. 
For Larger the better, it can be found using Eq. 2
\[ X_{ij} = (Y_{ij} - \min (Y_{ij})) / (\max (Y_{ij}) - \min (Y_{ij})) \]  
(2)
For smaller the better, it can be found using Eq. 3
\[ X_{ij} = (\max (Y_{ij}) - Y_{ij}) / (\max (Y_{ij}) - \min (Y_{ij})) \]  
(3)
Where \( X_{ij} \) and \( Y_{ij} \) are the normalized and evaluated S/N ratio; \( \min (Y_{ij}) \) and \( \max (Y_{ij}) \) are minimum and maximum S/N ratio values respectively.

Step 2: Determination of grey relation grade. 
Grey relational coefficient is obtained from Eq. 4
\[ GC_{ij} = (\Delta_{\min} + \Psi \Delta_{\max}) / (\Delta_{ij} + \Psi \Delta_{\max}) \]  
(4)
Where ‘GCij’ is the grey relational grade. \( \Psi \) is 0.5 has been assumed. \( \Delta_{\text{min}} \) and \( \Delta_{\text{max}} \) are the minimum and maximum absolute difference and can be considered as quality loss.

**Step 3:** Determination of grey relation Coefficient.

On averaging GRC, grey relational grade is obtained from Eq. 5

\[
G_i = \left( \frac{1}{m} \right) \sum G_{Cij}
\]  

(5)

Where ‘m’ refers to response variables. Optimal response can be obtained for high grey grades in the process, as it has strong relation between the present and ideal sequence. Table 4 shows the average grey relational analysis coefficients and ranks for MRR, SR and WWR.

| Trial no | GCI MRR  | GCI SR  | GCI WWR  | Grade     | Rank |
|----------|----------|---------|----------|-----------|------|
| 1        | 0.333333333 | 0.599381194 | 0.539683582 | 0.490799369 | 16   |
| 2        | 0.337692097 | 0.393039701 | 0.916878246 | 0.549203348 | 11   |
| 3        | 0.727795826 | 0.396171156 | 0.407967325 | 0.510644769 | 14   |
| 4        | 0.559610079 | 0.435181971 | 0.552096469 | 0.515629506 | 13   |
| 5        | 0.454015188 | 0.771069847 | 0.491127247 | 0.572070761 | 8    |
| 6        | 0.373979256 | 0.485796127 | 0.699341454 | 0.519705612 | 12   |
| 7        | 0.365659041 | 0.498940245 | 0.464037241 | 0.421660518 | 20   |
| 8        | 0.34518787  | 0.333333333 | 0.586460351 | 0.515629506 | 13   |
| 9        | 0.409104611 | 0.44821159  | 0.805787298 | 0.554367833 | 9    |
| 10       | 0.870368258 | 0.390237999 | 0.895137303 | 0.718581187 | 2    |
| 11       | 0.357005842 | 0.405866457 | 0.618875144 | 0.460582481 | 18   |
| 12       | 0.526453731 | 0.394103287 | 0.890273665 | 0.603610228 | 6    |
| 13       | 0.860761924 | 0.454393925 | 0.333333333 | 0.549496394 | 10   |
| 14       | 0.445343291 | 0.446211131 | 0.608453832 | 0.500002751 | 15   |
| 15       | 0.406306062 | 0.374764088 | 0.648159464 | 0.476409872 | 17   |
| 16       | 0.510103667 | 0.398777305 | 1           | 0.636293657 | 5    |
| 17       | 0.982414136 | 0.386098488 | 0.655265617 | 0.674592744 | 4    |
| 18       | 0.430121602 | 0.569289836 | 0.799694252 | 0.599701897 | 7    |
| 19       | 1           | 1         | 0.521232426 | 0.840410809 | 1    |
| 20       | 0.644653987 | 0.469507073 | 0.994165053 | 0.702775371 | 3    |

The final result obtained after the optimization is that trial no.19 is the optimum one which fulfills all the 3 conditions that is minimum WWR and surface roughness as well as maximum MRR. The optimum Reading is gap voltage 17V, Feed rate 65 m/min, Duty Factor-0.877193.

**4. Confirmation Test**

After analysing the experimental values by grey-relational multi response analysis we have found an optimum value which is suitable for controlling all the 3 responses that are MRR, WWR and SR. Trial no. 19 is the optimum reading. We are going to conduct a confirmation
experiment based on the parameters of trial 19 and find out the error existing in the reading. The final confirmation experiment was conducted and is tabulated in Table 5.

Table 5. Confirmation experiment.

| Response | Optimize value of input parameters | Previous Experiment values | Current experiment values | % Error |
|----------|-----------------------------------|---------------------------|--------------------------|---------|
| MRR (g/min) | Duty factor | 0.877193 | 65 | 17 | 0.0075374 | 0.0078363 | 3.96 |
| SR (μm) | Feed Rate (m/min) | 0.877193 | 65 | 17 | 2.7896 | 2.8497 | 2.15 |
| WWR | Gap Voltage (V) | 0.877193 | 65 | 17 | 0.132405 | 0.130368 | 1.53 |

The confirmation test suggests that the values are having very minor errors in the confirmation test. So, it can be conclude that the parameters of trial 19 are the best parameters for machining Nimonic 80A.

5. Conclusion

The 20 experiments were conducted using response surface method with using Nimonic 80A material and using molybdenum wire of (0.25mm) as tool. There are many conclusions made from the above study.

1. The duty factor has the dominating effect on MRR, surface roughness and wire wear rate. As there is increase in the value of duty factor MRR, WWR and SR value increases. The reason behind such result is that duty factor is the prime input parameter as it controls the pulse-ON-time as well as pulse-OFF-time. Hence, it can be related that raise in duty factor will increase the exposure of spark field to the work piece and the tool wire.

2. The effect of feed rate has also been predominant in the study. Feed rate is seen to be directly related to MRR, SR and WWR. As the feed rate increase, all the 3 factors increases. The reason behind such result is the nature of the input parameter. The feed rate is the rate of supplying the tool wire to the machining site, the more the feed rate more will be the MRR and rougher the surface will get.

3. The effect of gap voltage is also significant. The gap voltage shows the reverse effect on MRR but shows increasing values against the surface roughness. This is because the gap voltage is the value which shows the gap voltage intensity generated. The more will be the value of gap voltage more will be surface roughness. The wire wear also increases with increase in the gap voltage.

References

[1] Petronić, S., Čolić, K., Dordević, B., Mišković, Ž., Katnić, Đ., & Vučetić, F. (2018). Comparative Exemination of the Strengthened and Non-Strengthened NIMONIC Specimens with Laser Shot Peening Method. Procedia Structural Integrity, 13, 2255–2260.
[2] Sunulahpasic, R., Hadzalic, M., Oruc, M., & Begovic, E. (2015). Contribution to investigation of the influence of chemical composition on machinability of superalloy Nimonic 80A. Procedia engineering, 132, 480-485.

[3] Sykora, R., & Zetek, M. (2015). Increasing cutting tool efficiency when machining regulatory spindles made from ion nitrided nimonic 901 for steam turbine valves. Procedia Engineering, 100, 1424-1433.

[4] Genna, S., Leone, C., Palumbo, B., & Tagliaferri, F. (2015). Statistical approach to fiber laser microcutting of NIMONIC® C263 superalloy sheet used in effusion cooling system of aero engines. Procedia Cirp, 33, 520-525.

[5] Goswami, A., & Kumar, J. (2017). Trim cut machining and surface integrity analysis of Nimonic 80A alloy using wire cut EDM. Engineering Science and Technology, an International Journal, 20(1), 175-186.

[6] Goswami, A., & Kumar, J. (2014). Optimization in wire-cut EDM of Nimonic-80A using Taguchi’s approach and utility concept. Engineering Science and Technology, an International Journal, 17(4), 236-246.

[7] Sonawane, S. A., & Kulkarni, M. L. (2018). Optimization of machining parameters of WEDM for Nimonic-75 alloy using principal component analysis integrated with Taguchi method. Journal of King Saud University-Engineering Sciences, 30(3), 250-258.

[8] Abbas, N. M., Solomon, D. G., & Bahari, M. F. (2007). A review on current research trends in electrical discharge machining (EDM). International Journal of machine tools and Manufacture, 47(7-8), 1214-1228.

[9] Pant, P., & Bharti, P. S. (2020). Electrical Discharge Machining (EDM) of nickel-based nimonic alloys: A review. Materials Today: Proceedings, 25, 765-772.

[10] Kumar, U. A., Saidulu, G., & Laxminaryana, P. (2020). Experimental investigation of process parameters for machining of Nimonic alloy 75 using wire-cut EDM. Materials Today: Proceedings.

[11] Shastrri, R. K., & Mohanty, C. P. (2020). Machinability investigation on Nimonic C263 alloy in electric discharge machine. Materials Today: Proceedings.

[12] Singh, M., & Singh, S. (2020). Multi-objective Optimization of Electrical Discharge Machining of Nimonic 75 using Teaching Learning Based Optimization (TLBO) Algorithm. Materials Today: Proceedings, 24, 576-584.

[13] Subramanyam, M. & Nancharaiah, Tata. (2019). Optimization of process parameters in wire-cut EDM of Inconel 625 using Taguchi’s approach. Materials Today: Proceedings. 23. 10.1016/j.matpr.2019.05.449.

[14] Sonawane, S. A., & Kulkarni, M. L. (2018). Multi-quality Response Optimization of Wire EDM for Ni-75 using PCA based Utility theory. Materials Today: Proceedings, 5(2), 4584-4591.

[15] Sreenivasa Rao, M., & Venkaiah, N. (2015). Parametric optimization in machining of Nimonic-263 alloy using RSM and particle swarm optimization. In 2nd International Conference on Nanomaterials and Technologies (CNT 2014), Procedia Materials Science (Vol. 10, pp. 70-79).