Empirical modeling of cutting speed during WEDM of nimonic 263

B Singh and J P Misra
National Institute of Technology Kurukshetra-136119, Haryana, India
er.bsch@gmail.com

Abstract. Cutting speed (CS) is a main process performance measure parameter of WEDM process. CS is mainly affected by input process parameters of WEDM and hence production and machining efficacy. Therefore, it is essential to pick the optimal combination of input parameters to get better CS. In this study, four parameters; Spark on (S_{on}), Spark off (S_{off}), servo voltage (S_v), and peak-current (I_p) were selected for developing an empirical model of CS during WEDM of nimonic 263. Total 81 samples were machined on different WEDM parametric conditions based on three level full-factorial design of experiment with one replication of each run. This paper describes user-defined RSM based mathematical modeling for predicting optimal parametric setting for cutting speed. Furthermore, analysis of variance (ANOVA) was applied to find significant parameters and it was depicted that S_{on} and I_p were the key parameters affecting average CS.

1. Introduction
WEDM is one of the widely accepted advance machining processes used to cut tricky profile from hard-to-machine materials, which are hard-to-machine by other conventional and non-conventional machining techniques [1] and hence, this process has extensive applications in air craft industry, biomedical implants, electronics industry, automotive industries, etc. It is an electric thermal type advance machining technique in which removal of material is occur by melting and evaporation owing to a successive series-of-sparks between work surface and tool wire (φ=0.05-0.3 mm). A pulsating DC power is supplied to the electrodes (wire-tool and workpiece). When wire to workpiece voltage reaches the dielectric strength of the dielectric fluid, then dielectric fluid breakdowns and gets ionized, at this stage deionized liquid changes to conductor from insulator and made an ionized column between tool and workpiece. The electrons travel easily through this ionized column of dielectric liquid, and makes the crater on the workpiece surface by a bombard. This generated Plasma of heat vaporizes removed workpiece material, which is flushed away by continuously following deionized water. During each spark, millions of electrons flows b/w tool-wire and workpiece at the approximate speed of light. The dielectric fluid is deionized and the vapor cloud is cooled, and, thus, an EDM chip is formed and flushed out by dielectric pressure [1-4]. Nickel-base superalloys have many industrial applications i.e. gas-turbine and aerospace-industry. So, nimonic-263 is selected as work-material for present study. The developed empirical model will give guidelines to the possible users of WEDM [7]. In addition, this study concluded the optimal values of parameters for WEDM of nickel-based superalloys.

2. Experimental Procedure
This experimental study was conducted on WEDM electronica sprintcut-734. The detailed mechanism of WEDM is available in references [1, 2]. From the literature survey, it was observed that less research
work has been reported on nimonic 263 and therefore nimonic 263 has been selected for the present study [5, 8, 9]. Nimonic alloy 263 is a nickel-chromium-cobalt-molybdenum alloy, it is commonly used in aerospace, marine, hot section components of gas turbine and spacecraft and able to withstand high operating temperature, approximately between 540° C and 1000° C without damaging strength. Brass wire-tool of φ=0.25 mm is used as wire-tool. Figure 1 shows the schematic of WEDM technique.

![Figure 1. Schematic diagram of WEDM technique.](image)

This experimental study consists of four factors: \( S_{on} \), \( S_{off} \), Ip, Sv and each parameter is having three levels. In order to conduct the user defined-RSM technique, it is required to represent all the process parameters into same range (-1-1), such that the maximum level of a parameter is defined as 1 and the minimum level is defined as -1. The ranges of influencing parameters for main-experimentation were considered as per out-come of pilot-experiments [8]. Table 1 presents the ranges and values for fixed and input parameters. According to three level full-factorial design, 81 experiments were performed under different process parametric conditions with one replication for each experimental run [7]. Table 2 shows the combination, order, design of experiments and experimental results for CS [10].

**Table 1. Input and fixed process parameters range and values.**

| Factors | Levels & Ranges | Parameter | Fixed Value | Fixing criteria |
|---------|-----------------|-----------|-------------|-----------------|
| \( S_{on} \) (μs) | L₁ 105 L₂ 118 L₃ 131 | Dielectric fluid | De-ionized | Literature review |
| \( S_{off} \) (μs) | 30 45 60 | Peak Voltage | 2 v | and Pilot experiments |
| Ip (A) | 40 130 220 | Water Pressure | 1 μm | |
| | | Wire Feed | 8 mm/min | |
| | | Wire Tension | 12 μm | |
| | | Servo Feed | 2200 μm | |
| Sv (V) | 20 50 80 | Workpiece | Nimonic 263 | Industrial application |

**3. Result and Discussions**

Table 2 presents the design, parametric combination and corresponding experimental results for average cutting speed. It is obvious from table 2 that max. cutting speed (4.27 mm/minute) was found from experiment no. 80 (\( S_{on} \): 131 μs; \( S_{off} \): 60 μs; Ip: 220 A; Sv: 50 V), while experiment no. 73 (\( S_{on} \): 105 μs; \( S_{off} \): 60 μs; Ip: 40 A; Sv: 80 V) delivers the lowermost cutting speed (0.30 mm/minute) and % of change is 92.97. It was also obvious that, seventeen experiments were not performed due to continuous wire-breakages [11-13]. Table 3 presents ANOVA for cutting speed. Model f-value 23.57 indicates that the model is highly significant. In this case \( S_{on} \), \( S_{off} \), Ip, \( S_{on} \times S_{off} \), \( S_{on} \times Ip \), \( S_{off} \times Sv \), \( S_{on}^2 \), \( S_{off}^2 \) and \( Sv^2 \) are significant model terms [14-16].


Table 2. Experimental design, parametric combination and corresponding results.

| Ex. No. | $S_{on}$ (μs) | $S_{off}$ (μs) | Ip (A) | Sv (V) | Output parameter | CS (mm/min) |
|---------|----------------|----------------|--------|--------|-----------------|-------------|
| 1       | 105            | 60             | 40     | 20     |                 | 0.33        |
| 2       | 131            | 30             | 40     | 80     |                 | 1.51        |
| 3       | 118            | 60             | 220    | 50     |                 | 2.12        |
| 4       | 118            | 45             | 220    | 20     |                 | 2.44        |
| 5       | 131            | 45             | 220    | 80     | WIRE-BREAKAGE   |             |
| 6       | 118            | 60             | 40     | 80     |                 | 0.64        |
| 7       | 118            | 45             | 40     | 80     |                 | 0.99        |
| 8       | 105            | 45             | 220    | 50     |                 | 0.99        |
| 9       | 105            | 30             | 40     | 80     |                 | 0.75        |
| 10      | 131            | 30             | 130    | 80     | WIRE-BREAKAGE   |             |
| 11      | 105            | 60             | 130    | 50     |                 | 0.49        |
| 12      | 118            | 60             | 130    | 80     |                 | 1.04        |
| 13      | 131            | 60             | 220    | 80     |                 | 3.05        |
| 14      | 118            | 30             | 220    | 20     | WIRE-BREAKAGE   |             |
| 15      | 131            | 60             | 130    | 20     | WIRE-BREAKAGE   |             |
| 16      | 118            | 30             | 130    | 80     |                 | 3.03        |
| 17      | 105            | 45             | 130    | 20     |                 | 0.91        |
| 18      | 118            | 30             | 130    | 50     |                 | 2.08        |
| 19      | 105            | 45             | 40     | 80     |                 | 0.52        |
| 20      | 131            | 60             | 40     | 50     |                 | 0.74        |
| 21      | 118            | 30             | 40     | 20     |                 | 1.05        |
| 22      | 105            | 45             | 40     | 50     |                 | 0.55        |
| 23      | 105            | 60             | 130    | 20     |                 | 0.54        |
| 24      | 105            | 45             | 130    | 50     |                 | 0.84        |
| 25      | 131            | 30             | 220    | 80     | WIRE-BREAKAGE   |             |
| 26      | 131            | 45             | 40     | 20     |                 | 1.94        |
| 27      | 105            | 45             | 220    | 20     |                 | 1.09        |
| 28      | 118            | 60             | 40     | 50     |                 | 0.68        |
| 29      | 105            | 60             | 220    | 20     |                 | 0.64        |
| 30      | 118            | 30             | 40     | 50     |                 | 1.92        |
| 31      | 105            | 30             | 130    | 20     |                 | 0.63        |
| 32      | 118            | 45             | 130    | 50     |                 | 3.66        |
| 33      | 105            | 45             | 130    | 80     |                 | 0.74        |
| 34      | 105            | 30             | 220    | 80     |                 | 1.08        |
| 35      | 131            | 30             | 220    | 50     | WIRE-BREAKAGE   |             |
| 36      | 131            | 30             | 130    | 20     | WIRE-BREAKAGE   |             |
| 37      | 105            | 30             | 40     | 50     |                 | 0.66        |
| 38      | 131            | 30             | 40     | 20     |                 | 1.03        |
| 39      | 131            | 45             | 130    | 50     | WIRE-BREAKAGE   |             |
| 40      | 131            | 60             | 130    | 80     |                 | 1.51        |
| 41      | 105            | 60             | 40     | 50     |                 | 0.32        |
| 42      | 118            | 45             | 220    | 80     |                 | 2.69        |
| 43      | 131            | 45             | 40     | 80     |                 | 1.04        |
| 44      | 131            | 45             | 130    | 20     | WIRE-BREAKAGE   |             |
| 45      | 131            | 45             | 220    | 50     | WIRE-BREAKAGE   |             |
| 46      | 131            | 45             | 220    | 20     | WIRE-BREAKAGE   |             |
| 47      | 105            | 45             | 40     | 20     |                 | 0.64        |
Table 3. Analysis of variance results.

| Source | SS   | DF | MS   | F-Value | P > F | % Contribution |
|--------|------|----|------|---------|-------|-----------------|
| Model  | 52.27| 14 | 3.73 | 23.57   | < 0.0001 |                 |
| A-Son  | 25.37| 1  | 25.37| 160.2   | < 0.0001 | 42.26 %         |
| B-Soff | 5.58 | 1  | 5.58 | 35.26   | < 0.0001 | 9.29 %          |
| C-Ip   | 18.84| 1  | 18.84| 118.9   | < 0.0001 | 31.38 %         |
| AB     | 0.84 | 1  | 0.84 | 5.33    | 0.0253  | 1.39 %          |
| AC     | 8.11 | 1  | 8.11 | 51.18   | < 0.0001 | 13.50 %         |
| BD     | 1.29 | 1  | 1.29 | 8.12    | 0.0064  | 2.14 %          |
| A²     | 0.64 | 1  | 0.64 | 4.06    | 0.0495  |                 |
| B²     | 1.23 | 1  | 1.23 | 7.78    | 0.0075  |                 |
| C²     | 0.25 | 1  | 0.25 | 1.55    | 0.2186  |                 |
| D²     | 1.72 | 1  | 1.72 | 10.85   | 0.0018  |                 |
| Residual | 7.76 | 49 | 0.16 |         |        |                 |
| Cor Total | 60.03 | 63 |      |         |        |                 |
Figure 2 shows the effects of $S_{on}$, $S_{off}$, Ip and Sv on cutting speed. It is obvious that $S_{on}$ is highly significant parameter. It is evident from the figure 2 that highest cutting speed was obtained at highest $S_{on}$ and Ip. While, $S_{off}$ and Sv are having some contrary effects on cutting speed. A smaller value of Sv lesser down the gap between tool-wire and workpiece surface, which results in a greater number of sparks per unit time. Therefore, it increases the material removal rate [7]. It is obvious from ANOVA results that the process parameters also having some interactions on process performance characteristic as shown in figure 3: (a) $S_{off}-S_{on}$ vs CS; (b) Ip-$S_{on}$ vs CS; (c) Sv-$S_{off}$ vs CS. Equation 1 illustrates the regression model for CS. The coefficient-of-determination ($R^2$) is 0.8707. The pred. $R^2$ 0.7812 is in sensible pact with the adj. $R^2$ of 0.8338. Adequate precision ratio of 20.33 indicates an adequate signal (greater than 4 is required). Finally, optimization was done to find out the optimal parameter combinations to conduct confirmation experiments. Table 4 presents the optimal parametric combinations and corresponding results of confirmation experiments [7]. Optimal solution: $S_{on}$: 127 μs, $S_{off}$: 42 μs, Ip: 215 A and Sv: 30 V gives the maximum cutting speed: 4.74 mm/min.

Figure 2. Effects of Son, Toff, Sv and Ip on cutting speed [X-axis in coded value].

Figure 3. 3D graphs (a) Soff-Son vs CS; (b) Ip-Son vs CS; and (c) Sv-Soff vs CS.
Table 4. Confirmation experiments results.

| Optimized process parameters | Cutting speed | % of Error |
|-----------------------------|---------------|------------|
| Son 45                      | Ip 214        | Sv 50      | Pred. 4.54 | Experimental 4.48 | 1.32 |
| Son 42                      | Ip 215        | Sv 30      | Pred. 4.74 | Experimental 4.65 | 1.89 |

\[
CS = -30.18993 + 0.39180 \times Son + 0.25805 \times Soff - 0.052805 \times Ip + 0.091140 \times Sv \\
- 1.11102 \times 10^{-3} \times Son \times Soff + 6.09720 \times 10^{-4} \times Son \times Ip \\
- 2.72308 \times 10^{-4} \times Son \times Sv - 9.42502 \times 10^{-5} \times Soff \times Ip \\
- 4.91362 \times 10^{-4} \times Soff \times Sv - 9.18032 \times 10^{-6} \times Ip \times Sv \\
- 1.35466 \times 10^{-3} \times Son^2 - 1.34767 \times 10^{-3} \times Soff^2 - 1.71981 \times 10^{-5} \times Ip^2 \\
- 3.87215 \times 10^{-4} \times Sv^2
\]

3.1. Microstructure analysis

Figure 4 illustrates the microstructure appearances of the WEDM machined surfaces, captured by SEM (Make: JOEL) with an accelerating voltage of 20.0 keV. Three samples were selected for SEM study (at minimum, medium and maximum CS). It was evident from this microstructure study; molten metal is deposited on WEDM machined surfaces. This could be due to melting and re-solidification of wire and workpiece material on the machined surface. Figure 4 (a) illustrates the machined surface corresponding to low cutting speed, where the parameters: Son (105 μm) and Ip (40 A) were set at their lowest values and Soff (60 μm) and Sv (80 V) were set at their highest values. This microstructure seems to be plane, due to less heat. Figure 4 (b) shows the surface at medium cutting speed, some wide and deep cracks depicted on this microstructure. Figure 4 (c) illustrates the surface at high discharge energy, which provides a high CS (4.27 mm/min) as well as wider and deeper cracks on the work surface due to high Son (131 μm) and Ip (220 A). In this parametric combination, high Son value, increases the spark duration for a long period and high Ip value increases thermal energy distribution in machining zone and thus, results in maximum CS.

Figure 4. Microstructure of the WEDMed surfaces at (1000X & 3000X): (a) for experiment no. 73 at LDE: Ton= 105 μs; Toff= 60 μs; Ip= 40 A; and Sv= 80 V; (b) for experiment no. 66 MDE: Ton= 118
μs; Toff= 60 μs; Ip= 130 A; and Sv= 20 V; and (c) for experiment no. 80 at HDE: Ton= 131 μs; Toff= 60 μs; Ip= 220 A; and Sv= 50 V.

3.2. **EDS analysis of WEDMed surfaces**

EDS analysis of WEDMed surface reveals that residuals of wire tool material: copper and zinc are get deposited on the WEDMed surface. This may be due to the high melting, evaporation, and re-solidification of the brass wire-tool and work surface. The EDS analysis reveals the elements from both the wire electrode and the dielectric fluid diffused into the machined surface, which results in high-temperature oxidation of the WEDMed surfaces. Therefore, it reduces the proportion of important alloying elements of the nimonic 263 and affects the properties of the WEDMed parts. Figure 8 illustrates the composition and plots of identified phases at LDE, MDE, and HDE. The EDS analysis reveals that the lowest percentage of migrated elements from the wire tool to the workpiece surface is at low discharge energy as shown in figure 5. This may be due to the low melting, evaporation, and re-solidification of the brass wire tool and work surface.

![EDS analysis of WEDMed surfaces](image)

**Figure 5.** EDS analysis of WEDMed surfaces at: (a) minimum CS (b) Medium CS and (c) Max. CS.

4. **Conclusion and future scope**

In present research work optimization and modeling of WEDM process has been done by using user-defined RSM. 81 experiments had been conducted to develop empirical model of WEDM process for nimonic 263. Then the obtained optimal solutions were compared with the confirmation test results. Following decision has been made from the analysis of the experimental and optimized outcomes:

- It was observed that Son is highly significant parameter, followed by peak current. Furthermore, a very higher values of Son and Ip also results in wire break. In addition, if servo voltage is too low, an amount
of thermal energy is absorbed by tool-wire and removed material cannot be flushed properly by the dielectric, it results in the abnormal arcing and wire-break occur.

• Microstructure study revealed that WEDM machined surface at low cutting speed seems to be smooth as fewer micro-voids, cracks and craters were present on the machined surface due to low discharge energy (LDE) during WEDM process.

• The EDS study revealed the highest percentage of migrated elements from wire-tool are: Cu= 19.02% and Zn= 6.33%.

• The developed CS model is found appropriate as it displayed the minimum prediction error (~1%) and hence, can be utilize by potential operators for future application of the WEDM process. Optimal setting for the maximized cutting speed is: Son: 127 μs, Soff: 42 μs, Ip: 215 A and Sv: 30 V.

• Future study could consider the tribological and microstructure study of WEDM machined miniature parts: gear, spline etc. for obtaining better insight of the process.

References
[1] Jamson E C 2001 Electrical Discharge Machining Michigan: E-Publishing Inc.
[2] Jain V K 2002 Advanced Machining Processes Third ed. New Delhi.
[3] Ho K H Newman S T Rahimifard S and Allen R D 2004 State of the art in wire electrical discharge machining (WEDM) Int. J. Mach. Tools Manuf. 44, 247-1259.
[4] Singh B and Misra J P 2016 A critical review of wire electric discharge machining DAAAM International Scientific Book, 249-266.
[5] Tosun N Cogun C and Tosun G 2004 A study on kerf and material removal rate in wire electrical discharge machining based on Taguchi method J. Mater. Process. Technol. 152, 316-322.
[6] Singh B and Misra J P 2018 Empirical Modeling of Average Cutting Speed during WEDM of Gas Turbine Alloy ICDME MATEC Web of Conferences, 221, 01002.
[7] Singh T Misra J P and Singh B 2016 Experimental investigation of influence of process parameters on MRR during WEDM of Al6063 alloy 5th Int. Conf. Mat. Proc. Charac. Mat. Today: Proceed. Hyderabad, India, 4, 2242–2247.
[8] Shandilya P Jain P K and Jain N K 2013 RSM and ANN Modeling Approaches For Predicting Average Cutting Speed during WEDM of SiCp/6061 Al MMC Procedia Engineering 64, 767-774.
[9] Singh T Misra J P Upadhyay V and Rao P S 2018 An adaptive neuro-fuzzy inference system for Wire-EDM of ballistic grade aluminium alloy Int. J. Auto. Mech. Engg. 15, 5295-5307.
[10] Myers R H Montgomery D C and Anderson-cook C M 2009 Response Surface Methodology Wiley.
[11] Singh B and Misra J P 2018 Empirical Modelling of Wear Ratio during WEDM of Nimonic 263 IConAMMA Mat. Today: Proceed. 5, 23612-23618.
[12] Okada A, Konishi T, Okamoto Y, and Kurihara H, 2015 Wire-breakage and deflection caused by nozzle jet flushing in wire EDM CIRP Ann. - Manuf. Technol. 64.
[13] Singh B and Misra J P 2018 Empirical modeling of average cutting speed during WEDM of hastelloy C22 ICMMM MATEC Web of Conferences 249, 02003.
[14] Singh B and Misra J P 2019 Surface finish analysis of wire electric discharge machined specimens by RSM and ANN modeling Measurement, 137, 225-237.
[15] Singh B and Misra J P 2019 Modelling of surface characteristics of wire-electro discharge machined combustor material specimens Material Research Express, 6(5), 056549.
[16] Misra J P, Prateek, Singh B and Singh T 2018 Manufacturing of Miniature Gear of AA6082 by WEDM Process, 1st International Conference on New Frontiers in Engineering, Science & Technology, New Delhi, India, January 8-12.