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ScienceDirect
Procedia CIRP 41 (2016) 886 – 891
www.elsevier.com/locate/procedia

48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015

# Analysis of response variables in WEDM of Inconel 718 using Taguchi technique

U. A. Dabade[a,]*, S. S. Karidkar[b]

[a]Professor, Department of Mechanical Engineering, Walchand College of Engineering, Sangli, Maharashtra, India-416 415
[b]Research scholar, Department of Mechanical Engineering, Walchand College of Engineering, Sangli, Maharashtra, India-416 415

* Corresponding author. +91-9423400516; fax: +91-233-2300831 E-mail address: uday.dabade@walchandsangli.ac.in

**Abstract**

Wire Electrical Discharge Machining (WEDM) is used extensively in the machining of conductive materials where it is essential to generate intricate and complex shapes with higher dimensional accuracy and surface finish. The applications are in the field of aerospace, automobile, mould making and medical industries. Over the years, WEDM has remained as a competitive and economical machining option fulfilling the machining requirements imposed by the short product development cycles and the growing cost pressures. Taking into consideration the development of mechanical industry, demands for alloy materials having high hardness, toughness and impact resistance are increasing. Machine tool industry has also made exponential growth in its manufacturing capabilities in last two decade but still machine tools are not utilized at their full potential. This limitation is a result of the failure to run the machine tools at their optimum operating conditions. The problem of arriving at the exact analysis of the operating parameters has attracted the attention of the researchers and practicing engineers for a very long time. In the present work, an attempt has been made to analyse the machining conditions for Material Removal Rate (MRR), Surface Roughness (SR), cutting width (kerf) and dimensional deviation during WEDM of Inconel 718 using DoE such as Taguchi methodology, $L_8$ Orthogonal Array. The experimental analysis is carried out using Minitab 16 software and it was observed that pulse-on-time is the most influential factor for all the response variables such as MRR, SR, Kerf and dimensional deviation at 95 % confidence level, with contributions of 54.32 %, 58.42 %, 83.21 % and 36.11 % respectively. Along with this, peak current was observed to be next significant parameter for kerf and dimensional deviation whereas for MRR and SR servo voltage was observed to be the next significant parameter.


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*Keywords:* Wire electrical discharge machining (WEDM); Surface roughness (SR); Cutting width (kerf); Dimensional deviation; Taguchi method

## 1. Introduction

Wire Electrical Discharge Machining (WEDM) has become an important non-traditional machining process. It is widely used in the aerospace, nuclear, automotive and medical industries [1]. Recently, WEDM process is also being used to machine a wide variety of miniature and micro-parts in metals, alloys, sintered materials, cemented carbides, ceramics and silicon [2-4]. WEDM is a special form of traditional EDM process in which the electrode is a continuously moving electrically conductive wire (made of thin copper, brass or tungsten of diameter 0.05 – 0.3 mm). The movement of this wire is numerically controlled to achieve the desired three dimensional shapes and accuracy. The wire is kept in tension using a mechanical tensioning device reducing the tendency of producing inaccurate parts. The mechanism of material removal in WEDM process involves a complex erosion effect by rapid, repetitive and discrete spark discharges between the wire tool and the job immersed in a liquid dielectric (kerosene/deionized water) medium. These electrical discharges melt and vaporize minute amounts of work material, which are ejected and flushed away by the dielectric, leaving small craters on the work piece. During the WEDM process, the material is eroded ahead of the wire and there is no direct contact between work piece and wire, eliminating mechanical stresses during machining. In addition, WEDM


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doi:10.1016/j.procir.2016.01.026

process is able to machine exotic and high strength and temperature resistive (HSTR) materials and eliminate the geometrical changes occurring in the machining of heat-treated steels [5-7]. Achieving improved process performance, e.g., MRR, SR, KERF and Dimensional Deviation is a challenging task in WEDM operation due to presence of large number of process parameters and complicated stochastic process mechanism. Fig. 1 shows different process parameters affecting performance measures in WEDM.

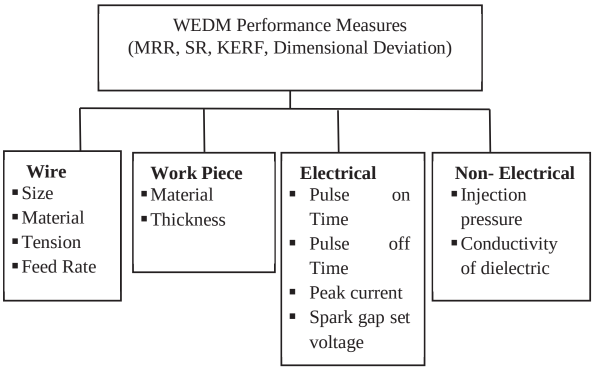


Fig. 1 Process Parameters and Performance measures for WEDM

## 2. Literature Review

Most of the experimental research work was carried out on different materials to study the influence of different process parameters on WEDM operations and optimize the same [8-18]. MRR and SR decides the production efficiency and quality of WEDM. The Kerf variations influencing the dimension accuracy of the micro-parts are more important in micro-WEDM. Gowd et al. [8] reported that pulse on time and pulse off time were the most significant parameters while WEDM on SS304 for MRR and SR. Mathew et al. [9] and Goswami and Kumar [10] observed increment in MRR with increase in pulse on time. This is because discharge energy increases with pulse on time. Also as pulse off time decreases, the number of discharges within a given period increases hence MRR increases. Saedon et al. [11] reported an optimal combination of cutting parameters within their scope of experimentation for maximum MRR as pulse-off time (5 μs), peak current (12 A), wire tension (10 N) and wire feed (4 mm/min). Manjaiah et al. [12] investigated WEDM properties of $Ti_{50}Ni_{40}Cu_{10}$ SMA (shape memory alloy) using Taguchi technique for peak current, pulse on time, pulse off time, servo voltage and wire feed process parameters and reported that peak current, pulse on time and servo voltage were major significant factors affecting MRR and SR whereas pulse off time and wire feed were reported to be insignificant. Han et al. [13] observed influence of process parameters on SR in finish cut of WEDM and reported that by decreasing both pulse duration and discharge current, SR could be improved. Rao et al. [14] reported that SR was influenced by wire tension and spark gap voltage. As wire tension increases, vibration reduces and improves surface quality. Raju et al. [15] observed increase in SR with increase in pulse on time and peak current. For increase in servo voltage and wire tension, SR was reported to be decreasing. Tilekar et al. [16] reported for longitudinal direction, pulse on time and for transverse direction, pulse off time as significant parameter in case of aluminum whereas for mild steel in both longitudinal as well as in transverse direction, current was reported as the most effective parameter. For kerf in aluminum, wire feed was the most significant parameter whereas for mild steel, pulse on time was reported as a significant parameter. Shandilya et al. [17] observed decrease in kerf for lower level of voltage and wire feed rate. Gupta and Jain [18] performed analysis and optimization of micro-geometry total profile deviation and accumulated pitch deviation of the WEDMed fine-pitch miniature spur gears made of brass and reported all four input parameters i.e. voltage, pulse-on time, pulse-off time and wire feed rate were significant. Larger deviations in profile and pitch were reported with higher values of voltage and pulse-on time and with lower values of wire feed rate and pulse-off time. Main reasons of deviations in profile and pitch of WEDMed miniature gears were reported as irregular shaped craters created due to violent sparks having high discharge energy and wire lag due to various forces generated during machining.

The literature review indicates that most of the researchers have investigated influence of a limited number of process parameters on the performance measures of WEDMed parts. Also the influence of machining parameters on Inconel-718 has not been fully explored using WEDM with zinc coated Brass wire of diameter 250 μm. As Inconel-718 (Nickel-based super alloy) is a high strength, temperature resistant (HSTR) material which is extensively used in aerospace applications, such as gas turbine, rocket motors, and spacecraft as well as in nuclear reactors, pumps and tooling. Therefore the analysis of effect of different process parameters on Inconel-718 is very essential.

## 3. Experimental setup and procedure

### *3.1. Design of Experiment based on Taguchi Method*

In Taguchi method, process parameters which influence the products are separated into two main groups: control factors and noise factors. The control factors are used to select the best conditions for stability in design or manufacturing process, whereas the noise factors denote all factors that cause variation [19]. According to Taguchi based methodology, the characteristic that the larger value indicates better machining performance, such as MRR is addressed as the-larger-the-better type problem and smaller value indicates the better machining performance, such as SR, Kerf width, Dimensional deviation are addressed as the-smaller-the-better type of problem.

The experiments were carried out on a wire-cut EDM machine (ELEKTRA SPRINTCUT) of Electronica Machine Tools Ltd. using Inconel 718 as a work piece material with dimensions as 120 x 100 x 16 mm. Zinc coated brass wire of 0.25 mm diameter is used as a tool electrode with deionized water as a dielectric. The different process parameters used in experiments were shown in Table 1 whereas Fig. 2 shows the details of experimental setup.

Table 1. Control parameters and their levels

| Parameter | Level | |
|---|---|---|
| | I | II |
| Pulse on time, $T_{ON}$ (Machine Unit/MU) | 108 | 124 |
| Pulse off time, $T_{OFF}$ (Machine Unit/MU) | 40 | 60 |
| Peak current, IP (A) | 70 | 230 |
| Wire feed, WF (m/min) | 4 | 6 |
| Wire tension, WT (g) | 4 | 12 |
| Spark gap set voltage, SV (V) | 20 | 80 |

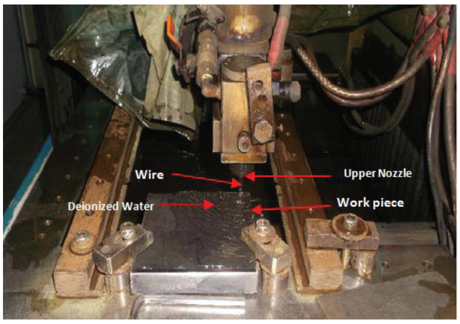


Fig. 2. Experimental setup

### 3.2. Response Variables

In this study, Mitutoyo surftest is used to measure the average arithmetic surface roughness (Ra) with a cut-off length of 0.8 mm. The surface roughness was measured five times and the average is reported for analysis purpose. MRR is calculated using equation (1),

$$MRR = KW * Vc * Mt \quad (1)$$

Where, *KW* = Kerf Width, *Vc* = Cutting Speed and *Mt* = Material thickness

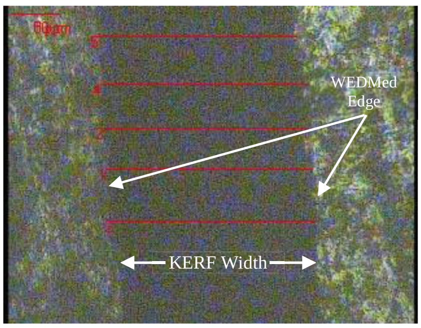


Fig. 3. Kerf Width measurement

The Kerf was measured using the measurement facility available on Omni Tech Micro Vickers Hardness Tester. It was measured at five different points and average is reported (Ref. Fig. 3). Dimensional Deviation (DD) is calculated by using equation (2),

$$DD = [(OV - AV)/AV] * 100 \quad (2)$$

Where, *OV*=Observed Value and *AV*=Actual Value

## 4. Results, analysis and discussion

In this work, eight experiments based on Taguchi ($L_8$) DoE were conducted (Ref. Table 2) and results were obtained for MRR, SR, Kerf and dimensional deviation. The statistical software, Minitab 16 was used and the results obtained for all the experimental runs were statistically analyzed using analysis of variance (ANOVA) at 95 % confidence level and the effects of the selected variable were evaluated.

Table 2. $L_8$ orthogonal array with experimental parameters

| Exp. No. | $T_{ON}$ | $T_{OFF}$ | IP | WF | WT | SV |
|---|---|---|---|---|---|---|
| 1 | 108 | 40 | 70 | 4 | 4 | 20 |
| 2 | 108 | 40 | 70 | 6 | 12 | 80 |
| 3 | 108 | 60 | 230 | 4 | 4 | 80 |
| 4 | 108 | 60 | 230 | 6 | 12 | 20 |
| 5 | 124 | 40 | 230 | 4 | 12 | 20 |
| 6 | 124 | 40 | 230 | 6 | 4 | 80 |
| 7 | 124 | 60 | 70 | 4 | 12 | 80 |
| 8 | 124 | 60 | 70 | 6 | 4 | 20 |

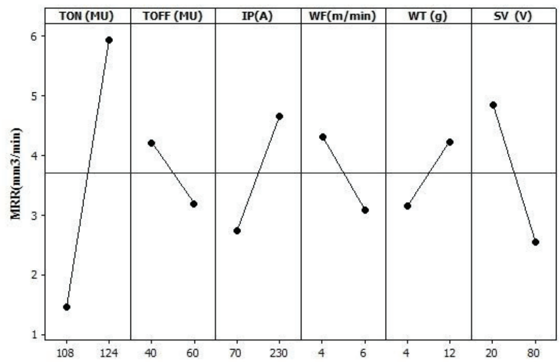


Fig. 4. Main effects plot for MRR

F-ratio establishes whether the process parameter is significant or not at a particular confidence level. According to Tosun et al. [20], higher value of F-ratio shows that any small variation of the process parameter can make a significant influence on the performance characteristics. Increase in pulse-on time and peak current increases MRR because increasing pulse-on time and peak current, number of electrons striking the work surface in a single discharge increases thus eroding out more material from the work surface per discharge. Fig. 4 shows the main effects plot for MRR versus pulse-on time($T_{ON}$), pulse-off time ($T_{OFF}$), peak current (IP), wire feed (WF), wire tension (WT) and spark gap set voltage (SV). According to this figure, MRR increases with increase in pulse-on time, peak current and wire tension. Pulse-on time is found to be the most significant factor (Ref. Table 3) affecting MRR with contribution of 54.32 %.

Table 3. ANOVA for MRR ($mm^3$/min), using Adjusted SS

| Source | DF | Seq SS | Adj SS | Adj MS | F | % Contri. |
|---|---|---|---|---|---|---|
| $T_{ON}$ | 1 | 40.254 | 40.254 | 40.254 | 4.73 | 54.32 |
| $T_{OFF}$ | 1 | 2.097 | 2.097 | 2.097 | 0.25 | 2.83 |
| IP | 1 | 7.323 | 7.323 | 7.323 | 0.86 | 9.88 |
| WF | 1 | 3.071 | 3.071 | 3.071 | 0.36 | 4.14 |
| WT | 1 | 2.298 | 2.298 | 2.298 | 0.27 | 3.10 |
| SV | 1 | 10.551 | 10.551 | 10.551 | 1.24 | 14.24 |
| Error | 1 | 8.512 | 8.512 | 8.512 | | 11.49 |
| S = 2.91746 R-Sq = 88.51% R-Sq(adj) = 19.60% | | | | | | |

The percent contribution of spark gap set voltage and peak current for MRR are 14.24 and 9.88 % respectively. High pulse-on time ($T_{ON}$) results in faster erosion of the material as longer duration of spark results in higher spark energy release hence increase in MRR was observed. High peak current results in high discharge frequency, hence results in higher MRR. Machining speed increases with decrease in spark gap set voltage value. Increasing spark gap set voltage increases the spark gap which fails in ionization of dielectric fluid and hence MRR decreases. Increasing wire tension does not show any significant effect on MRR.

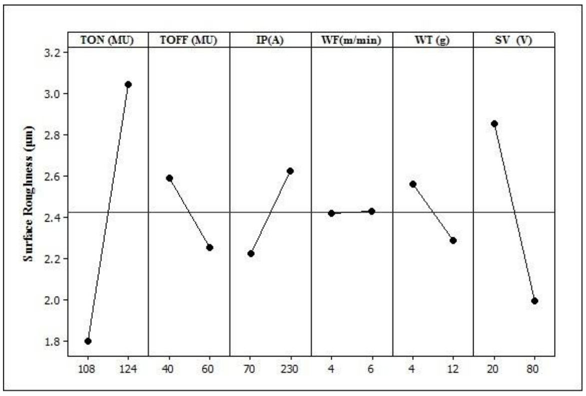


Fig.5. Main effects plots for SR

Table 4 shows the ANOVA results for SR where again pulse-on time found to be the significant factor with 58.42 % contribution. Fig. 5 shows increasing pulse-on time and peak current, SR increases. This is because increase of pulse duration means discharge will last a longer time, which leads to a higher discharge energy. When pulse duration was kept constant, an increase in discharge current would also increase discharge energy which affects SR by increase in diameter and depth of the discharging craters.

Table 4. ANOVA for SR (μm), using Adjusted SS

| Source | DF | Seq SS | Adj SS | Adj MS | F | % Contri. |
|---|---|---|---|---|---|---|
| $T_{ON}$ | 1 | 3.100 | 3.100 | 3.100 | 83.870 | 58.42 |
| $T_{OFF}$ | 1 | 0.227 | 0.227 | 0.227 | 6.140 | 4.27 |
| IP | 1 | 0.323 | 0.323 | 0.323 | 8.750 | 6.10 |
| WF | 1 | 0.000 | 0.000 | 0.000 | 0.000 | 0.003 |
| WT | 1 | 0.150 | 0.150 | .150 | 4.050 | 2.82 |
| SV | 1 | 1.469 | 1.469 | 1.469 | 39.740 | 27.68 |
| Error | 1 | 0.037 | 0.037 | 0.037 | | 0.7 |
| Total | 7 | 5.307 | | | | |
| S = 0.192262 R-Sq = 99.30% R-Sq(adj) = 95.12% | | | | | | |

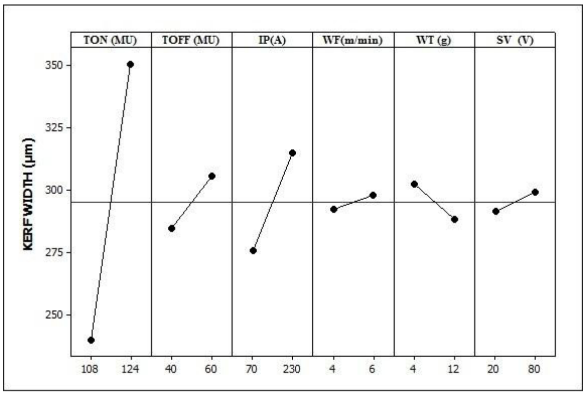


Fig.6. Main effects plots for Kerf Width

Table 5. ANOVA for Kerf Width (μm), using Adjusted SS

| Source | DF | Seq SS | Adj SS | Adj MS | F | % Contri |
|---|---|---|---|---|---|---|
| $T_{ON}$ | 1 | 24467 | 24467 | 24467 | 67.4 | 83.21 |
| $T_{OFF}$ | 1 | 880.9 | 880.9 | 880.9 | 2.43 | 3 |
| IP | 1 | 3116.9 | 3116.9 | 3116.9 | 8.59 | 10.6 |
| WF | 1 | 63.3 | 63.3 | 63.3 | 0.17 | 0.22 |
| WT | 1 | 385.6 | 38 .6 | 385.6 | 1.06 | 1.31 |
| SV | 1 | 129.1 | 129.1 | 129.1 | 0.36 | 0.44 |
| Error | 1 | 362.8 | 362.8 | 362.8 | | 1.23 |
| Total | 7 | 29405 | | | | |
| S = 19.0469 R-Sq = 98.77% R-Sq(adj) = 91.36% | | | | | | |

SR was observed to be improving with pulse-off time, wire tension and spark gap set voltage. As wire tension increases, vibration reduces and improves surface quality which is in agreement with the findings of Rao et al. [14]. For kerf width, the percentage contribution of pulse-on time was observed to be 83.21 % and becomes the most significant factor from the ANOVA Table 5. The main effects plot for kerf reflects that pulse-on time, pulse-off time and peak current produces adverse effect on kerf (Ref. Fig. 6). Hence the only improvement factor was observed as wire tension. This is because as wire tension increases, vibration reduces and narrow width produces. Wire feed and servo voltage was observed to be insignificant factors.

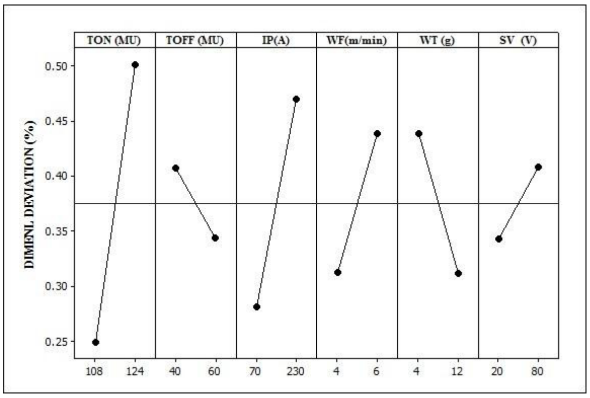


Fig.7. Main effects plots for Dimensional Deviations

Table 6. ANOVA for Dimen. Devia.(%),using Adj. SS for Tests

| Source | DF | Seq SS | Adj SS | Adj MS | F | % Contri |
|---|---|---|---|---|---|---|
| $T_{ON}$ | 1 | 0.127 | 0.127 | 0.127 | 1.8 | 36.11 |
| $T_{OFF}$ | 1 | 0.0082 | 0.0082 | 0.0082 | 0.1 | 2.33 |
| IP | 1 | 0.0715 | 0.0715 | 0.0715 | 1 | 20.33 |
| WF | 1 | 0.0319 | 0.0319 | 0.0319 | 0.4 | 9.06 |
| WT | 1 | 0.0322 | 0.0322 | 0.0322 | 0.5 | 9.17 |
| SV | 1 | 0.0087 | 0.0087 | 0.0087 | 0.1 | 2.49 |
| Error | 1 | 0.0721 | 0.0721 | 0.0721 | | 20.5 |
| Total | 7 | 0.3516 | | | | |
| S = 0.268503 R-Sq = 79.50% R-Sq(adj) = 0.00% | | | | | | |

Table 7. Rank Table for Response Variables

| Process Parameters | Response Variables | | | |
|---|---|---|---|---|
| | MRR ($mm^3$/min) | SR (μm) | Kerf Width (μm) | Dimen. Devia. (%) |
| $T_{ON}$ (Machine Unit) | 1 | 1 | 1 | 1 |
| $T_{OFF}$ (Machine Unit) | 5 | 5 | 3 | 5 |
| IP (A) | 2 | 3 | 2 | 2 |
| WF (m/min) | 4 | 6 | 6 | 4 |
| WT (g) | 6 | 4 | 4 | 3 |
| SV(V) | 3 | 2 | 5 | 6 |

Fig. 7 shows the main effects plot for dimensional deviation which shows that increment in pulse-on time, peak current, wire feed and servo voltage affects dimensional deviation whereas it improves with increment in wire tension and pulse-off time. Dimensional deviation value increases if the energy contained in a pulse increases to a larger value. That's why when pulse on time is very high the dimensional deviation increases. Similar trend was reported by Mathew et al. [9] and Sarkar et al. [21]. Table 6 shows most significant factor as pulse on time with contribution of 36.11 % followed by peak current with 20.33 %.The comparison made for all the response variables against all the process variables to obtain the rank of process variables, it reflects only pulse-on time as the most significant factor (Ref. Table 7).

## 5. Conclusions

In this study, the effect of process parameters on the response variables (MRR, SR, Kerf width and Dimensional deviation) of Inconel 718 was investigated experimentally in WEDM.

- Pulse-on time ($T_{ON}$) was found to be the most significant factor for all the response variables such as MRR, SR, Kerf width and Dimensional deviation at 95% confidence level, with percentage contributions as 54.32 %, 58.42 %, 83.21 % and 36.11 % respectively.
- Increase of pulse duration causes higher discharge energy and also increase in discharge current causes increase of discharge energy which affects SR by increasing in diameter and depth of the discharge craters.
- Surface roughness improves with increase in pulse-off time, wire tension and spark gap voltage.
- Wire feed and servo voltage was observed to be insignificant factors for kerf width.
- Dimensional deviation is affected by increase in pulse on time, peak current, wire feed and spark gap set voltage. However, increasing pulse off time and wire tension found to be improving dimensional deviation.

**Acknowledgement**

The author Uday A. Dabade wish to acknowledge the DST, FAST Track Young Scientiest Award sponsored by Department of Science and Technology, Government of India, (DST No: SERC/ET – 0046/2011) for providing facilities to carry out this experimental work.

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