Revista de Metalurgia 52(4)
October–December 2016, e077
ISSN-L: 0034-8570
doi: http://dx.doi.org/10.3989/revmetalm.077

Prediction of material removal rate and surface roughness for wire electrical discharge machining of nickel using response surface methodology

Thangam Chinnadurai, Subbiah Arungalai Vendan✉

VIT University, Division, School of Electrical Engineering (SELECT), Industrial Automation and Instrumentation, Near Katpadi Road, Vellore, Tamil Nadu 632014, India
✉Corresponding author: arungalaisv@yahoo.co.in

Submitted: 16 December 2015; Accepted: 17 May 2016; Available On-line: 19 December 2016

ABSTRACT: This study focuses on investigating the effects of process parameters, namely, Peak current (Ip), Pulse on time (Ton), Pulse off time (Toff), Water pressure (Wp), Wire feed rate (Wf), Wire tension (Wt), Servo voltage (Sv) and Servo feed setting (Sfs), on the Material Removal Rate (MRR) and Surface Roughness (SR) for Wire electrical discharge machining (Wire-EDM) of nickel using Taguchi method. Response Surface Methodology (RSM) is adopted to evolve mathematical relationships between the wire cutting process parameters and the output variables of the weld joint to determine the welding input parameters that lead to the desired optimal wire cutting quality. Besides, using response surface plots, the interaction effects of process parameters on the responses are analyzed and discussed. The statistical software Mini-tab is used to establish the design and to obtain the regression equations. The developed mathematical models are tested by analysis-of-variance (ANOVA) method to check their appropriateness and suitability. Finally, a comparison is made between measured and calculated results, which are in good agreement. This indicates that the developed models can predict the responses accurately and precisely within the limits of cutting parameter being used.

KEYWORDS: Brass wire; Material removal rate (MRR); Nickel; Response surface methodology (RSM); Surface roughness (SR); Zinc coated wire; Wire-EDM

Citation / Cómo citar este artículo: Chinnadurai, T., Arungalai Vendan, S. (2016) “Prediction of material removal rate and surface roughness for wire electrical discharge machining of nickel using response surface methodology”. *Rev. Metal.* 52(4):e077. doi: http://dx.doi.org/10.3989/revmetalm.077

RESUMEN: *Predicción de la tasa de eliminación de material y rugosidad de la superficie de mecanizado por electroerosión de alambre de níquel utilizando la metodología de superficie de respuesta.* Este estudio se centra en la investigación de los efectos de los parámetros del proceso, a saber, corriente máxima (Ip), duración del impulso (Ton), duración de desconexión del impulso (Toff), presión del agua (Wp), velocidad de alimentación del alambre (WF), tensión del alambre (Wt), servo voltaje (Sv) y ajuste de avance del servo (SFS), velocidad de eliminación de material (MRR) y rugosidad de la superficie (SR), para la fabricación de alambre de níquel por descarga eléctrica (Wire-EDM) utilizando el método “Taguchi”. Se ha adoptado la metodología superficial de respuesta (RSM) con objeto de desarrollar relaciones matemáticas entre los parámetros del proceso de corte de alambre y las variables de salida de la junta de soldadura para determinar los parámetros de potencia de la soldadura que conducen a la calidad óptima deseada de corte del alambre. Además, usando gráficas superficiales de respuesta, los efectos de interacción de los parámetros del proceso en las respuestas son analizados y discutidos. El software estadístico “Mini-tab” se utiliza para establecer el diseño y obtener las ecuaciones de regresión. Los modelos matemáticos desarrollados son probados por el método de análisis de la varianza (ANOVA) para comprobar su aptitud e idoneidad. Por último, se hace una comparación entre los resultados medidos y calculados, que están en buen acuerdo. Esto indica que los modelos desarrollados pueden predecir las respuestas con exactitud y precisión dentro de los límites de los parámetros de corte usados.

PALABRAS CLAVE: Alambre-EDM, Alambre recubierto de cinc; Hilo de latón; Metodología superficial de respuesta (RSM); Níquel; Rugosidad superficial (SR); Velocidad de eliminación del material (MRR)

1. INTRODUCTION

WEDM (Wire Electrical Discharge Machining) is categorized as a sophisticated and advanced process in tooling and manufacturing industry. This process is however confined to machining materials or alloy that is electrically conductive regardless of the hardness. In WEDM, the rapid and repetitive spark discharges across the gap between the tool and the work piece facilitates the material removal. In WEDM process, spark discharge occurs between a small diameter wire electrode (usually less than 0.5 mm diameter) and a work piece with de-ionized water as the dielectric medium. This subsequently enforces the erosion of the work piece to produce complex two and three dimensional shapes according to a *numerically controlled* (NC) path. Considering the beneficial aspects of the process, the components of defense related products such as cartridge, magazines appear to be effectively machined with the employment of WEDM for those materials**.** WEDM is expected to be a feasible process her nickel. Owing to the inadequacy in the literature on reports pertaining to WEDM for Nickel using RSM, this study attempts to address this application oriented concern. Some of the prominent literatures directly contributing to this research study are presented briefly.

Khan *et al.* (2013) investigated the suitability of wire electric discharge machining of high strength and low alloy (HSLA) steels. HSLA steel is considered in their study as it provides better mechanical properties and greater resistance to atmospheric corrosion. The optimum machining parameter range was obtained by using the analysis of signal-to-noise (*S*/*N*) ratio, analysis of means and analysis of variance (ANOVA). Further, the level of importance of the machining parameters on micro-hardness was identified using ANOVA. Esme *et al.* (2009) provided the evidence on the fact that the surface finish of the machined surface mainly depends on the pulse duration, open voltage, wire speed and dielectric flushing pressure. The mathematical relation between the work piece, surface roughness and WEDM cutting parameters were established by regression analysis method. This mathematical model may be used in estimating the surface roughness without performing any experiments. Amitesh and Jatinder (2012), presented information on the influence of machining parameters on cutting speed and material removal rate for machining of Nimonic 80A with brass wire as tool electrode during wire electrical discharge machining process. Investigation indicated that cutting speed (CS) and material removal rate (MRR), both increases with increase in pulse-on-time (Ton) and peak current(IP), while decreases with increase in pulse-off-time (Toff) and spark gap set voltage (SV). Sreenivasa Rao and Venkaiah (2013) review the effects of various WEDM process parameters such as pulse on time (Ton), pulse off time (Toff), servo voltage (SV), peak current (IP), dielectric flow rate (DFR), wire speed (WS), wire tension (WT) on different process response parameters such as material removal rate (MRR), surface roughness (Ra), wire wear ratio (WWR) and surface integrity factors. Besides various optimization methods adapted by the research in various literature repeat and constructive suggestions to overcome few intricacies posed by the process are presented, while parallelly extrapolating few ideas for feature trends. Hassan *et al.* (2009) provided an insight through experimental investigation on the parameters such as high tensile residual stresses, high surface roughness, presence of micro-cracks and micro-voids that proven to be a detrimental factors. These properties vary with different levels of the main machining parameters. This paper presents an experimental work that has been done in order to quantify the effect of some of the main WEDM parameters on the surface texture of AISI 4140 steel. 2D surface measurements are taken on all WEDM samples and 2D surface characterization is being carried out in order to calculate the different surface texture parameters.

1.1. Response Surface Methodology (RSM)

The RSM is an empirical modeling approach is adopted her determining the relationship between various process parameters and responses with the various preferred criteria and penetrating the significance of these process parameters on the coupled responses (Myers and Montgomery, 1995). RSM is used to get just around the corner of the response around an existing working point, which depends on few main effects only. Design of experiments that allow estimating interaction and quadratic effects, which result in information about the shape of the response surface. It is a sequential testing approach for building and optimizing the experimental model. Therefore, RSM is a collection of mathematical and statistical procedures that are useful for the modeling and analysis of problems in which response of demand is affected by several variables and the objective is to optimize this response (Ozcelik and Erzurmlu, 2005). The second order mathematical models have been developed to predict the better MRR and SR condition values. The polynomial equation are considered in the present case is (Myers *et al.*, 2009).

$$y = \varepsilon_0 + \sum_{i=1}^{b} \varepsilon_i x_i + \sum_{i=1}^{b} \sum_{j=i+1}^{b} \varepsilon_{ij} x_i x_j + \sum_{i=1}^{b} \varepsilon_{ii} x_i^2 \qquad (1)$$

Where, y is the response; where weld strength; x_i represents pressure, weld time and amplitude; ε_0, ε_i, ε_{ij} and ε_{ii} represent the constant, linear, quadratic and interaction terms respectively.

Then response surface *y* contains the linear terms, squared terms and cross product terms. Using this quadratic model of *y* in this study is not only to investigate over the entire factor space, but also to locate region of desired target where the response approaches its optimum or near optimal value.

2. EXPERIMENTATION

Nickel being a stipulate material for military and aerospace systems with electroplating & corrosive resistances is used for this study. The chemical composition of the material (expressed at wt.%) is C: 0.02, Si: 0.3, Mn: 0.3, S: 0.01, Ni: min 99.00, Cu: 4.60, and Fe: 0.4, and the physical properties are melting point 1455 °C, boiling point 2730 °C, density 8.908 gr.m^{-3}, heat of fusion 17.48 KJ.mol^{-1}, heat of vaporization 379 KJ.mol^{-1}. The materials dimension 5×5×24 mm respectively.

The selection of optimum cutting parameters plays a significant role for producing high material removal rate (MRR) and greater surface roughness. Parameter selection also gets altered during cutting time, wire breakage; wire and work-piece short-circuit. In order to accommodate all these parameter while parallelly limiting the number of experimental trails, DOE is being adopted for the experimental study. The parameter levels are presented in Table 1.

The work is carried out with "Specification of CNC Ultracut Machines", 5 axial cnc, table size 650×440 mm, best surfaces finish 0.4 Ra, maximum cutting speed 210 mm.min^{-1}. The two different wires used one for brass wire and zinc coated brass wire. In machining bras is typically preferred owing to its low cost, great conductive, high tensile strength and flush ability. Zinc coated wire is expected to posses higher conductivity, which will eventually improve the machining speed. For pure brass wire tensile strength ranging from 70,000 to 130,000 psi and a diameter of 0.025 is used. Zinc Coated Brass wires produce exceptional surface finishes when cutting tungsten carbide and are often utilized for cutting PCD and graphite (Kern, 2007).

Sparks are initiated while machining removes small amount of materials depending on the pulse on time and generated spark sizes. During pulse on time, the sparks sizes are small and the material removal rate is less which exhibits improved surfaces roughness. Bigger spark yield higher MRR and exhibit more roughness. Pulse on time produces a high temperature at the range of 1240 °C–1450 °C. During pulse off time, the dielectric fluid passes through high pressure prevailing between the wires and work pieces that removes the debris and readies the fluid to the next ionization process.

Brass wires were opted for the WEDM due to its high tensile properties. Brass wires are blend of copper and zinc. They alloying is in varying rate of 35–37% zinc and 63–65% copper. The rigidity and rating of vapor pressure of brass wire increases in addition of zinc. Besides, the rate of zinc contains in brass wire decreases its dissolving point. The cutting execution and velocity enhance in machining with brass wire because of stable release amid machining. Amidst the procedure for cutting, the zinc in the brass wire really boils off, or vaporizes, which cools the wire and conveys more usable vitality to the work zone. Expanding the zinc content in brass wire can improve the machining speed (more than 40%) nevertheless framing a wire with rate of zinc that is a weak stage in the compound will lead to intricacies. Properties of wire material are shown in Table 2.

The zinc coated wire was delivered to determine the past wire's defects and to increment generously the cutting speed and cutting accuracy. Additionally, it was said that creating the wire with 40% zinc substance is troublesome in light of the fact that wire's grain structure changes and it makes fragile. There are a limited number of coating materials accessible for wires in WEDM. Zinc combination is the most widely recognized material that is connected as the wire coated layer. The zinc combination was chosen because it has a low vaporization temperature compared with the core material. The wire covering is effortlessly vaporizes when a pulse is applied and core is secured because of cooling impact of coated material. Likewise,

TABLE 1. Process parameters and three level

Sl N°	Parameter	Level-1	Level-2	Level-3
1	Peak current (Ip) A	1	2	3
2	Pulse on time (Ton) µs	20	23	26
3	Pulse off time (Toff) µs	40	45	50
4	Water pressure (Wp) Mps	11	12	13
5	Wire feed rate (Wf) mm.min^{-1}	2	3	4
6	Wire tension (WT) N	7	8	9
7	Servo voltage (SV) V	15	20	25
8	Servo feed setting (SFS) m.min^{-1}	95	100	105

TABLE 2. Properties of wire materials

Wire Name	Brass	Zinc-Coated Brass
Material	Brass Special Composition	CuZnBrass, 63/37 Core composition with zinc coating
Tensile strength	142,000 + PSI	130,000 PSI
Wire diameter	0.25 mm	0.25 mm

zinc must be coated on the core of metallic wire in view of low melting point. Subsequently, brass or copper ordinarily are utilized as core of these sorts of wires. An amazing combination of low cast, better flush capacity, high mechanical quality and great electrical conductivity are the benefits of zinc coated wires as opposed to brass or copper wires. Furthermore, the coated layer diminishes the danger of breaking wires since it ensures the core of the wire from thermal shock of electrical release. All specified preferences for zinc coated wires upgrade the execution of WEDM, expanding in cutting velocity and accuracy.

In order to reduce the number of experiment trials and avoiding material wastage, Tagugi L18 full factorial experimental design is being implemented. Table 3 and Table 4 respectively provides the details of the various trials conducted and the corresponding MRR and surface roughness measured. Higher machining rate is achieved with tap water as the dielectric fluid with zero electrode wear (Tariq Jilani and Pandey, 1984). Wire EDM is produced a stress free cutting.

3. RESULTS AND DISCUSSION

The material removed from the raw work piece by WEDM and the corresponding CNC display is compiled into a conclave and is furnished in Fig. 1 shows the machine diagram and its results with specimen and CNC display. The specimen dimension is 5×5×24 mm with 18 samples are shown in the picture. This trial are conducted to analyze the influence of interdisciplinary process parameters on the material removal rate and optimize using ANOVA.

3.1. Brass wire analysis

Figure 2a, shows the mean effect plot of MRR against the input parameter such as peak current *(Ip)*, pulse on time *(Ton)*, pulse off time *(Toff)*, water pressure *(wp)*, wire feed rate *(Wf)*, wire tension *(Wt)*, servo voltage *(Sv)*, servo feed setting *(Sfs)* on cutting speed has the selected machining condition. It is clearly noted that the pulse on time, pulse off time, Water pressure and servo voltage is proportional to the cutting speed. Moreover it is observed that there is a greater dependency of cutting speed on the *Ton*/*Toff* of the pulse. Figure 2b, shows the mean effect plot of surface roughness *(SR)* in brass wire *Vs* the all input parameters *Ip, Ton, Toff, Wp, Wt, Wf, Sv, Sfs*. This graph demonstrate the fact that wire tension (*Wt*), water pressure (*wp*), pulse off time (*Toff*) and pulse on time (*Ton*), majorly alters governs the surfaces roughness values. As the water pressure increase, flushing is higher and removed materials are pulsed away, yielding grater *Ra*. Wire tension is another affecting factor for *Ra*, her varying wire tension values such as 7, 8, and 9 respectively. Another factor is *Toff,* flushing rate which increases during pulse off timing, eventually leading to attainment or improve *Ra*. *Ton* when maintained for longer time produces sparks with

TABLE 3. Input parameters and its corresponding *material removal rate* (MRR) and *surface roughness* (SR) for Brass wire cutting

Ip	Ton	Toff	Wp	Wf	Wt	Sv	Sf	MRR Br	SR Br
1	20	40	11	2	7	15	95	1.32	2.2566
1	20	45	12	3	8	20	100	1.09	2.4543
1	20	50	13	4	9	25	105	0.72	1.8824
1	23	40	13	2	8	20	105	1.46	2.2927
1	23	45	11	3	9	25	95	1.12	2.1456
1	23	50	12	4	7	15	100	0.93	2.4008
1	26	40	13	3	7	25	100	1.36	2.338
1	26	45	11	4	8	15	105	1.29	2.3882
1	26	50	12	2	9	20	95	0.89	2.2094
2	20	40	11	4	9	20	100	1.33	1.9849
2	20	45	12	2	7	25	105	1.2	2.2858
2	20	50	13	3	8	15	95	0.93	2.4696
2	23	40	12	3	9	15	105	1.65	2.4876
2	23	45	13	4	7	20	95	1.3	2.5341
2	23	50	11	2	8	25	100	0.89	2.3896
2	26	40	12	4	8	25	95	1.75	2.6316
2	26	45	13	2	9	15	100	1.82	2.4514
2	26	50	11	3	7	20	105	0.85	2.3337

TABLE 4. Input parameters and its corresponding *material removal rate* (MRR) and *surface roughness* (SR) for Zinc coated wire cutting

Ip	Ton	Toff	Wp	Wf	Wt	Sv	Sf	MRR Zc	SR Zc
1	20	40	11	2	7	15	95	1.4	2.1445
1	20	45	12	3	8	20	100	1.2	2.4829
1	20	50	13	4	9	25	105	0.76	2.452
1	23	40	13	2	8	20	105	1.534	2.5045
1	23	45	11	3	9	25	95	1.263	2.3218
1	23	50	12	4	7	15	100	1.04	2.5483
1	26	40	13	3	7	25	100	1.56	2.5124
1	26	45	11	4	8	15	105	1.59	2.2798
1	26	50	12	2	9	20	95	1.07	2.4732
2	20	40	11	4	9	20	100	1.38	2.2115
2	20	45	12	2	7	25	105	1.05	2.0818
2	20	50	13	3	8	15	95	1.03	2.2525
2	23	40	12	3	9	15	105	1.74	2.4889
2	23	45	13	4	7	20	95	1.4	2.4111
2	23	50	11	2	8	25	100	0.92	2.366
2	26	40	12	4	8	25	95	1.8	2.4423
2	26	45	13	2	9	15	100	1.68	2.8251
2	26	50	11	3	7	20	105	1.36	2.2223

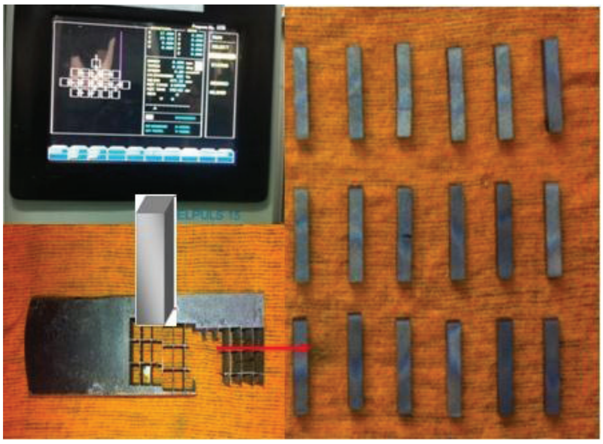

FIGURE 1. Material Removed from the work piece subjected to WEDM and its CNC display.

higher time or sustenance yielding smoother surfaces. With more material removed due to heat.

3.2. Zinc coated wire analysis

Figure 3a shows plot for MRR against *Vs* all input parameters on cutting speed with zinc coated brass wire. According to this Fig. 3b *Toff* and *Ton, Ip and Sv*, values are the governing parameters. MRR depends mainly on these 4 parameters. Role of *Ton* is more effective compared with the pure brass wire, conductivity to the wire and displays higher toughness and tensile strength. Figure 3b shows the plot for Surfaces roughness (*Ra*) vs. all input parameters. Surfaces roughness (*Ra*) mainly depends on the water pressure, wire tension, pulse on time and servo feed setting. Water pressure affects the *Ra* value. High water pressure range gives better flushing which improves the *Ra* values. Ton and wire tension contribute to *Ra* value, while the pulse on time is long, with a spark at less energy that removes material in small volume. The removed voids enables flushing rate indirectly governing the *Ra* values improved. Figure 3 (a, b) gives the interaction plot of process parameters.

Figure 4 (a, b) illustrate the surface plot of all input parameters in various trials with respect to the material removal rate (MRR) for using brass wire cutting. The plot indicate that the prominently significant factor quenching the process are *Ton, Toff* and water pressure (*Wp*). As the On time (*Ton*) increases, there is a corresponding increases in the materials removal rate proving a propositional relationship. MRR majorly relies on the current discharge for the stipulated time duration. Conversely, With the increases in the *Toff*, MRR decreases as it is directly being affected by the decreases discharge which is an important factor. Another important observation was the dependency of MRR on water pressure. As the water pressure increases, there is a step hike in the MRR owing to the high flow flush. Nevertheless, if the pressure of water is decreases, the debris are re-solidified in base material. Re-solidification layer leade to a decreases in the MRR rate due to the objection needed by the

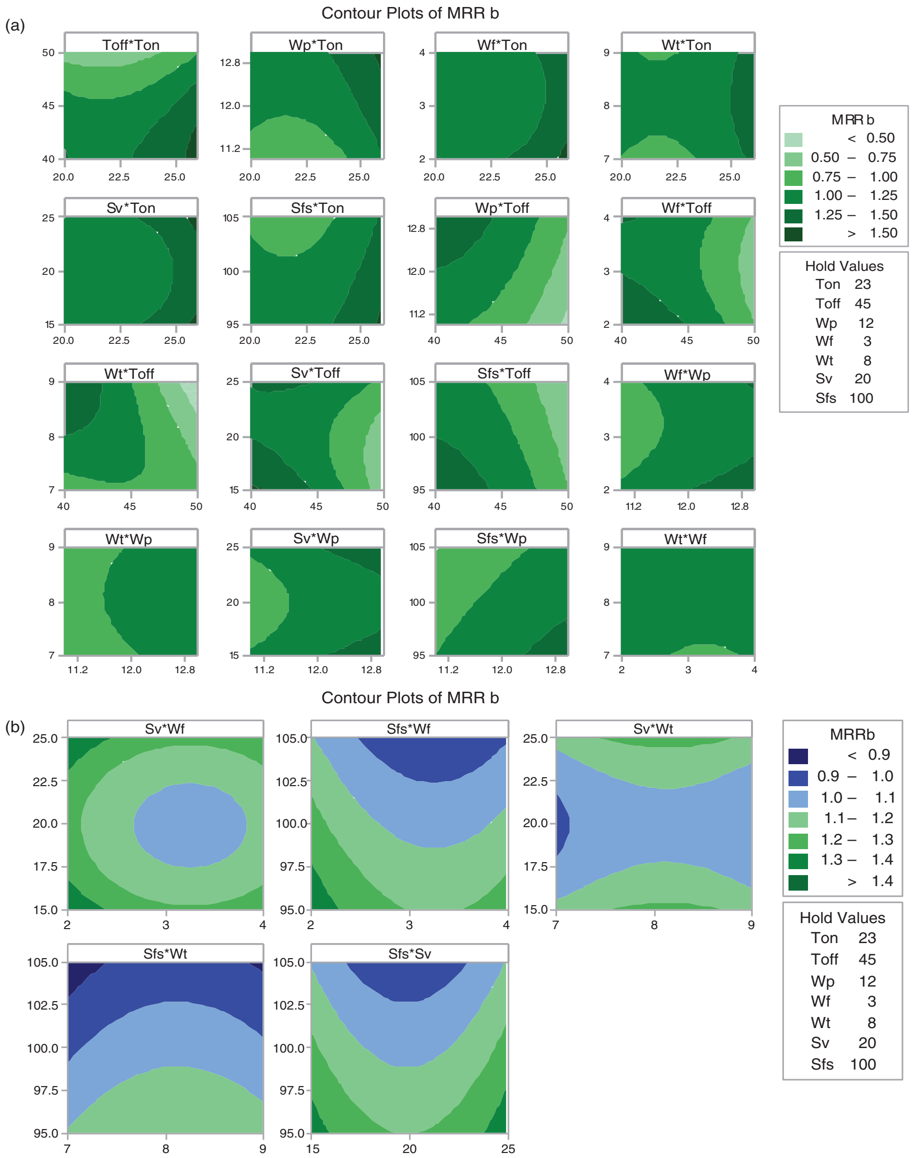

FIGURE 2. Contour plot of material removal rate (MRR) for: a) brass wire and (b) nickel base material after WEDM.

debris layers. Figure 5 (a, b) shows the corresponding contour plot for material removal rate (MRR) vs. input combinations. These plots show how the response variable is related to the two factors. The best MRR is achieved at middle of the plot range experimented. This is consistent with the fact that the output term is significant.

The material removal rate (MRR) for brass wire for p-value of less than 0.05 for the model having 95% confidence level indicates that the model terms are statistically significant. The ANOVA (Table 5) result shows that the pulse on time (*Ton*), pulse off time (*Toff*) and water pressure (*Wp*) are the significant model terms associated with MRR brass wire. The other model terms are not significant and thus, eliminated by backward elimination process to improve model adequacy (Sharma *et al.*, 2013). The final mathematical models for MRR brass wire, may be used for prediction within the same design space, are given as follows:

$$\text{MRR B} = -17.35 - 0.8667\ Ton + 0.7370\ Toff + 0.7667\ Wp - 1.058\ WF + 3.833\ WT - 0.5172\ SV - 0.006167\ SFS + 0.02000\ Ton{*}Ton - 0.005200\ Toff{*}Toff - 0.02500\ Wp{*}Wp + 0.1117\ WF{*}WF - 0.07333\ WT{*}WT + 0.006367\ SV{*}SV - 0.000100\ SFS{*}SFS + 0.007333\ Toff{*}WF - 0.05867\ Toff{*}WT + 0.005867\ Toff{*}SV$$

Figure 5 (a, b) gives the interaction plot of process parameters. Figure 6 (a, b) illustrate the surface plot of all input parameters in various

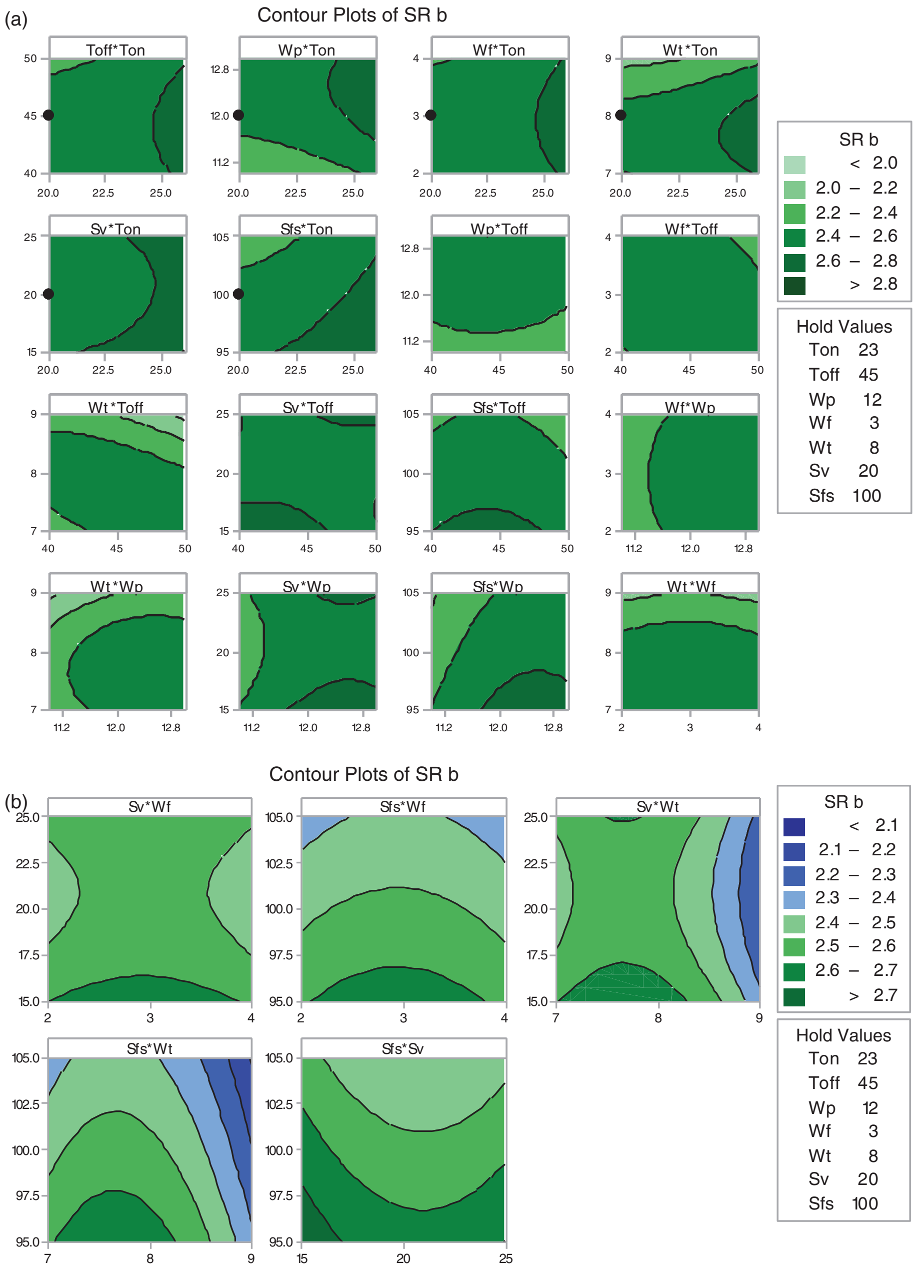

FIGURE 3. Contour plot of surface roughness (SR) for: a) brass wire and (b) nickel base material after WEDM.

trials with respect to the surface roughness (*SR*) for using brass wire cutting. The plot indicate that the prominently significant factor quenching the process are *Toff*, water pressure (*Wp*) and wire feed rate (*Wf*). As the Off time (*Toff*) increases, there is a corresponding decreases in the surface roughness (*SR*) proving a opposing relationship. *SR* majorly relies on the current discharge for the stipulated time duration. Conversely, with the decreases in the *Toff, SR* increases as it is directly being affected by the decreases discharge which is an important factor. Another important observation was the dependency of *SR* on water pressure. As the water pressure increases, there is a low in the *SR* owing to the high flow flush. Nevertheless, if the pressure of water is decreases, the debris are re-solidified in base material. Re-solidification layer lead to a increases in the SR rate due to the objection needed by the debris layers. Figure 7 (a, b) shows the corresponding contour plot for surface roughness (*SR*) vs. input combinations. These plots show how the response variable is related to the two factors. The best SR is achieved at middle of the plot range experimented. This is consistent with the fact that the output term is significant. The surface roughness (SR) for

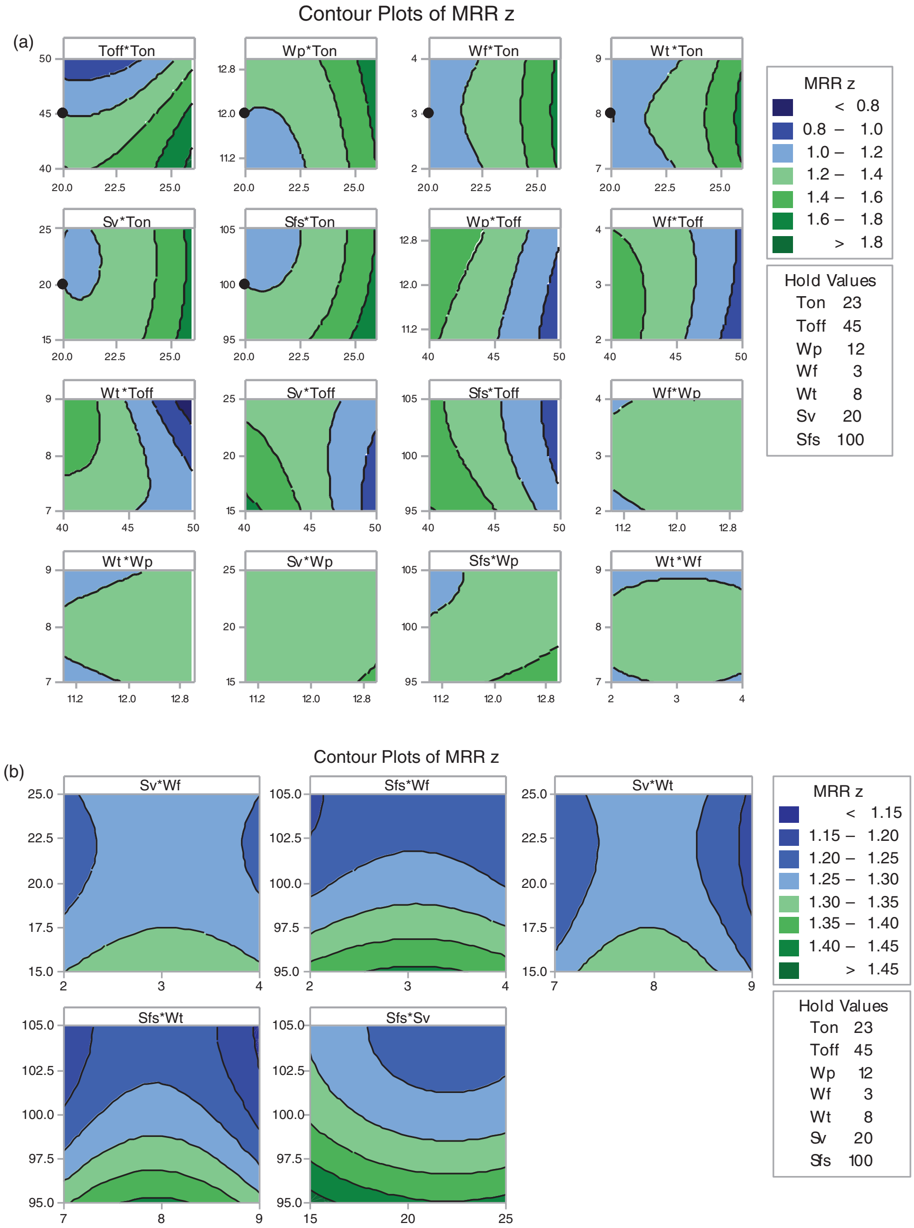

FIGURE 4. Contour plot of material removal rate (MRR) for: a) zinc coated wire (z), and b) nickel base material after WEDM.

brass wire for p-value of less than 0.05 for the model having 95% confidence level indicates that the model terms are statistically significant. The ANOVA (Table 6) result shows that the pulse off time (*Toff*), water pressure (*Wp*) and wire feed rate are the significant model terms associated with *SR* brass wire. The other model terms are not significant and thus, eliminated by backward elimination process to improve model adequacy (Sharma *et al.*, 2013). The final mathematical models for *SR* brass wire, may be used for prediction within the same design space, are given as follows:

$$SR\ B = -32.84 - 0.1675\ Ton + 0.4070\ Toff + 2.777\ Wp + 0.7106\ Wf + 4.348\ Wt - 0.4268\ Sv - 0.04073\ Sfs + 0.004457\ Ton{*}Ton - 0.002806\ Toff{*}Toff - 0.1104\ Wp{*}Wp - 0.06018\ Wf{*}Wf - 0.1897\ Wt{*}Wt + 0.003697\ Sv{*}Sv + 0.000088\ Sfs{*}Sfs - 0.007937\ Toff{*}Wf - 0.03207\ Toff{*}Wt + 0.006042\ Toff{*}Sv$$

Figure 5 (a, b) gives the interaction plot of process parameters. Figure 5 (a, b) illustrate the surface plot of all input parameters in various trials with respect to the material removal rate (MRR) for using zinc coated wire cutting. The plot indicate

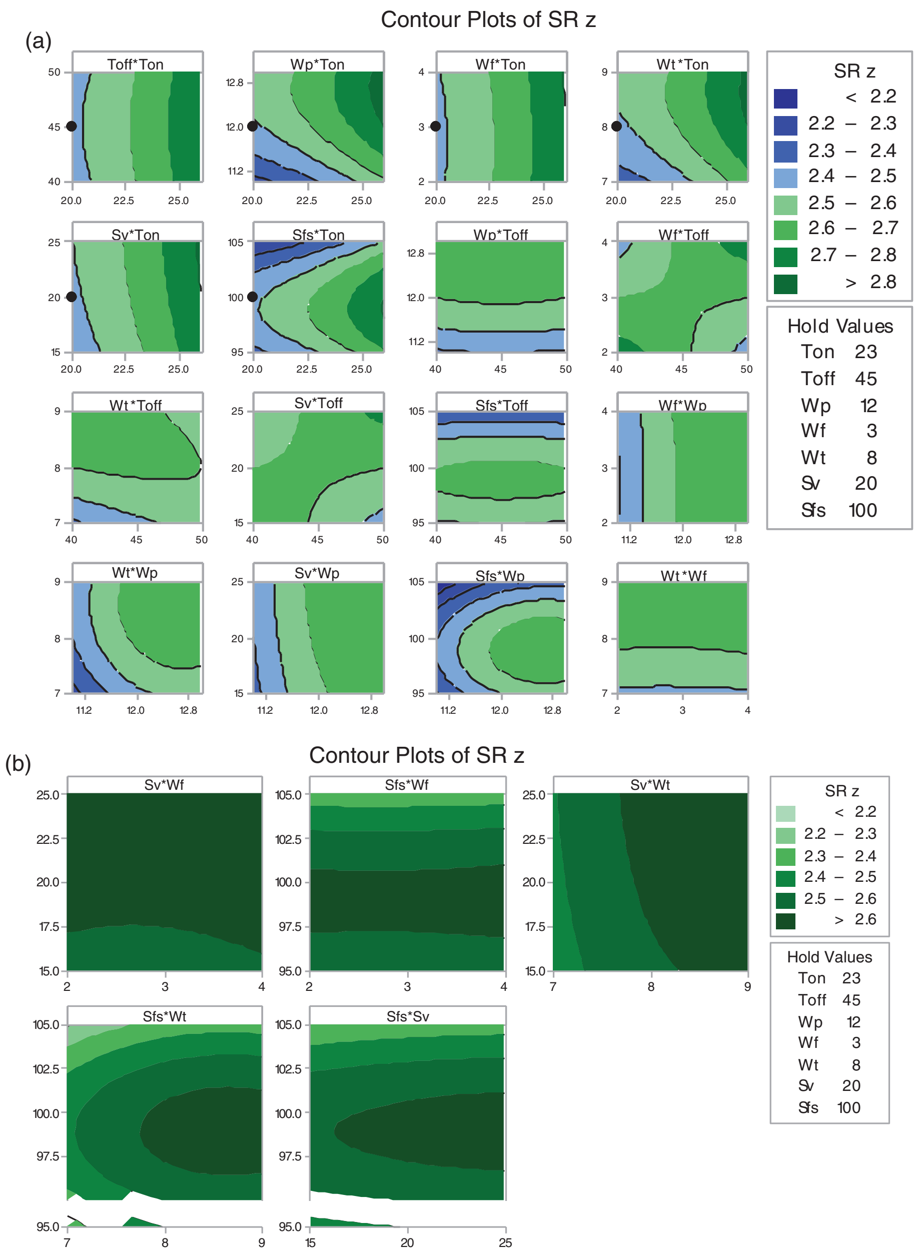

FIGURE 5. Contour plot of surface roughness (SR) for: a) zinc coated wire (z), and b) nickel base material after WEDM.

that the prominently significant factor quenching the process are *Ton, Toff* and servo voltage. As the On time (*Ton*) increases, there is a corresponding increases in the materials removal rate proving a propositional relationship. MRR majorly relies on the current discharge for the stipulated time duration. Conversely, with the increases in the *Toff,* MRR decreases as it is directly being affected by the decreases discharge which is an important factor. Another important observation was the dependency of MRR on servo voltage. As the servo voltage increases, there is a step hike in the MRR owing to the high accurate servo movement. Nevertheless, if the servo voltage is decreases, the servo mechanism operate at a slow speed, so wire movement in-betweens the material is slow. This slow speed of wire lead to a decreases in the MRR rate**.** Figure 5 (a, b) shows the corresponding contour plot for material removal rate (MRR) vs. input combinations. These plots show how the response variable is related to the two factors. The best MRR is achieved at middle of the plot range experimented. This is consistent with the fact that the output term is significant. The material removal rate (MRR) for zinc coated wire for p-value of less than 0.05 for the model having 95% confidence

TABLE 5. Material removal rate (MRR) ANOVA analysis for brass wire cutting

Analysis of Variance (MRR b)					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	7	1.42656	0.20379	6.58	0.004
Ton	1	0.15641	0.15641	5.05	0.048
Toff	1	1.11630	1.11630	36.03	0.000
Wp	1	0.05201	0.05201	1.68	0.024
Wf	1	0.00563	0.00563	0.18	0.679
Wt	1	0.02708	0.02708	0.87	0.372
Sv	1	0.06750	0.06750	2.18	0.171
Sfs	1	0.00163	0.00163	0.05	0.823
Error	10	0.30984	0.03098	-	-
Total	17	1.73640	-	-	-

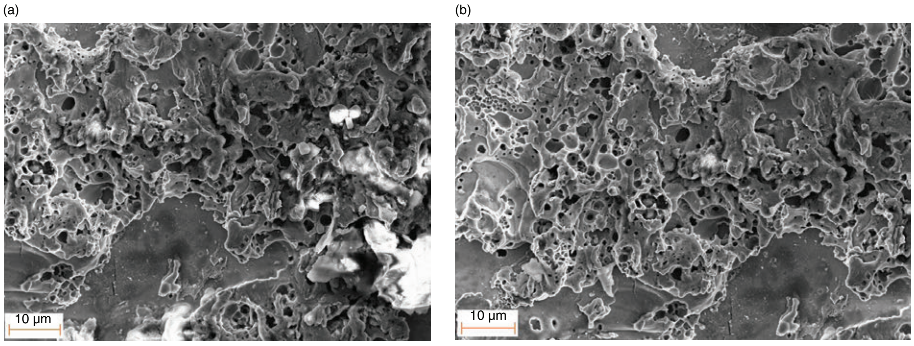

FIGURE 6. SEM image of: a) brass wire used for cutting nickel and b) nickel base material after WEDM.

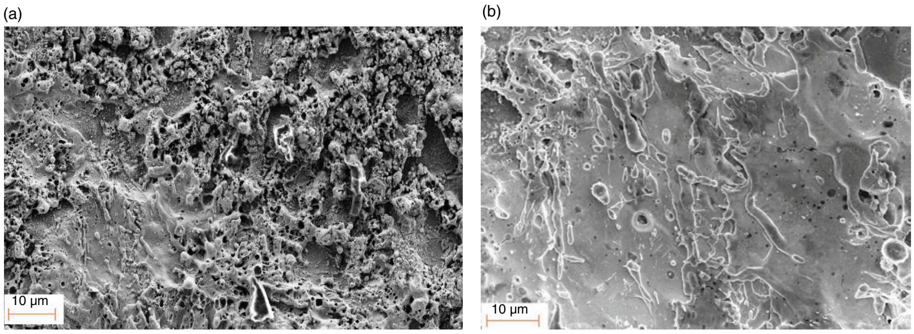

FIGURE 7. SEM image of: a) zinc coated wire used for cutting nickel and b) nickel base material after WEDM.

level indicates that the model terms are statistically significant. The ANOVA (Table 7) result shows that the pulse on time (*Ton*), pulse off time (*Toff*) and servo voltage are the significant model terms associated with MRR zinc coated wire. The other model terms are not significant and thus, eliminated by backward elimination process to improve model adequacy (Sharma *et al.*, 2013). The final mathematical models for MRR zinc coated wire, may be used for prediction within the same design space, are given as follows:

$$\text{MRR z} = 12.87 - 0.7096\,Ton + 0.3796\,Toff - 0.2795\,Wp - 0.2231\,Wf + 3.135\,Wt - 0.2844\,Sv - 0.3758\,Sfs + 0.01709\,Ton{*}Ton - 0.002573\,Toff{*}Toff + 0.01475\,Wp{*}Wp - 0.03613\,Wf{*}Wf - 0.08042\,Wt{*}Wt + 0.001388\,Sv{*}Sv + 0.001790\,Sfs{*}Sfs + 0.009900\,Toff{*}Wf - 0.04133\,Toff{*}Wt + 0.004953\,Toff{*}Sv$$

Figure 5 (a, b) gives the interaction plot of process parameters; illustrate the surface plot of all

Table 6. Surface roughness (SR) ANOVA analysis for brass wire cutting

Analysis of Variance (SR b)					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	7	3.72300	0.53186	5.49	0.008
Ton	1	0.08025	0.08025	0.83	0.384
Toff	1	0.44310	0.44310	4.58	0.058
Wp	1	1.71038	1.71038	17.66	0.002
Wf	1	0.71859	0.71859	7.42	0.021
Wt	1	0.33745	0.33745	3.48	0.092
Sv	1	0.26439	0.26439	2.73	0.129
Sfs	1	0.16886	0.16886	1.74	0.216
Error	10	0.96841	0.09684	-	-
Total	17	4.69142	-	-	-

Table 7. Material removal rate (MRR) ANOVA analysis for zinc coated wire (z) cutting

Analysis of Variance (MRR z)					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	7	1.40507	0.200725	17.49	0.000
Ton	1	0.41813	0.418133	36.44	0.020
Toff	1	0.87156	0.871563	75.95	0.003
Wp	1	0.00022	0.000217	0.02	0.893
Wf	1	0.00832	0.008321	0.73	0.414
Wt	1	0.00057	0.000574	0.05	0.828
Sv	1	0.10584	0.105844	9.22	0.013
Sfs	1	0.00042	0.000420	0.04	0.852
Error	10	0.11476	0.011476	-	-
Total	17	1.51983	-	-	-

input parameters in various trials with respect to the Surface Roughness (*SR*) for using zinc coated wire cutting. The plot indicate that the prominently significant factor quenching the process are Ton, water pressure (*Wp*) and wire tension (*Wt*). As the On time (*Ton*) decreases, there is a corresponding increases in the surface roughness (*SR*) proving a opposing relationship. *SR* majorly relies on the current discharge for the stipulated time duration. Conversely, with the decreases in the Ton, *SR* increases as it is directly being affected by the decreases discharge which is an important factor. Another important observation was the dependency of *SR* on water pressure. As the water pressure increases, there is a low in the *SR* owing to the high flow flush. Nevertheless, if the pressure of water is decreases, the debris are re-solidified in base material. Re-solidification layer lead to a increases in the SR rate due to the objection needed by the debris layers**.** Figure 5 (a, b) shows the corresponding contour plot for surface roughness (*SR*) vs. input combinations. These plots show how the response variable is related to the two factors. The best SR is achieved at middle of the plot range experimented. This is consistent with the fact that the output term is significant. The surface roughness (*SR*) for zinc coated wire for p-value of less than 0.05 for the model having 95% confidence level indicates that the model terms are statistically significant.

The ANOVA (Table 8) result shows that the pulse on time (*Ton*), water pressure (*Wp*) and wire tension are the significant model terms associated with *SR* brass wire. The other model terms are not significant and thus, eliminated by backward elimination process to improve model adequacy (Sharma *et al.*, 2013). The final mathematical models for *SR* zinc coated wire, may be used for prediction within the same design space, are given as follows:

$$\text{SR z} = -91.65 - 0.07772\,Ton + 0.002553\,Toff + 2.257\,Wp - 1.335\,Wf + 1.714\,Wt - 0.1759\,Sv + 1.551\,Sfs + 0.002830\,Ton{*}Ton - 0.000622\,Toff{*}Toff - 0.08874\,Wp{*}Wp + 0.006512\,Wf{*}Wf - 0.06008\,Wt{*}Wt - 0.000348\,Sv{*}Sv - 0.007838\,Sfs{*}Sfs + 0.02888\,Toff{*}Wf - 0.01495\,Toff{*}Wt + 0.004329\,Toff{*}Sv$$

Table 8. Surface roughness (SR) ANOVA analysis for zinc coated wire (z) cutting

Analysis of Variance (SR z)					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	7	0.344179	0.049168	2.70	0.075
Ton	1	0.106390	0.106390	5.84	0.036
Toff	1	0.000009	0.000009	0.00	0.083
Wp	1	0.166075	0.166075	9.12	0.013
Wf	1	0.000209	0.000209	0.01	0.917
Wt	1	0.060506	0.060506	3.32	0.048
Sv	1	0.010969	0.010969	0.60	0.4456
Sfs	1	0.000022	0.000022	0.00	0.973
Error	10	0.182163	0.018216	-	-
Total	17	0.526342	-	-	-

From these analysis, it may be concluded that only *Ton, Toff, Wp, Wt* and *Sv* has considerable impact on the MRR and *SR* whereas the other process parameters has no or negligible impact on the MRR and *SR*. The plot obtained from the ANOVA – Mini Tab Software depicting the variation of MRR and *SR* with the governing parameter.

3.3. Scanning electron microscopy (SEM)

Scanning Electron Microscopy (SEM) perspectives of the cutted surfaces were taken with a specific end goal to look at the impact of various wire types on machining of different work piece materials by examining surface integrity and attributes. The surface integrity comprises of roughness, size of pits and depth of a recast layer and heat affected zone that are examined in this area. Figure 6 (a, b) demonstrates the surface of nickel work pieces which are machined with brass wire materials.

From the examination of the surface attributes that are appeared in Fig. 6 (a, b), it is watched that fast brass wire brought about a poor surface completion. Additionally, it can be seen zinc coated wire creates less edge on the work piece surface observed in Fig. 7 (a, b). Low quality surfaces by uncoated wire results from the non-uniform thermal load on the sample. This non-uniform thermal load is because of non-uniform flash arrangement and insufficient flushing qualities. Improper flushing can also bring arc formation, which can promote harm the surface.

To be sure, the harmed layers comprise of 3 layers, in particular white layer, recast layer and heat affected zone. The recast layer is characterized as the material liquefied by electrical sparks and not removed by flushing. Same conclusions can be made when utilizing nickel work piece and different electrode materials as indicated by Fig. 7 (a, b). The heat-affected zone was observed to be restricted in its thickness and couldn't be recognized effectively. Therefore, the depth of harmed layer reported here was measured from the extreme surface to the end of recast zone. As appeared in Fig. 7 (a, b) the thickness of harmed layer of nickel machined with zinc coated wire is lower than the other one created by brass wire. Zinc coated wire has great electrical conductivity that helps the wire exchange energy to work piece effectively. At that point, it prompts apply low heat energy to the specimens' surface and decline the harmed layer framed. High cutting temperature, more energy conveyed to the work piece and solid grip between the electrode and the nickel lead to poor surface quality. These issues are made because of the low heat conductivity and high compound reactivity of titanium composites. The microstructures reveal a reduction in the grain size at the HAZ as compared to the base material there by increasing the hardness slightly in the region without significantly altering the brittleness. This technique is technically viable due to its higher accuracy and preciseness avoiding material loss and reduction in cost. In longer run, this technique for nickel/ nickel alloy cutting proves to be economical.

4. CONCLUSIONS

- The feasibility of WEDM for Nickel is established using RSM method. Further, the process parameters are optimized.
- In Brass wire, MRR mainly depends on the pulse of time (*Toff*) and surfaces roughness (*SR*) depends on the pulse on time (*Ton*), water pressure (*Wp*) and wire tension (*Wt*).
- In Zinc coated wire, MRR mainly depends on the pulse on time (*Ton*) and pulse off time (*Toff*) and servo voltage (*Sv*).
- Surfaces roughness (*SR*) depends on the pulse off time (*Toff*), water pressure (*Wp*) and wire tension (*Wt*).

ACKNOWLEDGEMENT

The authors thank the management and officials in CIPET, Chennai for extending WEDM facility to carry out this research study.

REFERENCES

Amitesh, G., Jatinder, K. (2012). An investigation into the machining characteristics of nimonic 80A using CNC wire-EDM. *Int. J. Adv. Engineering Technology* (*IJAET*) 3 (1), 170–174.

Esme, U., Sagbas, A., Kahraman, F. (2009). Prediction of surface roughness in wire electrical discharge machining using design of experiments and neural networks. *Iranian J. Sci. Technol., Transaction B, Engineering* 33 (B3), 231–240.

Hassan, M.A., Mehat, N.S., Sharif, S., Daud, R., Tomadi, S.H., Reza, M.S. (2009). *Study of the Surface Integrity of AISI 4140 Steel in Wire Electrical Discharge Machining*. Proceedings of the International Multi Conference of Engineers and Computer Scientists (IMECS 2009), Vol II, Hong Kong.

Kern, R. (2007). Properties of EDM wire. *EDM Today Journal* (Jan–Feb), 10–17. http://www.gedms.com/technicalArticles/TechTipsJ-F-7.pdf.

Khan, N., Wahid, M., Singh, S., Siddiquee, A., Khan, Z. (2013). A study on micro hardness in wire electrical discharge machining based on taguchi method. *Int. J. Mech. Produc. Eng.* 1 (1), 10–15.

Myers, R.H., Montgomery, D.C. (1995). *Response Surface Methodology: Process and Product optimization using designed experiments*. John Wiley & Sons, USA.

Myers, R.H., Montgomery, D.C., Anderson-Cook, Ch.M. (2009). *Response surface methodology: process and product optimization using designed experiments*. 3rd Edition, Wiley-Blackwell.

Ozcelik, B., Erzurmlu, T. (2005). Determination of effecting dimensional parameters on warpage of thin shell plastic parts using integrated response surface method and genetic algorithm. *Int. Commun. Heat Mass* 32 (8), 1085–1094. http://dx.doi.org/10.1016/j.icheatmasstransfer.2004.10.032.

Sharma, N., Khanna, R., Gupta, R. (2013). Multi quality characteristics of WEDM process parameters with RSM. *Procedia Engineering* 64, 710–719. http://dx.doi.org/10.1016/j.proeng.2013.09.146.

Sreenivasa Rao, M., Venkaiah, N. (2013). Review on Wire-Cut EDM Process. *Int. J. Adv. Trends in Computer Science and Engineering* 2 (6), 12–17.

Tariq Jilani, S., Pandey, P.C. (1984). Experimental investigations into the performance of water as dielectric in EDM. *Int. J. Mach. Tool D. R.* 24 (1), 31–43. http://dx.doi.org/10.1016/0020-7357(84)90044-1.