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ORIGINAL ARTICLE

# Investigation of wire electric discharge machining of stainless-clad steel for optimization of cutting speed

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## Abstract

The use of cladded materials has grown up in manufacturing industry as it provides a blend of properties in end-use applications. However, the cutting of a cladded material is really considered as a challenging task owing to their heterogeneous nature; therefore, it is often subjected to thermal cutting processes like gas cutting or plasma arc cutting. But thermal cutting processes offer poor surface finish and require subsequent finishing operations. Wire electric discharge machining (WEDM) is a competent alternate in terms of surface finish, but this process offers relatively low cutting rates. In this research work, an attempt has been made to evaluate and optimize the cutting performance of WEDM for cutting stainless-clad steel in terms of cutting speed which is one of the most crucial considerations in manufacturing. In addition to the commonly studied WEDM parametric effects, the influence of workpiece orientation, layer thickness of individual layer, wire diameter, and pressure ratio of dielectric fluid on the cutting speed is mainly evaluated. Taguchi's L18 orthogonal array has been used for experimental design. Optimal combinations of machining parameters to maximize the cutting speed are extracted through various statistical analyses, and it has been found that the proposed optimal set of parameters results into an improvement of about 20% in cutting speed in WEDM of stainless-clad steel. It has also been observed that the individual layer thickness of the cladded material plays a vital role in controlling the cutting speed of WEDM. The contribution of stainless steel layer thickness on cutting speed is found to be two times as compared to the contribution of mild steel layer.

**Keywords** WEDM · Stainless-clad steel · Cutting speed · Layer thickness · ANOVA

## 1 Introduction

The increasing demands of industry have led to the development of new materials, which are not only very hard but difficult to cut by any conventional machining process [1]. Wire electric discharge machining (WEDM) process has gained the popularity as a promising thermoelectric cutting mechanism for cutting such difficult-to-cut materials. In this thermoelectric process, material erodes by series of discrete electric sparks between the wire electrode and the workpiece. The temperature of spark reaches up to 8000 to 12,000 °C that causes melting and vaporization of the material. The debris produced in the process are flushed away by the flowing dielectric fluid which is continuously circulating [2, 3].

Wire EDM has a capability to machine harder, high-strength, and wear-resistant materials with high accuracy. The formation of complicated shapes that are difficult to form by conventional means can easily be produced using this cutting technique [4]. Conventional machining processes have

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many inherent problems like chatter, vibrations, and mechanical stresses which are eliminated in WEDM as there is no direct contact between workpiece and wire electrode [5]. WEDM has found its applications in various fields, such as dies and molds, aerospace, automotive, and medical industry [6]. Although, the machining performance of WEDM has been evaluated for variety of difficult-to-cut materials like titanium, stainless steels, ceramics, tool steels, and metal matrix composites [7–11]. The area of wire electric discharge machining of cladded material is still to be explored. No significant literature was found in this regard.

The use of cladded materials is growing in industry owing to their inherent advantage of having a blend of properties such as that copper is cladded with steel to combine the thermal and electrical properties of copper with the strength of steel and stainless steel is cladded to mild steel to improve the corrosion, oxidation, and abrasion resistance [12]. Cladded materials offer the desired level qualities at relatively low cost in comparison to use of a single solid alloy [13]. Claddings process can save up to 80% cost of using solid alloy [14]. Stainless-clad steel is a material commonly used in a variety of applications like in boilers, pressure vessels, tubings, fractionators, heat exchangers, reactors, and chemical plants etc. [15]. Stainless steel cladding improves the resistance against corrosion, abrasion, and oxidation whereas the backing material not only maintains the structural strength but also improves the thermal conductivity of the composite as well [13]. Stainless-clad steel is not only cheap and incredible but also offers durability as well [16]. Despite all the advantages of cladded materials, the cutting is considered very challenging. The heterogeneous nature of the material produces a variation in the cutting forces that leads to the damage of the cutting tool [17]. So, often, this material is subjected to thermal cutting by either plasma arc cutting or gas cutting [18]. Although these cutting processes are faster in terms of cutting speed, they yield poor surface finish that requires subsequent finishing operations and ultimately increasing the associated machining cost.

An appropriate level of surface finish is essential for proper weldability in various applications of stainless-clad steel. The scales formed at the cut surfaces by these processes pose a difficulty in machining. This is not only prolonging the manufacturing lead time of the product but also adds cost. Additionally, the formation of heat-affected zones is another quite prominent disadvantage of these cutting techniques [18]. These issues can be minimized using wire electric discharge machining process.

WEDM is an expensive and complex stochastic process controlled by a number of process variables. A minute change in the value of machining parameters may influence the WEDM process in a complex manner. Hence, it necessitates finding the optimal settings of control factors to maximize the process yield. The selection of optimum control factor combination is essential for obtaining higher cutting efficiency and accuracy in WEDM process.

Cutting speed and surface quality hold vital importance for governing the cutting efficiency of WEDM process [19, 20].

Numerous researches have been reported in the past related to this important response characteristic while cutting a variety of materials using WEDM. Ravindranadh Bobbili et al. [21] studied the effect of six WEDM input parameters, namely, pulse on time, pulse off time, servo voltage, wire feed, flushing pressure, and wire tension on cutting rate during WEDM high-strength armor steel. Cutting rate was found to be increased with the increase in pulse on time while the reverse seemed to be true for off time and servo voltage. In another study, carried on WEDM of Nimonic C-263 super alloy using multi-cut strategy, on time, off time, and servo voltage were found to be the most influential process parameters for cutting rate [22]. Cutting rate was also observed to be affected by arc off time, servo voltage, wire feed, and wire tension in WEDM of tungsten [23]. M. P. Gopal et al. [24] reported that pulse on time and reinforcement percentage were the two most influential parameters that affect cutting rate during WEDM of hybrid metal matrix composite (Mg/BN/CRT). In another research, the impact of WEDM input parameters on cutting speed during machining of titanium was evaluated. The study concluded that pulse on time, pulse off time, and servo voltage were the most contributing factors for cutting speed [25]. Pulse on time was proved to be the most influential factor for cutting speed in case of machining AISI D3 tool steel [26]. Vikram Singh et al. [27] reported that pulse on time, pulse off time, and servo voltage were the significant factors for cutting rate in WEDM of AISI D2 steel. Cutting speed increases with the increase in pulse on time and decreases with the increase in pulse off time and servo voltage in wire electric discharge cutting of Ti-6-2-4-2 Alloy [19]. The cutting performance of zinc-coated wire in terms of cutting speed was evaluated for machining high-speed steel (M2, SKH9) in another research work. Results revealed that pulse peak current, pulse duration, pulse off period, and wire feed were the influential parameters for selected response characteristic [28]. It was also reported that surface quality reduces as cutting rate increases. An increase in cutting rate was observed with the increase in dielectric fluid pressure whereas the reverse seemed to be true in the case of wire tension, linear velocity of wire, and dielectric electrical conductivity in WEDM of ASP30 steel. [29]. Machining feed rate was also seemed to have a significant effect on cutting rate. Increase in feed rate resulted in increasing the cutting rate [30]. Cutting rate was also observed to be influenced by pulse off time, power, and pulse frequency in WEDM of high-strength low-alloy (HSLA) steel [31]. The effect of wire diameter on cutting rate in WEDM was investigated in another research work. The study concluded that smaller-diameter wire was found to be the most effective for increasing the cutting rate [32].

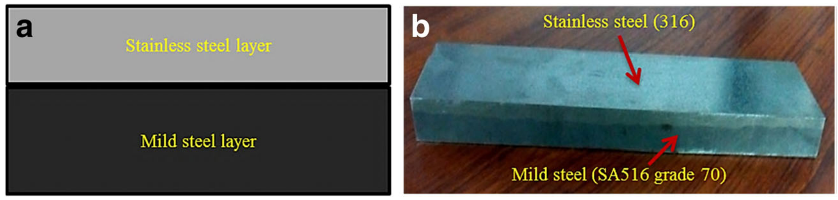


**Fig. 1** Workpiece material. **a** Schematic front view. **b** 3D view of workpiece material

Although considerable research has been carried out in the field of WEDM for a variety of materials, the area of cutting of cladded materials is still to be explored. The effect of cladded workpiece material factors like workpiece orientation and layer thickness of individual layer thickness on the performance of WEDM process is not specifically studied which is mainly carried out in this research. Furthermore, in addition to other common machining parameters, the focus is shifted to study the effect of wire diameter and pressure ratio of dielectric fluid on the cutting performance of WEDM for cladded material. Taguchi's L18 experimental design technique has been used to conduct the experimentation by considering workpiece orientation, layer thickness of each individual layer, wire diameter, servo voltage, wire feed, pressure ratio, and pulse on time as input factors. ANOVA and signal-to-noise ratio analysis have been performed to identify significant control factors and their optimal levels for optimum cutting speed, respectively. Finally, regression model for cutting speed during WEDM of stainless-clad steel has been developed and validated through confirmatory experiments.

## 2 Experimental details

Material selected in this research work is cladded material, comprises of two layers, i.e., stainless steel (SS316) layer and mild steel (SA 516 grade 70) layer joined by weld overlay process. Schematic and 3D view of workpiece material is shown in Fig. 1. The composition of the material taken as workpiece in current work is presented in Table 1. Optical emission spectrometry has been employed to verify the composition against standard ASTM composition using standard method ASTM E 1676-4. The workpiece material's selected physical mechanical, thermal, and electrical properties as taken from the literature [33–35] are shown in Table 2. In this study, rectangular-shaped blocks (7 mm × 4 mm) has been produced from various thickness specimens on CNC Wire EDM (CHEMER, Model: G43S). Actual experimental setup has been shown in Fig. 2.

Wire breakage is a very common problem that directly affects the cutting performance as well as cut quality. Therefore, the phenomenon of wire breakage has been taken into consideration during preliminary experimentation in order to minimize the chance of wire breakage. Hence, the factor levels used for mature experimentation under Taguchi L18 are so selected that wire breakage chances are minimum. Furthermore, the experiment/s in which wire was broken down those experimental runs were not considered true and repeated. Cutting speed was directly recorded from the machine control unit throughout the experiment, and then average value is reported. Additionally, to authenticate the reported values of cutting speed, a stopwatch has been used to record the time of cut for predetermined cut length of 24 mm during each experimental run. In this way, the cutting speed was manually calculated by dividing the total cut length to time consumed. Both values of cutting speed (machine recorded and manually calculated) have been found in good agreement.

The robust Taguchi's experimental technique has been used for the design of experiment. This efficient technique helps to determine the variation in any manufacturing process. The cost of the WEDM process and the time involved in

**Table 1** Workpiece composition

| Stainless steel layer | | | Carbon steel layer | | |
|---|---|---|---|---|---|
| Element | Actual (%) | ASTM (%) [33] | Element | Actual (%) | ASTM (%) [34] |
| C | 0.08 | 0.08 | C | 0.17 | 0.1–0.2 |
| Si | 0.83 | 0.75 | Si | 0.468 | 0.4–0.6 |
| Mn | 0.92 | 0.9–2 | Mn | 1.13 | 1–1.7 |
| P | 0.05 | 0.045 | P | 0.0420 | 0.03 |
| S | 0.013 | 0.03 | S | 0.0111 | 0.03 |
| Cr | 17.6 | 16–18 | – | – | |
| Mo | 2.36 | 2–3 | – | – | |
| Ni | 10.0 | 10–14 | – | – | |
| Fe | Balance | | Fe | Balance | |

**Table 2** Workpiece material properties [33–35]

| Physical/thermal properties [33, 34] | Stainless steel | Carbon steel | Mechanical properties [35] | | Electrical properties [33, 34] | |
|---|---|---|---|---|---|---|
| Density | 8.07 g/cm$^3$ | 7.8 g/cm$^3$ | Ultimate tensile strength | 595 MPa | Resistivity of stainless steel layer | $81 \times 10^{-6}$ Ω cm |
| Specific heat | 0.5 J/g-°C | 0.47 J/g-°C | Percentage elongation | 14.8% | Resistivity of mild steel layer | $17 \times 10^{-6}$ Ω cm |
| Thermal conductivity | 17 W/m-K | 52.0 W/m-K | Hardness of stainless steel layer | 50 (HRA) | Conductivity of stainless steel layer | $12.35 \times 10^{3}$ ohm$^{-1}$ cm$^{-1}$ |
| Coefficient of thermal expansion | 16 μm/m-°C | 12.0 μm/m-°C | Hardness of mild steel layer | 39 (HRA) | Conductivity of mild steel layer | $58.52 \times 10^{3}$ ohm$^{-1}$ cm$^{-1}$ |

experimentation were the main reasons for the selection of this design technique as it emphasizes the use of fewer experiments [36]. Experimentation was performed according to L18 orthogonal array with randomization. Eight input factors have been considered in this study, namely, workpiece orientation, stainless steel layer thickness, mild steel layer thickness, pressure ratio, pulse on time, wire feed, servo voltage, and wire diameter whereas cutting speed was the selected response. The selection of the WEDM parameters such as pressure ratio, pulse on time, wire feed, servo voltage, and wire diameter were based on the rationale that literature revealed those to be significant factors for the prescribed response [7, 27–29, 31, 32]. The remaining parameters were selected on the rationale that impact of these factors are yet to be evaluated on the mentioned response during wire EDM of stainless-clad steel. Preliminary experimentation was done for the selection of factor level values. Those settings of control factors were opted that have minimized the chance of wire breakage. Parameters other than control factors were kept constant. The resistivity of the dielectric was repeatedly observed from resistivity meter and kept maintained. Table 3 shows the factors and respective level values. It is worth noting that pressure ratio, workpiece orientation, and individual layer thickness of cladded material are not studied at all in open available literature. Pressure ratio is basically the ratio of upper nozzle flushing pressure to the lower nozzle flushing pressure whereas orientation means that cladded specimen can be placed in two different ways (orientation "A", stainless steel layer is at top; orientation "B", mild steel layer is at top) as shown in Fig. 3.

## 3 Results and discussion

Stainless-clad steel strips were cut on wire electric discharge machining as per Taguchi's experimental design technique (L18). A cut length of 24 mm was machined in each experimental run. For every time, machine has given due time for warm up. The workpiece was properly clamped to the machine bed and perpendicularity of the specimen was assured using set square. The results of the experimentation are tabulated in Table 4.

### 3.1 Analysis of variance

Analysis of variance (ANOVA) was carried out after recording of experimental results. ANOVA is a key statistical tool frequently used to assess the significant factors for the selected response characteristic. In this research, the confidence interval was set at 95% ($\alpha = 0.05$). Any factor having a $p$ value less than the defined alpha value (0.05) was considered to be the significant factor. Additionally, F-value also highlights the significance of a control factor for a particular response.

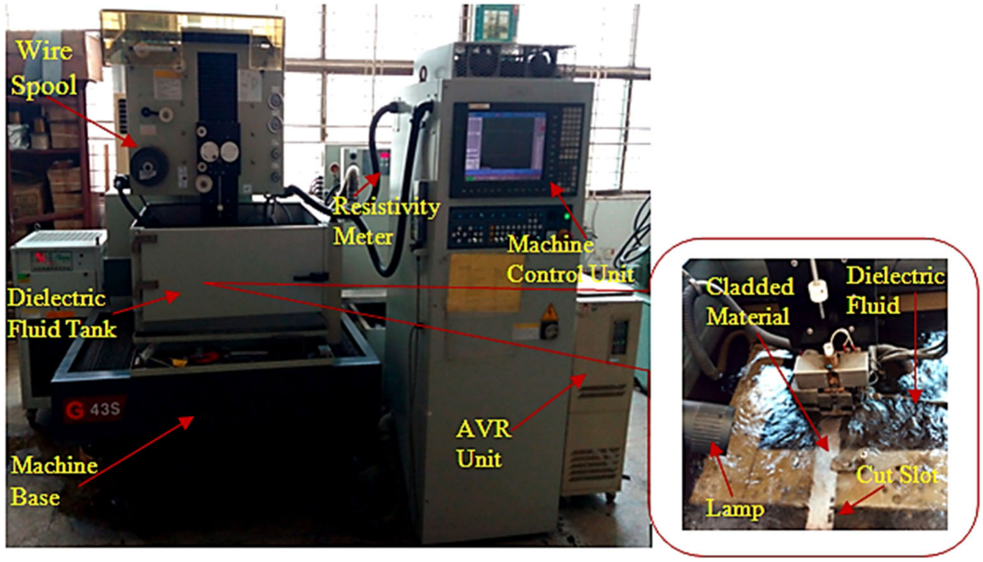


**Fig. 2** CNC wire cut machine

Higher F-value means that a minute change in the process parameter can cause a significant change in the response attribute [37]. Both F-value and *p* value were used as decision criteria for rating a control factor as significant in this study. The results of ANOVA for cutting speed in WEDM of stainless-clad steel are tabulated in Table 5.

It is evident from Table 5, presenting ANOVA for cutting speed, that the *p* values of four control factors, namely, pulse on time $P_{ON}$ (0.011); stainless steel layer thickness $LT_{SS}$ (0.024); wire diameter $W_D$ (0.027); and mild steel layer thickness $LT_{MS}$ (0.048), are lesser than the predefined alpha value (0.05) and also have higher F-values showing these factors to be significant for cutting speed. Pulse on time ($P_{ON}$) was found to be the most contributing control factor with respect to cutting speed during WEDM of stainless-clad steel having a percentage contribution of 42.3% followed by stainless steel layer thickness, wire diameter, and mild steel layer thickness having percentage contributions as 19.4, 17.5, and 9.6%, respectively. It is important to notice that the accumulative impact of layer thickness is about 37% in controlling the cutting speed which is fairly a large value of percentage contribution towards the prescribed response. Hence, due consideration should be given while selecting the individual layer thickness.

## 3.2 Parametric effects analysis

ANOVA revealed the significant control factors for cutting speed as previously discussed. The next step is to evaluate the trend of the control factors for cutting speed during WEDM of stainless-clad steel material. Main effects plot analysis has been carried out to perceive the trend of input control factors for the selected response as shown in Fig. 4.

### 3.2.1 Effect of pulse on time ($P_{ON}$)

The cutting speed was found to be mainly influenced by pulse on time ($P_{ON}$) as depicted from Table 5 (eighth row). It has been found from the main effects plot that with the increase in pulse on time from 3 to 5 μs, the cutting speed increases from ~1.8 to ~2.3 mm/min (approximately 28% increase) as presented in Fig. 4. Actually, with the increase in pulse on time ($P_{ON}$), electric spark duration prolongs which leads to increase

**Table 3** WEDM process parameters and their level values

| Levels (j) | Parameters (i) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Or Workpiece orientation[a] | $LT_{SS}$ SS layer thickness (mm) | $LT_{MS}$ MS layer thickness (mm) | $D_W$ Wire diameter (mm) | Pr Pressure ratio | SV Servo voltage (V) | $P_{ON}$ Pulse on time (μs) | $F_W$ Wire feed rate (mm/s) |
| 1 | A | 2 | 6 | 0.2 | 0.7 | 30 | 3 | 60 |
| 2 | B | 3 | 7 | 0.25 | 1 | 40 | 4 | 140 |
| 3 | – | 4 | 8 | 0.3 | 1.3 | 50 | 5 | 220 |

[a] Orientation "A" means that stainless steel layer is at the top and mild steel layer is at the bottom during wire electric discharge machining of workpiece. On the other hand, in the case of orientation "B," mild steel layer is at the top and stainless steel layer is at the bottom during machining

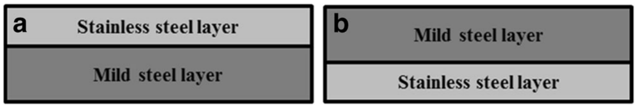


**Fig. 3** Workpiece orientations

in the amount of discharge energy produced. This increase in discharge energy tends to generate more heat for longer period of time which enhances the metal vaporization rate, and consequently, the cutting speed increases. Although the increase in pulse on time tends to increase the cutting speed, at the same time, the depth of crater produced also increases owing to the generation of larger discharge energy. Figures 5 and 6 present the two scenarios in this regard. In Fig. 5, cladded specimen is subjected to maximum value of pulse on time (5 μs) for WEDM whereas, in Fig. 6, the machining has been performed at a pulse on time of 3 μs. Scanning electron microscope (SEM) micrographs have been taken for both the conditions as presented in Figs. 5 and 6. It has been observed that the machined surface contain craters, spherical modules, and melted re-deposits. The formation of these craters is due to a succession of sparks. The generation of spherical module on the machined surface is attributed to the surface tension of molten material. On the other hand, melted re-deposits formed by the melted debris that were not flushed away by the dielectric fluid rather re-solidified on the machined surface. The SEM micrographs taken for both machining conditions clearly indicate that the machined surface is more irregular having deeper crater and larger melted re-deposits at higher pulse on time as shown in Fig. 5. However, in the case of lower value of pulse on time, the machined surface seemed to have a better surface quality as described in Fig. 6. It is interesting to note that the surface texture of the stainless steel layer is observed to be better in comparison to the mild steel layer surface texture. It is attributed to the fact that both the materials have different electrical conductivities. Owing to this difference in electrical conductivities, different spark strengths have been produced at the machined surface. The spark produced against the surface of mild steel is more intense in comparison to the spark formed in front of the stainless steel layer. Thus, more material is melted and removed from mild steel layer producing deeper craters and lager melted re-deposits as compared to stainless steel layer. Consequently, the machined surface of stainless steel layer seemed to be better in comparison to mild steel layer as shown in Figs. 5 and 6. A similar kind of trend of pulse on time with respect to cutting speed was also reported by other researchers during WEDM of AISI D3 tool steel [26].

### 3.2.2 Effect of layer thickness ($LT_{SS}$ and $LT_{MS}$)

The effect of individual layer thickness was found to be opposite to that of pulse on time ($P_{ON}$) as shown in Fig. 4. This is attributed to the reason that with the increase in the layer thickness of each layer, the overall thickness of the specimen increases which offers a larger contact area and as a result larger target for vaporization. Hence, more heat is required that prolongs the time for machining larger workpiece thickness which resulted into a decrease in cutting speed. It has been noticed that with the increase in stainless steel layer

**Table 4** Experimental results according to Taguchi's L18 design

| Exp. No. | Or | $LT_{SS}$ (mm) | $LT_{MS}$ (mm) | $D_W$ (mm) | Pr | SV (V) | $P_{ON}$ (μs) | $F_W$ (mm/s) | Cutting speed (mm/min) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | A | 2 | 6 | 0.30 | 0.7 | 30 | 3 | 60 | 2.07 |
| 2 | A | 2 | 7 | 0.20 | 1.0 | 40 | 4 | 140 | 2.38 |
| 3 | A | 2 | 8 | 0.25 | 1.3 | 50 | 5 | 220 | 2.15 |
| 4 | A | 3 | 6 | 0.30 | 1.3 | 40 | 5 | 140 | 2.32 |
| 5 | A | 3 | 7 | 0.20 | 0.7 | 50 | 3 | 220 | 1.99 |
| 6 | A | 3 | 8 | 0.25 | 1.0 | 30 | 4 | 60 | 2.07 |
| 7 | A | 4 | 6 | 0.20 | 1.0 | 30 | 5 | 220 | 2.31 |
| 8 | A | 4 | 7 | 0.25 | 1.3 | 40 | 3 | 60 | 1.66 |
| 9 | A | 4 | 8 | 0.30 | 0.7 | 50 | 4 | 140 | 1.50 |
| 10 | B | 2 | 6 | 0.25 | 1.0 | 50 | 3 | 140 | 1.87 |
| 11 | B | 2 | 7 | 0.30 | 1.3 | 30 | 4 | 220 | 2.01 |
| 12 | B | 2 | 8 | 0.20 | 0.7 | 40 | 5 | 60 | 2.59 |
| 13 | B | 3 | 6 | 0.20 | 1.3 | 50 | 4 | 60 | 2.22 |
| 14 | B | 3 | 7 | 0.25 | 0.7 | 30 | 5 | 140 | 2.55 |
| 15 | B | 3 | 8 | 0.30 | 1.0 | 40 | 3 | 220 | 1.42 |
| 16 | B | 4 | 6 | 0.25 | 0.7 | 40 | 4 | 220 | 2.04 |
| 17 | B | 4 | 7 | 0.30 | 1.0 | 50 | 5 | 60 | 1.87 |
| 18 | B | 4 | 8 | 0.20 | 1.3 | 30 | 3 | 140 | 1.68 |

**Table 5** ANOVA results for cutting speed

| Source | DF | Seq SS | Adj SS | Adj MS | F-value | P-value | % contribution |
|---|---|---|---|---|---|---|---|
| Or | 1 | 0.002 | 0.002 | 0.002 | 0.50 | 0.555 | 0.12 |
| $LT_{SS}$(mm) | 2 | 0.366 | 0.366 | 0.183 | 40.01 | *0.024* | 19.4 |
| $LT_{MS}$(mm) | 2 | 0.181 | 0.181 | 0.091 | 19.82 | *0.048* | 9.6 |
| $D_W$(mm) | 2 | 0.330 | 0.33 | 0.165 | 36.04 | *0.027* | 17.5 |
| SV (V) | 2 | 0.106 | 0.106 | 0.053 | 11.60 | 0.079 | 5.6 |
| $F_W$(mm/s) | 2 | 0.026 | 0.026 | 0.013 | 2.88 | 0.257 | 1.4 |
| Pr | 2 | 0.066 | 0.066 | 0.033 | 7.21 | 0.122 | 3.5 |
| $P_{ON}$ (μs) | 2 | 0.798 | 0.798 | 0.399 | 87.16 | *0.011* | 42.3 |
| Error | 2 | 0.009 | 0.009 | 0.005 | | | 0.6 |
| Total | 17 | 1.886 | | | | | |
| Model summary: S = 0.068, R-Sq = 99.51%, R-Sq(adj) = 95.87% | | | | | | | 100 |

thickness ($LT_{SS}$) from 2 to 4 mm, the cutting speed reduces from 2.17 to 1.84 mm/min (approximately 17.7% decrease), and the cutting speed decreases from 2.14 to 1.902 mm/min (~ 12.5% decrease) with the increase in mild steel layer thickness ($LT_{MS}$) from 6 to 8 mm. It has also been observed that the influence of stainless steel layer thickness ($LT_{SS}$) on cutting speed (having percentage contribution of ~ 19.4%) is more in comparison to mild steel layer thickness $LT_{MS}$ (having percentage contribution of ~ 9.6%) as indicated by ANOVA results presented in Table 5.

The percentage contribution of stainless steel layer thickness ($LT_{SS}$) is approximately double than that of mild steel layer thickness ($LT_{MS}$). It is because of the reason that stainless steel has lower electrical conductivity ($12.35 \times 10^3$ $ohm^{-1}$ $cm^{-1}$), lower thermal conductivity (17 W/m K), and higher density (8.07 $g/cm^3$) as compared to mild steel layer (as can be seen from Table 2). In WEDM, the amount of discharge energy produced during machining is primarily responsible for the material erosion process. The generation of this discharge energy is mainly influenced by the electrical characteristics (mainly electrical conductivity) of the workpiece material. Electrical conductivity of the workpiece material has a significant effect on the cutting rate in WEDM [38]. The higher the electrical conductivity of workpiece material, the higher is the cutting rate. Similar findings regarding electrical conductivity effect on cutting speed in WEDM were reported during cutting of Al/SiCp-MMC [39]. Cutting speed was found to be higher in cutting Al-matrix material as compared to Al/SiCp-MMC material as Al/SiCp-MMC has lower electrical and thermal conductivity. The more the value of electrical conductivity, the more will the spark strength be. Hence, more discharge energy is produced that resulted into higher material erosion rates. Therefore, cutting speed increases with the rise in the value of electrical conductivity of the target material. As the electrical conductivity of mild steel layer ($LT_{MS}$) is higher than of stainless steel layer ($LT_{SS}$), it is

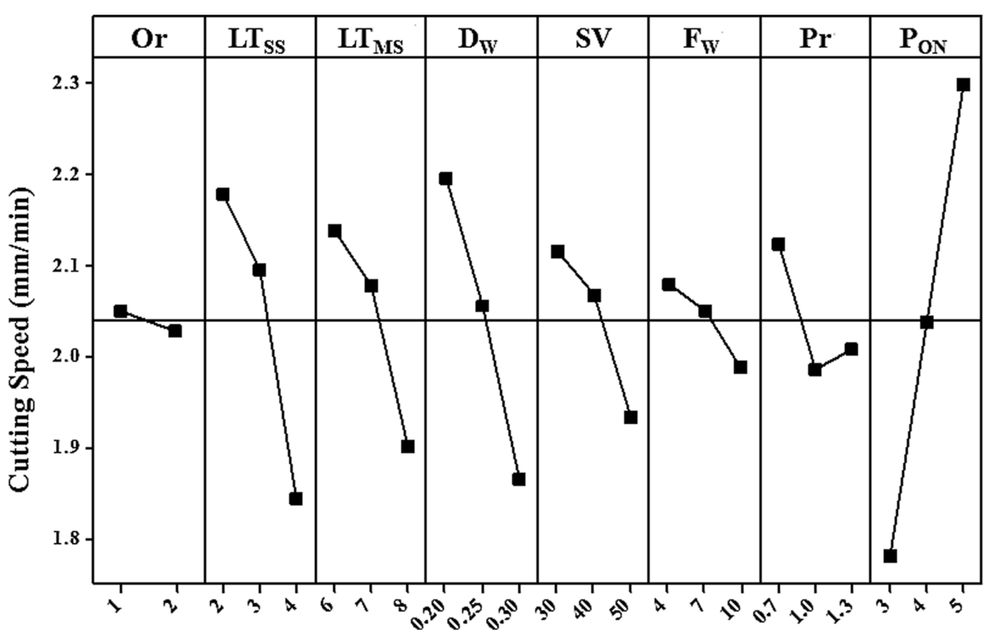


**Fig. 4** Main effects plot analysis for cutting speed

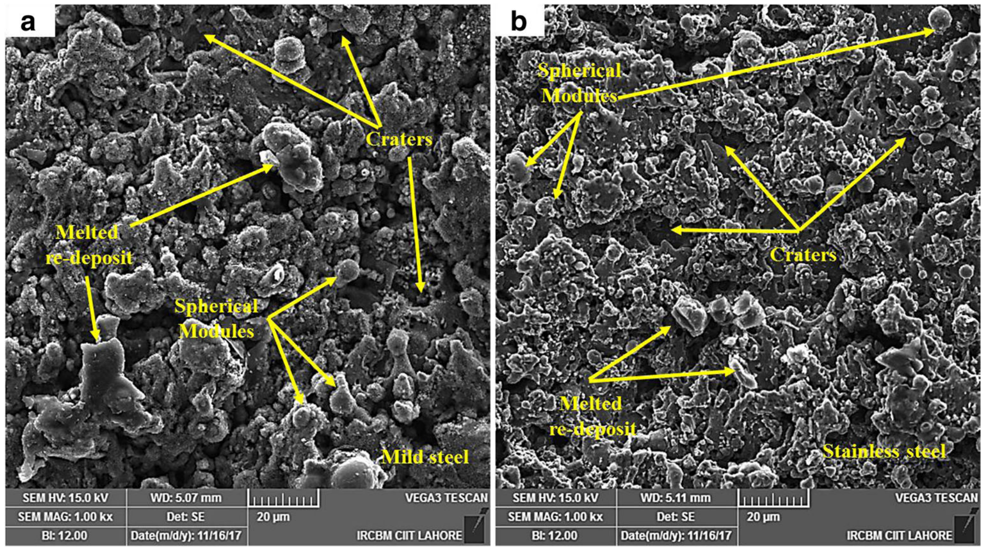


**Fig. 5** SEM micrograph of machined surface at pulse on-time of 5 μs; (**a**) mild steel layer, (**b**) stainless steel layer

subjected to more powerful spark as compared to stainless steel layer which enhances the vaporization rate of mild steel layer. However, in stainless steel layer ($LT_{SS}$), due to its lower electrical conductivity, erosion of material takes more time. Hence, the stainless steel layer offers a hindrance to the wire feed inside the material although the wire has already produced a cut in the mild steel layer, thus acting as a limiting factor for cutting of stainless-clad steel that is why percentage contribution of stainless steel layer thickness ($LT_{SS}$) is approximately double than that of mild steel layer thickness ($LT_{MS}$).

### 3.2.3 Effect of wire diameter ($W_D$)

The impact of wire diameter ($W_D$) on cutting speed was found to be similar as that of layer thickness as can be seen from Fig. 4. The cutting speed increases from ~ 1.86 to ~ 2.2 mm/min as wire diameter ($W_D$) decreases from 0.3 to 0.2 mm (approximately 17.6% increase in cutting speed). Actually, with the increase in diameter of wire, the exposed surface area of the wire to the workpiece also increases. Therefore, a wider area of the workpiece is to be vaporized which not only requires more heat but also consumes more time. This, in turn, reduces the wire feed in the workpiece compared to small diameter wire ($W_D$). Thus, cutting speed reduces with the increase in wire diameter ($W_D$). A similar trend of wire diameter ($W_D$) on cutting speed was described in wire electric discharge machining of Inconel 706 [32].

### 3.2.4 Effect of workpiece orientation (Or)

The effect of workpiece orientation (Or) on cutting speed has been found to be quite minimal (insignificant as per ANOVA results) as depicted from Fig. 4. Although, the improvement in cutting speed is not significant (about 2%), the orientation of the workpiece plays its role on controlling cutting speed of WEDM. This improvement is observed if the workpiece is placed in orientation "A" (stainless steel layer is on top) as compared to

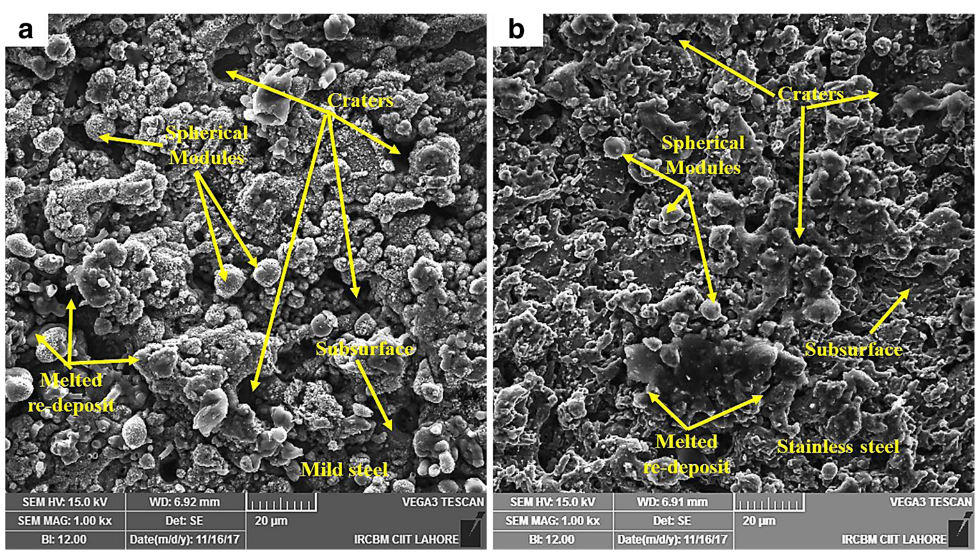


**Fig. 6** SEM micrograph of machined surface at pulse on-time of 3 μs; (**a**) mild steel layer, (**b**) stainless steel layer

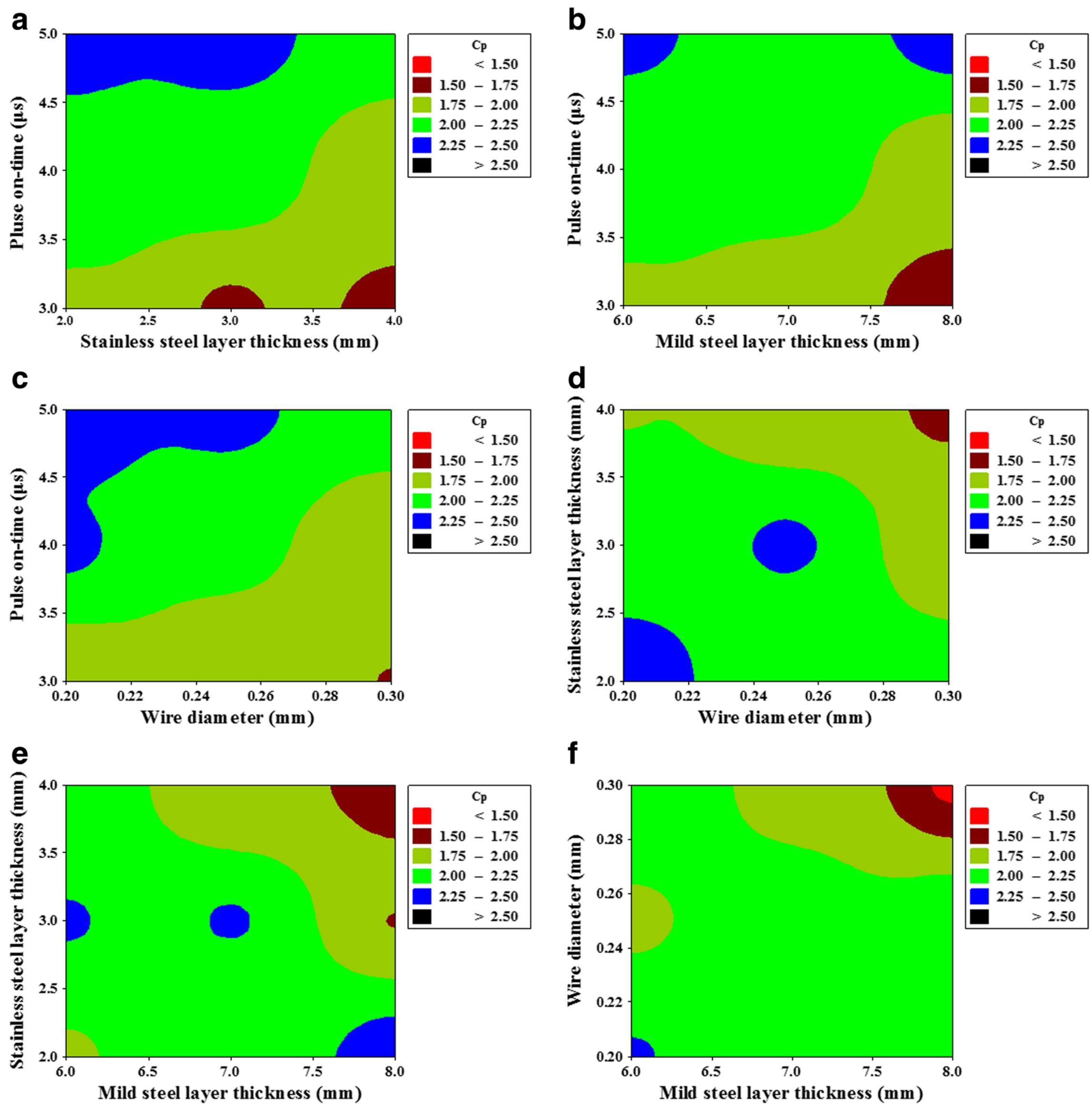


**Fig. 7** Contour plots for cutting speed. **a** $P_{ON}$ Vs $LT_{SS}$. **b** $P_{ON}$ vs $LT_{MS}$. **c** $P_{ON}$ vs $D_W$. **d** $LT_{SS}$ vs $D_W$. **e** $LT_{SS}$ vs $LT_{MS}$. **f** $W_D$ vs $LT_{MS}$

orientation "B" (mild steel layer is on top). Thus, while cutting stainless-clad steel through WEDM, the preferred placement of the workpiece should be in such a way that the stainless steel should be at the top, i.e., the wire starts cutting with stainless steel layer and ends with mild steel layer.

### 3.2.5 Effect of pressure ratio (Pr)

Pressure ratio (Pr) is basically the ratio of upper flushing nozzle pressure to lower nozzle flushing pressure. It is evident from Fig. 4 that cutting speed would be better if the flushing pressure of the upper nozzle is kept higher in comparison to lower nozzle flushing pressure. An improvement of about 6.89% has been observed in cutting speed by using the abovementioned setting of flushing pressure (Pr, 0.7). It might be due to the fact that using such combination of dielectric flushing pressures results into better flushing of debris. If the flushing of debris is not properly carried out, it will not only lead to wire breakage but also prolong the cutting duration. Hence, appropriate value (0.7) of dielectric pressure ratio (Pr) provides a cleaner cutting gap that subsequently results into higher cutting speed.

### 3.2.6 Effect of wire feed ($F_W$)

As per the results of the main effect plot analysis, increase in wire feed ($F_W$) seemed to have a negative impact on the cutting speed as presented in Fig. 4. By increasing the wire feed ($F_W$), the cutting speed drops down as the contact duration of

**Table 6** Response table for signal-to-noise ratios (larger is better)

| Level | Or | $LT_{SS}$ | $LT_{MS}$ | $D_W$ | SV | $F_W$ | Pr | $P_{ON}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 6.2 | 6.7 | 6.6 | 6.8 | 6.4 | 6.3 | 6.4 | 5.0 |
| 2 | 6.0 | 6.3 | 6.3 | 6.2 | 6.1 | 6.1 | 5.8 | 6.1 |
| 3 | | 5.2 | 5.4 | 5.3 | 5.7 | 5.9 | 6.0 | 7.2 |
| Delta | 0.2 | 1.5 | 1.2 | 1.5 | 0.8 | 0.4 | 0.7 | 2.2 |
| Rank | 8 | 2 | 4 | 3 | 5 | 7 | 6 | 1 |

the wire electrode with the workpiece becomes short and inappropriate sparking occurs, the result of which is low cutting speed. For example, increasing wire feed from 60 to 220 mm/s, the cutting speed reduces from 2.08 to 1.988 mm/min (about 4.6% reduction).

#### 3.2.7 Effect of SV

The behavior of servo voltage (SV) is alike as that of layer thickness with respect to cutting speed. The decrease in servo voltage (SV) from 50 to 30 V increases the cutting speed from 1.93 to 2.12 mm/min (approximately 9.8% increase) as shown in Fig. 4. Actually, the SV is responsible for maintaining a safe distance between the wire electrode and the workpiece to avoid short circuiting. The increase in the value of SV makes the wire electrode stay at a bit farther distance from the workpiece material; thus, the amount of discharge energy transferred to the specimen reduces. This reduction in energy prolongs the metal vaporization rate. As a result, cutting speed reduces.

### 3.3 Contour plot analysis

Contour plot analysis has been carried out to evaluate the optimal ranges of the significant factors obtained from ANOVA results (Table 5), for the selected response variable. Figure 7 shows the contour plot for cutting speed considering the contributing factors for cutting speed, i.e., pulse on time and stainless steel layer thickness, wire diameter, and mild steel layer thickness as input variables.

In all the contour plots, the region highlighted by blue color represents the optimal ranges of the significant control factors for higher cutting speed during WEDM of stainless-clad steel material. Figure 7a–c represents the contour plots among pulse on time $P_{ON}$ versus stainless steel layer thickness ($LT_{SS}$), mild steel layer thickness ($LT_{MS}$), and wire diameter ($W_D$). It has been found from the contour plots (Fig. 7a–c) for cutting speed during WEDM of stainless-clad steel that pulse on time ($P_{ON}$) of about 4.5–5 μs, stainless steel layer thickness ($LT_{SS}$) of ~ 2–3 mm, mild steel layer thickness ($LT_{MS}$) of ~ 6 mm, and wire diameter ($W_D$) of about 0.2–0.22 mm resulted into higher cutting speed. This increase in cutting speed is owing to the fact that the amount of discharge energy produced increases by the selection of the mentioned factor values which in turn promotes the material melting and vaporization rate.

As a result, cutting speed increases, but on the other hand, this increase in discharge energy also produces more irregular-machined surface as shown in Fig. 5. The depth of craters produced are deeper at higher cutting speed. The contour plot of stainless steel layer thickness ($LT_{SS}$) versus wire diameter ($W_D$) further shows that stainless steel layer thickness ($LT_{SS}$) of about 2–2.4 mm and wire diameter ($W_D$) of ~ 0.2–0.22 mm provides higher cutting rates as shown in Fig. 7d. As stainless-clad steel material has to be used as a composite material, the optimal combination of the layer thickness of both the layers that resulted into faster cutting are either 2 mm stainless steel layer thickness ($LT_{SS}$) and 8 mm mild steel layer thickness ($LT_{MS}$) or 3 mm stainless steel layer thickness ($LT_{SS}$) and 7 mm mild steel layer thickness ($LT_{MS}$) as described by contour plot (Fig. 7e) of $LT_{SS}$ versus $LT_{MS}$, among the selected nine combinations of layer thicknesses. The contour plot (Fig. 7f) of $W_D$ versus

**Table 7** Optimal levels of input variables for selected response features

| Sr. No. | Input WEDM parameters | Notation | Optimal settings for cutting speed | | |
|---|---|---|---|---|---|
| | | | Optimal levels | Level value | Units |
| 1 | Orientation | "Or" | 1 | A | – |
| 2 | SS layer thickness | "$LT_{SS}$" | 1 | 2 | mm |
| 3 | MS layer thickness | "$LT_{MS}$" | 1 | 6 | mm |
| 4 | Wire diameter | "$D_W$" | 1 | 0.2 | mm |
| 5 | Servo voltage | "SV" | 1 | 30 | V |
| 6 | Wire feed | "$F_W$" | 1 | 60 | mm/s |
| 7 | Pressure ratio | "Pr" | 1 | 0.7 | – |
| 8 | Pulse on time | "$P_{ON}$" | 3 | 5 | μs |

**Table 8** Confirmatory experiment results for cutting speed

| Factors settings | Levels of parameters | Pred. value (mm/min) | Exp. value (mm/min) | Error (%) | Pred. S/N ratio (dB) | Exp. S/N ratio (dB) | Error S/N ratio (%) |
|---|---|---|---|---|---|---|---|
| Optimal settings | Or1, $LT_{SS}1$, $LT_{MS}1$, $D_W1$, SV1, $F_W1$, Pr1, $P_{ON}3$ | 2.88 | 3.1 | 7.6% | 9.82 | 9.5 | 3% |
| Non-optimal settings | Or2,$LT_{SS}1$, $LT_{MS}3$, $D_W1$, SV2, $F_W1$, Pr1, $P_{ON}3$ | 2.6 | 2.59 | 0.3% | 8.31 | 8.3 | 0.5% |
| Percentage improvement in response value | | 19.7% | | | Percentage improvement in S/N ratio | | 15.4% |

$LT_{MS}$ emphasizes that wire diameter of 0.2 mm and mild steel layer thickness of about 6 mm has given faster cutting rates.

### 3.4 Parametric optimization

As per the results of contour plot analysis, optimal settings have been identified within selected range of control factors. A need has been established to find the best possible combination of control factor levels that results into higher cutting rate. Signal-to-noise (S/N) ratio method was used for the optimization of the selected response variables as literature mentioned this technique to be of significant importance for parametric optimization [40]. Based on the selected response characteristic, larger-the-better S/N ratio (higher cutting speed) has been used in this research work. The formulas for calculating the said S/N ratio is presented in Eq. 1 [40]:

$$\eta ij = -10 log\left(1/n \sum_{k=1}^{n} \frac{1}{Y_{ij}^2}\right) \quad (1)$$

where $\eta_{ij}$ is the S/N ratio of $i$th response characteristic in $j$th experiment, $n$ represents the number of tests, and $Y_{ij}$ is the actual value of the $i$th response variable (cutting speed) in the $j$th experimental run. The results of S/N ratio analysis are presented in Table 6.

In S/N ratio analysis, not only optimal levels of control factors are found rather factor classification based on their significance towards the selected response characteristic has also been done by calculating the delta value of each control factor as indicated by the Table 6 (fifth row).

Higher delta value of a control factor highlights the higher significance towards the prescribed response and has higher rank. Pulse on time ($P_{ON}$) has found to have a rank of 1 followed by stainless steel layer thickness ($LT_{SS}$, rank 2), wire diameter ($W_D$, rank 3), mild steel layer thickness ($LT_{MS}$, rank 4), servo voltage (SV, rank 5), pressure ratio (Pr, rank 6), wire feed ($F_W$, rank 7), and workpiece orientation (Or, rank 8) in WEDM of stainless-clad steel. The control factor significance has also been evaluated using ANOVA and was found exactly the same as revealed by the S/N ratio analysis thus validating the results of ANOVA. Graphical description of S/N ratio analysis is found exactly alike as that of main effect plot analysis and thus not shown herein. Based on the results of the S/N ratio analysis, optimal settings of cutting speed are developed. These settings are tabulated in Table 7.

**Table 9** ANOVA for cutting speed for multiple linear regression

| Source | DF | Seq SS | Adj SS | Adj MS | F | *P* value |
|---|---|---|---|---|---|---|
| Regression | 4 | 1.63 | 1.63 | 0.41 | 20.8 | 0.0000149 |
| Error | 13 | 0.26 | 0.26 | 0.02 | | |
| Total | 17 | 1.89 | | | | |

It is evident from Table 7 that orientation (Or) A is the preferred orientation (stainless steel layer at top) for the selected response. However, level 1 of stainless steel layer thickness $LT_{SS}$ (2 mm), mild steel layer thickness $LT_{MS}$ (6 mm), wire diameter $W_D$ (0.2 mm), servo voltage SV (30 V), wire feed $F_W$ (60 mm/s), and pressure ratio Pr (0.7) and level 3 of pulse on time $P_{ON}$ (5 μs) are found to be the optimal settings for cutting speed in WEDM of stainless-clad steel workpiece material.

### 3.5 Confirmatory tests

Based on the S/N ratio analysis, optimal settings have been developed as presented in Table 7. To validate the optimal parametric combinations, confirmatory experiment has been performed to maximize the cutting speed in wire electric discharge machining of stainless-clad steel. Equation 2, as described by A. Mohammadi et al. [41], has been used to envisage the S/N ratio using optimum levels:

$$\begin{aligned}\eta pr = \eta om + (\eta Or - \eta om) + (\eta LT_{SS} - \eta om) \\ + (\eta LT_{MS} - \eta om) + (\eta D_W - \eta om) \\ + (\eta SV - \eta om) + (\eta F_W - \eta om) \\ + (\eta Pr - \eta om) + (\eta PON - \eta om) \quad (2)\end{aligned}$$

Here, $\eta_{om}$ is representing the overall mean S/N ratio whereas $\eta_O$, $\eta_{ST}$, $\eta_{MT}$, $\eta_{WD}$, $\eta_{SV}$, $\eta_{WF}$, $\eta_{PR}$, and $\eta_{PON}$ are showing the S/N ratios of control factors at their optimum levels (Or1, $LT_{SS}1$, $LT_{MS}1$, $W_D1$, SV1, $F_W1$, Pr1, $P_{ON}3$). The results of

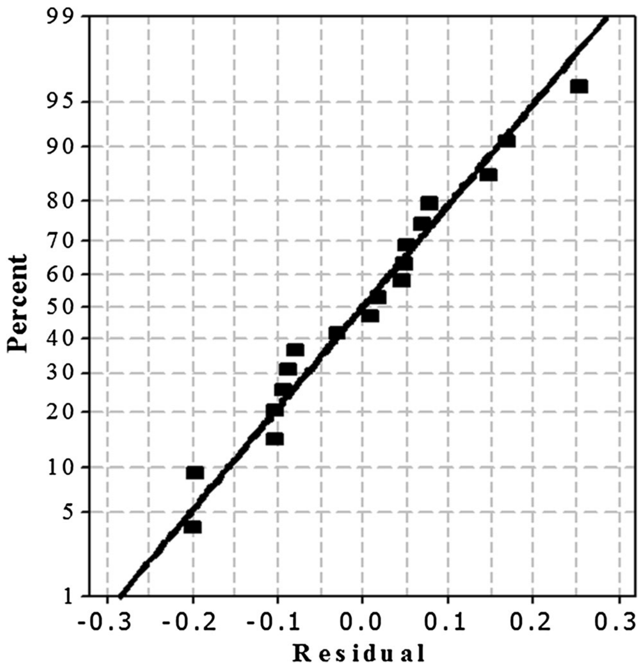


**Fig. 8** Normal probability plots of residuals for cutting speed

confirmatory experiment are shown in Table 8. Optimal settings are the settings of control factors that are found based on the said analysis for maximizing the cutting speed whereas non-optimal settings accounts for that experimental run (Exp. No. 12) which gives the maximum cutting speed under the designed experimentation. It has been found that by using optimal settings of control factors as shown in Table 8, about 20% improvement is there in cutting speed from the maximum value of cutting speed recorded during experimentation, and 15.4% improvement in S/N ratio of cutting speed has been observed. Percentage error in response value and S/N ratio of the response characteristic has also been calculated. It has been noticed that percentage error in both the scenarios is quite low, i.e., 7.6% in response value and 3% in S/N ratio of cutting speed.

### 3.6 Mathematical modeling

Mathematical relationship of WEDM input parameters with the response variables has been established in this part of the study using multiple linear regression analysis. The basic equation of multiple linear regression model is shown as Eq. 3 [42]:

$$Y = b_0 + b_1X_1 + b_2X_2 + \ldots + b_NX_N \quad (3)$$

In Eq. 4, "$Y$" represents the value of response variable whereas $X1 \ldots X_N$ are the values of predictor variables, and $b_0$ is regression constant when the value of all the predictors are set at zero. The coefficients $b_1 \ldots b_N$ are showing the anticipated change in mean response for each unit change in the predictor value. The least square method has been opted for calculating the constants and coefficients. Only those control factors have been considered for the development of regression model that are found to be significant for the selected response. The regression model for cutting speed is described by Eq. 4:

**Table 10** Percentage error in experimental and predicted cutting speeds

| Exp. No. | Exp. cutting speed (mm/min) | Pred. cutting speed (mm/min) | % error |
|---|---|---|---|
| 1 | 2.1 | 1.9 | 8.8 |
| 2 | 2.4 | 2.3 | 0.3 |
| 3 | 2.2 | 2.3 | 8.4 |
| 4 | 2.3 | 2.3 | 3.1 |
| 5 | 2.0 | 1.9 | 2.5 |
| 6 | 2.1 | 1.9 | 7.8 |
| 7 | 2.3 | 2.4 | 4.3 |
| 8 | 1.7 | 1.6 | 2.9 |
| 9 | 1.5 | 1.6 | 5.5 |
| 10 | 1.9 | 2.1 | 9.6 |
| 11 | 2.0 | 1.9 | 0.1 |
| 12 | 2.6 | 2.5 | 3.1 |
| 13 | 2.2 | 2.3 | 4.4 |
| 14 | 2.6 | 2.3 | 11 |
| 15 | 1.4 | 1.5 | 5.2 |
| 16 | 2.0 | 1.9 | 0.1 |
| 17 | 1.9 | 2.0 | 4.8 |
| 18 | 1.7 | 1.7 | 1.2 |
| Average percentage error | | | 4.8 |

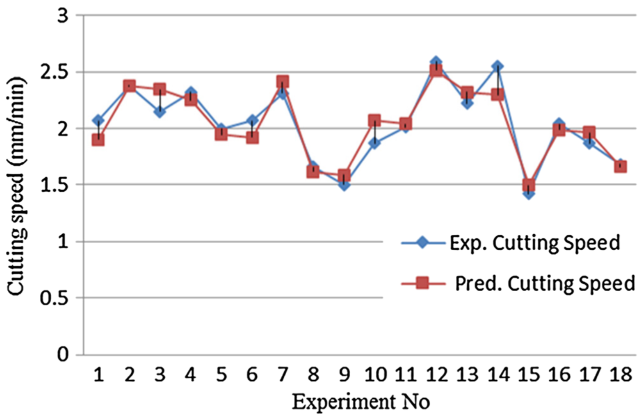


**Fig. 9** Comparison between exp. and pred. values of cutting speed

$$\textit{Cutting speed} = 3.16508 - 0.16775LT_{SS} - 0.118333LT_{MS} - 3.30333D_W + 0.25791P_{ON} \quad (4)$$

where "$LT_{SS}$," "$LT_{MS}$," "$D_W$," and "$P_{ON}$" are representing stainless steel layer thickness (mm), mild steel layer thickness (mm), wire diameter (mm), and pulse on time (μs), respectively. The developed regression model is then validated by ANOVA at 95% confidence interval. It has been found that the purposed model has a $p$ value less alpha value ($\alpha = 0.05$) as presented in Table 9 (second row) showing that the developed model is statistically significant.

The adequacy of the model is often accessed by normal probability plot analysis [43]. Moreover, normal probability plot of residuals for the cutting speed has also been drawn as shown in Fig. 8. Normal probability plot has shown that residuals are normally distributed for the said response, highlighting that the adequacy of the proposed model is very high. Furthermore, validity of the developed model has also been checked by forecasting the response value for each experimental run performed as per experimental design by using the developed Eq. 4. It has been found that an error of just 4.8% occurs between the model predicted and the experimental values of cutting speed. The detailed errors (between model predicted and experimental values) against each experimental run are presented in Table 10. The same has also been shown graphically in Fig. 9.

It is evident from Fig. 9 that there exists a slight difference between experimental and predicted values of cutting speed. Even there are certain data points like experiments number 2, 5, 12, and 18 where the difference is lesser than 1%. The maximum difference between experimental and predicted cutting speed has been observed in experiment number 14 as indicated in Fig. 9.

The average error calculated between experimental cutting speed and predicted cutting speed in WEDM of stainless-clad steel comes out to be 4.8%.

## 4 Conclusions

In this work, the effect of workpiece and process-related factors on the cutting performance of WEDM in terms of cutting speed has been studied for cutting stainless-clad steel. Experimentation has been carried out according to Taguchi's L18 orthogonal array followed by comprehensive statistical analyses (ANOVA, contour plot, S/N ratio analysis, and regression analysis) to access and quantify the effect of significant control factors on the response characteristic. Based on the results and discussion, the following conclusions may possibly be drawn:

1. Higher values of pulse on time ($P_{ON}$) results into the high cutting speed whereas increase in wire diameter ($W_D$) and layer thickness of individual layer ($LT_{SS}$ and $LT_{MS}$) lowers down the cutting rate.
2. Pulse on time ($P_{ON}$) is found to be the most significant factor with a percentage contribution of 42.3% for cutting speed in WEDM of stainless-clad steel. Whereas, the stainless steel layer thickness ($LT_{SS}$), wire diameter ($W_D$), and mild steel layer thickness ($LT_{MS}$) are the factors significantly contributing towards controlling the cutting speed with percentage contributions 19.4, 17.5, and 9.6%, respectively.
3. Cutting speed is also affected by the overall thickness of workpiece. Higher workpiece thickness results into low cutting speed and lower thickness offers high cutting speed.
4. The contribution of stainless steel layer thickness ($LT_{SS}$) to the cutting speed is twofold as compared to the thickness of mild steel layer ($LT_{MS}$). The main reason behind this is the difference in the thermo-electrical properties (especially electrical and thermal conductivity) of stainless steel and mild steel.
5. Workpiece orientation does not significantly affect the cutting speed. However, orientation A (stainless steel layer at the top) is observed to be the preferred orientation for better cutting speed.
6. S/N ratio analysis reveals that the optimal settings for maximum cutting speed during WEDM of stainless-clad steel are pulse on time ($P_{ON}$) at 5 μs, stainless steel layer thickness ($LT_{SS}$) at 2 mm, wire diameter ($W_D$) at 0.2 mm, mild steel layer thickness ($LT_{MS}$) at 6 mm, servo voltage (SV) at 30 V, wire feed ($F_W$) at 60 mm/s, and pressure ratio (Pr) at 0.7.
7. With respect to the maximum cutting speed (2.59 mm/min) obtained during experimental runs performed under

DOE, an improvement of about 20% in the cutting speed (3.1 mm/min) has been achieved by using the purposed optimal combinations of control factors

8. Regression model has been developed to predict the value of cutting speed during WEDM of stainless-clad steel. It has been inferred that the developed model predicts the cutting speed with an average error of 4.82% showing the high degree of congruity of experimental and predicted values.

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