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Effect of process parameters on cutting speed of wire EDM process in machining HSLA steel with cryogenic treated brass wire

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ABSTRACT

Wire electrical discharge machining (wire EDM), a most common non-conventional machine tool, is extensively employed to produce precise, delicate and intricate profiled shaped parts especially from hard to machine materials. The performance of wire EDM is mainly based on the electrical conductivity of both electrode wires and workpiece materials. The aim of research is to increase cutting speed (*CS*) of high strength low alloy (HSLA) hardened steel by determining main contributing input process parameters and effect of cold treatment on electrical conductivity of brass wire at –70 °C. Fractional factorial design is used to determine the relationship of *CS* with input process parameters includes; open voltage, pulse on time, pulse off time, wire tension, flushing pressure of deionized water and brass wires (cold treated – CT, and non-cold treated – NCT). Empirical model for *CS* is developed based on selected input process parameters and their contribution is analyzed through ANOVA technique. It is learned that pulse on time, pulse off time and wire electrode are the main contributing input process parameters that provide assistance to increase *CS* of wire EDM. In wire electrodes, cold treated brass wire is observed as a best alternative to enhance machining performance with an increase of electrical conductivity by 24.5 %.

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1. Introduction

Electric discharge machining (EDM) principle based on erosion phenomena in which high frequency electric sparks removes material of conductive alloys [1]. Inadequacy of conventional machining processes for the machining of intricate and aero profiled shapes of extremely hard materials compels the manufacturer to use non-conventional machine tools. Based on the principle of electric discharge machining, WEDM used wire as cutting tool for machining of intricate profiles with high accuracy [2]. Nowadays, non-conventional machining processes are getting more attention of manufacturer due to less burr formation, residual stresses and low tooling cost [3]. Tools, molds and dies having complex shapes which are mostly used in automobile, aerospace and surgical industries are commonly manufactured by EDM [4].

In electric discharge machining, a series of electric sparks are produced between workpiece and electrode. Current is discharged from the electrode to the workpiece in the presence of dielectric fluid with a very little spark gap in the range of 1/1,000,000 of a second or less [5]. The heat of each electric spark (8,300-11,650 °C), erodes workpiece material in the form of tiny bits that are vaporized and melted from the workpiece surface. Deionized water is mostly used as dielectric fluid, also flushed away debris from tool and workpiece interface. It is noticed that process time of machining is reduced with increase in pulse on time and spark current intensity as compare to pulse off duration [6, 7]. Usually the tools used in WEDM process are tungsten, molybdenum and brass wire. Wire electrodes used in WEDM for cutting having diameter ranges from 0.05-0.3 mm [8].

2. Literature review

In highly competitive and globalized environment, it is necessary for industrial practitioner to work on value added manufacturing techniques to deliver quality product to the customer well in time. It has been seen that in electric discharge machining the properties of electrode significantly affect the machining performance [9]. Different treatments are being developed to improve the mechanical and electrical properties of cutting tools to reduce manufacturing time. It includes also sub-zero treatments of cutting tools other than thermal and coating techniques. A substantial improvements have been seen with sub-zero treatments in physical (wear resistance, hardness, tensile strength etc.), electrical and thermal properties of cutting tools as compared to thermal and coating techniques [10].

Sub-zero or cryogenic treatment is a low temperature processing normally used to alter physical and electrical properties of materials includes wear resistance, electrical conductivity, toughness, dimensional stability etc. Sub-zero treatments with feasible lower most temperature has been classified in three different categories: Cold treatment with a temperature range of 223-193K, shallow cryogenic treatment ranges from 193-113 K and deep cryogenic treatment ranges from 113-77 K [11]. Cutting tools of conventional machining (turning, milling, drilling etc.) have been cryogenically treated to enhance wear resistance, hardness, toughness for better cutting performance.

A limited research has been reported on the cryogenic treatment of wire electrode in WEDM process. A detailed literature study carried out by Kumar *et al.* [10] which clearly depicts the benefits of sub-zero treatment of electrode and workpiece in EDM that are presented in Table 1 and Table 2 respectively. The effects of sub-zero treatment have been analysed on the basis of material removal rate *MRR*, tool wear rate *TWR*, and surface roughness *SR*. Brass wire which mainly consists of zinc (63-65 %) and copper (35-37 %), provide helps to deliver more usable energy to the machined surface area by electric discharges [17]. Addition of zinc contents contribute to increase tensile strength and vapour pressure ratio on account of decrease in electrical conductivity [18].

Sharma *et al.* [8] found that pulse on time T_{on} and pulse off time T_{off} are the main contributing factors for cutting speed in WEDM process for HSLA steel. Maximum *MRR* has been reported while machining at optimum range of T_{on} (3-4μs) and T_{off} (14-16 μs) using Response surface methodology for high speed steel (HRC 62), [25]. Moly wire has been used for the machining of hardened HSLA steel (30CrMnSiA) and found that higher cutting speed *CS* obtained at lower pulse frequency and T_{off} with higher value of power [26]. Selvakumar *et al.* [27] observed that T_{on} and peak current are the most significant input parameters for cutting speed in trim cut while using aluminium AA5083 alloy. Bhuyan *et al.* [28] used Central composite design to investigate the effects of peak current, pulse on time T_{on} and flushing pressure F_{p} on material removal rate. Multi objective optimization of experimental investigation has been performed using overall evaluation criteria, entropy weight measurement and fuzzy logic techniques.

Singh *et al.* [29] compared zinc coated cryogenically treated brass wire with simple cryogenically treated brass wire as electrode to investigate their effects on cutting performance of AISI D3 die steel. Their results indicate that zinc coated cryogenically treated brass wire yields better *MRR* using Taguchi L9 array for experimental design. Kapoor *et al.* [16] also used deep cryogenically (−184 °C) treated brass wire and simple brass wire as electrode. Taguchi design has been used to investigate the effects of process parameters on *MRR*. Wire type (cryogenic treated wire) has been observed as most effective input parameter followed by pulse width, pulse duration and wire tension.

Table 1 Summary of cryogenic treated electrodes in non-conventional machining [6]

First author [ref.] (Year)	Electrode Tool	Work material	No. of samples	Non-conventional machining	Key findings		
					TWR	*MRR*	*SR*
Sundaram [12] (2009)	Copper	Be-Cu	16	EDD	NC	↑	NR
Kumar [13] (2012)	Copper	Inconel 718	18	Additive Mix EDM	NR	↑	NR
Jafferson [14] (2013)	copper, brass, tungsten	AISI 304	NR	Micro EDM	↓	NR	NR
Sharma [15] (2015)	copper, brass, graphite	AISI D3	3	EDM	58 %↓	↑	↓
Kapoor [16] (2012)	Brass	En-31	9	EDM	NR	↑	NR

↑, increase; ↓, decrease; NC, no change; NR, not reported;

Table 2 Summary of cryogenic treated workpiece in non-conventional machining [6]

First author [ref.] (year)	Work piece material	Tool material	Number of samples	Non-conventional machining	Key findings		
					SR	*MRR*	*TWR*
Gill [19] (2010)	Ti-6246	Electrolyte copper	18	EDD	...	↑8.5 %	↓34.78 %
Yildiz [20] (2011)	Be-Cu	Copper electrode	2	EDM	...	↑30 %	...
Kumar [21] (2014)	Ti, Ti-6Al-4 V and Ti-5Al-2.5Sn	Copper, Copper–Chromium, Copper–Tungsten	1	EDM	...	↑	...
Jatti [22] (2014)	NiTi	Electrolyte copper	5	EDM	...	↑19 %	...
Khanna [23] (2016)	D3		27	WEDM	↓10.6 %	↓5.6 %	...
Goyal [24] (2017)	D2	Copper electrode	3	EDM	↓	↑	↓

↑, increase; ↓, decrease;

The present work studied the effect of cold treated brass wire on the machining performance of HSLA steel using Fractional factorial design 2^{6-1}_{VI}. Experiments are run using different combinations of input process parameters including open voltage, pulse on time, pulse off time, wire type (cold treated – CT, and non-cold treated – NCT), wire tension, flushing pressure of dielectric fluid. This experimentation will certainly useful for industry practitioners to improve productivity by increasing *CS* based on developed empirical models for both CT and NCT brass wires.

3. Materials and methods

This section consists of complete description of CT process for brass wire, testing procedure to measure the significant changes after CT process, Fractional factorial design to execute the WEDM process to analyze the effect of input variables on *CS* of HSLA hardened steel (50-51 HRC).

In the presented research, the following abbreviations are used:

WEDM, Wire EDM	wire electric discharge machining	T_{off}	pulse off time
HSLA	high strength low alloy	W_{t}	wire type
CT	cold treated	T_{w}	wire tension
NCT	non cold treated	F_{p}	flushing pressure
ANOVA	analysis of variance	*MRR*	material removal rate
CS	cutting speed	*TWR*	tool wear rate
OV	open voltage	*SR*	surface roughness
T_{on}	pulse on time		

3.1 Cold treatment of brass wire

Temperature chamber (CTT-SC-7520-02FI) is used for the cold treatment of brass wire. The soaking process is carried out at –70 °C for 24 hours at a ramp rate of 2 °C/min. Universal testing machine (Sintech 65G) is used to measure the tensile strength of both CT and NCT brass wires as per ASTM E8M standard while electrical conductivity is measured by portable Kelvin Bridge tester. It is observed that after CT process, electrical conductivity of brass wire is increased by 24.8 % whereas tensile strength is reduced by 5.64 % as showed in Table 3.

Table 3 Brass wire properties

Properties	NCT wire	CT wire	% change	
Tensile Strength (MPa)	727	686	5.64	↓
Electrical Conductivity(S/m)	12.5×10^6	15.6×10^6	24.8	↑

↑, increase; ↓, decrease

3.2 Workpiece material

HSLA steel contains alloying elements as shown in Table 4. It includes Cr, Mn, Si which are responsible for its better strength, forming, impact toughness and corrosion resistant properties. High strength to weight ratio and corrosion resistance of these alloys is the main reason of being widely used in aerospace industry. The carbon content along with other constituent elements makes it a hardened steel alloy.

Spectromax-Ametek® is used to test chemical composition of workpiece material. Specified Index range and actual elemental composition of this steel are enumerated in Table 4. A plate with dimensions of $100 \times 200 \times 15$ mm^3 is hardened by quenching and tempering heat treatment process given in Table 5. After heat treatment, hardness of specimen plate is observed in range of 50-51 HRC measured by hardness tester (INDENTEC:6187.5LK) with diamond indenter of cone angle 120° using minor load of 10 kg and test load of 150 kg.

Table 4 Chemical composition of workpiece material

Comp.	C	Si	Mn	Cr	Cu	Ni	Mo	V	P
weight %	0.29	1.55	0.8	1.1	<0.25	<0.25	0.45	0.09	<.015

Table 5 Heat treatment cycle of HSLA steel

HT Process	Temp. (°C)	Soaking time (min)	Cooling medium
Quenching	920	60	Oil (25 °C)
Tempering	300	160	Air

3.3 Design of experiment

In design of experiment, a full factorial design is considered an appropriate design provide the information of all main effects and all level of interactions (two/three way or of higher orders). However, it seems difficult to run large number of experiments using full factorial design. Fractional factorial design is a reasonable option to evaluate the responses with large number of input parameters [30].

In the present study, Fractional factorial design is selected to evaluate the machining performance based on CS using process parameters OV, T_{on}, T_{off}, W_{t}, T_{w} and F_{p}. The ranges of input process parameters are as follows; OV (75-120) V, T_{on} (1-8) μs, T_{off} (10-48)μs, W_{t} (CT and NCT), T_{w} (4-10) g and F_{p} (3-7) l/min. In design matrix NCT wire is coded as –1 and CT wire as 1 as shown in Table 6. For experimentation, 25 mm length of test pieces is machined with CNC CHMER WEDM. The CT and NCT brass wires of 0.3 mm are used as electrode. Cutting speed is determined by using the expression $CS = L/T$ (mm/min), where L is the length of workpiece in mm and T is the time in min.

Table 6 Design matrix with response values

Run No.	Input process parameters						Response variable
	A: Open voltage (OV)	B: Pulse on time (T_{on})	C: Pulse of time (T_{off})	D: Wire type (W_t)	E: Wire tension (T_w)	F: Flushing pressure (F_p)	Cutting speed (CS)
	V	μs	μs	-	G	l/min	mm/min
1	120	8	48	1	4	3	2.4
2	75	8	48	1	10	3	1.8
3	75	1	48	-1	4	7	0.19
4	120	8	48	-1	10	3	1.66
5	120	8	10	1	10	3	3.5
6	75	8	10	-1	10	3	2.14
7	75	1	48	-1	10	3	0.16
8	75	1	10	1	10	3	1.02
9	120	8	10	-1	10	7	3.05
10	75	1	10	1	4	7	0.77
11	75	8	10	-1	4	7	2.14
12	75	8	10	1	4	3	2.89
13	75	1	10	-1	4	3	0.85
14	120	1	48	-1	10	7	0.42
15	120	1	48	-1	4	3	0.41
16	75	8	48	-1	4	3	1.03
17	120	1	10	-1	4	7	0.697
18	120	8	48	1	10	7	2.31
19	120	1	48	-1	10	3	0.566
20	75	1	48	1	10	7	0.4
21	120	8	48	-1	4	7	1.58
22	75	1	48	1	4	3	0.62
23	120	8	10	1	4	7	3.5
24	120	1	10	1	4	3	1.3
25	120	1	48	1	4	7	0.79
26	120	1	10	-1	10	3	0.697
27	75	1	10	-1	10	7	0.394
28	75	8	10	1	10	7	2.83
29	120	8	10	-1	4	3	2.8
30	75	8	48	-1	10	7	1.11
31	75	8	48	1	4	7	1.9
32	120	1	10	1	10	7	1.67

4. Results and discussion

4.1 Statistical modeling and analysis

In statistical analysis, developed regression model depicts the relationship between CS and input process parameters (OV, T_{on}, T_{off}, W_t, T_w and F_p). Mathematical model for CS in term of coded variables is represented in Eq. 1.

$$CS = 1.5 + 0.23 \cdot OV + 0.79 \cdot T_{on} - 0.39 \cdot T_{off} + 0.29 \cdot W_t + 0.1 \cdot T_w - 0.13 \cdot F_p + 0.078 \cdot OV \cdot T_{on} \quad (1)$$

The model for cutting speed is significant as its p-value is less than 0.05 shown in Table 7. Analysis of variance reveals that OV, T_{on}, T_{off} and W_t are significant parameters for cutting speed as they have p-value less than 0.05 whereas T_w and F_p impart little contributions. The value of R^2 is 0.984 which indicates that the developed model for CS is adequate. The predicted R^2 is 0.9646 which isclosed to adjusted R^2 of 0.9771. Adequacy precision ratio is 39.587 indicates an adequate signal as it is more than 4 that is desirable [9].

The Normal plot of residuals in Fig. 1(a) clearly shows errors are normally distributed as residuals which are closer to normal straight line with minor deviations. In Fig. 1(b), plot of residuals versus predicted values confirmed the statistical assumption of independence and constant variance are not varied. It almost reflects the same pattern and structure from left to right.

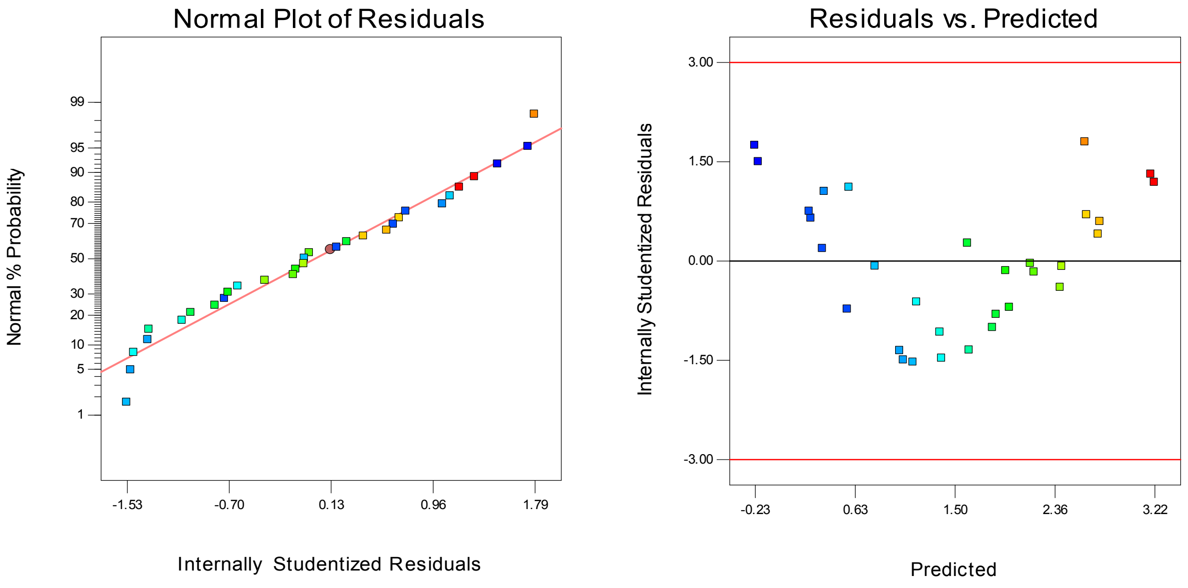
Table 7 ANOVA of model and process variables

Source	Sum of squares	Degree of freedom	Mean square	F value	p-value Prob > F	% Contribution
Model	30.35	9	3.37	143.13	< 0.0001	Significant
A: OV	1.65	1	1.65	69.92	< 0.0001	5.51
B: T_{on}	19.24	1	19.24	816.43	< 0.0001	64.34
C: T_{off}	4.73	1	4.73	200.9	< 0.0001	15.83
D: W_t	2.56	1	2.56	108.68	< 0.0001	8.56
E: T_w	9.45E-04	1	9.45E-04	0.04	0.8432	Not significant
F: F_p	5.02E-03	1	5.02E-03	0.21	0.6491	Not significant
AB	0.19	1	0.19	7.9	0.0105	Not significant
BC	0.92	1	0.92	38.88	< 0.0001	3.06
BD	0.12	1	0.12	4.99	0.0364	0.39
Residual	0.49	21	0.024			
Cor. total	30.85	30				
Std. Dev.		0.15	R^2		0.984	
Mean		1.52	Adj. R^2		0.9771	
C.V. %		10.12	Pred. R^2		0.9646	
PRESS		1.09	Adeq. Precision		39.587	

4.2 Effects of process parameters on cutting speed

In WEDM, mainly heat energy removes a very small portion of material by melting and evaporating workpiece material. Discharge process occurred several times in a second during pulse on time which erodes and vaporizes the material. High value of Ton substantially increases machine's *CS* as depicted in Fig. 2(a).

Conversely, high value of T_{off} a decrease in *CS* as shown in Fig. 2(b). Process of re-solidification can be reduced by selecting minimum value of T_{off}. For higher production rates, lower value of T_{off} is desired. However, if T_{off} is too short, the eroded debris not properly contributes to reduce the deionization process of dielectric fluid.



(a) (b)

Fig. 1 (a) Normal plot of residuals, (b) Residual vs. predicted

On the other hand, Fig. 2(c) shows an increase value of electrical conductivity of brass wire by CT process which significantly improves the *CS* with more powerful spark explosions. The effect of *OV* on *CS* has been presented in Fig. 2(d). High voltage produces more energetic pulses leads to increase the *CS*. However, water pressure and wire tension has shown no major contribution (as shown in Table 7) on *CS* as compare to other selected input parameters. Combined effect of significant parameters (*OV*, T_{on} and T_{off}) on *CS* are also considered through contour plots shown in Fig. 2. The Fig. 2(a) shows combined effects of T_{on} and T_{off} on cutting speed. This helps the practitioners to select the desirable value of CS by adjusting T_{on} and T_{off}. Contour plot of T_{on} and OV is shown in Fig. 2(b).

Contour lines with different CS values are shown in Fig. 3. Contour lines provide the option to choose different values of input parameters for the same value of CS. For example, in Fig. 3(a), a number of combinations on a similar contour line of T_{on} and T_{off} can be selected to achieve a CS of 1.7556 mm/min. Similarly, CS of 1.2860 mm/min can be achieved by selecting open voltage and pulse on time in Fig. 3(b).

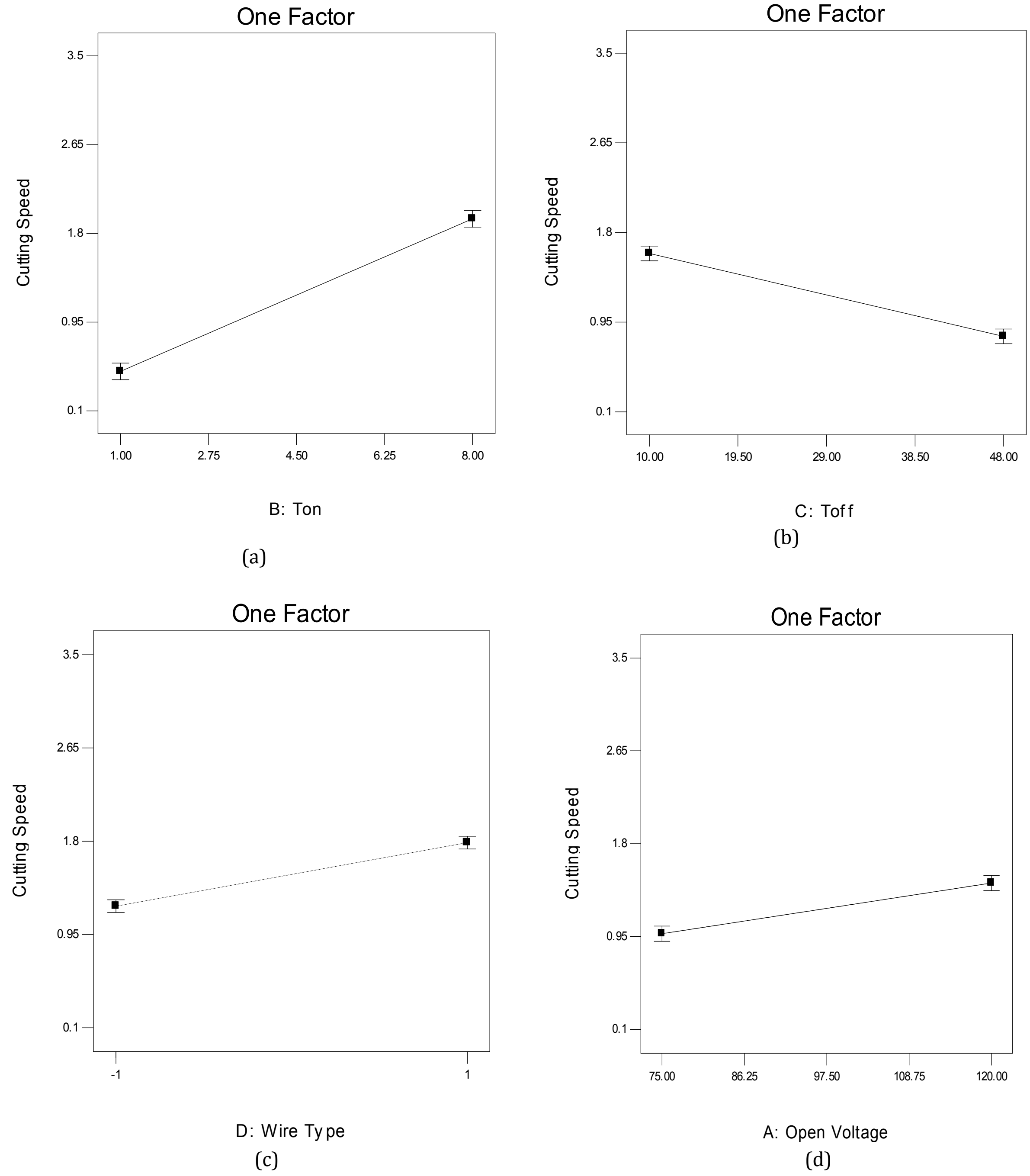
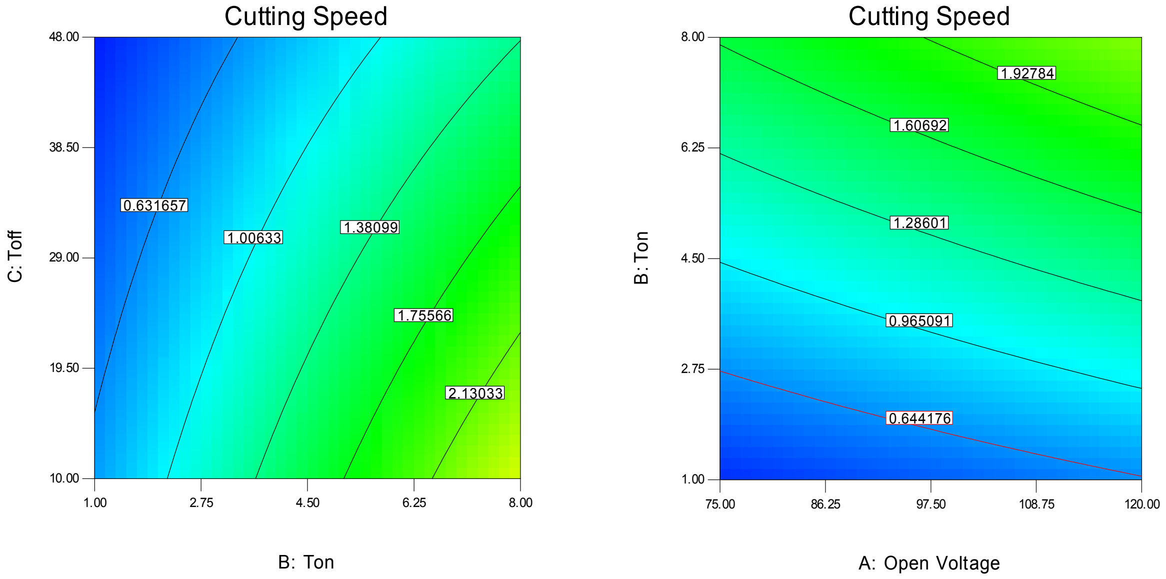


Fig. 2 (a) Effect of T_{on} on CS (b) Effect of T_{off} on CS (c) Effect of W_{t} on CS (d) Effect of OV on CS



(a) (b)

Fig. 3 Contour plots for (a) T_{on} and T_{off} vs. CS (b) OV and T_{on} vs. CS

4.3 Validation tests

Additional experiments have been conducted to validate the statistical model mentioned in Eq. 2 and Eq. 3 for cutting speeds CS_{CT} and CS_{NCT} in case of CT and NCT wires, respectively.

$$CS_{\mathrm{CT}} = 0.396 + 0.00585 \cdot OV + 0.223 \cdot T_{\mathrm{on}} - 0.00899 \cdot T_{\mathrm{off}} + 0.00185 \cdot T_{\mathrm{w}} \tag{2}$$

$$CS_{\mathrm{NCT}} = -0.0224 + 0.00585 \cdot OV + 0.187 \cdot T_{\mathrm{on}} - 0.00899 \cdot T_{\mathrm{off}} + 0.00185 \cdot T_{\mathrm{w}} \tag{3}$$

Treatment combinations with predicted and actual response are presented in Table 8 which clearly shows that percentage error is less than 5 %. These validation runs satisfy the developed model as mentioned in Eq. 2 and Eq. 3 based on fractional factorial design. This model can be used as a reference for production of HSLA steel to determine the CS by using these input parameters.

Table 8 Experimentation confirmations

Trial No.	Open voltage	Pulse on time	Pulse off time	Wire type	Wire tension	Flushing pressure	Cutting speed		
							Predicted	Actual	% Error
1	110	7	15	NCT	6	5	2.26	2.157	4.6
2	110	7	15	CT	6	5	2.94	2.854	2.9
3	80	4	25	NCT	8	4	1.017	1.05	3.2
4	80	4	25	CT	8	4	1.5	1.559	3.9

5. Conclusion

In this study, an attempt is made to determine the effect of cold treated brass wire with other main contributing factors OV, T_{on} and T_{off} for the machining of HSLA at 51 HRC. From the present research following conclusions can be drawn:

- Improvement in wire conductivity is responsible for reduced machining time with an increase of electrical conductivity by 24.5 % by cold treatment process for 24 hours. However, it reduces the tensile strength by 3.6 %.
- Pulse on time and pulse off time are the main contributing factors for cutting speed with percentage contributions of 64.34 % and 15.83 % respectively.

- Contour plots provide assistance to select optimal process parameters with a simple and efficient way. Maximum cutting speed 2.1 mm/min can be achieved by setting T_{on} and T_{off} values in range of about 6.5-8.0μs and 10-20 μs respectively with the help of contour plot.

In future, both surface roughness and formation of recast layers on HSLA specimens can also be studied and analyzed by using multi objective approach.

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References

[1] El-Hofy, H. (2005). *Advanced machining processes: Nontraditional and hybrid machining processes,* McGraw-Hill, New York, USA.

[2] Soni, H., Sannayellappa, N., Rangarasaiah, R.M. (2017). An experimental study of influence of wire electro discharge machining parameters on surface integrity of TiNiCo shape memory alloy, *Journal of Materials Research,* Vol. 32, No. 16, 3100-3108, doi: 10.1557/jmr.2017.137.

[3] Mohd Abbas, N., Solomon, D.G., Bahari, Md.F. (2007). A review on current research trends in electrical discharge machining (EDM), *International Journal of Machine Tools and Manufacture,* Vol. 47, No. 7-8, 1214-1228, doi: 10.1016/j.ijmachtools.2006.08.026.

[4] Chen, Z., Zhang, Y., Zhang, G., Huang, Y., Liu, C. (2017). Theoretical and experimental study of magnetic-assisted finish cutting ferromagnetic material in WEDM, *International Journal of Machine Tools and Manufacture,* Vol. 123, 36-47, doi: 10.1016/j.ijmachtools.2017.07.009.

[5] Singh, B., Misra, J.P. (2016). A critical review of wire electric discharge machining, In: Katalinic, B. (ed.), *DAAAM International Scientific Book 2016,* DAAAM International, Vienna, Austria, doi: 10.2507/daaam.scibook.2016.23.

[6] Jameson, E.C. (2001). *Electrical discharge machining*, Society of Manufacturing Engineers, Michigan, USA.

[7] Sommer, C., Sommer, S. (2005). *Complete EDM Handbook,* Advance Publishing, Texas, USA.

[8] Sharma, N., Khanna, R., Gupta, R.D., Sharma, R. (2013). Modeling and multiresponse optimization on WEDM for HSLA by RSM, *The International Journal of Advanced Manufacturing Technology,* Vol. 67, No. 9-12, 2269-2281, doi: 10.1007/s00170-012-4648-4.

[9] Raza, M.H., Wasim, A., Ali, M.A., Hussain, S., Jahanzaib, M. (2018). Investigating the effects of different electrodes on Al6061-SiC-7.5 wt% during electric discharge machining, *The International Journal of Advanced Manufacturing Technology,* Vol. 99, No. 9-12, 3017-3034, doi: 10.1007/s00170-018-2694-2.

[10] Singla, A.K., Singh, J., Sharma, V.S. (2018). Processing of materials at cryogenic temperature and its implications in manufacturing: A review, *Materials and Manufacturing Processes,* Vol. 33, No. 15, 1603-1640, doi: 10.1080/10426914.2018.1424908.

[11] Mohan Lal, D., Renganarayanan, S., Kalanidhi, A. (2001). Cryogenic treatment to augment wear resistance of tool and die steels, *Cryogenics,* Vol. 41, No. 3, 149-155, doi: 10.1016/S0011-2275(01)00065-0.

[12] Sundaram, M.M., Yildiz, Y., Rajurkar, K.P. (2009). Experimental study of the effect of cryogenic treatment on the performance of electro discharge machining, In: *ASME 2009 International Manufacturing Science and Engineering Conference,* West Lafayette, Indiana, USA, Vol. 2, 215-222, doi: 10.1115/MSEC2009-84247.

[13] Kumar, A., Maheshwari, S., Sharma, C., Beri, N. (2012). Machining efficiency evaluation of cryogenically treated copper electrode in additive mixed EDM, *Materials and Manufacturing Processes,* Vol. 27, No. 10, 1051-1058, doi: 10.1080/10426914.2011.654151.

[14] Jafferson, J.M., Hariharan, P. (2013). Machining performance of cryogenically treated electrodes in microelectric discharge machining: A comparative experimental study, *Materials and Manufacturing Processes,* Vol. 28, No. 4, 397-402, doi: 10.1080/10426914.2013.763955.

[15] Sharma, A., Grover, N.K., Singh, A. (2015). Effect of current and deep cryogenic treated EDM electrodes on surface roughness of AISI D3 steel, *Applied Mechanics and Materials,* Vol. 813-814, 521-525, doi: 10.4028/www.scientific.net/AMM.813-814.521.

[16] Kapoor, J., Singh, S., Khamba, J.S. (2012). Effect of cryogenic treated brass wire electrode on material removal rate in wire electrical discharge machining, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* Vol. 226, No. 11, 2750-2758, doi: 10.1177/0954406212438804.

[17] Schacht, B. (2004). *Composite wire electrodes and alternative dielectric for wire electrical discharge machining, PhD thesis,* Katholieke Universityeit Leuven, Belgium.

[18] Kaneko, H., Onoue, M. (1984). *Electrode material for travelling-wire type electrical discharge machining,* US Patent No. 4424432.

[19] Gill, S.S., Singh, J. (2010). Effect of deep cryogenic treatment on machinability of titanium alloy (Ti-6246) in electric discharge drilling, *Materials and Manufacturing Processes,* Vol. 25, No. 6, 378-385, doi: 10.1080/10426910903179914.

[20] Yildiz, Y., Sundaram, M.M., Rajurkar, K.P., Nalbant, M. (2011). The effects of cold and cryogenic treatments on the machinability of beryllium-copper alloy in electro discharge machining, In: *Proceedings of 44th CIRP Conference on Manufacturing Systems,* Madison, Wisconsin, USA.

[21] Kumar, S., Batish, A., Singh, R., Singh, T.P. (2015). A mathematical model to predict material removal rate during electric discharge machining of cryogenically treated titanium alloys, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* Vol. 229, No. 2, 214-228, doi: 10.1177/0954405414527955.

[22] Jatti, V.S., Singh, T.P. (2014). Effect of deep cryogenic treatment on machinability of NiTi shape memory alloys in electro discharge machining, *Applied Mechanics and Materials,* Vol. 592-594, 197-201, doi: 10.4028/www.scientific.net/AMM.592-594.197.

[23] Khanna, R., Singh, H. (2016). Comparison of optimized settings for cryogenic-treated and normal D-3 steel on WEDM using grey relational theory, *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications,* Vol. 230, No. 1, 219-232, doi: 10.1177/1464420714565432.

[24] Goyal, R., Sngh, S., Kumar, H. (2018). Performance evaluation of cryogenically assisted electric discharge machining (CEDM) process, *Materials and Manufacturing Processes,* Vol. 33, No. 4, 433-443, doi: 10.1080/10426914.2017.1317789.

[25] Ishfaq, K., Mufti, N.A., Ahmad, J., Sajid, M., Jahanzaib, M. (2018). Analysis of the effect of wire electric dischage machining process parameters for the formation of high speed steel form tool, *Advances in Science and Technology Research Journal,* Vol. 12, No. 1, 89-98, doi: 10.12913/22998624/81001.

[26] Azam, M., Jahanzaib, M., Abbasi, J.A., Wasim, A. (2016). Modeling of cutting speed (CS) for HSLA steel in wire electrical discharge machining (WEDM) using moly wire, *Journal of the Chinese Institute of Engineers,* Vol. 39, No. 7, 802-808, doi: 10.1080/02533839.2016.1191377.

[27] Selvakumar, G., Thiruppathi Kuttalingam, K.G., Ram Prakash, S. (2018). Investigation on machining and surface characteristics of AA5083 for cryogenic applications by adopting trim cut in WEDM, *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* Vol. 40, Article Number 267, doi: 10.1007/s40430-018-1192-7.

[28] Bhuyan, R.K., Routara, B.C., Parida, A.K. (2015). Using entropy weight, OEC and fuzzy logic for optimizing the parameters during EDM of Al-24% SiC P MMC, *Advances in Production Engineering & Management,* Vol. 10, No. 4, 217-227, doi: 10.14743/apem2015.4.204.

[29] Singh, N., Kumar, P., Goyal, K. (2013). Effect of two different cryogenic treated wires in wire electrical discharge machining of AISI D3 die steel, *Journal of Mechanical Engineering,* Vol. 43, No. 2, 54-60, doi: 10.3329/jme.v43i2.17827.

[30] Montgomery, D.C. (2017). *Design and analysis of experiments, 9th edition,* John Wiley & Sons, Hoboken, New York, USA.