Chapter 15

Investigation into the Surface Quality in Wire-Cut EDM of M42 HSS: An Experimental Study and Modeling Using RSM

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Abstract This article has been attempted to experimentally examine the surface quality produced while performing the wire-cut electrical-discharge machining of M42 high-speed steel using cryogenically treated brass wire under the effect of different process variables. High-speed steels are alloyed steels that are self-hardened. It acquires excellent fracture toughness, fatigue, and shock resistance. The M42 is also a widely employed high-speed steel having applications in numerous industries. Despite its wider industrial applications, M42 is very less investigated on machining grounds especially with advanced machining operations. For design of experiments, response surface methodology (RSM) has been employed. The variance analysis (ANOVA) has also been performed to reveal out the significant process factors. The reliability and competence of the mathematical model developed with the test results were established. ANOVA analysis results for surface roughness revealed pulse off time, pulse on time and spark gap voltage as the most substantial factors for the studied machining response. The best parametric setting for SR is devised as pulse on time-0.85 µs, spark gap voltage-50 V, pulse off time-36 µs, and wire feed-7 m/min.

Keywords Wire-cut EDM · HSS · RSM · M42 · ANOVA

Nomenclature

RSM	Response surface methodology
HSS	High-speed steel
WEDM	Wire electric discharge machining
SR	Surface roughness

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15.1 Introduction

With the improvement in the innovation, the technologists, and researchers in the field of manufacturing are tackling new and more confronts. Technically advanced industries such as nuclear power reactors, aeronautics, and automobile industry have been demanding elevated strength temperature-resistant materials having high strength-to-weight ratio. HSS has excellent fracture toughness, fatigue, and shock resistance. M-42 has the greatest hot strength [1, 2]. Its applications are found in the production of twist drills, milling cutters, taps, reamers, broaches, saws, knives, and thread rolling dies. A very limited literature has been found on the study and investigation of different expects of M42 HSS by machining them with the help of advanced machining operations. Wire electrical discharge machining (WEDM) is a modern machining method which has been reported very less for performing machining operations on these type of high-speed steels. Wire EDM was initially accessible to the manufacturing industry in late 1960s [3]. Its comprehensive capacities have enabled it to cover manufacturing in the aerospace and automotive industries and nearly all conductive material machining areas [4, 5].

WEDM uses continuously moving wire-shaped electrode. As recorded in Fig. 15.1, wire is acting on upper spool which is to be fed upon the workpiece, and after the wire is used, it is brought up on the lower spool. The de-ionized water, which acts as a dielectric is flooded into the opening between the workpiece and the wire in WEDM. The matter is detached from the succession of electrical discharges [7–9]. In this operation, the cryogenically treated brass wire for performing various experiments on M42 HSS has been employed. For the creation of complex two- and three-dimensional shapes to machine complicated electrical conductive materials, WEDM acts as an obligatory machining technique [10]. A second-order mathematical model, in requisites of process factors, was advanced for dimensional deviation cutting speed and surface roughness using response surface methodology

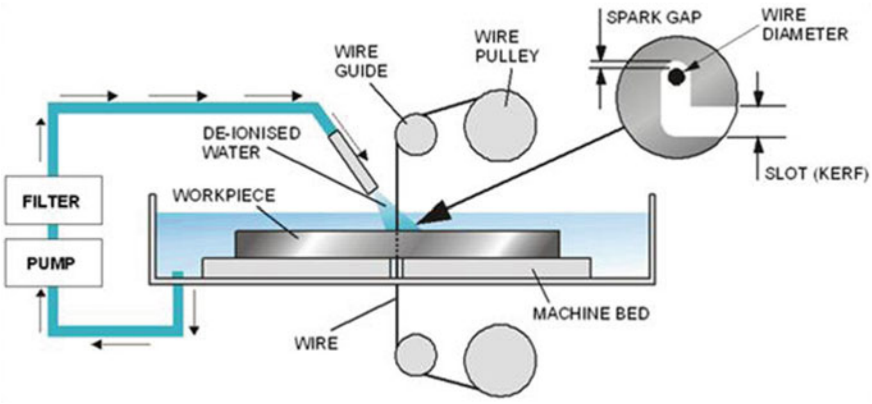


Fig. 15.1 Schematic of WEDM system [6]

[11]. Aniza Alias et al. [12] researched feed-rate control on WEDM performance on Titanium Ti–Al-4 V. This research involved brass wire as the electrode. As feed rate rises, MRR also rises until optimum value is reached. The technique of cooling a material at temperatures far below room temperature is cryogenic processing. Cryogenic treatment is carried out in a chamber where the materials to be treated are constantly reduced at room temperature. Deep cryogenic treatment is carried out at −180 to −196 °C for 18–24 h, whereas shallow cryogenic treatment is performed at around −110 °C for 4–8 h.

Figure 15.2 represents the schematic view of cryogenic processor. Cryogenic treatment has been widely recognized as a technology to reduce costs and improve efficiency. The stress relief advantages obtained through cryogenic treatment are used to allow critical tolerance sections to be manufactured. Cryogenic treatment is friendly to the environment. During the process, no waste or residue will be developed. It decreases cutting tool consumption due to increased wear resistance, increasing conductivity by 5–8%. The wide range of published work concerning the advancement of the wire electrode and its performance characteristics has been categorized into diverse sections, namely plain wire electrodes, coated wire electrodes, dispersion annealed wire electrodes, gamma-coated electrode wire, composite wire electrodes, and porous wire electrodes. The brass wires are a mixture of zinc and copper, alloyed together in a range of 63–65% copper and 35– 37% zinc [13]. Figure 15.3 represents the plain brass wire electrode.

Coated wires are formed by re-drawing wire (0.9 mm) plating or hot-dipping and consequently drawn to the final size. Zinc-coated brass wire electrodes consist of zinc coating over a core that is one of the usual brass alloys of EDM.

This wire provides a significant rise in cutting velocity over simple brass wires, without giving up on any of the other critical properties [15]. Shallow cryogenic treatment relates to materials being treated at very low temperatures, usually around −110 °C. Bensely et al. [16] recognized that steel with profound and shallow cryogenic

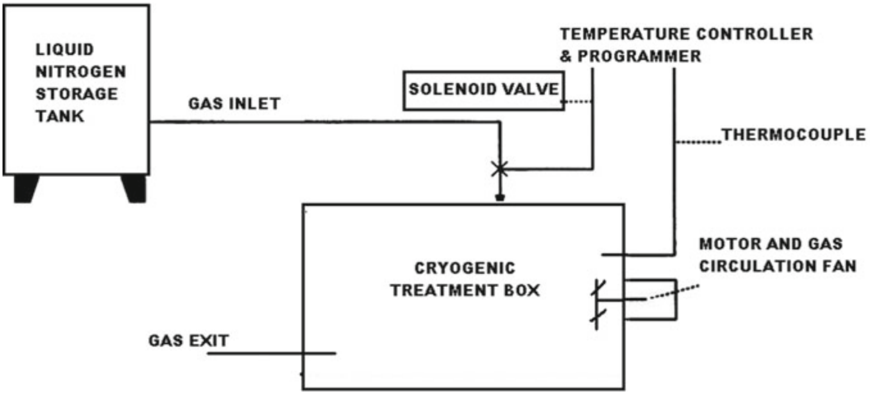


Fig. 15.2 View of cryogenic processor

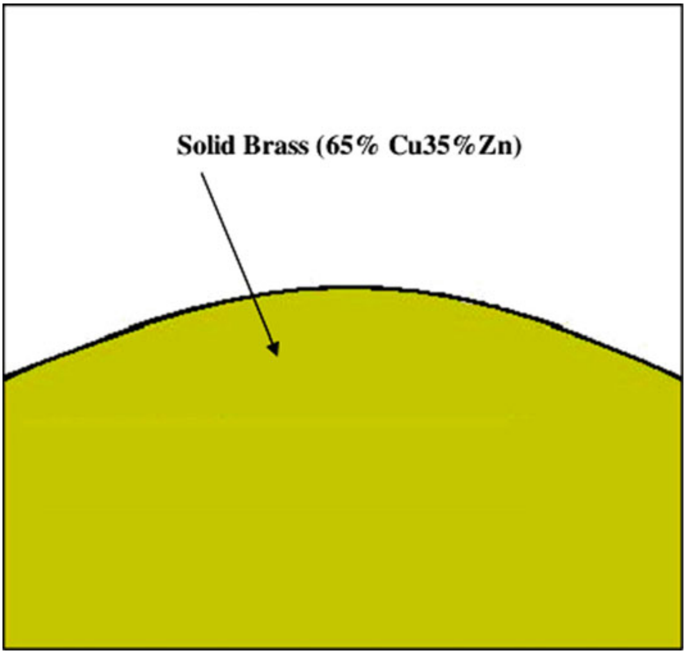


Fig. 15.3 Plain brass wire electrode [14]

treatment has increased wear resistance compared to standard heat treatment. Jatinder et al. [17] explored the impact of profound and shallow cryogenic-treated wire electrodes on the surface roughness (SR) and rate of material removal of WEDM-machined EN-31 steel. All the three process parameters, namely type of wire, pulse width, and wire tension significantly affect the MRR and SR in WEDM. Deep and shallow cryogenic-treated wire electrodes appreciably enhance the MRR. Scanning electron microscope (SEM) photographs confirm that cryogenically treated wires give smoother surface than untreated wire electrode. EDS analysis revealed that Cu and Zn elements from brass wire electrode were deposited on the machined surface of workpiece.

15.2 Materials and Methods

The research study of different aspects by going through extensive literature survey brings the light on one of important response parameters, i.e., surface roughness of the materials. The machining efficiency measurements are therefore surface roughness and wire EDM-processed M42 HSS surface characterization. The process parameters considered are wire feed, pulse on time, spark gap voltage, and pulse off time. The effect of these process parameters on surface roughness has been investigated when

Table 15.1 M42 HSS chemical composition

Element	C	Si	Cr	W	Mo	V	Co
Weight%	1.08	0.45	3.85	1.50	9.50	1.20	8.00

Table 15.2 Different properties of brass wire

Material	Chemical composition	Hardness (VH)	Tensile strength (N/mm^2)	Conductivity (%IACS) (%)
Brass	Cu 63% Zn37%	255	905	21
Shallow cryogenated brass wire	Cu 63% Zn37%	220	850	27.9

using cryogenically treated brass wire for machining of M42 HSS with WEDM. The designs of experiment approaches have already been proven to be more effective to understand the process insights [2, 18–20]. As surface roughness is an important performance characteristic and it is very less investigated while performing the advanced processing of M42 HSS. For the current experimental tests, the 100 mm × 80 mm × 12 mm high-speed steel (HSS) plate M42 was used as job piece material. Its applications are twist drills, milling cutters, taps, reamers, broaches, saws, knives, and thread rolling dies. The chemical composition of M42 HSS is represented in Table 15.1.

The brass wire electrode selected for the experimentation on WEDM was manufactured by VSL Pvt. Ltd. Ludhiana, India. The brass wire comes in the shape of wire spools, which are to be fitted on the machine. The various properties of brass wire are shown in Table 15.2.

The tests were conducted on Electronica Machine Tools Ltd's wire-cut EDM machine (ELEKTRA ECOCUT). The mechanism of WEDM process is influenced by many process parameters while the machining is in progress. The main effects or even the interaction effects of these parameters influence the machining characteristics in a complex way. Given that such parameters control the WEDM process, a fundamental outline of these parameters is required. The process parameters of the WEDM can be sorted as (i) electrical parameters and (ii) non-electrical parameters. Fundamental electrical parameters comprise of spark gap voltage (SV), peak current (I_p), pulse off time (T_{off}), and pulse on time (T_{on}). Wire tension (WT), water pressure (WP), and wire feed (WF) are the non-electrical parameters. Parameters of the input method such as T_{on}, T_{off}, SV, and WF and their limiting concentrations were selected based on literature study, experience, meaning, and relevance. In the present study, experiments are performed on a four-axis Electronica ecocut wire EDM machine. The electrode material used is half-hard brass wire with a diameter of 0.25 mm. The work material used is 100 mm × 80 mm × 12 mm M42 HSS. Table 15.3 shows various control parameters and their ranges.

A small gap between the workpiece and the wire electrode of 0.025–0.05 mm is maintained. Spark is started when high voltage is applied at the smallest distance

Table 15.3 Selected control parameters and their ranges for experimentation

S. No.	Control parameters	Symbol	Range (mu)	Range (actual unit)
1	Pulse on time	T_{on}	110–120	0.6–1.1 μs
2	Pulse off time	T_{off}	45–55	18–36 μs
3	Spark gap voltage	SV	40–60	40–60 V
4	Wire feed	WF	3–7	3–7 m/min

Table 15.4 Design matrix and output response values for the conducted tests

			Factor 1	Factor 2	Factor 3	Factor 4	Response
Std	Exp. Run	Block	A:T_{on} (μs)	B:T_{off} (μs)	C:SV (V)	D: WF (m/min)	SR: Ra (μm)
2	1	Block 1	120	45	50	5	1.75
15	2	Block 1	115	45	60	5	1.32
24	3	Block 1	115	55	50	7	1.1
7	4	Block 1	115	50	40	7	1.35
27	5	Block 1	115	50	50	5	1.22
6	6	Block 1	115	50	60	3	1.22
25	7	Block 1	115	50	50	5	1.23
20	8	Block 1	120	50	60	5	1.48
10	9	Block 1	120	50	50	3	1.6
16	10	Block 1	115	55	60	5	1.26
18	11	Block 1	120	50	40	5	2.18
11	12	Block 1	110	50	50	7	1.18
12	13	Block 1	120	50	50	7	1.45
4	14	Block 1	120	55	50	5	1.34
9	15	Block 1	110	50	50	3	1.19
28	16	Block 1	115	50	50	5	1.36
19	17	Block 1	110	50	60	5	1.76
5	18	Block 1	115	50	40	3	1.31
3	19	Block 1	110	55	50	5	1.29
22	20	Block 1	115	55	50	3	1.12
29	21	Block 1	115	50	50	5	1.45
21	22	Block 1	115	45	50	3	1.31
8	23	Block 1	115	50	60	7	1.24
13	24	Block 1	115	45	40	5	1.5
1	25	Block 1	110	45	50	5	1.13
17	26	Block 1	110	50	40	5	1.29
26	27	Block 1	115	50	50	5	1.34
14	28	Block 1	115	55	40	5	1.24
23	29	Block 1	115	45	50	7	1.26

between the electrode and the workpiece. The elevated energy density erodes material both from the workpiece and from the wire by local fusion and vaporization. On both sides of the job piece, which removes the eroded particles generated during spark formation, the machining area is continually washed with dielectric liquid passing through the nozzles.

The designed experiments have been proved very effective while investigating the process responses in a combined manner [21–25]. The surface response methodology was used to design the experiments. The selected process variables such as pulse on time (T_{on}), wire feed (WF), spark gap voltage (SV), and pulse off time (T_{off}) have been varied up to three levels, and Box–Behenken Design (BBD) was adopted to design the experiments. Experiments are carried out using the design expert 6.0.8 software on a four-axis Electronica ecocut CNC wire EDM machine. Box–Behenken Design (BBD) has been employed to design the experiments. In this study, most important output performance parameter in WEDM, i.e., surface roughness considered for investigating machining conditions of M42 HSS with cryogenically treated brass wire. Surface roughness is a metric of a surface's texture. It is quantified from its ideal form by the vertical deviations of an actual surface. Surface roughness (Ra) relates to the close-spaced brief wavelength and high frequency irregularities on the machined surface triggered by the nature and activities of the manufacturing processes [26–28]. Average surface roughness (R_a) is simple to describe as it measures the surface amplitude and provides a general description.

15.3 Results and Discussions

Adequacy of the model is checked using ANOVA as shown in Table 15.5. It shows that the model's F-value is 20.55 and that the P-value is below 0.0001. The quadratic model is therefore important at a confidence level of 95%. Moreover, lack of fit value of 0.7750 suggests that it is not significant with respect to pure error. Further, predicted R^2 of 0.7717 is in reasonable agreement with adjusted R^2 of 0.8747 and it demonstrates a high correlation among observed values and predicted values. Adequate precision value is 21.657, and it demonstrates that quadratic model can be used to find the way in the design space. Design matrix and output response values for various conducted tests have shown in Table 15.4.

The developed regression model for surface roughness (SR: Ra) is given as:

$$\begin{aligned}\text{Surface roughness (SR)} = {} & +19.43167 - 1.00367 * T_{\text{on}} + 0.94850 * T_{\text{off}} \\ & + 0.55367 * \text{SV} + 0.27625 * \text{WF} + 0.007016 * T_{\text{on}}^2 \\ & - 0.00308 * T_{\text{off}}^2 + 0.001141\,\text{SV}^2 - 0.028333 * \text{WF}^2 \\ & - 0.0057 * T_{\text{on}} * T_{\text{off}} \\ & - 0.00585 * T_{\text{on}} * \text{SV}\end{aligned}$$

Table 15.5 ANOVA for surface roughness

Source	Sum of squares	DF	Mean square	F-value	Prob > F	Remarks	% Contribution
Model	1.34	10	0.13	20.55	< 0.0001	Significant	
A	0.32	1	0.32	49.21	< 0.0001	Significant	22.06
B	0.071	1	0.071	10.84	0.004	Significant	4.89
C	0.029	1	0.029	4.46	0.049	Significant	2
D	0.00241	1	0.00241	0.37	0.5505	Not significant	0.16
A^2	0.2	1	0.2	30.68	< 0.0001	Significant	13.79
B^2	0.039	1	0.039	5.92	0.0256	Significant	2.68
C^2	0.085	1	0.085	13	0.002	Significant	5.86
D^2	0.083	1	0.083	12.81	0.0021	Significant	5.72
AB	0.081	1	0.081	12.49	0.0024	Significant	5.58
AC	0.34	1	0.34	52.61	< 0.0001	Significant	23.44
Residual	0.12	18	0.00651				
Lack of fit	0.08	14	0.00572	0.62	0.775	Not significant	
Pure error	0.037	4	0.00925				
Cor Total	1.45	28					

Std. Dev. 0.081 R-Squared 0.9195
Mean 1.36 Adj R-Squared 0.8747
C.V. 5.93 Pred R-Squared 0.7717
PRESS 0.33 Adeq Precision 21.657
Legend A—Pulse on time, B—Pulse off time, C—Spark gap set voltage, D—Wire Feed Rate

The effect of different process parameters, i.e., pulse on time, pulse off time, spark gap voltage, and wire feed on the studied machining response, i.e., surface roughness has been shown in Figs. 15.4, 15.5, 15.6 and 15.7. The 3D interactive plot for surface roughness has been shown in Fig. 15.8. It is reflecting the influential behavior of spark gap voltage and pulse on time on the studied machining response.

15.4 Conclusion

The following inferences can be made from the present study. These are as below:

1. The pulse on time (T_{on}) and pulse off time (T_{off}) have more discernable impacts on the surface roughness of the processed M42 work material.
2. Utilized cryogenically treated wire electrodes revealed to offer superior surface finish of machined workpiece and less wire wear of wire is also obtained with these employed electrodes. The effect of shallow cryogenic treatment on wire

Fig. 15.4 Effect of pulse on time on surface roughness

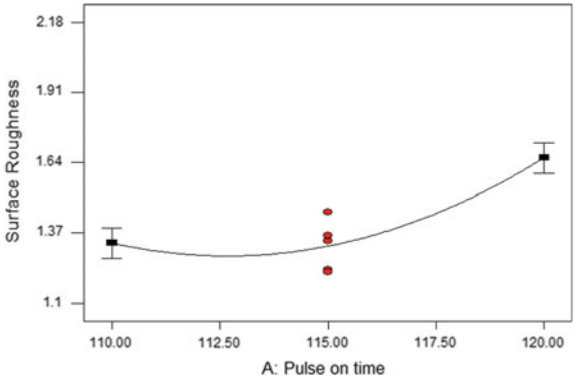


Fig. 15.5 Effect of pulse off time on surface roughness

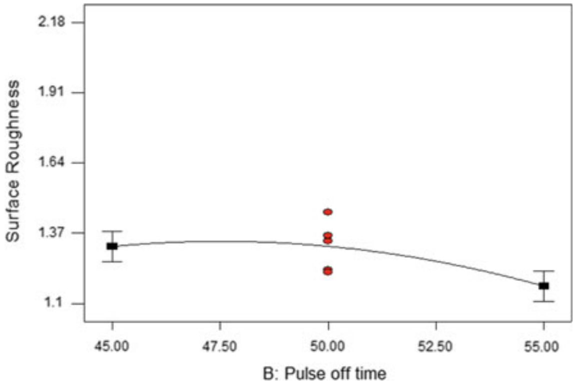
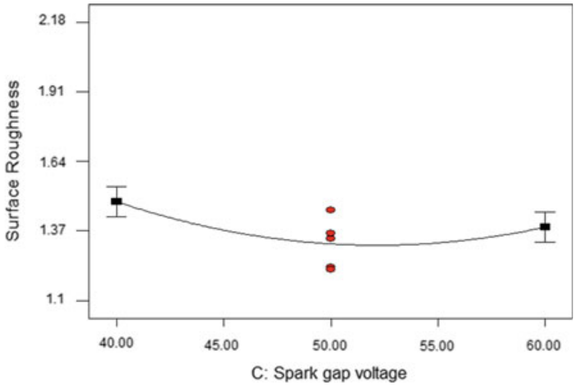


Fig. 15.6 Effect of spark gap voltage on surface roughness



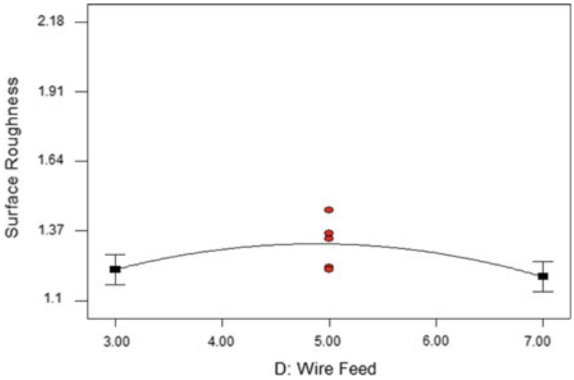


Fig. 15.7 Effect of wire feed on surface roughness

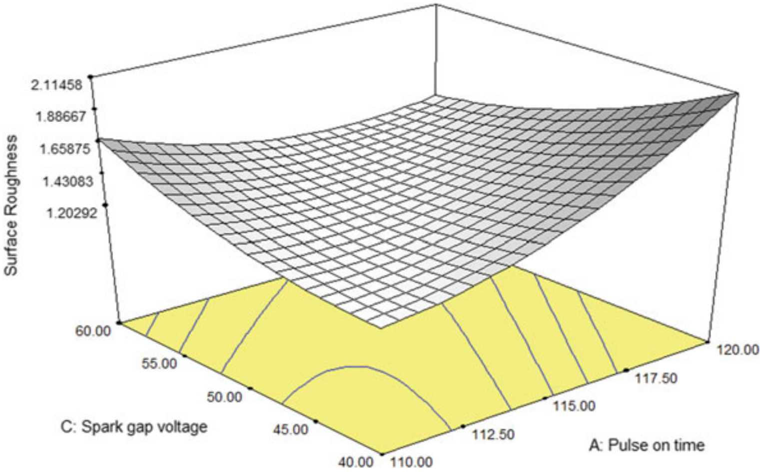


Fig. 15.8 Interaction plot between spark gap voltage and pulse on time for surface roughness

electrode in WEDM results into significant improvement in surface roughness value.

3. The electrical conductivity of brass wire electrode is also enhanced with shallow cryogenic treatment. The shallow cryogenic treatment improved the conductivity to 27.90 (%IACS).
4. Pulse width and time between two pulses interact with the wire while affecting the Ra. The low value of pulse width and shallow cryogenic treated wire electrode is recommended setting for minimum Ra.
5. The best parametric setting for SR is devised as pulse on time-0.85 µs, pulse off time-36 µs, spark gap voltage-50 V, and wire feed-7 m/min.

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