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RESEARCH ARTICLE-MECHANICAL ENGINEERING

Investigation and Optimization of Cutting Performance of High Chrome White Cast Iron by Wire Erosion

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Abstract

Wire electric discharge machining (WEDM) is an emerging approach to producing more accurate and precise complex products in the unconventional machining process. The WEDM process is affected by several process factors. Therefore, the appropriate combination of process factors is required to achieve economical and quality machining. Machining is very difficult due to the presence of chromium carbide in the structure of high-Cr white cast irons (HCCIs) with 12–17% Cr content in machining processes. Therefore, the machinability of HCCIs has always been a disadvantage. In this study, specially molded HCCIs samples were subjected to softening, casting (not heat treated) and hardened heat treatment processes, respectively. We aimed to experimentally investigated the changes in HCCIs samples characteristics, pulse on time, pulse of time, wire speed, and cutting performance in the WEDM process in this study. The L_{18} orthogonal array was used using the Taguchi method, and an experimental study was prepared. Afterward, an optimization study was carried out using mathematical models for WEDM with the help of performance outputs via ANOVA analysis. The experimental performances examined in this study are material removal rate and surface roughness. The experimental study determined that the material removal rate and surface roughness increased when the pulse on time increased. Later, machined samples morphological and structures properties were analyzed X-ray spectroscopy (EDS), scanning electron microscopy, microhardness and surface roughness. Furthermore, electrical conductivity of them was measured.

Keywords WEDM · HCCIs · Taguchi · Surface roughness · MRR

List of symbols

ANOVA	Analysis of variance
WEDM	Wire Electrical discharge machining
MRR	Material removal rate (g/min)
T_{on}	Pulse on time (µs)
T_{off}	Pulse off time (µs)
WF	Wire feed (m/s)
SEM	Scanning electron microscope
Ra	Surface roughness (µm)
HCCI	High Cr white cast iron

1 Introduction

Wire electro-erosion method (WEDM) is called an electro-thermal method, which is carried out by arranging sparks between the workpiece and the material, which is used to process hard and complex materials that are difficult to process with traditional processing methods [1, 2]. Nowadays, WEDM attracts attention as a practical and rapidly developing production technology, which meets the increasing demand in the manufacturing industries and can work for hours without supervision [3]. Since there is no direct contact between the workpiece and the wire electrode during the WEDM process, the problems such as tension, vibration and cracks are reduced [4]. In this WEDM process, the material is removed by melting between the workpiece and the wire electrode by electric discharge, and the machining area is regularly cleaned with dielectric fluid. Generally, water is used as dielectric fluid. It is widely preferred because of its low viscosity, environment-friendly and easy availability of water [5]. In the WEDM process, it is aimed to obtain products with

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high hardness and low surface roughness on machined surfaces without compromising mass production at low cost.

A large number of performances of WEDM are followed by input and output process parameters. Output parameters such as surface integrity, material removal rate (MRR) and surface roughness (Ra) are dependent on input parameters such as pulse on time, pulse off time, peak current, dielectric fluid pressure, wire type wire speed and wire tension [6] Detailed information about the WEDM can be found in [7, 8]. In the scientific literature, different studies affecting based on WEDM input parameters have been examined. Rao et al. [9] developed correlations to examine the effects of input parameters on output properties in CNC WEDM. Dinesh et al. [10] ınput parameters such as pulse on time, pulse off time and current were changed at equal intervals. A linear increase in surface roughness was observed when the pulse on time increased gradually, while it remained constant throughout the pulse off time. Also, there is an exponential increase in processing time when the current increases gradually. Rajmohan and Kumar [11] determined the optimal material removal rate and surface roughness values using the input process parameter (pulse on/off time, wire speed, wire tension, and current) to duplex stainless steel during WEDM. Takayama et al. [12] optimized the surface quality, cutting precision of the workpiece and wire break frequency in the WEDM process of SDK-11 by using a closed loop system. Dzionk et al. [13] investigated process efficiency, accuracy and workpiece surface integrity on WEDM pulse on time, pulse off time and dielectric MRR control parameters for Inconel 617. Somashekhar et al. [14] suggested that the MRR and Ra were improved by variations in the gap voltage and resistance range to the aluminum alloys material. Mostatfafor and Vahedi [15] showed the influencing machining processes on magnesium alloy. Urtekin et al. [16] WEDM machinability of AZ91 alloy was investigated experimentally with different parameters. They reported that the processing speed and current directly affect the porosity, density and microstructure of the samples. Sarkar et al. [17] stated that an increase in cutting speed would be positive for surface roughness. Basavaraju et al. [18] have detailed the titanium grade 7 alloy by analyzing MRR and Ra during WEDM machining. Mahapatra and Amar [19] reported that MRR in WEDM increased with pulse open time and peak current. However, they stated that it causes significant decreases with pulse off time and servo voltage. Manjaiah et al. [20] demonstrated how WEDM process parameters of AISI D2 steel affect MRR and Ra. As a result of their study, they explained that the pulse on time is important for maximum MRR and minimum Ra compared to other parameters. In a different scientific study, Saha et al. [21] investigated the WEDM processing of A286 super alloy under variable control modes. When the studies were examined, the effects of servo feeding speed, dielectric water pressure, wire tension and servo voltage on the evaluated machining time and corner errors were associated with the ANOVA test.

A statistical study such as the Taguchi method can be performed using the analysis of the experimental results to obtain the optimum output in response to the optimal input parameters of the WEDM process [22, 23]. The first study on the surface integrity and machinability of Nimonic 80A alloy by WEDM trim cut machining was presented using Taguchi optimization in the design and planning of experiments These experiments clearly demonstrate the potential for fine cutting for high surface quality compared to rough cutting machining [24]. Lodhi and Agrawal [25] investigated MRR and Ra for tool steels using the Taguchi method by optimizing the WEDM process parameters and they pointed out that the discharge current is the most effective factor on the surface roughness. Majumder and Maity [26] investigated the optimum Ra affecting the appropriate cutting speed of Ni–Ti shape memory alloy in WEDM process and applied the Taguchi method. They observed that for WEDM responses, the pulse on time was the most important process parameter. Manna and Kumar [27] Taguchi analyzed the effect of various cutting parameters using the L_{18} approach. They WEDM process control parameters were selected as peak current, pulse off time and conic angle and investigated on Aluminum 5454 alloy. Optimized by ANOVA statistical analysis over four different variables. They pointed out that regression models and optimized parameter values for various conic angle workpieces can be applied in industry as a result of the research to increase productivity and improve results [28]. In another study, Mandal et al. [29] proposed a Taguchi optimization method to optimize corner accuracy on WEDM machining parameters of Al 7075 alloy. He emphasized the influence of pulse on time, servo voltage, pulse off time, and wash pressure on corner accuracy.

As it can be understood from the literature review given here, although there have been many studies on WEDM however there is no study on HCCIs. A comparative study has not been performed on the experimental parameters required to cut HCCIs of optimum quality with the Taguchi method. For that reason, in this study, changes in workpiece material removal rate (MRR) and surface roughness (Ra) were determined for three different samples according to process parameters as a result of machining with HCCIs wire electric discharge machining The morphological, microstructural and mechanical properties of them were characterized by EDS, SEM, and micro-hardness. In addition, the samples were examined electrical conductivity.

2 Materials and Methods

HCCIs are known to be wear resistant. Because it's widely used as it enables the manufacture of complex shapes and

Table 1 Chemical compositions of the HCCIs

Chemical composition in mass (wt.%)					
C	Mn	Si	Mo	Cr	Fe
2.2	6	1	0.56	18	Balance

high precision agricultural tools, machines, pistons, gears, and segments parts used in the mining, metallurgy, cement production and paper manufacturing industries [30]. The HCCIs samples having chemical compositions of measured with the thermos scientific niton XL2 plus brand XRF analyzer device. The chemical properties composition of the HCCIs samples is shown in Table 1. High chrome white cast iron with 90 mm diameter ball sample supplied by Çemaş A.Ş from Turkey has been used. In this experimental study, the workpiece material was taken from HCCI balls approximately 3 mm thick, 20 mm long and 10 mm wide [31].

The methodology of the study, in which various heat treatment conditions are established for the samples, is shown. The heat treatment process involves heating and cooling a metal or alloy to change its mechanical and physical properties, making them more desirable. The samples were processed according to the defined heat treatment conditions and then the wire was subjected to electric discharge machining. HCCIs samples were subjected to softening, casting (not heat treated) and hardened heat treatment processes. After casting, the samples were heat treated using an electric furnace. Therefore, Fig. 1 summarizes the evaluation method such as hard, raw and soft.

In the experiments for wire EDM, Ultracut F1 (ELPULS 501) type machine was used as the machine tool (shown in Fig. 2). High chromium white cast iron was chosen for the workpiece material in the experiments. Copper wire was used as the wire electrode. Deionized dielectric fluid, the standard in wire erosion, is preferred. The surface images of the machined samples were examined with the FEI-NOVA brand Nano SEM model. In addition, elemental analysis was performed on the sample surfaces with the EDS detector. DUROLINE-M branded microhardness device was used to measure the hardness of the machined samples. In the experiment, measurements were made under 100 g of load, during 10 s of waiting time, on the condition that they stay away from the corners of the samples. Each measurement was repeated at least 3 times and average results were recorded for final evaluation. Surface roughness values were measured using Mitutoyo SJ-210 type surface roughness tester (Mitutoyo, Kawasaki, Japan). The arithmetic mean roughness (Ra) was performed at 5 different locations on the machined surface and the average value was adopted to increase the accuracy of the measurement. Current–voltage measurements of raw, hard and soft samples processed in the WEDM process were measured at room temperature in the potential range of 0–3 V using the two-point probe method via Keithley 2400 source meter. The radii of the probes used in the measurement are

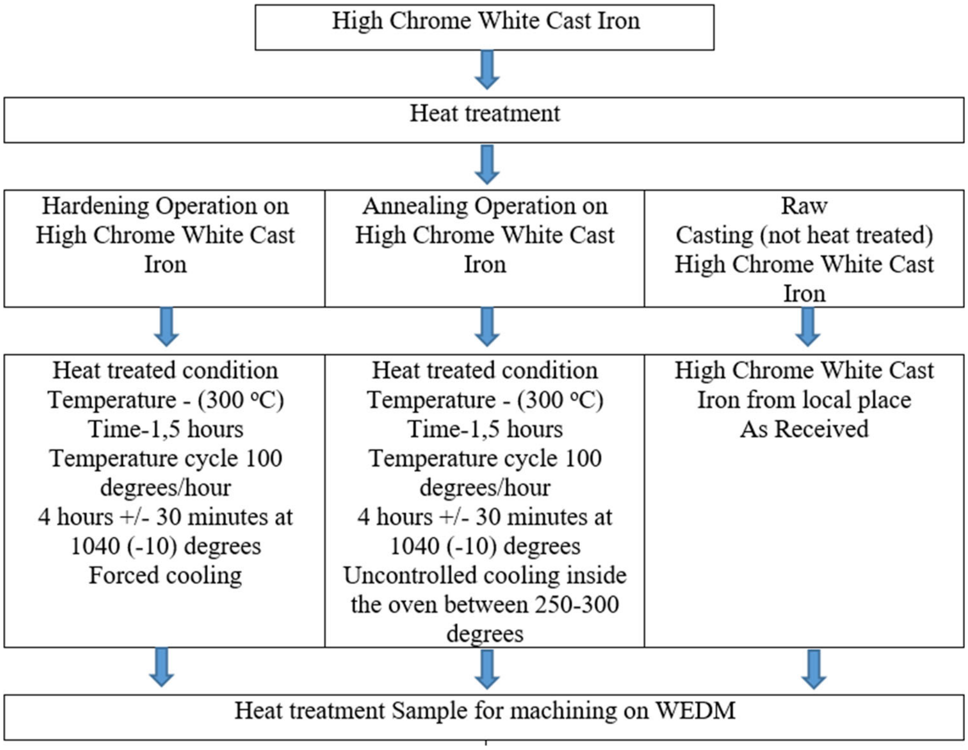
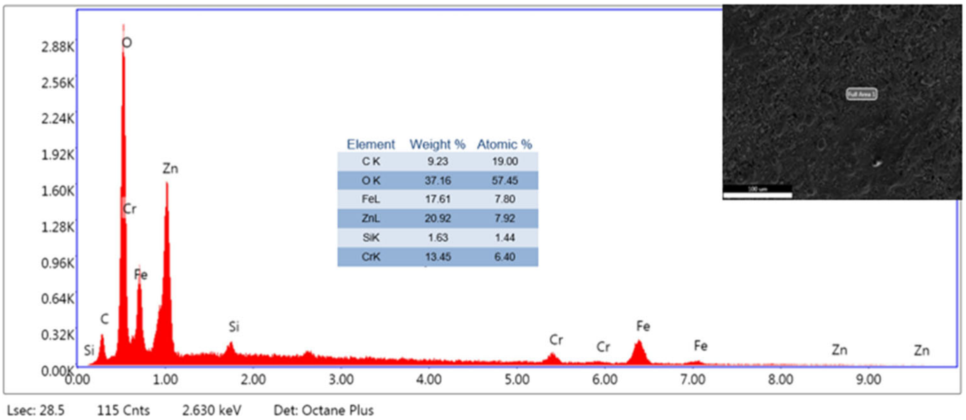


Fig. 1 Method of the study



Element	Weight %	Atomic %
C K	9.23	19.00
O K	37.16	57.45
FeL	17.61	7.80
ZnL	20.92	7.92
SiK	1.63	1.44
CrK	13.45	6.40

Fig. 2 EDS spectrum of HCCIs

Table 2 Process parameters

Parameters designation	Level 1	Level 2	Level 3
T_{on} (μs)	110	115	125
T_{off} (μs)	53	56	60
WF	4	6	–
Material	1	2	3

0.5 mm. It was repeated at least twice for each sample. This device allows measurement with a very sensitive voltage current source. In this method, time dependent V-I graphs are obtained by applying potential from the range of $-, +$.

Experimental numbers were selected using the Taguchi technique. Taguchi is a successful and efficient experimental design method that can improve process performance with the least number of experimentations. It minimizes the production and experimental process in experimental research and reduces costs. The purpose of the Taguchi method in the production method is to determine the optimal values of the functions. Compared to traditional methods, Taguchi uses an orthogonal array design to investigate quality characteristics with the least number of experimental processes. Converts test results into S/N ratios to estimate performance factors. Thus, Taguchi process targets the results of variations in grade aspects rather than averages. The Taguchi process renders the operation performance insensitive to changes in out-of-control noise factors. Then, the most suitable parameter requirements are determined by designing the parameters. The most suitable orthogonal array can be selected by determining the required parameter amount and levels. Parameters used in the experiments are material (raw, soft, and hard), T_{on}, T_{off}, and WF. The observed test results are MRR and Ra. The parameters used are tabulated in Table 2. Therefore, Taguchi experimental design used in the experiment was made as in Table 3.

Table 3 Design of experiments

Experiment No.	Material	T_{on}	T_{off}	WF
1	Raw	110	53	4
2	Raw	115	56	4
3	Raw	125	60	4
4	Raw	110	60	6
5	Raw	115	53	6
6	Raw	125	56	6
7	Hard	110	56	4
8	Hard	115	53	4
9	Hard	125	60	4
10	Hard	110	56	6
11	Hard	115	60	6
12	Hard	125	53	6
13	Soft	110	56	4
14	Soft	115	60	4
15	Soft	125	53	4
16	Soft	110	53	6
17	Soft	115	56	6
18	Soft	125	60	6

3 Result and Discussion

3.1 Morphological Analysis, Hardness, MRR and Surface Roughness Measurement of the Machined Samples

Energy dispersive spectroscopy (EDS) analysis shows the chemical composition of HCCIs (see Fig. 2). According to the EDX measurements taken, it was observed that O, Zn elements were more dominant in the structure. The determined chromium ratio was determined between 12 and 14%. WEDM machined SEM images of soft, raw, and hard samples are presented in Fig. 3. In the WEDM process, the materials, pulse off time, pulse on time and wire speed parameters

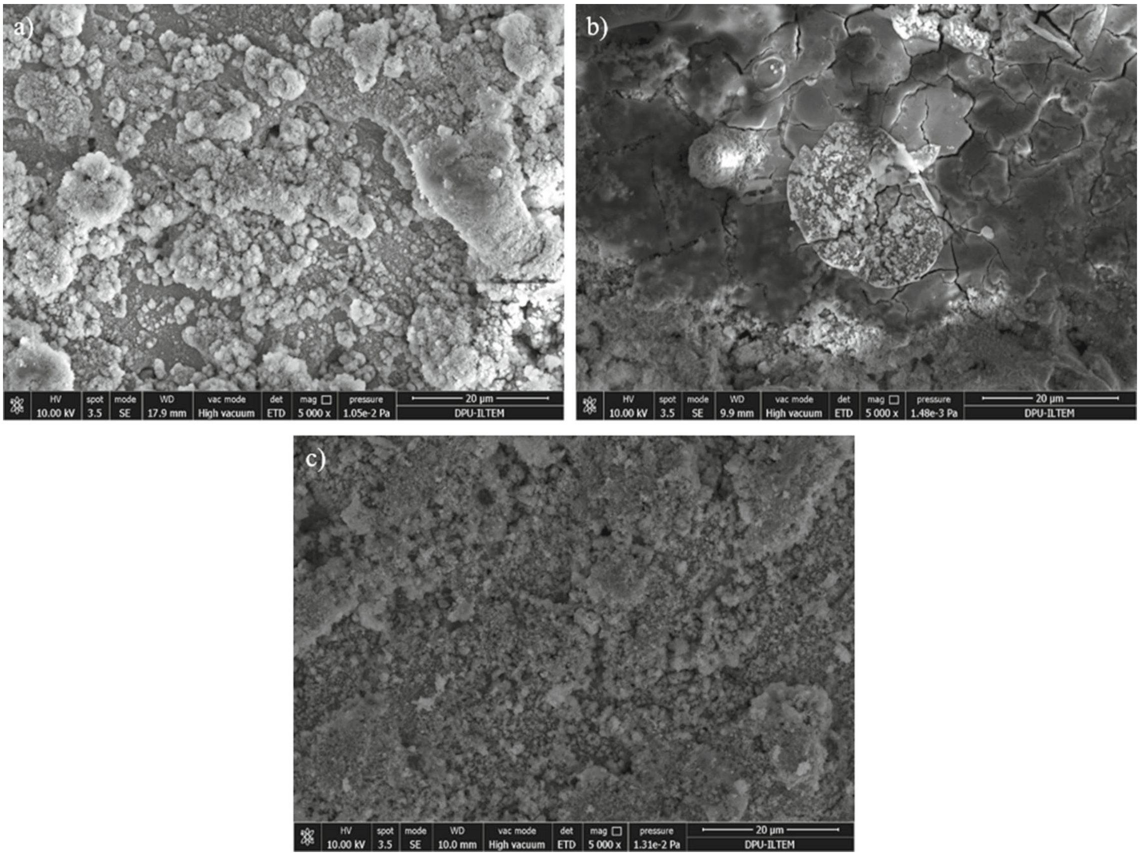


Fig. 3 SEM image of WEDM machined surface **a** soft, **b** raw, and **c** hard (at 5000X)

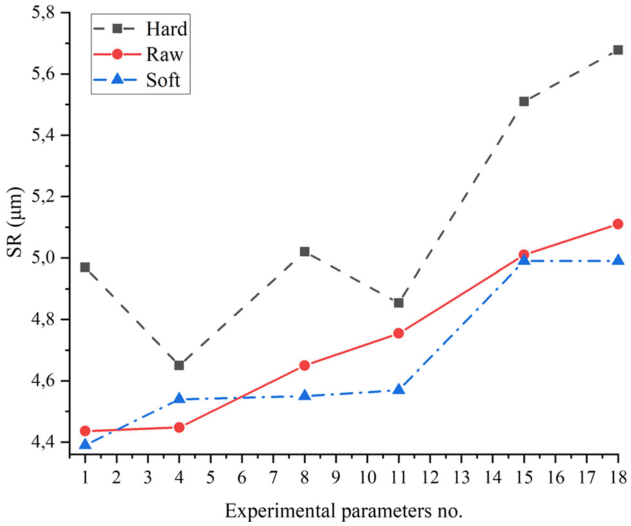


Fig. 4 Ra-parameters relationship of HCCI samples

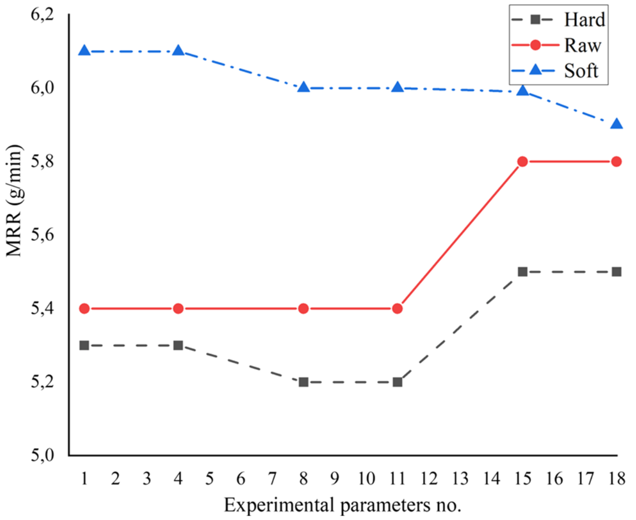


Fig. 5 MRR-parameters relationship of HCCI samples

affected the surface of the sample. The machined surfaces appear to contain craters, globules, debris and microcracks [32, 33]. As the pulse on time increased, a significant increase was obtained in the surface roughness values of the HCCIs samples. However, cutting speed did not have any effect on surface roughness. The increase in the pulse on time applied to the samples increases the amount of heat transfer on the surface, causing the sample to melt. Thus, it caused the formation of craters on the surfaces of the samples. If the molten residues are not removed from the surface by the dielectric

Table 4 Vickers hardness test values of samples

Parameter	Soft	Raw	Hard
Vickers hardness no	288	488	745

fluid, the surface roughness will result. As the pulse on time increased, a significant increase was obtained in the surface roughness values of the HCCIs samples. Ra and experimental parameters relationship is given in Fig. 4.

As a result of the experimental study, when the effect of the processing parameters on the processing speed was examined, it was observed that the processing time increased with the increase in the stroke time, the stroke waiting time and the wire speed. It has been determined that the change in processing speed is very small in soft materials. In hard and raw materials, it was observed that the processing speed increased with the increase of processing parameters. MRR and experimental parameters relationship is given in Fig. 5.

Microhardness testing is a procedure to find the surface hardness of a workpiece on a microscopic scale. Vickers hardness values are presented in Table 4. While the hardness of the soft HCCIs material was 288 $HV_{0.1}$, the surface hardness value of the Raw HCCIs samples showed 488 $HV_{0.1}$. The surface hardness value of the complex HCCIs samples showed higher hardness than the others. Because complex HCCIs samples are dense in the casting stage, and their hardness properties are improved by forced cooling after heat treatment. Therefore, we observe that the hard material has the highest hardness among the other considered samples.

Evaluation of appropriate surface parameters allows not only the wear and service life of a component to be predicted, but also its reliability. It is necessary to minimize the defects that occur on the surface of the materials after the WEDM process. Surface topography analyzes of wire cutting processes of raw, soft and hard materials in different parameters were displayed. It is seen that the surfaces of hard materials have the worst surface when compared to other materials. Due to this situation, it is understood that the surface quality

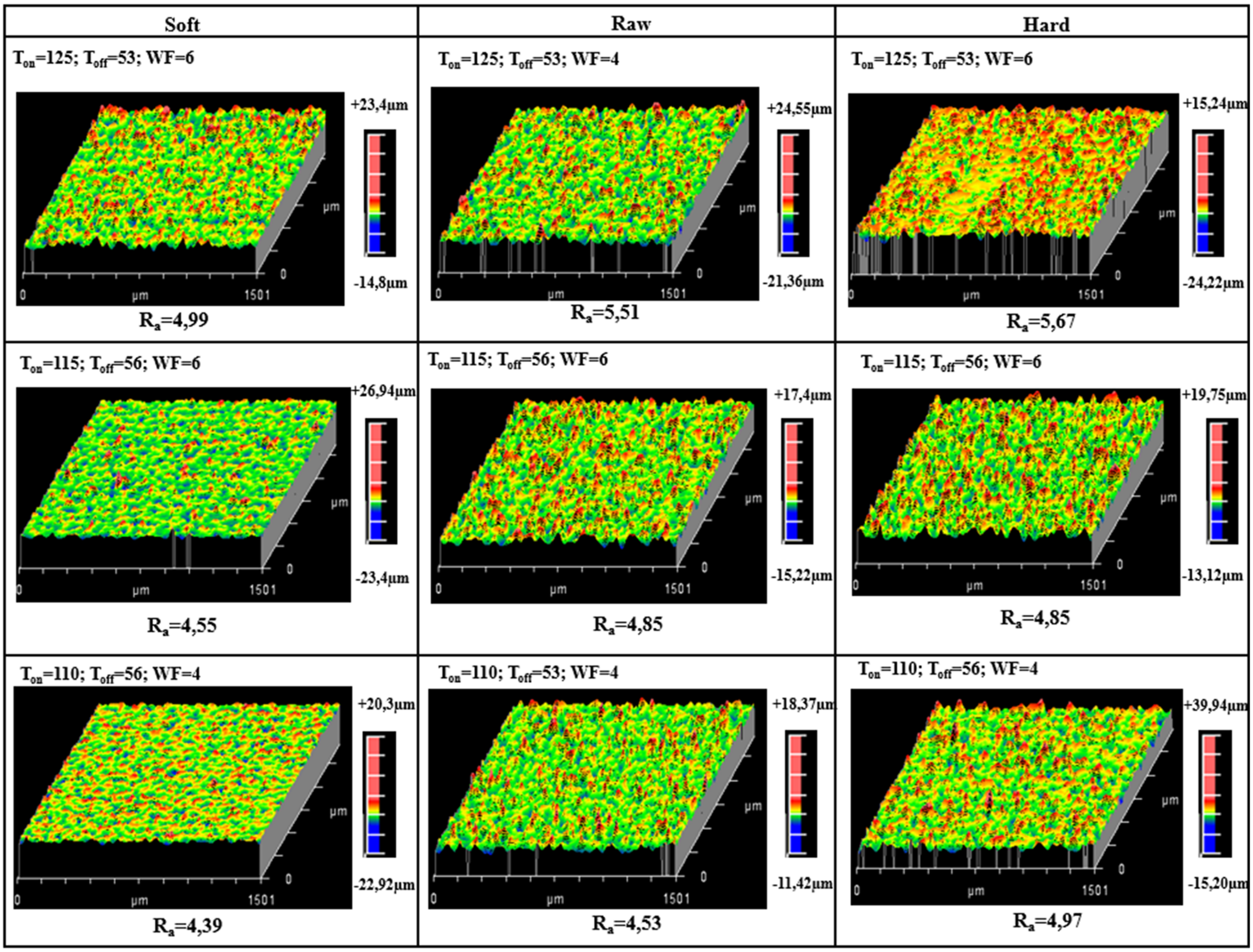


Fig. 6 Surface topography image of the samples

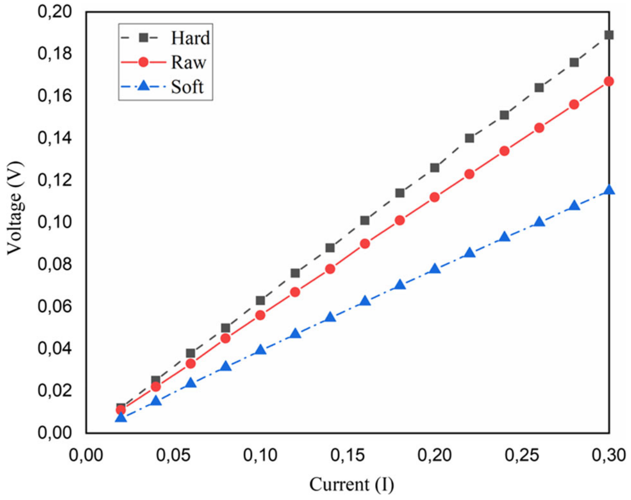


Fig. 7 Current–voltage relationship of HCCI samples

is low, and the machinability is bad. Obtained images are given in Fig. 6. As seen in Fig. 6, the upper and lower limit surface roughness values of the parameters in the experimental study are shown in detail. Notably, the machined surfaces of soft materials do not have micro-cracks and deep cavities due to the action of high pulse on time. For this reason, the surface roughness values of soft materials are better than raw and complex materials. In addition, the pulse on time significantly contributes to the surface roughness. Exposure to high pulse on time to concentrated sparks applied to surfaces adversely affects surface roughness. On the other hand, in the WEDM process, direct contact of the fees rate to the gaps between the electrodes results in micro-irregularities formed on the surface. For this reason, WEDM process input parameters input parameters cause changes in the shape/height of the surface.

Materials (soft, raw, and hard) current–voltage relationship is given in Fig. 7. The slope of the voltage-current lines gives the resistance. The resistivity value increases with the increase of the slope and causes a decrease in conductivity. The electrical conductivity is high in the soft material where the machined speed is high. In other words, it has low electrical resistance.

3.2 Optimization by Applying Taguchi Technique

Experimentations were carried out using the L_{18} orthogonal design to determine the effect of machining parameters on MRR and surface roughness [34]. The ANOVA table is used to use all the techniques called parameters. Response curves were plotted to find the effect of baseline responses. Ra indicates the grade of functional wire erosion, and MRR indicate its functionality. Therefore, the larger and smaller methods are better for analyzing the MRR and Ra S/N ratios. The outcome of procedure parameters on MRR was found as given below. Table 5 shows the workpiece machining results.

Table 5 Workpiece machining results

Experiment No.	MRR	S/N Ratio
1	5.40	14,6479
2	5.40	14,6479
3	5.80	15,2686
4	5.40	14,6479
5	5.40	14,6479
6	5.80	15,2686
7	6.10	15,7066
8	6.00	15,5630
9	5.99	15,5485
10	6.10	15,7066
11	6.00	15,5630
12	5.99	15,5485
13	5.30	14,4855
14	5.20	14,3201
15	5.50	14,8073
16	5.30	14,4855
17	5.20	14,3201
18	5.50	14,8073

Figure 8 is drawn according to the results obtained in the experiments. In Fig. 9, it was observed that in material No. 2, MRR increased when T_{on} increased and MRR decreased when T_{off} increased. This is due to increased discharge current and T_{on}, resulting in faster MRR. As the T_{off} increases, the number of discharges in a given time is less, resulting in a lower MRR. The effect of processing parameters on RA was found as given below. The results of the parameters on the Ra and the S/N ratios are given Table 6.

When Figs. 10, and 11 are examined, the surface roughness decreases when the T_{on} decreases, and T_{off} increases in material No. 3 WF was found to have little effect on surface roughness. Material, and T_{on} are the most critical parameters for surface roughness. The discharge energy increases at impact time, and the peak current and more significant discharge energy create a larger crater, resulting in a greater surface roughness value on the workpiece. When the results of the S/N ratios are examined, it is concluded that material No. 3 can be selected to minimize the surface roughness, and $T_{on} = 125$, and $T_{off} = 110$ values can be adjusted to the result.

The primary goal of ANOVA is to identify the essential factors, including the machining operation, to enhance the machining properties of HCCIs material in the WEDM

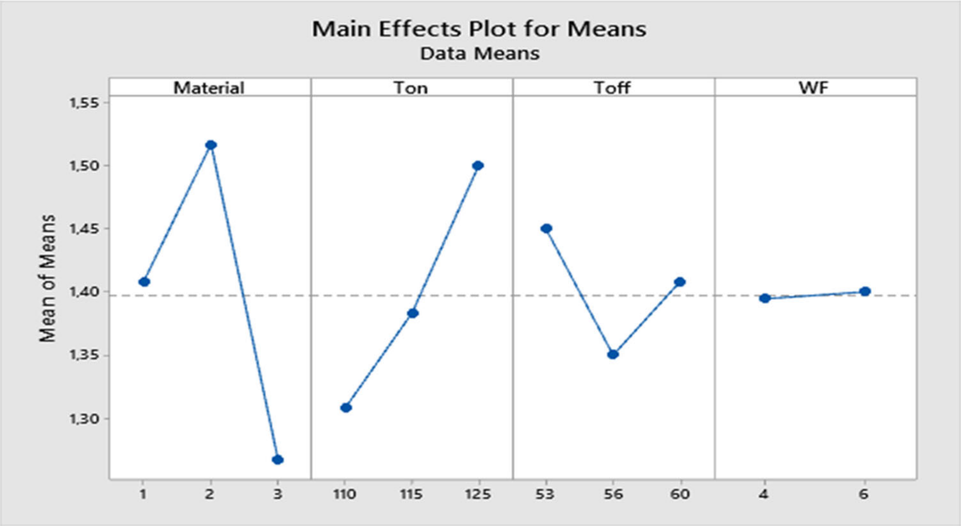


Fig. 8 Results of MRR parameters

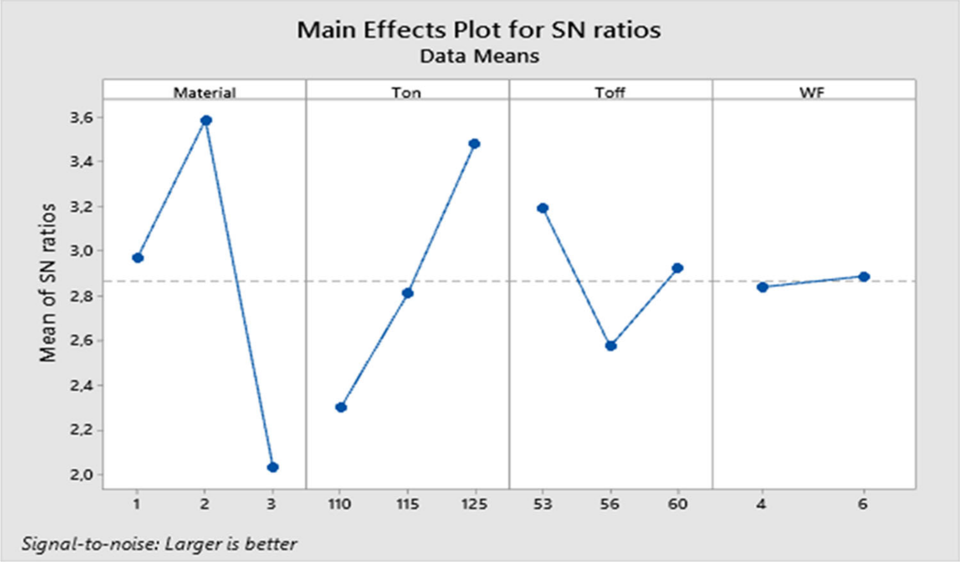


Fig. 9 Effect of essential parameters MRR S/N Ratio

process. Pie chart showing percentage additive ratios of process parameters are given in Figs. 12, and 13. The standard deviation is calculated for surface roughness and workpiece machining speed. It is understood from these standard deviation values that the Ra and MRR distribution are in close range. Considering all conditions, the maximum observed standard deviation was Ra = 0.36 and MRR = 0.33. In the tables below, variance analysis results for MRR and Ra are given in Tables 7, and 8.

ANOVA analysis material, T_{on} confidence rate is 95%. Therefore, the control factors are statistically influential at the 95% confidence level. The R2 value for the MRR is 0.9275, which means that the design can explain 92.75% of the variability in the MRR. The design's corrected R square (R adj) is 0.8767, close to the R2 value. Thus, it states that nominal terms are not included in the empirical modeling for MRR. The contributions of material, pulse duration, pulse cooldown, and WF to MRR are 82%, 10%, 1%, and 0.018%, respectively.

ANOVA analysis for Surface Roughness Material, T_{on}, confidence ratio is 95%. Therefore, the control parameters are statistically significant at the 95% confidence level. The R2 value for Ra is 0.9558, which can explain 95.58% of the design. The design's corrected R square (R adj) is 0.9249, close to the R2 value. Thus, it states that unimportant terms are not included in the empirical modeling for Ra. The contributions of material, hit time, hit cooldown, and WF in Ra is 30%, 63%, 2%, and 0.056%, respectively.

Table 6 Result of surface roughness

Experiment No.	Ra	S/N Ratio
1	4.436	– 12.9398
2	4.65	– 13.3491
3	5.01	– 13.9968
4	4.51	– 13.0835
5	4.755	– 13.5430
6	5.11	– 14.1684
7	4.97	– 13.9271
8	5.02	– 14.0141
9	5.51	– 14.8230
10	4.65	– 13.3491
11	4.8537	– 13.7215
12	5.6781	– 15.0841
13	4.3957	– 12.8606
14	4.55	– 13.1602
15	4.991	– 13.9638
16	4.448	– 12.9633
17	4.57	– 13.1983
18	4.999	– 13.9777

4 Conclusions

In this study, considering the difficulties in machining and cutting of HCCIs alloy by machining, cutting with wire erosion, one of the non-traditional manufacturing methods, was investigated and its machinability. The machinability of the HCCIs alloy by wire erosion was investigated. Experiments were carried out on the base material (raw material), softened and hardened materials by heat treatment according to different parameters. The main purpose here is to determine the relationship between the resistivity and hardness of the alloys produced and the machining parameters. According to the experimental results, the parameters were optimized by performing the Taguchi analysis. According to these experimental results and optimization, the following results were obtained.

- The HCCIs alloy obtained from casting into a sand mold was defined in the experimental study as three different (raw, soft, and hard) materials. The presence of C, O, Fe, Zn, Cr elements, which are HCCIs alloy components, has been confirmed by EDS analysis. Higher current and processing speed values were obtained for high-power level (HPL) settings for all sample types.
- Since the Voltage-Current ratio is related to the resistivity, it can be said that the higher this ratio in hard materials, the lower the electrical conductivity, and the lower the machining speed for hard materials. It has been observed that the voltage-current ratio is almost the same for soft and raw materials, and the close working speed values confirm this.
- It was determined that there was no significant difference in the roughness values depending on the processing speeds. On the other hand, it was observed that the roughness value increased with the increase in hardness, albeit partially. When all roughness values were evaluated, it was concluded that the resistivity and hardness of the materials were interpreted together.

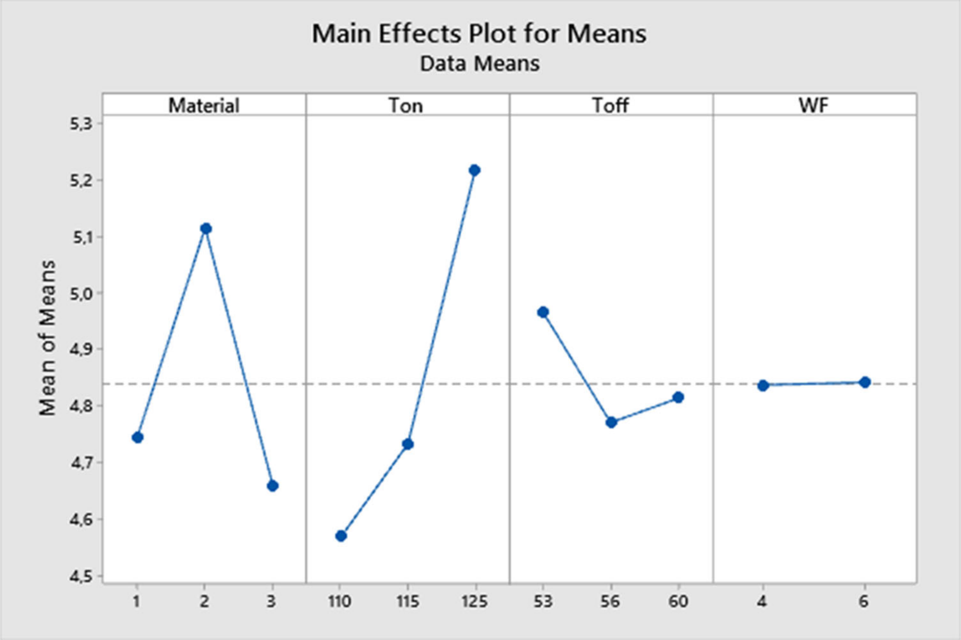
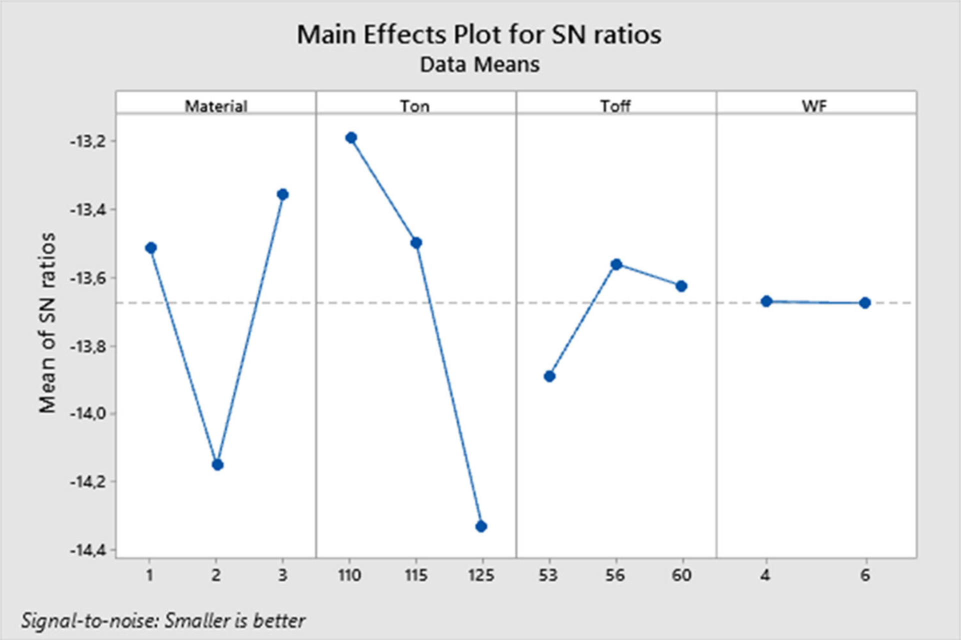


Fig. 10 Results of Ra parameters

Fig. 11 Effect of essential parameters Ra S/N Ratio



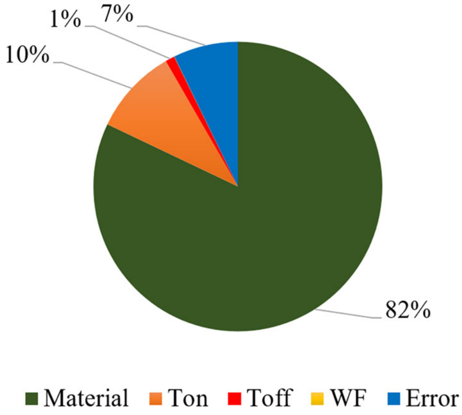


Fig. 12 Pie chart showing MRR % of parameters in WEDM process

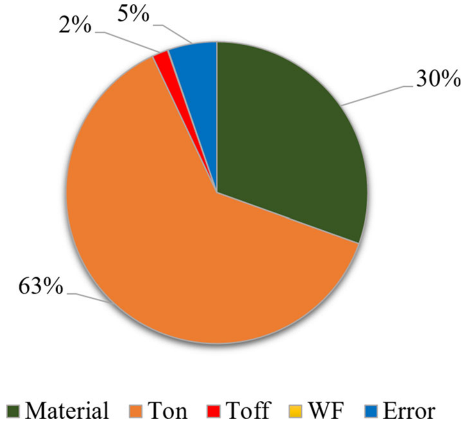


Fig. 13 Pie chart showing Ra % of parameters in WEDM process

- At the same power levels, it has been determined that denser structures are obtained with hardening, and they exhibit lower machining speed values due to slightly higher resistivity. Accordingly, higher current values are required.
- According to the SEM results, micro cracks were observed on the sample surfaces due to melting, evaporation, and rapid solidification of the material due to crater formation on the surface in all samples.
- It was determined that material and T_{on} had the most significant effects on MRR and Ra in the results of processing high chromium white cast iron with WEDM.
- As a result of Taguchi analysis, the ideal parameters for MRR are material no.2 shows $T_{on} = 125$, $T_{off} = 53$, and WF = 6. The contributions of material, T_{on}, T_{off}, and WF in MRR is 82.06%, 9.62%, 1.04%, and 0.18%, respectively.
- The optimal setting for Ra suggested by Taguchi technique is, material no.3 shows $T_{on} = 110$, $T_{off} = 56$, and WF = 4. The contributions of material, T_{on}, T_{off}, and WF in Ra is 30.48%, 62.49%, 1.72%, and 0.056%, respectively.
- In future studies, it will be useful to add microstructure analyses to the study and determine the relevance of microstructure change to resistivity.

Table 7 MRR variance analysis results

Source	DF	Seq SS	Adj SS	Adj MS	F	*P*	Contribution (%)
Material	2	3.61316	3.64637	1.82318	57.08	0.000	82.06412
T_{on}	2	0.42360	0.45322	0.22661	7.09	0.012	9.621041
T_{off}	2	0.04586	0.04669	0.02334	0.73	0.506	1.041598
WF	1	0.00083	0.00083	0.00083	0.03	0.876	0.018851
Error	10	0.31941	0.31941	0.03194			7.254619
Total	17	4.40285					

S = 0.1787 R-Sq. = 92.75% R-Sq. (adj) = 87.67% SD = 0.36

Table 8 Ra variance analysis results

Source	DF	Seq SS	Adj SS	Adj MS	F	*P*	Contribution (%)
Material	2	2.14662	2.00237	1.00118	33.40	0.000	30.48193
T_{on}	2	4.23454	4.16592	2.08296	69.49	0.000	62.49579
T_{off}	2	0.10441	0.10725	0.05362	1.79	0.217	1.722251
WF	1	0.00300	0.00300	0.00300	0.10	0.758	0.056582
Error	10	0.29973	0.29973	0.02997			5.243444
Total	17	6.78831					

S = 0.1731 R-Sq. = 95.58% R-Sq. (adj) = 92.49% SD. = 0.36

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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