Effects of Cryogenically-treated Stainless Steel on Eco-friendly Wire Electrical Discharge Machining Process

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Research Article

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Abstract

In this research, the influences of cryogenically treated stainless steel-grade 317 on the eco-friendly near-dry wire-cut electrical discharge machining (NDWEDM) processes have been investigated using minimum quantity of water mixed with oxygen gas dielectrics. The stainless-steel Grade-317 has been applied to make the various biomedical components. The wear ratio (WWR), and cutting rate (CR) are compared using cryogenically treated and un-treated work materials. The water flow rate, gas pressure, spark current, and pulse width had been considered as process parameters. All the tests were performed and compared by Taguchi's L27 orthogonal array. The surface topography of the machined surfaces and wear of wire had been illustrated for both treated/untreated materials by scanning electron microscope (SEM) images. It was reported that the WWR and CR of cryogenically treated materials are 20.31% lower and 22.32% higher than untreated materials respectively.

1. Introduction

The Wire-cut Electrical discharge machining is one of the micro-machining process to cut the hard materials without demaging surfaces(Amorim et al. 2019). After ISO-14000 implementations in materials processing industries, eco-friendly manufacturing methods have been proposed to minimize environmental impacts. The high-quality complex structures have been formed in hard materials by electrical discharge machining processes. It was observed that many harmful contaminants have been emitted during liquid dielectric EDM processes(Valaki et al. 2015). The change of the working medium with minimum quantity of lubrication is one of the important EDM development activities to minimize the environmental impacts(De Mello Belentani et al. 2014). In dry EDM processes, the pressurized gas/air had been applied as the fluid to replace the liquid dielectric system(Dhakar et al. 2019). However, the machining performance of the pure air/gas dielectric EDM process is lower than liquid processes. The air-must/ gas-mist near-dry EDM is an alternative method to enhance the performance of dry EDM (Ganachari et al. 2019; Sundriyal et al. 2020). Many research activities have been performed to increase the machining performance of the dry WEDM.

The literature on cryogenic treated/cooled workpieces and tool materials used in various EDM research have been discussed below. The cryogenically cooled copper tool was used in dry EDM experiments to boost the cutting rate and surface finish and minimize tool wear rate while comparing untreated tools used in EDM (Srivastava and Pandey 2012a). The electrode wear rate of kerosine dielectric-based EDM processes had significantly been decreased by cryogenically treated copper and brass electrodes (Singh and Singh 2012). The ultrasonic-assisted cryo-cooled copper electrode EDM process using has been performed to enhance the machining characteristics by recast-layer in the surfaces (Srivastava and Pandey 2012b). The tool wear rate of micro-EDM is momentously reduced by cryogenically treated Tungsten, brass, and copper electrodes while comparing untreated electrodes (Jafferson and Hariharan 2013). Electrode wear rate and surface topography of workpiece of liquid dielectric EDM were significantly reduced cryogenically cooled square-shaped copper electrodes (Kumar S and Kumar M 2015). The effect of cryogenic treated and untreated tool electrodes on cutting rate and surface roughness of conventional EDM have been compared using Inconel-625 workpiece material. It was observed that the machining characteristics have been improved by cryogenic treatments(Goyal et al. 2017). In the above-mentioned literature, the cryogenically cooled/ treated various tools were only used in conventional EDM experiments. In the dry die-sinking EDM, the cryo-cooled copper tool was first applied using titanium alloy to investigate the effect of process parameters on electrode wear rate and surface topography. It was concluded that the reduction of EWR of the cryogenically cooled electrode is 27% lower than untreated tools (Abdulkareem et al. 2009). The cryogenically cooled wire tool was first presented in the water-assisted dry WEDM experiments to cut the Inconel-718 material. It was revealed that the cryogenically cooled wire wear ratio is decreased to 29%, SR is reduced to 7.23% and MRR is increased to 15.6% while comparing using untreated wire tools (Myilsamy and Sampath 2021; Sampath and Myilsamy 2021). Very recently, the influences of cooled Inconel work materials on the ecofriendly WEDM process have been investigated and optimized to find the best operating conditions(Boopathi and Rameshkumar 2011).

It was revealed from the aforementioned literature that very few cryogenically treated work materials were investigated in the dry wire-cut EDM. However, there are no experimental investigations found on NDWEDM of cryogenic-treated stainless steel. This research gap has been fulfilled by this research work. The cryogenically treated Stainless Steel material is cut by near-dry WEDM using oxygen-mist dielectrics to improve the performance.

2. Materials And Methods

The 5 mm thickness of Stainless Steel Grade-317 work material and 0.2mm diameter of Molybdenum wire tool is applied. The stainless steel Grade-317 has been used to make the bio-medical-human parts(Dhakar et al. 2015). The work material was cooled at -195°C temperature of liquid nitrogen for 20 hours. Initially, It was cooled from room temperature 30°C to -195°C for 8 hours. In the second phase, the low temperature was constantly maintained for the next 20 hours. Later, the temperature was amplified from – 195°C to 30°C in the last 8 hours. The chemical structure of the Stainless Steel sheet is listed in Table 1.

The CNC-E3-DK7720 model wire-cut electrical discharge machine was used to conduct the experiments. The schematic arrangement and experimental setup of the Near-dry WEDM setup to cut the cryogenic treated Stainless Steel are shown in Figs. 1 and 2respectively. The water and pressurized oxygen gas were passed in the two coaxial hoses. At the end of the coaxial tubes, the minimum quantity of water has been atomized by pressurized oxygen gas. While oxygen was supplied in the nozzle, the velocity has been increased and pressure and temperature were dropped to 15°C. The low temperature cooled oxygen-mist is used to increase the cooling and efficiency in the cutting zone. The eroded materials have been disposed of by the high velocity of oxygen-mist. The oxygen pressure and flow rate of water were measured and controlled by a fabricated hydro-pneumatic circuit. The machining parameters have been monitored and controlled by a numerical control program.

Table 1
Chemical composition of Stainless Steel Grade-317 Sheet

Composition	Ni	Mn	P	S	Mo	C	Cr	Si	Fe
Percentage of weight (%)	13.0	2.0	0.045	0.030	3.50	0.080	19.00	1.00	61.0

The wire wear ratio (WWR) has been measured from the loss of wire materials during the cutting process and the initial weight of the wire is to be taken before the machining process (Mohammed 2018) (Eq. (1)).

$$WWR = \frac{Weight\ loss\ of\ wire\ by\ cutting\ process}{Initial\ weight\ of\ wire\ taken\ for\ experiment} \times 100\% \quad (1)$$

Cutting rate (CR) is found by the ratio of the volume of debris with the specified period as shown in Eq. (2)(Myilsamy and Sampath 2021; Sampath and Myilsamy 2021).

$CR = w \times L \times (d + 2G) / ti$ mm^3/min (2)

Where, w - workpiece width in mm, L – cutting length in mm, d- tool diameter in mm, G- Kerf width, in mm, ti - time in minutes.

Table 2
Process parameter levels

Factor Name	Unit	Low	Medium	High
Pressure (P)	bar	3	5	7
Flow Rate (F)	ml/min	8	12	16
Current (C)	A	3	4	5
Pulse Width (PW)	μs	16	22	28

The process parameters values for the L27 design are shown in Table 2(Myilsamy and Sampath 2021). Every trial is repeated by two times. The mean values of WWR and CR have been recorded in Table 3.

Table 3 Experimental observations

S.N.	P	F	C	PW	WWR × 10^{-3} (%)		CR (mm^3/ min)	
					Treated	Untreated	Treated	Untreated
1.	3	8	3	16	0.65	0.83	5.73	5.30
2.	3	8	3	22	0.80	1.01	7.00	6.45
3.	3	8	3	28	0.84	1.08	7.87	7.26
4.	5	12	4	16	0.52	0.63	8.81	8.24
5.	5	12	4	22	0.63	0.77	10.78	10.03
6.	5	12	4	28	0.66	0.82	12.11	11.29
7.	7	16	5	16	0.55	0.62	10.97	10.71
8.	7	16	5	22	0.67	0.76	13.42	13.04
9.	7	16	5	28	0.71	0.81	15.08	14.66
10.	3	12	5	16	0.75	0.90	7.39	7.27
11.	3	12	5	22	0.91	1.09	9.04	8.85
12.	3	12	5	28	0.96	1.16	10.16	9.95
13.	5	16	3	16	0.45	0.54	9.36	8.54
14.	5	16	3	22	0.55	0.66	11.44	10.39
15.	5	16	3	28	0.57	0.70	12.86	11.69
16.	7	8	4	16	0.56	0.68	8.01	7.54
17.	7	8	4	22	0.68	0.82	9.79	9.17
18.	7	8	4	28	0.71	0.88	11.00	10.32
19.	3	16	4	16	0.65	0.77	7.04	6.74
20.	3	16	4	22	0.79	0.94	8.61	8.20
21.	3	16	4	28	0.83	1.00	9.67	9.23
22.	5	8	5	16	0.64	0.75	9.53	9.30
23.	5	8	5	22	0.78	0.91	11.66	11.32
24.	5	8	5	28	0.82	0.97	13.10	12.73
25.	7	12	3	16	0.45	0.57	8.25	7.46
26.	7	12	3	22	0.55	0.69	10.09	9.09
27.	7	12	3	28	0.58	0.73	11.34	10.22

3. Results And Discussions

Analysis of wire wear ratio and cutting rate of Near-dry WEDM using cryogenically treated /untreated Stainless Steel are shown in Tables 4 and 5 respectively. The percentage of contribution of each parameters are calculated for the both machining conditions.

Table 4
Analysis of WWR of Near-dry WEDM using cryogenically treated and Untreated Stainless Steel

Cryogenically Untreated Stainless-Steel Material						
Parameter	DF	Seq. SS	Adj. SS	Adj. MS	F	Percentage of contribution
P	2	0.3390	0.3390	0.1695	493.19	48.367
F	2	0.0734	0.0734	0.0367	106.73	10.467
C	2	0.0768	0.0768	0.0384	111.74	10.958
PW	2	0.2056	0.2056	0.1028	299.02	29.325
Residual Error	18	0.0062	0.0062	0.0003	-	0.883
Total	26	0.7010	-	-	-	-
Cryogenically Treated Stainless-Steel Material						
P	2	0.197	0.197	0.099	432.250	42.393
F	2	0.031	0.031	0.015	67.670	6.637
C	2	0.101	0.101	0.051	221.490	21.723
PW	2	0.132	0.132	0.066	289.220	28.365
Residual Error	18	0.004	0.004	0.000	-	0.883
Total	26	0.465	-	-	-	-

Table 5
Analysis of Cutting rate of near-dry WEDM using cryogenically treated Untreated Stainless Steel

Cryogenically Untreated Stainless-Steel Material						
Parameter	DF	Seq. SS	Adj. SS	Adj. MS	F	Percentage of contribution
P	2	51.415	51.415	25.7076	248.42	40.04
F	2	12.817	12.817	6.4085	61.93	9.98
C	2	17.932	17.932	8.9659	86.64	13.97
PW	2	44.377	44.377	22.1884	214.41	34.56
Residual Error	18	1.863	1.863	0.1035		1.45
Total	26	128.404				
Cryogenically Treated Stainless-Steel Material						
P	2	79.096	79.096	39.5479	118.78	31.78
F	2	21.609	21.609	10.8046	32.45	8.68
C	2	83.875	83.875	41.9377	125.96	33.70
PW	2	58.282	58.282	29.1408	87.52	23.42
Residual Error	18	5.993	5.993	0.3329	-	2.41
Total	26	248.855	-		-	-

3.1. Process parameters' effects on cutting characteristics

The effect of oxygen pressure, the flow rate of tap water, spark current, and pulse width on WWR of dry WEDM using cryogenically treated and untreated work materials are shown in Figs. 3(a), (b), (c), and (d) respectively. The WWR of the cryogenically treated material is lower than the untreated workpiece. However, the variations of all process parameters on WWR on cryogenically treated and untreated materials are comparable. It was revealed that WWR is maximum at a low pressure of oxygen due to poor dielectric strength and low flushing efficiency(Boopathi and Sivakumar 2016; Yadav et al. 2019). While increasing pressure and flow rate, the WWR is significantly minimized by increasing the spark intensity, cooling, and flushing efficiency(Saha and Choudhury 2009; Boopathi and Sivakumar 2016; Mohammed 2018; Chityal et al. 2019). While increasing C and PW, the WWR is increased by increasing the intensity of spark and depth of crater(Abdulkareem et al. 2009). While increasing PW, the WWR is increased by growing heat in the cutting zone(Valaki and Rathod 2016). It is observed that 7 bar of pressure, 16ml/min of the flow rate of mixing water, 3A of current, and 16μs pulse width are optimum values of parameters for minimum WWR (Cryogenically treated: 0.4022 $\times 10^{-3}$%; Untreated: 0.4840 $\times 10^{-3}$%) of dry WEDM. It is also detected that P, C, and PW are the significant factors for WWR.

The influences of each process parameter (oxygen pressure, the flow rate of tap water, spark current, and pulse width) on the cutting rate of dry WEDM using cryogenically treated / untreated materials are shown in Figs. 4(a), (b), (c), and (d). While increasing oxygen gas pressure, the Cutting rate is improved from 3 bar to 5 bar and decreased from 5 to 7 bar(Boopathi and Sivakumar 2013, 2016). The maximum CR has been obtained at moderate pressure (5 bar). The spark transfer efficiency between tool and work materials has been interrupted by the high velocity of oxygen-mist at a high-pressure level(Boopathi et al. 2012; Boopathi and Sivakumar 2013, 2016). The cutting rate is improved by increasing the flow rate of mixing water. The flushing efficiency and dielectric strength in the plasma zone While increasing water flow rate with oxygen gas (Boopathi and Sivakumar 2014; Boopathi and Myilsamy 2021). While increasing pulse width and spark current, the cutting rate has been changed by high heat and spark intensity produced in the cutting zone (Abdulkareem et al. 2009; Boopathi and Sivakumar 2013; Garg et al. 2017). It was revealed that the overall cutting rate of dry WEDM has been improved by cryogenically treated work material. However, the impact of each process parameter on the CR of both processes is comparable. It is revealed that 5 bar of pressure, 16ml/min of the flow rate of mixing water, 5A of current, and 28µs pulse width are the best values of parameters for maximizing cutting rate (Cryogenically treated: 17.6719 mm^3/min; Untreated: 14.6112 mm^3/min) of dry WEDM. It is also noticed that P and PW are significant factors for maximizing the cutting rate.

3.2. Comparative Analysis

It was also revealed from Table 6 that the WWR of oxygen-mist dry WEDM using cryogenically treated Stainless Steel is 20.31% higher than untreated material. The SEM 400X enlargement images of wire tools used in dry WEDM processes for both treated and untreated work materials are shown in Figs. 5 (a) and (b) respectively. It was revealed that the wire wear has occurred along with the traveling (longitudinal) direction. The wire tool damages in the cutting of cryogenically treated material are lower than wire damages during the untreated work material because of high heat dissipation capacity and electric conductivity of treated material(Kennedy 2001; Kalsi et al. 2010; Fard et al. 2013; Akincioğlu et al. 2015; Mohanty et al. 2018). The heat dissipation capacity of the work material is increased by increasing the thermal conductivity of cryogenically treated Stainless Steel. The thermal conductivity of the work material is also improved by increasing electrical conductivity (Mohanty et al. 2018). The cutting rate of the dry WEDM using cryogenically treated work material is 22.32% higher than the cutting rate of untreated work material. It is improved by increasing electric and thermal conductivities by the cryogenic treatment process and wide cutting path in the cutting zone(Akincioğlu et al. 2015; Garg et al. 2017). The flammable oxygen-mist dielectric is also increasing the cutting rate due to accelerating the spark erosion process by ionization, heating, and melting of work material. The microstructure of the machined surfaces of cryogenically treated / untreated stainless steel of Near-dry WEDM is exposed in Figs. 6 (a) and 6(b). The specimens for the microstructural analysis has been prepared using optimum cutting rate condition($P_2F_3C_3PW_3$). It was observed that the surface roughness of the cryogenically treated materials(surface roughness: 2.71 µm) is lower than untreated steel(surface roughness: 3.06 µm).

The confirmation tests were supported to authorize the results predicted by the Taguchi technique using optimum parameters settings. The maximum cutting rate of dry WEDM using cryogenically treated work material and untreated work materials are predicted as 17.8719 mm^3/min and 14.6112 mm^3/min respectively. Similarly, the optimum WWR using cryogenically treated and untreated Stainless Steel is obtained as 0.4022×10^{-3}% and 0.4840×10^{-3}% respectively.

Table 6
Comparison of dry WEDM performances using Cryogenically treated and untreated Stainless Steel.

Response	Material	Optimum parameters	Prediction	Confirmation Experiments
CR (mm^3/min)	Cryogenic treated Stainless Steel	P_2-F_3-C_3-PW_3	14.6112	14.52
	Untreated Stainless Steel		17.8719	17.65
WWR (%)	Cryogenic treated Stainless Steel	P_3-F_3-C_1PW_1	0.4022	0.41
	Untreated Stainless Steel		0.4840	0.48

4. Conclusions

In this research, cryogenically treated and untreated Stainless Steel materials have been maintained by oxygen-mist NDWEDM processes.

The CR of dry WEDM using cryogenically treated and untreated materials is amplified by increasing oxygen gas pressure up to 5 bar, then reduced from 5 to 7 bar pressure. The spark transfer has been interpreted by the high pressure of gas in the cutting zone at the maximum pressure. The CR is improved by increasing pulse width, spark current, and mixing water flow rate for both processes. Maximum CR and minimum WRR of both NDWEDM processes is obtained by increasing the water flow rate by enhancing the flushing efficiency, sufficient cooling, and good dielectric strength in the plasma zone.

From comparative analysis, it was also revealed that the WWR of cryogenically treated material used in NDWEDM is 20.31% higher than untreated materials by high heat dissipation capacity and electric conductivity. The cutting rate of the cryogenically treated work material is 22.32% higher than the cutting rate of untreated material. The flammable oxygen-mist dielectric is increasing the CR due to accelerating the plasma spark by plasma development, ionization, heating, and melting of work material in the cutting zone. It was discovered from SEM images that the wire damage for cryogenically treated work material is lower than for untreated work material. The cutting path during the process of cryogenically treated work material is higher than the untreated work material cutting process.

Declarations

Ethics approval

Not Applicable

Consent to participate

Not Applicable

Consent for publication

Not Applicable

Authors Contributions

Sampath Boopathi contributed to conducting experiments, experimental design, analyzing and interpreting the data regarding the near-dry WEDM.

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Competing Interests

The author declares that no competing interests.

Availability of data and materials

The datasets generated during and/or analysed during the current study are available from the corresponding author and included in this article.

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Figures

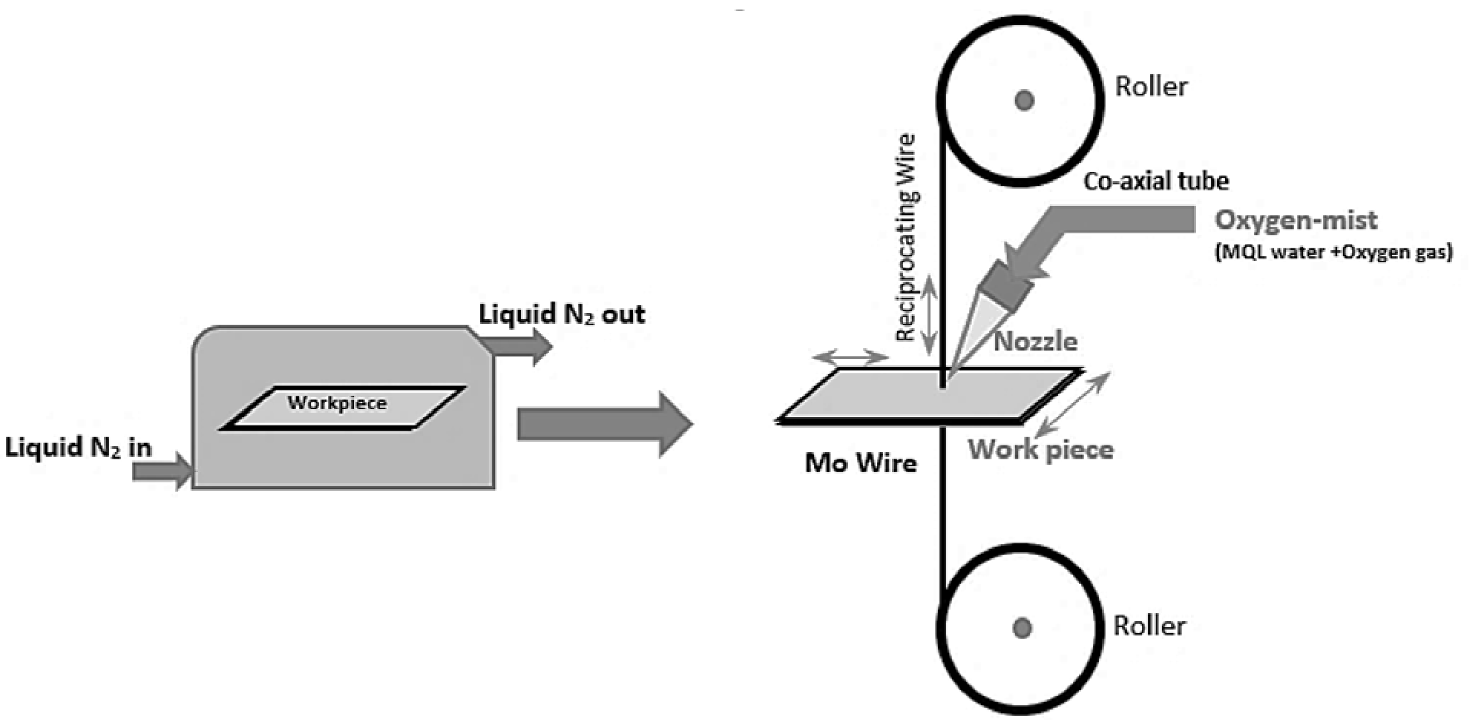

Figure 1

Schematic arrangement of NDWEDM of cryogenic treated Stainless Steel

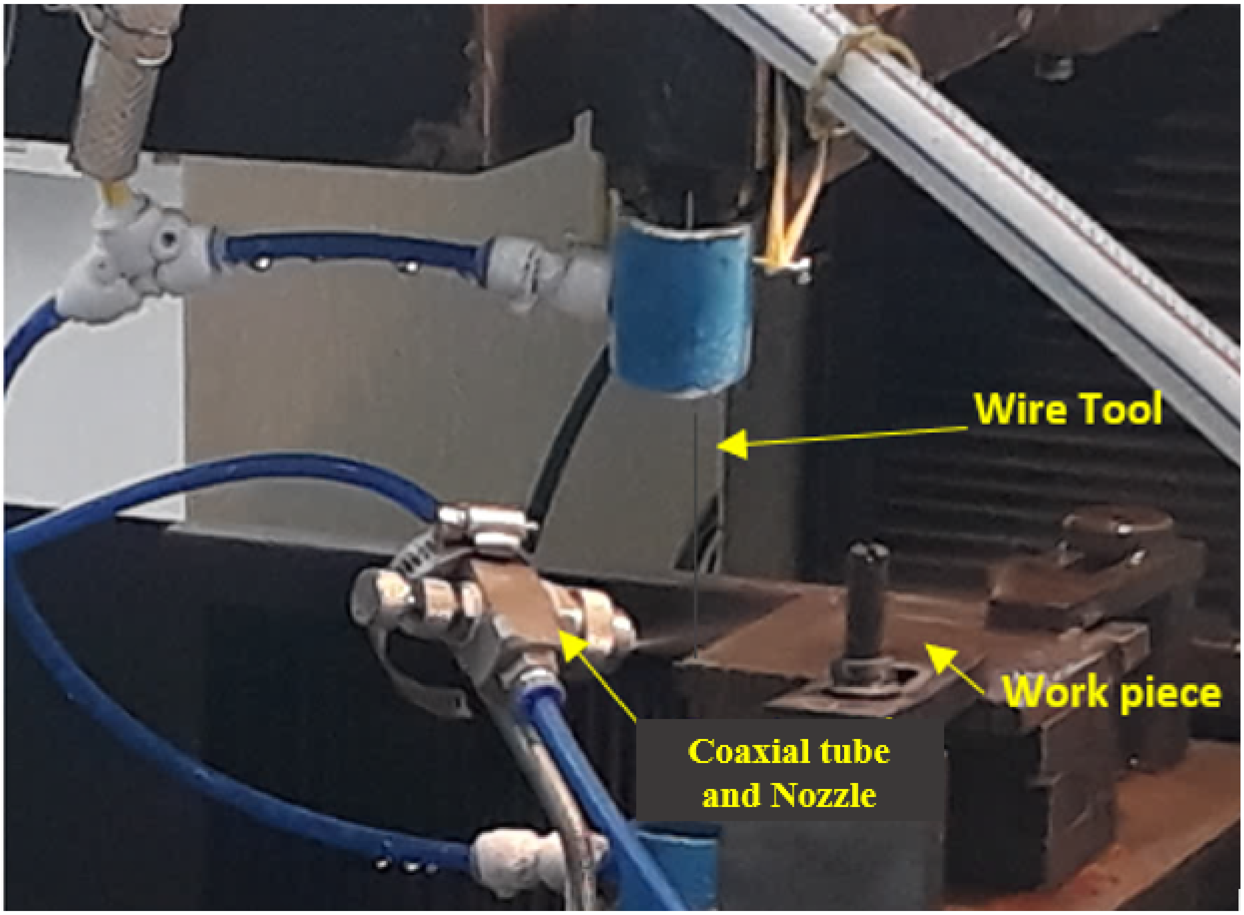

Figure 2

Experimental Setup for Near-dry WEDM

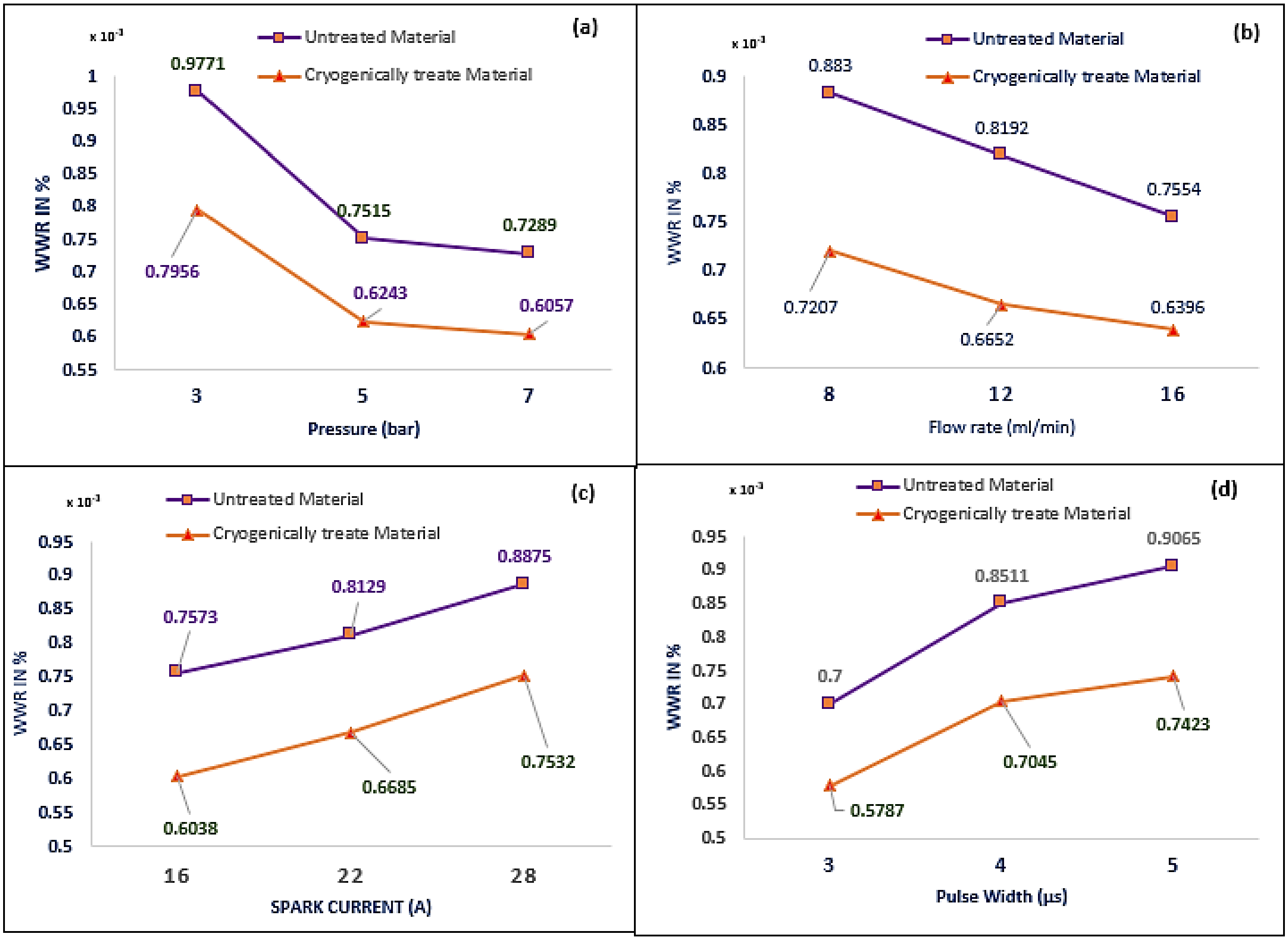

Figure 3

Comparison of process parameter's effects on WWR of dry WEDM (a) Pressure vs WWR. (b) Flow rate vs WWR. (c) Spark Current Vs WWR. (d) Pulse width vs WWR

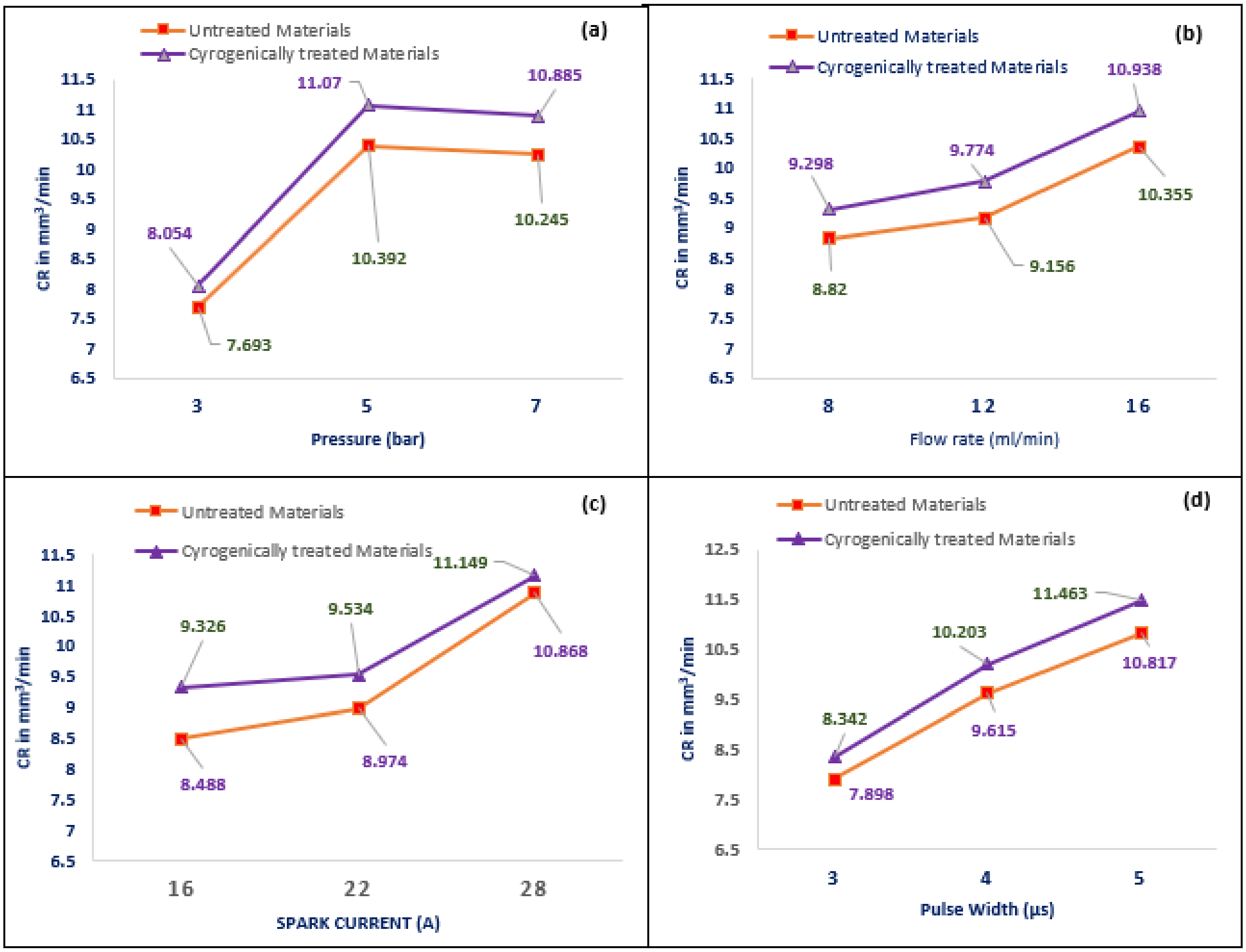

Figure 4

Comparison of process parameter's effects on CR of dry WEDM (a) Pressure vs CR. (b) Flow rate vs CR. (c) Spark Current Vs CR. (d) Pulse width vs CR

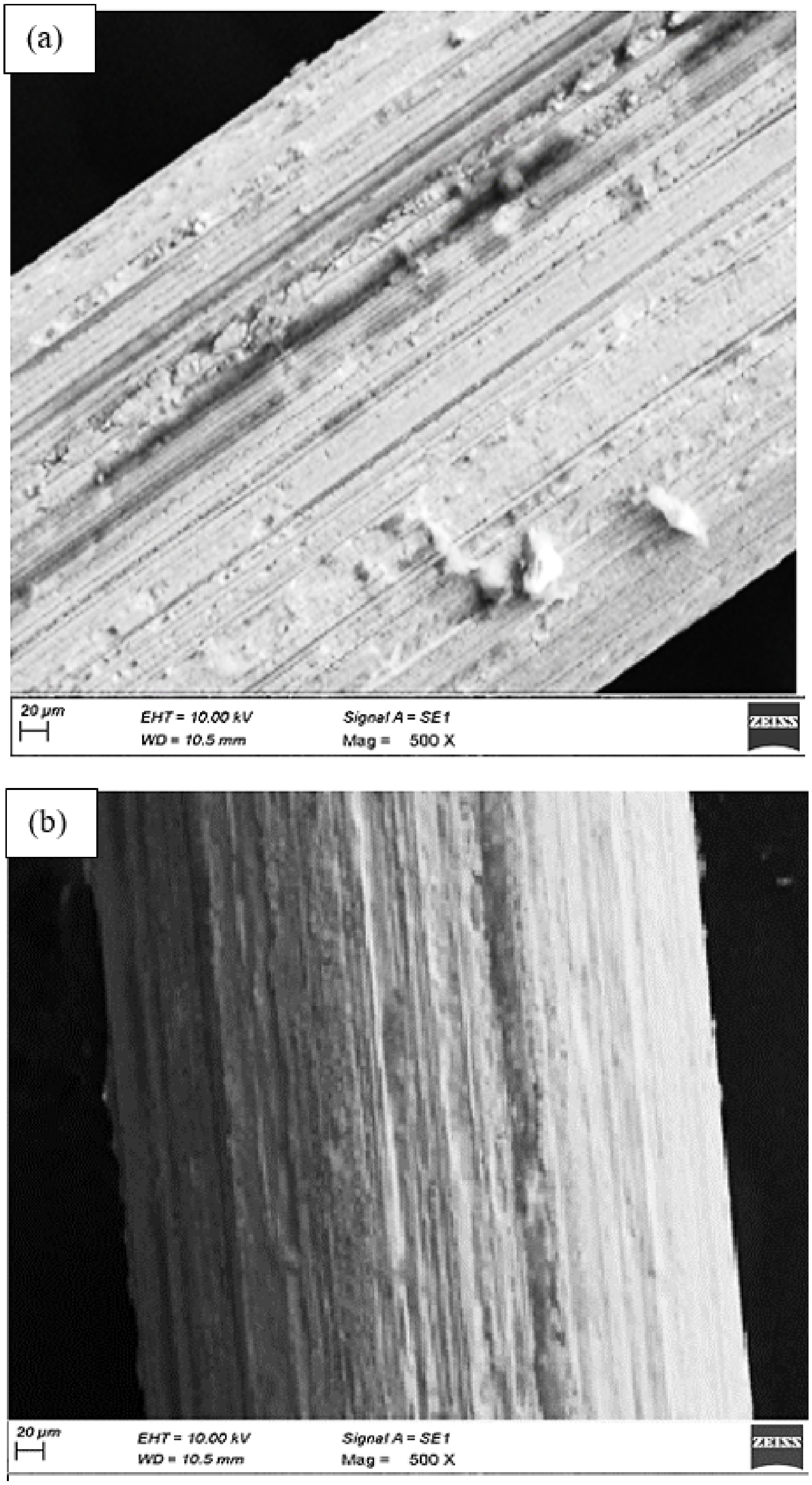

Figure 5

Microscopic Analysis of wire wear of NDWEDM Processes using best parameters' settings (P3F3C1PW1) for minimizing WWR using (a) Cryogenically treated Stainless Steel, (b) Untreated Stainless Steel.

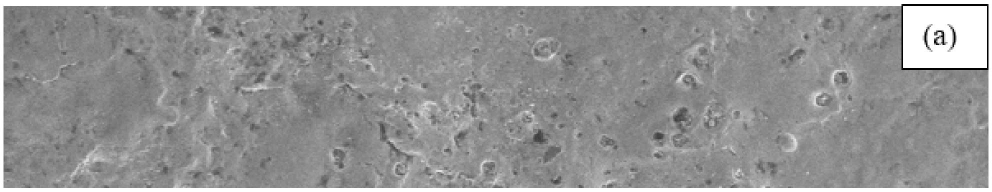

Figure 6

Microscopic view of (a) Cryogenically treated Stainless Steel(surface roughness: 2.71 μm), (b) Untreated Stainless Steel(surface roughness: 3.06 μm) best parameters' settings ($P_2F_3C_3PW_3$) for maximum Cutting rate