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ANALYSIS OF A CRYOGENICALLY COOLED NEAR-DRY WEDM PROCESS USING DIFFERENT DIELECTRICS

ANALIZA KRIOGENSKO OHLAJENEGA SKORAJ POPOLNO SUHEGA PROCESA EROZIJE Z UPORABO RAZLIČNIH DIELEKTRIKOV

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In this research, a cryogenically cooled, near-dry, wire-cut, electrical discharge machining (CNDWEDM) investigation was performed using air, oxygen, and helium gases mixed with the minimum quantity of dielectric water as the working medium to cut Inconel-718 alloy with a molybdenum wire tool. All the experiments have been performed using the –150 °C temperature of the liquid-nitrogen-cooled wire electrode. The comparative analysis of the wire wear ratio (WWR), and the material removal rate (MRR) have been performed using an L27 orthogonal array. The air/gas pressure, mixing water-flow rate, spark current, and pulse duration are considered as influencing parameters on the cutting characteristics. It was observed from a comparative analysis that the WWR of oxygen-mist and helium-mist CNDWEDM processes are 30.39 % and 27.91 % higher than air-mist CNDWEDM, respectively. The MRR of the oxygen-mist and helium-mist CNDWEDM processes are 7.09 % and 3.60 % higher than the air-mist CNDWEDM, respectively. The contributions of the process parameters on the MRR and WWR for all three dielectric media have also been illustrated. It was observed from scanning electron microscope (SEM) images that the crater size in the wire tool of the oxygen-mist CNDWEDM is higher than the crater-size of the wire in the air-mist and helium-mist CNDWEDM.

Keywords: liquid nitrogen, Inconel-718 alloy, wire wear ratio, material removal rate

V članku avtorji opisujejo raziskavo obdelave materiala s kriogensko hlajeno skoraj popolnoma suho žično erozijo (CNDWEDM; angl.: cryogenically cooled near-dry wire-cut electrical discharge machining) z mešanjem minimalne količine dielektrične vode z zrakom, kisikom in helijem pri rezanju zlitine Inconel-718 z molibdensko žico. Vse poskuse so izvedli pri temperaturi –150 °C s tekočim dušikom ohlajene žične elektrode. Primerjalno analizo razmerja obrabe žice (WWR; angl.: wire wear ratio) in hitrosti odstranjevanja materiala (MRR; angl.: material removal rate) so izvedli z ortogonalno matrico L27. Kot vplivne parametre za oceno lastnosti procesa rezanja materiala so izbrali naslednje parametre: razmerje med tlakom zraka in plina, hitrost pretoka vode, električni tok v obloku in trajanje impulzov. S pomočjo primerjalne analize so ugotovili da je 30,39 % »megla« (sprej, pršec) kisika WWR in helija v procesu CNDWEDM učinkovitejša kot uporaba 27,91 % zračne megle v tem procesu. MRR z uporabo kisikove in helijeve megle v izbranih CNDWEDM procesih s 7,09 % oziroma 3,60 % sta učinkovitejša kot CNDWEDM z uporabo zračne megle. Avtorji so v članku prav tako ilustrirali učinek procesnih parametrov na MRR in WWR z uporabo vseh treh dielektričnih medijev. Opazovanje posnetkov nastalih rezov, izdelanih z vrstičnim elektronskim mikroskopom (SEM) je pokazalo, da povzroča rezanje z uporabo elektrodne žice obdane s kisikovo meglo večje kraterje kot rezanje z elektrodama obdanima z zračno oziroma helijevo meglo.

Ključne besede: tekoči dušik, zlitina Inconel-718, razmerje obrabe žice, hitrost odvzema materiala

1 INTRODUCTION

In modern production industries, the materials are machined with high machining performances and minimum environmental impacts. The harmful hazardous contaminants emitted during electrical discharge machining (EDM) and wire-cut electrical discharge machining (WEDM) should be minimized or eliminated by a modification of the dielectric medium, reducing machining time and proper disposal of wastes.[1] The lives of the machine operators have been shortened by breathing harmful smoke from boiled liquid dielectric fluid from EDM/WEDM processes. Thus, many EDM research activities have been concentrated to change the dielectric fluid to eliminate the above issues.[2–4] Air or harmless gases have been one of the replacements for using liquid medium and it is called a dry-machining process. In this research, pressurized air, oxygen, helium gases have been used. However, it was observed that more machining time is elapsed during the dry EDM/WEDM process. These drawbacks have been eliminated by gas/air mixed with a small amount of liquid as a working medium. Thus, the near-dry EDM processes were attempted to attain significant and stable machining performances.[5,6] Some near-dry EDM researches were focused on vibrating tools and work materials, non-reacting gases as the working medium, change of spark gap, and changing the direction of the tool and workpiece feed mechanism to enhance the machining performances.[6–9] Still, a few types of research were specially made on wire-cut EDM processes due to some technical difficulties while apply-

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ing cryogenic cooling to the wire-work gap during the machining process. The cryogenically cooled work and tool materials is another way of research in EDM/WEDM to improve the machining characteristics. The surface roughness and tool wear rate of the cryogenically cooled near-dry EDM process have been enhanced to 27 % and 20 %, respectively.[10] The MRR and tool wear rate of the cryogenic treatment of copper tool and titanium workpiece in EDM process are enhanced by 60.4 % and 58 %, respectively.[11] The good surface finish and tool wear rate of the cryogenically cooled copper electrode have been attained while machining of titanium alloy work material in the dry die-sinking EDM process.[12] The MRR of cryogenically cooled gases in the dry EDM processes had been improved to 50 % and the surface rough has been reduced to 10 %, compared to the dry EDM process.[13]

Very recently, cryogenically cooled molybdenum wire was used in the near-dry WEDM (NDWEDM) process to minimize the wire wear ratio, surface roughness and maximize the MRR.[14] The MRR and wear resistance of a wire of the CNDWEDM process have been further improved by using an oxygen-mist dielectric medium.[15] It was observed from the dry and near-dry EDM process review article that cryogenic cooling is one of the important methods to enhance the cutting characteristics of dry and near-dry EDM/WEDM processes.[16]

It was observed from a deep literature survey that very few CNDWEDMs have been performed. However, there are no comparative analyses found using air-mist, oxygen-mist and helium-mist in the CNDWEDM investigation. This research gap is considered that the CNDWEDM performances have been compared using air-mist, oxygen-mist and helium-mist dielectric mediums using a Taguchi L27 orthogonal array. The experimental methods for conducting CNDWEDM processes using different gases have also been illustrated. In this article, the influences of process parameters on WWR and MRR of air-mist, oxygen-mist and helium-mist CNDWEDM have been examined. The microstructure of the wire wear using various dielectric mediums in CNDWEDM processes have also been illustrated.

2 EXPERIMENTAL PART

2.1 Cryogenic cooled NDWEDM experimental setup

The Inconel 718 alloy (size of (80 × 8 × 10) mm) was used as work material to perform all CNDWEDM machining processes. The pictorial representation of the CNDWEDM is shown in **Figure 1**. The experimental setup for supplying the air-mist/oxygen-mist/helium-mist circuit was designed and replaced the existing liquid dielectric circuit of WEDM. The pressurized air/gas mixed with the small amount of dielectric water is mixed to air/gas-mist.[17,18] The bi-axial hoses were used to supply both fluids and it was mixed at the convergent nozzle in which the air/gas-mist developed. Below –150 °C the liquid nitrogen is stored in the Dewar flask to maintain it. Liquid nitrogen was supplied to both sides from two separate hoses. Hence, the wire was additionally cooled by liquid nitrogen to improve the electric conductivity and wire wear ratio.[19,20]

The MRR can be determined by the ratio of the quantity of erosion in the workpiece with respect to time.[21] The WWR was measured from the loss of wire materials during the cutting process concerning the time and initial weight of wire is to be taken before the machining process[22] (Equation (1)).

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

Initially, the wear resistance and electric conductivity of the cryogenically treated and untreated wire tools were by exploratory experiments. It was revealed that electrical conductivity and wear resistance were enhanced by increasing the cryogenic cooling rate to the wire.[17] The ranges of process parameters were finalized using a one factor at a time approach.[18] The values of the

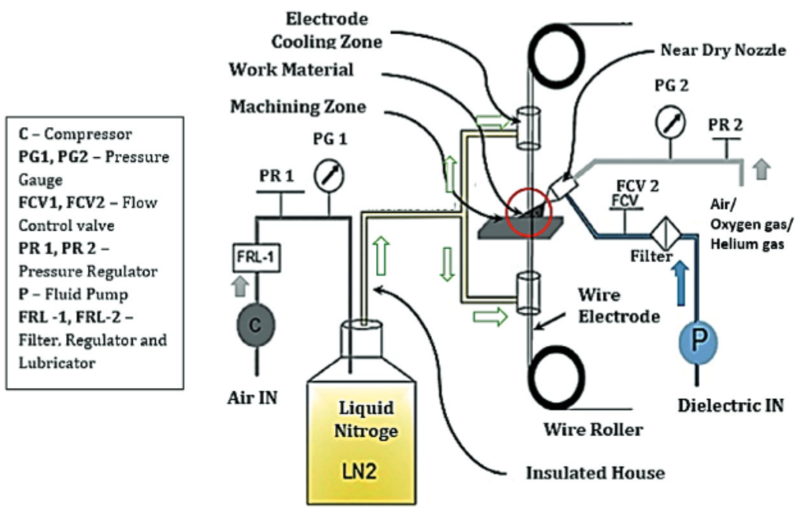

Figure 1: Representation of CNDWEDM process

sources and levels of each parameter for Taguchi design of experiments are shown in **Table 1**.

Table 1: Various parameters to perform the cryogenic cooled NDWEDM experiments

Parameters	Symbol/unit	Levels		
		Level 1	Level 2	Level 3
Air/gas pressure	*p*/Pa	3×10^5	5×10^5	7×10^5
Flow rate	$q_v/(m^3/s)$	1.3×10^{-7}	1.3×10^{-7}	2.7×10^{-7}
Current	*I*/A	3	4	5
Pulse duration	*t*/µs	16	22	28
Dielectric medium	–	air-mist, oxygen-mist, helium-mist		
Wire tool	–	cryogenic cooled molybdenum wire 0.2 mm diameter		
Work material	–	Inconel-718 alloy		

2.2 Systematic experiments using the Taguchi method

All the CNDWEDM experiments were designed and performed using an L27 orthogonal array. The 3 levels of four process parameters are considered to measure the MRR and WWR. 27 trails of reading were measured from the combination of the process parameter levels.

Case 1: CNDWEDM experiments were performed using pressurized air mixed with the minimum quantity and a cryogenically cooled wire tool.

Case 2: CNDWEDM experiments were performed using a pressurized oxygen gas mixed with the minimum quantity and a cryogenically cooled wire tool.

Case 3: CNDWEDM experiments were performed using pressurized helium gas mixed with the minimum quantity and a cryogenically cooled wire tool.

The mean values of two replications of the MRR and WWR for each case of the experiment are shown in **Table 2**. After conducting the experiments, a Taguchi analysis was made to compare the three mode CNDWEDM processes. The contributions and effects of each parameter on responses were compared. The variations of each parameter on the WWR and MRR were analysed and compared.

3 RESULTS AND DISCUSSION

3.1 Parameters' influence on the wire wear ratio

The effect of pressure, flow rate, current, and pulse duration variations of the air-mist, oxygen-mist, and helium-mist CNDWEDM on WWR are shown in **Table 3** and **Figure 2**. It was revealed that WWR is high at a low

Table 2: CNDWEDM experimental results through L27 orthogonal array

S.No.	Pressure ($\times 10^5$ Pa)	Flow rate ($\times 10^{-7}$ m^3/s)	Spark current (A)	Pulse duration (µs)	WWR			MRR (1.7×10^{-11} m^3/s)		
					Air-mist	Oxygen-mist	Helium-mist	Air-mist	Oxygen-mist	Helium-mist
1.	3	8	3	16	0.5400	0.7064	0.6549	4.172	5.725	5.2974
2.	3	8	3	22	0.6520	0.8589	0.7972	5.068	7.002	6.4491
3.	3	8	3	28	0.6920	0.9148	0.8399	5.779	7.867	7.2552
4.	5	12	4	16	0.4790	0.5371	0.5160	7.624	8.810	8.2425
5.	5	12	4	22	0.5780	0.6530	0.6282	9.262	10.775	10.0344
6.	5	12	4	28	0.6130	0.6955	0.6619	10.561	12.106	11.2886
7.	7	16	5	16	0.4560	0.5285	0.5507	10.397	10.974	10.7070
8.	7	16	5	22	0.5500	0.6425	0.6704	12.630	13.422	13.0347
9.	7	16	5	28	0.5840	0.6844	0.7063	14.401	15.080	14.6640
10.	3	12	5	16	0.6400	0.7620	0.7451	6.665	7.390	7.2669
11.	3	12	5	22	0.7730	0.9264	0.9071	8.097	9.038	8.8466
12.	3	12	5	28	0.8200	0.9867	0.9557	9.233	10.155	9.9524
13.	5	16	3	16	0.3740	0.4581	0.4482	7.410	9.355	8.5371
14.	5	16	3	22	0.4510	0.5570	0.5457	9.002	11.442	10.3930
15.	5	16	3	28	0.4790	0.5932	0.5749	10.264	12.855	11.6921
16.	7	8	4	16	0.4930	0.5745	0.5572	6.695	8.006	7.5359
17.	7	8	4	22	0.5950	0.6984	0.6784	8.133	9.792	9.1742
18.	7	8	4	28	0.6310	0.7439	0.7147	9.273	11.002	10.3209
19.	3	16	4	16	0.5200	0.6544	0.6458	5.900	7.037	6.7387
20.	3	16	4	22	0.6270	0.7957	0.7862	7.167	8.606	8.2036
21.	3	16	4	28	0.6660	0.8474	0.8284	8.173	9.669	9.2291
22.	5	8	5	16	0.5750	0.6375	0.6411	8.853	9.531	9.2961
23.	5	8	5	22	0.6940	0.7751	0.7804	10.755	11.657	11.3169
24.	5	8	5	28	0.7360	0.8256	0.8222	12.264	13.096	12.7316
25.	7	12	3	16	0.3950	0.4806	0.4495	6.330	8.253	7.4631
26.	7	12	3	22	0.4760	0.5843	0.5472	7.690	10.094	9.0855
27.	7	12	3	28	0.5060	0.6224	0.5765	8.768	11.341	10.2212

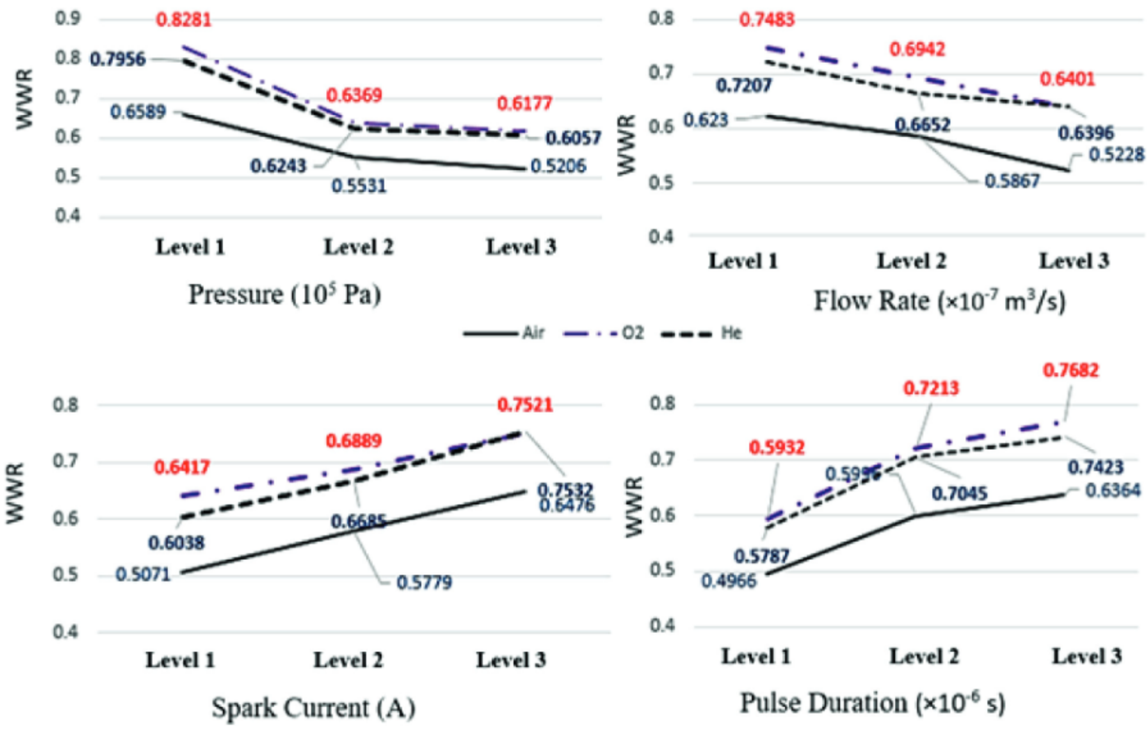

Figure 2: Comparisons of process parameter effects on the WWR of CNDWEDM

pressure of air/gases due to discontinuous sparks between the wire and the workpiece. While increasing pressure, the WWR is reduced due to the high spark intensity. While increasing the flow rate, the WWR is reduced due to an increase in the cooling effect.[22] While increasing the pressure, the WWR is also increased due to the strong impingement of the electrons and the maximum oxidation in the plasma zone.[23] While increasing the pulse duration, the WWR is enhanced by a long period of discharge energy distribution in the plasma channel of striking electrons on the wire surfaces.[23] Thus, the maximum WWR of the air-mist, oxygen-mist and helium-mist NDWEDM can be attained at level-3 of pressure, level-3 of flow rate, level-1 of spark current, and level-1 of pulse duration (**Table 3**).

3.2 Parameters' influence on the material removal rate

The effects of process parameters on the MRR of three dielectric mediums of CNDWEDM processes are illustrated in **Table 4** and **Figure 3**. While increasing air/gas pressure from 3 × 10^5 Pa to 5 × 10^5 Pa, the MRR is enhanced and reduced by the pressure from 5 × 10^5 Pa to 7 × 10^5 Pa due to minimizing the spark-transfer rate.[20,21] The maximum MRR was achieved at a moderate pressure (5 × 10^5 Pa) by improving the spark strength in

Table 3: Influence of process parameters on WWR of air-mist, oxygen-mist and helium-mist CNDWEDM

Parameter	Wire wear ratio								
	Air-mist dielectric medium			Oxygen-mist dielectric medium			Helium-mist dielectric medium		
Level	1	2	3	1	2	3	1	2	3
Pressure (× 10^5 Pa)	0.6589	0.5531	**0.5206**	0.8281	0.6369	**0.6177**	0.7956	0.6243	**0.6057**
Flow rate (× 10^{-7} m^3/s)	0.623	0.5867	**0.5228**	0.7483	0.6942	**0.6401**	0.7207	0.6652	**0.6396**
Spark current (A)	**0.5071**	0.5779	0.6476	**0.6417**	0.6889	0.7521	**0.6038**	0.6685	0.7532
Pulse duration (µs)	**0.4966**	0.5996	0.6364	**0.5932**	0.7213	0.7682	**0.5787**	0.7045	0.7423

Table 4: Effect of process parameters on MRR of air-mist, oxygen-mist and helium-mist CNDWEDM

Parameter	Material removal rate (1.7 × 10^{-11} m^3/s)								
	Air-mist dielectric medium			Oxygen-mist dielectric medium			Helium-mist dielectric medium		
level	1	2	3	1	2	3	1	2	3
Pressure (× 10^5 Pa)	6.695	**9.555**	9.369	8.054	**11.070**	10.885	5.96	6.676	**8.004**
Flow rate (× 10^{-7} m^3/s)	7.888	8.248	**9.483**	9.298	9.774	**10.938**	6.335	6.869	**7.436**
Spark current (A)	7.165	8.087	**10.366**	9.326	9.534	**11.149**	5.746	6.791	**8.102**
Pulse duration (µs)	7.116	8.645	**9.857**	8.343	10.203	**11.463**	5.552	6.8	**8.288**

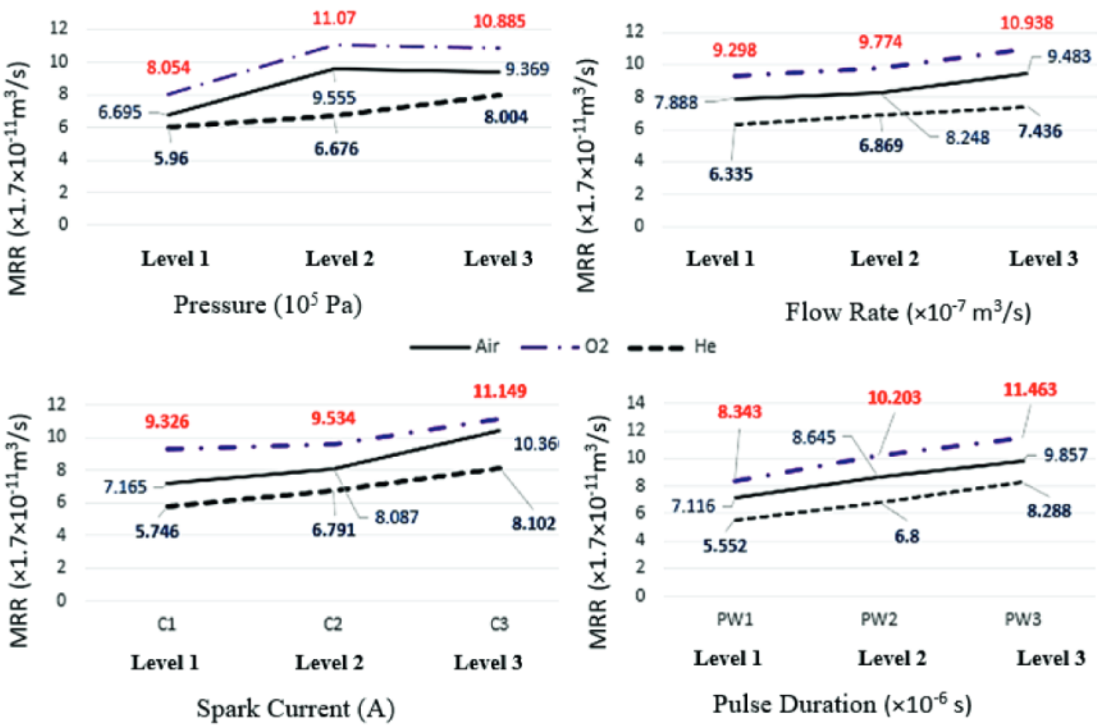

Figure 3: Comparisons of effects of process parameters on the MRR of CNDWEDM

the cutting zone. At a high-pressure level (7 × 10^5 Pa), the spark-transfer rate is reduced by the high-velocity dielectric medium. It reduces the intensity of the spark energy and is insufficient to cut the work materials.[18] The MRR is improved by the flow rate due to the good flushing efficiency in the plasma zone. The behaviour of the flow rate on the MRR is similar for the air-mist, oxygen-mist, and helium-mist mediums. The MRR is improved by increasing the pulse duration due to a long period of spark energy spreading in the plasma channel of striking electrons on the work material.[18] The maximum MRR is attained by increasing the spark-current in the plasma zone due to an increase in the distribution of the electric energy.[20] Thus, the maximum MRR of air-mist and oxygen-mist CNDWEDM can be attained by level-2 of pressure, level 3 of flow rate, level-1 of spark current and level-1 pulse duration (**Table 4**). However, the maximum MRR of helium-mist CNDWEDM can be attained at a level-3 of pressure, level 3 of flow rate, level-1 of spark current, and level 1 of pulse duration.

3.3 Comparisons of air-mist, oxygen-mist and helium-mist CNDWEDM processes

The overall behaviours of all the process parameters on WWR and MRR for air-mist, oxygen-mist, and helium-mist CNDWEDM processes are similar (**Figures 2** and **3**). The comparisons of the MRR and WWR of three working mediums using 27 experimental observations are illustrated in **Figures 4a** and **4b**, respectively. Oxygen-mist CNDWEDM process has a maximum MRR with the higher WWR than the air-mist and helium-mist processes. However, the WWR of the air-mist process is lower than the oxygen-mist and helium-mist CNDWEDM processes. From **Figure 3**, the minimum WWR of all three processes is obtained by the highest level of gas pressure, level-3 of flow rate, level 1 of spark current and level-1 of pulse duration. It was also revealed that the percentage of the contribution analysis that oxygen and helium mist pressure is significantly impacted on both WWR and MRR. Thus, the oxygen-mist dielectric is suitable for the expectation of maximum MRR and air-mist dielectric was selected to fulfil the requirements of a lower WWR.

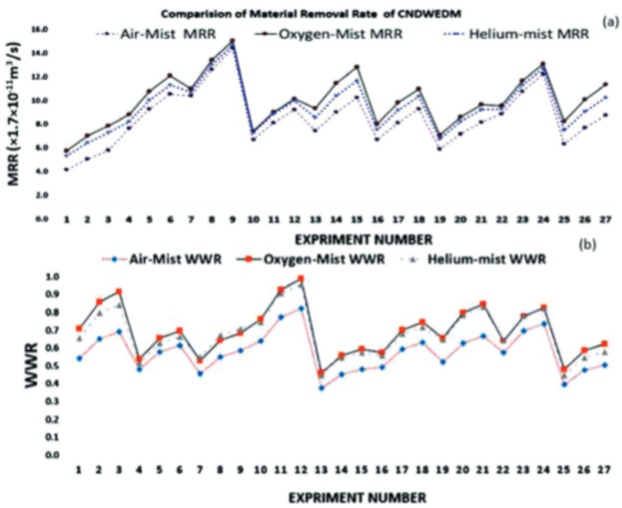

Figure 4: Comparisons of for air-mist, oxygen-mist and helium-mist CNDWEDM: a) material removal rate, b) wire wear ratio

Table 5: Parameter contribution on air-mist, oxygen-mist and helium-mist *CNDWEDM*

Parameter	Percentage of contribution on MRR (%)			Percentage of contribution on WWR (%)		
	Air-Mist	Oxygen-Mist	Helium-Mist	Air-Mist	Oxygen-Mist	Helium-Mist
Pressure (× 10^5 Pa)	31.78	40.04	33.87	28.83	48.36	42.39
Flow rate (× 10^{-7} m^3/s)	8.68	9.98	9.59	14.15	10.47	6.64
Spark current (A)	33.71	13.96	23.26	27.16	10.96	21.72
Pulse duration (μs)	23.42	34.56	31.65	28.91	29.33	28.36

Table 6: Confirmation of experiment vs predicted result from Taguchi analysis

Condition	Responses	Levels of optimal process parameters	Predicted result	Experimental result
Air-mist CNDWEDM	WWR	p_3-q_{v3}-I_2-T_2	**0.3145**	**0.3013**
	MRR (1.7 × 10^{-11} m^3/s)	p_2-q_{v3}-I_3-T_3	13.643	13.533
Oxygen-mist CNDWEDM	WWR	p_3-q_{v3}-I_2-T_2	0.4101	0.4181
	MRR (1.7 × 10^{-11} m^3/s)	p_2-q_{v3}-I_3-T_3	**14.611**	**14.531**
Helium-mist CNDWEDM	WWR	p_3-q_{v3}-I_2-T_2	0.4023	0.4153
	MRR (1.7 × 10^{-11} m^3/s)	p_3-q_{v3}-I_3-T_3	14.103	14.060

The process-parameter contributions on the WWR and MRR for all three dielectric media are shown in **Figures 5a** and **5b,** respectively. In the oxygen-mist process, 48.36 % of oxygen pressure, 10.47 % of flow rate, 10.96 % of spark current, and 29.33 % of pulse duration are contributed to the WWR as shown in **Table 5**. In the helium-mist process, 42.39 % of helium pressure, 6.64 % of flow rate, 21.91 % of spark current, and 28.36 % of pulse duration are contributing to the WWR. 28.83 % of air pressure, 14.15 % of flow rate, 27.16 % of spark current, and 28.91 % of pulse duration are contributing to WWR in the air-mist process. It was concluded that pulse duration on the three dielectric fluids is a comparable pattern of behaviours due to the constant discharge of the spark energy.[22] The pressure of air/gases is highly contributed to the WWR to increase the spark intensity through the propagation of the ionization process.[24,25] The flow rate of water in the air-mist process is significantly involved to enhance the debris flushing and cooling processes in the cutting zone. The contributions of the spark current in the helium and oxygen gas-mist CNDWEDM is better than the air-mist process due to high dielectric strength in the gas mediums.[26,27] In the oxygen-mist process, the pressure of 40.04 % of oxygen gas pressure, 9.98 % of the flow rate, 13.96 % of spark current, and 34.56 % of pulse duration are contributed on MRR (**Table 5**). In the helium-mist process, the 33.87 % helium gas pressure, 9.59 % of the flow rate, 23.26 % of spark current, and 31.65 % of pulse width are contributing to MRR. Similarly, 31.78 % of air pressure, 8.68 % of the flow rate, 33.71 % of spark current, and 23.42 % of pulse duration on MRR of air-mist CNDWEDM process.

The optimum values of WWR and MRR were predicted from the Taguchi analysis as shown in **Table 6**. It was revealed that the oxygen-mist CNDWEDM process is a higher MRR with maximum WWR than the other two processes. The WWR of the air-mist process is 27.917 % lower than helium-mist and 30.397 % lower than oxygen-mist processes. The WWR of helium-mist CNDWEDM is 1.939 % less than the oxygen-mist process due to damaging wire surfaces by peak spark intensity.[28] The WWR of the oxygen-mist process is also increased by increasing debris rate by the gas mediums.[29,30]

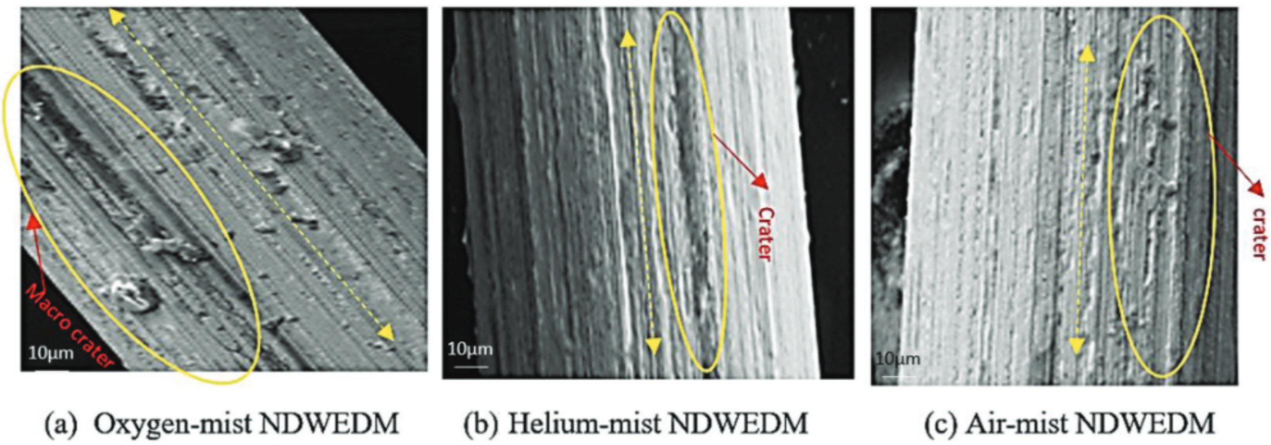

Figure 5: Microscopic analysis of wire wear of cryogenically cooled NDWEDM processes

It was observed from **Table 7** that the MRR of the oxygen-mist CNEWEDM process is higher than the air-mist and helium mist processes. The MRR of the oxygen-mist process is 7.095 % higher than the air-mist and is 3.372 % better than the helium-mist CNDWEDM. The MRR of the helium-mist process is 3.602 % higher than the air-mist CNDWEDM. The flammable oxygen-mist dielectric plays an important role to increase the MRR by plasma development, ionization, heating, and melting processes in the plasma zone.[31]

The SEM images of the oxygen-mist, helium-mist, and air-mist NDWEDM are illustrated in **Figure 5**. Wire wear happened along the longitudinal direction for all processes. It is observed that the macro crater developed on the wire during the oxygen-mist process due to a higher spark intensity than the other two processes.[28,29]

Table 7: Comparison of air-mist, oxygen-mist and helium-mist CNDWEDM processes

Output response	Percentage of response improvement (%)		
	Oxygen-mist versus air-mist	Helium-mist versus air-mist	Oxygen-mist versus helium mist
WWR	30.397	27.917	1.939
MRR	7.095	3.372	3.602

4 CONCLUSIONS

In this study CNDWEDM processes were experimentally studied using air-mist, oxygen-mist, and helium mist dielectric fluids and the following conclusions can be drawn:

It was observed from a Taguchi analysis that air/gas pressure and pulse duration are the most significant process parameters on both MRR and WWR for all CNDWEM processes. The impacts of each parameter on the MRR and WWR of all CNDWEDM processes are similar.

While increasing the air pressure, pulse duration and spark current, the MRR and WWR were increased by the growth of the spark intensity in the cutting zone. Conversely, while increasing the mixing dielectric water flow rate, the maximum MRR and minimum WWR have been obtained due to improving the flushing efficiency.

It was revealed from the comparative analysis that the MRR of the oxygen-mist CNDWEDM process is 7.095 % higher than the air-mist, and 3.372 % higher than the helium-mist process, which is 3.602 % higher than the air-mist process. The WWR of the air-mist CNDWEDM process is 30.397 % lower than oxygen-mist processes and 27.917 % lower than helium-mist, which is 1.939 % less than the oxygen-mist process. Thus, the oxygen-mist and air-mist dielectric mediums are recommended for higher MRR and lower WWR of CNDWEDM.

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