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Article

Analyzing process variables for WEDM of Nimonic alloy 75 with a cryogenic treated tool

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ABSTRACT

The present experimentation employs a Wire Electric Discharge Machining (WEDM) technique to investigate how various operational limiting factors influence Material Removal Rate (MRR), Micro Hardness (MH), and Vertex Angles (VA). Nimonic Alloy 75 sheets were used as the raw material for the experiments. Two types of tools were utilized: cryogenically treated brass wires and non-cryogenically treated brass wires. The primary process parameters analyzed in this research include the tool electrode, Ton, Wire Feed rate (WF), Wire Tension (WT), and Toff. The wire diameter was kept uniform at 0.25mm, as was the thickness of the work material Nimonic Alloy 75. The study compares MRR, MH, and VA when using a cryogenically treated tool versus a non-cryogenic tool, considering Ton, WF, WT, and Toff. The experimentations were structured with the help of a Taguchi L-9 OA, and an ANOVA was used to determine the maximum contribution of the variables: vertex angle, microhardness, and MRR. The microstructure of the machined samples, using untreated and CT brass wires, was examined with a Scanning Electron Microscope (SEM). Furthermore, chemical analysis was performed using EDS, comparing weight percentages before and after treatment.

1. Introduction

Electric Discharge Machining (EDM), particularly wire-cut EDM, is an electro-thermal subtractive manufacturing technique that cuts materials by rapidly melting and evaporating them using a wire electrode. This wire generates electrical pulses that create sparks between the workpiece and the electrode. Various dielectric fluids are used to cool, flush, and remove debris from the work material, with common choices including transformer oil, paraffin oil, and deionized water. Different types of wire can be used as the cutting tool, including brass wire coated with copper or zinc, an annealed brass electrode, and an abrasive-coated brass electrode. The diameter of the electrode wire can range from 0.1 mm to 3 mm, depending on the specific cutting requirements. Wire cut EDM is an electro-thermal subtractive manufacturing technique that cuts hard materials by rapidly melting and evaporating them using a wire electrode [1]. The electrode generates electrical pulses, creating sparks between itself and the workpiece. Dielectric fluids, such as transformer oil, paraffin oil, and deionized water, are used to cool, flush, and remove debris from the material [2-4]. Cutting wire types include brass wire coated with copper or zinc, annealed brass electrode, and abrasive-coated brass electrode [5]. Electrode wire diameters range from 0.1 mm to 3 mm, depending on cutting requirements [6]. Ashish Goyal et al. [7] used a cryogenically treated brass tool to improve maximum MRR and surface roughness on Nimonic alloy 80A. Rajesh Choudhary et al. [8] compared cryogenic and non-cryogenic tools to explore tool wear rate and recast layer thickness. Suresh Kumar Myilsamy et al. [9] reported that cryogenically treated molybdenum wire showed greater hardness, wear resistance, and electrical conductivity than untreated wire. Neeraj Sharma et al. [10] subjected D-2 tool steel to subzero treatment and used a brass tool, finding that surface roughness was highly influenced by Ton. Ashish Goyal [11] evaluated MRR and surface roughness of Inconel-625 with CT-treated Zn wire, considering wire diameter, tool, current, wire tension, Ton, Toff, and tool feed. Ramesh Krishnan et al. [12] used cryogenic-treated brass tools and micro EDM to conduct research on EN 24, taking into consideration input constraints like current, capacitance, Ton, and voltage in order to maximize linear characteristics such as overcut, circularity, and taper angle. Ranjit Singh et al. [13] experimented on M 42 HSS, using CT brass wire to evaluate electrical conductivity and dimensional variation. Working with Inconel 601, Neelesh Singh et al. [14] employed a CT copper tool and optimized MRR, TWR, and SR by altering input variables. Rahul et al. [15] used a cryogenically cooled copper tool to analyze the metallurgical properties and surface integrity of Inconel 825; they discovered that the CT tool gave better results compared to the standard tool.

Abbreviations

ANOVA	Analysis of Variance
CT	Cryogenic Treated
EDM	Electric Discharge Machining
EDS	Energy Dispersive Spectroscopy
MH	Micro Hardness
MRR	Material Removal Rate
SEM	Scanning Electron Microscope
SR	Surface Roughness
TOFF	Pulse time off
TON	Pulse time on
VA	Vertex Angle
WEDM	Wire Electric Discharge Machining
WF	Wire Feed Rate
WT	Wire Tension

In the case of Inconel 718, B.K. Tharian et al. [16] machined it using a CT graphite electrode and found that MRR was high compared with a non-treated tool. WWR of CT brass wire was less when machining EN-31 than when using non-treated wire, as shown by Kapoor et al. [17]. On Monel 400 alloy, N.E. Arun Kumar et al. [18] ran experiments with CT brass wire to obtain MRR, SR, and kerf width, declaring that CT brass gave better results than the non-treated variant. For cutting speed and SR measurements of M-42 AISI steel, Anish Kumar et al. [19] used a CT brass tool during machining, finding high cutting speed and lower SR. Jatinder Kapoor et al. [20] conducted experiments on EN-31 to evaluate SR; they found that a shallow cryogenically treated brass tool resulted in a good surface finish. Waseem Tahir et al. [21] machined HSLA steel by CT brass wire and found that the treated wire gave less RLT (Recast Layer Thickness) and infusion of wire on the machined surface. AISI D3 steel was machined with Zn-coated brass wire and CT Zn-coated brass wires to evaluate SR and MRR by Husandeep Sharma et al. [22] and found that the treated tool gave the best results. Satyanarayana et al. [23] machined Inconel 600 by CT and non-treated Zn wires to optimize the MRR and SR and stated that CT wire gave the best results. Using CT-treated brass wire, EN-31 material was machined by Jitender Kapoor et al. [24], and MRR was evaluated. From the experimentation, it was announced that the grain refinement and electrical conductivity of treated wire improved. Cryo-treated Ti6Al4V machined by WEDM showed discharge current as the major factor affecting MRR and SR [25]. Incoloy 925 with cryo-treatment and tempering exhibited refined microstructure, better surface morphology, and, when furnace-cooled, higher hardness and machinability [26]. Naveed Ahmed et al. [27] found errors in dimensions on Al2024/Al2O3/W using CT electrodes and concluded that CT electrodes gave less error on various dimensions. Muhammad Huzaifa Raza et al. [28] investigated Al2024/Al2O3/W with CT and non-CT wires and announced that there were fewer defects with CT wires as compared to non-CT wires. A cryogenically treated tool exhibits increased tool life, reduced surface cracks, and a thinner white layer on the machined part compared to a non-cryogenically treated tool [29]. Cryogenically treated wire also leads to reduced surface cracking, lower residual stresses, and a thinner white layer formation compared to standard tools [30]. Cryogenic treatment refines the grain structure and increases the hardness of Nimonic-90. The extent of these enhancements depends on the soaking period; longer soaking durations lead to greater hardness [31]. According to the experiments mentioned above, many researchers are studying the effect of various cryogenically treated wires on a variety of alloys; however, limited studies are focused on Nimonic alloy 75, which is widely used in aerospace and heat treatment equipment. When the Nimonic alloy 75 is machined using cryogenically treated brass wire, out puts such as MRR, microhardness, vertex angles, and microstructural changes are less investigated. Brass wire can be made more resilient and stronger by employing cryogenic treatment, which also enhances the wire's consistent grain size and minimizes flaws.

2. Objectives of research

The specific objective of the experimentation as follows: The study aims to analyze the effect of cryogenically treated brass wire on the machining performance of Nimonic alloy 75 using WEDM by evaluating input parameters such as Ton, Wire Feed Rate (WF), Wire Tension (WT), and Toff on MRR, microhardness, and vertex angle. The results are to be compared between cryo-treated and non-treated brass wires, with process optimization carried out using the Taguchi L-9 orthogonal array and ANOVA. Additionally, microstructural changes and EDS analysis of the machined surfaces with both wires are to be examined. Nimonic alloys are frequently utilized in the production of aero engine components due to their high strength and resistance to higher temperatures. Over time, exposure to elevated temperatures can lead to various metals experiencing corrosion, fatigue, cracking, and distortion. These are widely used due to their exceptional resistance to corrosion. The various properties of Nimonic alloy 75 at 20°C have been shown in Table 1.

Table 1. Various properties of Nimonic alloy 75 at 20°C

Mechanical properties	**Value**
Ultimate Tensile Strength	750 MPa
Youngs Modulus	221 GPa
Yield Strength	250 MPa
Electrical properties	**Value**
Resistivity	1.09 μΩ.m
Physical/Thermal properties	**Value**
Melting point	1340–1380°C
Thermal Conductivity	11.7 W/mK
Density	8.37 g/cm^3
Specific Heat	461 J/kg °C
Coefficient of Thermal Expansion	11 μm/m°C

Nimonic alloy-75 was cut by an untreated brass tool and a cryogenically treated brass tool, which was treated to -184°C. Cryogenic treatment is also known as cryogenic processing. It is a special type of cold treatment method, where the metals are exposed to very low temperatures to improve various mechanical properties of the materials. In this method, the metals are cooled to very low temperatures, i.e., up to -190°C. By using this method, manufacturers can improve the performance and durability of metals and alloys. Cryogenic treatment methods can be categorized based on the soaking temperature into two main types. The first method, known as the SCT method, was established by early investigators to boost the performance of softer materials like steel and its alloys. This method involves soaking the materials from -70°C to -140°C. Later, the deep cryogenic treatment (DCT) method was developed for super-hard materials, using a temperature from -140°C to -196°C to achieve even greater performance improvements. The Schematic diagram of Cryogenic process as shown in Figure1.

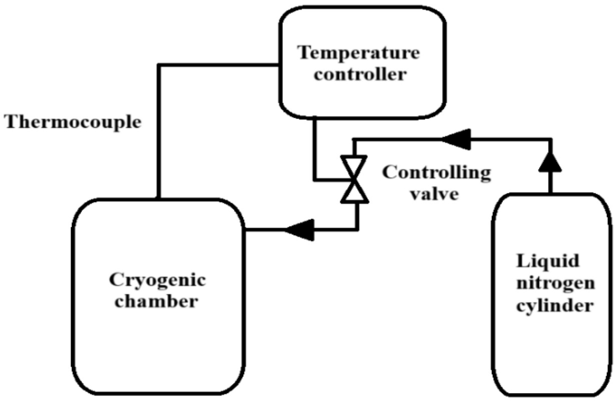

Figure1. Schematic diagram of cryogenic process

3. Experimental flow chart

In this research study, the following experimental process was conducted throughout the investigation as shown in Figure 2. Both treated and untreated brass tools were utilized for machining the Nimonic alloy 75. The parameters evaluated included WF, WT, Ton, and Toff to optimize the MRR, microhardness, and vertex angle.

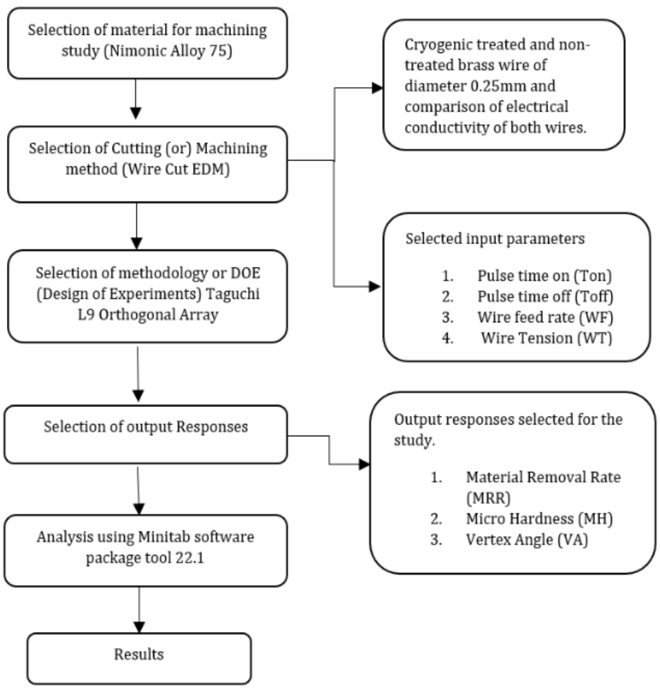

Figure 2. Flow diagram for experimental process

4. Specifications of cryogenic-treatment setup

The cryogenic chamber is made up of a stainless-steel body to resist corrosion, with proper insulation. The volume of the chamber is 1000 L. The temperature control range is up to -184°C. Power supply range is 230V. Liquefied nitrogen gas is used as a medium, with 300 psi pressure. A cryogenic plant is used to maintain the metals at very low temperatures, such as -184°C, and a liquified nitrogen gas LN2 (purity ≥ 99.9%) is used as a cryogenic fluid. The storage tank supplies the gas to the chamber by means of control valves. A temperature control unit is arranged in the chamber. The brass tool is placed in a cryogenic handling chamber, as shown in Figure 3, to enhance various mechanical properties. The process begins with the brass wire at room temperature, roughly 25°C. The chamber is then evacuated and filled with nitrogen gas. The cryogenic treatment involves three stages: ramp down, soaking, and ramp up, shown in Figure 4.

- During the ramp-down stage, the temperature was slowed down to -184°C at a rate of 1°C per minute.
- The wire is then soaked at this temperature for 24 hours.
- Finally, in the ramp-up stage, the temperature was raised back to 25°C at a rate of 1°C per minute, and no tempering was considered.

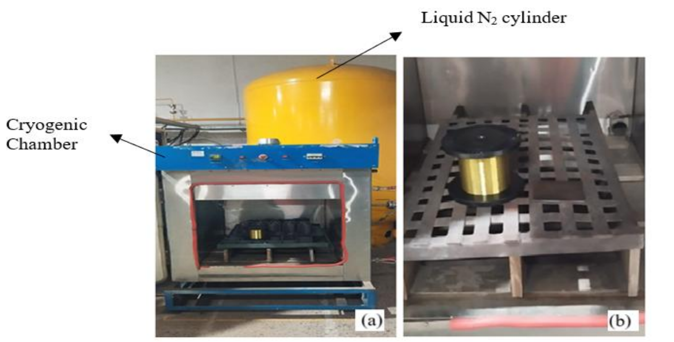

Figure 3. (a) Cryogenic treatment equipment (b) Wire placed inside the chamber

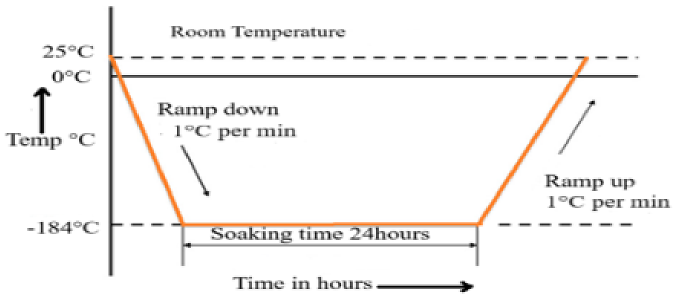

Figure 4. Time -Temperature cure considered without tempering

4.1 Electrical conductivity of brass wire

The electrical resistivity of brass wire was measured by the four-probe electrical resistivity testing method. The brass wire is placed on the platform, and four equally spaced probes are touched to the wire at four places as shown in Figure 5. From the two outer probes, current was passed, and the voltage drop was found using two inner probes. This will permit the exact circulation of electrical resistivity [32]. A 500 mm length of brass wire was taken for testing. Three CT and untreated wire samples were tested, and the average value of conductivity was plotted in the table for both wires. The electrical conductivity of treated and untreated brass wires was compared, and the results are summarized in the Table 2. After treatment, the brass wire's electrical conductivity rose by 23.88%.

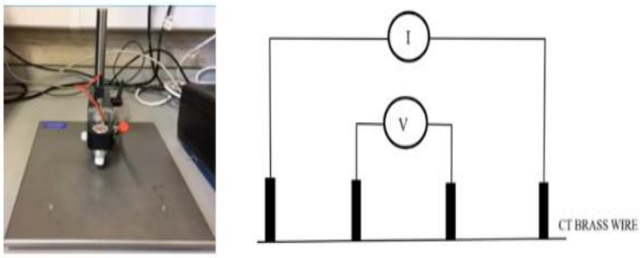

Figure 5. Testing Electrical Resistivity of cryo-treated brass wire

Table 2. Electrical conductivity of brass wire before and after CT

Tool material	Chemical constituent	Conductivity in S/m		
		Before CT	After CT	Rise in %
Brass	Cu 60%, Zn40%	15.567 x 10^6	19.285 x 10^6	23.88

5. Experimental methodology

The tests were performed by means of an Electronica Sprint cut wire EDM machine with Nimonic Alloy 75 material, measuring 200 mm x 100 mm x 2 mm. This machining process was followed by a cryogenic treatment. The experimental setup is as shown in Figure 6.

Figure 6. (a) Electronica sprint cut wire EDM setup, (b) Fixing of Nimonic alloy 75 sheets on Wire cut EDM table, (c) Machined Nimonic alloy 75 sheets

5.1 Video profile projector

A video profile projector is an optical precision measuring instrument that magnifies and projects a machined profile onto a computer screen. This tool allows for accurate measurement of the profile's dimensions and is widely used for inspecting manufactured components. Once the machining process is complete, the vertex angle is measured using the video profile projector.

5.2 Material removal rate

The experiments utilized brass wires 0.25 millimeters in diameter. To achieve outcomes, a digital stopwatch was employed to record the time taken for each experiment. A total of three trials were conducted to reduce the likelihood of errors. The MRR was intended to be used using the following equation:

$$MRR = Lt/T \quad mm2/min \qquad (1)$$

In this equation:
"L" denotes the length of the trimmed cut.
"t" stands for the thickness of the part, and
"T" represents the total duration of the machining process.

5.3 Microhardness

Microhardness is one type of mechanical property in which the material's surface is tested by applying a load using an indenter. Microhardness testing is similar to hardness testing but focuses on a small area. A load of 15 to 1000 gf can be applied, and the microhardness of the material can be evaluated. A microscope with a certain magnification can be used for observing indentations on the surface of the specimen and can evaluate the microhardness of the material. For each sample, the average of three readings was taken.

5.4 Vertex angle

The angle formed between the slots machined by the wire is referred to as the vertex angle, and it is measured in degrees. Depending on the geometry of the workpiece, the machined vertex angle was maintained at a constant of 60° shown in Figure 7. The deviation of the machined vertex angle was tested using a video profile projector. The average value of the vertex angle was taken from the bottom side and top side of the machined plate for 9 slots. The main process parameters that were selected are T on, T off, wire feed rate, and wire tension in three levels as shown in Table 3.

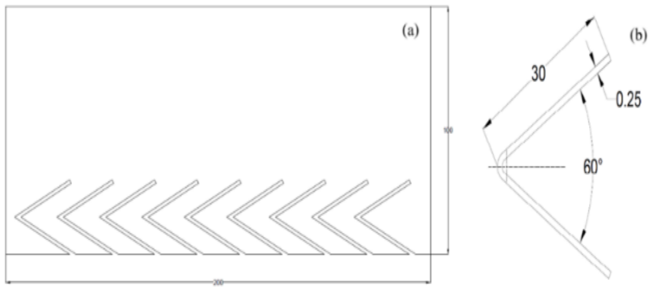

Figure 7. (a) Machined Nimonic alloy 75 sheet (b) Detailed view of machined slot

Table 3. List of controlling factors and levels

Process variable	Symbol	Level 1	Level 2	Level 3
Ton (µs)	A	105	115	125
T off (µs)	B	40	50	60
Wire feed rate (mm/min)	C	3	6	9
Wire tension (N)	D	4	8	12

6. Investigational outcomes of Non cryogenic and cryogenic treated tool

The experimental results of material removal rate, microhardness, and vertex angle are shown in Table 4 with a non-cryogenic treated brass tool by considering Ton, Toff, WT, and WF.

Table 4. Experimental results with Non cryogenic treated tool

No.	Ton (µsec)	Toff (µsec)	WF (mm/min)	WT (N)	With Non cryogenic treated tool		
					MRR (mm^2/min)	MH (N/mm^2)	VA (degree)
1	105	40	3	4	5.427	256	60.735
2	105	50	6	8	6.282	274	60.985
3	105	60	9	12	5.273	379	60.758
4	115	40	6	12	6.346	315	60.915
5	115	50	9	4	7.823	423	60.559
6	115	60	3	8	5.213	403	60.873
7	125	40	9	8	6.722	489	60.721
8	125	50	3	12	10.65	465	60.684
9	125	60	6	4	8.387	346	60.853

Table 5. Experimental results with cryogenic treated tool

No.	Ton (µsec)	Toff (µsec)	WF (mm/min)	WT (N)	With Cryogenic treated tool		
					MRR (mm^2/min)	MH (N/mm^2)	VA (degree)
1	105	40	3	4	6.427	266	60.156
2	105	50	6	8	6.828	282	60.129
3	105	60	9	12	7.275	391	60.278
4	115	40	6	12	6.526	382	60.092
5	115	50	9	4	8.913	458	60.119
6	115	60	3	8	6.203	453	60.172
7	125	40	9	8	7.024	478	60.183
8	125	50	3	12	12.05	459	60.159
9	125	60	6	4	9.584	358	60.214

The experimental results of material removal rate, microhardness, and vertex angle are shown in Table 5 with a cryogenic treated brass tool by considering Ton, Toff, WT, and WF.

6.1 Comparison of MRR with cryogenic treated and non-treated wires under different parameters

The first graph shows that the MRR increases as the Ton value rises. Additionally, the MRR is higher for the treated tool than the non-cryogenically treated tool. However, in the second graph, it can be detected that as the value of Toff rises, the MRR declines for both types of wire. The overall value of the MRR has decreased due to a rise in the WF for both cryogenic and non-cryogenic treated wire. Initially, the MRR decreased with a rise in WT, but as the WT continued to rise, the MRR began to increase again as shown in Figure 8.

6.2 Comparison of microhardness with cryogenic treated and non-treated wires under different parameters

From Figure 9, the microhardness value tends to increase with a rise in Ton. Additionally, the overall microhardness of cryogenically treated wire is higher than that of non-treated wire. In the second graph, which plots microhardness against Toff, it shows that microhardness increases with higher values of Toff but then decreases when the value of Toff continues to increase further. The microhardness value decreased with an increase in WF, then increased again with a higher WF for both cryogenically treated and untreated wires. As the wire tension increases, the microhardness value rises, and further, as the wire tension increases, the hardness increases for both cryogenically treated and non-treated wires.

6.3 Evaluation of vertex angle with cryogenic treated and non-treated wires under different constraints

The graph above illustrates in Figure 10 how the Ton value affects the vertex angle. It shows that the vertex angle slightly decreases as the Ton value increases for both cryogenically treated and non-treated wires. Additionally, the vertex angle decreases when the Toff value increases, but then it rises again as the Toff value continues to increase for both types of wires. The vertex angle increases with the wire feed rate in both cryogenic-treated and non-treated cases. However, after a certain point, further increases in the WF led to a reduction in the vertex angle, as illustrated in the graph. The trend for the WF follows a similar pattern.

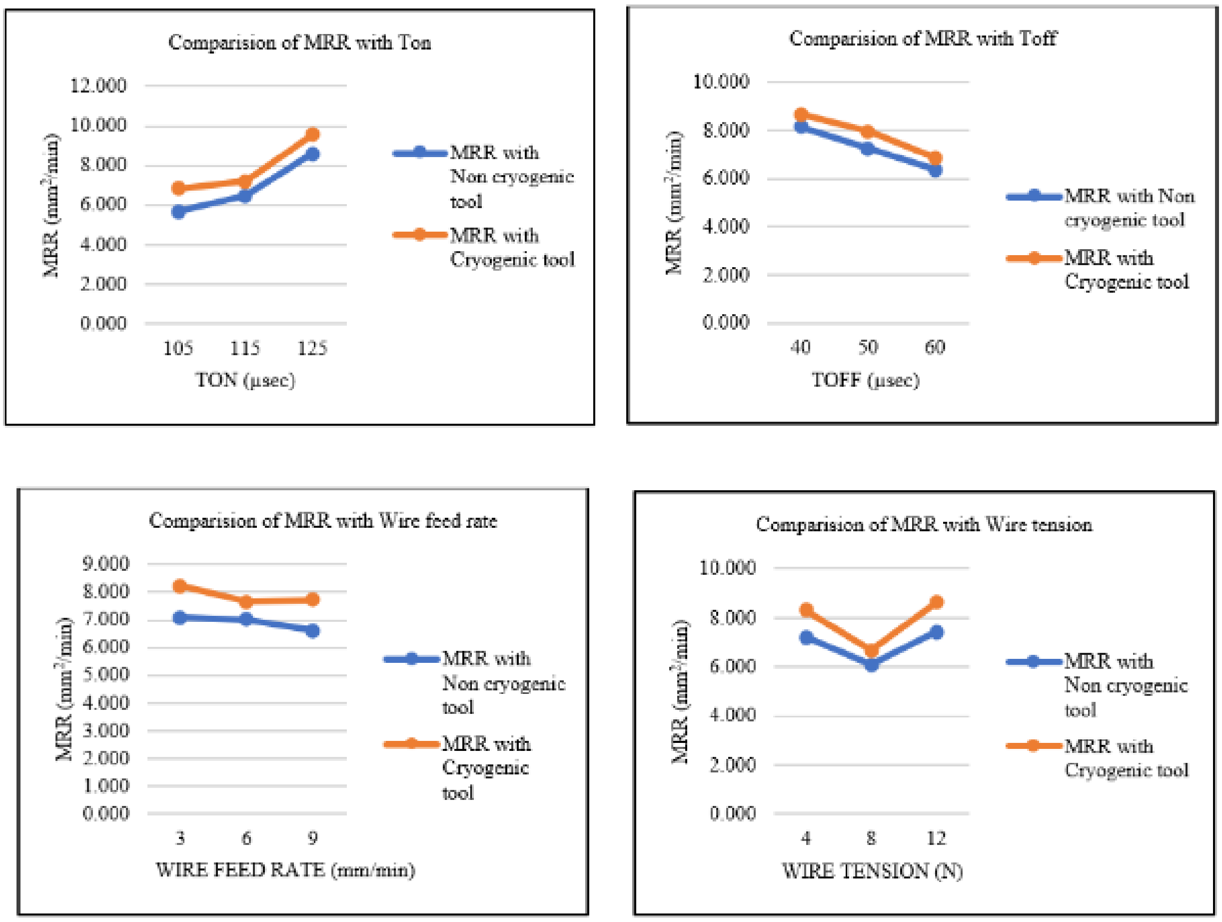

Figure 8. Assessment of MRR with cryogenic treated and non-treated wires under different parameters

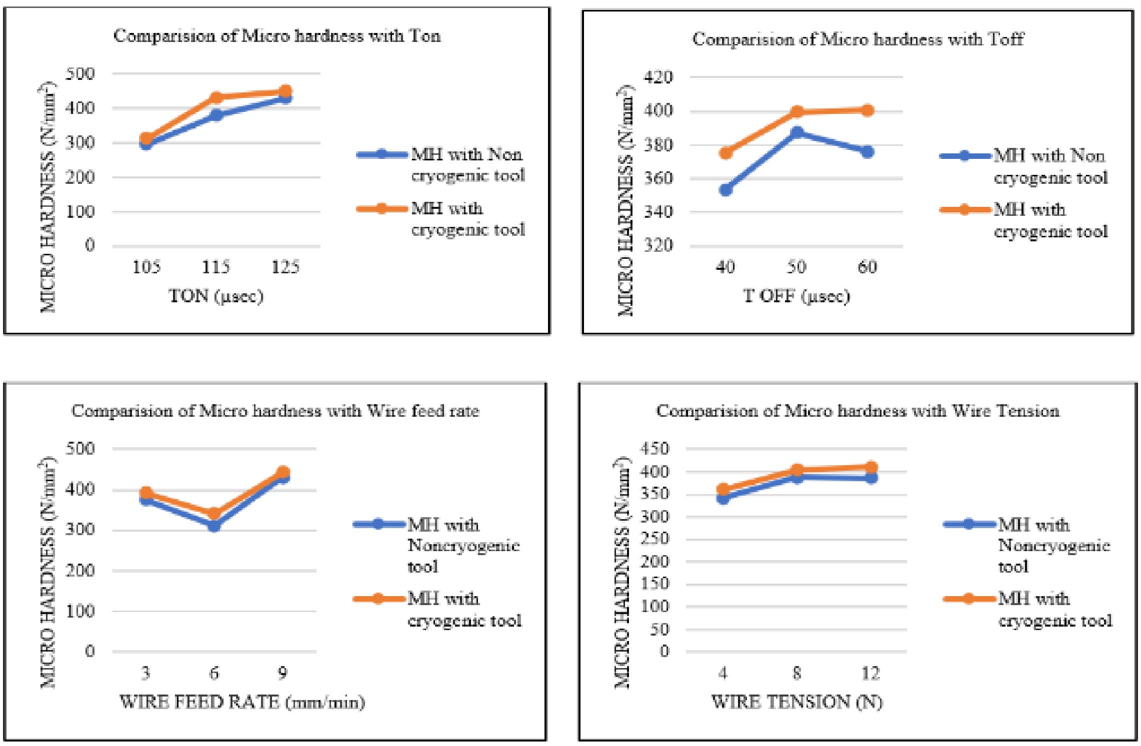

Figure 9. Assessment of microhardness with cryogenic treated and non-treated wires under different parameters

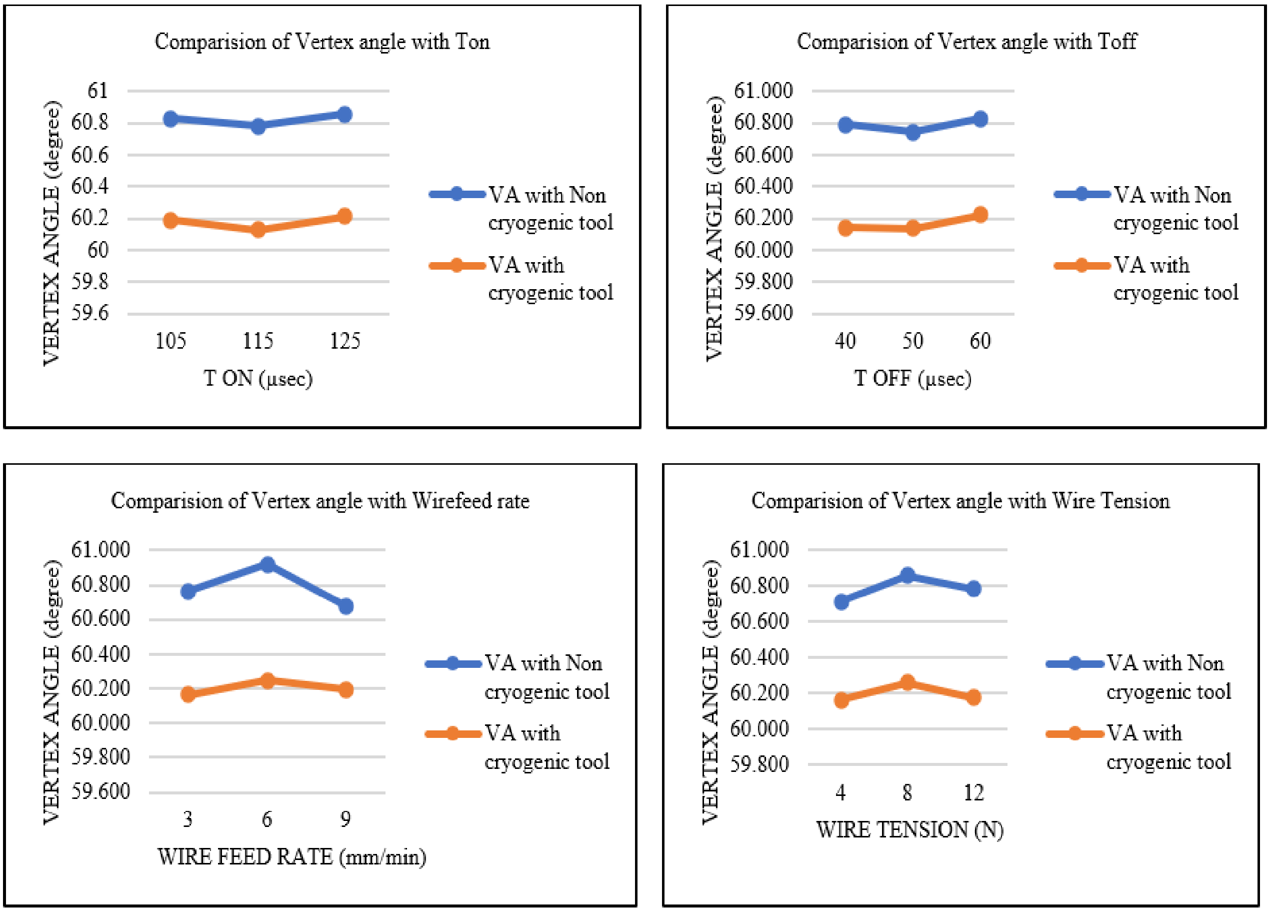

Figure 10. Assessment of Vertex angle with cryogenic treated and non-treated wires under different constraints

7. Results and discussions

The experimental work, known as the Design of Experiments, was conducted on a Nimonic alloy 75 sheet using both cryogenically treated and untreated brass wire, following the L-9 OA Taguchi method. The process outcomes evaluated included Material removal rate, microhardness, and vertex angle, while considering process variables such as Ton, Toff, WF, and WT to optimize the results. Tables for S/N ratios for MRR, MH and VA have shown below. The S/N ratios of MRR, MH, and VA are shown in Table 6 by considering Ton, Toff, WF, and WT in three levels. The ANOVA for MRR, MH, and VA are shown in Table 7 by considering Ton, Toff, WF, and WT in three levels. The MRR ANOVA results indicate that Ton (42.7%) and Toff (34.06%) are the most influential parameters, both of which are statistically significant at the 95% confidence level ($p = 0.029$ and $p = 0.036$, respectively). Although WF exhibited statistical significance ($p = 0.016$), its contribution was negligible (1.93%), indicating limited practical importance. WT contributed 21.31%, but the difference was not statistically significant ($p = 0.231$). Therefore, Ton and Toff are the primary factors influencing the machining response. The MH ANOVA results indicate that *Ton* ($p = 0.043$; 56.93% contribution) and *WF* ($p = 0.021$; 31.52% contribution) are statistically significant at the 95% confidence level, together explaining approximately 88.5% of the total variation. Therefore, machining performance is primarily influenced by Ton and WF, whereas Toff and WT contribute marginally.

Table 6. Result analysis of S/N Ratios for MRR, MH and VA

S/N ratios for MRR				
Level	**Ton**	**Toff**	**WF**	**WT**
1	16.69	16.46	17.88	18.26
2	17.05	19.1	17.54	16.49
3	19.39	17.57	17.72	18.38
Delta	2.7	2.64	0.34	1.89
Rank	1	2	4	3
S/N ratios for MH				
Level	**Ton**	**Toff**	**WF**	**WT**
1	49.78	51.24	51.62	50.93
2	52.66	51.82	50.57	51.91
3	52.63	52.01	52.88	52.24
Delta	2.88	0.77	2.31	1.31
Rank	1	4	2	3
S/N ratios for VA				
Level	**Ton**	**Toff**	**WF**	**WT**
1	35.59	35.58	35.59	35.59
2	35.58	35.58	35.58	35.59
3	35.59	35.6	35.59	35.59
Delta	0.01	0.01	0.01	0
Rank	2	1	3	4

Table 7. ANOVA for MRR, MH and VA

ANOVA for MRR					
Source	**DF**	**Adj SS**	**Adj MS**	**p-value**	**Percentage contribution**
Ton	2	12.947	6.4736	0.029	42.7
Toff	2	10.327	5.1633	0.036	34.06
WF	2	0.585	0.2925	0.016	1.93
WT	2	6.4622	3.2311	0.231	21.31
Error	0	-	-	-	0
Total	8	30.321			100
ANOVA for MH					
Source	**DF**	**Adj SS**	**Adj MS**	**p-value**	**Percentage contribution**
Ton	2	28006	14003.1	0.043	56.93
Toff	2	1235	617.4	0.36	2.51
WF	2	15507	7753.4	0.021	31.52
WT	2	4447	2223.4	0.314	9.04
Error	0	-	-	-	0
Total	8	49195			100
ANOVA for VA					
Source	**DF**	**Adj SS**	**Adj MS**	**p-value**	**Percentage contribution**
Ton	2	0.00693	0.00347	0.042	28.44
Toff	2	0.01344	0.00672	0.018	55.13
WF	2	0.0036	0.0018	0.219	14.76
WT	2	0.00041	0.0002	0.314	1.67
Error	0	-	-	-	0
Total	8	0.02437			100

ANOVA results for VA show that Toff ($p = 0.018$, 55.13%) is the most influential factor, followed by Ton ($p = 0.042$, 28.44%), both significant at the 95% confidence level. WF (14.76%) and WT (1.67%) have minimal effect, indicating that Toff and Ton together account for over 83% of the variation in machining performance.

7.1 Factors affecting MRR

Better results for MRR are attained by means of cryogenically treated wire compared to a non-treated tool. The graph in Figure 11 illustrates how the parameters of Ton, Toff, WF, and WT affect MRR. According to the graph, the optimal combination identified is A3B2C1D3, which corresponds to a Ton of 125 µs, a Toff of 50 µs, a WF of 3 mm/min, and a WT of 12 N. The optimized MRR obtained from the L9 orthogonal array is 12.05 mm^2/min. The S/N ratios for MRR on Nimonic Alloy 75 using a cryogenically treated brass electrode, along with the percentage contribution to MRR according to ANOVA, are presented in Figure 11. Analysis displays that the Ton is the greatest influential parameter on MRR when using cryogenically treated wire. In contrast, the WF is the least influential parameter, as shown in Figure 12.

7.2 Factors affecting microhardness

The best results for microhardness (MH) are achieved by means of cryogenically treated wire associated with non-cryogenically treated tools. The graph illustrates how various parameters, specifically the Ton, Toff, WF, and WT, affect MH. According to the graph in Figure 13, the optimal combination of these parameters is A2B3C3D3, which corresponds to a Ton of 115 µs, a Toff of 60 µs, a WF of 9 mm/min, and a WT of 12 N. The microhardness value of the material does not match any one of the nine combinations of the L9 orthogonal array, so the optimized value confirmation test was used and estimated as 510 N/mm^2. The S/N ratios for microhardness measurements on Nimonic Alloy 75 with a cryogenically treated brass electrode, along with the percentage contribution regarding microhardness as per ANOVA, are presented in Figure 13. Analysis shows that the parameter Ton greatly influences the microhardness number when machining with cryogenically treated wire. In contrast, the Toff rate has the least influence, as shown in Figure 14.

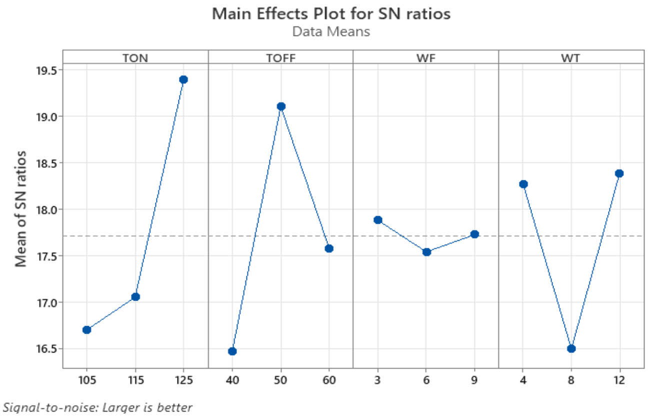

Figure 11. Displaying the S/N ratios of MRR on Nimonic Alloy 75 utilizing the Cryogenic treated brass electrode

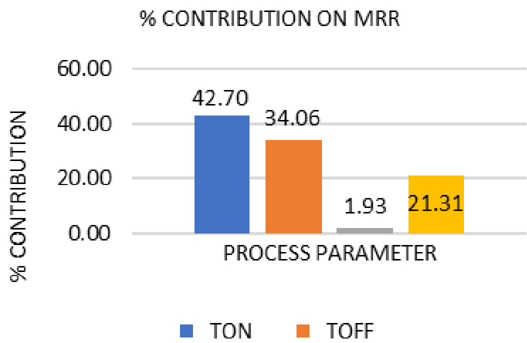

Figure 12. Percentage contribution on MRR with respect to ANOVA

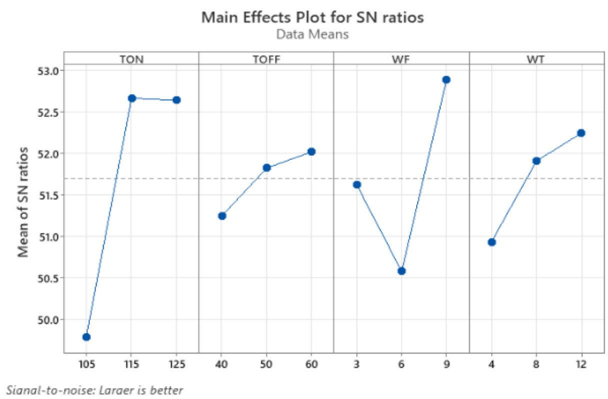

Figure 13. Illustrating the S/N ratios of Micro Hardness for Nimonic Alloy 75 utilizing the Cryogenic treated brass electrode

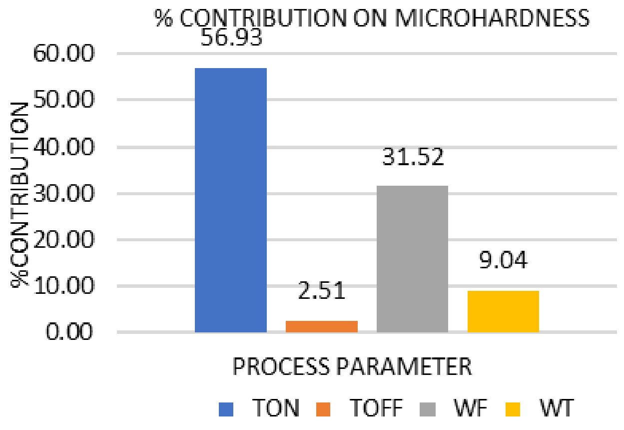

Figure 14. Percentage contribution on Microhardness with respect to ANOVA

7.3 Factors affecting vertex angle

Analysis shows from Figure 15 that Ton is the most effective parameter on MH when machining with cryogenically treated wire. In contrast, Toff is the least influential parameter. The results for the Vertex Angle (VA) were obtained using cryogenically treated wire compared to untreated tools. The accompanying graph illustrates how the parameters of Ton, Toff, WF, and WT influence VA. According to the graph, the optimal combination identified is A2B2C2D2. This combination corresponds to a Ton of 115 µs, a Toff of 50 µs, a WF of 6 mm/min, and a WT of 8 N. The optimum value for VA cannot be selected from the L9 Orthogonal Array, as it does not match any values within the array. A confirmation test has determined the value of VA to be 60.279. The S/N ratios of the vertex angle for Nimonic alloy 75 with the cryogenically treated brass electrode, as well as the percentage contribution related to the vertex angle according to ANOVA, are illustrated in Figure 15.

Analysis shows that Toff is the most influential parameter on VA when machining with cryogenic-treated wire. In contrast, wire tension is the least influential parameter, as illustrated in Figure 16. The SEM image of sample No. 5 is shown in Figure 17. This figure highlights the following features: A - blowholes, B - spherical globules, C - craters, D - microholes, E - debris, and F - microcracks.

Figure 15. Displaying the S/N ratios of Vertex angle on Nimonic alloy 75 using the Cryogenic treated brass electrode

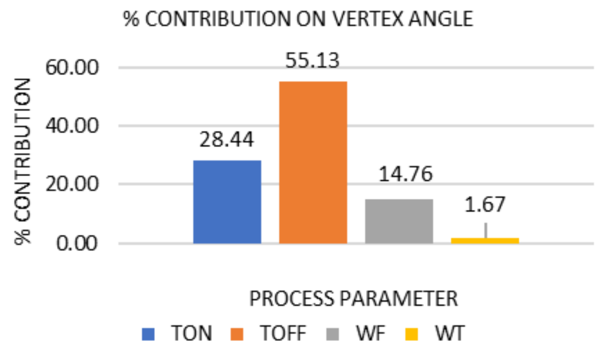

Figure 16. Percentage contribution on Vertex angle with respect to ANOVA

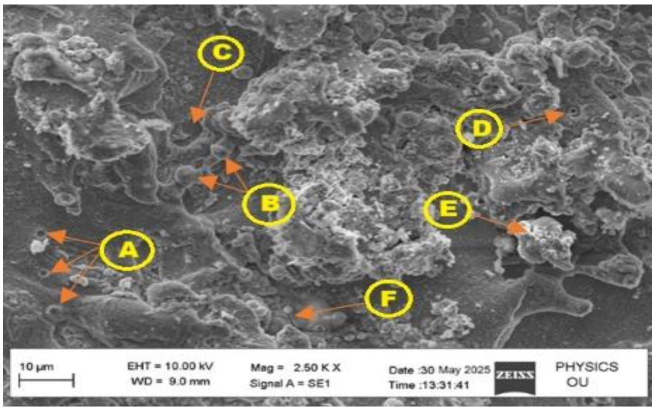

Figure 17. SEM image of machined sample No.5 with untreated brass wire

The various features are observed in the SEM image of Nimonic alloy 75 sample no. 5 after machining with untreated brass wire; those are blowholes, spherical globules, craters, microholes, debris, microcracks, etc. EDS result of sample no. 5 as shown in Figure 18, which shows various elements like C,O, Mn, Si, Ti, Cr,Fe, Ni, and Cu. The composition of sample No. 5 is presented in the Table 8, showing the weight and percentage differences before and after analysis. The SEM image of sample No. 6 is illustrated in Figure 19.

Table 8. Chemical composition of sample No.5

Element	Before Weight%	After Weight%	% Difference
C K	0.08	9.64	-9.56
O K	0	19.71	-19.71
Mn K	1	0.15	0.85
Si K	1	0.94	0.06
Ti K	0.2	0.38	-0.18
Cr L	18	14.55	3.45
Fe L	5	-1.67	6.67
Ni L	74.22	29.72	44.5
Cu L	0.5	26.58	-26.08
Totals	100	100	0

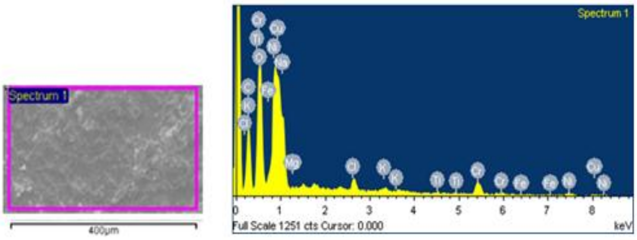

Figure 18. EDS result of sample No.5 with graph

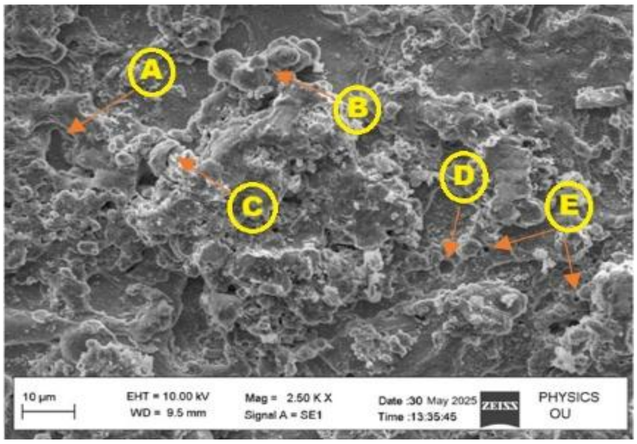

Figure 19. SEM image of machined sample No.6 with CT brass wire

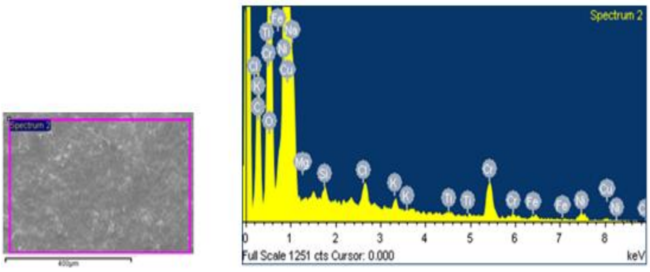

Figure 20. EDS result of sample No.6 with graph

Table 9. Chemical composition of sample No.6

Element	Before Weight%	After Weight%	% Difference
C K	0.08	8.05	-7.97
O K	0	18.59	-18.59
Mn K	1	0.06	0.94
Si K	1	0.62	0.38
Ti K	0.2	0.68	-0.48
Cr L	18	10.59	7.41
Fe L	5	3.33	1.67
Ni L	74.22	34.89	39.33
Cu L	0.5	23.19	-22.69
Totals	100	100	0

Figure 19 highlights the following features: A - craters, B - spherical globules, C - debris, D - blowholes, and E - microholes. The various features are observed in the SEM image of Nimonic alloy 75 sample no. 6 after machining with cryogenically treated brass wire; those are blowholes, spherical globules, craters, microholes, debris, etc. EDS result of sample no. 5 as shown in Figure 20, which shows various elements like C,O, Mn, Si, Ti, Cr,Fe, Ni, and Cu. The composition of sample No. 5 is presented in the Table 9, showing the weight and percentage differences before and after analysis.

8. Conclusion

After CT, the electrical conductivity of the brass wire rose by 23.88% when compared to the untreated brass wire due to relieving internal stresses, microstructural changes, and increased density. Because of higher conductivity, a greater amount of heat will be liberated; this leads to a rise in MRR. Cryogenically treated (CT) brass wire shows a smoother microstructure, free from scratches and imperfections, compared to untreated wire. Increasing Ton raises MRR and microhardness, while higher Toff reduces microhardness. Wire feed (WF) and wire tension (WT) also increase microhardness. The vertex angle increases with Ton but remains higher for non-treated wire across Toff, WF, and WT conditions. SEM images of Nimonis alloy 75 samples revealed craters, globules, debris, blowholes, and micro-holes in both wires, but no micro-cracks were observed with the CT wire. EDS analysis showed reduced Ni and Cr and increased Cu due to continuous flushing and higher heat energy. Overall, CT brass wire provides higher MRR, better surface quality, no micro-cracks, and improved efficiency, reducing material waste. This approach is cost-effective and can be applied to machining hard aerospace and nuclear alloys. Residual stresses in Nimonic alloy 75 can be investigated using cryogenically treated brass wire. Additionally, the performance of treated molybdenum wire may be examined and compared with that of untreated wire to determine optimal conditions.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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