Cryogenic treatment of wire for EDM

INDEX

Founding

INDUSTRIENS FOND

Christian Nielsens Fond

Contributors:

ARCTIKO true cooling specialists

Ransborg Reparation og Service eksklusiv forhandler af exeron EXPERTS IN EDM + HSC

1 Executive Summary

In this Technical report, extensive testing of cryogenically treated and untreated wires in the wire electrical discharge machining (WEDM) process is developed to achieve intriguing observations. Despite existing literature suggesting potential changes in Material Removal Rate (MRR) due to cryogenic treatment, our results revealed no significant alterations in MRR for wires subjected to different treatments. This apparent contradiction may be attributed to the high manufacturing standards of the wires used, rendering them resistant to alterations, or variations in the WEDM machines, such as the full submersion of the workpiece in dielectric in our machine compared to a jet-contact method in literature-referenced machines. Our findings underscore the complexity of WEDM processes and emphasize the need for meticulous consideration of both material properties and machine-specific factors when optimizing performance. While the maximum difference in MRR among tests is approximately 5%, indicating minor variability, our study emphasizes the importance of understanding the intricate relationship between these variables. Surface Roughness (SR) showed some significant changes among test samples, with the standard cable often obtaining the best SR result. However, as a general conclusion, SR was not substantially affected under the tested conditions. To gain deeper insights into wire properties, further exploration into microstructural alterations is essential. Analysing these changes may offer a more profound understanding of the underlying mechanisms influencing MRR. Our study highlights the need for additional research to unravel the intricate relationship between material properties, machine-specific factors, and their impact on MRR in the WEDM process.

2 Introduction:

Wire Electrical Discharge Machining (WEDM) is a non-contact and metal subtractive manufacturing process whereby a desired shape is obtained using electrical discharges between the work piece and the tool. The process is carried out by the electric discharge that occurs between two electrodes that do not have to be in contact and separated by a dielectric liquid. A voltage is applied between the two electrodes, connecting a DC power supply negative terminal to the wire and the positive to the workpiece until the electric field between both is broken, at which a spark is produced vaporizing atoms of the workpiece. Once the current is stopped, the new liquid dielectric is transported into the inter-electrode volume, allowing solid particles to be removed and the insulating properties of the dielectric restored, moment in which the process is repeated. The wire used for WEDM ranges in diameter from 0,1mm to 0,33 mm with 0,254 being the most common in the Danish industry. When electric field is broken, sparks are produced in forward 180° giving a cut width that in general is around of 1/3rd larger than the wire diameter, dependently of the power supplied. With this subtractive manufacturing process tolerance of 0,0025mm can be achieved. According to electrical data the discharge current is between 20 to 30 amperes and the frequency pulse between 50KHz to 1MHz.

DAMRC is looking to expand the experience within this subtractive manufacturing process, so it has been decided to approach an incubator project to demonstrate how the study of this high-precision technology can give interesting results to improving the efficiency of Danish industry processes. In the field of the electrical discharge machining process, certain scientific research has been carried out to study how to improve the efficiency of this technology using as study parameter the Metal Removal Rate (MRR) that is the amount of material removed by time unit, as well also the quality of the process measured across the surface roughness (SR) and the tolerances of the final parts. Although in most cases it has been under academic conditions, a significant number of developments affirm that these parameters could be improved by a cryogenic pre-treatment of the WEDM wire to increase the conductivity and material resistance producing change in the internal structure of it. Under this premise as starting point, DAMRC have decided to carry out a series of experiments to validate the applicability of this cryogenic pre-treatment in industrial conditions, for this, a cryogenically treated brass wire and an non-treated brass wire are evaluated in three of the most relevant material for the Danish industry in terms of WEDM. The wire selected is a brass wire NOVOTEK K125 0,25mm which has been selected due to the high consume of it for the WEDM industry in Denmark, based on information collected from the suppliers of this industrial material. At the same time, to get the most accessible option for the industry to treat the WEDM wire, the cryogenic treatment is performed under two different processes to evaluate, one in a Liquid nitrogen Dewars with possibility to decrease the temperature until -196°C (from Strandmøllen) and the other in a cryogenic freezer by air and electricity with possibility of treating at -150°C (from Arctiko). This set up of experiments gives place to nine experiments in which the MRR and SR are evaluated to measure the effect of the cryogenic treatment. The test parameters of the process to set up in the machine and test parts are defined with the help of the WEDM industry in Denmark, to decide the configuration of the test subjects and provide their expertise to ensure that the tests are as industrially realistic as possible. On the other hand, in all the scientific studies taken as reference, the cryogenic treatment was carried out using a three-step methodology (Cool down, Soak and Heat Up) in which there is a specific time and temperature gradient for each step - in order to avoid possible problems such as thermal shock in the bobbin wires and guarantee the correct treatment of all the material.

2.1 Success Criteria of the project:

The success criterion of the project is to obtain comparable values of MRR and SR by using three different coils of K125 brass WIRE, one without treatment, another treated with liquid nitrogen and maintaining temperatures below -195°C and the last one treated in the air and electricity freezer under a temperature diagram that reaches and maintains -150°C in a defined time. Specifically, DAMRC is looking for a successful cryogenically treatment of min. 2 spools of Ultra Brass P-5 (diameter: 0,25mm, Length: 9360m) at temperatures below -185 °C where can be evaluated the following improvements:

- +15% improvement of SR in at least 1 of the 3 materials compared to standard brass wire.
- +15% improvement of MRR in at least 1 of 3 materials compared to standard brass wire.

2.2 Project boundaries:

DAMRC has decided not to use any complex geometry as a test part due to the geometry of the part does not give an evaluation parameter directly related with the study parameters defined in the success criteria of the project. In addition, this approach could be justified by the fact that, according to information obtained from the main users of this technology, 90% of the WEDM cuts made are between 0 °-15 °based in our experience, which rules out the need to test complex parts. Also, if major angles are needed, more flexible wires are often used. It is also decided in this project not to examine the mechanical proprieties and grain structure of the wire before and after the cryogenic treatment, as the resource in this activity quickly exceeds the scope of this project, added to the fact that there is an overwhelming amount of scientific work confirming the changes in the microstructure of the materials.

2.3 Risk analysis / Uncertainties:

With respect to the different Risks/Uncertainties associated to a project we can mention the following factors:

- DAMRC equipment's (Liquid nitrogen Dewars and Cryogenic freezer by air and electricity) will not have the possibility to control the stages of the cryogenic process, so this can result in a thermal shock of the Wire increasing the possibility of the breakage of it.
- Exist the risk that we do not get the whole K125 brass wire spool treated in a way so the whole wire on the spool itself will be treated the same way, and the mechanical properties of the wire will be different along its length.

3 Pre-analysis and Literature review:

At the beginning of the project the existing literature and articles are reviewed to base the project on state-of-the-art knowledge and perspectives. This is reviewed to form an overview of which parameters have incidence on the performance of WEDM related to SR and MRR, also all experiments that have been previously performed on the cryogenic treatment of brass wire for WEDM machining, as well as to see what results have been achieved through this. The literature review serves as a basis for the experimental test setup as well as an indicative comparative basis.

K. Satynarayana, Et al [1] review different research that have been done on the cryogenically treated WEDM process and state in their research that different factors have influence on the SR and MRR referred to the WEDM process. They mention that pulse duration, current (flowing through the brass wire), voltage and wire feed are related to MRR and SR. On how these factors impact our study parameters, they conclude the following:

- The Higher the ampere (Current), the larger material erosion, increasing the surface roughness which is the same as lower surface finish on the material. In addition, we can associate the erosion of the material with the MRR, so the increase of current increases the MRR.
- The higher the voltage rate the higher the erosion rate, which means more SR and MRR.
- To talk about Pulse duration, we can imagine a square wave in a current/time chart (Figure 1) where the time in which the current is in the top of the wave is called Pulse on time (Ton) and the time when the wave is in zero ampere is called Pulse off time (Toff).

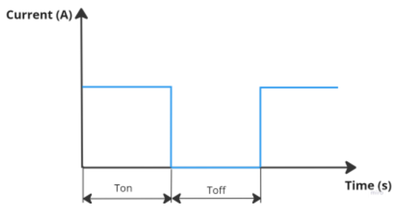


Figure 1 – Current / Time chart.

The authors affirm that the longer Ton, the more spark, and heat generated is equivalent to more Material Removal Rate. In other hand, the lower the Toff the higher MRR.

- The higher the feed rate, the lower the tool wear rate, and the more the surface finish (minor SR value).
- Sudden cooling or sudden heating then causes cracks, internal defects, and sudden breakage of the material.

Regarding the wire material, we focus our interest on this article's study around brass wire, where the tendency of this material to break when exposed to heat is mentioned, validating the application of a cryogenic treatment if it is considered to have the potential to improve the material's resistance and mitigate the response to heat. In general wire of pure materials as brass or cupper are used as they are more conductive.

The article concludes that the Cryogenic treatment improves the properties of the wire in terms of conductivity, tool wear and material removal rate, considering that this treatment can be done without tempering if is made with slow steady ramp-down, soak and ramp-up process. One of the processes mentioned in the article has been conducted by keeping the material 24hs at -185° C and using gradient for ramp-down and ramp-up of 1° C/min. With this methodology.

K. Singh, Et al [2] in his study a test is carried out using two different wires (a cryogenically treated wire and a non-cryogenically treated wire) on an AISI D3 workpiece with the goal to obtain the MRR. For this purpose, a set with three repetitions of nine experiment were conducted with the cryogenically treated wire and three repetitions of nine experiment with non- cryogenically treated wires, where for both set of experiment the main parameters (Pulse width, time between two pulses, wire mechanical tension and wire feed rate) are modified to establish the optimum set of these. For the tests, a 0,25mm diameter zinc coated brass wire is used as tool electrode and sixty work pieces of 40mm x 25mm x 11mm are taken as the result of the cuts. To carry out the experiments the temperature is decreased at the rate 0,51 °C /min from room temperature to -184 °C in 6hs (ramp down), then the temperature is held at -184 °C during 12hs and in the last step of the cryogenic process, the temperature is increased at the rate of 0,51 °C /min (ramp up) per 6hs to achieve the room temperature. Measurements of MRR is taken measuring the difference between the initial weight and final weight of the work piece divided by time of the cut.

As a result of the tests, the following conclusions are addressed:

- For the same set of main parameters, the wire cryogenically treated wire has a major MRR than the non-cryogenically treated wire. This condition is achieved for all the different sets of parameters. In average, the improve of the MRR is around of 19,2% considering all different sets of parameters.
- The pulse width and time between two pulses are found to be the most significant factors for MRR. The MRR increases when the pulse width is increased, and it decreases with increase in time between two pulses (Toff).
- The effect of wire mechanical tension and wire feed rate is negligible.

K. Singh, Et al [3] repeats the test mentioned in K. Singh, Et al [2] with the same set of experiments, varying the same parameters, and using the same workpiece and electrode wire, but with the goal of taking SR measurements, where they concluded the following:

- The SR measured for the pieces cut with the Cryogenically treated wire is lower than the SR measured for the pieces cut with the non-cryogenically treated wire, which is equivalent to saying that the cut surface finish made with the cryogenically treated wire is better. In

average, the improvement of the SR is around 18,38% considering all different sets of parameters.
- The pulse width and wire mechanical tension is the most significant factors for SR.

W. Tahir, Et al [4] conduct an experiment using a 0,3mm Cryogenically treated brass wire and non-cryogenically treated brass wire electrode to cut a piece of HSLA steel. The brass wire is treated by a soaking process that keeps the wire at -70 °C for 24hs with temperature ramps of 2°C/min. In this Jobs, the authors state the conclusions below:

- Cryogenic processes increase the electrical conductivity by 24.8%, which leads to an improvement in the MRR rate, since improving the electrical conductivity results in more powerful spark bursts, which increases erosion and, consequently, the MRR.
- Pulse on time and pulse off time are the main contributing factors for cutting speed with percentage contributions of 64.34 % and 15.83 % respectively.

Sabogal, Sierra [5] makes an experiment where test tubes of Brass 60/40 and Bronze SAE 64 are exposed to the cryogenic treatment, manipulating the time of exhibition, where the variable studied is the influence of the time in the properties of the material (size of grain, hardness, and micro hardness). The test addressed cooling the pieces from the environment temperature (20°C) until the temperature of the liquid nitrogen (-196°C), and holding the temperature during 24, 48, 72 and 120hs. After each one of these times leave them go back to environment temperature of gradual way.

The test result can be concluded that the size grain becomes finer again as the cryogenic time increases, whereas the micro hardness and hardness observe an increase until 120 hrs. With the refinement of grain, it´s possible to conclude that the material suffers a hardening by reduction of size of grain and gain more resistance to the abrasive wear. For other hand, the authors observe a more organized microstructure with a finer grain in the material, that generates a greater dimensional stability and elimination of tensions. For last, in brass we can observe that between more times of cryogenic it increases the apparition of lead in the limits of grain of the material.

J.Kapoor, Et al [6]. This study explores the impact of deep cryogenic treatment on a brass wire electrode used in wire electrical discharge machining, with a focus on material removal rate (MRR). A Robofil-290 CNC wire cut electrical discharge machine and brass wire as electrode was used for conducting the experiments. EN-31 plate of thickness 11 mm was selected as workpiece material. It involves a thorough examination of the cryogenically treated and non-cryogenically treated wire electrodes, assessing their microstructure and crystalline phase through scanning electron microscopy and X-ray diffraction. Utilizing Taguchi experimental design, optimal parameters for maximizing MRR are determined, considering factors like wire type, pulse width, pulse interval, and wire tension. ANOVA analysis identifies significant factors affecting MRR, visualized through main effect plots. The electrical properties of the brass wire are analyzed using a Kelvin Bridge, allowing the calculation of conductivity, which is critical for understanding its role in the machining process. The MRR is quantified based on performance characteristics and observation data from each experimental trial, offering a comprehensive view of the effects of deep cryogenic treatment on the wire electrode's performance.

The study found that Deep cryogenic treatment significantly enhances the conductivity of brass wire electrodes by promoting an ordered, structured arrangement of the crystal molecules within the wire. In its untreated state, the wire's random crystal pattern introduces obstacles for the flow of electrons, resulting in reduced heat conductivity coefficient and electrical resistance. However, the cryogenic treatment aligns the crystal structure into a more uniform and compact configuration, removing kinetic energy, and subsequently improving the wire's electrical conductivity. This enhanced conductivity is maintained when the brass wire electrode returns to ambient temperatures, making it an advantageous choice for electrical applications.

The Author observes that more MRR is obtained from cryogenic treated wire electrode. This is since high-conductive wires give more energy to the process as additional conductivity promotes more electron emission. The temperature of the wire drops due to less resistance.

In conclusion, the application of cryogenic treatment to the brass wire electrode in wire electrical discharge machining led to notable improvements in both its microstructure and electrical conductivity compared to non-cryogenic treatment. The utilization of Taguchi experimental design successfully pinpointed the optimal parameters for achieving maximum material removal rate (MRR), with the type of wire, pulse width, time intervals between pulses, and wire tension emerging as significant factors.

J. M. Jefferson and P. Hariharan [7]. This research studies the performance of brass electrodes using for a micromachining electrical discharge machine. This paper is interesting due to some of the results obtained from the experiment go in opposite direction with the article reviewed before. The authors concluded that Cryogenic treatment significantly reduced tool wear rate (TWR) and material removal rate (MRR) in micro electric discharge machining (MEDM) for different electrode materials, including brass, copper, and tungsten. For brass electrodes, cryogenic treatment resulted in a 51% reduction in TWR and a 39% decrease in MRR. Copper electrodes showed a 35% reduction in TWR and a 34% reduction in MRR after cryogenic treatment. Tungsten electrodes exhibited a 58% reduction in TWR and a 55% reduction in MRR when subjected to cryogenic treatment. Cryogenic treatment also led to a decrease in electrical resistivity and an increase in microhardness values for all electrode materials.

As a conclusion, In Figure 2 we can see a compendium of the different temperature curves as a function of time used by the different authors to carry out the thermal treatment of Brass coils. In it, we can see in comparison how the different authors have carried out their experiments with different approaches, using different cooling/heating slopes, different periods of time during the soaking stage, and even subjecting the material to different temperatures during the soaking stage. soaking, giving rise to processes with different intensities with respect to thermal levels.

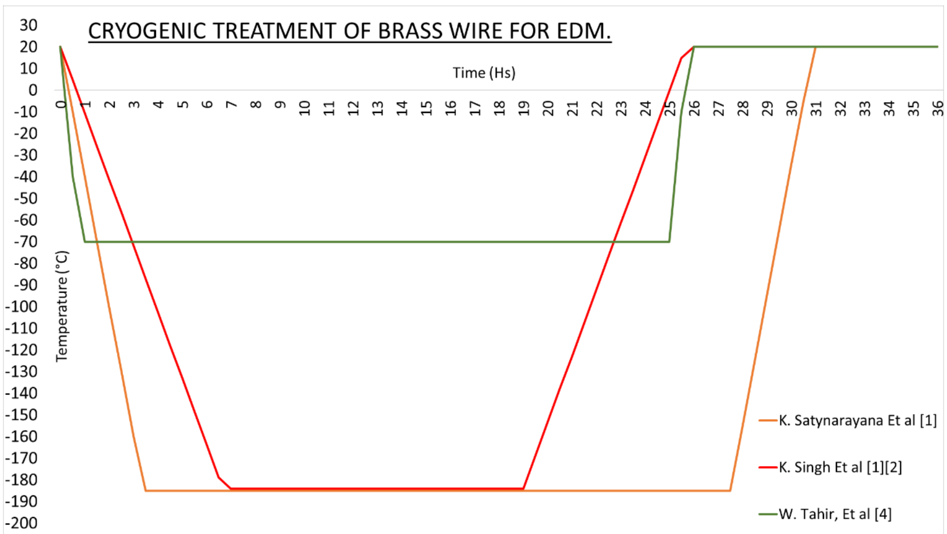


Figure 2 - Temperature / Time chart - Cryogenic Treatment.

As a result of these treatments and based on different experiments conducted by the authors mentioned in the literature analysis, Table 1 shows a summary of the experiments carried out by the different authors, where the temperature and soaking time, the cable material, the machine in which the cable coils were tested, and the thermal gradients used to process the coils during the experiments can be appreciated. Likewise, for each experiment it is possible to observe the conclusion derived from each of these experiments regarding the measured variation of MRR and SR.

Reference	Soak Temp (°C)	Soak Time (Hs)	Wire Material	Machine	Material	Gradient of Temperature ramp (°C/min)	Conclusion
K. Satynarayana, Et al [1]	185	24	Brass wire / cupper wire / tungsten wire.	N/A	N/A	1	No quantified conclusion.
K. Singh, Et al [2]	184	12	0.25 mm diameter zinc coated diffused brass wire.	Charmilles Technologies Robofil 290	AISI D3 steel	0,51	Increase 19,2% MRR (Average of different set of parameters).
K. Singh, Et al [3]	184	12	0.25 mm diameter zinc coated diffused brass wire.	Charmilles Technologies Robofil 290	AISI D3 steel	0,51	decrease 18,4% SR (Average of different set of parameters).
W. Tahir, Et al [4]	70	24	xxxx	xxxx	xxxx	2	Increase 24.8% electrical conductivity (directly related with MRR, MRR not quantified)
J.Kapoor, Et al [6]	185	18	Brass wire	Robofil 290	EN-31 / SAE	0,37	Increase 20% approx. of MRR

			Brass Cu63% Zn37% Hardness (VH)255 905 N/mm2 Conductivity (%IACS)21%		En-31 C-1.0% Si-0.31% Mn-0.50% P-0.31% S-0.042% Cr-1.40% HRC 58 MM11		

Table 1 – Literature summary.

4 Set Up of the experiments:

In this section, the process carried out by DAMRC with which the test performed is discussed, as well as the different resources used to achieve the objective of the study, like materials, equipment, and tests process. Summarizing the goal, which is to measure the change in MRR and SR obtained when cutting a set of parts in an WEDM using one coil of brass wire without cryogenic treatment and two coils of brass wire with cryogenic treatment, where the cryogenic treatment is performed in two different ways for each one, with a conventional air and electric freezer (to try to make the treatment as simple as possible), and with an NL2 immersion freezer.

Figure 3 - Pilot test materials to test.

4.1 Material for the test

The three wire coils are evaluated on three of the most used materials in the WEDM process based on data from the Danish industry, which will result in 9 different cutting experiments.

The three materials to cut in the WEDM are IMPAX® SUPREME, ORVAR® SUPREME and UNIMAX®. The test pilots of 80x80x35mm can be visualized in Figure 3. In general, these are material with High levels of hardiness used for dying casting dies, forging tools, extrusion tooling, injection molds for thermoplastics, blow molds etc., whose machining would be inefficient and sometimes impossible to make with other technology different than WEDM. The mechanical proprieties of these steel alloys can be appreciated in Table 2.

MATERIAL	MODULUS OF ELASTICITY	YIELD STRENGTH (Mpa)	TENSILE STRENGTH (Mpa)	ACHIEVED HARDENESS

	(Mpa)			
IMPAX® SUPREME (AISI P20)	205000	900	1020	50 HRC
ORVAR® SUPREME (AISI AISI H13)	210000	1520	1820	54 HRC
UNIMAX®	2130000	1720	2050	54HRC

Table 2 – Mechanical properties of test pilots.

Figure 5 - MITSUBISHI MV1200S TYPE II.

To cut these materials, three brass wire Novotec Ultra Brass P-5 (diameter: 0,25mm, Length: 9360m) are used. This material is suitable for cutting between 0-15 °. For higher angles, more flexibles wires must be evaluated, but if we keep in mind that our objective of study is independent of the complex of the part to cut, we can dismiss this limitation.

4.2 Equipment for the test:

To perform the WEDM process, a MITSUBISHI electric Model MV1200S TYPE II located in DAMRC facilities and provided by RANSBORG SALES & SERVICES was used. This machine is shown in Figure – 5. This machine can work with pieces of 500Kg and 640x540mm using wires between 0,10 and 0,30mm. As a different against more conventional WEDM machine where the dielectric is delivered to the cutting zone by a jet, in the MV1200S the part is fully submerged in dialectic during the cutting process.

In terms of the equipment to make the cryogenic treatment, two different devices are used. First, an ARCTIKO CRYO 230 air- electric freezer with capability to achieve -150°C with an average ramp down of ≈0,56°C/min ramp up of ≈ ≈0,183°C/min and 233L, see Figure – 6.

Figure 7 - M505K LIQUID NITROGEN STORAGE VESSEL

Then, a TAYLOR WHARTON™ 10K-M505K liquid nitrogen storage vessel is used to test one of the coils of wire to -195°C, which has a capacity of 165L. The liquid nitrogen vessel has a control system that has the possibility to connect to a PC and obtain the temperature-time graph, but an external system is used to validate the temperature curve and control the three stages of the process (Cool down, soak and heat up.). This control system is made in base of Arduino and is connected to the on/off liquid nitrogen valve of the freezer and to a thermocouple type K that is placed in the middle of the brass coil. The Arduino board is programmed to follow the desired curve of temperature for the process according to the three stages mentioned, and if the reading of temperature in the freezer has a deviation from these values, the system acts over the valve opening and closing it.

When the tests have been done, the measurement of and MRR are taken. SR is measured with a surface roughness equipment Mar Surf PS1 showed in Figure – 8, where the measurement range is 350 µm maximum (-200 µm + 150 µm) and max Length of palpation traverse is 17,5mm.

Figure 8 - MarSurf PS1.

To take MRR measurements, the WEDM MV1200S can calculate this parameter, but to validate it, an additional process is carried out by taking measurements of the weight of the pieces before and after the WEDM process, in order to see the difference in material removal through the weight, and then applying the time in which the process was carried out, to calculate the MRR. For this proposal, the KERN EMS 3000 – 0.01G balance is used, which is shown in Figure - 9.

Recording of the temperature is done with a SEFRAM 9816B data logger thermometer with 4 inputs and is compatible with thermocouple type K,J,E,N,T,R and S. for the measurement there was used a type K thermocouple. The SEFRAM 9816B is shown in Figure 9-b

Figure 6 - ARCTIKO CRYO 230

Figure 9 - KERNS EMS 3000-0,01.

Figure 9B - SEFRAM 9816B

5 Design of test:

In order to carry out the experiments that allow us to derive the evaluation of the success criteria proposed in this technical report, a step by step of the tasks to be carried out during the experiments was developed, below is the guide that accompanies the development of the tests.

1) The Cryogenic process is done in first place, and each one of the two process is described below:

   a) Cryogenic Process with Air – Electric Freezer (ARCTIKO CRYO 230)
   The brass wire coil is placed in the freezer so that the coil is vertical and cantered as much as possible in the center of the freezer to have a temperature profile the most homogeneous as possible. Considering that the electric freezer, is generally used for medicinal use, has a descent and ascent ramp defined by the hardware that makes up the freezer, these parameters cannot be modified to obtain a treatment different from that conceived during its manufacture. Therefore, for the coil treated in the electric freezer, the only control parameter is the soaking temperature and the soaking time, where the soaking temperature is defined as the lowest temperature that the commercial freezer can reach (-150 °C), and the time is defined based on the most conservative value obtained from literature research (24hs). For additional control, an external system is used to validate the temperature curve. Once the system is installed, the freezer is turned on and monitored until the temperature reaches -150°C and is maintained for 24 hours. After that, the temperature is raised to room temperature. Figure 10 shows the characteristic graph with the ramp down and ramp up of the freezer defined by the supplier.

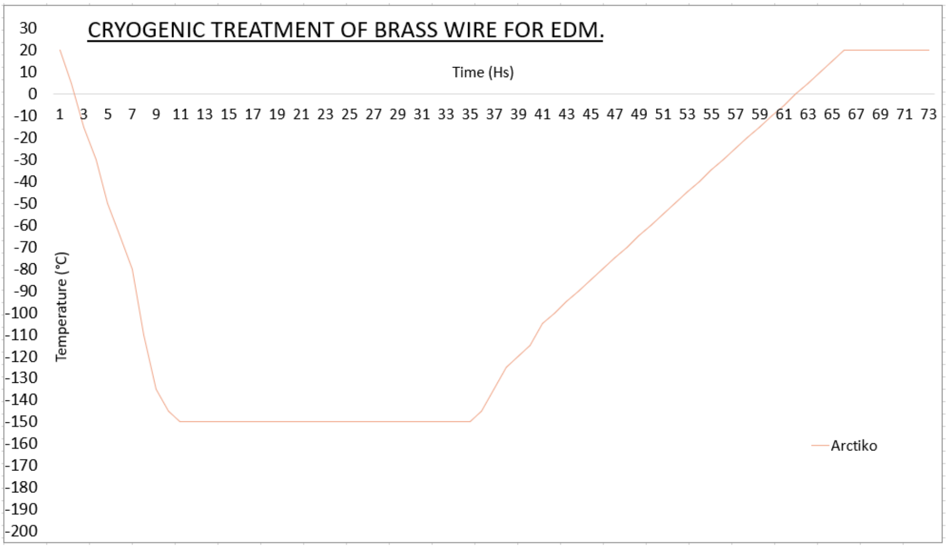


Figure 10 - Electric - Air Freezer - ARCTIKO.

The choice of the soaking time is defined based on a conservative point of view, because, if we consider that our temperature is among the different cases we found in the literature, taking the treatment of W. Tahir, Et al [4] performed at -70 °C, we see that it was 24hs. We take this case as conservative, and we take the same time because our objective is not to find the indicated time, but to determine the effect of the treatment on the wire. Because the treatment with the electric freezer is done by Arctiko in their facilities, a test process sheet was generated to them and is shown in appendix 1.

5.1 Cryogenic Process with Liquid Nitrogen (TAYLOR WHARTON™ 10K-M505K).

To perform the cryogenic process with liquid nitrogen, the liquid nitrogen tank and the external controller is connected to the freezer. Then, the brass wire coil is placed and centered in the volume of the freezer to obtain the most homogeneous temperature profile as is possible during the treatment. Once the systems are installed and the piece is placed in the freezer, the temperature cools at a rate of 0.5°C/min, delivering liquid nitrogen at a pressure of up to 1.5 bar, until it reaches -185°C, then it is maintained in this condition for 24 hours to then heat the freezer by increasing the temperature at 0.5°C/min until reaching room temperature. The setup to perform the experiment is shown in Figure 11 and the curve to be followed by the controller is shown in Figure 12.

Figure 11 – Cryogenic freezer 10K-M505K and Liquid Nitrogen vessel.

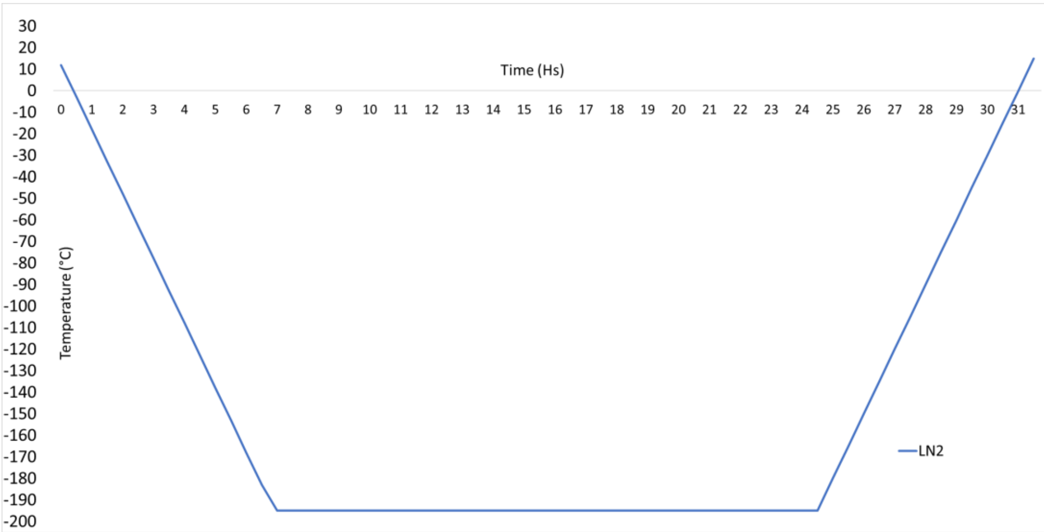


Figure 12 – Temperature curve for Cryogenic treatment with liquid nitrogen.

2) The next step is to measure the weight of our pilot tests to obtain a value to compare after the cut and to be able to obtain a validation value of the MRR. To take these measurements, the KERNS EMS 3000-0.01 is used.

5.2 Test setting of the WEDM Machine:

- **Test 1**: The process is performed with the control system of the machine setting the cutting parameters automatically based on the cutting conditions measured during the process. The default settings for brass wire are used. Regarding the geometry of the cut, it began with a perpendicular cut to the surface of the block for the first 30mm, a transition to 15° over a length of 10mm, to continue with this angle to the rest of the block.

- **Test 2**: The process is carried out with the control system of the machine setting the cutting parameters automatically based on the cutting conditions measured during the process. The default settings for a brass wire are used to start, but then, these settings are changed in intervals of 2 mins increasing a parameters that the machine have that is called “aggressiveness” (The control system of the machine is actively working to ensure that the wire does not break, when we increase the aggressiveness, the machine modified the pulse frequency and pulse length to push the parameters more close of the limit). Regarding the geometry of the cut, straight cuts through material are used.

- **Test 3**: This test is performed by removing the automatic control of the cutting parameters, starting with the default setting, and then increasing the feed gradually from 3mm/min to 5mm/min in intervals of 4mm giving place to 20 different steps. Regarding the geometry of the cut, straight cuts through material are used.

- **Test 4:** Using manual control over the feed rate and power setting for the cut. Straight cuts through the material are used to test the limit of the wire. The cut began with a feed rate of 2.6mm/min and a power setting of 11, which is the machine's standard for the cutting conditions. Once the cut was started and stabilized, the feed rate is slowly increased in 0.1 intervals until the wire broke. The feed is reduced by 0.1 and if it lasted for 1 minute is deemed stable. The power level is then increased by one and if the wire does not break after one minute the feed rate is increased as before. This was repeated until the wire broke within 60 seconds of increasing either the power level or the feed rate.

3) Once the parts are cut, they are weighed again to get the difference before and after each cutting, and then this difference is divided by the cutting time to obtain the MRR parameter in each case. Furthermore, these values are compared with the MRR values obtained from the WEDM machine.

4) The surface roughness is then measured and recorded with the MarSurf PS1.

6 Result of test:

In this section, the results of tests on three different wires, each subjected to different treatments, are presented. The objective is to evaluate the performance of these wires after they have been treated with deep cooling using liquid nitrogen (LN2), an electric freezer, or left untreated. These tests are being conducted on three different materials using the WEDM machine presented in DAMRC´s Technology Center, and the outcomes of four specific experiments are being showcased. Detailed insights into the parameters used during the deep cryogenic treatment of the wires are also provided to give a better understanding of the factors influencing their performance. Section 6.1 shows the parameters of the cryogenic treatments evaluated during the process, while in section 6.2 we can find the data collected after WDEM machining.

6.1 Cryogenic Treatment.

In Table 3 and Table 4 the parameters used for the different cryogenic treatments are showed together with the chart of the temperature curve recorded.

Cryogenic Device	Temperature Gradient – Ramp down.	Soaking time	Soaking Temperature	Temperature Gradient – Ramp up.
ARCTIKO CRYO 230	-0,5 °C/min	24hs	-150°C	0.183°C/min

Temperature – Time chart

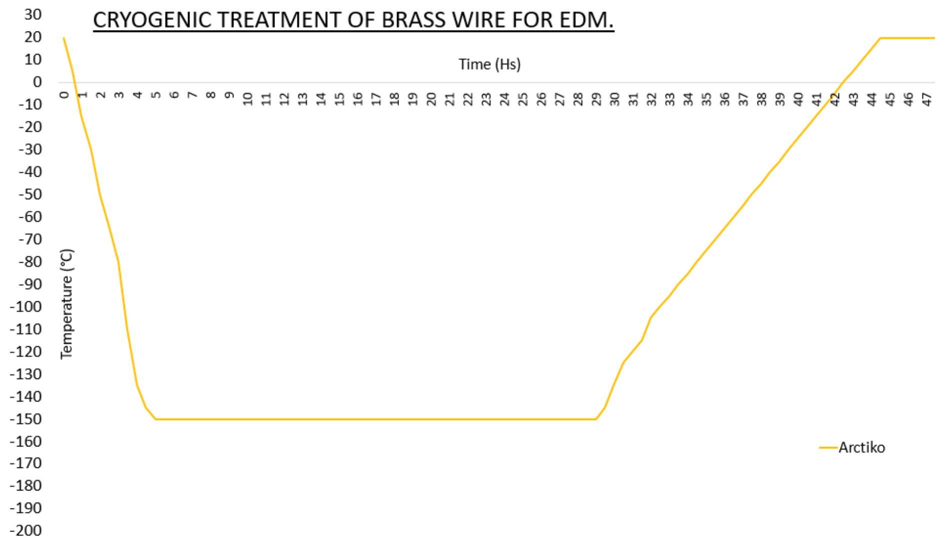


Table 3 - Temperature – Time chart ARCTIKO CRYO 230

Cryogenic Device	Temperature Gradient – Ramp down.	Soaking time	Soaking Temperature	Temperature Gradient – Ramp up.
TAYLOR WHARTON™ 10K-M505K	-0.5°C/min	18 hs	-195°C	0.5°C/min

Temperature – Time chart

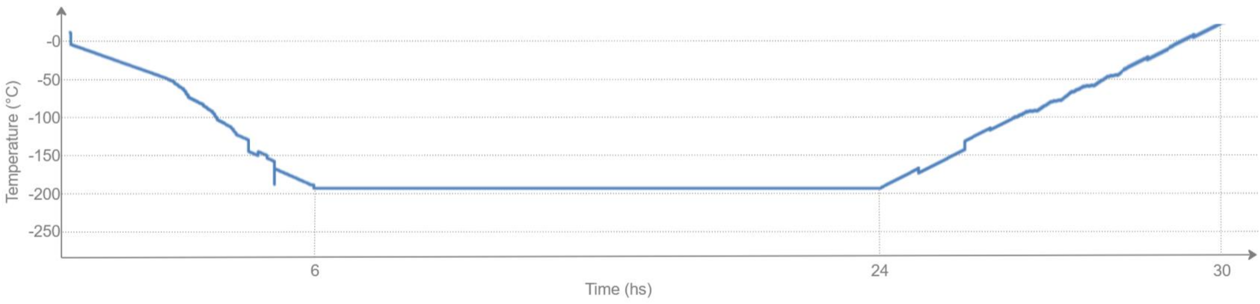


Table 4 - Temperature – Time chart TAYLOR WHARTON™ 10K-M505K.

6.2 WDEM machining results.

In the following we discuss about the result of the experiments mentioned in section 5.

For the **Test 1** where the cutting parameters of the machine were configurated automatically by the control unit based in the real time measures of the cutting conditions and the default settings for brass wire, the cuts began with a perpendicular cut to the surface of the block for the first 30mm, then transitioned to a 15° cut over the length of 10mm, and then continued the remainder of the block at 15°. The results of this tests are presented in Appendix 2 and Appendix 3 where in first table is presented an evaluation of the MRR across the difference in the weight after and before cutting, and in second one we have result about the performance through the speed that is directly related with the Material Removal Rate, data extracted from the control unit of the machine. For this test, the coils used in the WEDM process with the IMPAX® SUPREME samples (A1, A2 and A3) showed no appreciable difference when the MRR calculation is carried out through weight. Although, looking at the speed defined by the unit of control of the machine, a higher speed can be seen in the coil treated with LN2 (A3) of approximately 4%. This difference between the MRR taken as proportional to the speed and the calculation through weight could be interpreted as basically the machine is operating without a real improvement in the MRR because at a lower speed more material is removed than at the 4% higher speed, keeping the MRR at the same level. For OVAR® SUPREME material the situation is different, given that for two ways to study the MRR an increase of approximately a 5% can be observed for the coil treated with LN2 (B3) regarding the one without treatment, showing a real change in the MRR. For UNIMAX® the situation is similar, giving the higher increase for the coil treated with LN2 (C3) but with a difference of 3% approximately.

For **Test 2** the results can be found in Appendix 4. In this test the control unit of the machine set the cutting parameters automatically in based of the cutting conditions measure in real time and the process is started with default seatings for brass wire to then be modified in intervals of 2min. The Mitsubishi MV1200S TYPE II have a parameter that can be changed during the process called "aggressiveness" that is a level of how the machine adjust the parameters to ensure that the wire dos not break, so when the aggressiveness is increased, the wire is pushed closer to the limit of maximum performance increasing the risk of a failure. In order to evaluate whether the cryogenic treatment has an effect on the resistance of the wire, allowing it to work with higher levels of aggressiveness during machining, and allowing it to work at a higher level of performance, the mentioned parameter is increased every 2 minimum intervals to allow the machine record the parameters during cutting and stabilize the cutting parameter for the subsequent evaluation process. During this test, the feed rate, meters of wire consumed, time and average speed are evaluated. The result of these experiments for IMPAX® SUPREME shows a slight increase in the average speed for both the coil treated with LN2 and the electric freezer (2% and 4%) compared to the coil without treatment, and at the same time it is possible to observe better behaviour when the aggressiveness was increased to the maximum because the wire did not break for the coil treated with LN2 unlike the other two coils. The results can be extrapolated to the other two materials where similar results were found, but with an interesting observation given by a decrease in the average speed for UNIMAX® SUPREME close to 12% with the coil treated with LN2. In Figure 12, the resulting cut of the test 1 and test 2 can be appreciated where in the left is possible to appreciate the transition in the angle of the wire during the experiment.

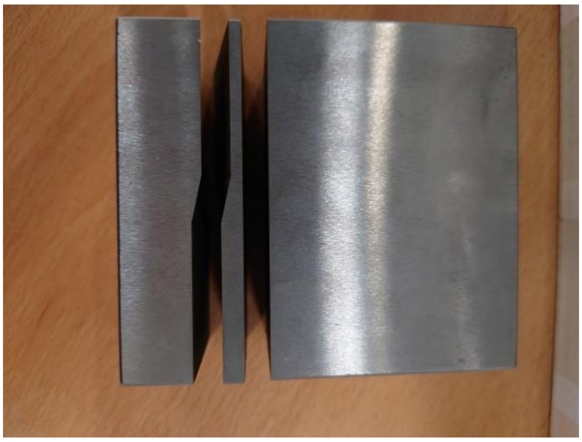


Table 12 – Resulting cut of Test 1(left) and Test 2 (right) in one of the samples.

During **Test 3**, the machine control unit that automatically sets parameters depending on cutting conditions was disabled to start with standard cutting conditions and gradually increase feed by making straight cuts through the material. To ensure that the cutting speed is stable before the feed change, 4 mm intervals are used. The goal of the test is to define the maximum feed rate to be achieved for each of the different wires under the cutting conditions defined for each material. The results can be found in Appendix 5 where the feed rate max achieved are shown for each treated coil and material combination, and then, the steps of feed rate used are in Appendix 6. For these experiments, any considerable changes around the different combinations and materials and wire coils were found.

The **Test 4** is performed using manual control over the feed rate and power setting of the wire, where straight cuts through the material is used to test the limit of the wire regarding the different combinations between power and speed. The process starts with a feed rate of 2.6mm/min and a power setting of 11, which is the machine's standard for the cutting conditions. Once the cut is started and stabilised, the feed rate is slowly increased in 0.1 intervals until the wire brake. The feed is reduced by 0.1 and if it lasted for 1 minute is deemed stable. The power level is then increased by one and if the wire does not break after one minute the feed rate was increased as before. This process is repeated until the wire broke within 60 seconds of increasing either the power level or the feed rate. The results can be seen in **Appendix 7**, where even if some small differences can be appreciated there is not a tendency that can define an improvement related with the coils treated.

To study the effect on the surface quality of the cryogenic treatment of the wire coils during the WDEM process, measurements were taken of the surface roughness of the pieces resulting from the cutting carried out in Test 1. The results of these measurements are shown in the Appendix 8 where a negative trend is seen for cryogenically treated coils. For all combinations of materials and cryogenically treated coils, the surface roughness increases about 10% compared to the process carried out by the untreated coils. Only in the UNIMAX® SUPREME machined by the coil cryogenically treated with LN2 is possible to see an improvement of 3% be observed in relation to the surface roughness, but it should be treated as an isolated case considering the results obtained for the rest of the samples.

6.3 Test results conclusions.

In summary, different tests were carried out to evaluate the effects of cryogenic treatment on wire coils in the WEDM process where different trends are seen in relation to the material removal rate and the surface roughness of the workpiece. The manual and automated tests explored various parameters, including aggressiveness, feed rate, and power setting, providing insights into the intricate relationship between cryogenic treatment and the WEDM process. The results indicated that the cryogenic treatment's influence on performance varied across different materials, with no consistent trend observed. While certain instances demonstrated increases in MRR and more stable wire behaviour, other cases did not exhibit significant improvements. The impact of cryogenic treatment on surface quality, as assessed through surface roughness measurements, generally showed a negative trend, with an overall increase of around 10% compared to untreated coils. However, there were isolated cases, such as the UNIMAX® SUPREME machined by the LN2-treated coil, where a 3% improvement in surface roughness was noted. For the MRR specifically, although improvements of the 5% and 3% level can be observed for OVERALL® SUPREME and UNIMAX® SUPREME machined by the cryogenically treated coil by LN, the trend is not constant in all the experiments that open doors to the study of other variables during the experiments such as the different automatic characteristics in the configuration of the cutting parameters carried out by the machine where the user today has no influence. At the same time, the treatment of the coils does not show any impact on the resistance of the wire, influence on the possible feeding speeds, as well as on the quality of the surface of the parts, given the worst result for those treated cryogenically in the case of the surface roughness.

7 Conclusion:

The results obtained from our extensive testing efforts have led us to intriguing observations. Throughout the tests, we monitored the Material Removal Rate (MRR) as a critical parameter under study. Surprisingly, no significant changes were recorded in the MRR for the wires subjected to various treatments, including deep cryogenic treatment, electric freezer treatment, and the untreated wire. This outcome contrasts with findings in the existing literature, which suggested that a cryogenic treatment can result in different wire's properties what might influence MRR and SR. This apparent contradiction in our results can be attributed to several factors. It is possible that the wires used in our experiments are manufactured to such high standards today that their inherent properties are inherently resistant to alteration, even under different treatment conditions. Alternatively, the discrepancy could be attributed to variations in the WEDM machines themselves. Our machine operates with automatic control over a wide range of parameters, which may differ from the machines discussed in the literature. For instance, in our machine, the workpiece to be cut is fully submerged in dielectric, whereas in the machines referenced in the literature, the dielectric encounters the cutting area through a jet. Considering these facts, our findings underscore the complexity of WEDM processes, and the multifaceted nature of the variables involved. As such, they highlight the importance of careful consideration of both material properties and machine-specific factors when attempting to optimize WEDM performance. Further research may be required to learn knowledge about the relation between these variables and their impact on the Material Removal Rate.

Additionally, it is worth noting that the maximum difference observed in the Material Removal Rate (MRR) between the various tests is approximately 5%, as is shown in the WDEM process carried out over ORVAR® SUPREME with the coil cryogenically treated by LN2. This suggests that, despite the lack of significant changes in the MRR, there still exists a minor variability in the performance of the wires under different treatments.

Regarding Surface Roughness, some significant change was seen for the different test samples and in most cases, the standard cable obtained the best result for Surface Roughness. As a general conclusion, the Surface Roughness was not affected negatively under the conditions of this process.

In conclusion, although the cryogenic treatment of the coils was carried out successfully, the success criterion proposed by the Project was not met, in which a 15% improvement in the MRR and Surface Roughness is sought, since the values of variations related to these parameters were considerably lower. To delve deeper into understanding the changes in wire properties, it is crucial to consider microstructural alterations. Examining these microstructural changes within the wire may provide a more profound insight into the underlying mechanisms that influence the Material Removal Rate. As our findings demonstrate, the WEDM process is characterized by a complex interplay of material properties and machine-specific factors. Therefore, further research is warranted to unravel the intricate relationship between these variables and their influence on the Material Removal Rate.

8 References:

1. Satynarayana, Kosaraju , Et al.(2020) "*A role of cryogenic in Wire cut WEDM process".*
2. Singh, kultar, Et al.(2019) *"Performance enhancement of material removal rate by using cryogenic treatment on zinc coated diffused brass wire in wire-cut WEDM process".*
3. Singh, kultar, Et al.(2017) *"Effect of cryogenically treated wire on surface roughness in wire WEDM process".*
4. Tahir, W, Et al. (2019) "*Effect of process parameters on cutting speed of wire WEDM process in machining HSLA steel with cryogenic treated brass wire*".
5. Sabogal, Sierra. (2016) *" Influence of the cryogenic treatment in micro structure, hardness and micro hardness of the Brass 60-40 and Bronze SAE 64".*
6. *Jatinder Kapoor , Sehijpal Singh and Jaimal Singh Khamba. (2012) "Effect of cryogenic treated brass wire electrode on material removal rate in wire electrical discharge machining".*
7. *J. M. Jafferson and P. Hariharan (2013) "Machining Performance of Cryogenically Treated Electrodes in Microelectric Discharge Machining A Comparative Experimental Study".*

9 Appendix:

9.1 Appendix 1

DAMRC Danish Advanced Manufacturing Research Center	TEST PROCESS - DATA SHEET		
	PROJECT	P1001-4-5 CREDM	
	DAMRC CP	Giuliano Carrillo	gac@damrc.com
	TEST DATE		
	SUPPLIER	ARCTIKO	
	TEST PLACE	ARCTIKO FACILITIES	

PROCESS NAME
Cryogenic treatment of brass wire coil using aire-electric freezer.

MATERIAL DELIVERY BY DAMRC TO PROCCES	QTY
brass wire spools K125 (diameter: 0,25mm, Length: 9360m)	1

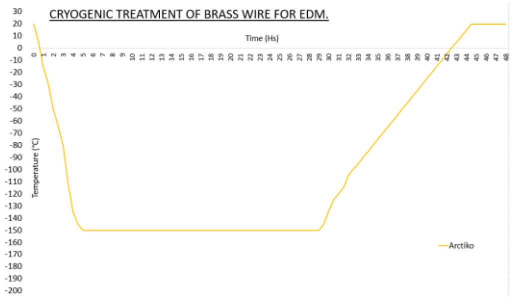
PROCESS DESCRIPTION

1) Place the brass wire spool in the freezer so that the coil is vertical and centered as possible in the center of the freezer.

2) Lower the temperature from room temperature until -150°C. If it´s possible record the temperature/time gradient (°C/seg) used during the process of ramp-down and time to reach the final temperature of this step.

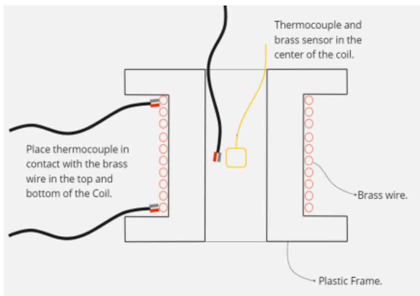
3) Keep the brass wire spool into the freezer at -150°C for 24 hours without interruption. Record any possible desviation during this process.

4) Gradually increase the temperature from -150°C to room temperature by keeping the coil of wire in the freezer. If possible, record the temperature/time gradient (°C/sec) used during the gradual increase process and the time required to reach the final temperature of this step.



DATA RECORDED DURING THE PROCESS

Temperature sensor location:
Center of coil, Use brass sensor and thermocouple
Outside diameter, top of coil - Thermocouple sensor
Outside diameter of the coil - bottom side - Thermocouple sensor



ADDITIONAL DATA - OBSERVATIONS

	SUPPLIER´S SIGNATURE

DATE OF RECIPT		RETURN DATE	

Appendix 1 – Test process Articko – Cryogenic treatment with electric freezer.

9.2 Appendix 2

Obs: The percentages presented in the table are measured with respect to the same material and cut with the wire without treatment.						
Pilot test Denomination	**Material**	**TREATMENT OF THE WIRE WITH WHICH IT IS CUT**	**Weight Before cutting (g)**	**Weight after cutting (g)**	**Cutting Time. (min)**	**MRR (measured by weight) (g/min)**
A1	IMPAX® SUPREM.	Whitout Treatment.	1662,26	1654,03	33:03	0,249
A2	IMPAX® SUPREM.	Cryogenic Treatment in Arctiko cryo 230.	1652,31	1644,29	32:23	0,248 (≈0%)
A3	IMPAX® SUPREM.	Cryogenic Treatment in TAYLOR WHARTON™ 10K-M505K.	1743,12	1735,12	31:48	0,252 (≈1%)
B1	ORVAR® SUPREME	Whitout Treatment.	1605,74	1597,75	33:3	0,242
B2	ORVAR® SUPREME	Cryogenic Treatment in Arctiko cryo 230.	1625,08	1617,1	32:33	0,245 (≈1,5%)
B3	ORVAR® SUPREME	Cryogenic Treatment in TAYLOR WHARTON™ 10K-M505K.	1656,42	1648,3	32:08	0,254 (≈5%)
C1	UNIMAX®	Whitout Treatment.	1653,41	1645,34	33:19	0,242
C2	UNIMAX®	Cryogenic Treatment in Arctiko cryo 230.	1649,7	1641,7	33:09	0,242 (≈0%)
C3	UNIMAX®	Cryogenic Treatment in TAYLOR WHARTON™ 10K-M505K.	1638,73	1630,7	32:22	0,248 (≈2,5%)

Appendix 2 – MRR Measurements trough weight– Test 1.

9.3 Appendix 3

Obs: The percentages presented in the table are measured with respect to the same material and cut with the wire without treatment.

Material	Treatment	ID	Wire Used (m)	Speed (mm/min)	Time	Comment
Impax Supreme	Normal	A1	187	3,2638	33:03	
Orvar Supreme		B1	308	3,2175	33:30	Broke twice near end due to pinching, made wire use much higher
Unimax Supreme		C1	187	3,2357	33:19	
Impax Supreme	Electric	A2	184	3,3310 (≈2%)	32:23	
Orvar Supreme		B2	184	3,3140 (≈3%)	32:33	
Unimax Supreme		C2	187	3,2481 (≈0%)	33:09	Broke once near end due to pinching
Impax Supreme	LN2	A3	181	3,3892 (≈4%)	31:48	
Orvar Supreme		B3	240	3,3515 (≈4%)	32:08	Water quality was not good
Unimax Supreme		C3	184	3,3269 (≈3%)	32:22	Water quality was not good

Appendix 3 – MRR Measurements trough speed from control unit of WEDM machine – Test 1

9.4 Appendix 4

Obs: The percentages presented in the table are measured with respect to the same material and cut with the wire without treatment.

Material	Treatment	ID	Feedrate 0-2 Min	Feedrate 2-4 Min	Feedrate 4-6 Min	Feedrate 6-8 Min	Feedrate 8-10 Min	Wire Used (m)	Aver Speed (mm/min)	Time	Comment
Impax Supreme	Normal	A1	2,3	3,5	3,8	4	4	127	4,1290	22:19	Wire Broke at end of block
Orvar Supreme	Normal	B1	2,3	3,5	3,8	4	4	125	4,2845	21:31	Wire broke at max aggressiveness twice
Unimax Supreme	Normal	C1	2,3	3,8	3,9	4	4,1	124	4,3716	21:30	Wire broke due to pinching twice
Impax Supreme	Electric	A2	2,3	3,8	3,8	4	4,1	124	4,2973 (≈4%)	21:30	Wire broke at end of block and could not rethread. Restarted and sparked the entire length of the cut region showing that the internal stresses pinched the wire
Orvar Supreme	Electric	B2	2,3	3,6	3,8	3,9	4	121	4,3776 (≈2%)	21:03	No Break
Unimax Supreme	Electric	C2	2,3	3,8	3,9	4	4,1	118	4,4709 (≈2%)	20:37	No Break
Impax Supreme	LN2	A3	2,5	3,5	3,9	3,9	4	124	4,2110 (≈2%)	21:53	No Break
Orvar Supreme	LN2	B3	2,6	3,6	3,8	4	4,1	121	4,3487 (≈1%)	21:12	No Break
Unimax Supreme	LN2	C3	2,7	3,7	3,8	4	4,1	143	3,8938 (≈-12%)	23:40	Wire broke once at max aggressiveness

Appendix 4 – Feed rate, meters of wire used and speed measurements – Test 2.

9.5 Appendix 5

Obs: The percentages presented in the table are measured with respect to the same material and cut with the wire without treatment.

Material	Treatment	ID	Feedrate Max (mm/min)	Comment
Impax Supreme	Normal	A1	4,05	Stable at 3.95
Orvar Supreme		B1	4,16	Stable at 4.05
Unimax Supreme		C1	4,16	Stable at 4.05
Impax Supreme	Electric	A2	4,05 (≈0%)	Stable at 3.95
Orvar Supreme		B2	4,16 (≈0%)	Stable at 4.05
Unimax Supreme		C2	4,16 (≈0%)	Stable at 4.05
Impax Supreme	LN2	A3	4,05 (≈0%)	Stable at 3.95
Orvar Supreme		B3	4,16 (≈0%)	Stable at 4.05
Unimax Supreme		C3	4,05 (≈-3%)	Stable at 3.95

Appendix 5 – Feed rate – Test 3.

9.6 Appendix 6

Step No.	Go to Position	Feed
1	4	3,00
2	8	3,11
3	12	3,21
4	16	3,32
5	20	3,42
6	24	3,53
7	28	3,63
8	32	3,74
9	36	3,84
10	40	3,95
11	44	4,05
12	48	4,16
13	52	4,26
14	56	4,37
15	60	4,47
16	64	4,58
17	68	4,68
18	72	4,79
19	76	4,89
20	80	5,00

Appendix 6 – Feed rate steps used – Test 3.

9.7 Appendix 7

Obs: The percentages presented in the table are measured with respect to the same material and cut with the wire without treatment.

Material	Treatment	ID	IP Max	Speed at Max IP (mm/min)	Comment
Impax Supreme	Normal	A1	12	4,2	Instant Break at IP=13
Orvar Supreme		B1	13	4,3	Same Max speed for IP=12 and IP=13
Unimax Supreme		C1	13	4,2	
Impax Supreme	Electric	A2	12	4,2 (≈0%)	Instant Break at IP=13
Orvar Supreme		B2	13	4,3 (≈0%)	
Unimax Supreme		C2	13	4,2 (≈0%)	
Impax Supreme	LN2	A3	13	4,5 (≈7%)	Instant Break at IP=13, Speed kept rising without breaking
Orvar Supreme		B3	13	4,2 (≈0%)	
Unimax Supreme		C3	13	4,2 (≈0%)	

Appendix 7 – Test 4 Results.

9.8 Appendix 8

Obs: The percentages presented in the table are measured with respect to the same material and cut with the wire without treatment.

Pilot test Denomination	Material	TREATMENT OF THE WIRE WITH WHICH IT IS CUT	Ra (µm)	Rz (µm)
A1	IMPAX® SUPREM.	Whitout Treatment.	3,725	25,4
A2	IMPAX® SUPREM.	Cryogenic Treatment in Arctiko cryo 230.	4,000 (≈7%)	28,5 (≈12%)
A3	IMPAX® SUPREM.	Cryogenic Treatment in TAYLOR WHARTON™ 10K-M505K.	3,718 (≈0%)	28,3 (≈11%)
B1	ORVAR® SUPREME	Whitout Treatment.	3,857	25,2
B2	ORVAR® SUPREME	Cryogenic Treatment in Arctiko cryo 230.	3,909 (≈1%)	28,0 (≈11%)
B3	ORVAR® SUPREME	Cryogenic Treatment in TAYLOR WHARTON™ 10K-M505K.	3,938 (≈2%)	27,0 (≈7%)
C1	UNIMAX®	Whitout Treatment.	3,731	24,1
C2	UNIMAX®	Cryogenic Treatment in Arctiko cryo 230.	3,993 (≈7%)	28,0 (≈16%)
C3	UNIMAX®	Cryogenic Treatment in TAYLOR WHARTON™ 10K-M505K.	3,594 (≈-4%)	23,4 (≈-3%)

Appendix 8 – SR Measurements.