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Surface quality after EDM cutting and qualification of damaged layer removal

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Abstract
This study describes the qualification of damaged layer removal after die-sink Electrical Discharge Machining (EDM) and wire EDM cutting to reach the high surface quality. Stainless steel, aluminium, copper OFE and niobium are the materials widely used within the accelerator applications. The requirements on their surface quality are very strict and therefore the thermally affected layer due to EDM should be removed. The objective of this work was to define the damaged layer thickness and to qualify the etching methods for its removal. The Scanning Electron Microscopy (SEM) and Focus Ion Beam (FIB) technique were used to determine affected layer depth and to confirm afterwards its chemical etching removal. The surface roughness measurement was realised to evaluate the final surface quality after the EDM and the chemical etching.

EDM cutting, niobium, white layer, chemical etching

1. Introduction

EDM is a non-traditional electro-thermal cutting technique based on erosion of the workpiece material using a successive discrete discharge between the electrode (wire or die electrode) and workpiece in dielectric liquid [1]. During the EDM cutting the surface is strongly heat-affected and a so-called white layer is generated [1]. The white layer is the fast melted and fast cooled surface layer which is not heated enough to be removed between the wire electrode and the workpiece. Its topography and metallurgical structure are changed and it can contain voids, cracks and some ejected particles that have been re-deposited on the surface (Figure 1). Each material exhibits different behaviour and the aspect and thickness of damaged layer as well. The EDM surface quality was examined on stainless steel 316LN, aluminium EN AW 6082, Oxygen Free Electronic copper (OFE) (C10100) and even on the difficult-to-machine metals such as pure niobium RRR300. Niobium is widely used for superconducting radio-frequency applications, e.g. acceleration cavities, higher-order mode (HOM) couplers.

The reason of EDM damaged layer removal is the same for all tested materials: recovery of bulk metal properties and microstructure as before manufacturing process. In case of stainless steel, the etching of damaged surface layer improves cleanability and wettability and reduces the adhesion of impurities and water outgassing due to the reduction of the intrinsic surface [2] and eliminates residual stresses in recast layer due to shrinkage. For niobium, the surface quality is essential in term of radio-frequency (RF) application. The smoothness and damaged-free surface is very important because any sharp topographic features or microstructure changes (porosity, cracks) can cause non-field-emitter quenches that contribute to higher surface resistance and to quality factor drop of SRF parts [3, 4]. The same requirements are on copper RF accelerating parts. In case of aluminium, any changes in recast damaged layer can affect mainly hardness and corrosion resistance so its removal is also preferable [5].

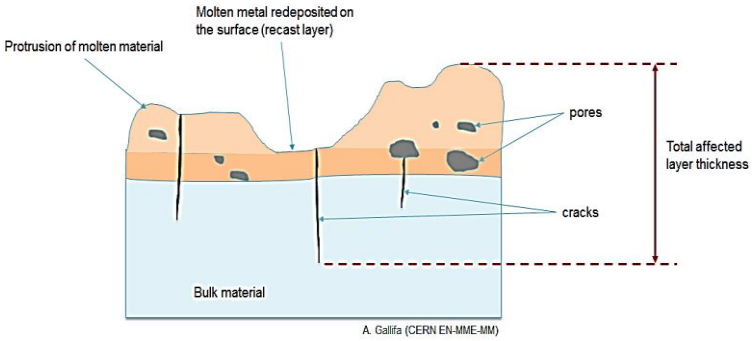


Figure 1. The representation of white layer features.

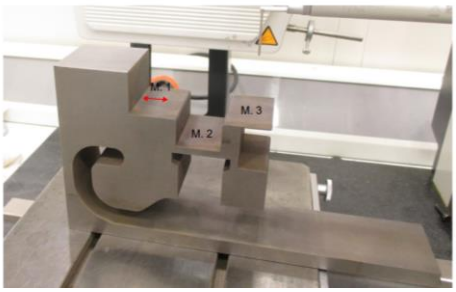
The objective of this study was to define the white layer thickness formed after EDM cutting and to qualify the etching methods for its removal.

2. Material and Method

Four materials were chosen for the EDM evaluation: stainless steel 316LN, OFE copper, aluminium EN AW 6082 and niobium RRR300. The samples dimensions were about 80 x 30 x 8 mm. The die EDM machine FORM P600 Agie Charmille was used with the copper electrode of diameter 15 mm (Figure 2a). For wire EDM cutting of additional niobium samples the Charmille ROBOFIL 501 machine was used with copper wire of diameter ø0.25 mm (Figure 2b).

The surface roughness was measured by contact probe device according to ISO standard 25178. Figure 2 shows the areas of interest and the measurement direction. The mean arithmetic roughness (Ra) and the maximum roughness (Rz) were evaluated. In case of niobium, SEM and FIB technique, were used to evaluate the surface structure and the white layer thickness. The metallography was also realised on the inclined wire EDM cut Nb sample to confirm the thickness of damaged layer.

a)



b)

Figure 2. The Surface roughness measurement by the contact probe device: a) stainless steel and copper OFE specimen cut by EDM electrode machine and b) Niobium block cut by wire EDM (dimensions 200 x 100 x 40 mm).

Subsequently, the etching method specific for each material were investigated. The etching techniques were chosen according to best practice at CERN. The common method of stainless steel chemical finishing technique is electropolishing (EP) with mixture of sulfuric and phosphoric acids. Then, for the copper OFE the SUBU (mixture of sulfamic acid, hydrogen peroxide, n-butanol and ammonium citrate [6]) etching were realized. The Aluminium underwent the etching by NaOH. For niobium, the Buffer-chemical polishing (BCP) etching composed of phosphoric acid (H3PO4, 85 vol.-%), nitric acid (HNO3, 60 vol.-%), and hydrofluoric acid (HF, 40 vol.-%). The removed thickness was 20 µm.

3. Results

3.1. Die EDM cutting

The Table 1 summarises the surface parameters for individual materials and makes a comparison of surface parameters after die EDM and after die EDM & chemical etching. The process parameters of die EDM machine were set-up to get the best surface finish (Ra < 1.0 µm). As shown in Table 1, only the stainless steel and copper OFE roughness were lower then 1.0 µm after EDM. But even the niobium and aluminium resulted in very suitable Ra < 1.6 µm.

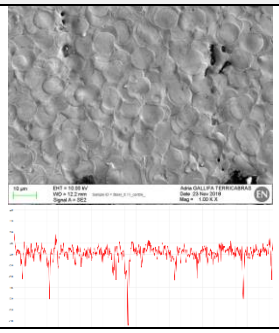
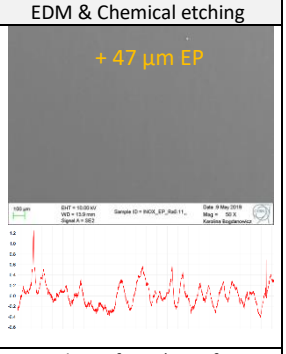
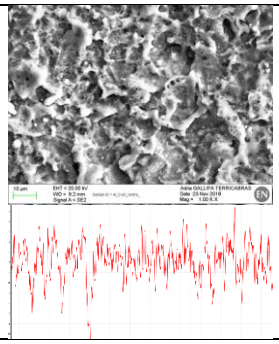
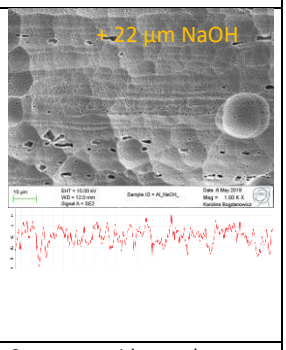
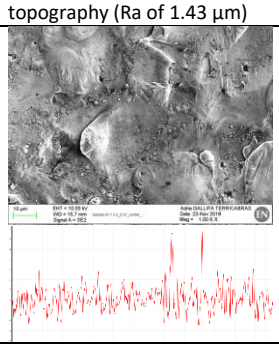
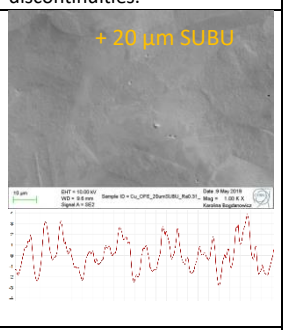
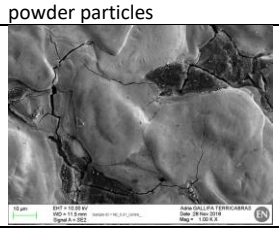
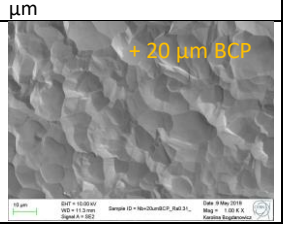
After chemical etching of EDM surfaces, the stainless steel EP improved the surface roughness in term of Ra by 40 % and Rz more then 70 %. The niobium roughness was also significantly improved after BCP about Ra of 0.88 µm. The Ra of aluminium remained equal after NaOH treatment, but in case of Cu OFE the surface roughness got worse from 0.87 µm to 1.15 µm.

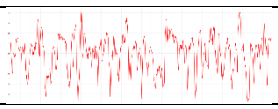
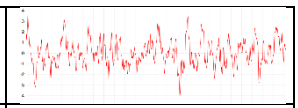
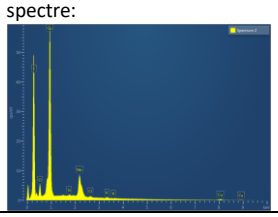
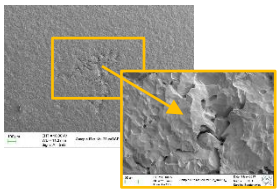
Table 1 Surface topographic parameters after die EDM and after die EDM & Chemical etching.

	Die EDM		Die EDM & chemical etching	
	Ra [µm]	Rz [µm]	Ra [µm]	Rz [µm]
316LN	0.31	4.07	0.18	1.17
Al 6082	1.43	9.64	1.46	9.75
Cu OFE	0.87	7.02	1.15	5.6
Nb	1.27	7.82	0.88	6.37

In Table 2, there is an scanning electron microscopy (SEM) evaluation of the damage layer with main surface features for each material before and after etching.

Table 2 The comparison of EDM damaged layers before and after chemical etching.

	EDM	EDM & Chemical etching
316LN		
	Cracks, round features surface, embedded and powder particles on the surface.	Smooth surface (Ra of 0.18 µm) , no inclusions or cracks.
Aluminium AW EN 6082		
	Craters, porosity, higher topography (Ra of 1.43 µm)	Craters, voids and some discontinuities.
Copper OFE		
	Dark spots and embedded powder particles	Wavy surface with Ra of 1.15 µm
Niobium		

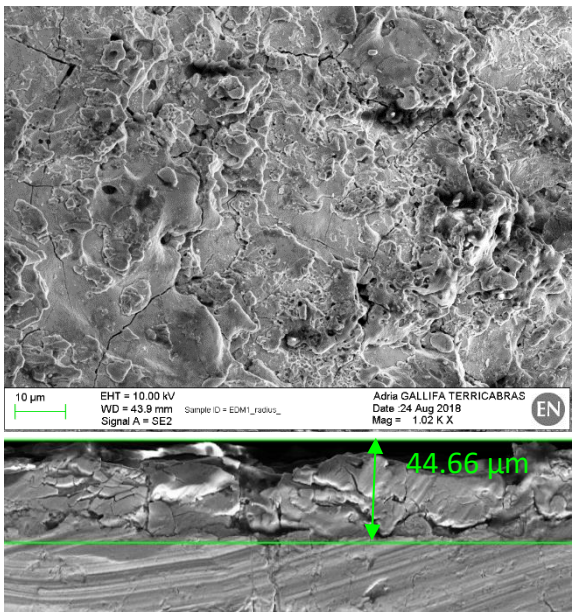
		
	Cracks, dark spots, embedded powder particles – Copper electrod traces with EDX spectre: 	Visible grains border. In centre a detachment was observed. 

The chemical etching of 20 - 45 µm removed the damaged layer for all materials.

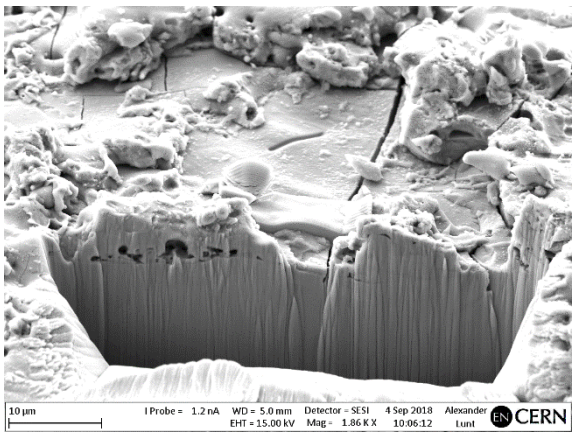
3.2. Wire EDM cutting

The additional tests by wire EDM for niobium material were realized because of frequent application in Superconductive radio-frequency (SRF). In this case, the wire EDM average from five measurements Ra was about 2.96 ± 0.02 µm and Rz 21.49 ± 0.48 µm. After subsequent BCP, the surface roughness was improved by more than 50 % with Ra = 1.55 ± 0.10 µm and Rz = 13.57 ± 3.14 µm.

The SEM observation showed a slightly higher damaged layer thickness than in case of die EDM cutting. Figure 3a) shows a top-view and a cross-section view of wire EDM rough surface with visible white layer of 30 – 60 µm. According to FIB observations the cracks propagates in the depth of 5 µm under melted layer (Figure 3b)). An additional macroscopic method, the metallography using a tilted sample analysed by optical microscope, was used to confirm the total white layer thickness around ~ 50 µm. Therefore the BCP removal was increased to 80 µm (with security margin) and the damaged-free surface is presented in Figure 3c).



a)



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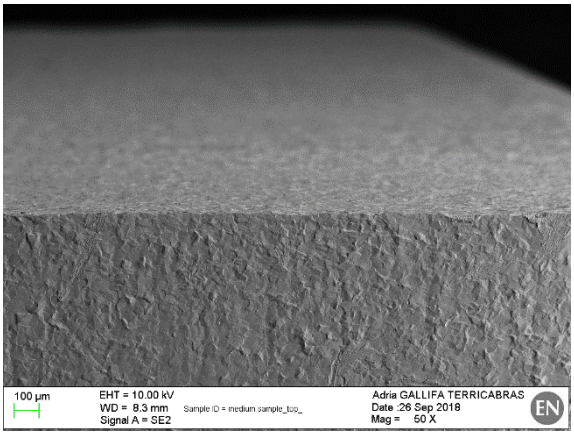

c)

Figure. 3 The SEM and FIB representations of Nb damaged layer after wire EDM: a) SEM top-view and cross-section view of white layer whit cracks, overlapping surface craters, plastic deformations, porosity, rubbing and cavitation patterns; b) FIB of crack depth propagation and c) The Nb specimen after 80 µm od BCP – no damaged layer.

4. Discussion

For the stainless steel and niobium, the chosen etching method were suitable in term of the damaged layer removal and the improvement of surface roughness which was the main goal of this study. Nevertheless, the SUBU etching of copper OFE generated higher surface topography and the investigation of EP method should be carried out in the next step for the copper. The NaOH etching of aluminium left some small porosities and craters on the surface which may be due to insufficient etching or the etching process itself. Therefore a futher investigation of aluminium surface treatment might be studied more closely.

5. Conclusion

The EDM damaged layer had different features for individual materials:

- Stainless steel: round recast topographic features;
- Aluminium 6082: High non-uniformity with craters and voids with over-lapped discontinuities;
- Copper OFE: Powder particles dispersion over the surface with impurities traces;
- Niobium: Cracks, porosities and copper electrodes traces.

The chemical etching of 20 µm removed damaged layer caused by die EDM in all materials, except of aluminium where the further investigation of the etching effect might be followed. The wire EDM of niobium requires higher BCP etching around 80 µm. The very significant surface roughness improvement was

observed for stainless steel and niobium. The aluminium Ra and Rz did not change after NaOH treatment and copper OFE resulted even in slightly worse surface roughness after SUBU attack.

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