Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia CIRP 6 (2013) 89 – 94

www.elsevier.com/locate/procedia

The Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM)

High precision electro discharge machining of Molybdenum and Tungsten

R. Demellayer*, J. Richard

University of Applied Sciences Western Switzerland
technology, architecture and landscape, hepia, 4 rue de la Prairie, CH 1202 Genève
Corresponding author. Tel.: +42 22 546 26 37;.*E-mail address*: rene.demellayer@hesge.ch ;jacques.richard@hesge.ch;.

Abstract

Refractory metals are known to be difficult to machine. Nevertheless, their mechanical or electrical characteristics are interesting for many industrial advanced applications. The research of methods to manufacture the electrodes in Molybdenum for the future "CLIC" accelerator at CERN has provided a pretext to study these issues. Click accelerator cavities are characterized by extreme quality objectives (dimensional precision < 1 µm, surface roughness Ra < 0.05 µm).
We have studied mainly the machining of Molybdenum and Tungsten; we have noticed that the choice of the dielectric was crucial for the Molybdenum. The formation of Molybdenum oxide prevents machining. The solubility of Mo in water also brings out problems of corrosion. This requires that these materials must be machined in oil.
Frost heaving of grain from this compacted material is also a long term problem.
The refractory materials behavior remains problematic due to the peculiar cracking, as “alligator cracks”, “lizard skin” or “crazing” that appears on the surface. The difference between cracking and “Crazing” is mentioned. Furthermore, this «Alligator cracks» phenomenon also appears in the case of samples Molybdenum submitted to strong and high frequency electric fields. This badly-known phenomenon endangers the use of molybdenum in CLIC accelerator.

Selection and/or peer-review under responsibility of Professor Bert Lauwers

Keywords: EDM; Molybdenum;Tungsten; Lizard skin;Alligator cracks, Crazing, Roughness;CLIC

1 Introduction

Refractory metals are known to be difficult to machine. Nevertheless, their mechanical or electrical characteristics are interesting for many industrial advanced applications. The research of methods to manufacture the electrodes in molybdenum for the future "CLIC" accelerator at CERN has provided a pretext to study these issues. This topic is the center of a research project managed by the University of Applied Sciences Western Switzerland: UMRePMi (Usinage Matériaux Réfractaire Précision Micrométrique). It should be noted here that these Click accelerator cavities are characterized by extreme quality objectives (dimensional precision < 1 µm, surface roughness Ra < 0.05 µm).
A part of this project was devoted to the high speed milling, but is not described here.
For the EDM project part, the study of the characterization of the machining of the molybdenum and tungsten highlighted that the choice of the dielectric was crucial for the molybdenum. Indeed the formation of molybdenum oxide surface significantly disrupts machining. The solubility of molybdenum in the water also brings out problems of corrosion. This involves that these materials must be machined in oil.
Frost heaving of grain from this compact material is also a long term problem.
Unfortunately the refractory materials behavior remains problematic due to a special cracking, named “alligator cracks”, “lizard skin” or “crazing”, that appears on the surface. The difference between cracking and “crazing” is mentioned. Significant thermal stresses occurring following the implosion of the spark are probably responsible for that. Furthermore, this «alligator cracks» phenomenon also appears in the case of samples molybdenum submitted to strong and radio frequency electric fields. Thus, this not well-known phenomenon can result from various origins and

Selection and/or peer-review under responsibility of Professor Bert Lauwers
doi:10.1016/j.procir.2013.03.030

this is a point that certainly endangers the use of molybdenum in CLIC accelerator.

Nevertheless, that opens a field for further investigations. An interesting study would be to seek what are the link between the parameters of mechanical strength, thermal conductivity, melting temperature and the “crazing” mechanism.

We had the opportunity to test mainly molybdenum and tungsten with some number of samples. Only two samples of niobium has been machined, previously to this study, with the same results.

The methodology to machine at high precision the cavities has been investigated. A mix of wire and dye sinking on the same machine has been tested.

2 Electro Erosion Machining

2.1 *EDM machines used in this survey.*

It is common to class EDM machines in two main types, Die Sinking and Wire. For the project we investigate non standard EDM machining situations and we consider separately dielectrics, (water/oil/silicon oil), machines types (wire/die sinking), electrodes (Cu,CuW) and EDM generators. For the die-sinking machining we used the copper / tungsten carbide settings with the copper / steel polishing settings added for fine roughness.

We have also used a special generator with impulses as short as 200 ns

2.2 *Machining methodology*

The CLIC cavities have mainly rotation symmetry. The cavities are an assembly of four identical parts. A simplified ¼ cavity is shown in [Fig 1].

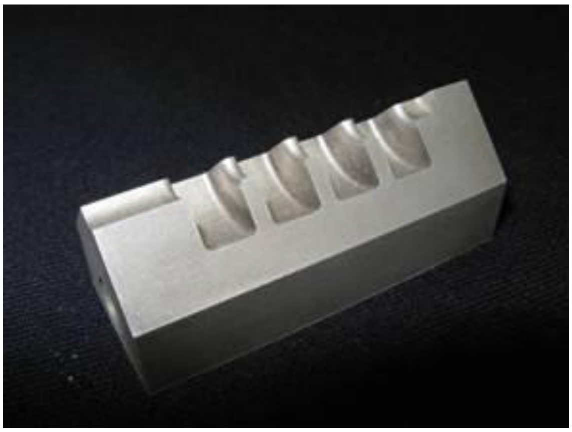

Fig.1. *Element (1/4) of a simplified accelerating cavity, EDM machined. Cavity length is 50mm, molybdenum*

To maintain symmetry, we use electrodes in slow rotation [Fig 2]. The other effect of this rotation is to increase the surface quality and decrease the Ra. The electrodes are profiled on the same die-sinking machine by an auxiliary EDM wire system mounted on the same table [Fig 3], so to avoid re-positioning errors inherent to multi machines machining.

Fig. 2 *Rotating electrode*

For the die-sinking machining we have used the copper / tungsten carbide settings with the copper / steel polishing settings added for fine roughness.

For wire EDM machining we have used zinced brass /steel settings.

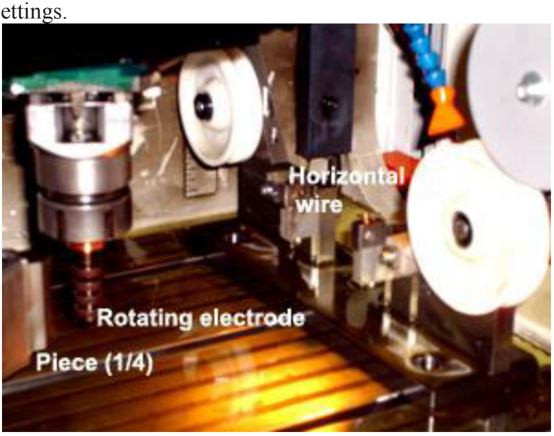

Fig. 3 Machining on a die sinking machine

The cavity is fixed on the machine table and the electrode on the machine spindle. With a good thermal stabilization of the room and the machine, good accuracies can be obtained.

The nominal shape of the electrode can be easily modified (wire cut) to compensate the geometrical defects observed when machining the cavity in order to obtain the accuracy needed.

Because of the disappointing surface quality obtain on molybdenum this optimization was not fully made and stopped at an overall accuracy of 25 µm [Fig.4]. This accuracy is in the order of completive methods.

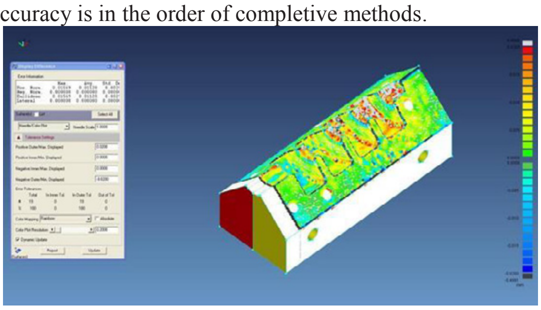

Fig. 4 *Optical 3D control of a machining test*

2.3 *Surface quality survey*

Very fine surface qualities are obtained with light and short pulses. The quality of the recast layer is also an important factor to obtain a good and fine surface on EDM. As seen in [Fig 1] wire machining is impossible according to the radial symmetry, but we tested it for completeness.

We have investigated surface quality by changing the main machining process as systematically as possible.[Table 1]

Graphite electrodes can form carbides incompatible with high electric field (~400MV/m)

Silicon oil had been rejected, as too difficult to clean for an accelerator.

	Water (Ra µm)		Oil (Ra µm)	
	Wire EDM	Die Sinking EDM	Wire EDM	Die Sinking EDM
Mo	X 0.2*	X bad	X 0.22	X 0.5
W	X 0.6	X 0.6		X 0.6
W mono-crystal	X 0.5			X 0.4
Nb				X

Table 1. Machining process tested, red ones generate oxides not compatible with CLIC application. The Ra in µm is shown.

We have observed problems machining molybdenum in water. Molybdenum is solvable in water with a typical color: molybdenum blue.

For wire EDM in water the process is more ECM than EDM, with molybdenum oxides on the surface.

The die sinking process in water degenerates rapidly with formation of a black conductive tar.

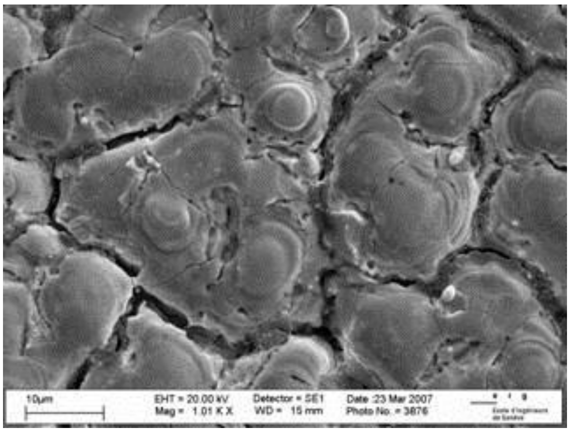

Fig. 5 *Crazing and cracking on molybdenum. Die sinking EDM*

Machining molybdenum in water create a dark tar difficult to evacuate from the gap. Electrolysis also can be observed. This electrolysis allows the best roughness from this survey by a form of ECM. The ECM way is not allowed in our case, because it induce chemical contamination.

Fig. 6 *Heavy cracking on steel machined for demonstration by EDM*

Machining molybdenum with water we can see formation of dichroïc layers of molybdenum oxides [Fig. 8]. These oxides are incompatible with the high electric field in the accelerator.

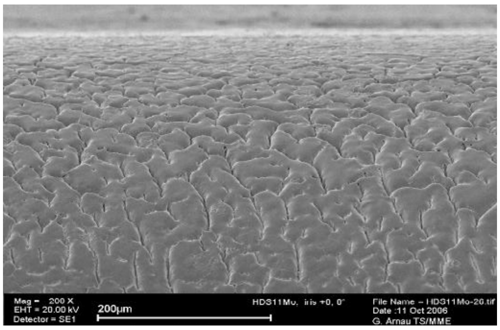

Fig. 7 Crazing of molybdenum in an accelerating cavity (CERN)

2.4 *Crazing versus Cracking.*

We always observe a higher roughness than expected, by analogy with steel machining.

The observation of different surfaces brings us to make an important distinction between "crazing", (alligator cracks) and cracking [Fig 5].

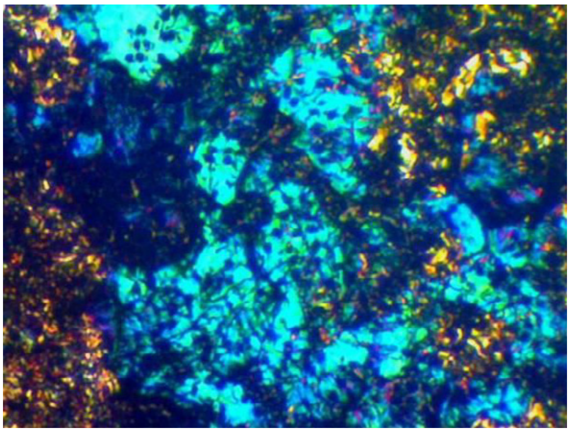

Fig. 8 *Machining molybdenum with die sinking EDM in water creates a dicroïc layer of oxides*

Cracking is a well known side effect of EDM. The important point for the explaining the birth of cracks is the volume difference of austenitic and martensitic crystals present in bulk and white layer, especially for steel.

We have observed a different crazing according of the crystallization of the metal, poly-crystalline [Fig 9] or mono-crystalline [Fig 10]. In [Fig 5] crazing occurred on pure Molybdenum and some cracks are visible on the "islands" of metal.

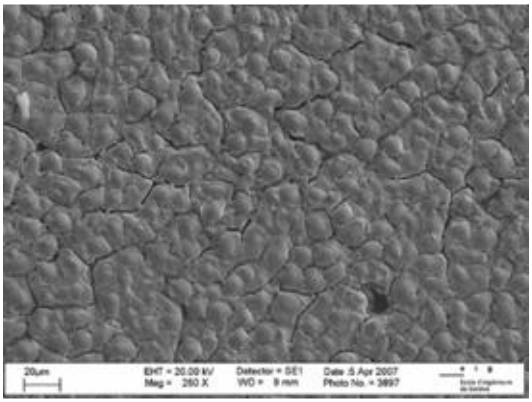

Fig. 9 *Example of crazing in tungsten (powder technology).Die sinking EDM*

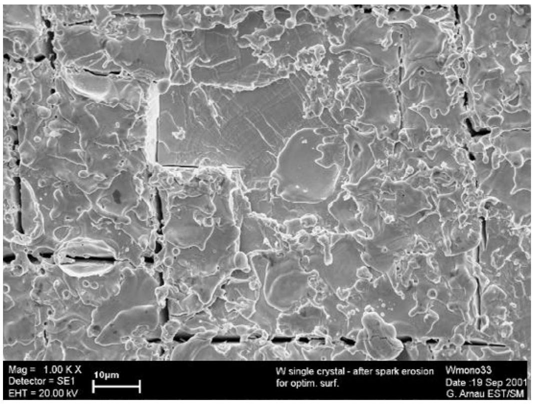

Fig. 10 *Crazing of mono criustaline tungsten with metal bridges. Die sinking EDM*

Recast metal bridges are visible showing that the formation of this net is a complex process. The [Fig.11] is an example of crazing on mono-crystalline Tungsten (body centered cubic). When the white layer is removed by a mechanical polishing, the crazing net stays under. Cracks generally don't propagate under the white layer

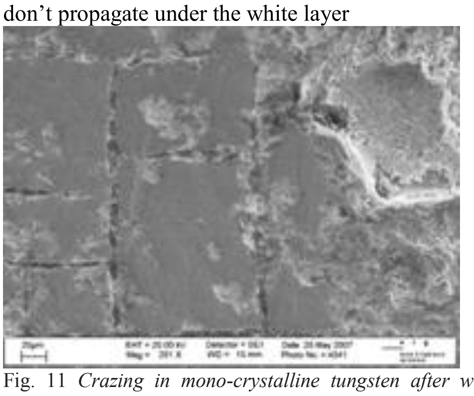

Fig. 11 *Crazing in mono-crystalline tungsten after white layer removal*

Crazing is a structural response of metals with high fusion point, at a thermal stress. [Fig. 12]

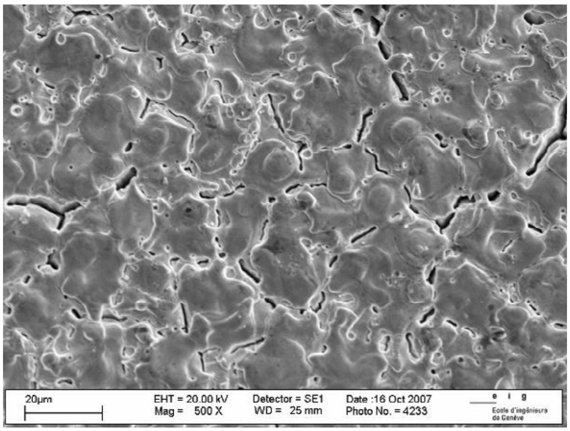

Fig 12 Crazing when finishing molybdenum (200V 200ns 5 A). Metal bridges filled crazing ditches. Die sinking EDM

In case of steel this defect is rarely identified [Fig. 13]. Up to now, these were no necessity to distinguish crazing from cracking. Both of them are defects related with EDM, and no investigation had been made to separate these defects for a better understanding of their origin. The crazing net is overcast with recast metal in most cases. Crazing is not observable with high and medium energy EDM machining. Sometimes "alligator cracks" or "orange skin" are reported without deep observations.

Other observations are reported as consequence of heavy thermal cycling on steel molds.

Undetected crazing can be the origin of low fatigue withstanding of some EDM parts unexplained up to now.

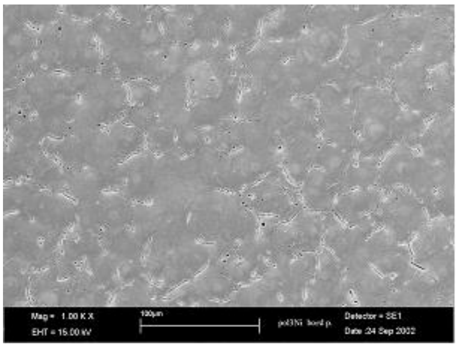

Fig.13 *Crazing on steel no identified in 2003 (FLEW-Ref.[8]). Die Sinking Polishing EDM*

It will be helpful to plan a study of crazing origins on metals, like for crazing on earthenware. The explanations for earthenware are not fully convincing and rather concerns the origins of cracks.

2.5 Standard Die Sinking machining

We have machined by Die Sinking surfaces of Molybdenum, Tungsten and Niobium in oil with Cu and Cu/W electrodes. We obtained Ra between 0.6 to 1µm.

On steel, the machine settings give Ra in order of 0.1µm. This smooth and fine recast steel layer is present with these settings. With high melting temperatures metals this layer is not formed and roughness is greater than for steel.

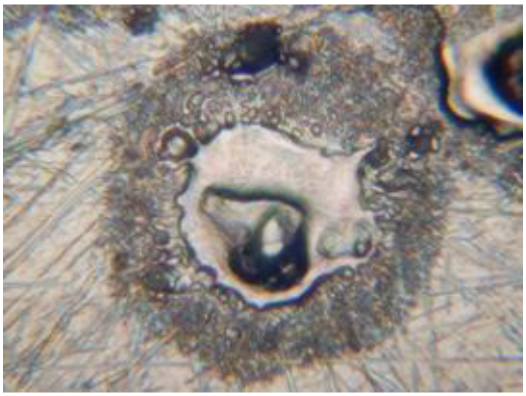

Fig 14 *Radial evacuation of metal with steel*

2.6 *Metal evacuation*

In conventional EDM steel machining the liquid metal is evacuated from the crater periphery as seen in [Fig. 14]. With refractory metals studied here the evacuation is done in the center of the crater [Fig. 15]. As remain of this evacuation a spiraling tip stay in the crater center. This particularity had already been seen in laser machining (so called Marangony effect). Added to the crazing these tips produce a rough surface, explaining bad Ra values.

2.7 *Die sinking with short pulses*

We have also used a special EDM generator from ACT with pulses in the order of 100ns. We machined molybdenum and mono-crystalline tungsten with Ra between 0.5 to 0.6 µm. Crazing is still present on these machinings.

We have finished by EDM a mechanical roughed molybdenum surface. The Ra is better with 0.4 µm and without crazing. The improvement in Ra is a consequence of the absence of crazing.

2.8 *Water Die Sinking machining.*

As a consequence of the solubility of molybdenum in water, molybdenum machining is not repeatable and difficult. We obtain magnificent dichroïc layers of molybdenum oxides incompatible with the high electric stress applied on the cavities. With tungsten machining is good.

2.9 *Wire EDM machining. Zn coated wires.*

Despite the presence of oxides, we have machined surface of Mo. The machining is difficult and electrolysis is great. We have obtained the best roughness of this survey: 0.2 µm. Due to the geometrical aspects of the cavities and the oxide layers this solution is not suitable for this application.

ACT has machined a piece for this study with a wire machine with oil dielectric. The result is good with a Ra of 0.22 µm.

2.10 *Material integrity.*

At this state of the survey, some molybdenum samples are 6 to 12 months old. We see that the EDM machined parts show formation of cavities. We observe that grains progressively cleave. The Mo and W sample are made by powder process. The porosity of these samples is very high, greater than 99.5 %. But grains are not fully glued each other. This defect shows a potential problem with Mo EDM machined parts.

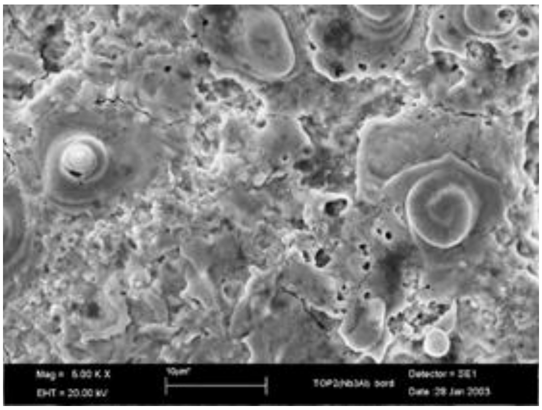

Fig. 15 *Central metal evacuation with niobium .Die sinking EDM*

3 Conclusion.

Refractory metals are difficult to machine by EDM to the surface roughness need, Ra ≈ 0.05µm. The best roughness obtained is 0.22 µm by Wire EDM not suitable for the geometries expected.

This study reveals misunderstood aspects of EDM like "crazing" and Marangony effect. This opens field for further investigations. The fatigue life is one of these important features.

As for Mo, this "crazing" appears also under high frequency and strong electric fields stress, as this "crazing" appears also with other materials, an interesting study would be to seek, from a fundamental point of view, what are the link between the parameters of mechanical strength, thermal conductivity, melting temperature and the "crazing" mechanism.

For CERN accelerator, the solution is to lower the working frequency, with less electrical stress. In this case bigger cavities can be made of Cu/Zr alloy.

4 Acknowledgements.

The authors thanks G. Waelder, M. Stücki from ACT for their help and M. Taborelli, S.Sgobba from CERN for their contribution to this survey

5 References.

[1] A. Descoeudre, Characterization of Electrical Discharge Machining Plasma Ph.D. thesis n°3542, EPFL 2006..

[2] B. Bommeli. Etude de la contamination sur l'amorçage des décharges dans les diélectriques liquides Ph.D. thesis n°1892,. Faculté des Sciences de l'Université de Genéve 1979

[3] D.DiBitonto, P.T. Eubank,M.R. Patel,M.A.Barrufet, (part 1 et 2) J.Appll. Phys.66,4095.1989.P-T.Eubank,M.R.Patel,M.A.Barrufet,B.Bozkurt (part 3), J. Appl. Phys. 73,79900,9993.

[4] D.DiBitonto, P.T. Eubank,M.R. Patel,M.A.Barrufet, (part 1 et 2) J.Appll. Phys.66,4095.1989.P-T.Eubank,M.R.Patel,M.A.Barrufet,B.Bozkurt (part 3), J. Appl. Phys. 73,79900,9993.

[5] F Dijck, "Physico-Mathematical Analysis of Elrectro Discharge Machining Process" Ph.D thesis. Katholieke Universiteit Leuven, Belgium, 1973.

[6] N. Mohri, M.Suzuki,N.Saito, Toyota Technological Institute ISEM XI.

[7] K.Kobayashi, Misubishiu Electric Corporation ISEM XI.

[8] R.Demellayer, F.de Mestral,hepia, R. Perez, ACT, R.Fluckiger, R Cusanelli Uni.Genève, Fatigue Life of EDM improved micro-alloyed White layer , KTI/CTI program report n°7396.2, 2008

[9] P.Bleys,J.P. Kruth,B. Lauwers,B. Schacht,V. Balasubramanian, L.Froyen,J.Van Humbeek,Surface and sub-surface quality of steel after EDM,Advanced Engineering Materials 2006,8,n°1-2

[10] J.P. Kruth,L.Froyen, L.Stevens,P.Dejonghe. In-procees alloying of write layer of a workpiece machined by die-sinking EDM. International journal of Electrical Machining 3:33-38, 1998

[11] R.Delpretti. Physical and chemical characteristics of the superficial layers. Proc. of 5th Int. Symposium for Electro-Machining,pages 209-212,Wolfsberg,1977