Simulation of the Current Density Distribution and the Material Removal Behavior on the Graphite/Iron-Matrix Interface in Cast Iron under Pulse Electrochemical Machining Conditions

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INTRODUCTION

Pulse Electrochemical Machining (PECM) is an unconventional procedure combining pulsed current and pulsed cathode feed rate (Figure 1), being very suitable for high precision production in series manufacturing. The main advantage compared to conventional electrochemical processes is that the current pulse is only triggered when the efficiency is at its maximum, i.e. at the bottom dead center. This allows reaching smaller gaps (between 10 and 30 micrometers) than by other electrochemical processes, which means more accuracy [1]. Besides, during the pulse off-time the electrolyte in the interelectrode gap is refreshed by the removal product free electrolyte, which guarantees an optimal electrochemical removal condition for each new current pulse.

However, the graphite phase cannot dissolve because it is electrochemically inert, and as iron is more electrically conductive as carbon, boundary effects appear on the iron/graphite interface. The electrical field is modified and hence the local current density [2], leading to inhomogeneous metal removal and thus poor surface integrity (Figure 2). Since so far no comprehensive scientific description is available for this mechanism, the PECM of cast iron is currently not industrially established.

One major parameter influencing the dissolution process is the current density distribution. However, it is hardly to predict and cannot be measured experimentally. This paper presents a developed tridimensional transient model which will help predicting this distribution and thus the material removal behavior of cast iron. This will allow for choosing the optimal process conditions to obtain the desired surface quality.

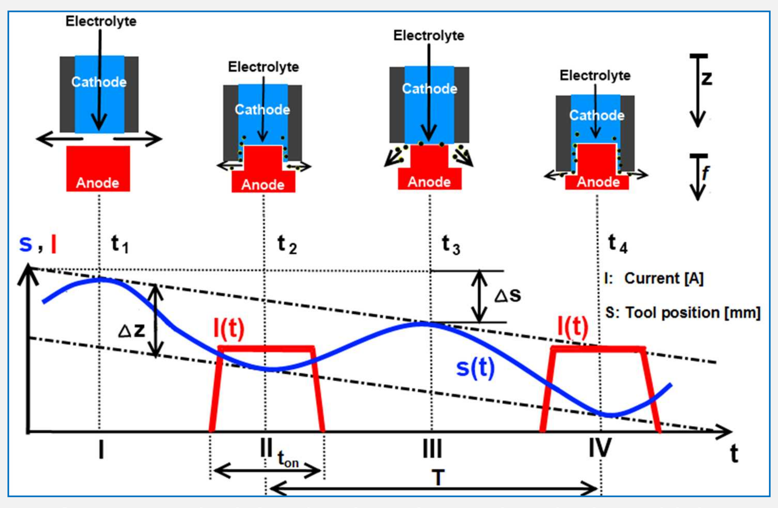

Figure 1. Principle of Pulse Electrochemical Machining

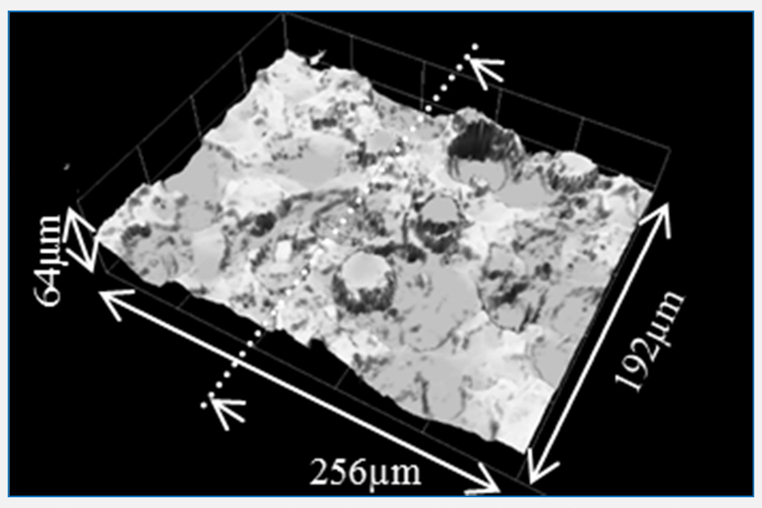

Figure 2. Topography of a machined cast iron surface

PROBLEM FORMULATION IN COMSOL®

MATHEMATICAL MODEL

EXPRESSION	DESCRIPTION
$\vec{v}_n = displ(x,y) \cdot \eta \cdot \frac{M}{z_A \cdot \rho \cdot F} \cdot \vec{J}_n$	**Faraday's law of electrolysis** linking the current density with the material removal rate
$displ(x,y) = 0 \cdot (Im1(x,y) < 0.37) + 1 \cdot (Im1(x,y) \geq 0.37)$	**Mesh displacement function** based on the imported image properties allowing material removal except of graphite
$\sigma_{local} = \sigma_{graphite} \cdot (Im1(x,y) < 0.37) + \sigma_{iron} \cdot (Im1(x,y) \geq 0.37)$	**Electrical conductivity import** via the image-to-material function
$\nabla.\vec{J} = -\nabla.\left[\left(\sigma_{local} + \varepsilon_0\varepsilon_r \frac{\partial}{\partial t}\right)\nabla\varphi - \vec{J}_e\right] = Q_j$	**Maxwell equation** for current density distribution

PARAMETER VALUES

SYMBOL	VALUE	DESCRIPTION
η	100%	Current efficiency [2]
M	55.85g/mol	Molar mass
z_A	3	Valency
ρ	7,920kg/m³	Mass density
F	$9.65 \cdot 10^4$C/mol	Faraday constant
$\sigma_{graphite}$	$3.00 \cdot 10^6$S/m	Graphite conductivity
σ_{iron}	$10.02 \cdot 10^6$S/m	Iron conductivity

BOUNDARY SETTINGS

BOUNDARY	CONDITION
1-4	$\vec{n}_A \cdot \vec{J}$
5	$\varphi = 0V$
6	*Continuity*
7-10	$\vec{n}_A \cdot \vec{J}$
11	*Continuity*
12-15	$\vec{n}_A \cdot \vec{J}$
16	$\varphi = 10V$

PROCESS CONDITIONS

SYMBOL	VALUE	DESCRIPTION
f	0.1mm/s	Tool/Cathode feed rate
Δz	373µm	Tool/Cathode peak-to-peak vibration amplitude
T	20ms	Tool/Cathode vibration period
t_{on}	5ms	Electric current pulse on-time

MODEL SET-UP

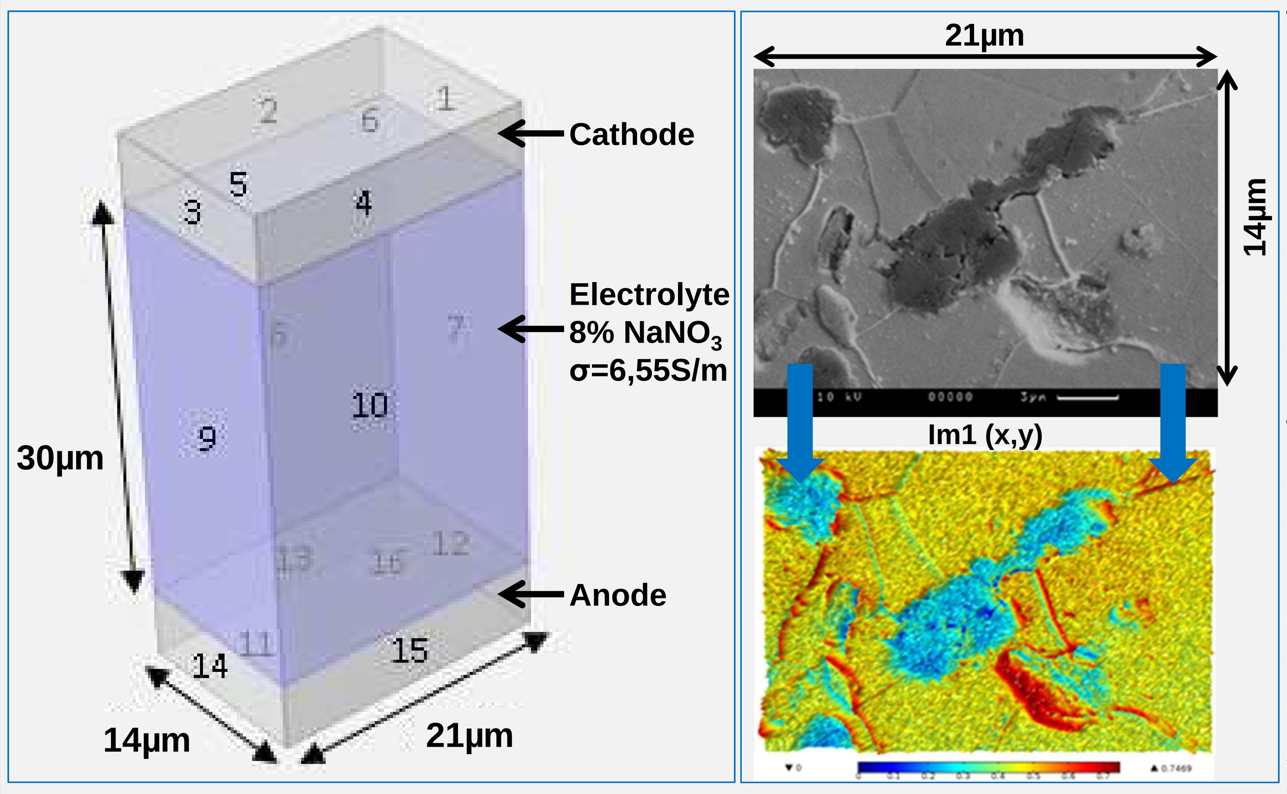

Figure 3. Geometry implemented in COMSOL Multiphysics® 4.2a

The geometry of the model was defined as two parallel plates separated by electrolyte. The implemented gap of 30µm corresponds to the initial gap used in the experiments.

To accurately simulate the anodic dissolution conditions, the gray cast iron microstructure was characterized by scanning electron microscopy and directly imported into the simulation model via the "image-to-material" function (Figure 3).

RESULTS ANS DISCUSSIONS

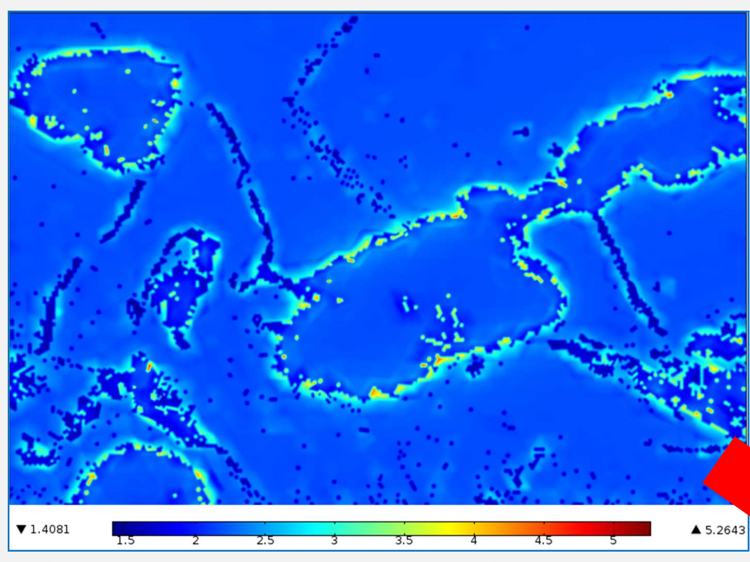

Figure 4. Simulated current density distribution (A/mm²)

The result highlights a restricted current density amplification on the interface graphite/iron-matrix (Figure 4). This localized phenomenon is due to the discontinuity in electrical conductivity between graphite and iron as well as to the graphite geometrical irregularities, which locally influence and increase the electrical field and thus also the current density.

The local current density increase induces a preferential material removal on the graphite/iron interface (Figure 5). As graphite cannot dissolve, the generated higher current is only employed to remove the matrix leading to crater formation.

These craters are responsible for a surface integrity deterioration, implying reduced mechanical characteristics after machining.

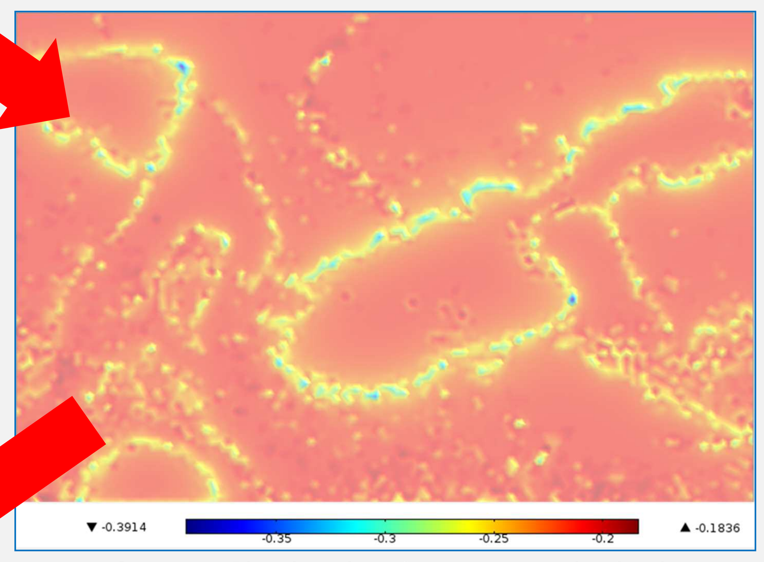

Figure 5. Simulated surface topography (µm)

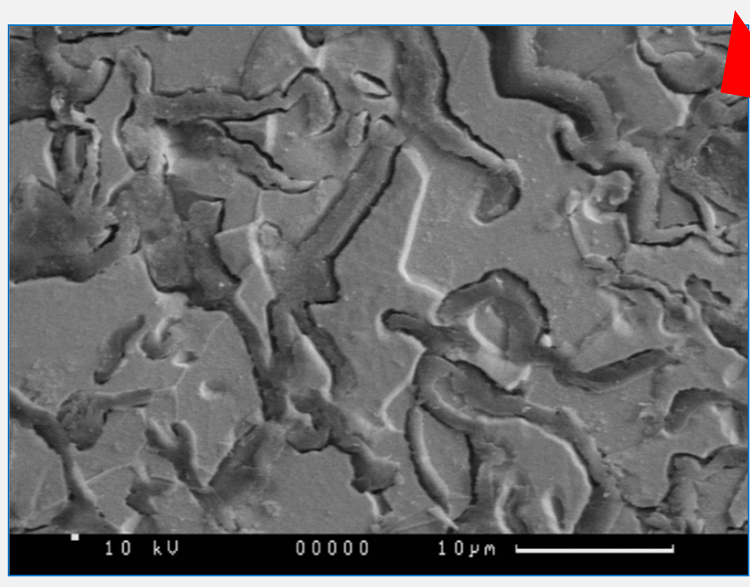

Figure 6. Machined gray cast iron microstructure

The simulation corresponds to the obtained experimental results. Figure 6 shows crater formation on the graphite/iron interface after machining.

An iterative variation of the process parameters in the simulation will help to identify the optimal machining conditions avoiding this phenomenon or limiting it to a minimum.

CONCLUSIONS

- COMSOL Multiphysics® 4.2a was used to model the current density distribution and the material removal behavior on the graphite/iron-matrix interface in cast iron under Pulse Electrochemical Machining conditions
- Local current density amplification appears on the graphite/iron boundary leading to enhanced material removal
- Simulation and experiments show a good accordance. The model can be employed to predict the surface topography
- Mesh and geometry do not allow the simulation of a longer process, improvements and the application of remeshing are necessary

REFERENCES

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