# 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

Olivier Weber*[1], Rouven Kollmannsperger[2], Dirk Bähre[2]
[1] Center for Mechatronics and Automatization, Saarbrücken, Germany
[2] Institute for Production Engineering, Saarland University, Saarbrücken, Germany
* Gewerbepark Eschberger Weg, D-66121 Saarbrücken, olivier.weber@mechatronikzentrum.de

**Abstract:** The Pulse Electrochemical Machining is especially suitable for the precise production of complex geometric contours with high precision and high surface quality demands in workpieces in series manufacturing. During this process, the negative structure of an electrode is copied to the workpiece without sub-surface damages. An adequate knowledge of the current density distribution and thus of the material removal behavior is required to plan the process according to the material properties and to effectuate surface qualities suitable for industrial applications.

Therefore, a simulation model was implemented and developed in COMSOL Multiphysics® in order to identify the optimal process conditions. The cast iron microstructure was directly imported using the image-to-material function.

**Keywords:** Pulse Electrochemical Machining (PECM), Cast iron, Material removal, Graphite/Iron Interface

## 1. 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 for reaching smaller gaps (between 10 and 30 micrometers) than in 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.

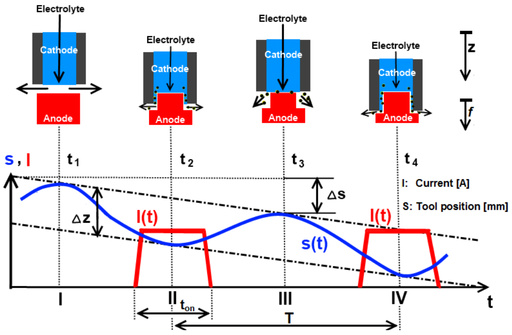

**Figure 1:** Principle of Pulse Electrochemical Machining

PECM is a fast technology for creating complex tridimensional geometries without any thermal and mechanical impact on the workpiece surface and regardless of the material's hardness, as the process occurs on atomic level.

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 influencing parameter of the dissolution process is the current density distribution. However, it is hard 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 enable choosing the optimal process conditions to obtain the desired surface quality.

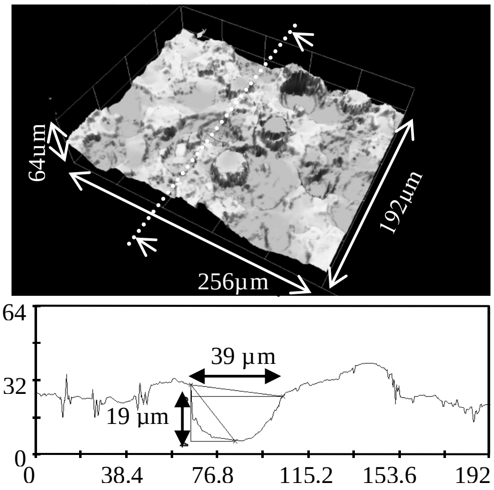

**Figure 2** Topography of a machined cast iron surface

## 2. Geometry and Mesh

### 2.1 Geometry

COMSOL Multiphysics 4.2a was used to simulate the electric current density distribution, and thus the dissolution behavior of cast iron, under pulse electrochemical machining conditions on a metallography-scale.

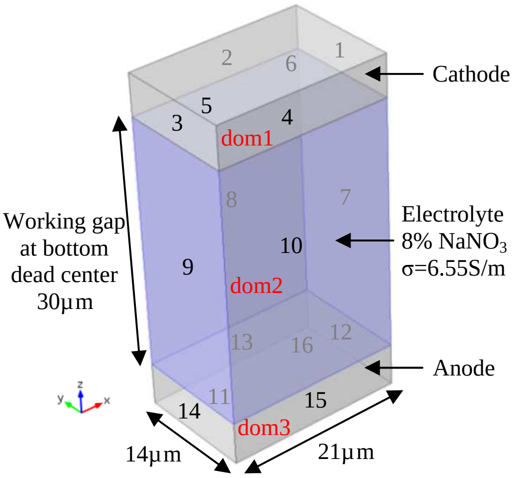

**Figure 3:** Geometry of the developed PECM-Model

The geometry used for the simulation is shown in Figure 3. The interelectrode gap of 30µm corresponds to the initial gap used in the experimental investigations.

In order to accurately simulate the experimental anodic dissolution conditions, the cast iron microstructure was characterized by scanning electron microscopy and imported into the simulation model via the “image-to-material” module (Figure 4).

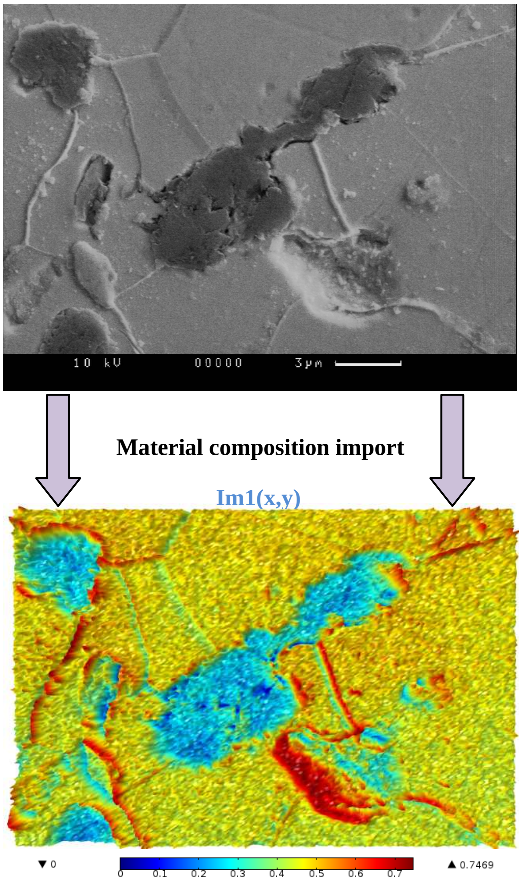

**Figure 4:** Material structure and composition import in COMSOL via the image to material function

### 2.2 Mesh

The FEM mesh at time t=0s is shown in Figure 5. The mesh consists of 387,926 elements. It was generated by using the automatic mesh creator with the option “extra fine”. At the anode surface, a maximum element size of 0.1µm was additionally defined because this surface is inhomogeneously deformed due to the dissolution process.

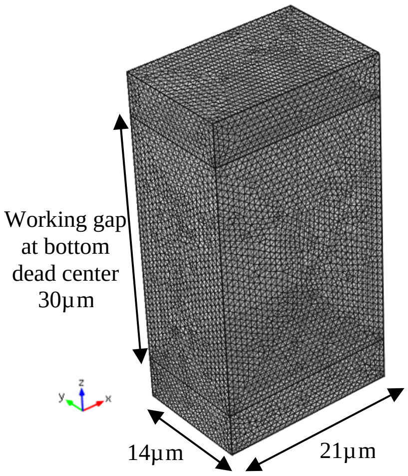

**Figure 5:** Mesh of the developed PECM-Model

## 3. Electrodynamics

The application mode “Electric Current” was used to define the electric parameters of the PECM-process. The material for subdomain dom1, which represents the cathode, was chosen out of the COMSOL material library as “Iron”. The electrolyte, which can be located as subdomain dom2, was defined with an isotropic conductivity of 6.55S/m, corresponding to the one used in the experimental investigations.

The electrical conductivity of the highly heterogeneous cast iron is represented by the function **$\sigma_{local}$(x,y)** which is defined in terms of the imported image **Im1(x,y)** as follows (Eq.1):

$$\sigma_{local} = \sigma_{graphite}\cdot(\mathrm{Im1(x,y)} < 0.37) + \sigma_{iron}\cdot(\mathrm{Im1(x,y)} \geq 0.37) \qquad (1)$$

At locations the image value is below a threshold of 0.37, the material electrical conductivity is set to $\sigma_{\mathrm{graphite}}$ and above 0.37 it is set to $\sigma_{\mathrm{iron}}$.

All electric boundary conditions are displayed in Table 1, where $\vec{J}$ is the current density vector, $\vec{n}_A$ is the normal to the surface vector and $\varphi$ is the electric potential. The total voltage of 10V, applied over the interelectrode gap, complies with the values used on an industrial machine. The simulated process conditions are presented in Table 2.

| Boundary | Definition |
|---|---|
| 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 | $\varphi = 10V$ |

**Table 1:** Boundary conditions for the boundaries numbered in Figure 3

| | Name | Value |
|---|---|---|
| $f$ | Feed rate | 0.1mm/s |
| $\Delta z$ | Vibration amplitude | 186.5µm |
| $T$ | Vibration period | 20ms |
| $t_{on}$ | Pulse on-time | 5ms |

**Table 2:** Simulated process conditions

## 4. Anodic Dissolution

According to the Faradays’ law, the anodic material removal taking place on boundary 11 is described as mesh displacement with a velocity in normal direction $\vec{v}_n$ depending on the normal current density $\vec{J}_n$ and various parameters characteristic of the material as shown in Eq.2. The variables and their respective values are listed in Table 3.

Besides, as graphite cannot dissolve, the mesh displacement has to be restricted to the iron zone. As for the electrical conductivity, a function based on the imported microstructure image is defined (Eq.3.). The mesh displacement only occurs at a threshold above 0.37.

$$\vec{v}_n = displ(x,y)\cdot\eta\cdot\frac{M}{z_A\cdot\rho\cdot F}\cdot\vec{J}_n \qquad (2)$$

$$\mathrm{displ(x,y)} = 0\cdot(\mathrm{Im1(x,y)} < 0.37) + 1\cdot(\mathrm{Im1(x,y)} \geq 0.37) \qquad (3)$$

| | Name | Value |
|---|---|---|
| $\eta$ | Current efficiency | 100% |
| $M$ | Molar mass | 55.85g/mol |
| $z_A$ | Valency | 3 |
| $\rho$ | Mass density | 7,920kg/m³ |
| $F$ | Faraday constant | $9.65\cdot10^4$C/mol |
| $\sigma_{graphite}$ | Graphite conductivity | $3.00\cdot10^6$S/m |
| $\sigma_{iron}$ | Iron conductivity | $10.02\cdot10^6$S/m |

**Table 3:** Variables in equation 2 and used for simulation and experiments

The current efficiency $\eta$ for PECM of cast iron was experimentally determined in [2].

## 5. Results

The simulations were made up to a processing time of 5ms which corresponds to one current impulse with a step size of 1ms. An example result for the calculated current density distribution is highlighted in Figure 6. The results highlight the restricted current density amplification on the graphite/iron-matrix interface. 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.

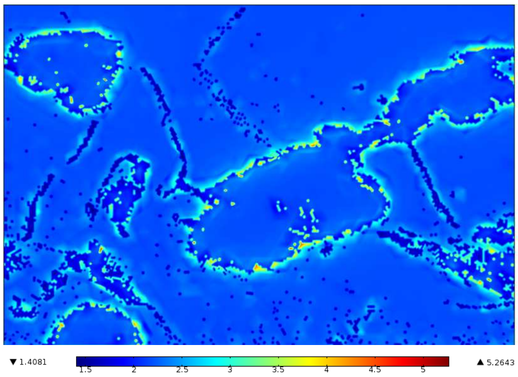

**Figure 6:** Simulated current density distribution (A/mm²)

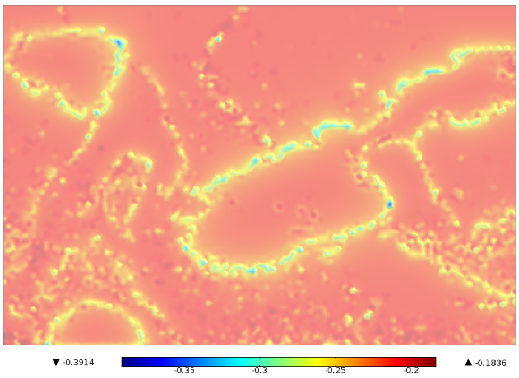

**Figure 7:** Simulated surface topography (µm)

The local current density increase induces a preferential material removal on the graphite/iron interface (Figure 7). 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

The simulation corresponds to the obtained experimental results. Figure 8 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.

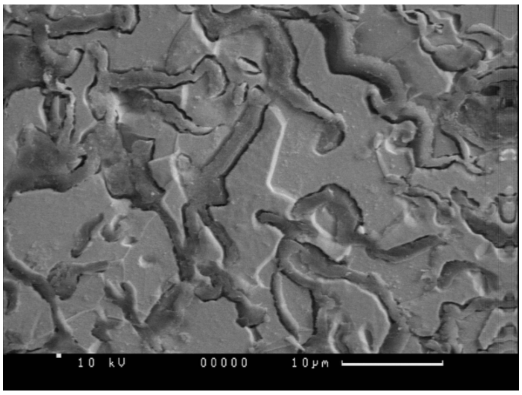

**Figure 8:** Machined cast iron microstructure

## 6. Conclusions

In this paper the current density distribution and the material removal behavior on the graphite/iron-matrix interface in cast iron under Pulse Electrochemical Machining conditions was simulated. In the model, only electrodynamics and mesh displacement were implemented. The material microstructure properties were directly imported into the model via the image-to-material function of COMSOL.

Experimental observations confirm the simulation. It could be verified that the simulated material removal depicts the same localized dissolution enhancement on the graphite-iron interface as the experimental investigations.

The presented results are profitable for both design and production engineers to predict the surface topography. The process parameters can be iteratively varied to identify the optimal machining conditions avoiding or limiting the surface integrity deterioration.

## 7. References

[1] Rajurkar K.P., Zhu D., McGeough J.A., Kozak J., De Silva A., 1999, New development in electrochemical machining, Ann. CIRP, 48/2:567-579

[2] Weber O., Natter H., Rebschläger A., Bähre D., 2011, Surface quality and process behavior during Precise Electrochemical Machining of cast iron, Proceedings of the 7th International Symposium on Electrochemical Machining Technology, 41-46.

## 8. Acknowledgements

The authors thank the European Regional Development Fund for the financial support.