Analysis of an Electrochemical Machining Process for Particle Reinforced Aluminium Matrix Composites

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Abstract: At the Technische Universität Chemnitz several academic institutions work on aluminium matrix composites (AMCs) within the Collaborative Research Centre SFB 692 HALS. The developed and examined AMCs consist for example of the alloy EN AW 2017 as matrix material, reinforced by SiC particles. Besides the development and analysis of these materials one main task is finishing machining of AMCs by an electrochemical machining (ECM) process.

One possible method of ECM is electrochemical machining with continuous electrolytic free jet (Jet-ECM) [1]. Within this study a 2-D axisymmetric model was developed which is representing the Jet-ECM of a SiC reinforced aluminium matrix. Corresponding to literature [2, 3], the size of the particle was derived from SEM-images [4, 5]. The geometry of the investigated unit cell was calculated from the composition of the AMC and the evaluated particle size. Using the interface primary current distribution in the field of electrochemistry with its predefined combination with deformed geometry material dissolution of particle reinforced AMC is investigated. The multiphysics simulation leads to a better understanding of the dissolution characteristics. It can be observed that in consequence of a local maximum of the current density in the area of the particle surface a higher material dissolution occurs.

Keywords: Electrochemical Machining, anodic dissolution, particle reinforced aluminium , aluminium matrix composites, AMC

1 Introduction

The finishing of components made of aluminium matrix composites (AMCs) by material removal processes is a particular challenge due to the inhomogeneous material properties. The ceramic particles like SiC within the quiet soft aluminium matrix are leading to different local conditions for example in metal cutting. In consequence of this there are an increased tool wear as well as imperfections on the workpiece surface.

Electrochemical machining (ECM) is a potential alternative for machining AMCs. The basic mechanism of ECM is the anodic metal dissolution. For this the workpiece is connected to the positive pole of a power supply, while the cathode is connected to negative pole. Aqueous saline solutions are used for the electrical charge transport between anode and cathode. The advantage of using ECM for machining AMCs is the non-contact processing. So there is no mechanical deformation of the workpiece surface or an undesirable physical influence on the boundary layer.

Final shaping of high-strength, particle-reinforced AMCs by electrochemical machining is one part of the research done within the Collaborative Research Centre SFB 692 HALS at Technische Universität Chemnitz. Here electrochemical machining with continuous electrolytic free jet (Jet-ECM) [1] is one method which is investigated. In figure 1 a scheme of the Jet-ECM process is presented.

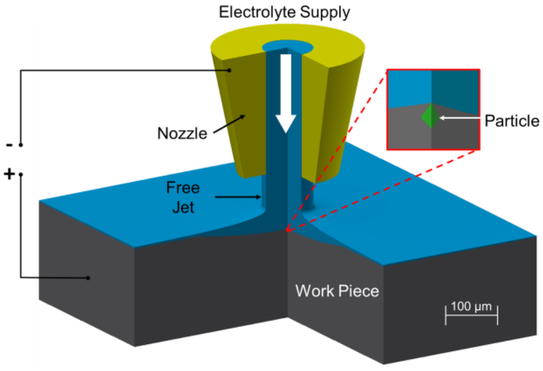
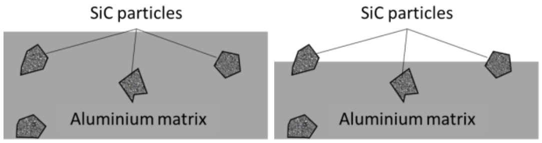


Figure 1. Scheme of jet electrochemical machining of AMC

As it can be seen, the workpiece is connected to the positive pole of a power supply. The electrolyte is supplied through a movable, electrically conductive nozzle, which is connected with the negative pole of the power supply. During the process the electrochemical removal area is highly localized by the geometry of the electrolyte jet.

Outside of the electrolyte jet area no material dissolution takes place.

One main aim applying Jet-ECM is to perform a selective electrochemical micro structuring of the surface in order to uncover the SiC particles partially out of the aluminium matrix. In figure 2 the intention of the research is presented schematically.



(a) Before machining (b) After machining

Figure 2. Scheme of the AMCs before and after the EC-processing for targeted uncovering of the reinforcement SiC particles

Figure 2(a) shows the AMC in the initial situation before the electrochemical machining process. The SiC particles are fully covered within the aluminium matrix. After the EC-processing the aluminium matrix is dissolved and the SiC particles are partially uncovered (figure 2(b)). This surface with protruding particles is part of the investigation of a new concept in diffusion welding of high-strength lightweight materials.

2 Model Description

2.1 Geometry and materials

Based on figure 1 a model geometry for simulating Jet-ECM of aluminium matrix composites was derived. In a first step the size of the ceramic particles had to be estimated. Corresponding to literature [2, 3], the size of the particles can be derived from SEM-images [4, 5]. Such a SEM-image of a SiC particle reinforced aluminium matrix composite is shown in figure 3.

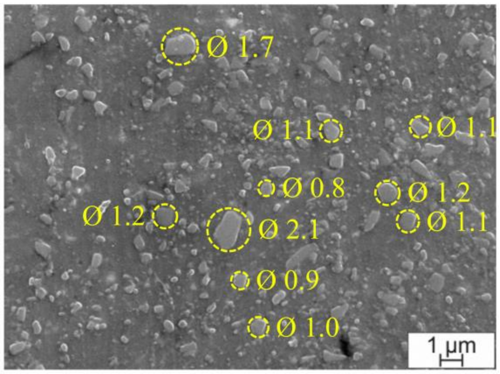


Figure 3. SEM-image of an AMC surface for ascertaining the averaged particle size

As it can be seen, there are different particle sizes. For a first approximation the particles are considered as spheres with diameters in the range of 0.8 µm to 2.1 µm. Based on this an averaged particle diameter of 1.0 µm was derived. Due to the fact that there are mostly no spherical particle geometries a more relevant particle geometry is needed. For this a double cone geometry was chosen. In consequence of this a transformation of the sphere into the double cone was done while maintaining the particle volume. Figure 3 illustrates this transformation.

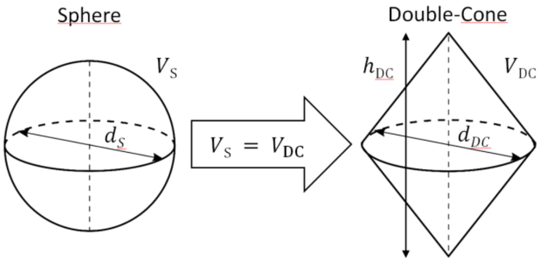


Figure 4. Transformation from spherical particle geometry to a double cone

The resulting geometry of the double-cone particle has a diameter and a height of $d_{\mathrm{DC}} = h_{\mathrm{DC}} \approx 1.26\ \mu\mathrm{m}$. Based on this values a 2-D axisymmetric model geometry was derived. Figure 5 shows the corresponding geometry.

The geometry is representing a unit cell with characteristic size relations of the regarded AMC. As it can be seen, the model consists of three domains. The first domain represents the aqueous electrolytic free jet. It is defined with a constant electrical conductivity of $\sigma = 70\ \mathrm{mS/cm}$ which meets very well saline electrolyte with a mass fraction of 8% sodium nitrate ($NaNO_3$). The electrolyte domain has a radius of $r_{\mathrm{El}} = 0.94\ \mu\mathrm{m}$. The height of the electrolyte domain is $h_{\mathrm{El}} = 100\ \mu\mathrm{m}$, which corresponds to working gaps used within the Jet-ECM process. For reasons of clarity, only a detailed view of the machining area is shown in figure 5.

The definition of the second domain is workpiece. The workpiece consists of the aluminium alloy EN AW 2017. The material properties of this alloy are a material density of $\rho = 2.8\ \mathrm{g/cm^3}$ and a molar mass of $M = 28.77\ \mathrm{g/mol}$. The radius of the cylindrical workpiece was derived from the particle volume fraction of 0.1 and is set to r_AL=0.94 µm with a height of h_AL=1.88 µm.

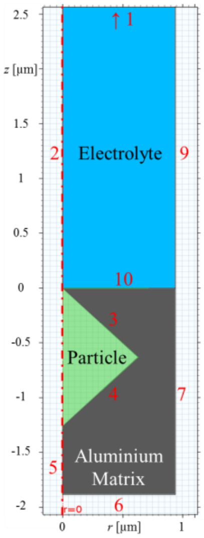


Figure 5. 2-D axisymmetric model geometry for Jet-ECM of particle reinforced AMC

The third domain represents the SiC particle. In the initial time step the particle protrudes 0.001 µm out of the matrix surface. Due to the electrical insulation characteristics of SiC this domain is not considered as domain within the model for simplification. The geometric dimension corresponds to the previously explained double cone.

In table 1 a short summary of the settings used in the model is given.

Table 1: Allocation of defined settings

Domain	Material	Defined setting
I	Electrolyte	$r_{\mathrm{El}} = 0.94\ \mu\mathrm{m}$ $h_{\mathrm{El}} = 100\ \mu\mathrm{m}$ $\sigma = 70\ \mathrm{mS/cm}$
II	Aluminium alloy EN AW 2017	$r_{\mathrm{AL}} = 0.94\ \mu\mathrm{m}$ $h_{\mathrm{AL}} = 1.88\ \mu\mathrm{m}$ $\rho = 2.8\ \mathrm{g/cm^3}$ $M = 28.77\ \mathrm{g/mol}$
III	SiC	$r_{\mathrm{DC}} \approx 0.63\ \mu\mathrm{m}$ $h_{\mathrm{DC}} \approx 1.26\ \mu\mathrm{m}$

2.2 Meshing

The FEM mesh was created using the automatic mesh generator of COMSOL. The mesh that was created for a time-dependent calculation is shown in figure 4.

To generate this mesh a user-defined mesh was chosen. The setting includes a general element size of 0.01 µm in minimum and a maximum size of 0.5 µm. The maximum growth rate is set to 1.1 and the curvature factor is 0.7. The resolution of small areas is discretized with at least 3 elements. Within the domain of the aluminium matrix a finer mesh is used. Here a maximum element size of 0.03 µm is set. These settings are leading to an initial mesh with 7819 elements.

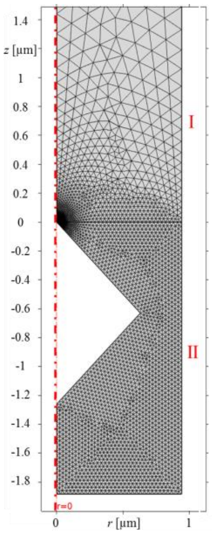


Figure 6. FEM mesh for the calculation of material dissolution

During the simulation the boundary of the workpiece surface will be deformed. In consequence of this a distortion of the mesh will occur. With the automatic remeshing option of COMSOL it is possible to define criteria when a remeshing starts. For this minimum mesh quality of 0.4 was chosen.

2.3 Physics

The investigation of machining SiC particle reinforced aluminium matrix composites was performed with a fully coupled model. In this connection the interface primary current distribution in the field of electro-chemistry with its predefined combination with deformed geometry was used. Figure 7 shows the considered phenomena and couplings.

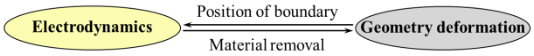


Figure 7. Considered couplings within the interface of primary current distribution in the field of electro-chemistry

In general the electrodynamics causes the deformation of the geometry due to the material removal. On the other hand the position of the workpiece boundaries has a huge influence on the electrical conditions. To simulate these interactions, boundary conditions are needed. For this the cathode potential of $\phi_{\mathrm{Cat}} = 0\ V$ is defined on boundary 1 and the anode potential ϕ_{An} is set to 5 V on boundary 10. The functional principle of ECM is the anodic dissolution of metals due to an electric charge transport Q_{el} following Faraday's law. The removed material volume V is calculated by equation 6 [7].

$$V = \eta \cdot \frac{M}{\rho \cdot z_{\mathrm{A}} \cdot F} \cdot Q_{\mathrm{el}} \tag{6}$$

M is the molar mass, ρ the density, z_{A} the electrochemical valence of the material, F the Faraday constant and η is the current efficiency. The velocity of material removal in normal direction $\vec{v}_{\mathrm{a}}$ depends on the current density in normal direction $\vec{J}_{\mathrm{n}}$.

$$\vec{v}_{\mathrm{a}} = \frac{M}{\rho \cdot z_{\mathrm{A}} \cdot F} \cdot \vec{J}_{\mathrm{n}} \cdot \eta(J) \tag{7}$$

For the case of dissolving aluminium the valence was set to $z_{\mathrm{A}} = 2.7$.

A summary of the boundary conditions used for modelling the material removal of aluminium matrix composites according to the domain and boundary definitions of figure 5 are listed in table 2.

Table 2. Boundary conditions for the boundaries numbered in figure 5

Boundary	Definition
1	Cathode $\phi_{\mathrm{Cat}} = 0\ V$
2, 5	Axis of symmetry
10	$\phi_{\mathrm{An}} = 5\ V$ Deforming surface
1-9	Non-deforming boundaries

3. Results of the simulation

The results of the time-dependent simulation of the material removal of AMC are presented in the following. In figure 8 an overview of the model geometry at the initial time step $t = 0$ s is shown. As it can be seen, the SiC particle is almost completely embedded within the aluminium matrix and no material dissolution took place.

After a machining time of t = 0.039 s the magnitude of current density distribution within the electrolyte is shown in figure 9. It can be seen that there exists a minimum of about 20 A/cm² at the tip of the SiC particle.

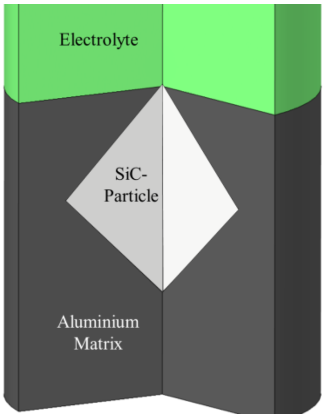


Figure 8. Overview of the model geometry at $t = 0$ s

A local maximum of about 69 A/cm² can be observed in the area, where the aluminium matrix encloses the particle. In addition to that the result of the material removal is obvious. At $t = 0.039$ s only half of the SiC particle remains embedded within the aluminium matrix.

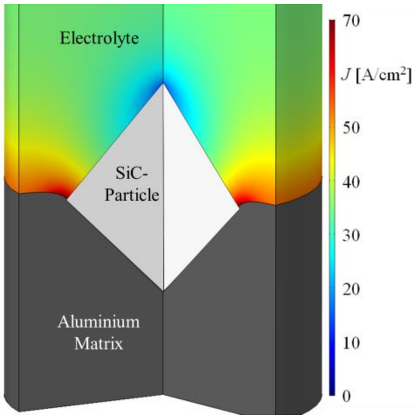


Figure 9. False color rendering of the electric current density at $t = 0.039$ s

Figure 10 shows the shape of the workpiece surface at different time steps beginning by $t = 0$ s until the time step of $t = 0.039$ s.

At $t = 0$ s the particle is almost completely embedded within the aluminium matrix. With progressing machining time the aluminium matrix is dissolved. Here the increased material dissolution at the interface between particle and matrix is distinctive. This result indicates a higher local electrical current density during the machining process and has to be taken into account while designing the process. At $t = 0.039$ s nearly half of the particle is uncovered by Jet-ECM. A further machining will lead to fall out of the particle out of the aluminium matrix.

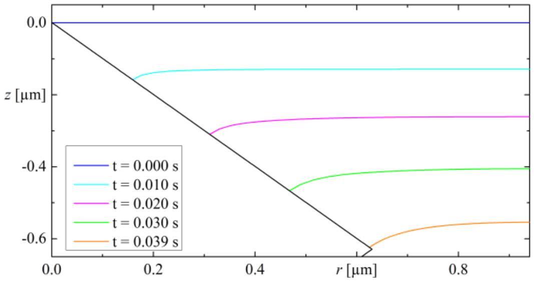


Figure 10. Resulting shape of the workpiece surface at different timesteps

4. Summary

In this study multiphysics simulation of jet electrochemical machining of SiC particle reinforced aluminium matrix composites were shown. Therefore a 2-D axisymmetric and fully coupled model was developed. Based on a representative SEM-image of a workpiece surface consisting of SiC particles within an aluminium alloy of EN AW 2017 size measurements were carried out to determine the characteristic size relations and to develop a unit cell with representative geometrical proportions. Using this unit cell simulations were performed with the interfaces of COMSOL Multiphysics called primary current distribution in the field of electrochemistry with its predefined combination to deformed geometry. As result of the simulation the magnitude of the electric current density distribution can be investigated as well as the resulting workpiece shape.

The simulation describes the electrochemical dissolution process of SiC particle reinforced aluminium matrix composites. Based on a simplification to a unit cell of one SiC particle within an aluminium matrix important information about the distribution and localization of the electric current density as well as the resulting geometry can be derived. For this the simulation model can help to understand the particularities of the machining process. Based on these results important advices for designing the ECM process for a targeted uncovering of particles can be given. For example the machining time using defined electrical parameters can be estimated. So the multiphysics simulation helps to reduce the amount of required costly and time-consuming experiments.

Acknowledgements

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