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Design of electrical contact surfaces for fast charging systems

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Abstract

E-mobility is of high interest for the energy transition and the achievement of climate targets. Nevertheless, this forward-looking technology still has a number of drawbacks. One example is the very long charging time of battery systems. To counteract this, an innovative fast charging system using a face contact instead of classic plug-in contacts is being developed that significantly reduces conventional charging times. To enable this, an electrical contact surface is functionalized in such a way that, on the one hand, the contact resistance is reduced and, on the other hand, the thermal as well as mechanical properties are improved. This can be achieved by a special design of the microstructure of the electrical contact surface. In the following, the procedure is described in detail. First, a single microcontact is designed to break up the oxide layers and minimize the constriction resistance. The thermal, mechanical and the electrical properties are described and optimized using analytical and numerical methods. Special attention must be paid to the heating of an a-spot during current flow. Then, the single microcontact is multiplied to exploit the principle of a parallel connection. This can significantly reduce the constriction resistance. Finally, this designed microstructure is manufactured and tested in experiments. Consequently, high charging currents can be transmitted via a face contact on a relatively small contact area.

Keywords: electrical contact, contact resistance, face contact, numerical analysis, FEM

1. State of the art of charging systems

E-mobility is a key technology for managing a successful energy transition and to transform the mobility sector. In order to make this forward-looking technology practicable, new methods of energy transmission up to the megawatt range must be found. Classic plug-in contacts, which are commonly used, are limited in the normal force due to their manual operability. This leads to a comparatively small contact surface and thus a limitation in the transferable electrical load to avoid overheating. To overcome this, the principle of face contacting is operated mechanically, which offers up to 20 times higher contact normal forces and therefore significantly higher transmittable power as well as greater thermal stability. This is achieved by increasing the current-carrying surface area of a given contact surface, ensuring the necessary wear protection and the mechanical-electrical development of the face contact with optimal heat conduction, taking into account the clearance and creepage distances.

2. Basics and design approach of electrical contact surfaces

In this section, the basics and the design approach for the electrical contact surfaces are presented. First, the basic relationship of the contact resistance is explained. The contact resistance R_{contact} is made up of the sum of the resistance of the base material R_{B}, the constriction resistance R_{c} and the external layer resistance R_{L}, see [1-2].

$$R_{\mathrm{contact}} = R_{\mathrm{B}} + R_{\mathrm{c}} + R_{\mathrm{L}} \tag{1}$$

The basic idea behind the electrical contact surfaces is that, on the one hand, face contacting of the microstructure breaks up the oxide layers and, on the other hand, the microstructure leads to the lowest possible constriction resistance, which enables higher transmittable power. Therefore, the design of the microstructure plays a very important role. As a consequence, the initial focus is on the design of a single microcontact (also known as an a-spot). The resistance of a single circular microcontact can be determined via the constriction resistance, see [1-4].

$$R_{\mathrm{c}} = \frac{\rho(T)}{2\,r_{\mathrm{K}}} \tag{2}$$

Here, ρ describes the specific electrical resistance and r_{K} the radius of the microcontact or the radius of the a-spot. Figure 1 shows two constriction resistance curves for two different radii of curvature R_{K}, each with flat counter body. Note that different radii of curvature lead to different contact radii r_{K} and thus to different constriction resistances for the same normal force F_{N}.

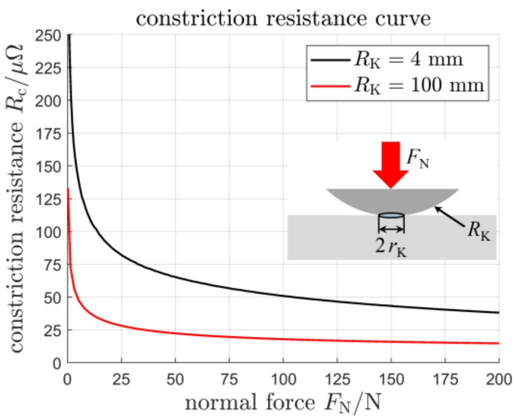

Figure 1. Constriction resistance curves for two different radii of curvature

Figure 1 shows that a certain normal force is required to significantly reduce the constriction resistance. The simulations were carried out with Tribo-X. Furthermore, it can be observed that no significant improvement occurs with increasing normal force. In direct comparison, $R_K = 4$ mm shows a higher constriction resistance due to the smaller contact area. In the following, a relationship between mechanical, thermal and electrical variables is derived, which enables a targeted design of the microstructure. It is obvious that the radius and the temperature T of the microcontact as well as the current flow I_K influence each other. Based on the approach of an ellipsoid model, a relationship can first be established between the maximum temperature T_{max} in the a-spot, the temperature of the boundary surfaces T_1 and the contact voltage U_K, see [2, 4].

$$T_{\max} = \sqrt{\frac{U_{\mathrm{K}}^2}{4L} + T_1^2} \tag{3}$$

Here, L describes the Lorenz number. Using Ohm's law, the current strength and the resistance can be built in and above this the radius of the a-spot. As a result, we obtain an evaluation equation, which shows the correlation of all important influencing variables.

$$T_{\max} = \sqrt{\frac{\rho^2\, I_{\mathrm{K}}^2}{16\, L\, r_{\mathrm{K}}^2} + T_1^2} \tag{4}$$

It should be noted that the investigations carried out here were performed for copper, more precisely Cu-ETP (CW004A). In addition, the temperature dependence of the specific electrical resistance $\rho(T)$ was taken into account. Finally, Figure 2 shows the 3D-plot of the maximum temperature in dependence of the current strength and the radius of the a-spot, which can be used to dimension the microstructure.

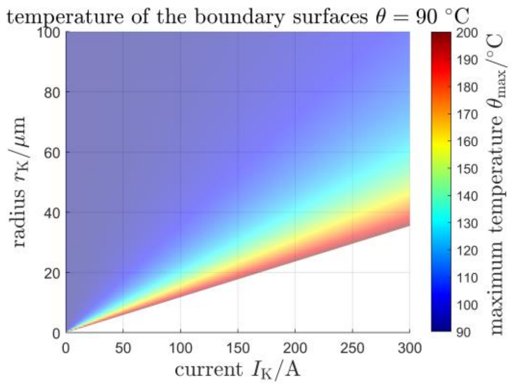

Figure 2. 3D-plot of maximum temperature in dependence of current strength and radius of a-spot

The figure clearly shows that there is a very sensitive relationship between the radius of the a-spot, the current flow and the maximum temperature in the a-spot. Consequently, the microstructure of the electrical contact surface cannot be made infinitely small. For example, if a current of $I_K = 300$ A is to be transmitted without a significant increase in temperature, the microstructure should have a radius of more than 80 µm. This radius or the resulting contact area must therefore be present when the normal force is applied. Our design approach is that no significant increase in temperature can be reached for the developed microstructure. After dimensioning a single microcontact, the structure is multiplied to utilize the principle of parallel connection [5].

$$R_{\mathrm{c}} = \frac{1}{n}\frac{\rho(T)}{2\, r_{\mathrm{K}}} \tag{5}$$

For this, the constriction resistance R_C is shown as a function of the normal force F_N and the number of a-spots n. Figure 3 shows that the constriction resistance decreases very fast with increasing normal force and increasing number of a-spots. Additionally, it should be mentioned that the constriction resistance curve from Figure 1 ($R_K = 4$ mm) represents the limit curve in Figure 3 for one a-spot.

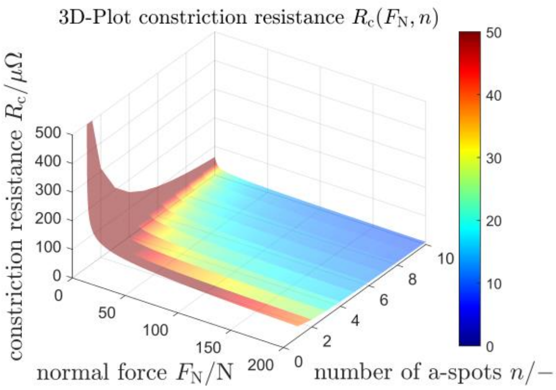

Figure 3. 3D-plot of constriction resistance in dependence of normal force and number of a-spots

It can be observed that just a few microcontacts (a-spots) are sufficient to reduce the constriction resistance significantly. In contrast, it should be taken into account that the effective contact radius also decreases with a large number of microcontacts since the normal force is evenly distributed among them. For a first prototype, a face contact with five microcontacts is designed. This setup offers the best compromise in terms of constriction resistance and available normal force. Figure 4 (left) depicts the contact surfaces with five microstructures.

3. Simulation with COMSOL Multiphysics

In this section, the current flow and the heat distribution are simulated for the previously designed prototype, consisting of a face contact with microstructure and a flat face contact. In [6], similar investigations were carried out for a multi-spot contact, but at very low currents (200 mA). The numerical calculations were performed using the finite element method (FEM) in COMSOL Multiphysics. A step file of a CAD model was used to create the finite element model. For the electrical boundary condition, a current density of $J = I/A = 5.9683 \cdot 10^6$ A/m² was specified (with $I_K = 300$ A and $D = 8$ mm). In addition, copper ETP was used for material characteristics and material properties. Figure 4 shows the FE-model (left) and the current flow (right).

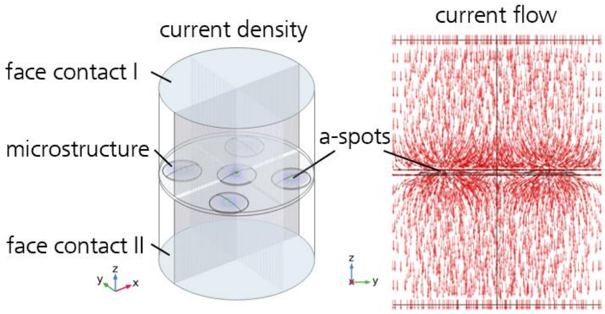

Figure 4. Face contact with five microstructures – display of current flow

As illustrated, the narrowing and subsequent widening of the current flow at the contact points (a-spots) can be seen very clearly. This is the cause of both the increase in resistance, which is introduced as constriction resistance and the increase in temperature. As a result, the electrical current transmission can be mapped physically. It should be noted that the influence of oxide layers caused by oxidation of the surface is not simulated here. Experimental tests will be carried out later to investigate their influence and their break up through face contact.

In the following, the maximum temperature in an a-spot from COMSOL Multiphysics is validated with the analytical design approach. For this, the maximum temperature of an a-spot is evaluated for an effective radius of $60\ \mu\text{m}$. The results are shown in Figure 5.

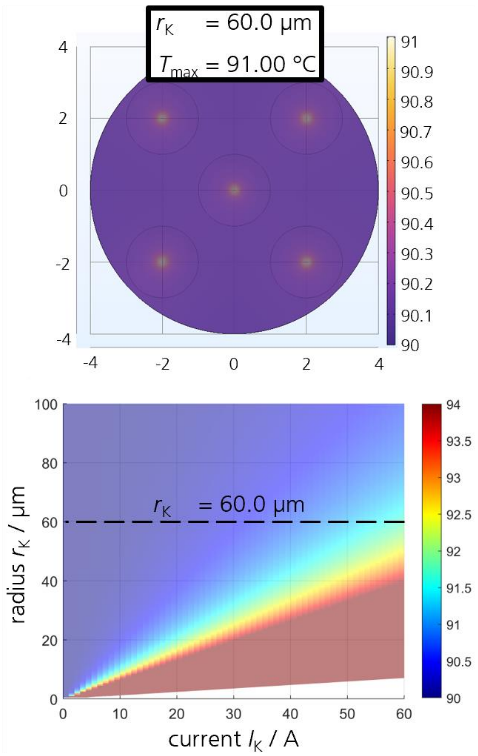

Figure 5. Comparison of the maximum temperature in an a-spot. Results from COMSOL Multiphysics (top) and results from analytical design map (bottom)

It can be stated that the FE-simulation leads to a maximum temperature of $91.0\ °\text{C}$ and the analytical design approach to $91.5\ °\text{C}$. The temperature of the boundary surfaces is $90.0\ °\text{C}$. Consequently, the design approach can be verified. In addition, investigations were also carried out into the mutual influence of the a-spots. It was found that the distances between the microcontacts are so large that no interaction takes place. This can also be confirmed by analytical approaches, see [5].

$$l > 20 \cdot r_K \tag{6}$$

Here, l describes the average distance between the a-spots and r_K, as already mentioned, the current a-spot radius.

4. Manufacturing of the microstructure

After dimensioning the face contact with microstructure, manufacturing is carried out using laser ablation. This production process is ideally suited for manufacturing prototypes with high accuracy. For the patterning experiments, an Nd:YVO_4-doped picosecond laser with a wavelength of $532\ \text{nm}$ and a maximum average output power of $8\ \text{W}$ was used. The linearly polarized Gaussian laser beam was focused to a focal diameter of $11\ \mu\text{m}$ using a f-θ lens array with a focal length of $100\ \text{mm}$. The workpiece was microstructured using Direct Laser Writing (DLW).

As a result, Figure 6 shows the manufactured face contact with five microstructures. The microstructure was applied to a cylinder with a diameter of $8\ \text{mm}$ (see Figure 4). The counter body is a flat cylinder with a diameter of $8\ \text{mm}$. It should be noted that the face contacts will later be provided with a special coating to minimize wear. These coatings are developed by the Fraunhofer Institute for Surface Engineering and Thin Films IST.

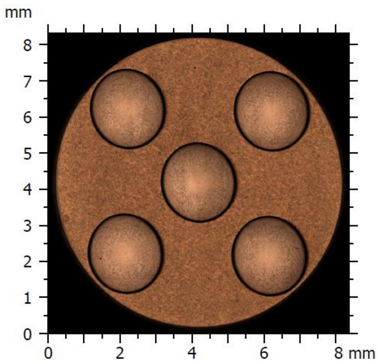

Figure 6. Face contact with five microstructures – surface manufactured by laser ablation

5. Surface measurement of the microstructure

Finally, the finished surface with five microstructures is measured using a confocal microscope MarSurf CM mobile from Mahr. Figure 7 shows a perspective view of face contact II.

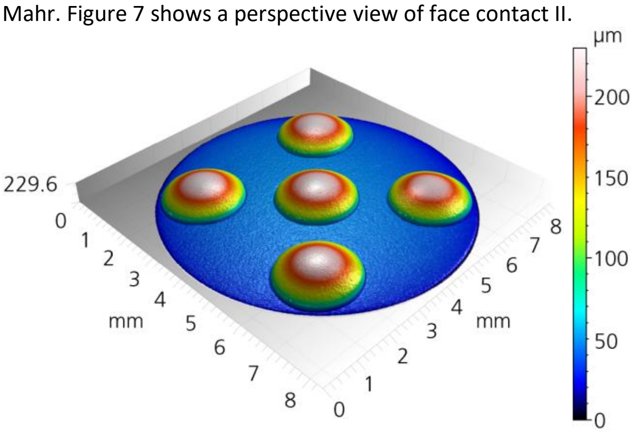

Figure 7. Face contact with five microstructures (perspective view) – surface measured with confocal microscope (Mahr)

A visual inspection already indicates a high quality regarding the geometry of the microstructures as well as their surface roughness. In the next step, they should be evaluated using a geometry and roughness analysis. For this, a profile cut is made first through three of the microcontacts and then evaluated (see Figure 8).

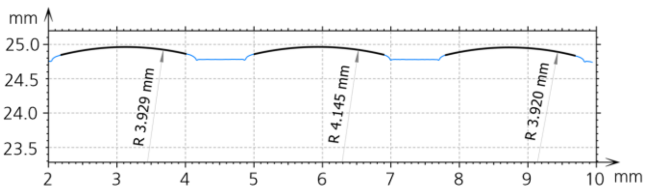

Figure 8. Evaluation of the surface profile – surface measured with confocal microscope (Mahr)

As can be seen from the diagram, the profile curve is well reproduced. The maximum deviation from the specified contour ($R_K = 4$ mm) is $f = 3.625$ % (average radius deviation). In the following, roughness evaluation is focused at the central microcontact. Surface roughness values according to DIN EN ISO 25178 and roughness derived from 10 single profiles are evaluated, see Table 1. Therefore, the spherical shape was eliminated and filtering was carried out.

Table 1 Roughness evaluation according to DIN EN ISO 25178 and DIN EN ISO 21920 of the central microstructure

DIN EN ISO 25178, $\lambda_c = 0.8$ mm	
S_a [µm]	0.267
S_k [µm]	0.830
S_{pk} [µm]	0.411
S_{vk} [µm]	0.450
DIN EN ISO 21920, $\lambda_s = 2.5$ µm, $\lambda_c = 0.8$ mm	
R_z [µm]	1.672
R_a [µm]	0.244

The high surface quality previously assumed visually is confirmed by the low roughness values. Consequently, the laser ablation process is very suitable for producing microstructured face contacts.

For later series production or volume production, a forming or replication process must be developed after completion of the prototype development.

6. Conclusion and Outlook

This paper describes a design approach that enables the dimensioning of electrical contact surfaces for fast charging systems. The aim is to design a face contact in such a way that a high current flow can be transmitted. The designed microstructure of spherical segments was optimized with regard to the constriction resistance and the maximum temperature occurring at the a-spot. After the analytical design, the face contact with microstructure was validated in COMSOL Multiphysics. The following results were obtained:

i. The physical principle of face contacts can be confirmed.
ii. The required current flow leads to identical maximum temperatures as in the analytical design.
iii. There are no interfering interactions between the microcontacts.

After the design, the face contact with microstructure was manufactured by laser ablation. The subsequent measurement with a confocal microscope shows that this method leads to very good surface quality and geometry.

In further investigations, the manufactured face contacts with microstructure will be tested experimentally. On the one hand, the functional principle should be checked and, on the other hand, the actual contact resistance should be determined. Therefore, a special test bench will be developed and equipped with appropriate measurement technology. Cyclic tests, tests at different current levels and wear tests will also be carried out.

After completion of all developments, a demonstrator of a fast charging system will be introduced together with the Fraunhofer Institute for Transportation and Infrastructure Systems IVI as well as the Fraunhofer Institute for Surface Engineering and Thin Films IST, which will enable energy transmission up to the megawatt range.

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