MODELING AND DESIGN OF CONTACTS IN ELECTRICAL CONNECTORS

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ABSTRACT

The presented paper focuses on modeling and simulation of electrical connector contacts' behavior and associated design. New solutions are developed, based on the Contact & Channel Approach validated by simulation and experiment.
Primary parameters such as contact resistance, tribological and thermal behavior, contact force, material and connector size strongly influence electrical connector's properties. Therefore, a great deal of experience or effort is needed to design application specific solutions mastering preceding interrelated parameters. However, many state of the art electrical connectors are, especially for high currents, designed by trial and error processes. In order to increase efficiency and effectiveness of the design process, appropriate models are needed. To generate new design solutions, models of a certain level of abstraction are required. In addition to this, holistic computer-aided models enable the prediction of connector's electrical and mechanical performance. Here, design solutions are developed systematically based on the Contact & Channel Approach. At the same time a Finite Element Model is built in order to investigate the behavior of designed connector's prototypes.

Keywords: electrical connector, modeling, finite element method, Contact- and Channel Modeling Approach (C&C-A), product design

1 INTRODUCTION

The general tendency towards modularity and increasing number of high current applications especially in the areas of manufacturing engineering and automotive design cause an increasing need for efficient and reliable electrical connection of independent modules. At the same time connectors have to follow the trend of miniaturization. The majority of connectors' electrical contacts are to be regarded as critical in two extreme working conditions: At very low currents and voltages conducting contact is difficult to ensure whereas at high currents and voltages effects of heat generation and electrical arcing are critical. With increasing number of high current carrying connectors the significance of their performance for the overall system efficiency increases correspondingly. High contact resistance leads to high temperature rise synonym to high power loss.
Taking into account the upcoming technologic developments in the context of Electro- and Hybrid-mobility, the number of high current connectors being particularly problematic with respect to power losses will increase accordingly. Hauck [1] states that vehicles' electrical systems will more and more have to fulfill the tasks of power trains with electric power of 200kW at continuous currents of around 400A instead of only transmitting signals and comparably low energies. Especially in the automotive area Himmel [2] is predicting new demands for high current capacities and reliability, which are going to be combined with general requirements, such as low production costs, small installation space and ergonomic handling properties, i.e. moderate insertion force.
Hence, the task is to design reliable connectors with highest current handling capacity and with resistivity as low as possible for highest efficiency. Efficiency in this context means energy efficiency i.e. the quotient of power output to power input, as well as efficiency of installation space, i.e. the quotient of transferable power to required volume of the connector.
Named requirements have strong interconnections as a low contact resistance causes less power losses and lower heat generation in the contact which in turn increases connector's reliability and lifetime. Furthermore a lower heat generation allows a more compact design and thus decreases the connector's overall volume. To design connectors according to those needs, deepened knowledge and understanding of actual occurring effects is essential. In order to support a corresponding design

process appropriate models are necessary. The major objective is simulation of contact performance based on these models.

2 MODELS OF ELECTRICAL CONTACTS

2.1 Theoretical background

The contact resistance is defined by Rieder [3] as the difference between the resistance of a closed contact and the one of a homogenous conductor of the same shape and dimension. Hence, any additional contact connecting current carrying conductors cause additional electric resistance, which heats the current path locally.

The reason for this contact resistance is not, as often expected, a transition resistance from one material into another. An interface between two metallic surfaces does not necessarily mean a higher resistance for the electron current, as any grain boundary of metallic structure would be. If metallically clean contacts were in real contact over the entire apparent contact area, there would theoretically be no remarkable resistance. Rather according to Rieder [3], resistance originates due to

- mechanical contact area, which takes the contact load, is always smaller than the apparent surface because of unavoidable macro- and microscopic bumps and asperities
- electrically conducting contact area might be smaller than the mechanical contact area due to impurities of almost insulating property
- conducting areas often are covered by non-metallic conducting layers (with higher specific resistivity).

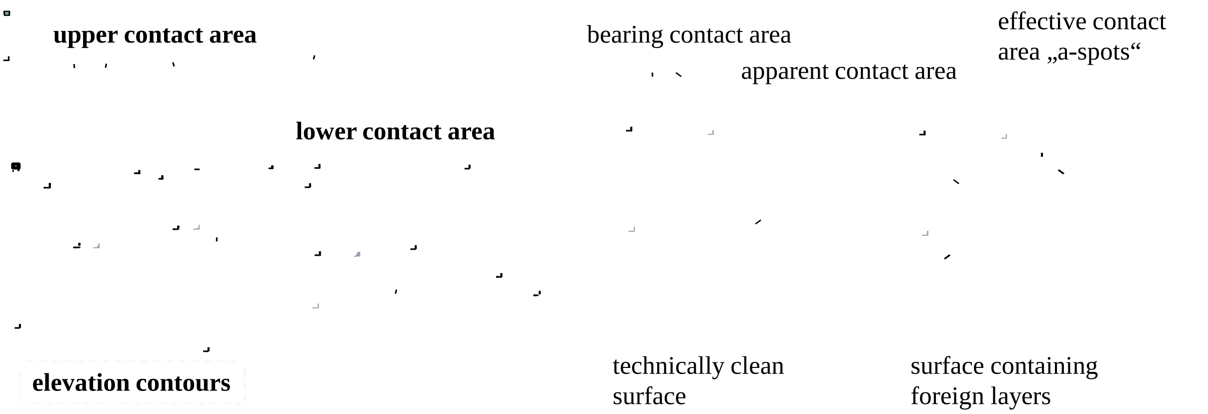

Figure 1: Differentiation between apparent contact area, bearing contact area and actual conducting contact area.

Electric resistance between two surfaces is caused by constriction of the current flow to small conducting areas, so called a-spots (Figure 1), and by the higher resistivity of foreign layers. This constriction is a consequence of the fact that only a number of a-spots conductively connect the contact partners.

Being exposed environmental air, on all materials not being extremely noble, there grow foreign layers. They are made of oxides, sulfides or other compounds and cannot be tunneled through. [3]

Greenwood [4] and Slade [5] state that the constriction resistance of a contact R_C is controlled by following equation:

$$R_c = \rho(\frac{1}{2na} + \frac{1}{2a}) \tag{1}$$

with n as number and a as radius of contact spots as well as ρ as resistivity. Respective distances between single contact spots, which also impact contact resistance, are described by a radius α of micro spot clusters.

The resistance defined as ρ/2a for a single contact area is only valid as long as the constriction effect on heat generation is sufficiently small (maximum supertemperature of 3 °C [5]). As under conditions of real high current applications significant joule heat might be produced within the constriction, this assumption cannot necessarily be used in a model assessing new unproven design solutions. Slade [5] deduces from potential theory that the crowding of current lines within an a-spot causes a thermal gradient normal to that constriction.

Parallelization of n contact areas theoretically decreases the overall resistance by 1/n. The overall area available though stays constant. Since each of the parallel switched contacting surfaces is limited in its (nominal) contact area by this division, contact radius decreases by the factor $1/\sqrt{n}$ accordingly. Hence, each single contact resistance theoretically increases by the factor $\sqrt{n}$. Combining tho se two effects, a multiplication of contact points by division of a constant overall contact area should decrease the overall resistance by $1/\sqrt{n}$.

2.2 Approaches in modeling electrical and mechanical contact performance

Contact surfaces of the mating partners in interaction with contact force and applied materials mainly control the conducting contact area and thus contact resistance. Difficulties in modeling connectors' performance are mainly driven by the additional aspects of real contact behavior, i.e. surface micro-topography in association with tribological effects, temperature rise and foreign layers on contact surfaces which are very difficult to model and thus to predict and assess.

Most published approaches deal with analysis and modeling of single aspects of contact behavior, such as Maul and McBride [6] who focus intermittency phenomena, fretting, influence of mutual positions of individual contacts on resistance and stiffness studied by Ervin and Sovostianov [7], Schoft and Kindersberger [8] investigating resistance of randomly rough surfaces, and other detail specific views.

There are also some approaches of building models and simulations integrating various mechanical and electrical properties of electrical contacts [9]. Validation is mostly restricted to assumptions like "crossed-rods" models or "sphere - flat-body" combinations. This is due to the fact that the computational models mostly are restricted to very small areas because high resolutions are required for accurate calculations. Another problem concerns the fact that the boundary conditions of connector systems in real applications are mostly very dynamic. For instance, impacts and environment's influences, such as ambient temperature, concentration of corrosive gases and vibrations can vary and scatter largely.

Leidner et al. [9, 11] generate surface topographies based on real measured surface data. They model elastic plastic contact between multi-layered bodies subjected to pressure and shear traction. Basing on the modeled contact, they calculate the resulting constriction resistance and voltage drop. Their models set the actual state of the art in modeling electro-mechanical contacts. However, their approach is focused on contacts transferring low energies at comparably low currents and therefore is not considering temperature effects. For modeling high current contacts a model neglecting temperature rise is insufficient. Simulation focuses only on small areas making an application for generalized design of entire connector systems more difficult. These difficulties reside especially in the objective to unite impacts of micro-scale modifications and macro-scale performance.

The objective is not to model only single a-spot clusters but entire contact areas over several square millimeters with modified surface topographies based on measured surface data. Especially the consideration of temperature rise caused by the electric current is expected to increase the significance of modeled high current contacts.

For creation of new design solutions by analysis and synthesis micro-geometrical models based on mathematical models are not suitable, as they require comprehensive information about design-form and boundary conditions. In order to design new connector principles instead of only varying material, plating, contact force or manufacturing method, the Contact & Channel Modeling-Approach (C&C-A), developed by Albers [10] and latest being developed further by Alink [11], is a suitable method to support abstract modeling and synthesis.

3 A NEW DESIGN APPROACH BASED ON C&C-A FOR ELECTRICAL CONTACTS OF A CONNECTOR

3.1 Analysis, abstraction and modeling

The following deliberations will be formulated using the notations defined by the Contact &Channel Approach [10] as the according model is used for analysis as well as for synthesis.

In order to achieve lowest contact resistance which causes lowest heat generation and thus allows for highest current handling capacity, perfectly smooth and clean contact surfaces would be necessary. Leidner et al. [12] confirmed that smoother surfaces show higher numbers of a-spots then rougher ones. However, this kind of perfection is impossible; production of technically smooth surfaces is very expensive and in this case not even sufficient. This would mean an idealized Working Surface Pair WSP 1.3 in Figure 2, Figure 3 and Figure 4. As described above, between real contact-surfaces there are surface asperities and insulating layers which are to be penetrated or broken mechanically in order to permit electric conductivity. Mechanical penetration could be managed by higher contact forces. However there are narrow limitations for those due to corresponding forces for insertion and withdrawal of the connector as well as resulting mechanical relaxation mechanisms.

Several manufacturers of high current connectors use additional components to decrease contact resistance and increase reliability of the connection. These components aim to provide multitudes of parallelized individual contacts with independent contact forces. It is realized as a lamellae packet or wire cage between pin and socket or also between flat contacting bodies, which creates defined contact areas at high contact pressures and thereby increases reliability and decreases resistance. Another principally related approach is to directly contact woven copper wires with a conventional pin [13]

Figure 2 shows a schematic cross-section of plug connector housing with one exemplary enlarged pin and socket connection. The waved lines illustrate Channel and Support Structures (CSS) transferring energy and the straight lines at their interfaces mark the according Working Surface Pairs (WSP). Interfaces and interrelation to surrounding environmental influences and boundary conditions are represented by so called connectors, marked by a “C” on the outer WSP. The advantage of the element modeling approach C&C-A is that there is a clear focus on the Working Surface Pairs and the accordant Channel and Support Structures fulfilling the system’s functions. This abstraction helps to identify the actual task-fulfilling elements, locations of occurring effects and respective properties, as it was shown by Thau an Alink [14].In this case the focus is set on the actual interface of two power lines which are to be connected conductively, i.e. WSP 1.3 (dashed line rectangle in Figure 2).

The very fact that there is electric contact between parts of plug and socket surfaces is not a function but only an effect (Figure 3, top), whereas the transfer of electric current from one wire to another is the actual function of the connector (Figure 2).

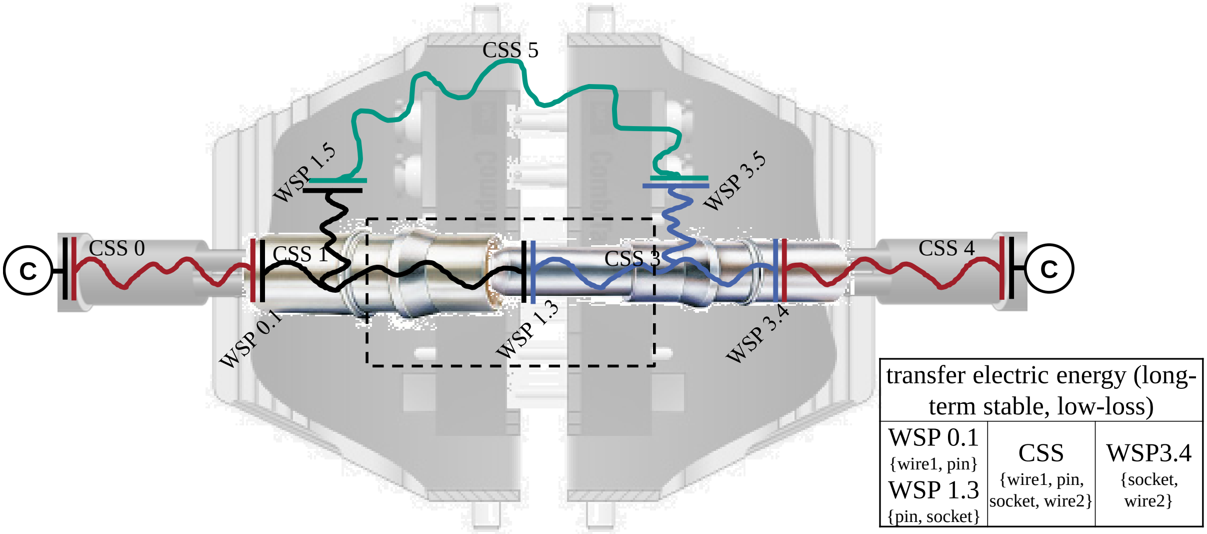

Figure 2: CSS and WSPs marked in a schematic connector with an enlarged view of one pin and socket connection. The tabular representation assigns the connector’s main function to single WSP and CSS.

As it was described in the first section, all real surfaces not being extremely noble are partially covered by insulating foreign layers. This can be modeled in an abstract way as a parallel circuit of conducting areas leading the current paths and insulating areas constricting the current paths. The insulating areas are represented by a Channel and Support Structure of unintentional property (CSS 8 in Figure 3 and Figure 4) with the function *locally prevent electric contact.* This CSS can hardly be prevented and consists of the entity of non-conducting media such as foreign layers, impurities or air between the surfaces. Hence it is the design approach of choice, to provide for a multiple parallelization of the effect *conducting electrically* in WSP 1.3. This leads to the design of multiple defined current carrying areas. As mentioned above, this design solution is already realized by various versions of multi-contacting elements (e.g. lamellae cage) between the two initial contact partners. This evolution of thoughts can be illustrated by the Contact and Channel-Approach as shown in Figure 3.

Main function of a connector – detachable stationary connector– is to transfer electric energy as lossless and long-term stable as possible. This main function can be divided in two sub-functions *make and release contact* and *remain electrical contact at low resistance*. The latter can in turn be divided into the sub-functions *uniformly distribute the current flow* and *dissipate heat.* Especially the sub function *uniformly distribute the current flow* is a key function, as its fulfillment also shows effects of decreasing resistance, thereby decreasing heat generation which in turn lowers the importance of dissipating heat and increases the possibility to remain at defined contact area.

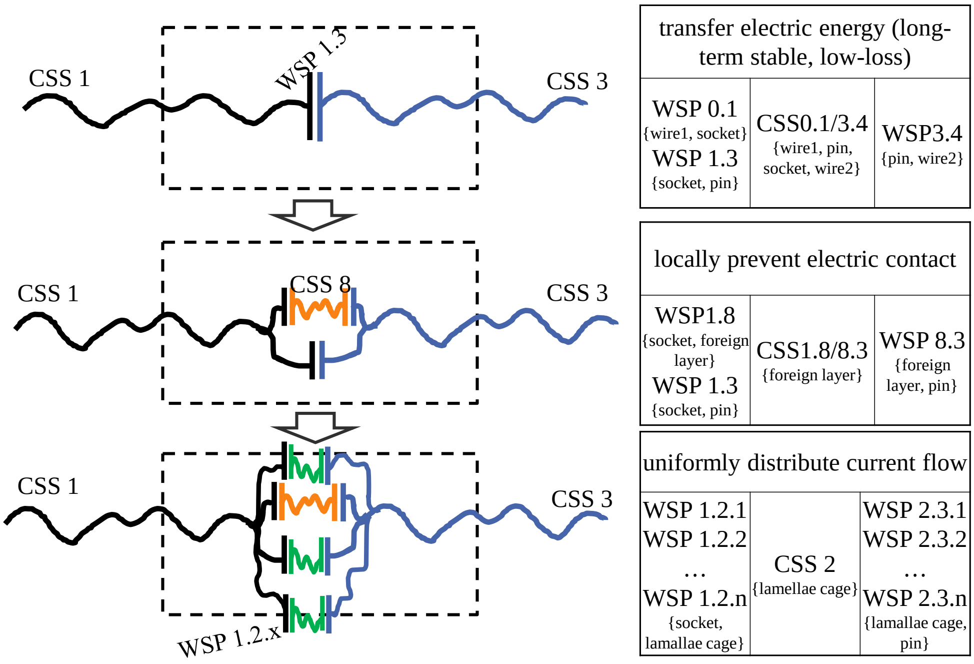

Figure 3: Steps of more detailed analysis of WSP between pin and socket.

The function *uniformly distribute the current flow* is fulfilled by parallelization of a multitude of contact lamellae. In combination with adequate contact forces respectively pressures the contact lamellae also fulfill the tasks of overcoming foreign layers at making contact, as well as hindering growth of foreign layers due to the defined WSP.

On the other hand the additional component between pin and socket provides two serial WSP, i.e. contacts, namelypin – lamellae packet (WSP 1.2) and lamellae packet – socket (WSP 2.3), which is an undesirable side effect. Additional serial contacts mean additional contact resistance and potential cause for malfunctions, as well.

3.2 Synthesis

The idea of uniformly distributing the paths of current flow is carried on onto the micro scale. Creating multitudes of individual contact spots each of very small dimensions equally distributed over the nominal contact area should be able to further decrease resistance and thus increase current handling capacity. Additionally Langhoff and Graesle [15] state that for high current contacts it is particularly important to keep reserve of contact areas in order to enable self-healing processes and prevent overheating. The resulting design approach is illustrated accordingly in Figure 4 (top and middle).

According to the principle of embodiment design *division of tasks* [16], for high production quantities it is favorable to choose the design principle of *integration of functions* rather than the *separation of functions*. Integration of functions generally results in a smaller number of parts or components fulfilling several functions at the same time. Whereas separation of functions consequently aims to a solution in which every part or component fulfills just the one function, which it is perfectly designed for. As every additional component creates double number of serial contacts and high production quantities can be assumed *integration of functions* is chosen.

In Terms of the C&C-A, the principles of embodiment design described above can result in different solutions following the design rules *integration of additional CSS* and/or *division of existing WSPs.*

Application of both of those design rules leads to the solution of integrating the CSS 2 *{lamellae cage}* and of dividing the macro WSPs 1.2 and 2.3 into multitudes of micro WSPs directly on the initial contact partners surfaces cf. Figure 4 (bottom).
This design solution, as a result of the synthesis by C&C-A complies with results of comparable approaches, e.g. application of Axiomatic Design [13].

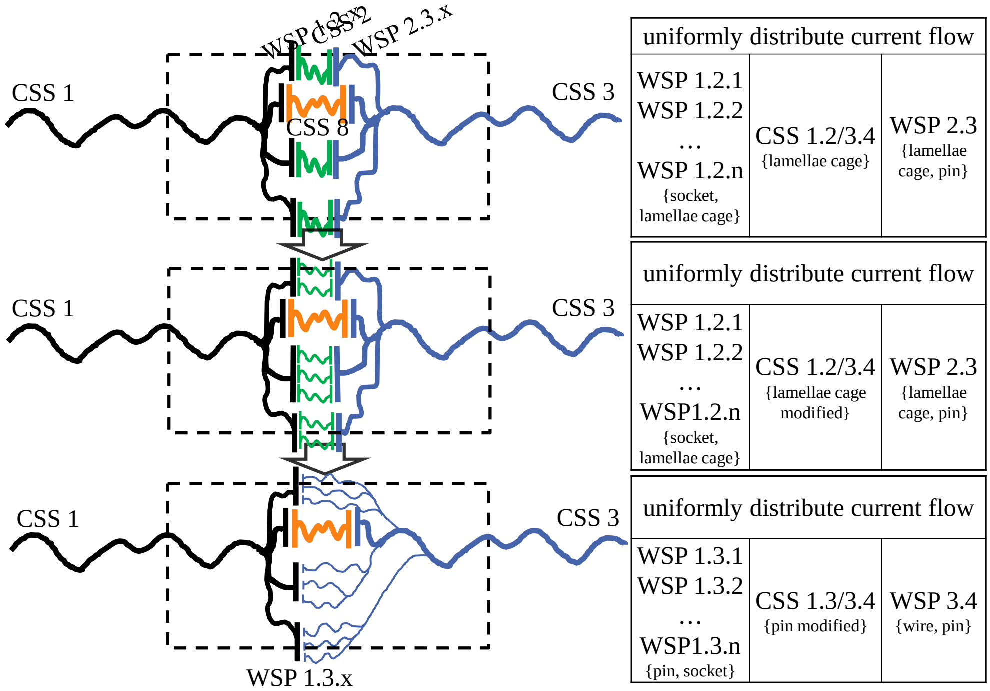

Figure 4: Steps of Synthesis towards new design for connector's contact area.

For synthesis of an improved plug connector system the abstract C&C-model is again linked to real shape design according to the respective requirements. The approach to create multitudes of individual micro contact spots can either be implemented on one of the nominal smooth contact partners or can additionally be applied on existing multi-contact-components. During development and test phase, this design is realized by physical vapor deposition at high vacuum of electrically conductive materials (high purity copper) on substrate specimen which represent the initial contact surface.
During deposition processes masks with different structure images are positioned on the substrate specimens so that various patterns of micro structured topography are designed (Figure 5).

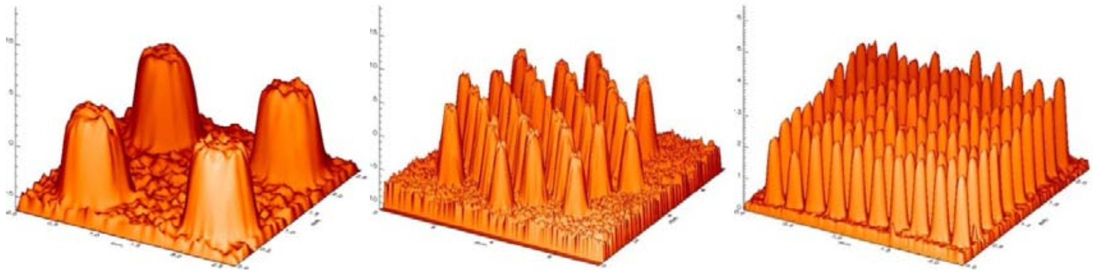

Figure 5: Different structure patterns taken by means of white light interferometry.
4, 29 and 100 contact spots per array (from left to right).

Every surface of micro structured specimens is studied by means of white light interferometry before test. There are three identical arrays of micro-structures in every studied contact to ensure actual contact of every array. Figure 5 shows one array each of different number of contact spots.
A further challenging task is to implement the synthesized C&C-model into a FEM-model of sufficient detail depth. As well, experimental data has to be generated in order to verify models and according simulation. Validated models can be used to investigate concept variants and only optimized ones have to be proved experimentally.

4 FINITE ELEMENT MODEL

4.1 Model development

A three dimensional model of a layer has been modeled, representing a contact between two discs (Figure 6). The upper one has a flat surface whereas the lower one takes into account the surface roughness of the three spot regions (right on Figure 6).

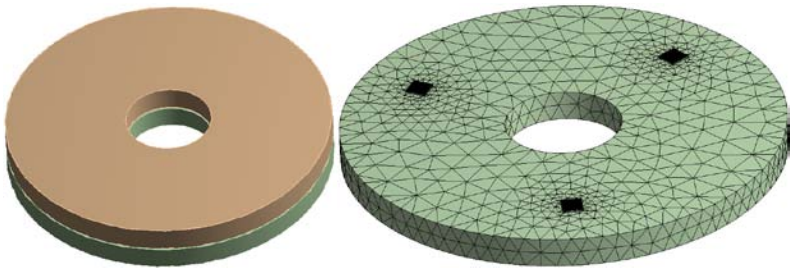

Figure 6: FEM model of a contact pair (left) composed of three spot –regions (right)

Each of the three structure pattern comprises four contact spots (12 for the whole model, as displayed in the left of Figure 5). The spots are made of copper whereas the rest of the plate is structural steel. As a consequence, the model is composed of 5 solids in contact: 3 rough spot layers (copper) and 2 flat discs (steel). The accordingly required simulation process is displayed in Figure 7.

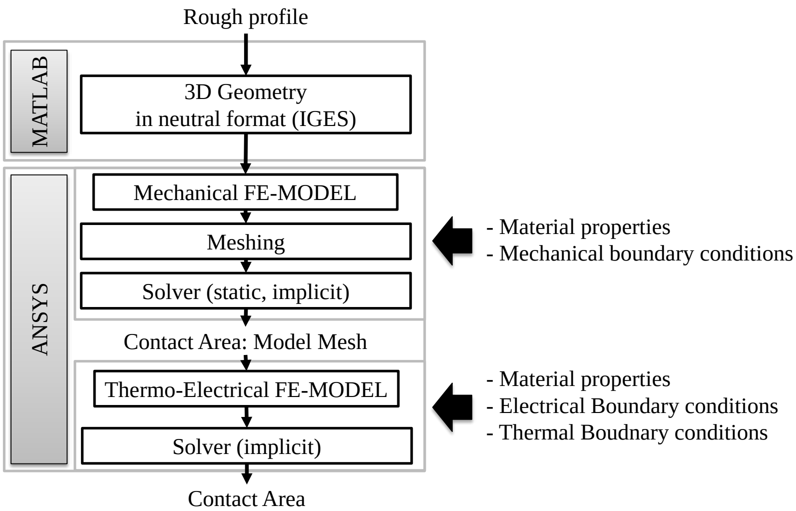

Figure 7: Modeling process

The first step is to import the spot topography into the finite element software. To achieve this, a Matlab script has been developed to generate B-Splines [17] with numerical data coming from the measuring facility in ASCII form. These data are a numerical discretization of the real topography.
Once generated, the three dimensional surface with five additional flat surfaces features a solid in a format neutral file (IGES) in order to avoid any finite element solver dependency. This solid generation is processed three times, as there are three spot regions to be generated. The rough structures are then imported into finite element modeler in order to complete the geometry by creating both steel discs. The three rough bodies are then fixed on the lower disc (Figure 6).
The simulation process composed of two main phases begins after the geometry is imported. The first phase is used to build the contact between both discs with comparable loads a used during experiments (≈ 3.5 N). The second one consists in applying electrical and thermal loads in order to measure the electrical resistance of the system. In order to achieve this, the application of adequate boundary conditions is necessary which is explained in the next subsection.

4.2 Applied boundary conditions and contact configuration

The initial state is an open contact as there is no real possibility to close all of the 12 potential contacts because of their non-planarity (cf. section 2). In order to generate a contact between spot regions and upper disc, a displacement is applied to the first structure whereas the second one is fixed.

As contact properties, the Augmented Lagrange Method is employed. The reason for this is a higher accuracy and better ability to avoid unrealistic high stresses and penetration depth. The algorithm is highly sensible on the contact pinball radius and contact stiffness. As a consequence using a very small pinball radius (≈ $8 \cdot 10^{-10}$ m) is necessary regarding to the structure finesse. Furthermore, contact stiffness is actualized every substep of the calculation to avoid unrealistic high contact pressure. Results of calculated contact pressure are displayed in Figure 9.

In the second phase, the mechanical contact properties are directly taken from the final state of the first phase and used for electro-thermal calculation. Electrical load consists in applying a current of 10 A flowing through both discs. Additionally, as thermal load, a convection flow (occurred by the surrounding air) is applied on both discs with a convective coefficient of 28 $W \cdot m^{-2} \cdot K^{-1}$.

Thermal contact properties are also dependent from the pinball region, as well as from the contact conductivity linked with the physical state of concerned surfaces regarding oxidation and impurities.

5 RESULTS AND DISCUSSION

The target effect of decreased contact resistance by multiplied number of individual micro contact areas could be verified by experiments (Figure 8). As nominal contact area the cross section of created micro spots is accounted. Every data point in Figure 8 represents the arithmetic mean of hundreds of thousands measured values each series taken over periods of 10 to 50 hours.

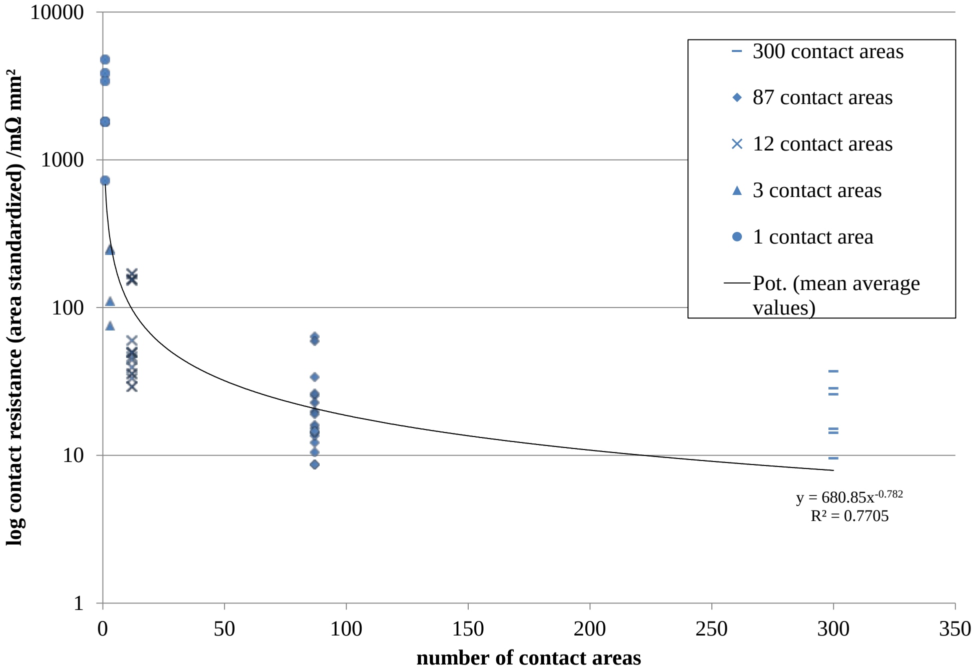

Figure 8: Area-standardized contact resistance over number of individual contact areas.

However, simulation results revealed the fact that the artificially created micro-spots in turn show varying numbers of actual contact spots (Figure 9) as well. Some areas show multitudes of a-spots, others show none. It is reasonable to expect this being real behavior.

This is one reason for a deviation between computational model and experimental data. Other reasons for this are the actual missing consideration of foreign layers in the model as well as the sum of remaining general sources of deviation. Future models are supposed to consider effects from Foreign/insulating layers, Temperature rise, Elastic/plastic deformation, Relaxation effects and Vibration/friction/wear. A main objective is to extend the system boundaries towards a model considering the whole connector, even including its housing.

In numerical simulations, various tests confirmed the significant impact of the normal load on the contact area. Figure 9 points out the differences between high loads (on the left) inducing larger contact areas and also more contacts in general and lower loads here leading to only one spot providing contact areas (on the right). Contact area strongly influences the electrical resistance of the modeled contact as explained before. Still, for higher loads contact pressures are remarkably higher (approx.500 MPa) than for low loaded surfaces (on the right) where the pressure is around 200 MPa.

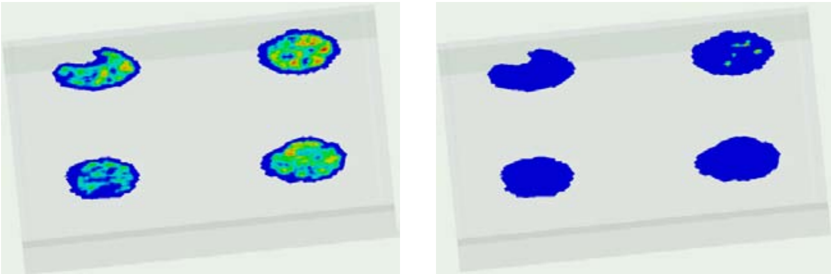

Figure 9: Contact pressure at one of the three spot regions with high load (left) and low load (right).

The thermal-electrical simulation was done with both preceding contact conditions. The applied current and convection gives realistic results but still with deviation compared to experimental measures. The temperature field displayed in Figure 10 corresponds to the contact zones calculated before. High loads induce better temperature homogeneity (on the left) in comparison with lower loads (on the right).

In addition to the calculations discussed before, the electrical resistance of the contact is simulated. Calculated resistance is of around 70 mΩ according to a voltage of approx. 700 mV for the low loaded version. The calculated temperature reaches about 50°C in the contact zones (Figure 10, dark). High loaded contacts show lower temperatures due to larger contact area and higher number of contacts resulting in lower contact resistance.

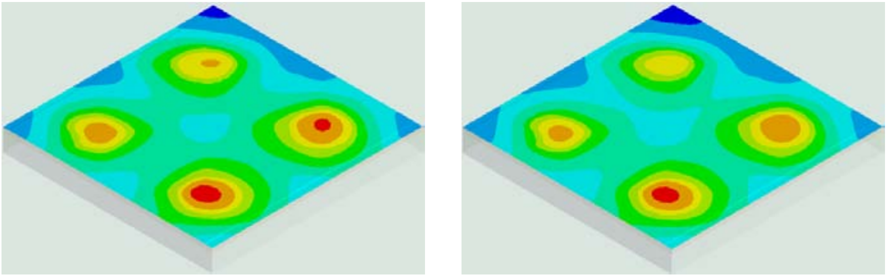

Figure 10: Temperature field in the contact, high load (left) and low load (right).

Comparison with experiments revealed a difference of voltage drop of around 500 mV between simulation and experiment. An explanation for this is found in the conductivity of the boundary layers as well as in size and number of contact areas depending on the contact tolerances of the model. These tolerances define contact identification (opened/closed). Nevertheless, the global trend that higher loads increase the number of contact points inducing a lower resistance was confirmed.

6 CONCLUSION AND OUTLOOK

The design solution of parallelization of electrically conducting contacts by means of micro structuring principally provides potential for high current connectors with higher energy efficiency and thus higher current handling capacity. It is not clear though, if this is valid scale-independent, what is planned to be studied closer during further investigations. Generally, it is a promising approach to overcome the conflict of objectives between connector's performance and its efficiency (energy, connector's size). Hence, the Contact & Channel Modeling Approach (C&C-A) was applied successfully to support focused analysis as well as target-oriented synthesis.

Next steps will be further development of the FEM-model including the influences of thermal conditions and generation of foreign layers. Objectives for design will continue to be decreasing contact resistance, leading to less heat generation and thus higher current handling capability. Finally one holistic model is planned to be used for generating and validating further potential innovative solutions for connector design. Holistic here means considering the entity of actuating variables on the entire connector system.

Only consequent union and comparison of simulation and experiment will allow generating holistic multi-physic models. With Physical Vapor Deposition a very flexible technology is used to create various surface topographies. All resulting designs have to be assessed regarding not only resistance and current handling capacity but also subsequent regarding manufacturing possibilities, wear and impact on actuating force.

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