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Temperature and Yield Stress Characterization of Electric Contacts by 3D Numerical Simulation

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Abstract: Electric contacts of riveted type are analyzed by 3D simulation of their mechanical, electrical and thermal characteristics. Special emphasis was put on dependencies of contacts' temperatures on chosen contact material and applied load conditions. Mechanical characteristics of contacts are considered through yield stress distributions and their maximum value dependences on contact material, geometry and dimensions. All simulations are performed for contacts within switching device, i.e. together with suitable supporting structure. Results are discussed on the basis of appropriate contact material selection and determination of reliable operating time for different geometry, dimensions and imposed loading conditions of contacts.

Keywords: Electric contacts; 3D simulation; Mechanical, Electrical and thermal characteristics.

1 Introduction

Nowadays, with global tendency of miniaturization and massive production of more cost effective electric devices, modern electric circuits often exploits power semiconducting devices for their closing and opening control. In spite this fact, for manufacturing of household appliances, automotive, telecommunication and aerospace engineering switches and relays still play an important role. Their basic parts are electric contacts that perform mechanical closing and opening of electric circuits.

Considering the versatility of switches and relays, electric contacts are available in different forms (rivets, profiles, blanks, disks, buttons, etc.) and types (solid and clad) and can be of different sizes. Solid contacts are entirely made of highly conductive materials (precious metals or their alloys), while clad ones are mostly produced of copper with their tops being plated by alloy of precious metals.

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During their exploitation electric contacts are subjected to high current levels, numerous and often on-off cycles, as well as, chemically active environment. Thus, contacts often fail because of material transfer and pitting, arc erosion, corrosion, sticking and welding and even plastic deformation. This reliability issue of performances of designed contacts is complex, due to the lack of information on all of the parameters affecting contacts under multiplicity of operating conditions.

Two crucial parameters for electrical contacts characterization are their temperature and yield stress values under imposed load conditions (i.e. with nominal current flow and appropriate contacting force applied). Namely, electrical contacts have predefined allowed excess temperatures depending on temperature and type of environment in which contacting is performed. Thus, knowing contact temperatures allows limiting of the current values that can be applied on them [1]. On the other hand, simultaneous influence of contacting force and equivalent electro-thermal strain, cause yield stress in some regions of the contacts which, due to numerous on-off cycles, leads to a fatigue or even a failure of contacts. For that reason, the number of on-off cycles that still obtain reliable operation of the contacts is important in design of electrical contacts and switching devices.

Development of electric contacts encompasses several steps, such as choosing contact materials, defining shape and size of the contact and setting minimum contact pressure. Realization of these steps requires knowledge of characteristics of contact materials (electrical and thermal conductivity, hardness and limit of elasticity, chemical activeness and resistance to mechanical wear, arc erosion and welding), geometrical and dynamic properties of contact's structure (shape and dimension of contact, force between contacts, amount of slide, rolling or twisting motion) and properties of the supporting structure (resiliency and tendency to enhance or inhibit bounce). Simulation of electric contacts in mechanical, electrical and thermal domains represents powerful CAD-CAE tool in all above mentioned steps. The results of simulation in 3-D domain enable designed contacts evaluation from proper material choice, adopted shape and size and reliability point of view.

In this paper results of 3-D simulation of mechanical, electrical and thermal characteristics of riveted type electric contacts are presented with special emphasis on dependencies of contact's temperatures and yield stress distributions on load conditions. Results are obtained for solid and clad contacts made of different materials, heaving four characteristic dimensions and two different geometries. Contacts are simulated together with appropriate supporting structure that determines degrees of freedom of contacts within switching device and conditions of electric load and heat dissipation. Steady state is assumed, where contacts are subjected to constant nominal current. For all simulated contacts distributions of current densities and yield stress are obtained, as well as, dependencies of contact temperatures and maximum stress on load current values. Obtained results are discussed on the basis of appropriate contact material selection and determination of reliable operating time for adopted dimensions and geometry of contacts.

2 Simulation Procedure and Design of Considered Contacts

Results of the simulation are obtained by software that complex multiphysic problems solve numerically utilizing finite element analysis (FEA) and multigrid approach. It solves Maxwell's equations simultaneously with heat generation/transmission and elasticity equations. Through appropriate user interface contact material parameters, geometry and dimensions of contacts and supporting structure are given, load conditions are set and obtained solution is displayed graphically. By load conditions, symmetry and degrees of freedom of contacts are specified, values of potential and pressure on contact surfaces are set, as well as method and areas of heat dissipation are defined.

Temperature and yield stress characterization were obtained for riveted type of electric contacts with rounded head since they are commonly used in home appliances, products of consumer electronics and in power switching devices as relays [2]. Cross-sections of rivet contacts with rounded head of both types (solid and clad) are shown in Fig. 1, while values of characteristic dimensions are listed in **Table 1**.

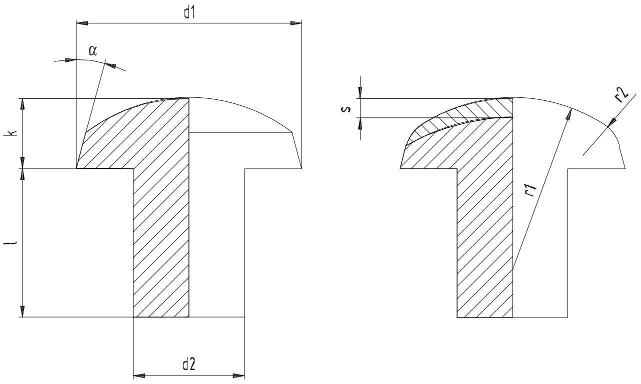
Table 1

Dimensions of rivet contacts [2].

Contact dimension	Value (mm)	
	solid	clad
Head diameter - d_1	3	5;5.5;6
Total head height – k	0.7	1
Shank diameter - d_2	1.5	2.5
Contact layer height – s	-	0.5
Shank length – l	0.7	1
Head and contact radii – r_1; r_2	10; 0.5	10
Head taper angle - α	15°	0°;15°

Head diameter of simulated solid contact was 3 mm, while for clad ones they were 5; 5.5 and 6 mm. For clad contact with head diameter 5 mm two geometries are considered (head taper angle 0° and 15°).

Contact materials (kind and composition) were chosen according to data from catalogues of the major world manufacturers [3-5] and market requirements. Silver with purity of 99.99% was selected to be material for solid contact, while copper and alloys: 90%Ag-10%Ni and 97%Ag-3%Cu (hard silver) for clad one. By electrical and thermal conductivity alloys Ag-Ni and Ag-Cu are very close to the pure silver but they have much better mechanical characteristics. Values of physical, mechanical, electrical and thermal parameters of considered materials are summarized in **Table 2**.



(a) (b)

Fig. 1 – *Cross-section of solid (a) and clad (b) rivet electric contacts with rounded head.*

Table 2

Physical, mechanical, electrical and thermal parameters of contact materials [3-5].

Material	Melting point (K)	Young's modulus of elasticity (GPa)	Poisson's coefficient	Brinell hardness (MN/m^2)	Specific electrical resistivity (Ωm)	Temperature coef. of specific electrical resistivity (K^{-1})	Thermal expansion coefficient (K^{-1})	Thermal conductivity (W/mK)
Cu	1356	130	0.34	40	$1.69 \cdot 10^{-8}$	$4.29 \cdot 10^{-3}$	$16.5 \cdot 10^{-6}$	401
Ag	1234	83	0.37	26	$1.62 \cdot 10^{-8}$	$4.1 \cdot 10^{-3}$	$18.9 \cdot 10^{-6}$	419
90%Ag -10%Ni	1234	83	0.37	65	$1.89 \cdot 10^{-8}$		$18.9 \cdot 10^{-6}$	310
97%Ag - 3%Cu	1173	83	0.37	45	$1.75 \cdot 10^{-8}$		$18.9 \cdot 10^{-6}$	350

As a supporting structure of contact is used copper plate with dimensions (10mm × 4mm × 0.5mm) for solid and (15mm × 6mm × 0.5mm) for clad contact. Cross-section of the system contact-supporting structure is shown in Fig. 2, with noted contacting surfaces (1 and 2) on which appropriate loading conditions are applied.

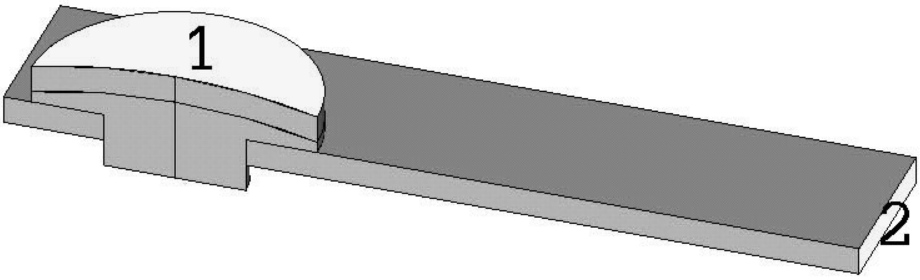


Fig. 2 – *Cross-section of the system contact-supporting structure.*

Loading conditions of the contacts are primarily determined by the area of their utilization. Thus, solid Ag contact is simulated for application in devices of consumer electronic and household appliances, where supporting structure is fixed only at contact surface 2 and nominal currents are below 15 A. Contacting force is applied on contact surface 1, with values of 0.15N/A for currents up to 1A and 0.2 N/A for higher current values. Simulated clad contacts have greater dimensions since their application is in high power switches for currents up to 50 A. Two sets of simulation results are obtained concerning supporting structure (plate) of clad contacts: a) plate is fixed only at contact surface 2 (Cu/Ag-Ni contact) and b) plate is fixed at contact surface 2 and at the bottom surface which disables its bending (Cu/Ag-Cu contact). For both sets contact surface 1 was subjected to contacting force of 0.36 N/A.

During the simulation, contact surface 2 was kept at the zero potential, while potential of contact surface 1, for different contacts, had taken value from the range of $1\cdot10^{-5}\div3\cdot10^{-3}$ V. According to these potential differences currents in contacts were ranged from 0.15A up to 45.5A.

For heat dissipation from free contact's surfaces and supporting structure (it is assumed that system is in the air) convection regime was assumed. Thus, convection coefficient of 28.4 W/m^{2}K and ambient temperature of 300 K were used in thermal simulation.

3 Results and Discussion

Structural deformation of the system Ag contact-supporting structure when contact pressure of 99KPa (for nominal current of 1.5A) on surface 1 is applied is shown in Fig. 3. Displacement of the system is determined by fixed contact surface 2 and contact pressure is mostly compensated by elastic properties of contact material of the supporting structure and contact. System before the deformation is also shown and value of a maximum bending of the structure is 0.012mm. This deformation can be of importance in design of switching devices since for higher contact pressure i.e. higher current the value of bending can be even 1 mm.

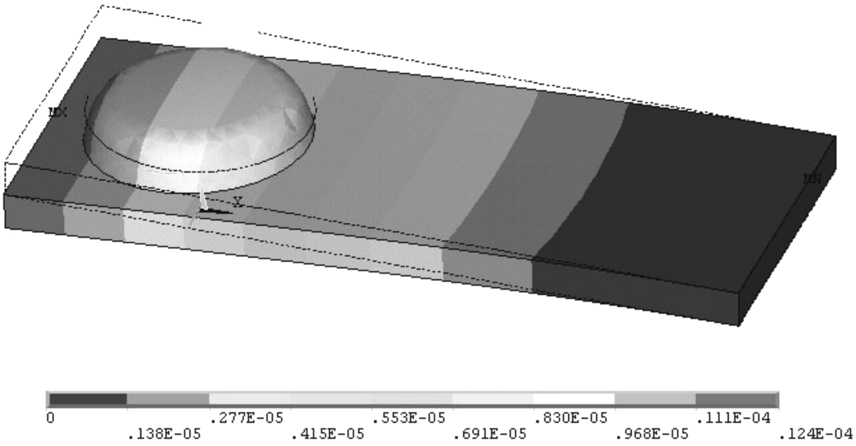


Fig. 3 – *Deformation of the system Ag contact – supporting structure.*

Distribution of electric potential and vector representation of current density inside the system with Ag contact while current of 1.5 A is applied are presented in Fig. 4 and Fig. 5, respectively. From Fig. 4 is evident that equipotential surfaces are determined by geometry of the structure, as well as, by high electrical and thermal conductivity of used materials. From Fig. 5 regions where current density reaches maximum and local Joule's heating of the contact is the most pronounced can be easily obtained. These regions are 'hot' areas in the structure, where initialization of different thermally activated degradation processes, such as welding and material migration, can be expected. In this case these regions are boundary of contact surface on contact head and junction between the contact's head and shank. Similar distributions of the current density are obtained for contacts made of Ag-Ni and Ag-Cu alloys since values of their electrical and thermal conduction parameters are very close to each other.

Distribution of temperature in the contact depends on load conditions, temperature coefficient of specific electric resistivity, thermal conductivity of the material, areas and regime of heat dissipation. Simulations showed that, due to high electrical and thermal conductivity of used materials and large heat dissipating areas of the contact, temperature distribution in contacts for adopted load conditions is uniform [6]. Dependencies of the contact temperatures on the current intensity for simulated contacts are given in Fig. 6. It is evident that clad Cu/Ag-Cu contact has higher temperature values than clad Cu/Ag-Ni contact for same current levels. This is due to different fixing methods of their plates since both clad contacts have the same geometries and their materials are with similar electrical and thermal conducting properties. Namely, Cu/Ag-Cu contact plate is additionally fixed at its bottom side and areas of heat dissipation are reduced. Therefore, for the analysis of contact application from the thermal point of view, knowledge of their assembling characteristics in the switching devices is of importance.

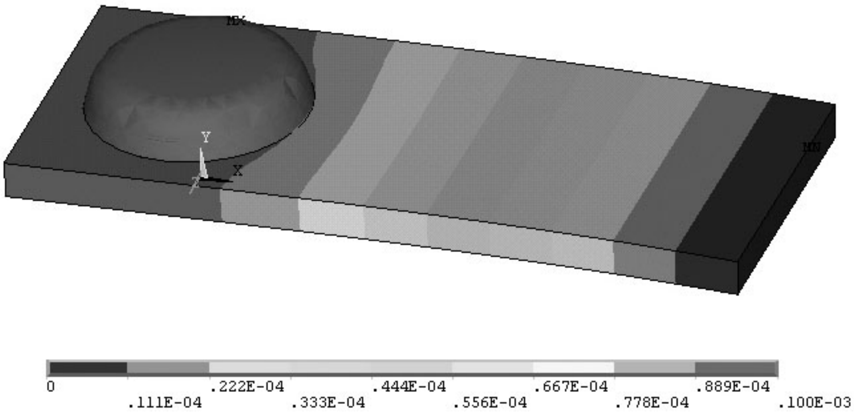


Fig. 4 – *Electrical potential distribution in system with Ag contact.*

Moreover, on the basis of dependencies from Fig. 6 and allowed excess temperatures respecting to the ambient temperature, limiting current levels for contacts and therefore areas of their application can be determined. Allowed excess temperatures are defined by appropriate standards and for silver plated contacts made of copper operating in the air it is 50 K [1].

Distribution of yield stress (induced by contact pressure and thermal expansion of the contact due to Joule’s heating) in solid Ag contact when current of 10.75A is applied is shown in Fig. 7. Point of maximum yield stress is a place of potential structural deformation of the contact and it can be easily obtained from the given figure. In this particular case it is at the contact edge along the supporting structure in the direction of maximum current density and has a value of $2.4 \cdot 10^7$ Pa. Simulation show that this is the place of maximum stress for all applied current values and dependence of these two quantities is given in Fig. 8 (for d1=3mm).

Almost linear dependence of maximum stress on current values is observed. It is a consequence of direct proportion between contact pressure and applied current (system is fixed only at the contact surface 2) since yield stress is mainly caused by mechanical load while electro-thermal effects are of a second order.

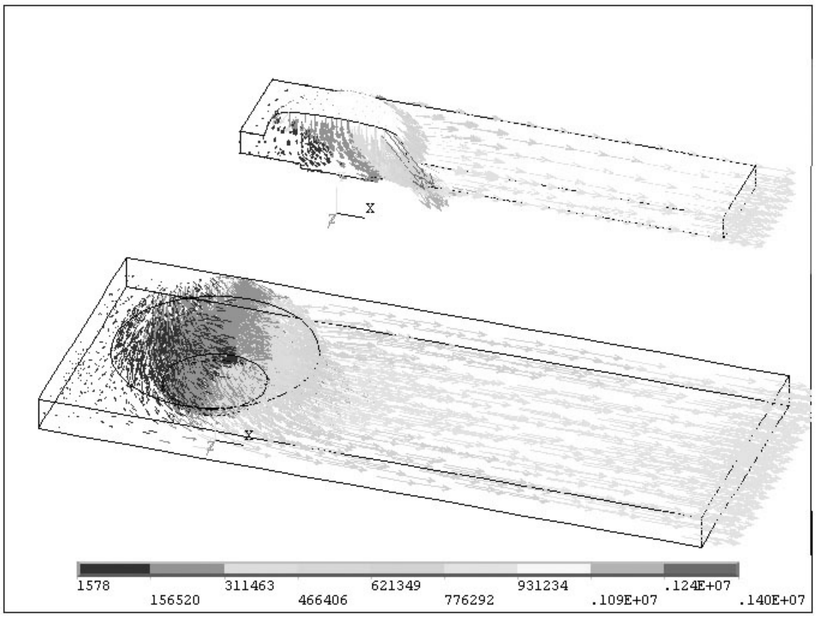


Fig. 5 – *Current density distribution in system with Ag contact.*

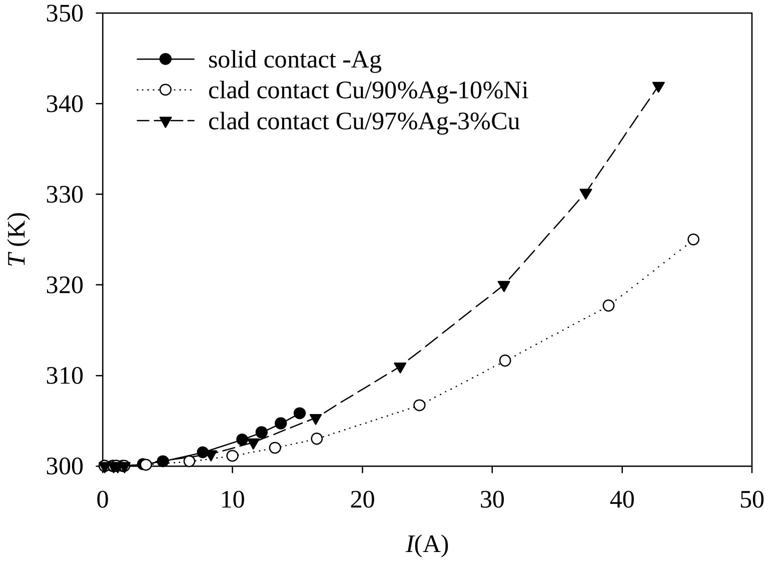


Fig. 6 – *Contact temperatures vs. current intensity.*

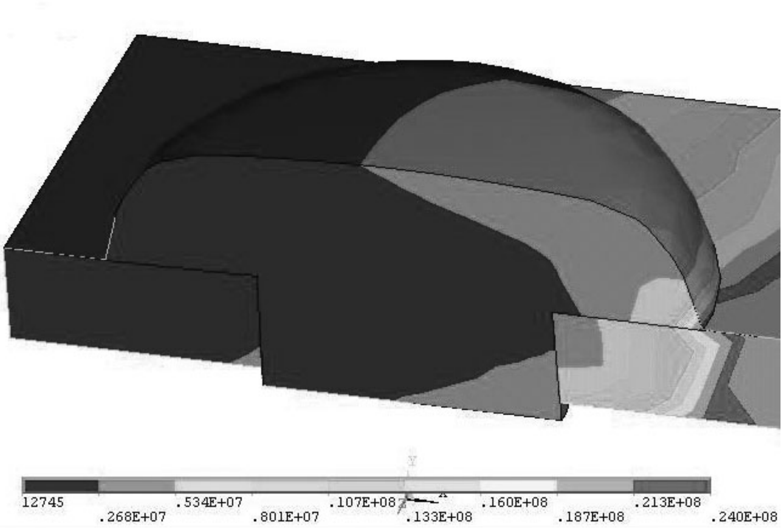


Fig. 7 – *Yield stress distribution in solid Ag contact.*

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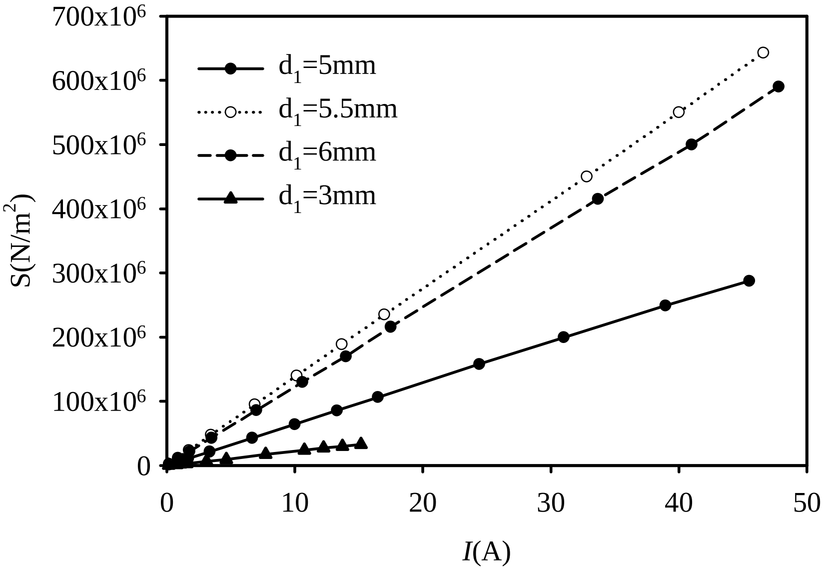

Fig. 8 – *Dependence of maximum yield stress on current values.*

In Fig. 8 dependencies of maximum yield stress on current values for Cu/Ag-Cu clad contacts with 3 different head diameters subjected to the same contact force (0.36 N/A) and fixed at contact surface 2 are also presented. As for solid contact, points of maximum stress are at the contact edge along the supporting structure in the direction of maximum current density and there is linear dependence between stress and current values. However, due to clad structure, where two materials of different mechanical, electrical and thermal parameters are in contact there is no straight connection between head diameter and maximum stress values.

Fig. 9 represents distributions of yield stress in the system with clad Cu/Ag-Cu contact additionally fixed at the bottom side, for two current values (I=1.67 A and I=30.9 A). It can be noted that for lower current values (Fig. 9(a)) maximum stress is in the shank of the contact and it is a consequence of the contact force acting on materials with different elastic properties. Namely, as it is shown in Fig. 6, for this current level thermal expansion does not have effect since the temperature of the contact equals referent one. In the case presented in Fig. 9(b) thermal expansion takes place and point of maximum stress is at the contact edge along the supporting structure in the direction of maximum current density.

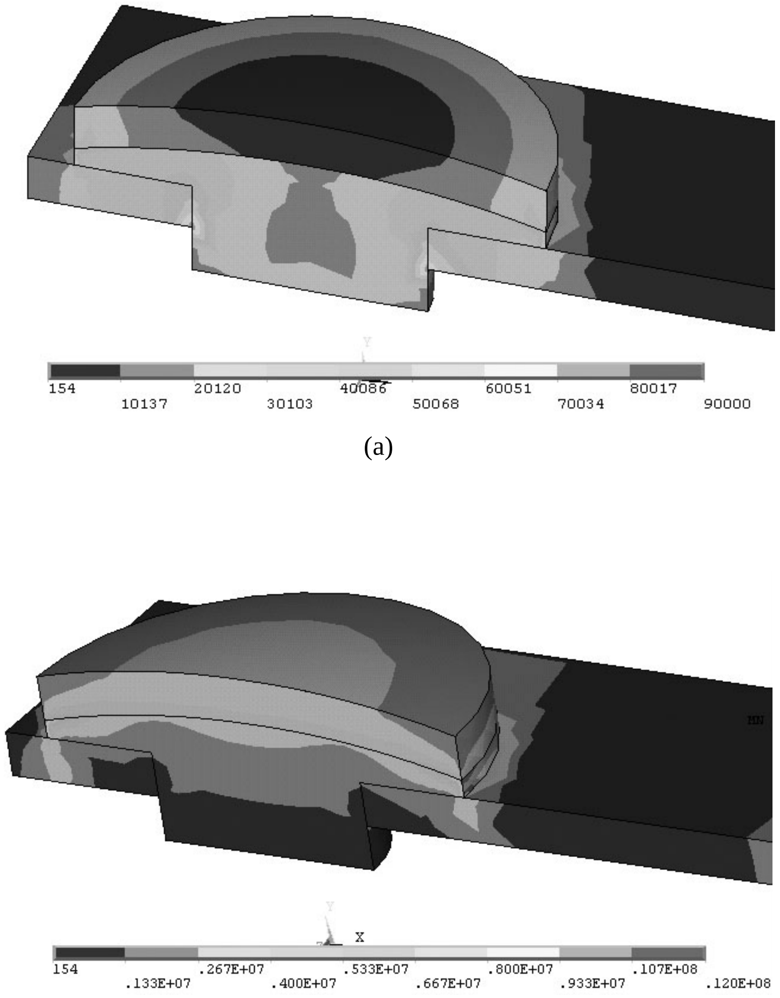

Fig. 9 – *Yield stress distribution in the system with Cu/Ag-Cu contact with head diameter of 5 mm for current of (a) 1.67 A and (b) 30.9 A.*

Values of maximum stress for the range of applied load currents and three different head diameters for the above mentioned system are given in Fig. 10. These values are lower then one shown in Fig. 8 due to redistribution of contact pressure from contact surface 1 to the whole contact structure.

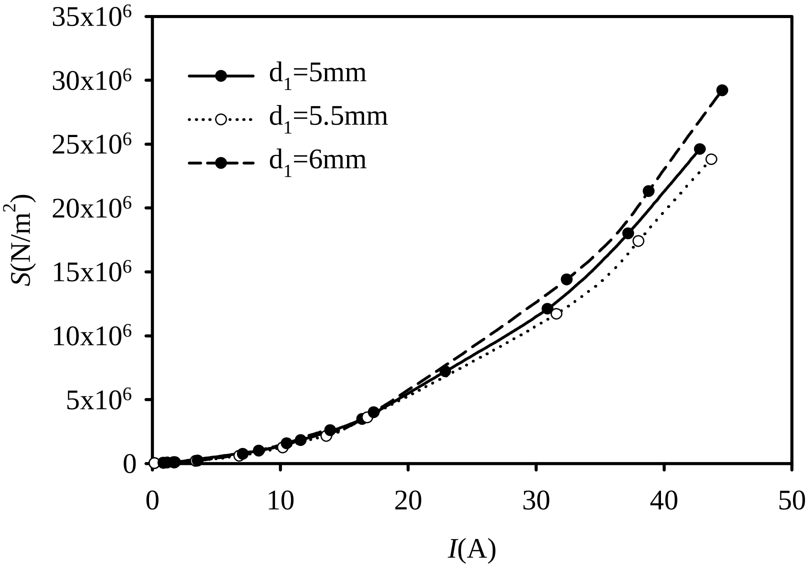

Fig. 10 – *Dependence of maximum yield stress on current values for contacts additionally fixed at the bottom side.*

Reliable operating time of the contacts under defined load conditions can be determined from so-called S-N curve of given material (dependencies of induced stress on applied number of loading cycles). For silver and copper (chosen contact materials) these curves are given in Fig. 11 [7, 8]. By comparison of Figs. 8 and 11 it can be concluded that considered solid Ag contact should provide reliable operation up to 10^6 contacting cycles. On the other hand, for clad contacts reliable operation is limited to 10^4 cycles for d_1=5mm and even less for d_1=5.5mm and d_1=6mm. Long term reliability is not fulfilled by this value which make this type of fixing of contacts unsuitable for massive production. However, additional fixing of supporting structure at the bottom side upgrades reliability of the system in grate extend (up to 10^6 cycles), as can be concluded from Figs. 10 and 11. Head diameter is not a critical parameter since maximum stress values are close for all diameter values and they can not be explicitly predetermined. These considerations on reliability issue of contacts determine their application areas and economical parameters of their massive production. In design of contacts they impose necessity of finding compromise between amount of used materials and obtained contact resistivity.

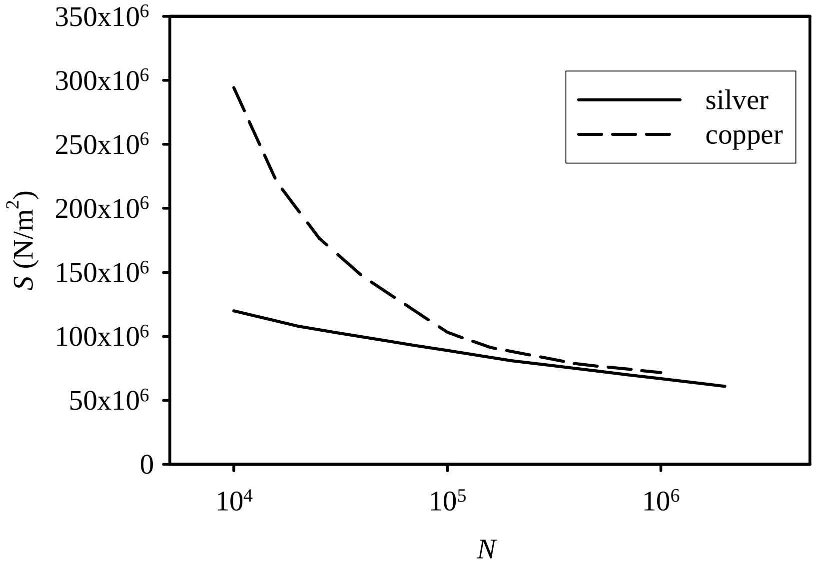

Fig. 11 – *S-N curves for silver and copper [7, 8].*

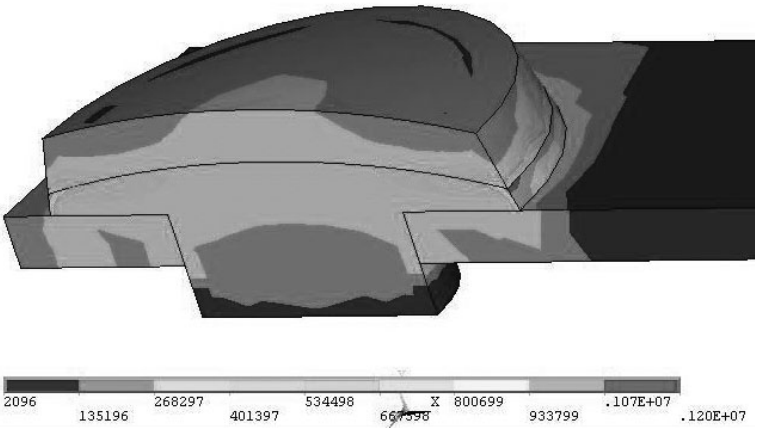

Fig. 12 – *Distribution of maximum stress in clad contact with* d_1*=5mm and* α*=15° for current of 9.9 A.*

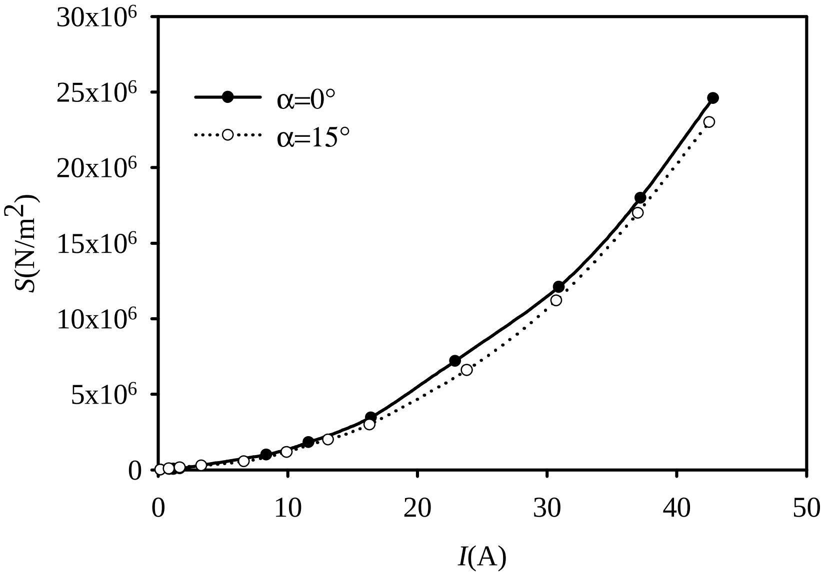

Fig. 13 – *Maximum stress dependencies on current for clad contact with two geometries and d_1=5mm.*

Clad contact with head diameter 5 mm was additionally simulated for geometry with head taper angle of α=15° and distribution of maximum stress in this structure for current value of 9.9 A is represented in Fig. 12. Point of maximum stress is in this case at the junction of copper body and Ag-Cu alloy, while for lower current values it is in the shank as for α=0°. This point is critical since there alloy plate can detach from solid copper body causing contact failure.

Maximum stress dependencies on current values for α=0° and α=15° are given in Fig. 13. Values for α=15° are little lower and this fact should be considered in design of switching devices that uses this type of contacts. In this case compromise should be find between lower material costs and lower maximum stress values against possibility of alloy detaching from the body of contact.

4 Conclusion

3-D simulation of electric contacts in mechanical, electrical and thermal domain provides data necessary for optimal design of contacts and switching devices. For given geometry, dimensions and contacting mode of contacts it enables proper choice of contact material for imposed load conditions. On the other hand, at pre-set contact material, thermal characterization enables definition of the limiting electrical conditions for the contact exploitation and therefore its area of application. Moreover, on the basis of the results of simulation in mechanical domain some changes in geometry of contacts and supporting structure can be suggested.

From the reliability point of view, values of maximum yield stress induced by mechanical and electro-thermal loading of contacts determine number of switching cycles for whom reliable operation of contacts is achieved. Simulation results obtained for different geometries and dimensions of contacts and different fixing methods, while knowing S-N curves of contact materials enable definition of optimal design parameters and exploitation conditions of contacts.

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