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ON THE PROBLEM OF CONTACT ELECTRIC RESISTANCE OF DIFFERENT-SIZED SURFACES

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The theory of electric contacts assumes an experimentally-verified inverse proportionality of electric transient resistance to applied load. The paper shows that this condition is not fulfilled at small compression forces of different-sized contacts, which take place, in particular, in excitation of electric arc by contact or breakup of thin conductor. Measurements of electric resistance of near-contact area between thin (0.75 mm diameter) conductor and sheet of steels St37 (steel 10) and 1.4301 (08Kh18N10), brass CuZn37 (L63) and aluminium alloy AlMg3 (AMg3) showed that there is an increase of electric resistance due to elastic deformation of contact surface under the effect of local load at the rise of force to specific limits. Under experimental conditions the boundary force was equal to 2–3 daN, depending on the mechanical characteristics of metal. Beyond these limits a generally accepted functional dependence becomes effective. 12 Ref., 1 Table, 8 Figures.

Keywords: *transient electric resistance, electric contacts, elastic deformation, stud welding*

Role of contact resistance as a nonlinear element of electric circuits is very large and extensive literature is devoted to it. A fundamental source is the book by R. Holm [1], in which the contact region is considered as that of electric current contraction, determined by the real area of surfaces coming into electric contact. Here, considering that roughness microprotrusions on the contacting surfaces have random distribution of height, it is assumed that they are plastically deformed under the impact of applied load, and, thus, the real area of contacting surfaces is determined by the compression force and mechanical characteristics of contact materials.

All the works related to study of transient resistance in electric contacts [1], electric resistance at resistance welding [2], development of physical contact at cold [3] and diffusion welding [4], as well as in mechanical engineering [5], consider the contact between flat (or spherical and cylindrical [1]) surfaces under the conditions of plastic deformation of the surface of an absolutely rigid body.

Considering the deformation of microprotrusions of various shapes, one of the surfaces is considered to be smooth and undeformable. Otherwise it would be necessary to take into account the probabilistic nature of conditions on the contact surface. By the data of work [5], the pitch of microroughnesses, which make up the roughness in their totality, changes from 2 up to 800, and their height varies from 0.03 up to 400 μm. At modeling attempts the real pattern is approximated by spherical, conical, pyramidal and prismatic protrusions, and their actual distribution over the surface is replaced by a scheme, where the notions of «contour» and «apparent» area are introduced. As is shown in work [6], the contour area is equal to 5–10 %, and the actual one is to 0.01–0.1 % of the nominal one.

At the same time, the indeterminateness of microprotrusion geometry and their topography, of randomness of unevenness meeting on the mated surfaces, and of their deformation conditions respectively makes any strict scheme unreal. The only proven by practice conclusion from the numerous models comes down to proportionality of the contact area and electric transient resistance to the applied load $1/P^{\alpha}$, where P is the force of compression of the contacting surfaces, and α is the empirical coefficient varying within 0.3–0.8. It follows from here that the contact electric resistance is independent on the apparent area of contact, i.e. on pressure, applied to the contacting surfaces. As will be shown below, this is valid only at relatively high loads, when elastic deformation in the contact area has been exhausted.

Review of attempts to derive a formula for calculation of contact resistance [7] showed the inapplicability of the known formulas without additional experiment.

Unlike the studied conditions of contacting of solids, at arc excitation by a melting thin conductor, which is in place in arc welding [8], and arc-contact stud welding, as well as at resistance spot welding, the shape of the contacting surfaces in electrode-part contact is characterized by a great difference of the areas of interacting surfaces and of their texture.

This aroused interest in the study of functional dependence of transient electric resistance on the applied force under the conditions, different from those studied earlier, namely, in contact of surfaces different in size.

To study the influence of load on electric resistance in the field of contacting, it turned out to be rational to use the method of arc-contact stud welding as the base. This is due to mass production of studs of an original shape, having a thin protrusion on the welded end. Studs are made by cold heading and that is why the scatter of protrusion diameters and their lengths is practically absent in one batch.

In arc-contact capacitor-type stud welding by the «preliminary contact» method, the process starts from the stud contacting the sheet (Figure 1), as the name suggests, without switching on the capacitor discharge current. Then discharge current is switched on, heating of the thin protrusion starts right up to its breakup with subsequent transition of the process to the arc stage. Such a process is realized with application of a welding gun with an adjustable force of stud pressing down within 1–10 daN.

Experiments were conducted in a device, consisting of a post, with RMK-2 welding gun fastened on it (Figure 2, *a*). As the stud is pressed to the sheet by the welding gun spring, the extension of the protrusion edge relative to the plane of gun supports is kept constant on the level of 2 mm. Resistance was measured by microhmmeter of GOM-802 type with 10 μOhm accuracy. Here, the instrument probes were located as shown in Figure 2, *b*. Resistance of sheet area between stud contact and measuring probe was equal from 61 μOhm (brass L63) to 130 (alloy AMg3).

Experiments (Figure 3) were conducted with M6 studs and sheets from steels St35 (steel 10) and 1.4301 (steel 08Kh18N10), brass CuZn37 (L63), aluminium alloy AlMg3 (AMg3), manufactured by Heinz Soyer Bolzenschweisstechnik GmbH Company. Here, 3 samples from one batch of the respective material were taken.

A characteristic feature of the change of contact resistance, noted by us at load increase, is the difference from the above inversely proportional dependence, namely, increase of the resistance at increase of compression force from 1 to 2–3 daN. Here, as shown by comparison of the graphs, the relative increment of resistance is the greater the higher the hardness of the stud material* and the sensitivity to work hardening at stud manufacturing by cold heading. The latter pertains to steel 1.4301 and two-phase brass CuZn37 [9].

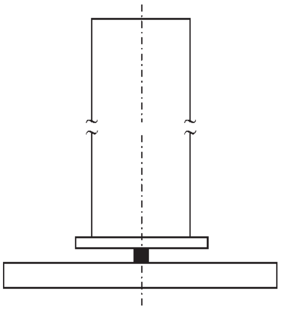

Figure 1. Scheme of the initial stage of the process of stud welding with preliminary contact

For stainless steel the maximum of resistance shifted to the 3 daN mark, whereas for other metals it is on the level of 2 daN (allowing for discreteness of sample compression force).

From the works known to us, only in paper [10] it is shown (Figure 4) that in electrode-part contact at spot welding the electric resistance first grows at increase of compression force, and starts decreasing only after a certain load has been achieved. Here, the dependence was obtained for aluminium alloy. Therefore, in materials characterized by higher elastic resistance than that of aluminium alloys, it was to be expected that this effect will be even more pronounced.

Qualitative increase of contact resistance can be explained, taking into account the difference in the textures of contacting samples (Figure 5). As shear modulus $G = \frac{E}{2(1+\vartheta)}$, where E is the Young's modulus, and ϑ is the Poisson's ratio, having a positive value in metals, it is clear that at elastic compression of parts, having mutually perpendicular texture, the first to deform is the part having a texture, normal relative to the load direction. Here, a gap forms and the area of loaded part contact becomes smaller, and electric resistance grows, accordingly.

Solution of the problem of elastic deformation of a semi-infinite body under the impact of pressure P, uniformly distributed over the end plane of a cylinder of radius r, is given in [11]. Assuming flatness of the contacting surfaces on the micro- and macrolevel, i.e.

Figure 2. General view of the device (*a*) and arrangement of the probes of GOM-802 instrument (*b*) at measurement of electric resistance of the contact region of a 0.75 mm dia protrusion on the stud and the sheet

*Normed hardness values of steel 10–1170 MPa (GOST 4041), steel 08Kh18N10 — 1700 MPa (GOST 25054), brass L64 — 700 MPa (GOST 13726), alloy AMg3 — 450 MPa (GOST 2208)

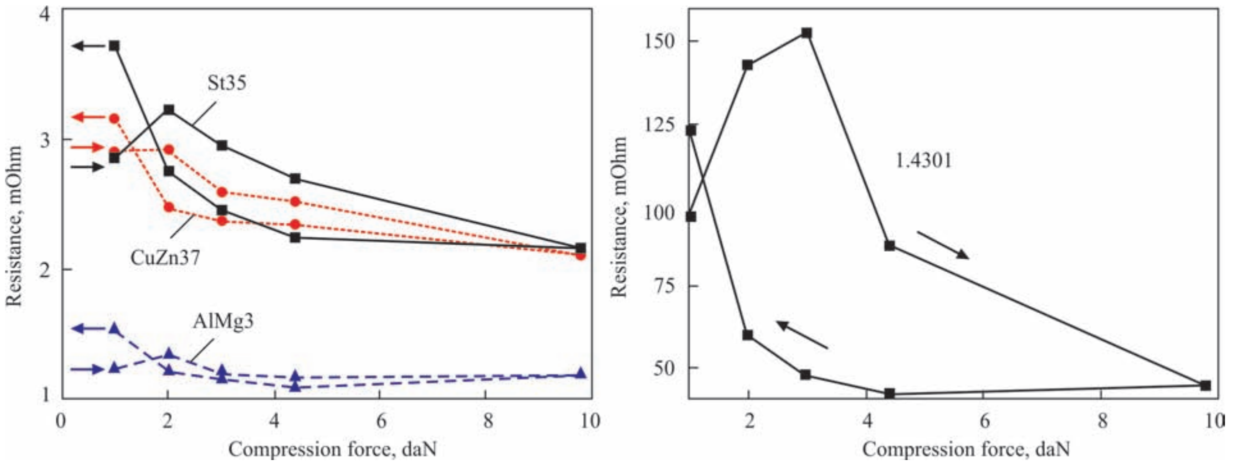

Figure 3. Dependence of electric resistance of the contact zone between the protrusion of 0.75 mm diameter and the sheet on the applied compression force at different scales

absence of their initial loose fit and impact of just the forces normal to the interface, as well as, in keeping with the above remarks, absolute rigidity of the cylinder, the equation of elastic movement of the surface of a semi-infinite body under load within the loaded surface is as follows:

$$u_z = \frac{4(1-\vartheta^2)}{\pi E} \Pr E\left(\frac{R}{r}\right),$$

where $E(R/r)$ is the full elliptic integral of the 2nd kind modulo (R/r), tabulated in [12].

This equation does not allow for movement of a rigid cylinder following the deformation of a plate outside the loaded region in such a way that the outer circumference of the cylinder base rests continuously on the plate.

Calculation of deformation in the central meridional plane of the studied metals, the characteristics of which are given in the Table, yields the value of deviation from the sheet plane (gap between the contacting surfaces), shown in the graphs (Figure 6). This Figure, of course, is just illustrative, as the structural changes in the sheet material at rolling were not taken into account in calculations, in particular, strengthening of the metal surface layer, and a purely elastic and only normal interaction of the compressed surfaces was assumed (we neglected the tangential stresses in this idealized scheme). This is justified by the fact that the protrusion does not have a sharp edge at cold heading (see Figure 7 below), stress concentration on the edge and its plastic deformation at small loads are absent, respectively. Considering what was said about the outer boundary of cylindrical contact resting on the edges of the deformation pit on the sheet, the final values of the gap between the contacting surfaces should be reduced.

With load increase deformation goes from purely elastic one into the elastoplastic region. This is noticeable from comparison of graphs in Figures 3 and 6 and the remark given above at analysis of graphs in Figure 3.

Note also that at low pressures just the surface layer of the compressed metal is deformed and, judging by the photos of metal cross-section after load, given in the above-cited work [10], the roughness microprotrusions at initial loading do not change their shape and do not affect the change of contact zone resistance.

With load increase, ever deeper-lying layers of sheet metal are involved in shear deformation, causing increase of reactive stress. When this stress reaches a certain level, dependent on elastic characteristics of metal and degree of its work hardening, first elastic and then plastic deformation of roughnesses starts at the protrusion end face. Such a behaviour of metal in

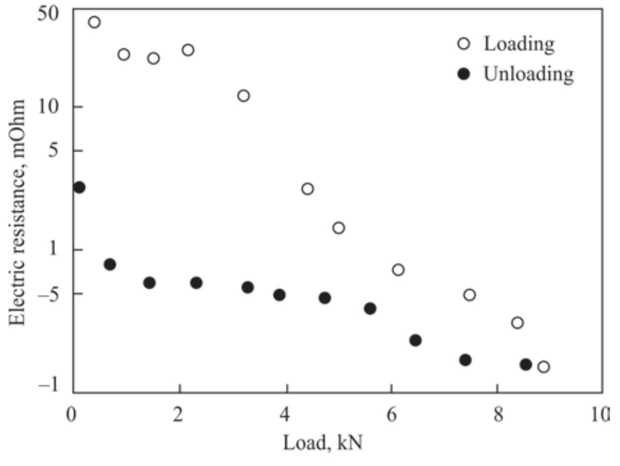

Figure 4. Dependence of electric resistance on the load in the contact of electrode-part from aluminium alloy 5482 in as-delivered condition. Electrode diameter is 7.5 mm [10]

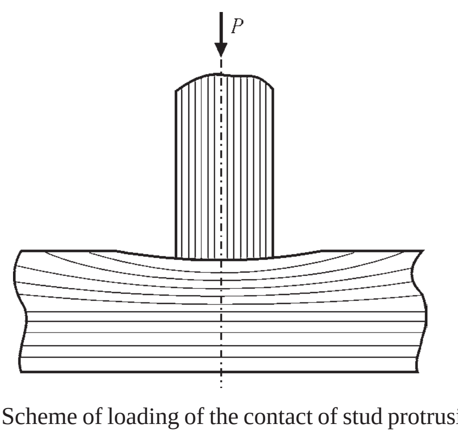

Figure 5. Scheme of loading of the contact of stud protrusion with the sheet

Characteristics of elastic properties of the studied materials

Metal	Modulus of elasticity, MPa	Poisson's ratio [6]
Steel 10 [5]	206	0.24–0.28
08Kh1810T [5]	196	0.25–0.30
Brass L63 [7]	100	0.33–0.42
Alloy AMg3 [7]	71	0.32–0.36

the contact influences lowering of contact resistance, when exceeding the respective boundary compression force (Figure 3). Plastic deformation results in drawing together of contacting surfaces and greater contact area at coincidence of their shape.

Further analysis of graphs in Figure 3 shows the presence of hysteresis, which is the greater, the lower the ductility of the studied metal. Hysteresis is indicative of the elastic nature of behaviour of near-contact zone metal at unloading. At load dropping below 4.5 daN, the electric resistance grows as a result of elastic change of the surface with appearance (or preservation) of second level roughnesses [2]. At final unloading (in our case to 1 daN), the electric resistance of the contact area turns out to be higher than the initial one for all the samples.

Analysis of the final shape of the protrusion contact surface at the stud end face was conducted in order to clarify the increase of contact resistance above the initial one after the loading-unloading cycle. For this purpose M4 stud with a protrusion ($d \times h$ = 0.55×0.65) was loaded by 10 daN force by the spring of RMK-2 gun. Studs were selected randomly from one batch of each material. The end face was photographed from the eyepiece of MBS-10 microscope at 56.3 magnification (Figure 7).

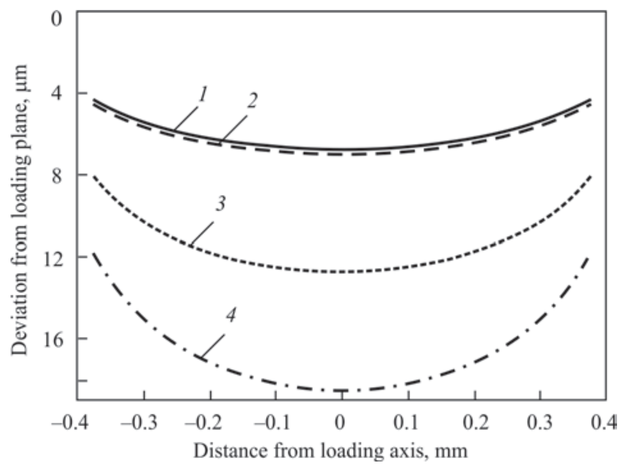

Figure 6. Deformation of sheet plane under the pressure of the protrusion on M6 stud with 2 dN force: *1* — carbon steel 10; *2* — 08Kh18N10T; *3* — brass L63; *4* — alloy AMg3

The presented photographs show that the initial relief obtained at cold heading of studs, changed after loading and subsequent unloading, becoming rougher as a result of plastic deformation, accompanied by material shifting, because of uncontrolled deviation from parallelism of the contacting surfaces and the thus caused appearance of tangential stresses. Judging by curves in Figure 3 and photos in Figure 7, such a plastic change of near-contact volume occurs at the loading stage, and the work-hardened metal is elastically deformed, restoring its shape at unloading. This is exactly what explains the fact that in all the exper-

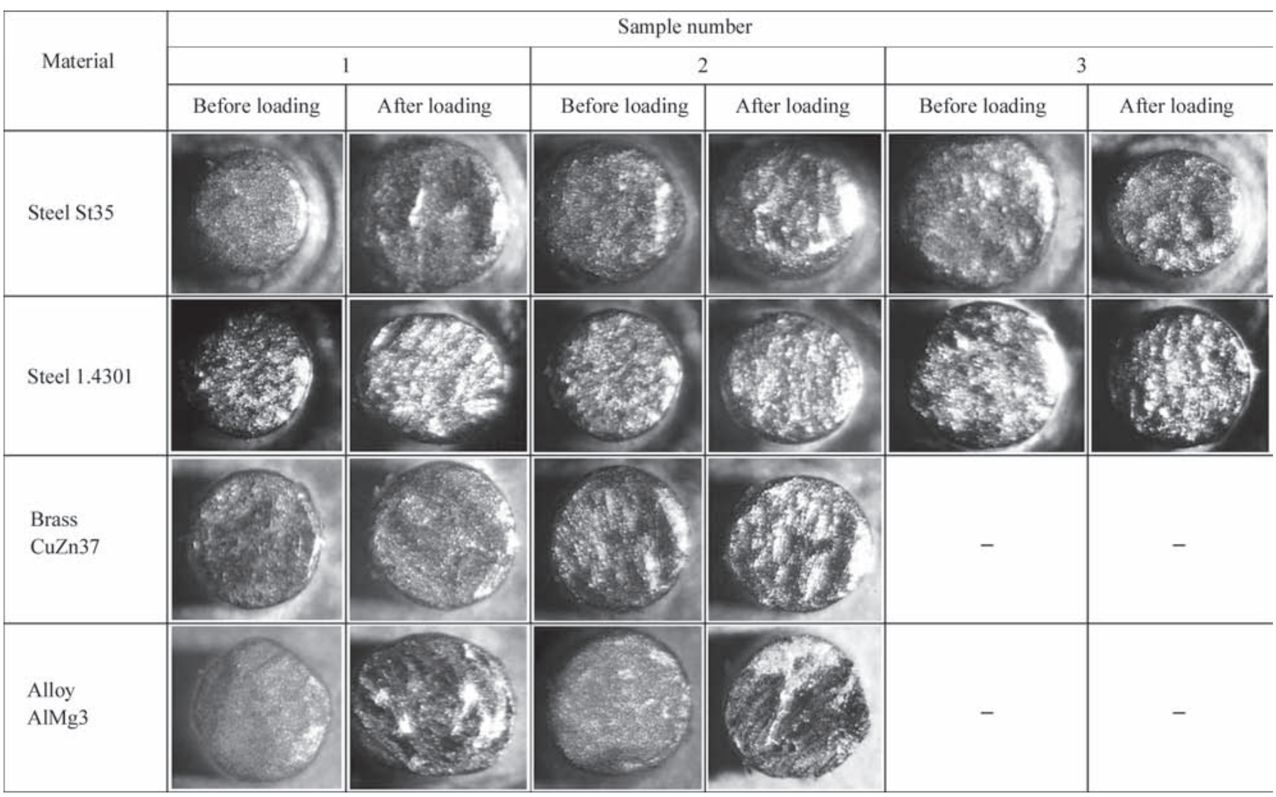

Figure 7. Shape of the protrusion contact surface before and after loading by 10 daN force

iments the contact zone resistance after unloading is greater than before loading.

An essential influence of plastic deformation on contact region resistance is demonstrated by Figure 8, which shows the change of electric resistance of the contact region at loading of M3 and M6 studs from steel 1.4301 with protrusion diameters of 0.6 (M3) and 0.75 (M6) mm, respectively. Pressure in the contact between the protrusion at the stud end face and the sheet at loading of M3 stud is 1.5 times greater, than at loading of M6 studs. As a result, plastic deformation in the near-contact region occurs at a lower force at loading of M3 stud, than at loading of M6 stud, and no above-mentioned increase of electric resistance at initial loading of the protrusion on M3 stud is observed in the graph. At 5–10 daN loading the graphs for M3 and M6 studs practically coincide. Therefore, here, the higher pressure on the protrusion of M3 stud results in the actual contact area due to plastic deformation being comparable to that of M6 stud, and the dependence of transient resistance on load being independent on the nominal contact area and following the inverse proportionality law, in keeping with the above Holm formula. On the other hand, the higher pressure and the thus caused strengthening, leads to the elastic component of deformation of the contacting surface on M3 stud being higher than that on M6 stud. This is indicated by the discrepancy of the graphs at relieving of the load from the above-mentioned 4.5 daN.

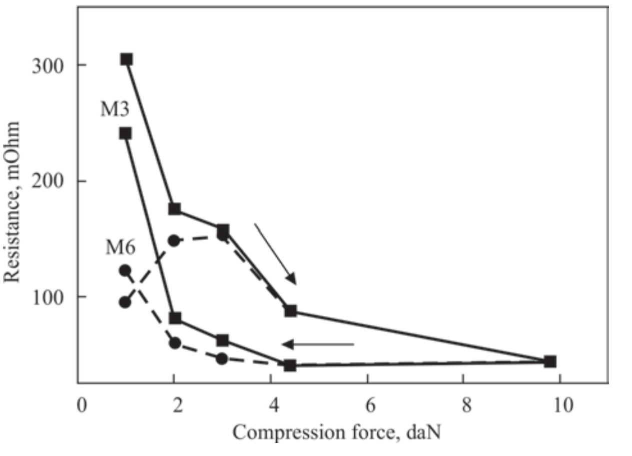

Figure 8. Dependence of electric resistance of the zone of contact between the protrusions of 0.6 (M3) and 0.75 mm (M6) diameter and sheet of steel 1.4301 on the applied compression force

Conclusions

1. The known inversely proportional dependence of electric contact resistance on the compression force of current-supplying surfaces is disturbed in the region of small forces, applied in the contact of areas of different size. A hypothesis was proposed about taking into account in this case not so much the plastic deformation of the contacting surfaces, but rather the elastic deformation of the surface layer of one of the elements under the impact of the load, distributed over the region of this surface limited by the area of the second element of the contacting pair.

2. At small compression forces of different-sized contacts, occurring, in particular, at excitation of the arc by touching or by exploding thin conductor, load increase leads to increase of electric contact resistance, as a result of elastic deformation of the surface and appearance of a local gap between the contacting surfaces, commensurate with the height of microroughnesses on the contacting surfaces. This results in decrease of the area of electric contact and increase of its electric resistance without current interruption.

3. Boundary value of load, at which the functional dependence of transient electric resistance of different-sized contacts from the applied force becomes inversely proportional, and the nominal current-conducting area looses its influence, depends on mechanical characteristics of material and the more the higher are its elastic properties.

4. At variation of the load from the maximum to minimum one, the inversely proportional dependence of electric transient resistance on the compression force of the current-carrying surfaces is preserved. But here plastic deformation of the contact interface at the loading stage leads to increase of its electric resistance at minimum compression force compared to the initial one.

5. Additional research specifying the dependence of electric resistance of different-sized contacts on mechanical properties of material and the ratio of areas of the contacting surfaces is of interest.

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