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The results of the so far performed investigations of Al-Cu butt cold pressure welding by the method of upsetting

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The paper presents the results of the author's investigation obtained so far concerning the relationships between the properties of the Al-Cu weld and the surface condition prior to welding, the properties of the welded material and the process of plastic deformation of the materials being welded. The investigation performed has shown evolution modification of the geometrical structure of the surface and the layers below it during the approximation of the welded surfaces to each other. After the first physical contacts of the surface irregularities and their squashing, new irregularities of larger sizes arise as a result of the mechanism of plastic deformation of grains in the surface layer. The new geometrical structure of the surface thus formed has no features of similarity to the primary structure. It has been found that modelling of the approximation of the welded surfaces to each other, from the first physical contact of the surface irregularities to the distance of atomic force interaction in the methods of metal forming, should incorporate evolution change of the surface geometrical structure including the phenomenon of closing the voids. Initial computer simulations of the Al-Cu cold pressure welding process confirm the possibility of applying the finite element method (FEM) for the determination strains and stresses present in the welded materials.

Keywords: *metal forming, cold pressure welding, Al-Cu joints*

1. Introduction

The development of the technology of joining metals by cold metal forming depends on the scientific description of the phenomena accompanying the preparation of the surfaces to be welded and welding itself. It is worth noting here that cold pressure welding is a technology which can economically and environmentally compete with the technologies involving heat supply or heat generation in intensive mechanical friction of the materials being welded.

Learning and scientific description of the phenomena taking place in the surface layer when preparing it and the description of the phenomena accompanying cold pressure welding, i.e. approaching of the welded surfaces to each other till a metallic bond is obtained require an interdisciplinary team of investigators, especially mechanics, physicists and chemists.

The author, due to his investigation possibilities, has concentrated on the cold pressure welding of aluminium with copper (Al-Cu) [1–5], searching for the relations between:

- surface condition prior to the pressure welding,
- properties of the material to be welded,

• the process of plastic deformation of the material to be welded, ensuring the formation of a metallic bond.

The paper presents some selected results of investigations performed so far.

2. Description and the results of the investigation

2.1. The method and conditions of welding

The pressure-welding mode shown in Figure1 has been adopted in the investigation. It is called butt cold pressure welding by the method of upsetting. The materials used were aluminium, Al (HB = 23) and copper, Cu (HB = 82) in the form of cold drawn rods with the diameter of 23 mm corresponding to the diameter of the samples. The samples were cold pressure welded on a hydraulic press with the force of P ≤ 630 kN and with two ram speeds: 30 mm/s and 50 mm/s.

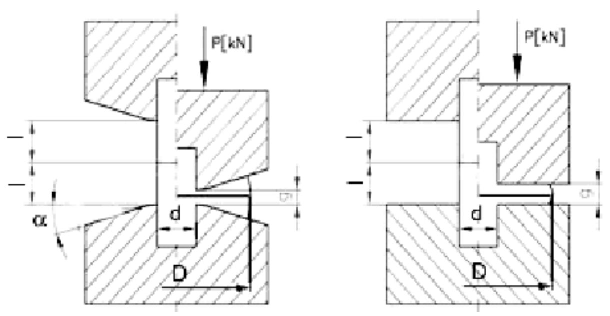

Fig. 1. A diagram of butt cold pressure welding of rods by the method of upsetting with conical and flat dies; angle α can be positive or negative

The variable parameters were: the way of preparation of the sample faces (turned, planed, milled, brushed), material condition (consolidated, recrystallized), die geometry (α = 0º, α = 16º), slenderness ratio of the sample free ends prior to welding (l/d), degree of deformation of the welded materials ε = ln(2l/g), welding velocity (v = 30 mm/s, v = 50 mm/s).

2.2. Experimental investigation results and their interpretation

In the experimental selection of the parameters of the sample surface preparation for cold pressure welding and in the selection of the parameters of cold pressure welding, it has been found that the trials of joining Al and Cu by this method brought two kinds of results: lack of metallic bond or metallic bond with the required strength. Such experiment results allowed to the elimination of the metallic bond strength factor from the program of the further investigation. This resulted in a significant reduction of the number of trials. The diameter of the metallic bond in the weld was larger than that of the samples but smaller than the diameter of the flange and amounted (1.2–1.4)d – Figure 2. In as few as 0.4% of cases the bond diameter was smaller than that of the samples.

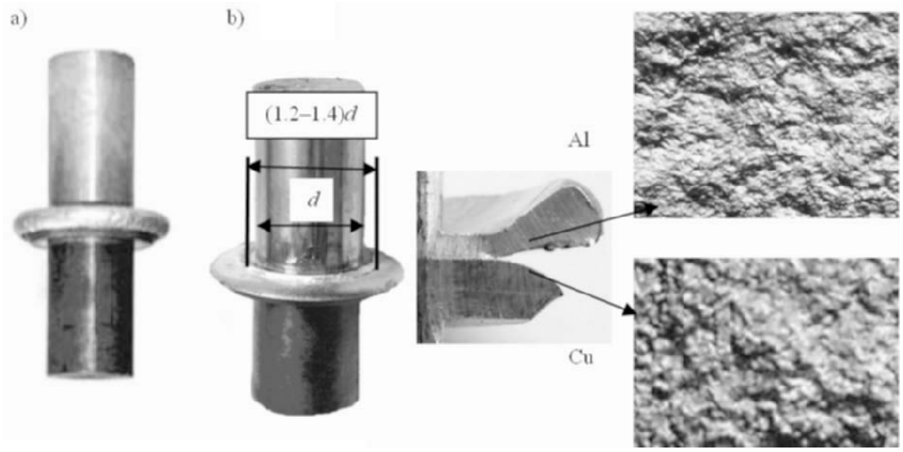

Fig. 2. Cold pressure welding: a) obtained sample with flange and b) flange structures in unwelded points Al and Cu on the flange periphery were separated manually by means of a wedge shaped tool

No traces of local metallic bonds (welds) – or traces of motion friction have been observed on the unwelded surfaces in the flange – Figure 2b. A similar structure was found in the unwelded surfaces of the samples which had been immersed in anhydrous alcohol and dried with an electric drier prior to the cold pressure welding.

Assessment of the joint strength

The joints strength was assessed in tensile, bending and rolling tests.

In tensile tests the samples underwent plastic deformation till breaking, always on the Al side beyond the area of the joint – Figure 3. The strength of the joint was, therefore, higher than that of the initial material. This is due to more plastic deformation and, consequently, higher hardening of the material within the joint as shown in the diagram of HV hardness increase – Figure 4.

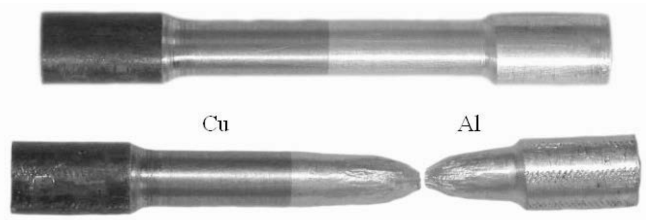

Fig. 3. A view of an Al-Cu sample before and after tensile test [4]

In the tests of bending by 90°, too, the samples did not break in the weld (Figure 5). The shift of the weld and the material during the process of bending are on the Al side at a very small distance from the Al-Cu boundary. Figure 6 and 7 show the deformation of cold pressure welding during longitudinal rolling for small and large deformation respectively. The material cracks on the Al side as in tensile test.

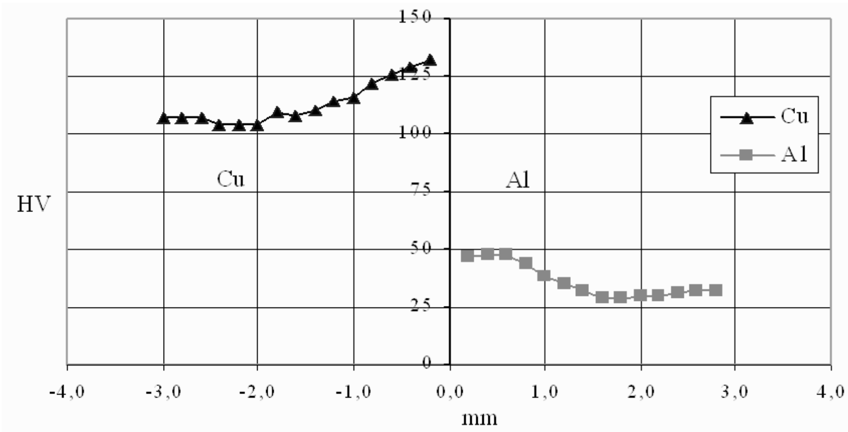

Fig. 4. Distribution of HV0.1 hardness measured in the sample axis.
Distance from the place of joining, mm

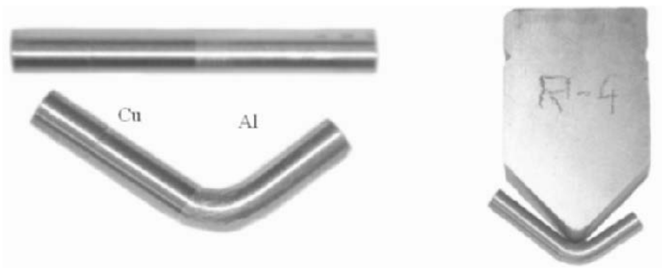

Fig. 5. A view of a cold pressure welded Al-Cu sample before and after 90° bending test [4]

Fig. 6. Al-Cu sample after longitudinal rolling with a small cold work in each pass [4]

Examining the fracture (Figure 7b), one can conclude that metallic bond has been obtained in the whole surface.

Scanning microphotography of the fracture (Figure 8) indicates clearly plastic character of the sample cracking.

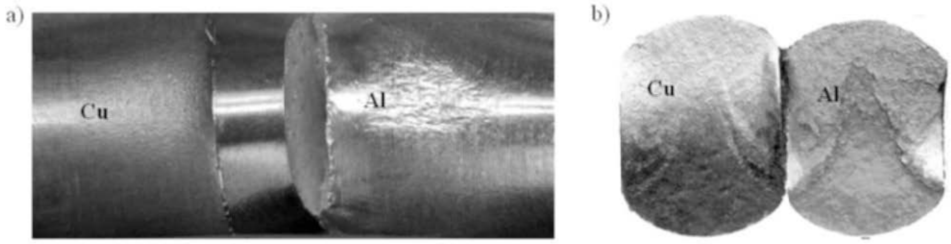

Fig. 7. Al-Cu sample after longitudinal rolling with maximum cold work in each pass: a) crack in the weld on the Al side, b) a view of the fracture

Microanalysis of the chemical composition has also been performed on the fracture on the Cu side (Figure 8). The presence of Cu indicates diffusion character of the cold pressure welding. These problems will be the object of further investigation.

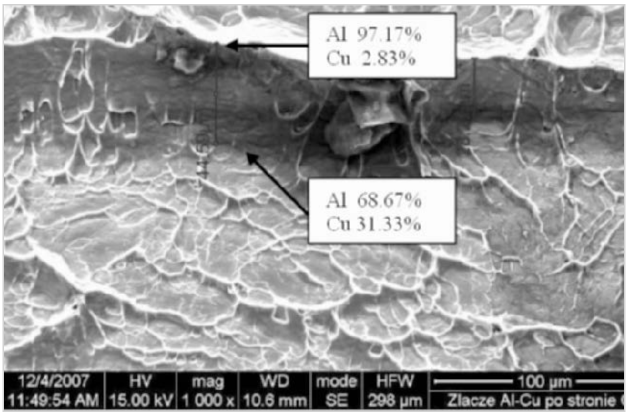

Fig. 8. View of the fracture of a sample broken in a rolling test; chemical composition microanalysis has been performed on the Cu side of the fracture by means of a scanning microscope

The influence of the sample butting face structure parameters prior to cold pressure welding and the upsetting parameters on the cold pressure welding:

1. The influence of the butting face parameters on the cold pressure welding effect was examined on samples with the following butting faces: turned ones, planed ones, milled ones, brushed ones. The Al and Cu samples with brushed surfaces (R_a = 0.54 µm, R_z = 3.0 µm, R_t = 3.9 µm, S_m = 138 µm) have not joined during the welding trials.

On the other hand, Al and Cu samples with turned, planed and milled surfaces joined in the same upsetting conditions although the geometrical structures (roughness) of the surfaces differed significantly.

As an example, Figure 9 shows the structures of planed and milled Cu surfaces. The average roughness parameters of the turned surface were: $R_a = 0.7$ µm, $R_z = 3.6$ µm, $R_t = 4.7$ µm, $S_m = 112$ µm.

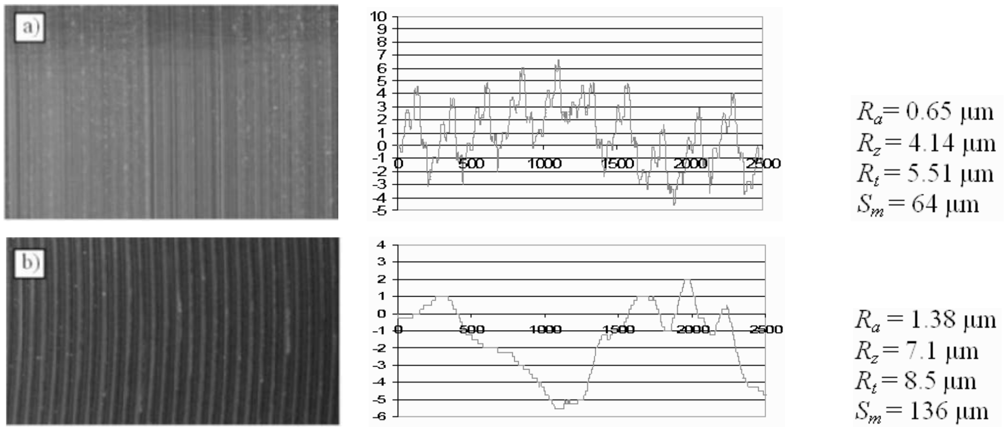

Fig. 9. Geometrical structures of Cu sample butting faces prior to cold pressure welding: a) a planed surface, b) a milled surface

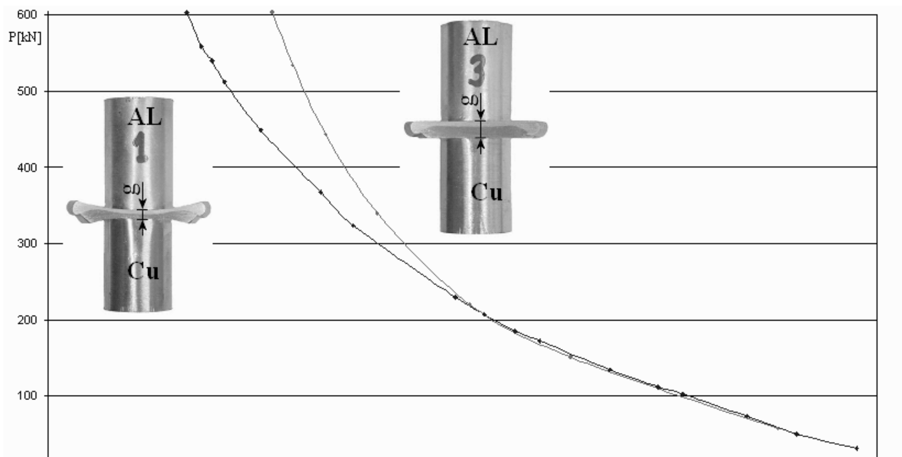

Fig. 10. Examples of the force curves in cold pressure welding with conical and flat working surface dies

2. The investigation of the influence of the upsetting parameters on the effect of cold pressure welding have shown that:

• Al and Cu samples got welded when the value of the quotient $l/d \geq 0.22$ and the deformation during upsetting was $\varepsilon = \ln(2l/g) \approx 1.4$. It can be supposed that the reason why the samples did not get welded if the quotient $l/d < 0.22$ was too small volume of freely upset material when the final texturing of the structures of the welded materials in the contact zone took place.

- Cold pressure welding by means of conical dies significantly increases the value of material deformation as compared to upsetting with flat dies with the same value of the upsetting force (Figure 10). This is advantageous considering tool life and the amount of technological waste.
- No differences have been observed in the process and in the results of cold pressure welding of Al and Cu at the press ram speeds of $v = 30$ and 50 mm/s.

The results of the initial computer FEM simulations

FEM simulation was carried out on MSC.Marc as axisymmetrical mechanical model. The SHEAR friction model was applied with the following coefficients of friction: 0.8 between Cu and Al and 0,1 between the punches and the deformable material The initial computer simulations of Al-Cu cold pressure welding confirm the possibility of application of the Finite Element Method (FEM) for the determination of strains and stresses present in the welded materials. The simulations were performed with aluminium and copper samples in work hardened condition and in recrystallized one (Figure 11).

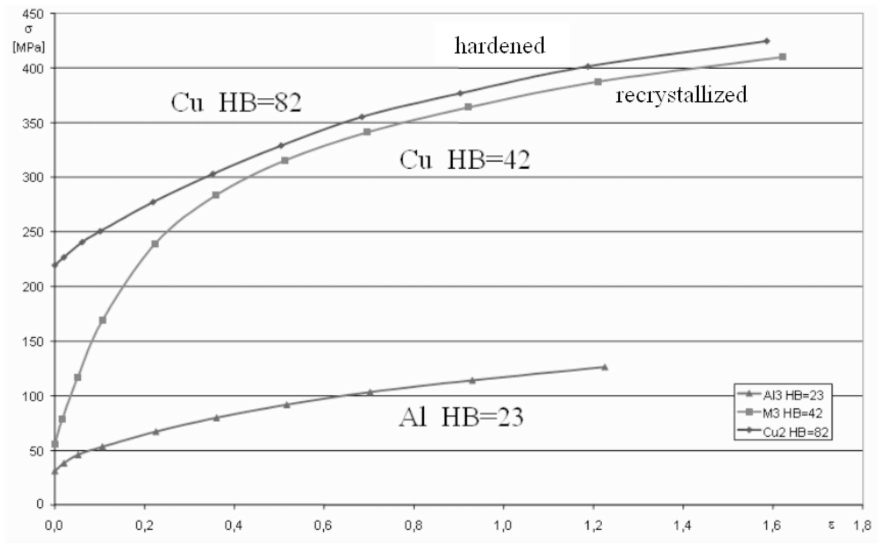

Fig. 11. Work hardening curves of the materials used in the investigation

The dimensions of the samples were the same as in the experiment. A very good shape conformance of the freely flowing surfaces and the Al-Cu contact surfaces in FEM has been obtained as well as welding forces of the virtual samples with the forces measured during the experiment (Figure 12).

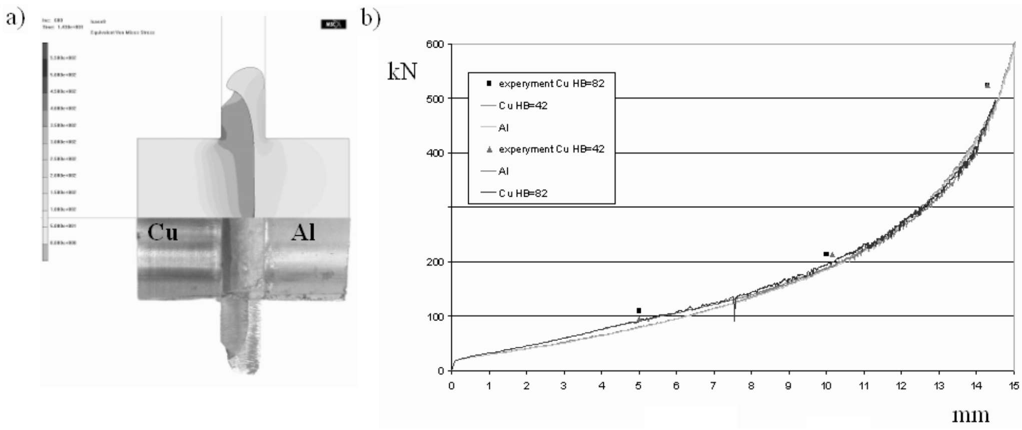

Fig. 12. Shape comparison of a virtual sample to a real one a) and a comparison of the welding force curves b). The continuous lines are simulation results while the plotted points are the results of the welding force measurements in cold pressure welding of aluminium samples to copper ones in work hardened condition and in recrystallized one

3. The results of the analysis of evolution change of the surface geometrical structure during the process of cold pressure welding

The surface approaching each other (“matching”) is a process of continuous plastic deformation of surface irregularities when upsetting the free ends of the samples. The matter is difficult to describe quantitatively because, in the author’s opinion, two kinds of surface irregularities should be considered, namely:

- primary surface irregularities, i.e. ones formed in the process of preparation for the cold pressure welding – Figure 9 and 13a,
- secondary surface irregularities, i.e. the ones which form during the cold pressure welding process (even if the primary irregularities are close to zero), Figure 2b and 13.

The primary irregularities are related to the technology of surface preparation and they deform (flatten) most intensely in the first phase of cold pressure welding. In the final phase, the primary irregularities disappear. They have less influence on the final result of cold pressure welding than the secondary irregularities.

The secondary irregularities are a result of deformation of the individual grains making up the surface to be welded. The process takes place simultaneously with the deformation of the primary irregularities and it accompanies the surfaces’ approaching each other. The intensity of the surface layer restructuring increases as the depth of the substrate plasticization grows. At the final stage of the surfaces approaching each other, the secondary structure has no features of similarity to the primary structure – Figure 13.

For comparison, Figure 14 shows the geometrical structure of the surface of a Cu sample upset in a frictionless test. The initial surface was turned $R_a = 1.73$ µm.

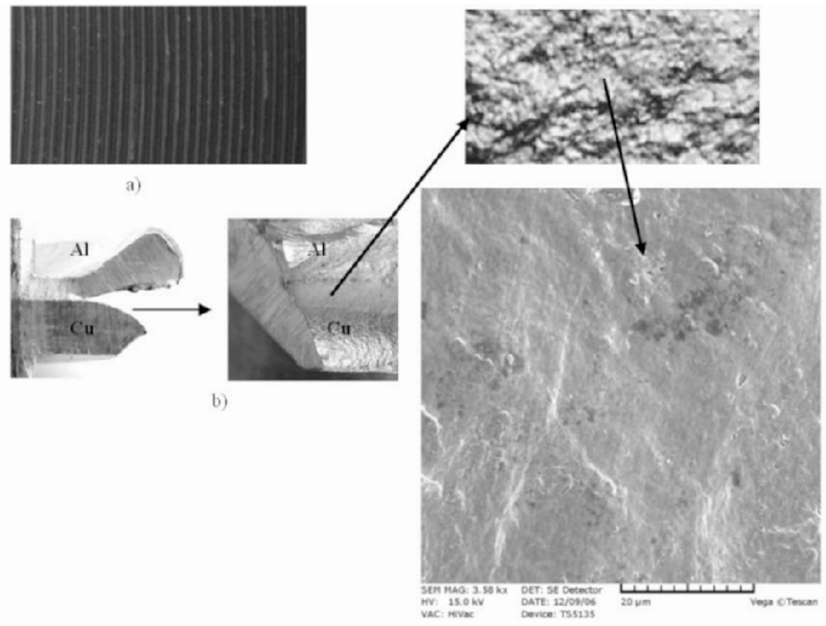

Fig. 13. Surface structure (Figure 9b) prepared for cold pressure welding a) and surface structure from the region of the joint b)

The test was performed on an INSTRON testing machine in accordance with the recommendations for the determination of the cold work curves $\sigma_p(\varepsilon)$. The relieves on the front faces of the samples were filled with paraffin.

The geometrical structure of the surfaces after upsetting did not show traces of the primary structure. The lack of traces of contact of the vertices of the irregularities with the pressing plates confirms the progress of the frictionless test.

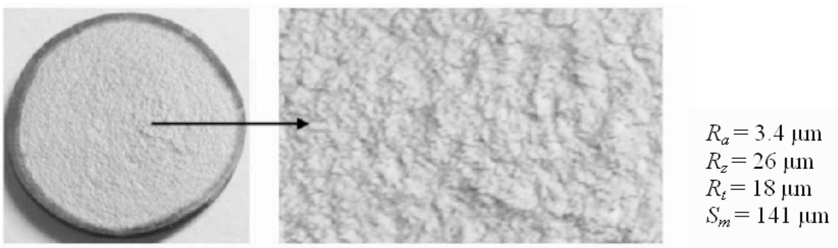

Fig. 14. Geometrical structure of the surface of a Cu sample upset in a frictionless test; the initial surface turned R_a = 1.73 μm

There is a clear similarity between the surface formed in the conditions of outer hydrostatic pressure due to the paraffin (Figure 14) and the surface formed during cold pressure welding (Figure 2b and 13b).

It should be pointed out here that to learn the evolution of the welded surface geometrical structure is an important thing. At the final stage, the surface irregularities cause a state in which areas of physical contact and isolated spaces-voids, filled or not filled with air, appear next to each other. Closing of the voids is possible provided that they are subjected to triaxial external pressure. If the possibility of further plastic deformation of materials in the welding zone is limited and a hydrostatic pressure, *p*, is made within it, assuming that both the void and the material surrounding have spherical shapes with the radii of *R* and *r*, respectively, plasticization of the material around the void (on the r radius) would take place provided that [6]

$$p \geq \frac{2}{3} \cdot \sigma_p \left(\frac{R^3}{r^3} - 1 \right). \tag{1}$$

The above formula indicates that "closing a void", i.e. when $r \to 0$ in hydrostatic pressing requires a pressure increasing up to $p \to \infty$. Therefore, completion of cold pressure welding on the whole surface is possible when voids are surrounded by triaxial uneven pressure and an adequate state of strain.

Experiment results confirm the relationship between the force compressing the welded surfaces and plastic deformation of the surfaces during the welding process. For example, the application of conical dies (Figure 1) causes bond of metals with more deformation of the welded surfaces (due to lower friction) but with a smaller force than in the case of the use of flat dies – Figure 10.

4. Conclusions

1. A scientific description of the phenomena taking place both in the preparation of surfaces for cold pressure welding and in welding itself is a condition of the development of the technology bonding metals and their alloys by the methods of cold plastic forming.
2. Learning and scientific description of the phenomena taking place in the surface layer during its preparation and description of those accompanying welding require an interdisciplinary team of researches, especially mechanics, physicists and chemists.
3. The investigation performed has shown evolution rebuilding of the geometrical structure of the surface layer and the subsurface ones when the welded surfaces approach each other.
4. It has been found that, after the first physical contacts of the surface irregularities of the two welded materials and after the first phase of plastic flattening of those irregularities, new larger irregularities arise; they are an effect of the mechanism of plastic deformation of the grains in the surface layer and in the subsurface ones.

5. The new geometrical surface structure formed in this way has no features of similarity to the primary structure.

6. It has been determined that the evolution change of the geometrical surface structure, as well as the phenomenon of closing the voids should be taken into consideration in modelling the surfaces approaching each other.

7. Preliminary computer simulations of Al-Cu cold pressure welding confirm that the Finite Element Method (FEM) can be applied to determine the strains and stresses present in the cold pressure welded materials.

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Wyniki dotychczasowych badań spajania doczołowego na zimno Al-Cu metodą spęczania

W referacie przedstawiono dotychczasowe wyniki badań autora odnoszące się do związków pomiędzy własnościami spoiny Al-Cu i stanem powierzchni przed spajaniem, własnościami materiału spajanego oraz przebiegiem odkształcania plastycznego spajanych materiałów. Przeprowadzone badania wykazały ewolucyjną przebudowę struktury geometrycznej powierzchni i warstw podpowierzchniowych podczas zbliżania do siebie powierzchni spajanych. Po pierwszych fizycznych kontaktach nierówności powierzchni i ich plastycznym zgniataniu powstają nowe nierówności, będące efektem mechanizmu odkształcania plastycznego ziaren w warstwie wierzchniej. Powstała w ten sposób nowa struktura geometryczna powierzchni pozbawiona jest cech podobieństwa do pierwotnej struktury. Stwierdzono, że ewolucyjna zmiana struktury geometrycznej powierzchni, łącznie ze zjawiskiem zamykania pustek, powinny być uwzględnione w modelowaniu przebiegu zbliżania do siebie powierzchni spajanych. Wstępne symulacje komputerowe przebiegu spajania Al-Cu potwierdzają możliwość zastosowania metody elementów skończonych (MES) do wyznaczania odkształceń i naprężeń panujących w spajanych materiałach.