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PROPERTIES OF JOINT IN THE BIMETALLIC RODS Cu-Al AND Cu-STEEL AFTER EXPLOSIVE CLADDING AND THE PROCESS OF ROLLING

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In the paper the microhardness, the microstructure and the bond strength of interface of bimetallic joint on the cross sections of the test bar have been investigated. For the experimental analysis, a bimetallic bar was manufactured using an explosive technique method and the process of rolling. For tests, 23 sets of specimens were prepared each consisting of copper tubes (grade M1-E), rolled steel rods (grade St3S), drawn rods (grade 55) and aluminium rods (grade PA6). The copper tubes and the steel and aluminium rods had different diameters, owing to which different distances between the rods and the internal tube walls were obtained. The results of the research show a significant deviation in microhardness distribution in the both layers near the joining border.

Key words: *explosive cladding, clad bar, bond strength, groove rolling*

Svojstva spoja u dvokovinskim motkama Cu-Al i Cu-čeliku nakon platiranja eksplozivom i valjanja. U radu su prikazani rezultati istraživanja mikrotvordoće, mikrostrukture i čvrstoće sljubljivanja dvokovinskog spoja na presijeku ispitne šipke. Za potrebe eksperimentalne analize dvokovinska šipka je izrađena metodom primjene eksploziva i naknadnog valjanja. Za ispitivanja su pripremljena 23 kompleta uzoraka od kojih se svaki sastoji iz kompleta cijevi (kvaliteta M1-E), valjanih čeličnih šipki (kvalitete St35), vučenih šipki (kvaliteta 55) i aluminijskih šipki (kvaliteta PA6). Bakarne cijevi i čelične i aluminijske šipke su imale su imale različite promjere zbog kojih su dobivene različite udaljenosti između šipki i unutrašnjih stijenki cijevi. Rezultat ispitivanja pokazuje u oba sloja značajnu odstupanja u raspodjeli mikrotvrdoće uz granicu spoja.

Ključne riječi: *platiranje eksplozivom, platirana šipka, čvrstoća sljubljivanja, valjanje žlijeba*

INTRODUCTION

For many years, the explosive cladding method has been used for the production of multi-layer materials featuring high physico-mechanical and service properties [1, 4]. The method consists in obtaining a fast bond between two or more metals as a result of a high-speed collision of layers to be joined. The high speed of collision is obtained by the detonation of an explosive positioned on the propelled layer [1].

By using this method, very good mechanical and technological properties of joints are achieved, which are characterized by corrosion and high-temperature resistance [2-4]. The paper describes the investigation of the properties of a joint of semi-finished products in the form of copper clad steel and aluminium bars obtained by the explosive method, and their further hot plastic forming.

H. Dyja, S. Mroz, Z. Stradomski, Faculty of Materials Processing Technologies and Applied Physics, Technical University of Częstochowa, Częstochowa, Poland

The methodology of the development of the applied bimetal rod production technology by using the explosive method has been described elsewhere [1-4].

Explosive welded clad rods can be a stock for the production of wire rod, from which, in turn, bimetallic wire can be obtained. For tests, 23 sets of specimens were prepared, each consisting of copper tubes (grade M1-E), rolled steel rods (grade St3S), drawn rods (grade 55) and aluminium rods (grade PA6). The copper tubes and the steel and aluminium rods had different diameters, owing to which different distances between the rods and the internal tube walls were obtained. Detailed description of the explosive technique method to the manufacturing of the bimetal rods is given in [1, 3].

Bimetallic rods (copper-steel) with an outer diameter of 22 mm and a copper layer share of 15 %, 30 %, 45 %, 50 % and 55 % Cu, after explosive welding, were rolled on a D 320 three-stand two-high shape mill. Heating of the bimetallic stock of an initial length of 250 mm was carried out in a chamber furnace. Rods heated up to a temperature of 960 °C were cooled down before being fed to the first roll groove. Owing to this, no delamination of layers occurred. The initial rolling temperature was approx. 900 °C, and the final rolling temperature was about 700 °C. Rolling speed was approx. 0.45 m/s. As a result of rolling in 4 and 6 passes, rods of a diameter of about 14.0mm were obtained. Six elongation grooves were used in the horizontal oval - vertical oval - horizontal oval - circle system [4].

EXAMINATION OF THE QUALITY OF THE BIMETAL ROD JOINT AFTER EXPLOSIVE CLADDING AND ROLLING

In order to examine the quality of the joint between the layers of bimetal rods taken from a charge obtained by the explosive method and then rolled in elongation roll grooves, the strength tests were performed on the bars (to determine the joint shear strength). The quality of the joint of bimetal layers with the steel and aluminium cores clad with copper was tested on testing dies shown in Figure 1. [2, 4]. Figure 1.a shows the shape and dimensions of test specimens used for testing for maximum shearing stresses at the joint interface, while Figure 1.b illustrates the shape and dimensions of testing dies used during strength tests.

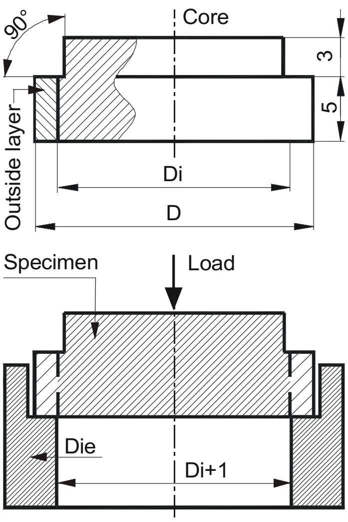


Figure 1. **Dimensions of test specimens (a) and testing dies (b) used for the examination of the quality of the bimetal rod joint after explosive cladding and groove rolling**

Slika 1. **Dimenzije ispitnog uzorka (a) i ispitne matrice (b) upotrebljene za ispitivanje spojeva na dvokovinskim šipkama nakon platiranja s eksplozivom i uvaljavanja žljeba**

Figure 2. shows the results of testing the quality of the joint of copper-steel layers (maximum shearing stresses) after explosive shearing.

The data shown in Figure 2. indicate that the difference between the least (test specimens obtained from the 4 - 6 systems; 173 - 180 MPa) and the greatest values of shearing stresses (test specimens obtained from 10, 12 and 15 systems; 205 - 214 MPa) does not exceed 20 %. For all specimens tested, the quality of the joint has proved to be so good that the respective layers have not broken apart, but instead, the copper layer has been squeezed out through the drawhole of the testing die. The obtained range of the

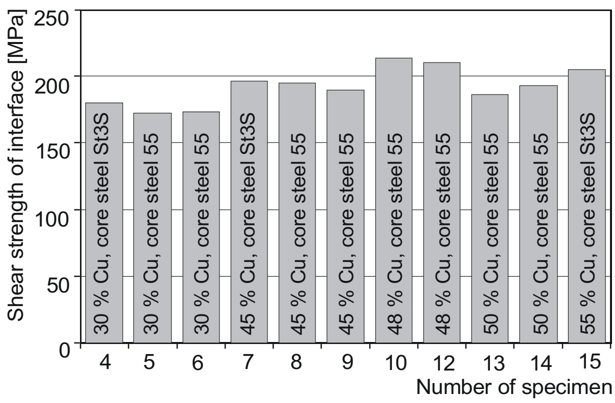


Figure 2. **Shear strength of explosive clad copper-steel test specimens**

Slika 2. **Čvrstoća smicanja eksplozijom platiranih ispitnih uzoraka od bakra - čelika**

values of shearing stress, τ_s = 173 - 214 MPa, for particular specimens corresponds to the values of shearing yield stress resulting from the condition of plasticity, $\tau_s = 0.57\ \sigma_p$ (where: σ_p - yield stress for copper), depending on the hardening of the copper layer caused by its deformation during explosive cladding.

Moreover, it can be noted that the quality of the joint of layers is not affected significantly by the initial thickness of the cladding layer, nor by the distance between the copper tube and the steel rod. For the steel grades used, i.e. the St3S steel - 0.1 % C, and the 55 steel - 0.58 % C, no effect of the core material on the quality of the joint of layers has been found, either (Figure 2.).

The quality of the joint of layers in steel rods clad with copper was also examined after the hot rolling of the rods in elongation grooves. Due to the finished product size (approx. 14.0 mm in diameter) and the proportional reduction of cladding layer thickness in relation to the initial rods, those bimetal rods were taken for tests, in which the copper layer fraction on the band cross-section was equal or greater than 45 %.

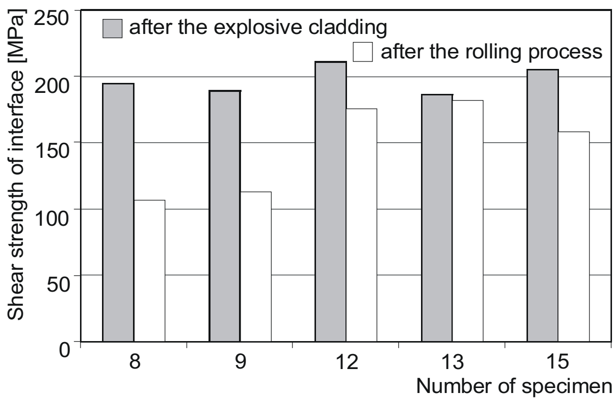


Figure 3. **Comparison of the shearing strength of the joint of (Cu-steel) bimetal specimens after explosive cladding and rolling**

Slika 3. **Usporedba čvrstoće smicanja na spoju bakar - čelik nakon platiniranja eksplozijom i valjanja**

Figure 3. shows the results of joint strength testing for specimens after explosive cladding followed by rolling. It can be seen from the data shown in this Figure that the greatest drop (by approx. 40 %) in the shearing strength of the joint has occurred for rods 8 and 9. This can be explained by too short time of cooling the specimen before the first pass and a network of cracks occurred at the layers joint interface over a length of about ¼ specimen perimeter during rolling in the first groove, which is illustrated in Figures 4.a and 4.b. Despite the fact that those cracks have not been welded in the subsequent passes and, as a consequence, reduced the joint strength, however, they have not negatively affected the geometry of the finished product (Figure 5.b).

The cause of the formation of cracks during the first pass is a great difference in resistance to plastic flow between steel and copper. In order to determine the value of yield stress for the 55 steel, plastometric tests were performed on a DIL 805A/D dilatometer-plastometer. The results of these tests indicate that with parameters corresponding to the first pass (temperature approx. 920 °C, deformation rate 5 s^{-1}, deformation 30 %), the value of resistance to plastic flow for the steel tested is approx. 225 MPa. On the other hand, data obtained with similar parameters for copper, reported in the literature [4], show that the value of resistance to plastic flow is about 40 MPa. This great difference in yield stresses between the both layers is the cause of occurring decohesion at the joint interface. Considering the high thermal conductivity of copper, the elongation of cooling time before the first pass will result in a sharp drop in the temperature of the tope layer (copper) relative to the steel core, which, as a consequence, will decrease the differences in resistance to plastic flow between the materials of the both layers, being responsible for occurring cracks at the joint interface.

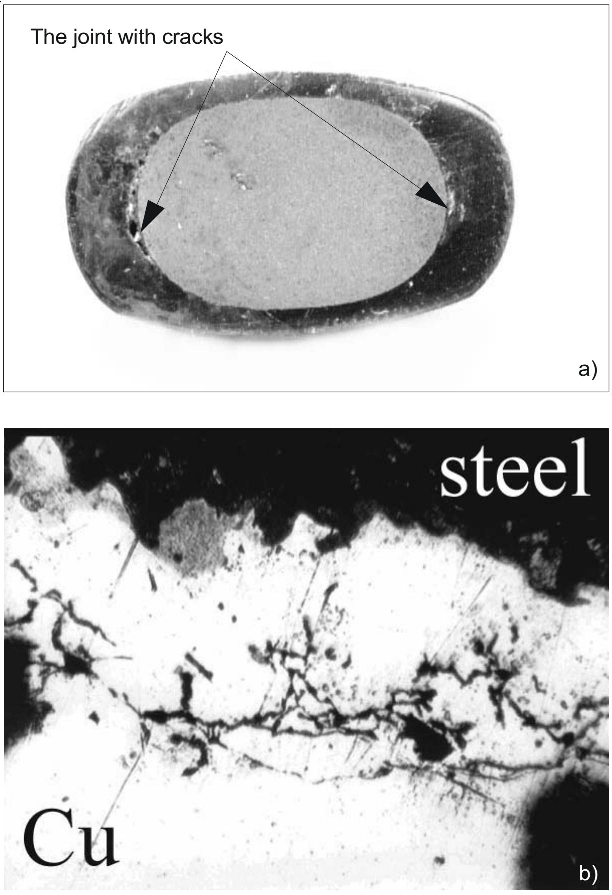


Figure 4. **a) Lateral templates taken from Cu-steel specimen no. 8 after the first pass, b) the character of the joint with a crack network visible in specimen 8 under a magnification of 250x**

Slika 4. **a) Bočni kalibar iz uzoraka Cu-čelik br. 5 nakon prvog prolaza, b) karakteristike spoja s mrežom pukotina vidljivih u uzorku 8 pod povećanjem od 250x**

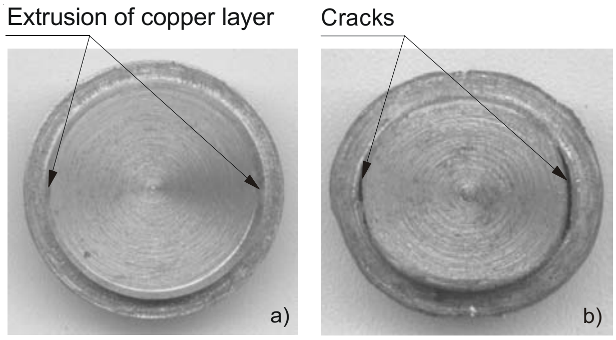


Figure 5. **Shape of Cu-steel specimens after the examination of the joint quality of bimetal rods after rolling: a) specimen no. 12, b) specimen no. 8**

Slika 5. **Oblik uzoraka Cu-čelik nakon ispitivanja kvalitete spoja dvokovinskih šipki poslije valjanja: a) broj uzorka 12, b) broj uzorka 8**

The change of joint strength for specimens 12, 13 and 15 was much less, being approx. 20% for specimen 15 and to 1% for specimen 13, compared to the strength of the joint in rods after explosive cladding. For any of these specimens, no cracking between the bimetal layers oc-

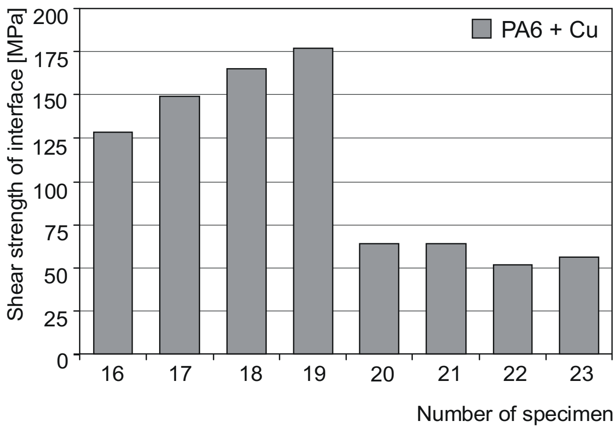
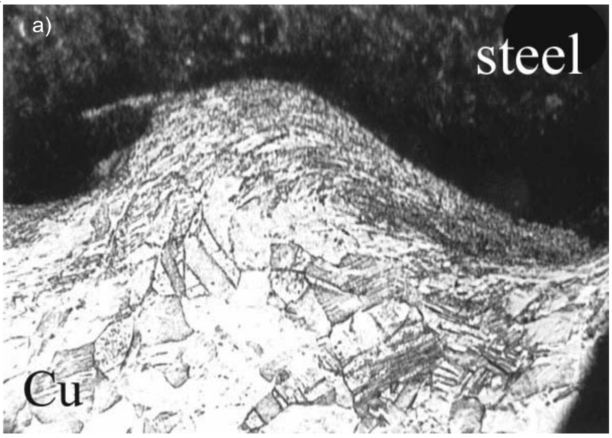


Figure 6. **Shearing strength of explosively clad PA6-Cu specimens**

Slika 6. **Čvrstoća smicanja uzoraka PA6-Cu platiranih eksplozivom** curred during performing joint quality examination, but only the squeezing out of the copper through the die drawhole took place instead (Figure 5.a). The elongation of cooling time before the first pass, with the remaining parameters of the rolling process (the roll pass design system) being correctly selected, assured the finished product in the form of bimetal rod to be obtained with a quality of the joint only slightly poorer compared to the initial materials, and for specimen no. 13 - the identical as that of rods after explosive cladding.



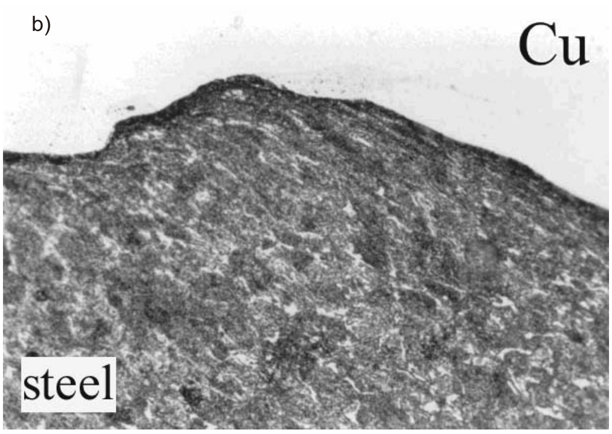


Figure 7. **Morphology of a steel-copper joint typical of the investigations discussed in this study (specimen 8 after explosive cladding): a) magn. 320x, etched with $FeCl_3$ + HCl; b) magn. 500x, etched with Nital**

Slika 7. **Morfologija spoja čelik-bakar tipična za istraživanje i diskusiju provedenu u ovom radu (uzorak 8 nakon platiranja eksplozivom): a) povećanje 320x, nagrizano s $FeCl_3$ + HCl, b) povećanje 500x, nagrizano s nitalom**

It can be concluded from the examination of joint quality performed for copper-aluminium bimetal rods that, contrary to copper-steel bimetal rods, the quality of joint is significantly influenced by the initial thickness of the cladding layer and the initial distance between the copper tube and the aluminium rod. Figure 6. shows the results of the performed tests for the quality of the PA6-Cu joint in respect of the maximum shearing stresses.

The above figure shows that for specimens obtained from systems 16 - 19 (30 % Cu), shearing stress values were achieved (128 - 176.84 MPa), which were, on the average, three times as high as those from specimens obtained from systems 20 - 23 (45 % Cu) (51.72 - 63.66 MPa). For specimen 19, the quality of joint turned out to be so good that no breaking of respective components occurred, but only the copper was squeezed out through the testing die instead.

The value of shearing stress, τ_p = 176.84 MPa, corresponds, from the conditions of plasticity 0.57 σ_p, to the yielding point of copper.

STRUCTURE AND PROPERTIES OF JOINT REGIONS

The high strength properties of the joint are conditioned by the character of bond between the bimetal layers and the rod, and rod microstructure.

The microstructure of the zone of the copper-steel joint after detonation cladding, shown in Figures 7.a and 7.b, indicates that the extent of the strong plastic deformation, occurring chiefly in joint humps, is very small and does not exceeds 40 - 60 μm.

Microhardness tests, covering only the zone of the explosively produced joint, are shown in Figures 8. - 9. The results of these measurements, an example of which is shown in Figure 8., indicate a reinforcement of copper by approx. 30 % (from ~97 to ~126 HV0.01) and by 12 - 25

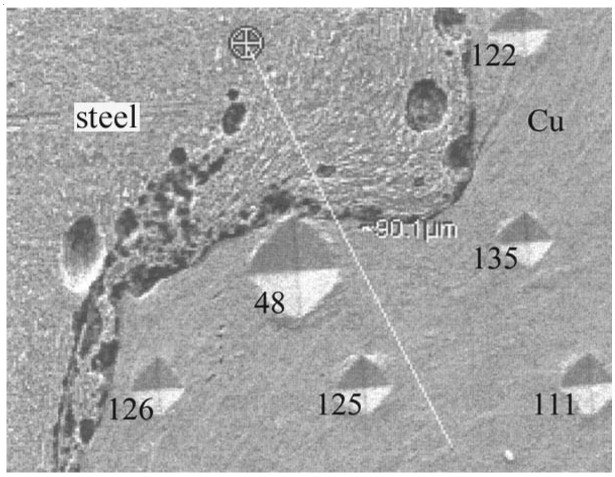


Figure 8. **Joint region and the results of HV0.01 microhardness tests (specimen 12 after explosive cladding), a scanning microscope, magn. 1600x**

Slika 8. **Područje spoja i rezultati ispitivanja mikrotvrdoće HV-0.01 (uzorak - 12 nakon platiranja eksplozivom), mikroskop sa skenerom, povećanje 1600x**

% for steels (from ~250 to 280 - 310 HV0.01). Besides typical waves, area are noticeable, which most often are an extension of hump tops, with a markedly different morphology and a microhardness of 125 - 135 HV0.01.

In the joint zone, also pores may occur, which are distinctly more numerous in the steel region (Figure 8.). Microhardness tests revealed also a very interesting phenomenon of a sharp, about 50% reduction of copper hardness after the wave top, i.e. in the region of strong turbulence. The results of microanalysis by the EDX method, shown in Figure 9., indicate that the locally occurring small

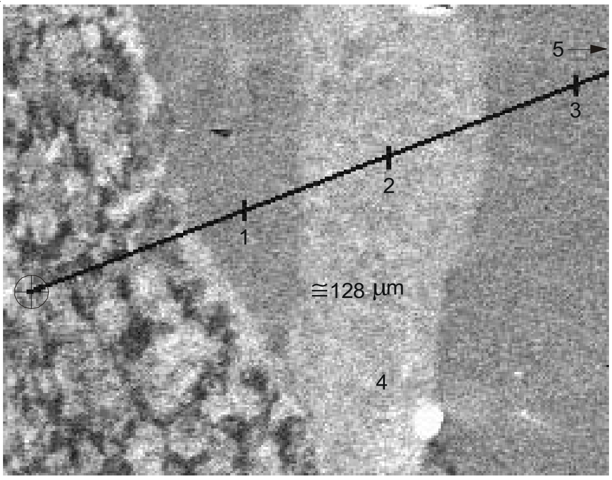


Figure 9. **Microstructure of the EDX analysis region**
Slika 9. **Mikrostruktura područja analiziranog EDX-om**

transitory layer is a mixture of copper and iron, containing 87 - 92 % Cu and 8 - 13 % Fe. Also, the ~25 µm wide zone, visible in Figure 9., which separates this region from the steel, is not pure copper, but contains ~ 3.5 % Fe. At the same time, the character of changes in the distribution of element concentrations indicates the presence of a clearly diffusive joint region of a thickness of 8 µm for iron and ~11 µm for copper.

The hot rolling process substantially modifies the joint microstructure and markedly reduces microporosity in this zone, which is shown in Figure 10. The copper undergoes recrystallization, and in areas of the greatest cold work, also a big grain growth (Figure 10.a). In the steel, the cold work texture vanishes completely - a considerable grain refinement occurs with the formation of very fine, polygonal ferrite forming a net-like arrangement around the pearlite grains (Figure 10.b).

The highly diverse results of joint strength testing, illustrated in Figure 6., suggest a different character of Cu-PA6 joints to occur in the both sets clad. Figures 11. and 12. show the character of the both joints to be typical of this technology, though little regular wavy surfaces, with an amplitude height not exceeding 40 µm and a length of 100 - 450 µm, assuring a good mechanical joint, whose properties may only be changed by the presence of the visible intermediary phase.

The presence of chain-like arranged discontinuities, particularly numerous on the PA6 side, is likely to be the

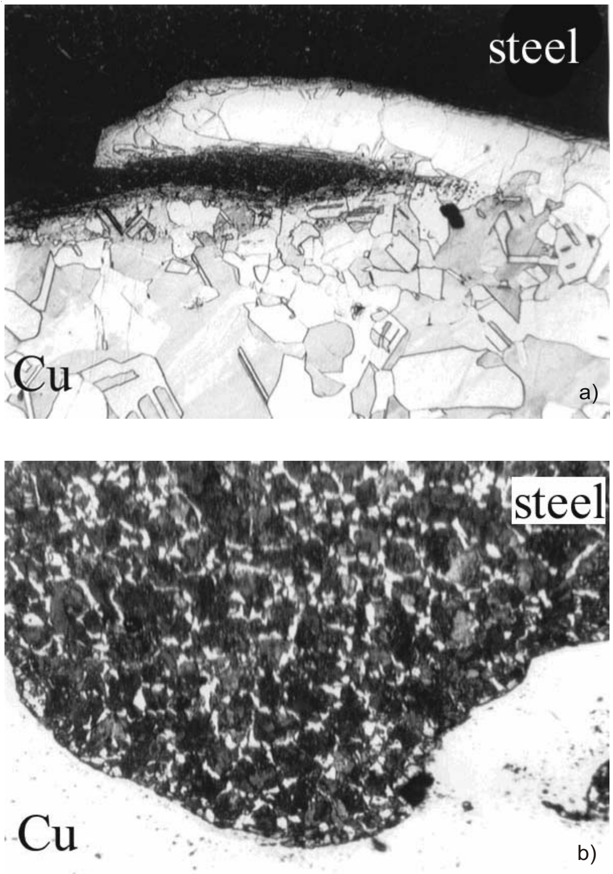


Figure 10. **Microstructure the steel-copper joint (specimen 12 after rolling): a) magn. 320x, etched with FeCl + HCl); b) magn. 500x, etched with Nital**
Slika 10. **Mikrostruktura spaja čelika-bakra (uzorak 12 nakon valjanja): a) povećanje 320x, nagrizano s FeCl + HCl, b) povećanje 500x, nagrizano s nitalom**

main cause of the sharp shearing strength of sets with a fraction of copper in the rod cross-section of 45 %. The results of microhardness tests, covering only the joint zone,

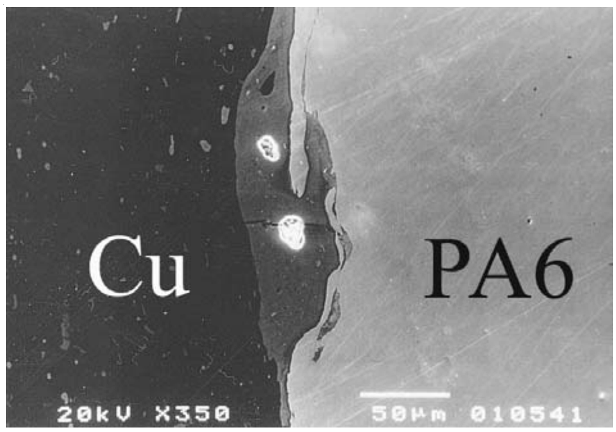


Figure 11. **Character of the Cu-PA6 joint in sets 16-19 with a visible intermediary layer and surface waviness**
Slika 11. **Karakteristika spaja Cu-Pa6 u kompletu 16-19 s vidljivim među slojem i površinskom valovitošću**

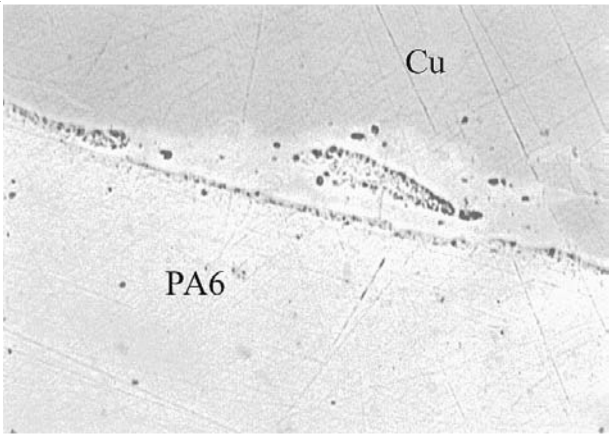


Figure12. **An intermediate layer with very numerous discontinuities being typical of sets 20 23**
Slika 12. **Međusloj s brojnim diskonituitetima tipičan za seriju 20 30**

performed under a load of 0.01N on an FM7 tester by Futur-Technic, are shown in Figure 13. Compared to the microhardness of the base materials, being ~ 132 HV0.01 for and ~ 146 HV0.01 for PA6, the layer exhibits values exceeding 500 HV0.01.

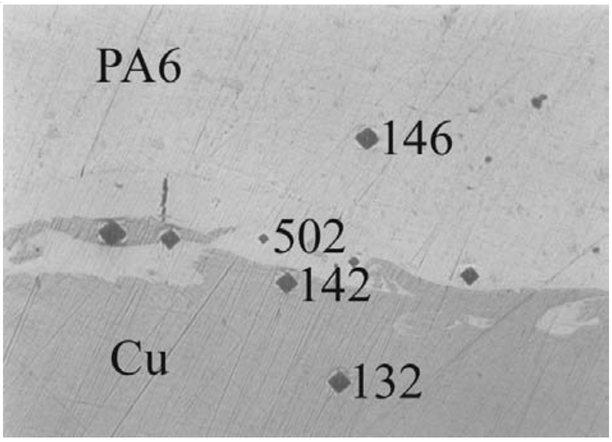


Figure 13. **Results of the HV0.01 microhardness tests of the joint region**
Slika 13. **Rezultati ispitivanja mikrotvrdoće HV0.01 na području spoja**

The character of the transitory layer, defined by using the analysis of chemical composition in microareas made by the EDX method on a scanning microscope, is shown in Figure 14. With the applied accelerating voltage 20 kV, the diameter and depth of the analyzed area did not exceed 2 μm.

The results of a phase analysis of the joint region performed on an XRD3003TT X-ray diffractometer supplied by Seifert, with a Co tube and an accelerating voltage of 40 kV, have confirmed the existence of the phase Θ based on the intermetallic compound $CuAl_2$. Comparison of the result Cu-Al equilibrium system indicates that the occurred structures are mixtures of the phase Θ and the eutectics (Θ + αAl), and suggests that the cladding temperature exceeded 600 °C, which has resulted in the formation of low melting-point, high-aluminium liquid phases - which explains the presence of discontinuities, plentiful in one of the cladding variants, and the increased amount of oxygen. There is, however, a possibility of those discontinuities to be welded in the subsequent plastic working process. The presence of the thick, very hard and, as can be seen from the visible crack, brittle joint zone continues, however, to be a problem, which reduces the cohesion of the joint and can make its using difficult.

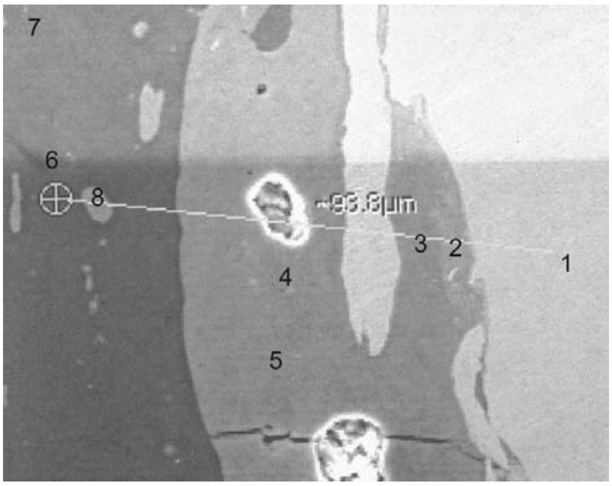


Figure 14. **Joint region analyzed on the scanning microscope, with marked locations of EDX point analysis**
Slika 14. **Područje spoja analizirano mikroskopom sa skenerom, s označenim lokacijama točaka za provođenje EDX analize**

CONCLUSIONS

1. The explosive cladding method assures obtaining round bimetal rods (Al-alloy core - copper cladding layer) with a high quality of the joint, whose shearing strength - with properly selected cladding process parameters - exceeds the strength of the starting materials.
2. A highly developed transitory layer and the occurred regular, wavy joint guarantee a good strength of the joint. The occurrence of an Al-rich, high-microhardness phase in the transitory zone may, however, be the cause of difficulties in further processing. Phase analyses performed by the EDX method and the discontinuities present show that this layer has formed from the liquid phase.
3. The circular symmetry of the cross-section of the bimetallic semi-finished product produced by the explosive method assures wire rod and wire to be produced with a uniform distribution of the thicknesses of layers.
4. The characteristic of a joint with regular waves, optimal from the strength viewpoint, and the presence a transitory layer being a Cu-Fe mixture with a variable

concentration of the both elements, have been obtained in the investigations. This bears evidence of the fact that the explosive cladding process is accompanied by an increase of temperature in the narrow joint zone, which permits partial melting and mixing of the materials being joined.

A properly performed rolling process assures the finished product in the form of bimetal rods to be obtained with a joint quality comparable to that of charge after explosive cladding. Incorrect choice of elongation rolling technological parameters (such as cooling rate, the roll pass design system, etc.) may cause a considerable reduction of the shear strength of the joint, reaching 40 %.

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