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S. MRÓZ*, P. SZOTA*, A. STEFANIK*, S. WĄSEK*, G. STRADOMSKI*

ANALYSIS OF Al-Cu BIMETALLIC BARS PROPERTIES AFTER EXPLOSIVE WELDING AND ROLLING IN MODIFIED PASSES

ANALIZA WŁASNOŚCI BIMETALOWYCH PRĘTÓW Al-Cu PO ZGRZEWANIU WYBUCHOWYM I WALCOWANIU W MODYFIKOWANYCH WYKROJACH

The paper presents the results of the experimental tests of Al-Cu bimetallic bars rolling process in multi-radial modified passes. The bimetallic bars consist of aluminium core, grade 1050A and copper outer layer, grade M1E. The stocks were round bars with diameter 22 mm with a copper layer share of 15 and 30%. As a result of rolling in four passes, bars of a diameter of about 16.0 mm were obtained. A bimetallic stock was manufactured using an explosive welding method. The use of the designed arrangement of multi-radial modified stretching passes resulted in obtaining Al-Cu bimetallic bars with the required lateral dimensions, an uniform distribution of the cladding layer over the bar perimeter and high quality of shear strength between individual layers.

Keywords: bimetallic bars, explosive welding, groove-rolling, connection quality

W pracy zamieszczono wyniki badań doświadczalnych procesu walcowania prętów bimetalowych Al-Cu w wielopromieniowych modyfikowanych wykrojach wydłużających. Pręty bimetalowe Al-Cu składały się z aluminiowego rdzenia w gatunku 1050A oraz miedzianej warstwy platerującej w gatunku M1E. Udział miedzianej warstwy platerującej w przekroju poprzecznym pręta wynosił 15 i 30%. średnica początkowa prętów bimetalowych wynosiła 22 mm, a średnica końcowa po walcowaniu w czterech przepustach wynosiła 16 mm. Wsad bimetalowy otrzymano z wykorzystaniem metody zgrzewania wybuchowego. Zastosowanie zaprojektowanego układu wielopromieniowych modyfikowanych wykrojów wydłużających zapewniło otrzymanie prętów bimetalowych Al-Cu o wymaganych wymiarach poprzecznych, równomiernym rozkładzie warstwy platerującej na obwodzie pręta oraz wysokiej wytrzymałości złącza na ścinanie.

1. Introduction

There is high demand on the domestic's and world's markets for homogeneous and multi-layer non-ferrous alloy products intended for the different industries [1, 2]. Multi-layer products (such as round bars) are manufactured to utilize the differences in the properties of metals making up a bimetal, e.g. in thermal expansion, electric conductivity, corrosion protection and mechanical strength [3-5].

Among bimetallic conductors, bimetallic bars and wires with an aluminium core and a copper clad layer find numerous applications, and are manufactured chiefly for the purposes of electrical power engineering, telecommunications and electronics. Bimetallic bars should be characterized by good bond quality and a uniform clad layer distribution on their perimeter and length [6, 7]. The most competitive method of obtaining bimetallic products, as against the methods being in use, is the combination of two methods: the explosive welding method to produce the stock with subsequent metal forming by groove-rolling [6, 8]. Its increasing popularity, this method owes to the fact that it is uncomplicated and relatively cheap, and ensures a durable bond to be achieved between the bimetal layers.

The process of rolling bimetallic bars in grooves is characterized by great non-uniformity of deformation of the band over its width. This may give rise to many defects, such as, e.g.: a non-uniform distribution of the cladding layer, inadequate filling of the grooves and a non-uniform stress state in individual layers of the bimetallic bar. The correctly selected roll pass design system and the rolling process run properly ensure a finished product in the form of bimetallic bars to be obtained with quality comparable to that of stock after explosive welding [6-8].

The use of a multi-radial oval and round passes allow a band to be obtained, which, in the subsequent rolling pass has a greater width of contact with the roll pass as the metal is bitten by the rolls. This modification provides the possibility of increasing the bite angle, and thus applying larger reductions in rolling passes. Also the stability of band plastic flow in the groove is improved, and a reduction in the non-uniformity of deformation over the bimetallic band width follows.

The aim of the study was to demonstrate that the use of the explosive welding method for Al-Cu stock production and

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* CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, FACULTY OF PRODUCTION ENGINEERING AND MATERIALS TECHNOLOGY, INSTITUTE OF METAL FORMING AND SAFETY ENGINEERING, AL. ARMII KRAJOWEJ 19, 42-200 CZĘSTOCHOWA, POLAND

then use of modified roll stretching passes for rolling Al-Cu bimetallic bars would have the effect of producing a more uniform distribution of the cladding layer over the core perimeter and good quality of joining region between individual layers.

2. Explosive welding of Al-Cu bimetallic bars

Ten sets of samples were prepared for tests, which were made of M1E grade copper tubes and 1050A grade aluminium bars. The grades of the metals and the range of individual layer thicknesses, as well as the distances between the layers, were selected so as to obtain bimetallic wire consistent with the products of the Copperweld [9]. Copper tubes and aluminium bars were prepared in two different arrangements to obtain varying distances between bars and inner tube walls [10]. As a result of explosive welding, 10 bimetallic bars: nos. 1-5 – with a Cu layer cross-sectional fraction of 15%, and nos. 6-10 – with a cladding layer cross-sectional fraction of 30%, were obtained. The inner diameter of all Al-Cu bars was approx. 22 mm. 5% Amonal, an explosive composed of ammonium nitrate (95%) and flaked aluminium powder (5%) was used for explosion welding. After making the detonation of the previously prepared assemblies, semi-finished products in the form of Al-Cu bimetallic bars without neckings were obtained, which were characterized by a fast bond along the entire length and perimeter [10].

Round bimetallic stock intended for rolling Al-Cu bimetallic bars should have a uniform distribution of cladding layer thickness over the core perimeter and high bond strength. In order to determine the thickness of the cladding layer, cross-wise samples were taken, which, after having been polished, were scanned to obtain a digital cross-section image. Figure 1 shows example samples taken for the examination of the cladding layer thickness distribution over the core perimeter.

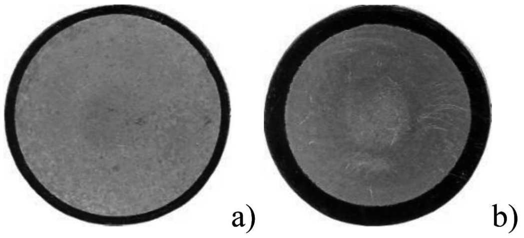


Fig. 1. View of the examples Al-Cu bimetallic bars after explosive welding: a) 15% Cu, (sample no. 1), b) 30% Cu, (sample no. 9), [11, 12]

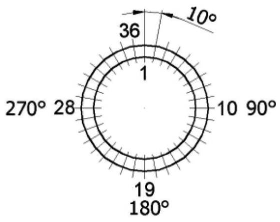


Fig. 2. Schematic illustrating the measuring grid used for determining the cladding layer thickness [11]

In order to accurately determine the thickness of the cladding layer on the aluminium core perimeter, digital sample images were read in to a CAD type software application. A measuring grid was plotted on the digital images, as shown schematically in Figure 2. Thirty six measurements corresponding to the multiple of the angle 10° were taken, starting from the orientation in the *N* direction.

In Figure 3, cladding layer thickness measurement results are represented for bimetallic stock with a 15% copper layer fraction (sample no. 1) and for bimetallic stock with a 30% copper layer fraction (sample no. 9).

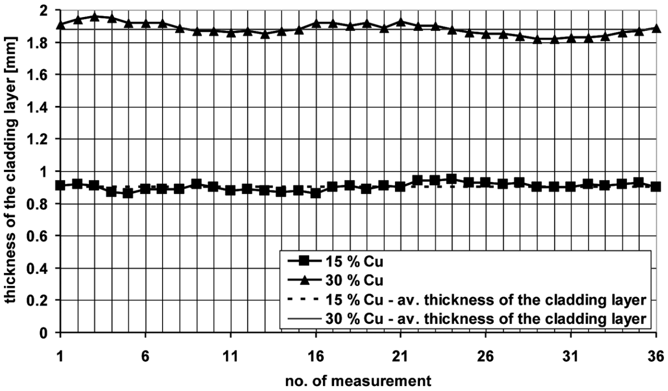


Fig. 3. Distribution of Cu layer thickness over the aluminium core after the explosive welding

By analyzing the data represented in Fig. 3 it can be found that the cladding layer thickness on the aluminium core is uniform, with thickness deviations of around 0.05 mm. The non-uniform distribution of copper layer thickness (K_{plat}) over the bar perimeter was defined as the ratio of the maximum copper layer thickness to the minimum copper layer thickness [11]. For the Al-Cu bimetallic bars with the 15% cladding layer fraction, differences in cladding layer thickness in the bimetallic stock cross-section did not exceed 10% (K_{plat} = 1.10), while for the 30% cladding layer fraction bimetallic bars, cladding layer differences did not exceed 8% (K_{plat} = 1.08). The obtained slight differences in Cu layer thickness on the aluminium core perimeter indicate good geometrical quality of the stocks.

In order to examine the quality of the joint between the layers of bimetal bars taken from a sample obtained by the explosive method the strength tests were performed on the Al-Cu stocks (to determine the joint shear strength). The quality of the joint of bimetal layers with the aluminium cores clad with copper was tested on testing dies [6, 10]. The mechanical tests of the joint were performed on a Zwick Z100 testing machine. Figure 4 illustrates the results of shear strength testing of the joint for samples taken from bars made from different sets.

The data represented in Fig. 4 show that the highest values of bond shear strength have been obtained for samples nos. 7, 8 and 9, that is for the samples with the highest (30%) cladding layer fraction of the bimetallic stock cross-section. For sample no. 10, slightly lower bond shear strength was obtained, which was due to the use of PVC tube with a larger diameter in the explosive welding, which resulted in a larger amount of the explosive. Hence, it can concluded that increasing the amount of explosive will result in a stronger detonation wave, which, in the case under consideration caused the occurrence of numerous fusions and cracks at the boundary between individual bimetal components. For samples with the 15% copper layer fraction (samples nos. 1-5), the bond strength was the lowest due to the use of a larger amount of explosive compared to the 30% copper fraction samples. It was also found that the greater the initial distance between the welded components, the better the quality of the finished bimetallic bar bond.

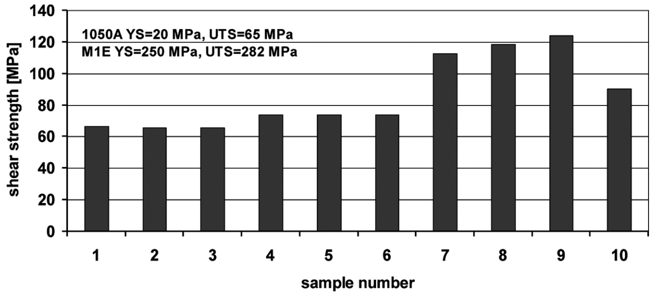


Fig. 4. Shear strength of the Al-Cu samples after explosive welding [10]

In order to explain the plastic bond share mechanism in a greater detail, the values of the yield strength and the tensile strength have been added for the individual components of Al-Cu bimetallic stocks in Fig. 4. Upon comparing the obtained values of bond shear strength with the tensile strength value for aluminium it can be stated that for test samples nos. 4÷10 the quality of the bond was good enough not to result in the breaking of individual layers, but only squeezing out of the aluminium core through the test die eyelet. By contrast, for samples nos. 1÷3, the obtained shear strength values corresponded approximately to the aluminium yield strength value. Hence, it can be presumed that the plastic shear of the sample occurred in the zone of junction of individual bimetallic bar layers.

Within the study, an analysis of the microstructure of Al-Cu stocks was also made in three zones, i.e. in the core, the intermediate layer and the outer Cu layer. For the microstructural examination, a Nikon Eclipse Ma 200 optical microscope was used. Figure 5 shows the microstructure and average $HV_{0.05}$ microhardness values in the bond region for 4 selected samples, i.e. a) sample no. 1-15% Cu; b) sample no. 2-15% Cu; c) sample no. 8-30% Cu; and d) sample no. 9-30% Cu.

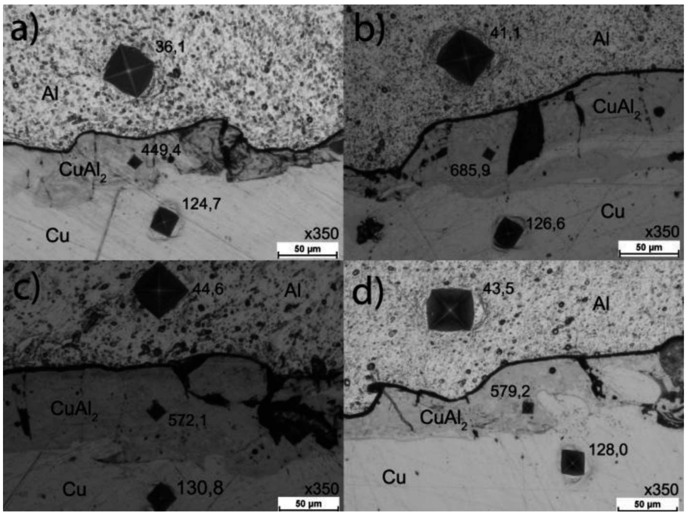


Fig. 5. The results of $HV_{0.05}$ microhardness measurements in the connection areas: a) sample no. 1, b) sample no. 2; c) sample no. 8, d) sample no. 9 [10]

As can be noticed in Fig. 5, the Al-Cu bimetallic stock bond region is made up of three layers: an aluminium core, an outer copper layer and a fused intermediate $CuAl_2$ layer, which was formed during the explosive welding. The bond region is a typical joint with an irregular and wavy shape, formed as a result of explosive welding [6]. The analysis of the bond region revealed numerous cracks and areas of discontinuities in the intermetallic layer occurrence zone or at the (Al) core–($CuAl_2$) transition layer. In the transition zone of sample no. 1, few cracks propagating from the sample axis were observed, which formed at the time of material cooling after the detonation wave had passed. Sample no. 2 exhibited a microstructure similar to that of sample no. 1, with the core having a uniform structure of aluminium α, and the bond region, similarly as for sample no. 1, being characterized by the occurrence of a fused $CuAl_2$ layer. The analyzed sample no. 8 had a microstructure similar to that of sample no. 1. However, in the $CuAl_2$ transition layer, sparsely occurring cracks were observed, which propagated radially from the sample core. In the bond region, on the other hand, numerous fusions could be seen. The $CuAl_2$ transition layer in this sample was heavily cracked. In the last analyzed sample, i.e. sample no. 9, the core microstructure was also consisted of a uniform aluminium α microstructure, though in contrast to sample no. 1, fewer visible fusions and cracks were found in the bond region.

3. Rolling of Al-Cu Bimetallic Bars

The process of rolling explosion-welded Al-Cu bimetallic stocks was carried out in the Rolling Engineering Laboratory at the Institute of Metal Forming and Safety Engineering of the Czestochowa University of Technology. A rolling mill of a nominal working roll diameter of 150 mm and a roll face length of 170 mm was used of the experimental tests. For rolling Al-Cu bimetallic bars with an initial outer cladding layer fraction of 15 and 30%, respectively, rolls with grooves machined by turning were used, whose assembly formed the following arrangement of passes: horizontal modified oval (1) – vertical modified oval (2) – horizontal modified oval (3) – round (4). As a result of rolling in 4 passes, bars of a diameter of about 16.0 mm were obtained.

Based on the analysis of the theoretical study results [11] its was determined that the oval passes should ensure a limitation on bimetallic band widening during rolling. Moreover, the width of the lateral oval pass surfaces should be smaller to avoid a cladding layer excess building up on the lateral surfaces of the oval bimetallic band during rolling in the modified round pass. To this end, the lateral roundings of the passes were substituted with plane lateral surfaces inclined at an angle of approx. 40° with roundings, which restricted the widening. A larger gap between the rolls and a greater radius of rounding in the location of the skew plane pass surface passing into the roll face was employed in those passes. This provides the capability to control the widening in the oval pass and to obtain a lateral oval band surface with a not very small rounding radius. Conducting precise rolling (with no pass overfill or underfill) is a prerequisite for obtaining uniform cladding layer thickness on the bar core. Figure 6 illustrates schematically the process of rolling in oval passes with inclined lateral surfaces and in a modified round and a round passes.

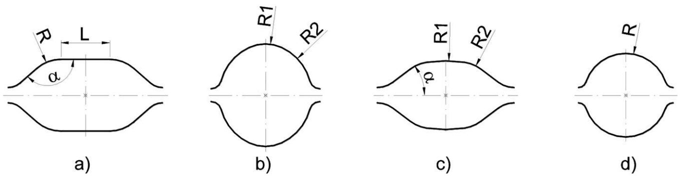


Fig. 6. Shape of grooves used during the rolling process: a) multi-radial horizontal oval, b) multi-radial vertical oval, c) multi-radial horizontal oval, d) round

Heating of the bimetallic stock of an initial length of 250 mm was carried out in a chamber furnace. Bars heated up to a temperature of 450°C. Rolling speed was approx. 0.2 m/s. The finished bimetallic bar rolling cycle included rolling the band in four rolling passes. After each rolling pass, templates were taken, (Fig. 7).

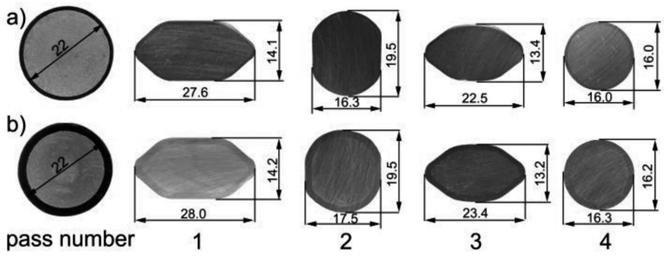


Fig. 7. View of lateral samples taken from the billet after rolling in particular passes: a) Al-Cu – 15% Cu, b) Al-Cu – 30% Cu

The correctly selected arrangement of elongating passes and the rolling process parameters have eliminated the copper layer ”flow-down”, layer delaminations, the potential for the cladding layer being lapped and the likelihood of delaminations occurring at the boundary of the bond between individual bimetallic bar components. Thus, it is possible to obtain finished product of the desired share of the copper layer in the bimetallic bar cross-section, only slightly differing from the copper layer fraction of the stock.

The increase in the band width caused by the increased share of the hard (Cu) layer as a cladding layer created the need for enlarging the inter-roll gap in the fourth rolling pass during rolling Al-Cu bars with the 30% Cu layer share (Fig. 7b). Increasing the inter-roll gap by 0.2 mm resulted in obtaining a finished bar that was characterized by a minimum circular ovality and eliminated the potential for a pass overfill occurring.

Comparison of the share of the cladding layer in the cross-section of the bimetallic bar after rolling in individual rolling passes indicates that this share slightly decreased in particular rolling passes, namely by 0.4% for Al-Cu bimetallic bars with the 15% Cu layer fraction and by 0.3% for Al-Cu bimetallic bars with the Cu layer fraction of 30%. The obtained constant cladding layer share after individual rolling passes proves that the roll pass design method presented herein assures the rolling process to be conducted correctly, without the effect of the cladding layer ”flowing down” from the bar core.

Also the geometrical parameters of the cross-sections of bimetallic bars obtained from the experimental tests were examined in the study. Figure 8 shows the distribution of the copper layer over the perimeter of the aluminium core for the final bimetallic bars with a Cu layer fraction of 15 and 30%, respectively.

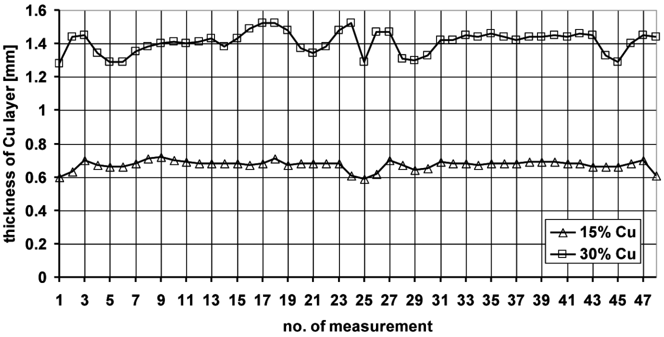


Fig. 8. Distribution of Cu layer thickness over the aluminium core after the final pass: a) Al-Cu – 15% Cu, b) Al-Cu – 30%Cu

When examining the data shown in Fig. 8 it can be noticed that the non-uniform distribution of copper layer thickness has been significantly minimized as compared with the results of studies [7, 13, 14]. The greatest “thinning” of the copper layer is noticed in the vertical band axis, whereas the greatest “thickening” of the copper layer is observed in the regions situated in the immediate proximity of the horizontal band axis. The thickening of the copper layer in those band regions can be explained by too large a width of the bimetallic band obtained from the third rolling pass. The excessive thickness of the Cu layer in the third rolling pass in the band regions adjacent to the transition of the pass groove into the roll flange, visible in particular for the 30% layer fraction, caused the excess of the Cu layer in the fourth rolling pass not to distribute uniformly on the bar perimeter, but instead thickened (”piled up”) in band regions lying in the immediate proximity of the vertical band axis. The presented experimental test results suggest that the cladding layer moves towards the roll groove, which contributes to the uneven distribution of the cladding layer over the bimetallic bar, which is consistent with the investigation results reported in references [7, 13, 14]. When examining the obtained testing results it can be found that by reducing the band width in the third rolling pass, a bimetallic bar of even more uniform cladding layer distribution over the bar perimeter could be achieved.

The non-uniform distribution of copper layer thickness (K_{plat}) over the bar perimeter for the final bimetallic bars with 15% Cu layer fraction was 1.22, while for the bimetallic bars with 30% Cu layer fraction was 1.19. The obtained values are significantly lower than the values obtained in references [7, 13, 14]. This provides evidence for the correctness of the employed modified stretching passes for rolling Al-Cu bimetallic bars.

A good bond of layers in bimetallic stock does not always ensures a good quality band to be obtained from groove rolling. With an unfavourable ratio of layer thicknesses and inadequately selected technological parameters (temperature, rolling reduction), a delamination of individual components may occur [6, 15]. The results of examination to determine the quality of bond between the components of Al-Cu bimetallic bars obtained from the process of rolling in the designed modified stretching passes are presented below.

The results of examination of the quality of bond in finished Al-Cu bimetallic bars are shown in Fig. 9. The numbering of samples corresponds to the designations of the Al-Cu bimetallic stocks in Fig. 4.

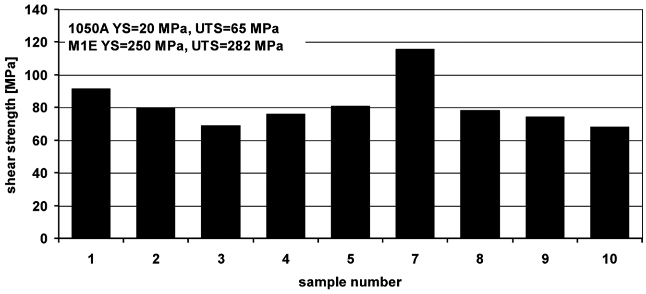


Fig. 9. Shear strength of the Al-Cu sample after groove-rolling process

It can be seen from the data in Figure 9 that the greatest bond shear strength values have been obtained for samples nos. 1 and 7. For sample no. 10, a slightly lower value of bond shear strength has been obtained, which might have resulted from the poorer quality of bond in the stock material, which showed numerous fusions and cracks in the bimetal layer bonding regions. The average shear strength of the bond was lower for bimetallic bars with the 15% copper layer fraction of the cross-section, compared to bimetallic bars with the 30% copper layer cross-sectional fraction. This was directly related to the quality of component bond in the bimetallic stock obtained from explosive welding. By comparing the bond shear strength values obtained for finished bimetallic bars with the values obtained for the explosive welded stocks (Fig. 4) it can be stated that after the rolling process the bond shear strength was higher for bars with the 15% copper fraction (on average, by 15%), while for bimetallic bars with the 30% copper fraction, a decrease in bond shear strength (on average, by 22%) was noted. The increase in bond strength for the 15% copper layer fraction bimetallic bars might have resulted from their faster cooling when transferring the samples from the furnace to the rolling mill and increased heat dissipation during the rolling process itself. The overcooling of the cladding layer has resulted in a change in the microstructure development mechanism, because the full recrystallization temperature is not reached, and hence recovery processes are taking place. As a consequence, no grain growth occurs in the cladding layer, which has a favourable effect on the shear strength of the bond. For the 30% copper layer fraction bimetallic bars, both the rate of cooling the stock prior to rolling, as well as the rate of heat dissipation through the contact with the rolls is lower, which results in the recrystallization of the cladding layer structure and the growth of copper grains. The reduction of the bond shear strength for the 30% Cu layer fraction bars is consistent with the results provided in reference [6].

In spite of the decrease in bond strength being noted for finished bimetallic bars, nevertheless the bond shear strength values obtained for finished bimetallic bars ensure the adequate bond quality, thus providing the possibility of their further plastic working into finished products (by drawing) for both the 15% and 30% copper layer fraction of the cross-section.

To determine the quality of bond in bimetallic bars, the analysis of the microstructure of the Al-Cu bimetal was made in three zone, namely the zone, the fused intermediate layer and the outer Cu layer. Samples were taken for analysis as follows: after the first rolling pass – rolling in the oval horizontal modified pass – to observe the changes and the effect of bimetallic stock preheating prior to the rolling process (sample no. 1, 15% Cu layer fraction; sample no. 9, 30% Cu layer fraction) and after the rolling process (sample no. 1, 15% Cu layer fraction; sample no. 9, 30% Cu layer fraction).

Figure 10 shows the microstructure and average $HV_{0.05}$ microhardness testing results in the bond region for the examined Al-Cu bimetallic samples after the process of rolling in the designed system of modified passes.

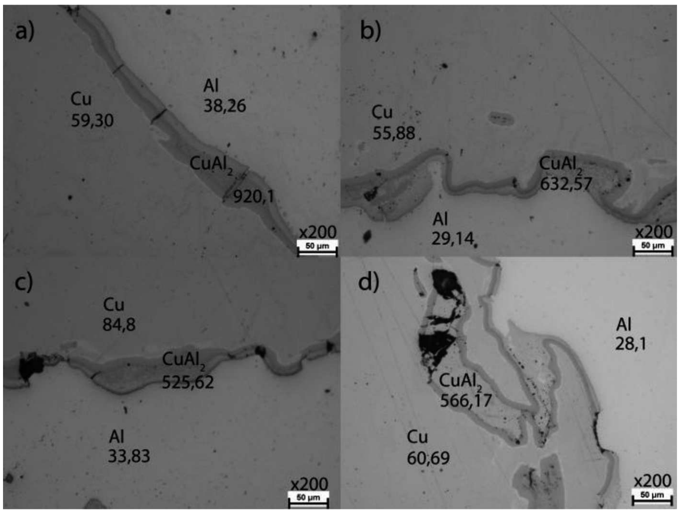
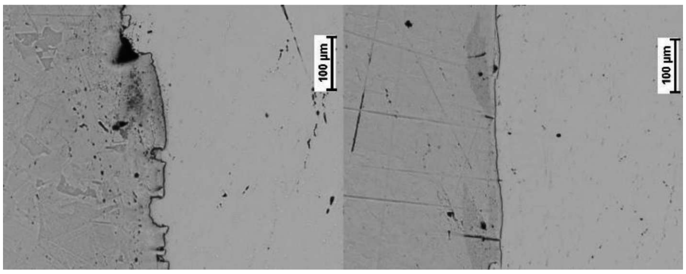


Fig. 10. The results of $HV_{0.05}$ microhardness measurements in the connection areas: a) sample no. 1, 15% Cu – after first pass, b) sample no. 9, 30% Cu – after first pass; c) sample no. 1, 15% Cu, after the final pass, d) sample no. 9, 30% Cu, after the final pass

From the data represented in Fig. 10 it can be found that, similarly as for the bimetallic stocks, the bond region of the Al-Cu bimetallic bar is composed of three layers: an aluminium core, an outer copper layer and a fused intermediate $CuAl_2$ layer formed as a result of explosive welding.

The microstructure of sample no. 1 (Fig. 10a) is characterized by an extended bond, particularly in the sample's corners. Over the entire bond length, the intermediate $CuAl_2$ layer occurs; this layer has a stratified structure, which may suggest the existence of different types of a hard intermetallic phase; in spite of the hard phase occurring over the entire perimeter, no delamination occurs. Sample no. 9 (Fig. 10b) had an extended bond, especially in its corners. Over the entire bond length, there occurs the intermediate $CuAl_2$ layer in a considerable proportion; similarly as in sample no. 1, this layer had a stratified arrangement. Despite the existence of the hard layer over the entire perimeter, no delamination was observed. In sample no. 1 (Fig. 10c), which was taken from a finished Al-Cu bar, an extended bond was observed, which was similar in character to the bond obtained in sample no. 9, but taken after the first rolling pass. A thin transition $CuAl_2$ layer occurs over the whole bond length. However, in this sample, the transition layer has distinct cracks across the whole perimeter; in a considerable part of the sample, breaches and a broken bond occurred. Also in this case, the $CuAl_2$ layer had a stratified arrangement. The last examined sample was sample no. 9 (Fig. 10d), which was also taken from the finished bimetallic bar after the rolling process. The examined sample was characterized by a good-quality extended bond. Over the whole bond length, a thin intermediate $CuAl_2$ layer was observed. Unfortunately, pronounced cracks were observed to occur on a considerable part of the perimeter. The $CuAl_2$ layer had a stratified arrangement and a varying thickness on its perimeter, similarly to the one obtained in sample no. 9, but taken after the first rolling pass.

By comparing the bond shapes obtained in the bimetallic stocks after explosive welding (Fig. 5) and in the bars after groove rolling (Fig. 10) it can be found that the bond region of the examined samples was much more extended compared to the samples taken from the bimetallic stocks after explosive welding. The transition $CuAl_2$ layer had a stratified structure, which might suggest the occurrence of various types of the hard intermetallic phase. A more extended, wavy type of bond could be observed for sample no. 9. For sample no. 1, on the other hand, higher microhardness values were noted, especially in the intermediate $CuAl_2$ layer, which resulted from its greater hardening due to faster heat dissipation. As a result, a wavy type of bond formed on the longitudinal sample section, on which a "meshing" of individual layers of the finished bimetallic bar is visible (Fig. 11). As a result, the rolled bimetallic samples with the 15% Cu layer fraction showed an increase in the value of bond shear strength, compared to similar bimetallic samples after explosive welding.



a) b)

Fig. 11. Microstructure of the bond region for samples taken from finished bimetallic bars: a) sample no. 1 (15% Cu), b) sample no. 9 (30% Cu)

4. Conclusion

From the obtained results it can be found that the explosive used and the adopted explosive welding parameters have ensure Al-Cu bimetallic bars to be obtained, which are composed of aluminium cores in grade 1050A and an outer copper layer in grade M1E. As a result of the explosion welding, a bimetallic semi-finished product with a circular cross-section symmetry was obtained. The obtained bimetallic stock was distinguished by a fast bonding of individual layers with a bond shear strength that might exceed the resistance to plastic flow of the aluminium core.

The application of the multi-radial modified stretching passes and the adopted rolling parameters has ensured Al-Cu bimetallic bars with the required lateral dimensions and a uniform cladding layer distribution over the bar perimeter to be obtained. It has also been found that by rolling bimetallic bars in the modified passes it is possible to produce finished bimetallic bars with high bond strength, comparable to that of bimetallic stocks. The hard transition $CuAl_2$ layer formed as a result of explosive welding did not cause the bimetallic bars to delaminate during rolling.

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