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S. MRÓZ*#, A. STEFANIK*, P. SZOTA*

GROOVE ROLLING PROCESS OF Mg/Al BIMETALLIC BARS

The paper presents the results of the experimental tests of Mg/Al bimetallic bars rolling process in classic and multi-radial modified round-oval-round passes. The bimetallic bar consist of magnesium core, grade AZ31 and aluminium outer layer, grade 1050A. The stocks were round bars with diameter 22.5 mm with an aluminium layer share of 28%. As a result of rolling in four passes, bars of a diameter of about 17 mm were obtained. A bimetallic feedstock was manufactured using an explosive welding method. The use of the designed arrangement of multi-radial modified stretching passes resulted in obtaining Mg/Al bimetallic bars with an uniform distribution of the cladding layer over the bar perimeter and high quality of shear strength between individual layers compared to Mg/Al bars obtained in the classic passes.

Keywords: bimetallic bars, Mg alloy, groove rolling, multi-radial passes

1. Introduction

Multi-layered products, including bimetallic bars, enjoy increasing interest both in scientific research and in industrial applications. In many instances, they can make an alternative to homogeneous products. As an example, multilayered sheets and bilayered Mg/Al bars can be mentioned [1-3]. In the world's market, and in recent years also in the domestic market, an increasing interest in Mg alloys intended chiefly for the automotive and aircraft industries has been observed [4,5]. A significant obstacle to a wider use of magnesium alloys in technology is their relatively poor corrosion resistance [6,7]. Thus, the use of aluminium cladding may be a perspective solution to ensure an increase in the corrosion resistance of the magnesium core, while not causing any significant increase in the specific weight of finished products.

Literature data shows that there are numerous methods of manufacturing these types of products [1-3,8-11]. However, the majority of those methods do not guarantee the satisfactory quality of the bond, the required thickness of the cladding layer and additionally, in the case of bimetallic bars, the uniform distribution of the cladding layer on the core perimeter. One of the technologies, which ensures the meeting of the aforementioned requirements, is the use of the explosive welding or the casting method for producing bimetallic stock [8], and then rolling in stretching passes [12,13]. However, a good bonding of layers in the bimetallic stock in many instances does not guarantee the high quality of bimetallic bars to be achieved during groove rolling. With an unfavourable ratio of layer thicknesses and inadequately selected process parameters (deformation scheme, temperature, pass shapes), a delamination of individual components and a non-uniform cladding layer distribution on the bar perimeter may occur [14,15].

Since the beginning of the 80s of the 20th century, research has been conducted at the Institute of Metal Forming and Safety Engineering of the Czestochowa University of Technology on the optimization of the shape of classic stretching passes to enhance the homogeneity of deformation during rolling homogeneous bars [16,17], and, in recent years, also bimetallic bars [18]. Studies [18,19] have demonstrated that by using multi-radial modified stretching passes in the round-oval-round arrangement for producing Al/Cu bimetallic bars, such a strain distribution can be obtained in individual components of rolled bilayered bars, which will provide a considerable increase in the uniformity of cladding layer distribution on the core perimeter, while assuring the high quality of the bond.

According to the data provided in work [20], the plastic flow of individual bimetal components in passes depends, among other factors, on the mutual flow stress relations, and on the share (thickness) of the cladding layer in cross-section of two-layer bars which makes it difficult to develop a universal system of passes, which could be used for different bimetallic bar types. Thus, within the framework of this study, a new system of modified stretching passes has been designed and process parameters have been selected to provide a uniform distribution of the aluminium layer on the magnesium core and a high-quality bond. The obtained rolling process results were compared with the conventional round-oval-round pass system.

* CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, FACULTY OF PRODUCTION ENGINEERING AND MATERIALS TECHNOLOGY,69 DĄBROWSKIEGO STR., 42-201, CZĘSTOCHOWA, POLAND

Corresponding author: mroz@wip.pcz.pl

2. Materials and testing methodology

Explosive welding of Mg/Al bimetallic feedstocks was carried out in cooperation with the company Explomet of Opole. The parameters taken for explosive welding are described in detail in the authors' previous works [8]. Eight sets of samples were prepared for testing, each consisting of aluminium tubes (grade 1050A) and magnesium bars (grade AZ31), respectively. Chemical composition of the materials used for the tests is given in Table 1. The initial dimensions of tubes and bars used for explosive welding are summarized in [8]. The diameter of Mg bars was 19.2 mm. And the outer diameter of aluminium tubes was 24 mm, while the tube wall thickness, 1.5 mm. The initial distance between the magnesium core and the inner tube diameter was 0.9 mm. After detotation, straight bimetallic bars with length of 500 mm and with a durable bond over the entire length was obtained, with no curving and necking.

Bimetallic bars obtained as a result of explosive welding were characterized by a slight difference in aluminium layer thickness on the magnesium core perimeter. The average thickness of the aluminium layer was 1.67 mm, and the share of the aluminium layer in the bimetallic bar cross-section was 28%. Whereas, the average diameter of the Mg/Al bimetallic stocks after explosive welding was 22.5 mm.

One of the major factors influencing the uniform distribution of the cladding layer and the bond quality is the shape of passes used for the rolling process. When designing a new pass system, the objective was to obtain the proper plastic flow of bimetallic band during rolling in individual rolling passes, so that a 17 mm-diameter Mg/Al bimetallic bar of correct dimensions (cross-sectional roundness) and the most uniform possible cladding layer distribution on the bar perimeter be obtained after rolling in the finishing pass.

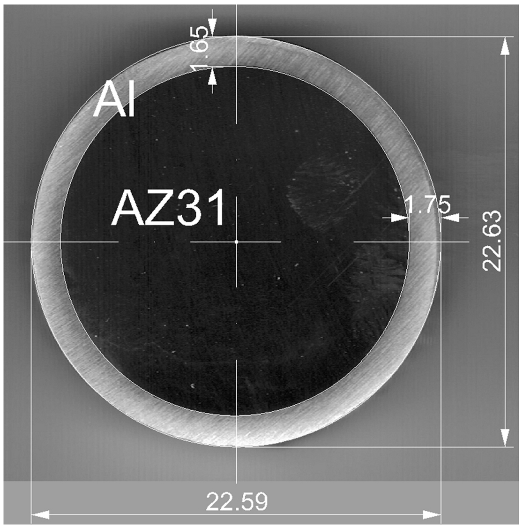

Fig. 1. A sample shape (cross-section) of Mg/Al bimetallic stock after explosive welding

For working out the design of new passes, computer simulations using a FEM-based software program were utilized. The computer simulations were performed using the software program Forge2011. Numerical modelling was carried out for two pass arrangement variants: the classic round-oval-round system and a system of modified-shape passes relying on the

TABLE 1

Chemical composition of the materials used for the tests

Material	Chemical composition, % mass.								
AZ31	Mn	Mg	Cu	Zn	Ca	Al	Si	Fe	Ni
	0.24	balance	—	0.72	—	2.8	0.01	0.003	0.001
1050A	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al	Pb
	0.06	0.18	0.002	0.003	0.002	0.008	0.020	99.74	—

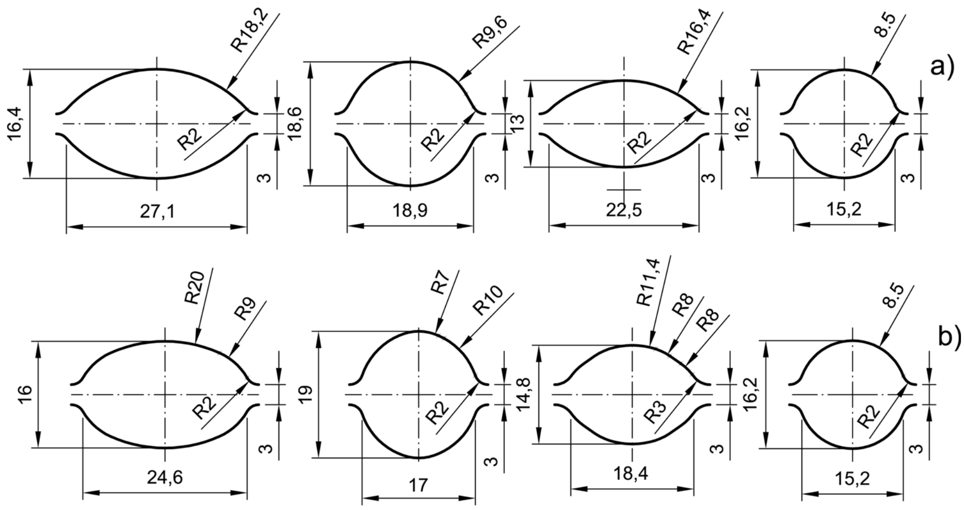

Fig. 2. The shape and dimensions of the designed stretching passes: a) the classic system of passes, b) the system of multi-radial modified passes

round-oval-round arrangement. The computer simulations made it possible to accurately design the individual passes and to determine the effect of initial process parameters (temperature and deformation) on the plastic flow of individual bimetal components, whereby the scope of laboratory tests necessary to be carried out was limited.

Using multiple radii makes it possible to create appropriate conditions during deformation, resulting in a reduction of the cladding layer "flowing down" from the Mg core. The shape of the two developed system of passes is shown in Fig. 2.

The developed new pass system consisted of two oval passes and two round passes that enabled the reduction of the bimetallic bar diameter from 22.5 mm to 17 mm. The temperature and deformation parameters were selected based on the results of physical and numerical modelling of the compression tests of bilayered Mg/Al specimens [21]. The rolling process was carried out for two temperatures, i.e. 400°C and a reduced temperature of 300°C. After each rolling pass, the specimens were reheated. The rolling speed was 0.2 m/s. For laboratory testing, a laboratory rolling mill with a working roll diameter of 150 mm was used. After each rolling pass, templates were taken.

3. Results and discussion

At the first investigation stage, changes in the shape and dimensions of Mg/Al bimetallic bands after individual passes were examined (Figs. 3 and 4). The data in Figs. 3 and 4 show that both rolling systems and the adopted process parameters allowed Mg/Al bimetallic bars of the correct shape to be obtained. In any instance, no pass overfilling occurred and no delamination was observed at the joint boundary. As predicted by the results of work [21], employing a reduced rolling temperature decreased the difference in the plastic flow resistance of individual bimetallic band components, which reduced the soft aluminium layer "flowing down" from the magnesium core. Thanks to this, a larger volume of the deformed band more vigorously moved in the rolling direction. The width of bars after this rolling pass was smaller.

As has been mentioned above, the main objective of using the new system of modified passes was to obtain a finished product with a more uniform cladding layer distribution on the magnesium core perimeter. To verify the set objective, measurements of the cladding layer thickness were taken on the perimeter of finished Mg/Al bars, as shown in Figs. 3 and 4. For this purpose, to assess the distribution of outer aluminium layer thickness, templates were taken from finished bars (after the fourth pass). The templates taken were subjected to polishing and then scanned at high resolution using a Nikon Eclipse MA-200 optical microscope based on data acquisition and analysis software, NIS-Elements. The presented results of outer layer thickness measurements are the arithmetical mean of measurements for 3 templates taken for respective rolling variants. Whereas, the total measurement error did not exceed 10%. The measurements were made according to the scheme shown in Fig. 5.

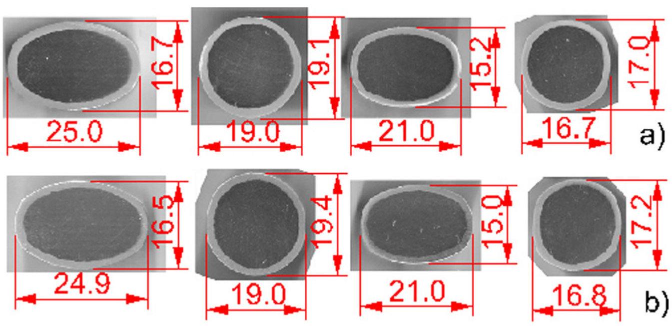

Fig. 3. The shape and dimensions of templates after rolling in the classic system of passes: a) rolling temperature, 300°C, b) rolling temperature, 400°C, (all dimensions in mm)

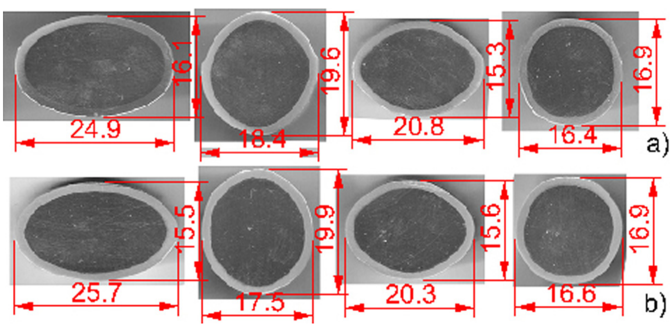

Fig. 4. The shape and dimensions of templates after rolling in the modified system of passes: a) rolling temperature, 300°C, b) rolling temperature, 400°C, (all dimensions in mm)

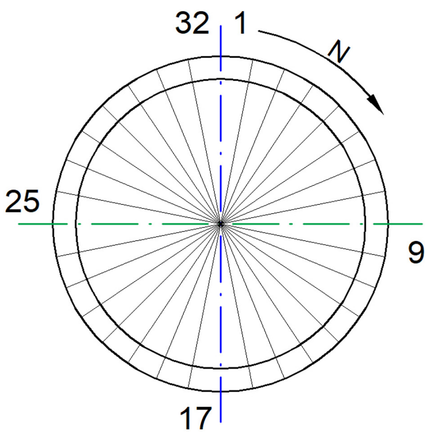

Fig. 5. Scheme of the measurements of cladding layer thickness on the Mg/Al bimetallic bar cross-section perimeter

For each specimen, 32 measurements were taken, which corresponded to the multiple of the angle 11.25°, starting from the orientation in the *N* direction (vertical symmetry axis of the pass). Whereas, the lines for measurements 1 and 17 define the layer thickness measured in the vertical axis of symmetry of the round Mg/Al bar cross-section, while measurement points 9 and 25 correspond to the horizontal symmetry axis of the bar (Fig. 5). The uniformity of the cladding layer thickness distribution on the bar core is defined by the cladding layer thickness distribution non-uniformity factor, K_{plat} [22,23], expressed as the ratio of the maximum to minimum cladding layer thickness in the cross-section of finished Mg/Al bimetallic bars.

Figures 6 and 7 illustrate the results of the measurements of cladding layer distribution on Mg/Al bimetallic bars.

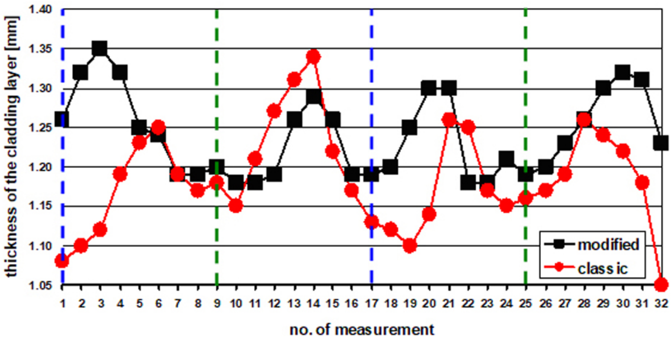

Fig. 6. Comparison of the distribution of Al layer thickness on the magnesium core for Mg/Al bars rolled at a temperature of 400°C

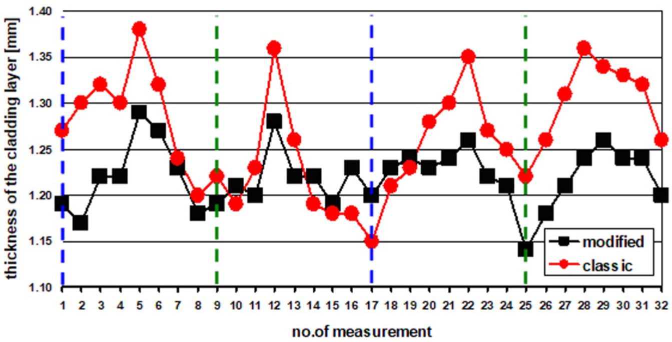

Fig. 7. Comparison of the distribution of Al layer thickness on the magnesium core for Mg/Al bars rolled at a temperature of 300°C

The data illustrated in Figs. 6 and 7 show that the obtained aluminium layer thickness distributions had a similar qualitative behaviour for both the results obtained for bimetallic bars rolled at the temperature of 400°C, as well as at a reduced temperature of 300°C. For each of the analyzed variants, a localized thinning of the cladding layer, occurring in the vertical and the horizontal specimen axes. It can be noticed from the data in Figs. 6 and 7 that the greatest thinning of the cladding layer occurred in the regions of the axis of symmetry. Those regions were the most deformed in individual rolling passes. Between these regions (occurring at an angle of 45° to the axis of symmetry of the specimen), a considerable thickening of the Al layer was noted, which was the result of the soft Al layer „flowing down“ from the magnesium core. The idea behind the use of the modified passes was to limit the uncontrolled „flowing down“ of the cladding layer, thanks to which it would be possible to obtain a finished Mg/Al bar distinguished by a more uniform Al layer.

The implemented modification of the passes, consisting in substituting the single-radial pass surface with multi-radial surfaces with straight line segments, had the favourable effect of changing the strain distribution and the plastic flow of individual components in the Mg/Al bimetallic bar in the roll gap during rolling. The new pass shape helped to limit the build-up of the cladding layer material and the ends of the passes in the direction of the axis of symmetry of the pass and, at the same time, to reduce the layer thinning in the rolling reduction direction. Also, lowering the rolling temperature to 300°C had a favourable effect on the homogeneity of the deformation and plastic flow of the bimetal components. The most uniform distribution of the cladding layer was obtained for the modified passes for the rolling temperature of 300°C. The difference between the plastic flow stress values for aluminium and the magnesium alloy at the temperature 400°C in the entire deformation range is considerable [21]. Thus, it should be endeavoured to change the process parameters by applying a lower plastic forming temperature to reduce the ratio of bimetal component plastic flow resistances.

Table 2 shows the averaged values of cladding layer thickness and the values of the K_{plat} factor. The obtained results show explicitly that the developed new pass system favourably influences the distribution of Al layer thickness. The average change of the distribution of bimetallic bar Al layer thickness for the analyzed cases was 10%. Greater difficulties in obtaining a uniform cladding layer occur when rolling Mg/Al bars at the temperature of 400°C. This is due to the greater ratio of the yield stress of Mg to Al at this temperature. In such conditions, the effect of the coating "flowing down" from the core is greater. Therefore, the rolling of bimetallic bars should be conducted at a temperature, at which the yield stresses of respective components are as close to one another as possible.

In order to examine the quality of the joint between the layers of bimetal bars taken from a specimens obtained by the explosive welding method and then rolled in 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 magnesium core with aluminum outer layer was tested on testing dies shown in Fig. 8 [24]. Fig. 8a shows the shape and dimensions of test specimens used for testing for maximum shearing stresses at the joint interface, while Fig. 8b illustrates the shape and dimensions of testing dies used during strength tests.

TABLE 2

Distribution of cladding layer thickness obtained in Mg/Al bars after rolling

Temp.	**Mg/Al stock**		**Classic passes**		**Modified passes**		**Change**
[°C]	**Av. thickness of the Al layer [mm]**	K_{plat}	**Av. thickness of the Al layer [mm]**	K_{plat}	**Av. thickness of the Al layer [mm]**	K_{plat}	**[%]**
300	1.67	1.12	1.28	1.34	1.21	1.23	9.2
400	1.67	1.12	1.22	1.45	1.27	1.29	11.7

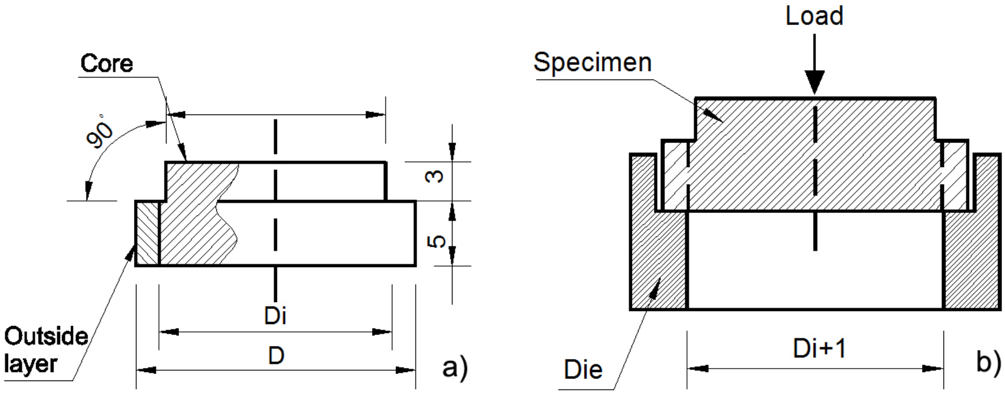

Fig. 8. Dimensions of test specimens (a) and testing dies (b) used for the examination of the quality of the bimetal rod joint after explosive cladding and groove rolling [24]

The mechanical tests of the joint were performed on a Zwick Z100 testing machine. Figure 9 illustrates the results of force obtained during testing of the joint for samples taken from bars made from different sets.

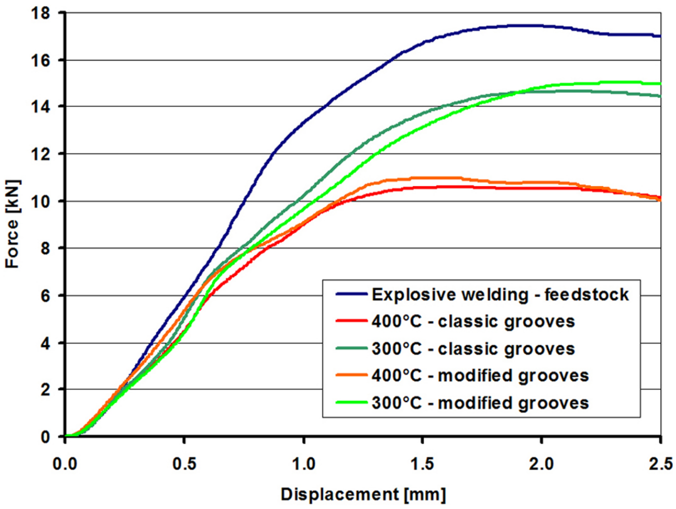

Fig. 9. Variations in the force during testing the strength of the Mg/Al bimetallic samples joint after explosive welding and rolling

When analyzing the data in Fig. 9, it can be found that, after attaining a maximum value, the force gently decreases, which is indicative of the plastic deformation of the cladding layer, and not of a break of bonding.

The joint quality test found that the correctly chosen explosive welding parameters and then rolling parameters provided a high quality of the bond (Fig. 10). The bond quality was found to be good enough that no single case of individual components becoming torn apart occurred, but only the Al layer was squeezed through the test die. Figure 10 also shows the cross-sections of samples taken from the stock after explosive welding and after groove rolling, respectively. No cracking at the joint boundary, but only in the cladding layer, was observed in any case, which proves the high quality of bonding. The shear strength for the stocks was 60 MPa. By contrast, the shear strength of the joint after groove rolling at 400°C was up to 45 MPa, while for specimens rolled at 300°C, the joint shear strength equalled that obtained for explosively welded Mg/Al stocks. No effect of the employed pass system was observed. The obtained shear strength of the joint was so good that no plastic deformation of the Al layer flange occurred during the attempt of squeezing the core out from the cladding layer. The bonding of the bimetal components was not broken or damaged.

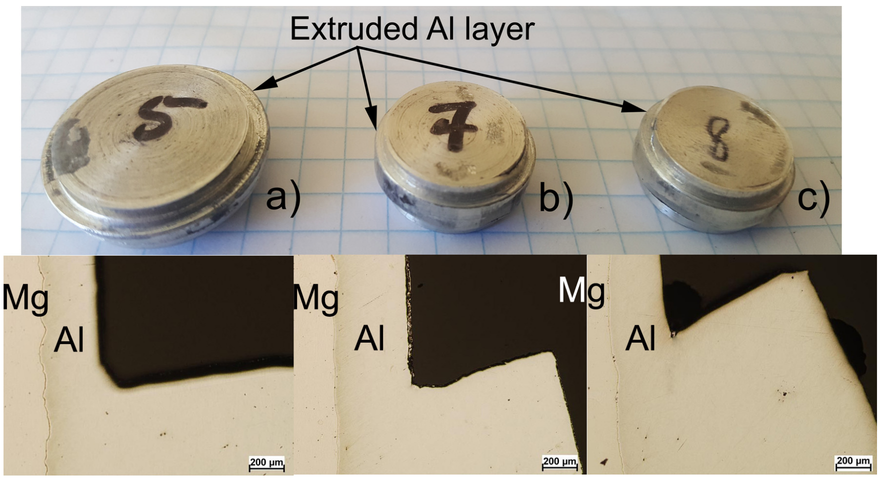

Fig. 10. A sample shape of Mg/Al bimetallic specimens after the shearing test of the joint: a) specimen after explosive welding (feedstock for the rolling process), b) specimen after rolling in the modified passes at 300°C, c) specimen after rolling in the modified passes at 400°C

4. Summary

Based on the obtained experimental test results it can be stated that the selection of the explosive welding parameters ensured a durable, high-strength Mg/Al joint and a uniform Al layer distribution to be obtained. The new system of stretching passes designed for rolling Mg/Al bimetallic bars provided a more uniform distribution of cladding layer thickness on the perimeter of the magnesium core. It has been demonstrated that using a rolling temperature reduced to 300°C enhances the uniformity of aluminium layer distribution, while increasing the joint strength, in comparison to the 400°C rolling temperature.

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