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EXPERIMENTAL INVESTIGATIONS OF THE BONDING ZONE IN THE EXPLOSIVE WELDING OF A DIFFERENTLY STRUCTURED STEEL-ZIRCONIUM PLATERS

In this work the results of trials aimed at selecting optimal settings of the explosion welding process of 10 mm thick zirconium (Zr 700 grade) plates with carbon steel (P265GH grade) are presented. A bimetal Zr-steel and trimetal Zr-Ti-steel and Zr-Zr-steel where: 2 mm Ti and 3 mm Zr were used as a technological intermediate layer facilitating the bonding. The research was carried out for as-bonded joints, i.e. immediately following explosion welding. Structural analyses in leyers near the interface were focused on the characteristic of the joint interface. Mechanical properties of the obtained clads were measured with shearing, peel and lateral bending tests. Systematic measurements of microhardness distribution enabled analyzing the strain-hardening of the material resulting from explosion welding both at the bond interface zone and throughout the whole section of the clad. It was established that during explosion welding with 10 mm Zr 700 the application of the 2 mm or 3 mm thick interlayers of Zr70 or Ti grade 1, respectively, allows obtaining a joint with good mechanical properties and optimal characteristic of the interface.

1. INTRODUCTION

The development of environmentally friendly technologies and increasing requirements regarding the economics of technological processes make it necessary for the manufacturers of metal products to search for new material composites, or to give currently used materials with improved or unique properties [1, 2]. The requirements of both high durability and relatively low production costs require using reactive metals (such as aluminum, titanium, zirconium, tantalum, etc.) or their alloys as layers deposited on the basic steel plate in the process of explosive welding. Apparatus used in the engineering processing, e.g. heat exchangers or reactors, contain elements (e.g. tube sheets) that should have a relatively "very thick" layer. While the technology of explosive welding with less-than-8-mm-thick metal sheets is well known [3-5], welding with the so-called thick sheets requires an individual approach in each case. In many cases, welding this type of plates requires using a technological interlayer made of a different material than the materials of welded plates. In

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the case of applying metal sheets with a large surface area and thickness exceeding 8 mm, accelerating bigger mass requires using a larger amount of explosive charge. This may have a negative result on the bond strength via an increase of process parameters (detonation velocity), and thus the formation of a larger melted zones and the increase of strain hardening of bonded sheets in layers near the interface. The necessity of using technological interlayer is also related to the properties of the welded materials. Material properties do not play a major role in the case of pure metals, but they are a key issue when using high strength alloys, e.g. titanium alloys. The results of preliminary tests [6] show that either welding Gr. 12 titanium with steel without the use of a technological interlayer is not possible or it will cause insufficient mechanical properties, even in the case of sheets with a thickness of less than 4 mm. In this case, the key issue is to minimize the strain hardening effect in the bonding zone.

The presented work deals with the problem of explosive welding when carbon steel is jointed with a 10 mm thick zirconium plate. In this experimental study one bimetal zirconium-steel clad and two trimetal clads welded with the use of a technological interlayer made of pure Ti and Zr were analyzed. The test systems were made by ZTW EXPLOMET Opole with various process parameters (detonation velocity and stand-off distance between welded plates). The results of mechanical and structural analyses of the bonding zone with a particular emphasis put on the characteristics of the bond interface are presented and discussed.

2. RESEARCH TECHNIQUES

2.1. MATERIALS FOR TESTING

In this study, special attempts were made to produce zirconium/carbon steel clads using commercial explosive welding technique. The sheets of Zr 700 zirconium of 10 mm thickness and sheets of P265GH steel of 25 mm thickness were used as flyer and base plates respectively. The chemical composition and mechanical properties of the materials used are shown in the Tables 1 and 2.

Table 1. The chemical composition of joined sheets, as per the supplier's certificate [7–9]

Material grade	Chemical composition [%]										
	C		Fe		H		O		Zr+Hf		N
Zr 700	0.004		0.060		< 0.0003		0.067		> 99.2		< 0.002
Ti Gr 1	0.020		0.020		0.010		0.070		-		< 0.01
	C	Mn	Si	P	S	Ni	Cr	Mo	Al	N	Nb
P265GH	0.147	0.959	0.260	0.011	0.006	0.030	0.022	0.005	0.051	0.004	0.008

Table 2. Mechanical properties of steel plates as per the manufacturer's certificate [7–9]

Material grade	Tensile strength R_m [MPa]	Yield point $R_{0.2}$ [MPa]	Elongation A [%]
Zr 700	280	143	35.0
Ti Gr. 1	240	240	24.0
P265GH	467	255	23.0

The welding process was carried out in two variants. In the first case, a simple bimetal zirconium/steel clad without using technological interlayer was produced. As a result of explosive welding tests a sample (A) was obtained, for which a solid state bond was made on approx. 30-40 % of the surface of the test clad. As the obtained results were unsatisfactory, an attempt was made to create a 3-layer clad with a technological interlayer made of titanium (Ti Gr.1) with a thickness of 2 mm (samples B) and Zr 700 zirconium with a thickness of 3 mm (sample C). It should be noted that these clads were made in a single blast. The process parameters and markings of the clads are shown in Table 3. In both cases, the test plates with dimensions of 300 mm×500 mm were made in a parallel system. The ammonium nitrate material with a layer thickness of 80 mm was used as the detonation material for explosive welding. Detonation velocities v_D were used in the lower range of parameters, i.e. 1900 $m \cdot s^{-1}$ and 2500 $m \cdot s^{-1}$ for the bimetal and trimetallic clads respectively. Literature review [3], [10–12] shows that the main factor which influences the stand-off distance between the welded plates is the thickness of the flyer plate (t). Usually, its value ranges between 0.5 t and 4 t. The stand-off distance of 15 mm was selected based the own experiments [4, 13]. For three-layered clads, diversified parameters of standoff distance *h* between the welded sheets were used. The plate markings and the process parameters used are shown in Table 3.

Table 3. Denominations of bimetal and trimetal plates and process parameters

Sample designation	Flyer plate *Th* = 10 mm	Technological intermediate layer *Th* [mm]	Base plate *Th* = 25 mm	Detonation velocity v_D [$m \cdot s^{-1}$]	Distance between the plates *h* [mm]
A	Zr 700	-	P265GH	1.9×10^3	15
B		Ti Gr.1$_{Th\,=\,2mm}$		2.5×10^3	10/4
C		Zr 700$_{Th\,=\,3mm}$		2.5×10^3	10/6

2.2. TESTS OF BONDING ZONE CONTINUITY AND MECHANICAL PROPERTIES

The quality of the obtained bond was determined for the produced clads by performing both non-destructive and destructive testing in accordance with PN-EN 13445-2 standard [14]. The above-mentioned standard requires carrying out bonding zone continuity tests with ultrasonic methods as well as tests of mechanical and technological properties including shearing, peel and lateral bending tests. The plate welded explosively with the marked sampling spot for mechanical tests is shown in Fig. 1.

Ultrasonic tests were carried out in accordance with ASTM A 578 / A 578M-96 [15] and PN-EN 10160-1 [16] standards on the surface of an explosively welded plate from the side of the flyer plate. The measurement covered the entire surface of the clad, both immediately after welding and after the straightening rolling procedure. The tests were performed with the Starmans DiO 652LC ultrasonic flaw detector with dual-element ultrasonic probe of an MSEB 4 type with a 10 mm transducer diameter. Depending on the type of the tested clad, different measuring ranges S_B (from 50 to 75 mm) and recording amplification V_R (from 6 to 38 dB) were used.

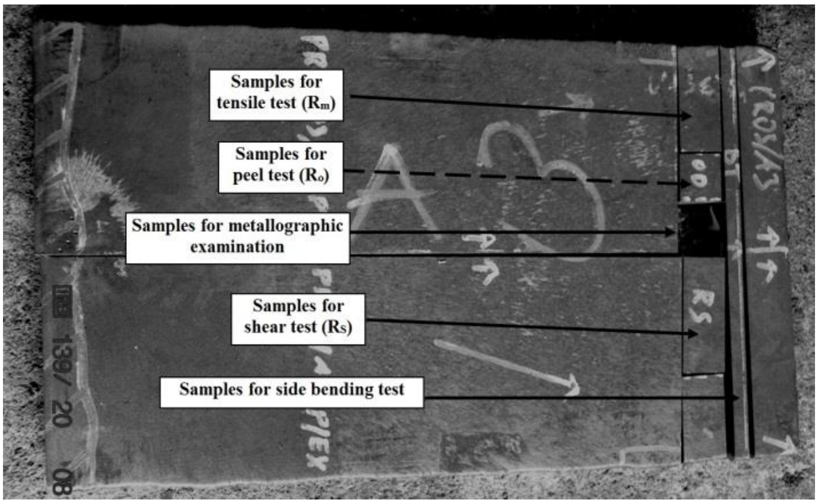

Fig. 1. An image of a bimetallic plate showing the spot of sampling for metallographic and mechanical tests

In the case of multilayered clads, the regulations do not allow for any delamination in the bonding zone, hence the next step was the lateral bending test prescribed by the standards (PN-EN 13445-2 [14]), aimed at assessing the quality of the bond interface. For the tests flat samples with a cross-section of 10 × g mm and a length of 200 mm (where g is the sum of thicknesses of welded materials), sampled perpendicularly to the direction of the detonation front propagation were used. During the test the samples were bent at an angle of 180° on a mandrel with a diameter $d = 40$ mm.

A shearing test was carried out in accordance with ASTM B 898-11 [17] standard to determine the strength of the bond. Samples in which the shearing plane was parallel to the direction of the detonation front propagation were selected, and then the tests were carried out in accordance with EN 13445-2 [14] standard. The shape and dimensions of the samples are shown in Fig. 2a. Samples including two- and three-layered clads were obtained by milling the flyer plate and the base plate. In the case of three-layer clads the tests were carried out in two variants. In the first variant, shear test covers the interface between the flyer plate and the technological interlayer, and in the second one – the interface between the technological interlayer and the base plate. The scheme of the shearing test is shown in Fig. 2b. The test was carried out until the material was completely separated and the maximum force corresponding to the joint damage was recorded. In addition, macroscopic observations to determine the place of shearing were carried out for each damaged sample.

Because the bending test may in many cases be subject to a large error due to the corrugated character of the bonding zone, a peel test (R_o) is carried out to assess the "resistance" against delamination. The shape and dimensions of the sample and the method of performing the peel test are shown in Figs. 2b and c. Similarly to the above-mentioned test, the place, where the peeling took place was also observed in macroscopic scale. With regard to the high-strength bimetal clads, most often the place of the damage is located in the material of the flyer plate or the base plate, i.e. in the material of lower strength. If the sample is damaged at the bond interface, it indicates low strength properties of the tested clad.

The third standard attempt is the tensile strength test (R_m). This test was carried out on the basis of the examination of non-normative samples of the shape and dimensions shown in Fig. 2d. For bi- and tri- metal clads, samples were made with the dimensions $g \times 10$ mm × 2 mm, in which the dimension g is the sum of the thickness of the welded materials (see Fig. 2e).

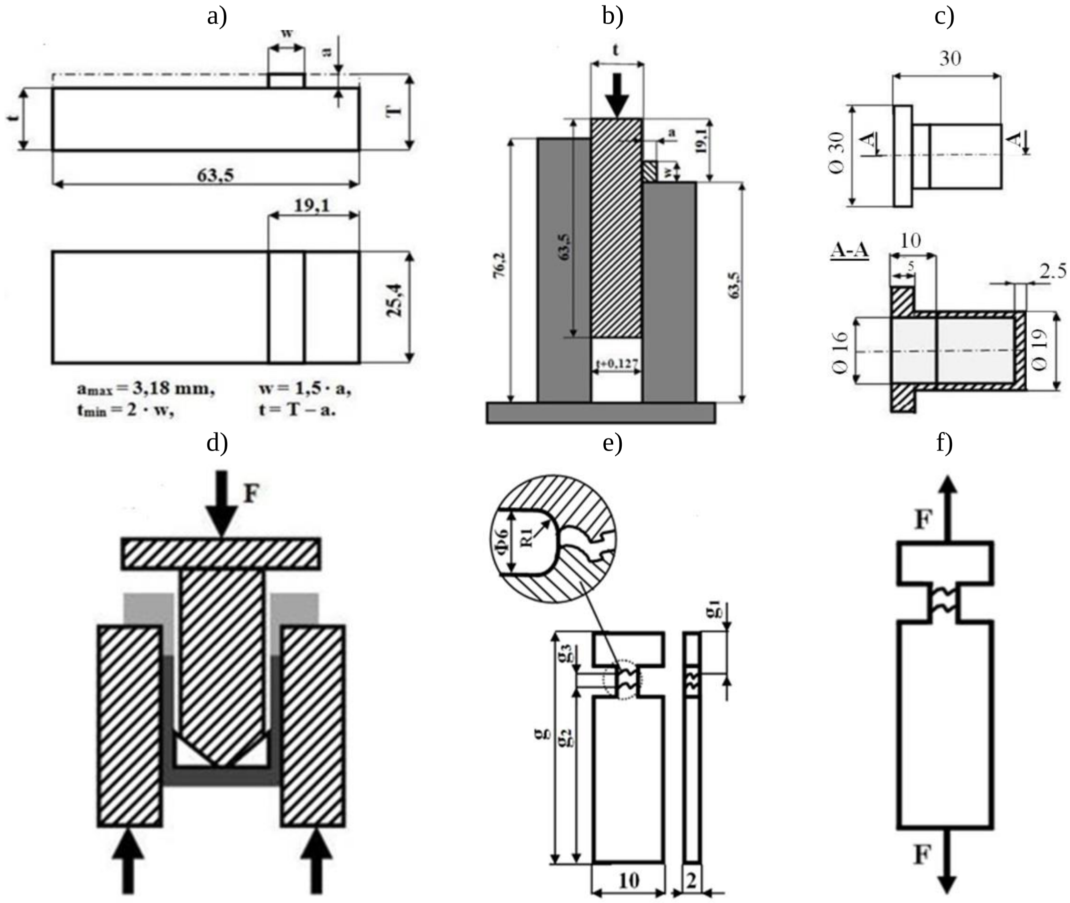

Fig. 2. Shape and dimensions of the sample and schematic presentation of the: a-b) shearing test, c-d) peel test e-f) tensile strength test

The necking of the sample was made using a cylindrical milling cutter of a diameter $\Phi = 6$ mm with a corner radius $R = 1$mm. The tensile strength tests (the ultimate tensile strength R_m) were carried out using an Instron 3382 tensile testing machine (max. sensor load range of 100 kN) according to the scheme shown in Fig. 2f. The mechanical properties of each clad were determined based on the average from three individual tests.

2.3. MACROSCOPIC EXAMINATION OF THE INTERFACE

Samples for microscopic examination were taken from both the initial materials and the clads. The metallographic specimens were made on a cross-section perpendicular to the surface of the metal sheet and parallel to the direction of the detonation front propagation. The specimens were prepared by grinding and mechanical polishing, and then by finish polishing and electrolytic etching on the LectroPol 5 polishing machine with Struers™ electrolyte of A3 type. The samples prepared in this way were examined with OLYMPUS IX 70 optical microscope. On the basis of these analyses, the structural changes of the welded materials and characterized the parameters of the bond interface were examined. The latter were also used to quantify the proportion of the melted layer in the bonding zone. In order to determine the characteristics of the bond interface of welded plates, the bond zone length (*L*), height (*H*) and the length (*n*) of the wave and surface of melted layer (*Pi*) were measured as shown in Fig. 3.

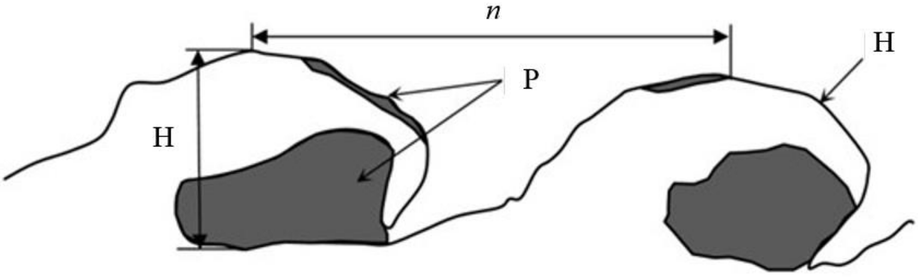

Fig. 3. Definition of basic bond parameters: *H* – wave height, *L* – length of the bond line, *n* – wave length, *P* – “fusion” surface area

As a result, the *RGP* [melt depth equivalent] coefficient was obtained determining the so-called equivalent thickness of melted layer on the basis of the average values of the above-mentioned parameters, by using the equation (1).

$$RGP = \frac{\sum_{i=1}^{n} P_i}{L}\ [\mu\text{m}] \tag{1}$$

where: P_i – melt surface area [μm^2], L – length of the bond line [μm].

2.4. MICROHARDNESS TESTING

The strain hardening changes across individual layers near the bond interface, i.e. on the longitudinal section of welded plates, were analyzed by microhardness measurements using the Vickers method and the LECO MHT Series 200. The measurements were carried out perpendicularly to the bond interface (3 series), in particular for bimetal clads: according to the measurement scheme presented on Fig. 4a, and for three-layered clads: according to scheme presented in Fig. 4b.

The test were made across the bond interface, outside the melted zones, with the first measurement point located at a distance of 0.02 mm from the part of the wave for each of the materials. The tests were carried out with load of 50 G load, in accordance with the guidelines of PN ISO 6507-1 standard [18]. The results presented in this paper represent the average values of three parallel tests.

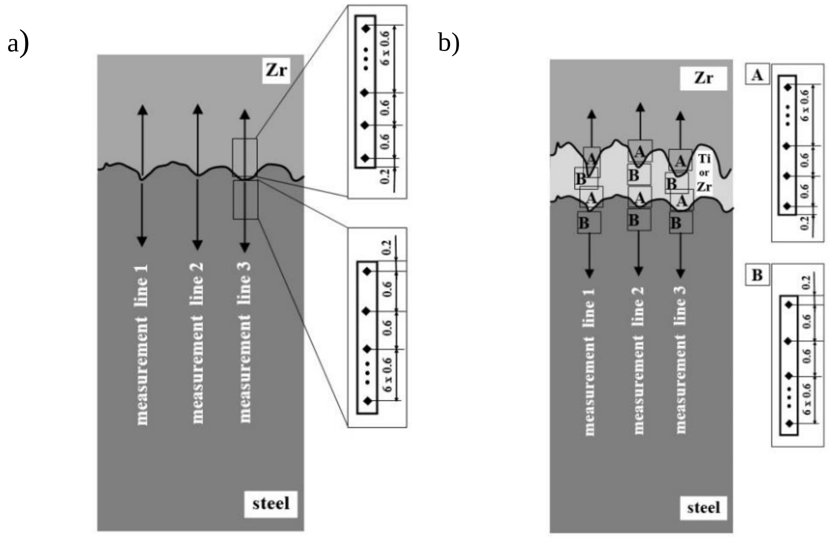

Fig. 4. The scheme of micro-hardness measurements with distances provided between points for: a) bimetal and b) trimetal

3. RESULTS AND DISCUSSION

3.1. STRUCTURAL OBSERVATIONS

The microstructures and initial materials and appropriate bonds were observed using classical optical microscopy. Fig. 5a shows the structure of Zr 700 zirconium sheet (on longitudinal section) in the initial state, i.e. before the welding process. This material is characterized by an approximately equiaxed structure of 'oriented packages' with a size of 70 to 170 µm, consisting of α phase grains.

Fig. 5b shows the microstructure of the base plate material, i.e. P265GH carbon steel prior to the welding process, which was characterized by equiaxed grains with a size range of 4–11 µm for pearlite and 10–20 µm for ferrite. In the case of pearlite a characteristic structure of bands of refined grains, typical for the materials after hot-rolling was observed. The material of the technological interlayer (Ti Gr. 1) was also characterized by the equiaxed grain structure of the Ti_{α} phase with a size range of 20–40 µm (Fig. 5c). The microstructure of metal sheets before the explosive welding process showed a fully recrystallized state.

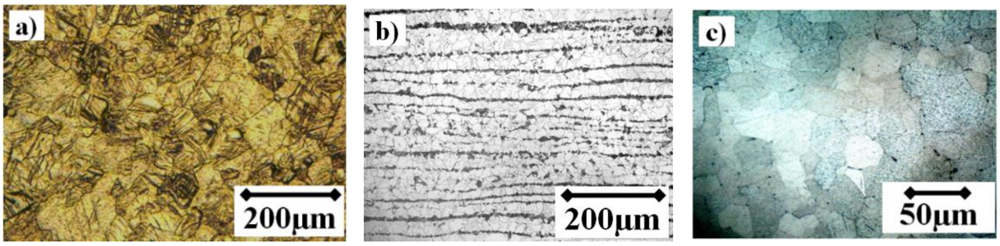

Fig. 5. The initial microstructure of: a) Zr 700 – polarized light image, b) steel P265GH, c) titanium Ti Gr. 1

In case of clads plated with 10 mm thick zirconium with additional technological interlayer of pure titanium the characteristics of the Zr/Ti and Ti/steel bond interfaces (samples B) were analyzed. For clad systems A and C the characteristics of the Zr/steel bond interface were determined. Figures 6a-c presents microscopic images of the bond interfaces of the analyzed clad systems, while the detailed measurement results are specified in Table 4.

Table 4. Parameters of the joint interface in 10 mm zirconium clad structures

Designation plate	A	B		C
Length of the bond line *L* [μm]	11 143	11 831	11 492	10 589
Wave height *H* [μm]	61	300	81	340
Wave lengthn [μm]	662	1 122	525	1 458
Melt surface area *P* [μ m^2]	5 791	35 788	73 549	777 747
Melt depth equivalent *RGP* [μm]	0.52	3.02	6.40	73.3
Joint border	Zr/steel	Zr/Ti	Ti/steel	Zr/steel

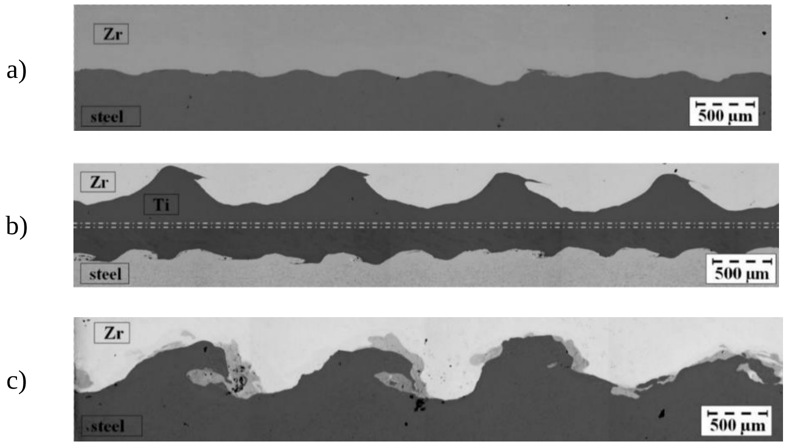

Fig. 6. The characteristics of the bond zone of bi- and tri- metals cladded with 10 mm zirconium. a) image showing microstructure of the Zr/steel joint interface - sample A ($v_D = 1.9\times10^3$ m/s^{-1}), b) Zr/Ti and Ti/steel bond interface - sample B ($v_D = 2.5\times10^3$ m/s^{-1}), c) bond zone Zr/steel - sample C ($v_D = 2.5\times10^3$ m/s^{-1})

Analysis of the obtained results revealed that in the zirconium/steel clad without a technological interlayer, a bond with an *RGP* coefficient of 0.52 μm was obtained, which indicates a small proportion of local melted zones resulting in high strength properties of such bimetallic clad. In the case of sample A, the lowest bond parameters were obtained of all three analyzed cases – the average wavelength is 662 μm and the wave amplitude is 61 μm. The application of the technological interlayer and the increase of the detonation velocity by 30% (samples B and C) resulted in an increase in the wave parameters. In the sample B the wavelength at the Zr/Ti bond interface increased by 60%, while the wave height increased 5 times (from 61 μm to 300 μm) in relation to the sample A. At the interface between the technological interlayer and base plate material (Ti-steel) wave parameters were close to those obtained in the sample A. On the other hand, there was an increase in the quantity of melted zones in layers near the interface: from the *RGP* = 0.52 μm for the sample A up to the *RGP* = 3.02 μm for the sample B, but such high value is acceptable from the point of view of the bond quality.

In the case of Zr-Zr-steel trimetal clad (sample C) the highest increase was observed in the parameters of the wave forming at the bond interface Zr/steel. The wave amplitude reached 340 μm and corresponding length is equal to 1458 μm. Such wave values significantly exceed the parameters obtained in the case of samples A and B at the interface with the base plate material. In the case of the Zr-Zr-steel clad, the serious technological problem is the formation of melted areas at the Zr-steel bond interface, as indicated by the high value of the *RGP* coefficient equal 73.3 μm. The high value of the *RGP* coefficient suggested a substantial decrease of the mechanical properties of the clad, which was confirmed in strength tests.

3.2. MECHANICAL PROPERTIES

In the case of clad systems plated with 10 mm thick zirconium sheet, it is noticeable that both the clads obtained without using technological interlayer (sample A) and the clad with the technological interlayer made of pure titanium (samples B) achieved high mechanical strength.

Tests required by the relevant standard applicable for explosively welded materials were carried out, i.e. shearing test R_S and peel test R_o. In both cases the damage of the material occurred in the material of the flyer plate or in the technological interlayer, which indicates high mechanical properties of the bond. The strength of the Zr-Ti-steel clad, measured with the R_o peel test, exceeded 350 MPa, while according to the shearing test, the titanium-steel clad was stronger, having the R_s value of about 470 MPa. The Zr-Zr-steel trimetallic clad was characterized by the lowest mechanical properties. In this case, in all tests the value did not exceed 200 MPa, and damage of the material occurred at the Zr-steel interface, which is unacceptable for explosively welded materials. Such low mechanical properties of the sample C are caused by the presence a combination of hard and brittle melted areas at the bond interface, which form an almost continuous layer. Characteristic values of mechanical properties of specific clads are presented in Table 5. However, apart from the fact that the shearing strength decrease, its minimum value significantly exceeded the minimum values required by the ASTM A264-12 standards (R_s = 140 MPa) for all the samples tested [19].

Table 5. Mechanical properties of 10 mm zirconium cladders determined in shearing R_s, peeling R_o and tensile R_m tests

Designation plate	A	B		C
Shear strength R_s [MPa]	393	458	471	184
Place of destruction	Zr	Ti	Ti	joint Zr/steel
Peel off strength R_o [MPa]	411	382		198
Place of destruction	Zr	Ti		joint Zr/steel
Tensile strength R_m [MPa]	453	252		182

3.3. MICROHARDNESS CHANGES WITHIN THE BONDING ZONE

Changes in the strain hardening distribution were analyzed by microhardness measurements in the bonding zone (0.5 mm from the interface) in a cross-section perpendicular to the bond surface and parallel to the direction of the detonation front propagation. Measurements were performed under 50 G load. The changes of micro-hardness were related to the average microhardness of steel, titanium and zirconium measured before the explosive welding (shown by dotted line in Fig. 7).

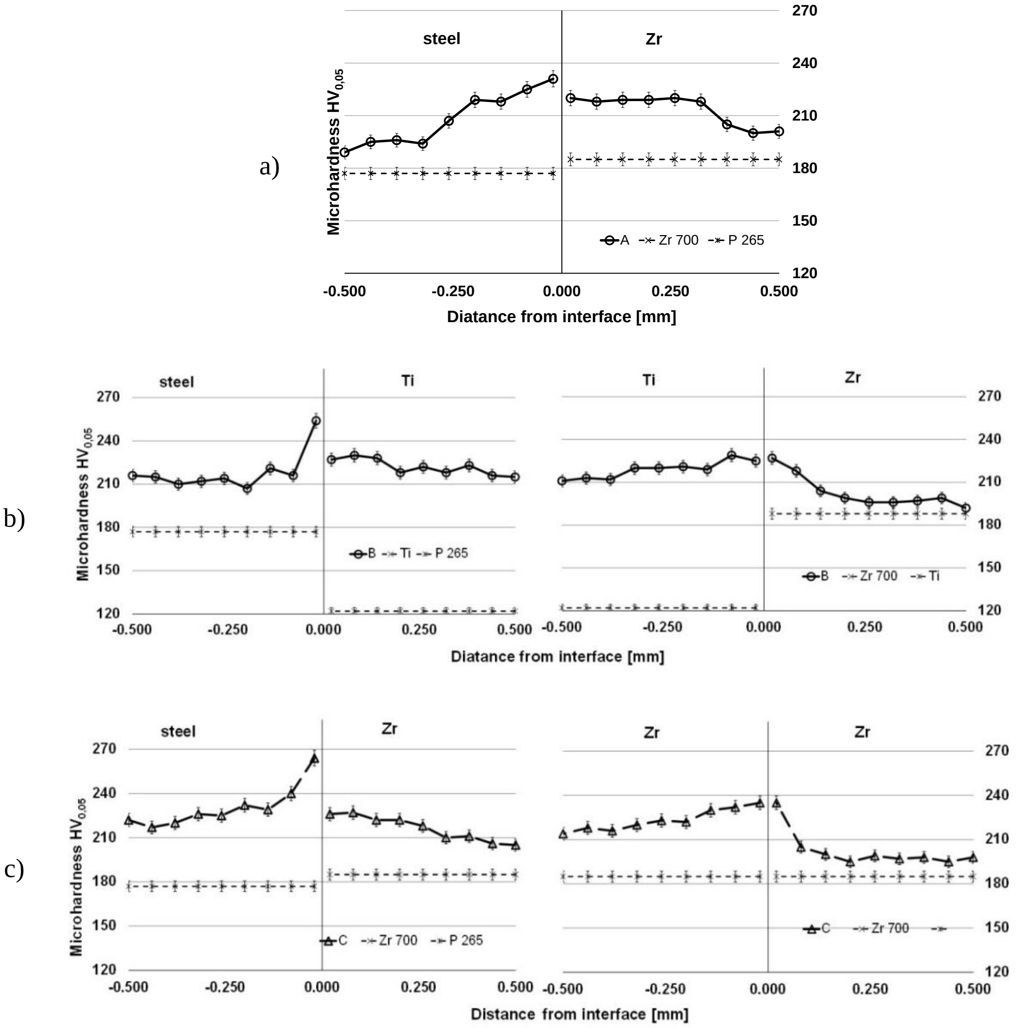

Fig. 7. Microhardness changes in the bonding zone: a) zirconium-steel – bimetal A, b) zirconium-titanium-steel – trimetal B, c) zirconium-zirconium-steel – trimetal C. Measurements 0.5 mm from the bond boundary. Load 50 G

The measurements of the hardness distribution at a distance of up to 0.5 mm from the bond interface of the bi- (Fig. 7a) and trimetallic clads (Figs. 7b-c) confirmed that the analyzed area was characterized by an increased strength of the clads in relation to the hardness of the metal sheets before the process of explosive welding. Figs. 7b-c shows microhardness changes in the bonding zone on the surface of the base plate material (steel). Analysis of the obtained results indicates a significant increase of microhardness in relation to the microhardness of steel (177 $HV_{0.05}$) measured before the welding process. In the case of a trimetallic clad (B and C), the hardness increased by about 45 %, while the hardness of the steel in bimetallic clad (A) increased by 30% in comparison with the microhardness of the initial steel sheet (Fig. 6a). The distribution of microhardness in the area of the technological interlayer suggests that the strain hardening in layers near the interface for both tested samples B and C is at a similar level and averages on about 220 $HV_{0.05}$. This means an 80% increase in comparison with the hardness of the titanium sheet before welding (122 $HV_{0.05}$), and about 20% increase in the hardness of zirconium used as a technological interlayer. In the case of flyer plate material (Zr700) an increase in hardness was noted for all three analyzed cases (Figs. 7a–c). In the case of trimetal clads, the hardness of zirconium in the direct vicinity of the bond interface is at a similar level (about 215–230 $HV_{0.05}$) as the hardness of titanium in the analyzed interface of the Zr-Ti bond (Fig. 7b).

4. CONCLUSION

In this paper, the structure of the bonding zone and the properties of zirconium-steel bimetal clad and zirconium-titanium-steel and zirconium-zirconium-steel trimetallic clads manufactured by explosive welding technology was analyzed, with the initial thickness of flyer plate material (Zr 700) equal to 10 mm. The experimental results allowed to formulate the following conclusions:

- Using Ti as a technological interlayer for zirconium-steel clads made by explosive welding makes it possible to obtain continuous bond with good mechanical properties in the process of cladding with 10 mm thick zirconium.
- In all analyzed cases the clads were obtained with a wavy interface and diversified wave parameters. A bond with the highest wave amplitude and length was obtained in the samples cut-off from trimetallic clads: on the bond interface between the flyer plate material (Zr700) and the technological interlayer (Ti Gr.1) and between the technological interlayer (Zr700) and the base plate material (P265). Bimetallic clad Zr700-P265 and trimetallic one (Ti Gr.1-P265) had similar values of the bond interface parameters (amplitude and period).
- The quantity of the melted zones near the interface assessed by *RGP* coefficient in Zr-steel and Zr-Ti-steel clads was kept on an acceptable level, i.e. $RGP < 10$ µm. The lowest proportion was obtained for the bimetallic clad, while the highest – for the trimetallic clad.
- The clads with optimal characteristics of the bond interface and adequately strength properties were obtained with the use of low detonation velocities ($v_D = 1.9\times10^3$ $\text{m}\cdot\text{s}^{-1}$) and low initial stand-off distance (h = 10/4 mm) between the welded plates.
- In all clads, the strengthening was observed in the material of the flyer base and the technological interlayer plates. In particular, strengthening effect was observed along the whole analyzed distance (up to 0.5 mm from the bond interface) but the highest values were obtained in the direct vicinity of the bond interface.

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