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THE EFFECT OF STAND-OFF DISTANCE ON THE STRUCTURE AND PROPERTIES OF ZIRCONIUM – CARBON STEEL BIMETAL PRODUCED BY EXPLOSION WELDING

WPŁYW ODLEGŁOŚCI BLACH NA STRUKTURĘ I WŁASNOŚCI BIMETALU CYRKON – STAL WYTWORZONEGO TECHNOLOGIĄ ZGRZEWANIA WYBUCHOWEGO

This study focuses on the effect of the stand-off distance between the bonded plates on the properties of zirconium (Zr700) – steel (P355NL2) bimetal produced by explosion welding. Bonding trials were carried out in parallel arrangement at constant detonation velocity. The analyses of microstructural transformations occurring in the bond zone and mechanical properties of the clad were performed for as-bonded welds, i.e. immediately following explosion welding.

A general description of the obtained welds was made (height and length of the wave was determined) and the quantitative fraction of the melt zones was calculated along the bond's length. Using optical microscopy and scanning electron microscopy (SEM) enabled the assessment of the quality of the formed bonds, initial identification of phases and quantitative analysis of the individual phases on the longitudinal section. The microhardness results were used in the analysis of hardening changes at the interface area.

The completed research proves the potential to obtain a proper bond for zirconium/carbon steel sheets. A strong effect of the stand-off distance on the strength properties of the fabricated plates was observed, and the 'direction' of these transformations was pointed out. Optical microscopy and SEM examinations allowed determining the characteristic of the bond interface for diverse stand-off distances. It was established that increasing the stand-off distance between the plates causes the reduction of the melt area along the length of the bond, which improves strength properties of the bimetal. The analysis of the strength distribution performed based on the microhardness measurements showed that the changes occur within the distances up to 500μm from the bond interface and the highest hardening, for both zirconium and steel, is directly at the interface and then successively decreases.

Keywords: explosive welding, Zr/carbon steel clad, hardening, melted zone, intermetallic phases

W pracy analizowano wpływ odległości pomiędzy płytami na własności układu warstwowego cyrkon (Zr700) – stal (P355NL2) wytworzonego technologią zgrzewania wybuchowego. Próby łączenia wykonano w układzie równoległym, przy stałej prędkości detonacji. Analizy zmian mikrostrukturalnych, jakie dokonują się w strefie połączenia oraz zmian we własnościach mechanicznych plateru prowadzono dla złączy w stanie wyjściowym, tj. bezpośrednio po zgrzewaniu.

Dokonano ogólnej charakterystyki otrzymanych połączeń (określono wysokość i długość fali) oraz obliczono ilościowy udział warstwy przetopień na długości połączenia. Zastosowanie mikroskopii optycznej oraz skaningowej mikroskopii elektronowej pozwoliło na ocenę jakości powstających złączy, wstępną identyfikację faz oraz analizę ilościową poszczególnych faz na przekroju wzdłużnym złącza. Badania mikrotwardości wykorzystano w analizie zmian umocnienia w strefie połączenia.

Przeprowadzone badania dokumentują możliwość uzyskania poprawnego połączenia dla układu blach cyrkon/(stal węglowa). Wykazano silny wpływ odległości pomiędzy płytami na własności wytrzymałościowe wytworzonych płyt próbnych, a także udokumentowano 'kierunek', w jakim te zmiany podążają. Badania z wykorzystaniem mikroskopii optycznej oraz elektronowej mikroskopii skaningowej pozwoliły na scharakteryzowanie granicy połączenia dla zróżnicowanych odległości pomiędzy blachami. Stwierdzono, że zwiększenie odległości pomiędzy łączonymi płytami powoduje zmniejszenie powierzchni przetopień na długości złącza, co polepsza własności wytrzymałościowe bimetalu. Analiza rozkładów umocnienia przeprowadzona w oparciu o pomiary mikrotwardości wykazała, że zmiany występują w odległości do 500μm od granicy złącza; największe umocnienie, zarówno dla cyrkonu jak i stali, występuje bezpośrednio przy granicy po czym sukcesywnie spada.

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1. Introduction

Controlled application of an explosive charge as a cheap and easy-to-use material capable of performing work has been a point of interest for engineers and constructors. Explosive technologies including forming, densification, hardening and bonding are used in nearly every branch dealing with the fabrication of metal parts.

One of the methods which takes advantage of the controlled detonation of an explosive charge is explosion welding, known also as 'explosion bonding' or 'explosion cladding'. This process may be used to join practically every combination of metals and alloys, both metallurgically compatible as well as those considered to be incapable of being joined by conventional bonding methods. Due to the fact that the process uses explosion energy, it occurs with extreme velocities. This in turn causes the lack of control over its parameters during the bonding process.

Optimal bonding parameters, effecting equally the quality of the bond and mechanical properties of the resulting clad, must be correctly selected at the stage of designing the blast arrangement. Explosion welding parameters include physical and mechanical properties of the welded materials, the quality and quantity of the explosive, the method of detonation initiation, and the geometry of the welding structure. The event that determines the joining of materials during explosion welding is the collision of the flyer plate with the base plate. Key parameters which are decisive for obtaining a 'proper' bond during explosion welding are the collision point speed v_C and the impact angle of sheets β. They are highly dependent on the detonation velocity of the explosive v_D and the stand-off distance between the sheets (so-called bond window) h[1-3,6]. The values of these settings are individually selected for particular combination of metals and alloys on the basis of equations widely available in literature. The stand-off distance is an independent variable which allows obtaining the required conditions of impact and directly influences the value of the impact angle. Literature review [1,2,4] shows that the main factor deciding about the particular stand-off distance between the plates to be used is the thickness of the flyer plate (t). Usually, this parameter ranges between 0,5t-4t. The appropriate selection of the stand-off distance will ensure obtaining the collision velocity specific for a given system of materials, e.g. [2-5].

The present study focuses on the analysis of the influence of the stand-off distance between the plates on the morphological changes in the bond zone and mechanical properties of the Zr700/P355NL2 clad.

2. Research techniques

The object of analysis is a bimetal structure made by explosion welding, where the base plate was an carbon steel for applications at elevated temperatures of P355NL2 grade with the initial thickness of 20 mm. The flyer plate (moving plate) was a zirconium sheet Zr700 (trade name Zircadyne) with 3,4 mm thickness. The chemical composition of both materials was shown in Table 1.

TABLE 1

The chemical composition of joined metal sheets, as per the supplier's certificate

Basic material	Chemical composition [%]						
	C	**Mn**	**FeCr**	**H**	**O**	**Zr+Hf**	**N**
Zr 700	<0,002	–	0,05	<0,0003	0,05	>99,2	<0,002
	C	**Mn**	**Si**	**P**	**S**	**Cr**	**Cu**
P 355NL2	0.17	1.13	0.35	0.008	0.011	0.15	0.170

Bonding was carried out in parallel arrangement as per the diagram shown in Figure 1, for which a constant detonation velocity (v_D =const) and a variable stand-off distance between the plates h were assumed.

Based on the literature review, the following scheme of changing the initial stand-off distance was employed: h, 1,5h, 2h and 3h. The measurements of detonation velocity v_D were taken for every analysed case using a system of three optical fibers connected to 'Explomet' meter. The constant detonation velocity was obtained by using a mixture of explosives with a strictly defined ingredients (identical explosion energy). As a result, 4 test plates were obtained with dimensions of 275 mm×450 mm, which were sampled for further research. The designation of the produced plates with process parameters were shown in Table 2.

The obtained bimetal plates were subjected to ultrasound tests which enabled the assessment of the bond consistency and continuity. The research was performed in two stages, i.e. in the as-bonded state and after flattening. In all of the analysed cases a positive result regarding the effective bond area was received.

Mechanical properties, based on technological tests of shearing, lateral bending and peeling trials were completed according to EN13445-2 standard and the obtained results were presented in Table 2.

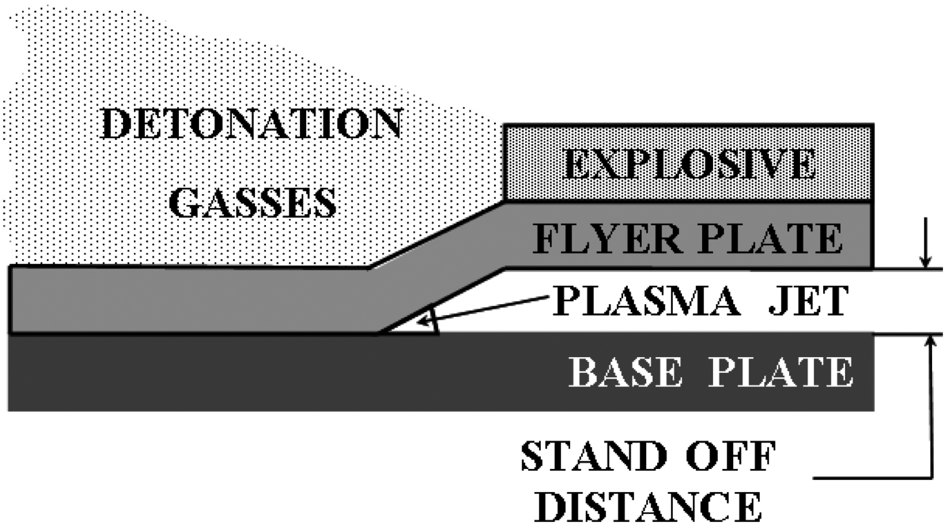

Fig. 1. Schematic illustration of the explosive cladding set-up

TABLE 2
Designation of the produced plates and the relations between process parameters

Plate	Detonation velocity v [m/s]	Stand off distance h [mm]	R_S [MPa]	R_O [MPa]
A17	v_D	H	318/Zr	360/bond
A16	v_D	1,5 H	311/Zr	333/bond
A8	v_D	2 h	351/Zr	449/Zr
A9	v_D	3 h	353/Zr	475/Zr

The material for microscopic examinations was sampled from the fabricated clads as well as from as-delivered sheets. The samples of output material were taken parallel and perpendicular to rolling direction. In the case of clads the polished specimens were produced as sections perpendicular to sheet surface and parallel to the detonation front motion. The specimens were prepared through initial mechanical polishing with abrasive papers and subsequently diamond pastes with decreasing gradation. Final stages of the specimens' preparation included polishing and electrolytic etching on LectroPol 5 polisher, using Struers TM A3 electrolyte (voltage 30V and time 12s) for Zr and clads, whereas in the case of steel the samples were chemically etched with 'Nital' reagent.

The analysis of the microstructural changes was conducted using an optical microscope Olympus IX 70 and an image analyzer LECO IA 32. In particular, the measurements of waves parameters were done on carefully polished surfaces using LECO IA 32 image analyzer, including: the length of the bond line L, height (H) and wave length (n) as well as the area of the melt surface P (Figure 2). Based on the obtained results, a characteristic was done of the joined plates interface by the calculation (from equation 1) of the value of 'RGP' factor, so-called melt depth equivalent factor.

$$RGP = S/L[\mu m] \qquad (1)$$

where: S – sum of the 'fusion' surface area P_i [μm^2],
L –length of the bond line [μm].

A detailed analysis of structural changes in micro-scale was performed with a high-resolution scanning microscope (SEM) Quanta 3D FEI equipped with a field emission gun. To clarify the mechanism of phase constitutions within melted zones, the energy dispersive X-ray spectrometry in SEM was used to analyze the distribution of the Fe and the Zr atoms across the intermetallic layer. Changes in the strength close to the weld zone and in the longitudinal section of the joined sheets were analysed by systematic microhardness measurements by Vickers' method using LECO MHT Series 200 microhardness tester. The measurements were performed along the line perpendicular to the interface (3 series) according to ISO 6507-3:1996 standard (metal hardness measurement by Vickers' method below HV 0.2) under 50G load.

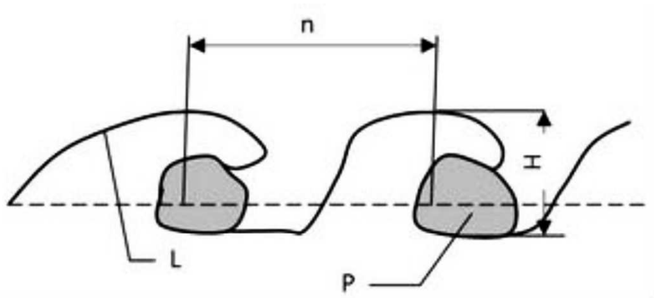

Fig. 2. Basic bond parameters: H – wave height, L – length of the bond line, n – wave length, P – 'fusion' surface area

3. Results and discussion

3.1. Structural observations

The preliminary observation of microstructre was performed by means of light microscopy. Figure 3a shows the structure Zr700 sheet in the as-is state, i.e. before bonding in the section perpendicular to lateral direction. It is evident that the material is characterized by the structure of oriented packs of 70 to 170 μm size consisting of α phase grains.

Figure 3b shows the microstructure of the as-is P355NL2 unalloyed steel. The image presents an equiaxed structure of middle-sized grains in the range of 4 to 11 μm for pearlite and 10-20 μm for ferrite. For pearlite, we can see a band structure of fine grains, typical for materials that underwent hot forming.

The analysis of the bond zone was carried out by means of the optical microscopy on longitudinal section (in the direction of detonation front movement). Based on the performed measurements of the wave settings (Table 3) and microstructural analysis of the bond zone (Figure 4) it can be concluded that a wavy bond was obtained in all 4 cases.

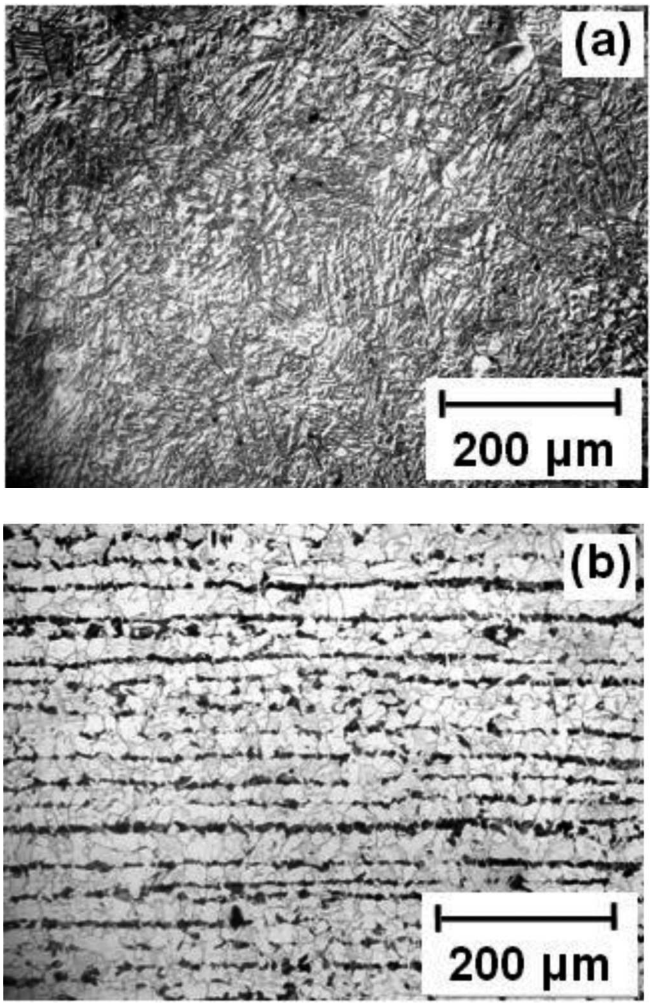

Fig. 3. The initial microstructure of: (a) Zr 700 – polarized light image, (b) steel P355NL2

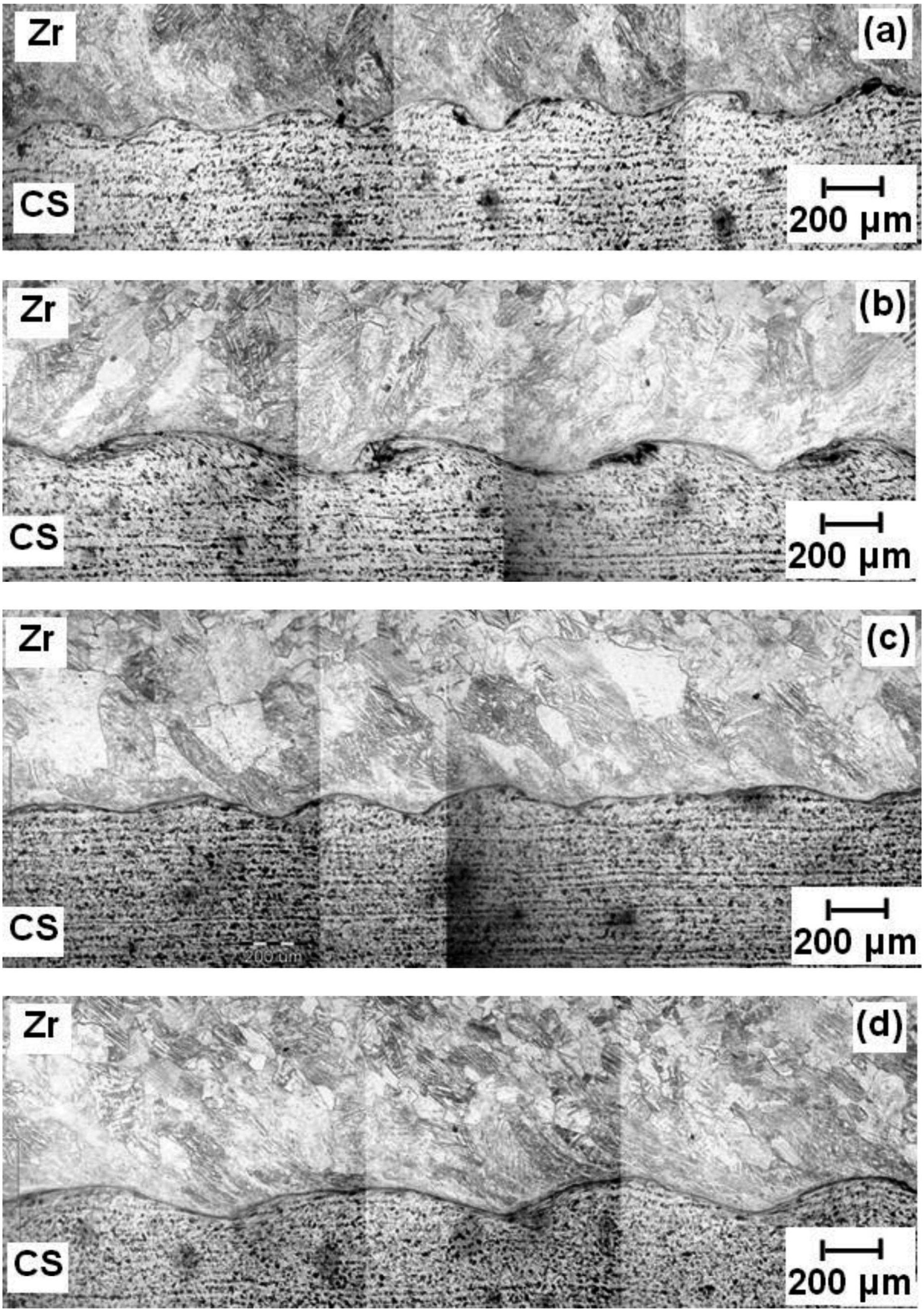

Fig. 4. The influence of stand-off distance on changes near the interface: (a) *h*, (b) 1,5*h*, (c) 2*h*, (d) 3*h*

For *h* and *2h* stand-off (samples A8 and A17) the height of the wave was 73 μm and 60 μm respectively, whereas for stand-off 1,5*h* and 3*h* (samples A16 and A9) the height of the wave was equal and reached 104 μm. For A8 and A17 samples, similar lengths of wave were observed – 435 μm and 471 μm. Whereas A16 and A9 samples exhibited 52% and 83% increase of the wavelength respectively as compared to A8 (Figure 5). In the same figure we can analyse the effect of the stand-off distance between the bonded plates on the 'intensity' of the melted zone occurrence. It was noticed that the increase in the stand-off distance caused the reduction of the melted area fraction in the bond, which can be established by the analysis of 'RGP' factor. Its greatest value – 5,51 μm was obtained for the smallest distance between the plates (sample A17) and the lowest – 0,20 μm for the arrangement where the stand-off distance was the greatest (sample A9). For the other two cases, it can be noticed that along with the distance increase the 'RGP' factor goes down; for A16 and A8 – 4,42 μm and 0,61 μm respectively.

On the basis of the performed observations and measurements it can be concluded that the distance between the plates strongly influences bond-defining parameters. It is noticeable particularly when analysing the fraction of melted layers at the bond interface. Namely, with the same explosion energy, the increase of the distance leads to a considerable reduction of the melted area. The mentioned decrease is due to the fact that wider distances cause the materials to be subjected to large pressures, induced by the detonation products' impact, for a shorter time. This in turn shortens the heating time of the impacting plates, and thus they melt to a lesser degree. The strength tests confirm that it causes the improvement in bond properties.

TABLE 3

Parameters describing wave shape and the quantity of the melted zone

Plate	Length of the bond line L [μm]	Wave height H [μm]	Wave length n [μ m]	Melt surface area P [μ m^2]	Melt depth equivalent RGP [μ m]
A17	8804	73	471	48 526	5,51
A16	8367	104	660	36 970	4,42
A8	9092	60	435	5 567	0,61
A9	9270	104	796	1 897	0,20

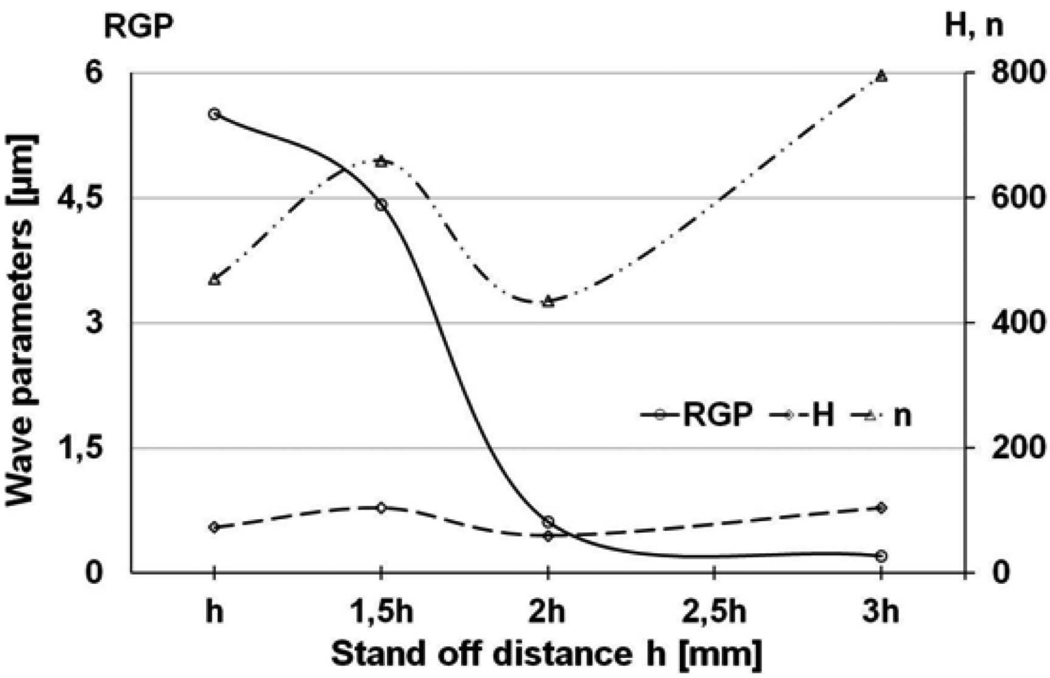

Fig. 5. Influence of the stand-off distance near the interface

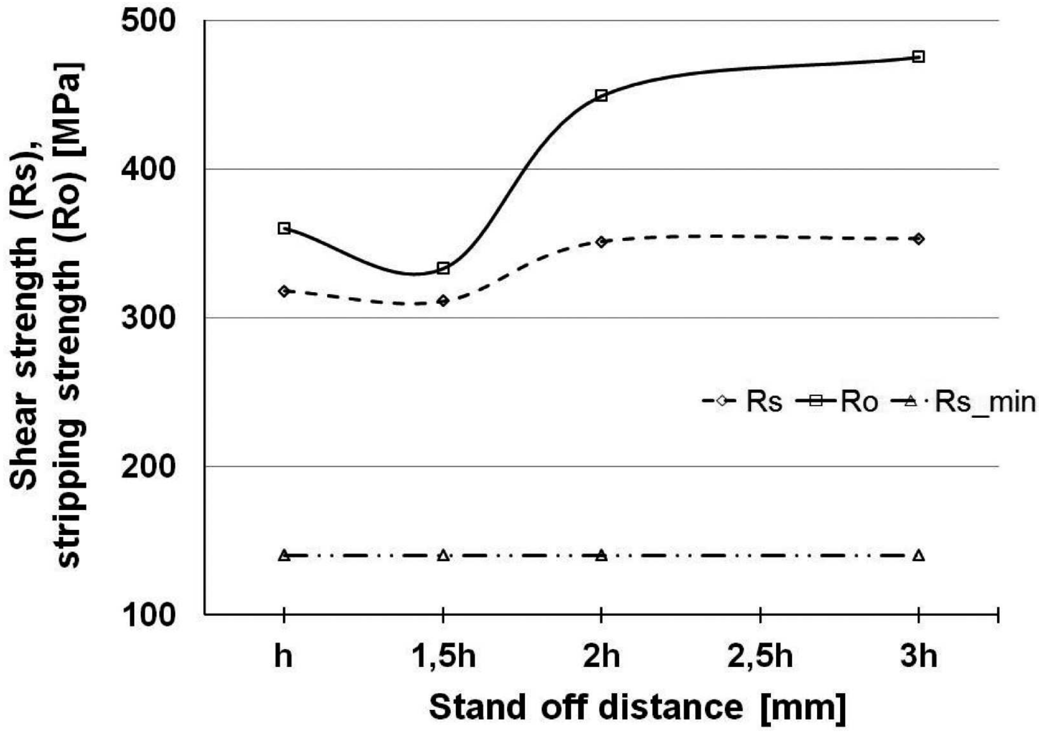

Fig. 6. The mechanical properties of Zr700/P355NL2 bimetals

3.2. Mechanical tests

The qualitative assessment of the obtained bond was performed based on mechanical properties determined by means of shearing tests, lateral bending and peeling tests. The average values resulting from individual strength tests were presented in Table 2 and in Figure 6. For shearing tests, in all analysed cases, the results exceeded more than twice the minimum standard threshold of R_s = 140MPa (Figure 6). The highest R_s values of about 350MPa were recorded for wide distances between the plates – A8 and A9 arrangements. Smaller distances added to decreasing the shear strength, which was 311MPa and 318MPa for A16 and A17 samples, respectively. The fact that both the tested samples were shorn in the covering material (Zr) also proves the good quality of A8 and A9 bonds. During the peel test the value of R_o was noticed to increase along with the increase of the stand-off distance.

The highest R_o value of 475MPa was obtained for specimens cut out from plates welded with the greatest distance between the sheets (A9), Figure 6. For A8 (2*h*) specimens a 5% decrease of peeling strength was recorded. In the case of bimetals fabricated with a small distance between the plates (1*h* and 1,5*h*) a 25-30% drop of R_o compared to the maximum result was observed. The lower quality of the weld is also confirmed by the fact that A17 (*h*) and A16 (1,5*h*) specimens were destroyed at the bond, whereas the other two in the covering material (Zr). Worsening the strength properties for smaller stand-off distances can be connected to the above-mentioned phenomenon of the formation of hard and brittle melted layers at the bond interface. As can be noted in Table 2, the largest fraction of the melted layer was recorded for the A16 specimen (1,5*h*) which had the worst results in the performed strength tests. Lateral bending test was also carried out for the analysed cases. In this case all materials passed the test. The samples were bent by 180° angle and no cracks or splitting was noticed.

3.3. Microhardness measurements

The analysis of bimetal hardness in the bond zone was done on the basis of microhardness variation. The measurements were carried out for all plates along 3 scan lines perpendicular to the interface both through the entire section of the clad and in the direct vicinity of the interface. In all the cases equal loads of 50G were used. The analysis of the microhardness distribution on the section's surface revealed a considerable increase of the hardening both in the base material as well as the cladding metal compared to the initial state material hardness. Close to the bond zone in the Zr plate, a 20% improvement of hardness was noticed, which was approximately equal to all the analysed arrangements. For the metal sheets, hardening increase by 40% to 80%

occurred (depending on the stand-off distance) compared to the initial state material.

A more detailed distribution of microhardness was analysed at the distance of 0,5 mm from the bond interface (Figure 7). The analysis of the obtained results confirms that the greatest hardening is displayed by the plate fabricated with the widest stand-off distance between the plates, i.e. A9 sample (3*h*), whereas the smallest was displayed by A8 (2*h*) and A16 (1,5*h*) samples. The graph shows an undeniable influence of the stand-off distance on the hardening improvement of steel. In particular, it was observed that widening the stand-off distance contributes to hardening improvement on the side of steel, but this tendency was not noticed for zirconium.

3.4. SEM structural observations and chemical composition measurements

3.4.1. Microstructural observations

The SEM imaging in the backscattered electrons reveal a structure without visible separations between the joined plates (Figure 8). In most observed cases the morphology of the interface was characterized by the mixture of wavy and flat patterns. In the case of wavy interface the formation of the intermetallic inclusions near the front slope of the wave or within the wave vortex was also typically observed.

Another characteristic feature was the cracks formation within the brittle intermetallic inclusions. The macro-cracks visible in the light microscope scale were

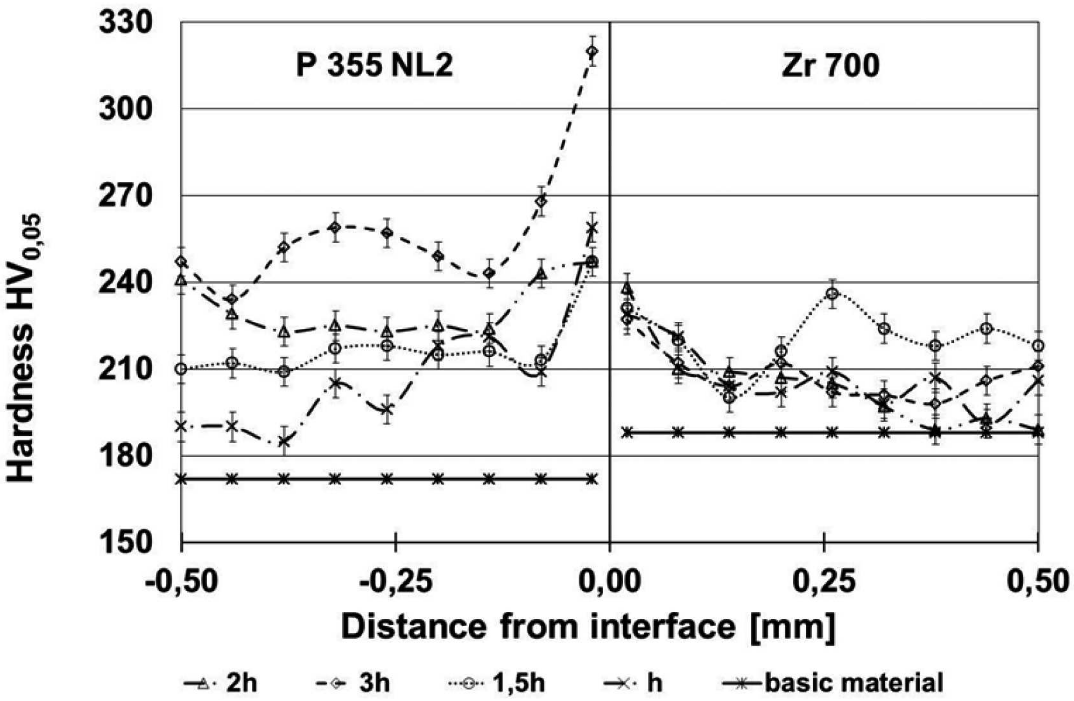

Fig. 7. Microhardness measurements along 3 ‘scan’ lines across the interface, for all analysed cases (up to 0,5 mm from the interface). Load 50G

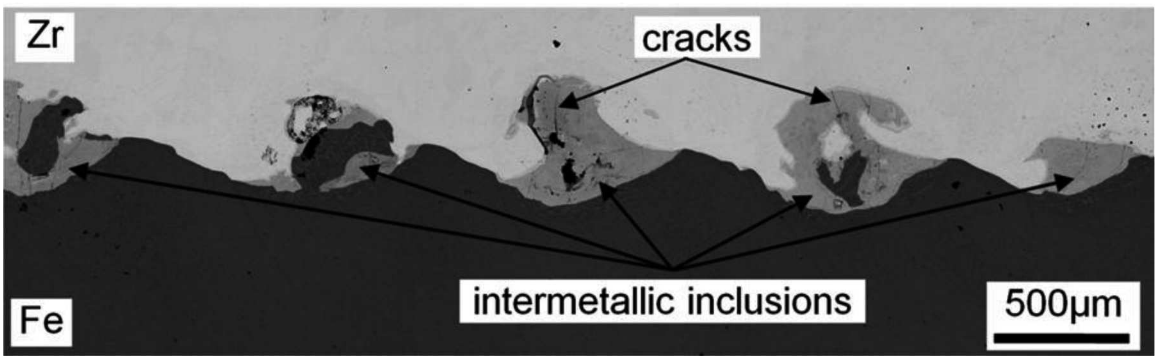

Fig. 8. Microstructure near the interface observed at SEM scale. Imaging in backscattered electrons

mostly situated perpendicularly to the interface, whereas the finer ones, which had been observed only in the SEM scale, formed a non-regular network of micro-cracks. The cracks were always limited to the melted zone and did not show any tendency for propagation across the base materials, either in the copper or in the aluminium sheet. The interfaces around the intermetallic inclusions and between steel and Zr sheets were always very sharp, suggesting strong chemical composition changes across the boundary.

3.4.2. Chemical composition changes

The regions of intermetallic inclusion observed at SEM scale reveal a non-uniform 'swirl-like' contrast of various intensity, indicating that these areas were composed of the layers of different compositions.

In the 'after bonding' state the general observation based on scanning electron microscopy equipped with energy dispersive X-ray spectrometry (SEM/EDX) measurements is that, there was no mechanical mixing between the welded metals in the solid state. However, the point SEM/EDX measurements of the elements distribution clearly indicates that some chemical composition fluctuations were observed inside the melted volume. On the one hand, those irregularities in the distribution of both elements were without any interrelation with respect to the parent sheets. This probably results from the intense stir of the melted metals. On the second hand, the rapid cooling, together with the extremely high pressure, make the solidification terms far from equilibrium and thus influence the occurrence of the 'metastable' phases.

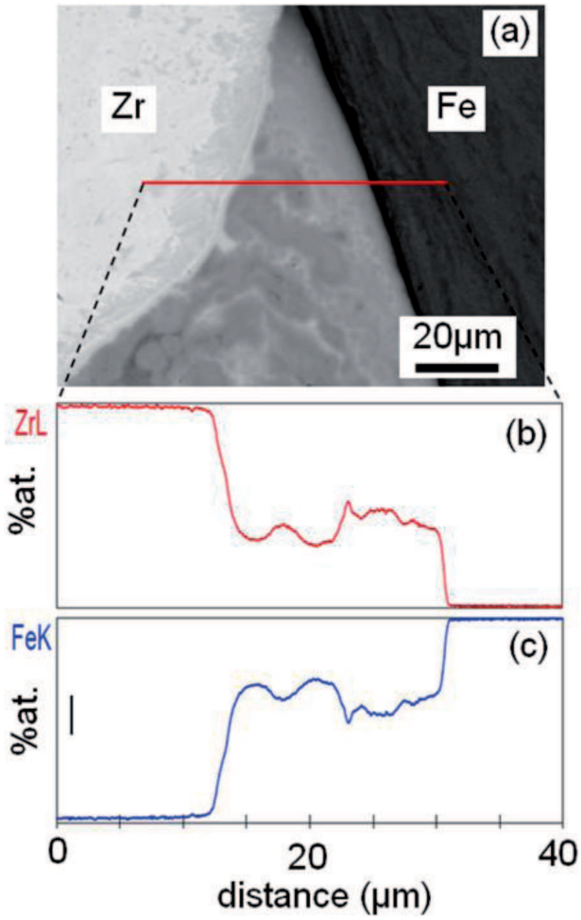

Fig. 9. Chemical composition changes across the intermetallic inclusion. (a) Microstructure observed in backscattered electrons, (b) and (c) the distribution of Zr and Fe elements, respectively, along line scan marked in (a). SEM/EDX line microanalysis

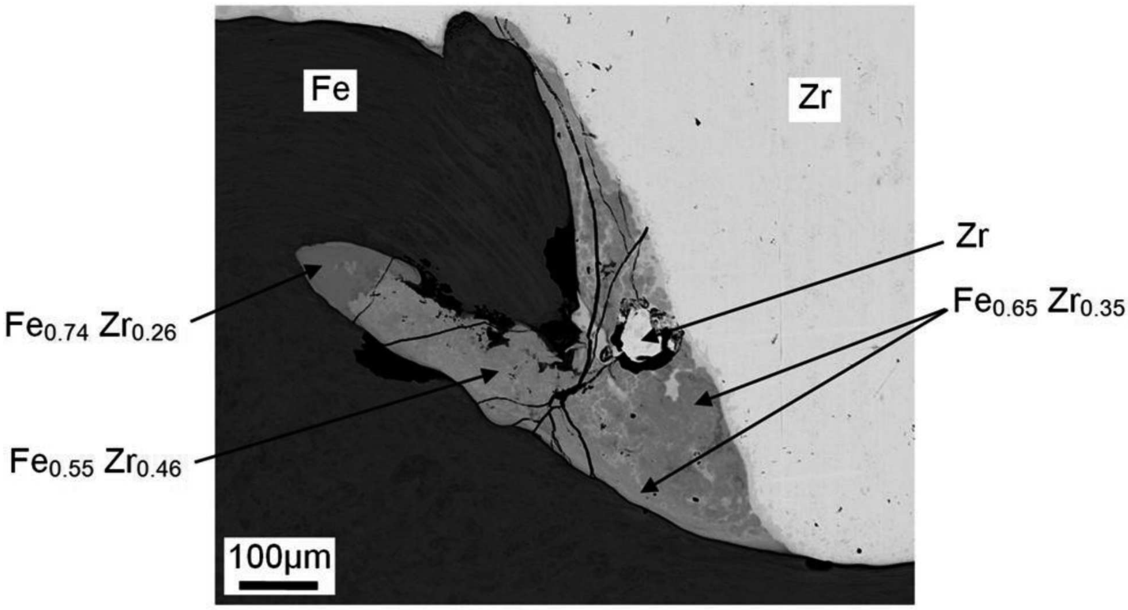

Fig. 10. Chemical composition changes near the interface. SEM microstructure observed in backscattered electrons with marked chemical composition of selected places. SEM/EDX point microanalysis

Closer analyses of the chemical composition changes across the intermetallic layer were done along line scan parallel to ND and by point measurements. The line scan is marked in the SEM image of Figure 9a and the result is presented in Figure 9b and c (changes of the Fe and Zr concentration, in %at. as a 'function' of the beam position). As expected, the area of intermetallic inclusion showed strong changes of chemical composition, inside the intermetallic layer, even along the very short distances.

The SEM/EDX point measurements clearly reveal a non-uniform intermixing of the phases, without any interrelation in respect to the parent sheets, as visible in Figure 10. Although the metastable phases (the phases that not occur in the equilibrium phase diagram) occupied the major part of the intermetallic inclusion, the equilibrium phases were also observed. They did not form layers but occupied small, rather irregular, volumes.

4. Conclusions

The present study analyses the effect of the stand-off distance between the joined plates during explosion welding on the properties of the Zr700/P355NL2 clad. The performed research allowed the formation of the following conclusions:

- The mechanical properties of the fabricated bimetals, i.e. shear strength R_S and peel strength R_o strongly depend on the stand-off distance between the plates; their values rise with extending the distance.
- Characteristic bond zone parameters, in particular the amount of melt in the bond are determined by the initial stand-off distance of the joined plates; extending the distance causes decreasing of the 'RGP' factor, i.e. the reduction of the melt volume in the bond zone occurs. However, the occurrence of the melted layer in the bond zone adversely affect the strength properties of the bimetal.
- As a result of explosion welding, hardening of the joined materials occur near the interface. Nevertheless, it is more pronounced in steel and less in Zr. The volume of the hardened area heavily depend on the stand-off distance. The greatest hardening, both in the steel and Zr plates, occurs in the areas adjacent to the boundary. It was also observed that the hardening of steel grows extensively after exceeding a distance of $2h$ between the plates.
- A further stage of the study includes an assessment of the influence of detonation velocity on the strengthening and structural changes in joint area. Future tests and results presented in this paper, will be used to determine the optimal welding process parameters (velocity of detonation, stand-off distance) to allow to produce of bimetals Zr/steel joints with high technological properties.

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