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Research paper / Praca doświadczalna

Studies of the microstructure of bimetallic titanium – austenitic steel joints obtained by explosive welding *Badania mikrostruktury złączy bimetalicznych tytan – stal austenityczna wytwarzanych metodą zgrzewania wybuchowego*

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Abstract: *The specific requirements of installations used in the chemical and petrochemical industries require materials with high corrosion resistance and adequate strength. Materials with these characteristics can be obtained by explosive cladding technology. Results of studies of the microstructure of titanium-austenitic steel 304L bimetallic joints in the welded and heat-treated condition are presented. Applications for this type of material include heat exchanger tube surfaces exposed to aggressive environments with high cyclical mechanical loads. The joints were tested using an optical microscope and a scanning electron microscopy. Heat treatment has contributed to a decrease in microhardness near the joint, which demonstrates a reduction in the strain hardening in this area.*

Streszczenie: *Szczególne wymagania instalacji stosowanych w przemyśle chemicznym i petrochemicznym powodują konieczność stosowania materiałów o dużej odporności korozyjnej oraz odpowiedniej wytrzymałości. Materiały spełniające te wymagania można wytworzyć technologią platerowania wybuchowego. W pracy przedstawiono wyniki badań mikrostruktury złączy bimetalicznych tytan-stal austenityczna 304L w stanie po zgrzewaniu i po obróbce cieplnej. Aplikacją tego typu materiałów są m.in. ściany sitowe wymienników ciepła, które narażone są na pracę w agresywnym środowisku, przy wysokich cyklicznych obciążeniach mechanicznych. Złącza badano z wykorzystaniem mikroskopu świetlnego oraz skaningowej mikroskopii elektronowej. Obróbka cieplna przyczyniła się do spadku mikrotwardości w pobliżu złącza, co świadczy o redukcji strefy umocnienia występującej w tym obszarze.*

Keywords: *explosion welding, 304L steel, titanium, microstructure, heat treatment*
Słowa kluczowe: *zgrzewanie wybuchowe, stal 304L, tytan, mikrostruktura, obróbka cieplna*

1. Introduction

For operation in aggressive corrosive environments with cyclical mechanical loads, heat exchanger tube sheets are manufactured from, among other things, so-called bimetallic materials, i.e. composite sheets of two metals. One of the technologies used to manufacture bimetallic materials is the explosive joining process, which enables materials of different composition and properties to be permanently bonded together. Materials with improved physical-mechanical and performance characteristics can be obtained with this process. This joining technique allows two or more metal sheets to be permanently bonded by colliding the parts being joined at high speed initiated by the detonation of an explosive [1, 2]. As a result of this process, significant changes occur in the microstructure of the sheets being joined, as well as within the joint itself. These are accompanied by the occurrence of intrusion strengthening, which results in a significant increase in micro-hardness within the joint. In order to eliminate the negative effects of explosive joining (strengthening, inherent stress), heat treatment is carried out. An appropriate heat treatment temperature is one of the key parameters accounting for the microstructure obtained and, consequently, the predicted properties of the cladding [3].

2. Experimental part

2.1. Materials and methods

The tests were performed on samples taken from clad plates prepared by Z.T.W. EXPLOMET (Poland). ANFO, with a detonation velocity of 2700 m/s measured by fibre optic sensing, was used to produce the joint. The system for the welding was a parallel arrangement with an initial distance between the sheets of 3 mm. In the studies performed, austenitic chromium-nickel 304L steel was used as the base material, the chemical composition and mechanical properties of which are shown in Table 1 [4, 5].

Table 1. Chemical composition and mechanical properties of 304L steel

Steel symbol	**Element content [%]**					**Yield strength [MPa]**	**Tensile strength [MPa]**	**Elongation at rupture [%]**
	C	**Cr**	**Ni**	**Tn**	**N**			
ASME SA-240 304L	≤0.03	19	11	≤2	≤0.11	246	447	41

Grade 1 titanium (ASME SB-265 Gr. 1) was used as the overlay material, the chemical composition and mechanical properties of which are shown in Table 2. Grade 1 titanium exhibits relatively good ductility which allows this material to be cold-formed up to a total intrusion of approximately 70%.

Table 2. Chemical composition and mechanical properties of Grade 1 titanium

Designation	**Element content [%]**						**Yield strength [MPa]**	**Tensile strength [MPa]**	**Elongation at rupture [%]**
	Fe	**O**	**N**	**C**	**H**	**Ti**			
ASTM SB-265 Grade 1	≤0.20	≤0.18	≤0.03	≤0.10	≤0.01	Rest	269	319	23

Samples for testing were taken from explosively-generated sheets from which a 220×300 mm plate was cut of the ‘descending’ area of the detonation wave, i.e. the location at the opposite corner of the plate relative to the detonation initiation point. Samples measuring 7×12×100 mm were cut from the test plate for strength testing. The thickness of the titanium layer was 2.5 mm, while that of the steel was 9.5 mm. Samples from the joining process and after heat treatment were used in the study. The heat treatment involved annealing the material at 600 °C for 1.5 h with subsequent cooling in still air. The heat treatment was aimed at relaxing the inherent stresses in the produced bimetallic plate. The test methods used were chosen to determine the structure of the materials under study. The following research techniques were used:

- titanium-steel interface metallography,
- scanning electron microscopy,
- X-ray microanalysis,
- micro-hardness measurement.

Surface observations of the materials, particularly the characteristics of the joint obtained by explosive welding, were carried out using a Keyence model VHX-600 digital light microscope. It is equipped with a high-resolution lens enabling the taking of images at magnifications ranging from ×20 to ×1,000. The samples were examined at a ×100 magnification. Distinctive parts of the resulting join were thoroughly examined with a Hitachi S-2600N Scanning Electron Microscope (SEM). The chemical composition of the use joint's distinctive parts quantitatively analysed with an EDS spectrometer. The Hitachi S-2600N SEM supports a resolution of 4 nm. Observations were carried out using a secondary electron (SE) detector, at magnifications from ×200 to ×1,800. An acceleration voltage of 20 kV was applied. Vickers micro hardness measurements were performed using a Neophot II's LECO AMH 2000 micro hardness tester. The tests were carried out before and after heat treatment. Measurement locations included the bottom of the wave formed by the explosive bonding. Measurements were taken along a line perpendicular to the joint, at a magnification of ×50, under a load of 0.1 kg. The first two measurements were taken at a distance of 0.02 mm from the joint. Subsequent measurements were made 0.24 mm apart in the direction of the steel and titanium. A graphical interpretation of the bottom and top of the wave is shown in Figure 1.

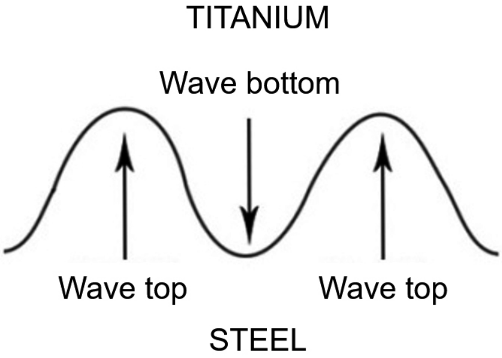

Figure 1. A graphical interpretation of the bottom and top of the wave

Quantitative analysis was carried out using photographs of metallographic samples showing the joint microstructure. Images of the microstructure were processed graphically and grain outlines were produced. The processed images were entered into MicroMeter v.086b [6], and a quantitative analysis performed. In this study, the equivalent diameter of the grain size was used for comparison. Based on that parameter, the influence of the joining process and heat treatment on the changes taking place in the material microstructure, was established.

3. Results and discussion

The joint obtained by the explosive joining of 304L austenitic steel and Grade 1 titanium shows a wavy geometry. This is typical of an explosive welded material. Steel, in the area of the joint and at a short distance from it, has a heavily deformed structure. In particular, it is characterised by significant deformation of grains which are elongated in the direction parallel to the direction of plate joining. The deformation of the structure decreases as the distance from the joint increases, as shown in Figures 2 and 3.

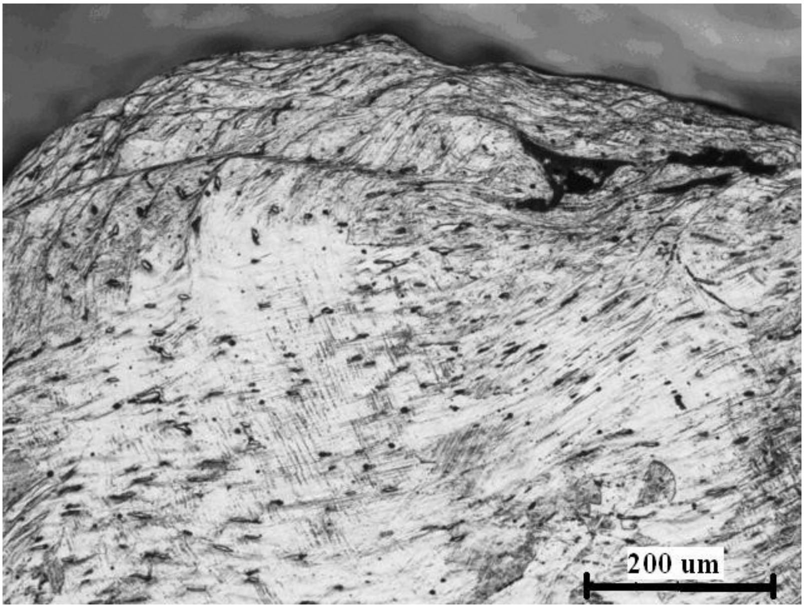

Figure 2. Microstructure of 304L steel at the joint (sample without heat treatment)

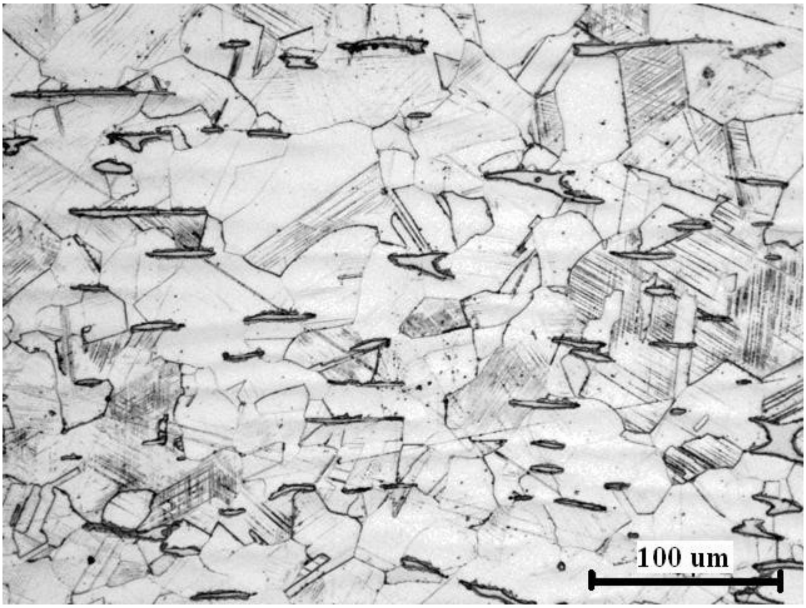

Figure 3. Microstructure of 304L steel at a distance of 6 mm from the joint (sample without heat treatment)

The microstructure in this area demonstrates equiaxial austenite grains which are typical of austenitic steel. Twinning boundaries are present in the microstructure of the steel. Figure 2 shows the presence of voids (shrinkage cavities) in the wave region, which may be indicative of the material transition into a liquid state at the time of joining. This results from excessive heating of the surface, as a result of very high plastic deformation.

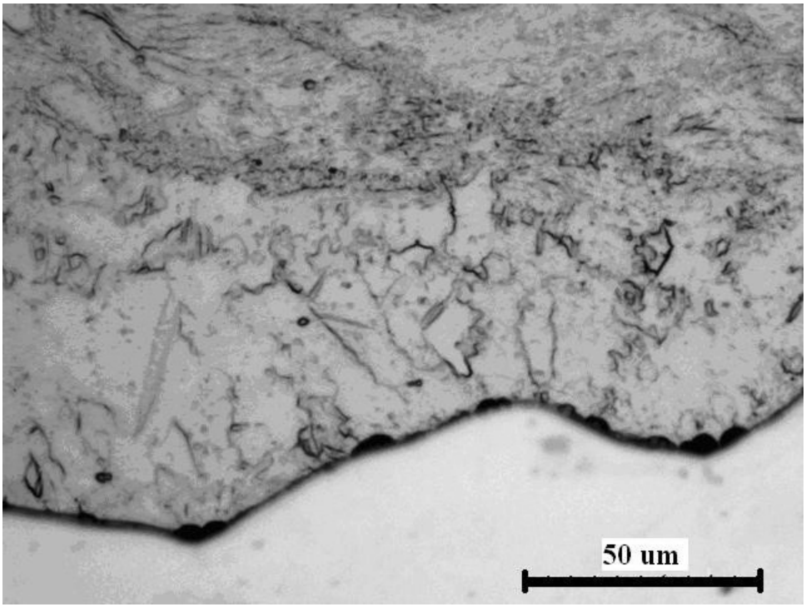

Figure 4. Titanium microstructure at the joint (sample without heat treatment)

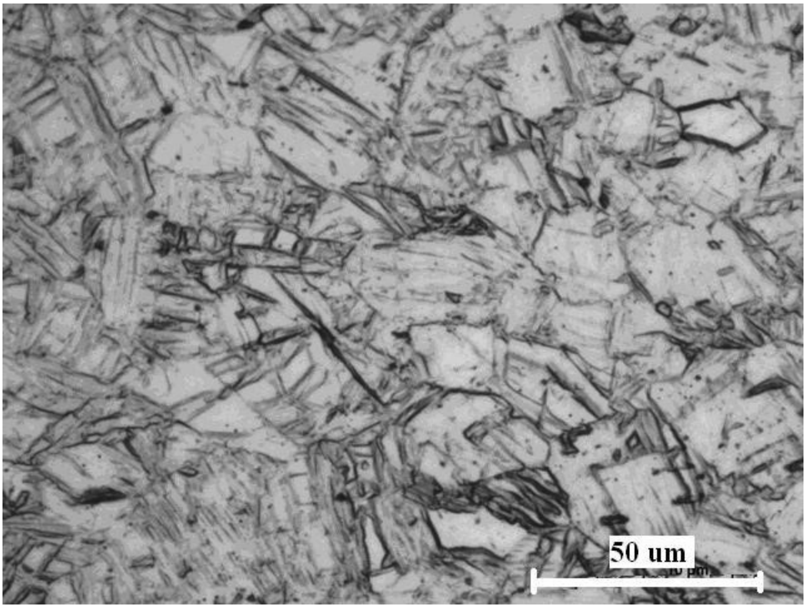

Figure 5. Titanium microstructure at 6 mm from the joint (sample without heat treatment)

The microstructure of 304L steel in heat-treated samples does not differ significantly from that of the untreated samples. Due to the heavily deformed structures within the joint, it is not possible to determine the average grain size of the steel in this area, while the grain size at a distance of 6 mm from the joint has a similar value in the pre- and post-treated samples of approximately 10 μm. The titanium microstructure in the explosively-bonded materials has not deformed to the same extent as that in steel, while it differs significantly from the welded condition following heat treatment. Titanium, after the treatment, is characterised by the typical equiaxial grains which had been deformed to some extent as a result of the welding, as shown in Figures 4-7. The average grain size of titanium is ca. 12 µm and did not change significantly following heat treatment.

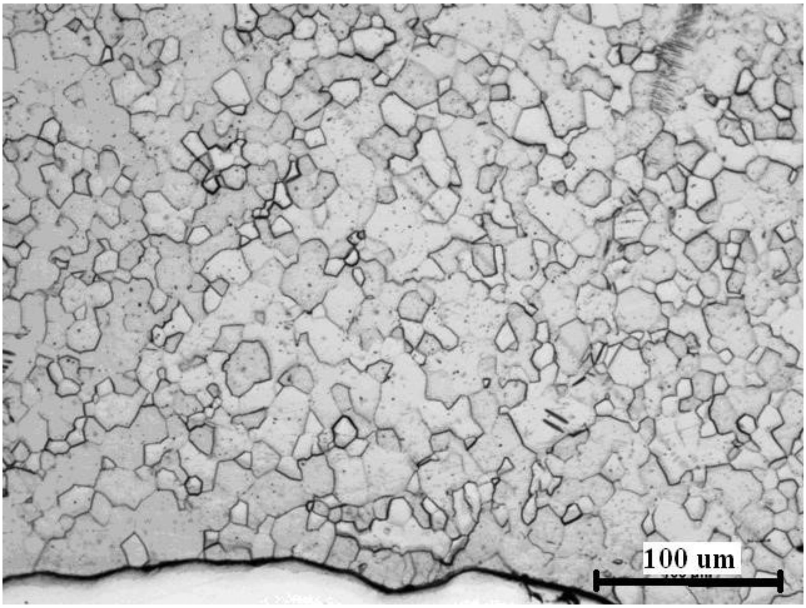

Figure 6. Microstructure of Grade 1 titanium at the joint (sample after heat treatment)

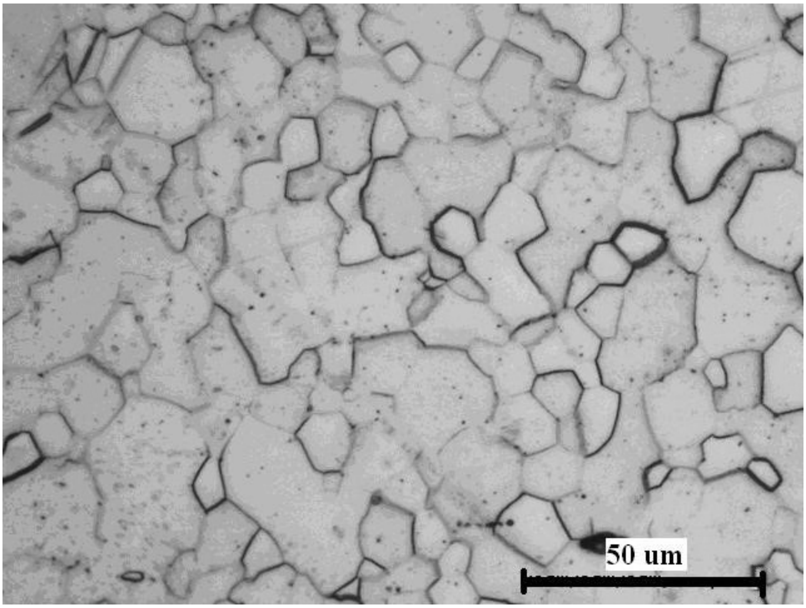

Figure 7. Microstructure of Grade 1 titanium at 1 mm from the joint (sample after heat treatment)

A transition zone with a thickness of approx. 15 µm, was discovered in the joints. The analysed test area, shown in Figure 8, illustrates the characteristic spot located within the joint. The chemical composition of this zone is shown in Table 3. This zone is formed by the thermal processes occurring during the joining of the plates, and is distinguished by the presence of elements found in both welded materials. This zone also shows numerous defects in the form of cracks. The resulting joint micro-hardness distributions at the bottom of the wave are shown in Figure 9.

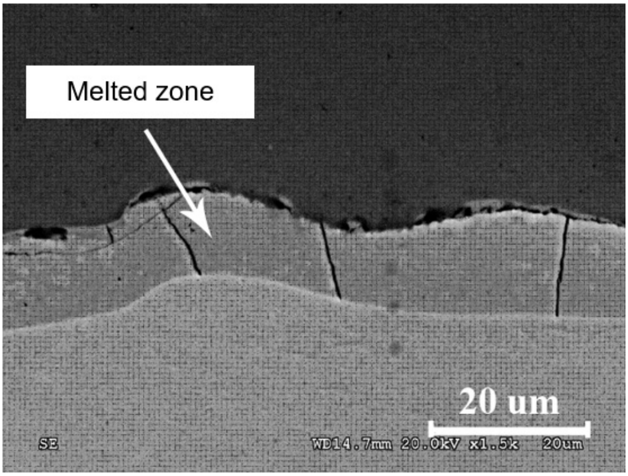

Figure 8. Joint surface of the sample with the transition zone marked

Table 3. Mass percentages of elements in the transition zone

Element content [%]				
Si	**Ti**	**Cr**	**Fe**	**Ni**
0.38	35.01	12.12	42.53	6.10

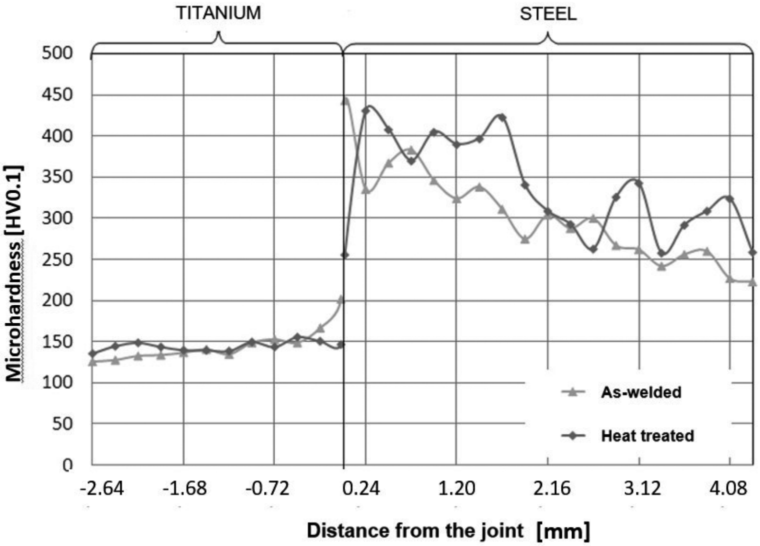

Figure 9. Microhardness diagram for samples before and after heat treatment at the wave bottom

The microhardness measurements demonstrate that the hardness of the explosively joined materials increases with proximity to the joint line. A significant change in hardness was evident within the 304L steel. At the joint itself, it reaches a maximum value of 443 HV0.1 for the sample immediately after the joining process. As the distance increases, the hardness decreases and begins to stabilise at 260-320 HV0.1, about 3 mm from the joint. The heat-treated sample exhibits a much lower hardness just at the joint, and reaches a value of 256 HV0.1. This indicates the presence of a strengthening zone close to the joint, the hardness of which is reduced following heat treatment. This is primarily due to the recrystallisation processes of the deformed grains and the relaxation of the residual stresses within the joint [7, 8]. The heat treatment also resulted in a decrease in hardness away from the joint, but significant differences in the microhardness at a further distance, due to the heterogeneity of the microstructure of the materials tested, make a more accurate analysis difficult. Vickers hardness testing showed that, further from the joint line, the hardness has a higher value for the joint immediately after welding than for the heat-treated material. By analysing the micro-hardness of titanium, it can also be seen that the strengthening zone is present just at the joint line. The hardness in this area is 202 HV0.1 and decreases as the distance from the joint line increases until it stabilises at 126-135 HV0.1, at a distance of 1 mm from the joint line. The heat treatment results in a reduction in the strengthening zone, which can be seen as a decrease in hardness just at the joint line, up to a value of 147 HV0.1. Heat treatment also alters the hardness further from the joint, as evidenced by the micro-hardness results obtained.

4. Conclusions

- Explosive welding of austenitic steel and titanium results in a durable joint with a wavy geometry. The material is strengthened after joining and has a deformed structure which is evident, among other things, in strongly deformed grains, especially in the area near the joint.
- The bimetallic joint, after the joining process and after annealing, is distinguished by the presence of individual voids (shrinkage cavities) and the presence of a transition zone with a width of approximately 15 µm in which cracks occur. The average grain size, at a distance of up to 6 mm from the joint, does not change after heat treatment. This applies to both steel and titanium. The material hardness is higher close to the joint line indicating the presence of a strengthened zone.
- Heat treatment causes a reduction in the this zone and a decrease in micro-hardness, both at the joint and throughout the material.

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