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IDENTIFICATION OF RESIDUAL STRESS PHENOMENA BASED ON THE HOLE DRILLING METHOD IN EXPLOSIVELY WELDED STEEL-TITANIUM COMPOSITE

IDENTYFIKACJA NAPRĘŻEŃ WŁASNYCH METODĄ NAWIERCANIA OTWORU W BIMETALU STAL-TYTAN OTRZYMANEGO TECHNOLOGIĄ ZGRZEWANIA WYBUCHOWEGO

The hole drilling method was used to determine residual stresses in bimetallic composite manufactured by explosive welding process. The analyzed bimetal consist of titanium Grade 1 (6 mm) and S355J2+N steel (40 mm). The aim of the paper is to establish the influence of the heat treatment on residual stress state in titanium layer. Residual stress calculations were performed according to standards developed by strain gauge manufacturer (TML) and ASTM standards. The main conclusion is the heat treatment considerably changes the residual stress state in titanium layer from tensile stress state (no heat treatment) to compression stress state (after the heat treatment).

Keywords: explosive welding, residual stresses, bimetallic composite, titanium grade 1

W pracy przedstawiono wyniki badań naprężeń resztkowych, wyznaczonych metodą nawiercania, w bimetalu stal-tytan otrzymanego w procesie zgrzewania wybuchowego. Analizowany bimetal to kompozyt stali S355J2+N (40 mm) oraz tytanu Grade 1 (6 mm). Celem badania było ustalenie wpływu obróbki cieplnej na kierunki i wartości naprężeń własnych w warstwie tytanu. Obliczenia naprężeń resztkowych przeprowadzono przy zastosowaniu: (i) procedury zalecanej przez producenta (TML) zastosowanych rozet tensometrycznych oraz (ii) zaleceń ASTM (American Society for Testing and Materials). W wyniku badań ustalono, że zastosowana obróbka cieplna bimetalu zasadniczo zmienia stan naprężeń własnych w warstwie tytanu. Próbki bez obróbki cieplnej wykazują naprężenia resztkowe rozciągające a w próbkach po obróbce cieplnej panują naprężenia ściskające.

1. Introduction

Composite materials produced from metallic materials and their alloys have wide range of application in different industrial branches. Durable connection between two materials with different properties enables obtaining of new groups of materials meeting new higher requirements. Joint of the titanium resistant to aggressive environment and high strength steel finds application in chemical processing equipment. Another example of bimetallic material applications are structural transition joints used in shipbuilding industry, high loaded slide bearings, metallurgical aggregates, turbine blades, chemical reactors [1-4]. Explosive welding technology allows production of metallic composites through the use of detonation energy. High pressure generated during explosives detonation cause collision of joined materials and creates joint between them. Explosive welding is classified as a solid state metal joining process [3]. Because explosive welding causes considerable deformations, explosively welded plates are usually subjected to cold flattening process. Depending on the joined material properties heat treatment is used to avoid material cracking during cold rolling. One of the main problem concerning explosively welded materials is residual stress determination. Information about the initial stress state (residual stress) is important for proper estimation of material behavior under monotonic and fatigue loading [5-7]. It is also helpful in selecting the explosive parameters. Residual stresses are created during technological processes as effect of thermal, mechanical or chemical affects causing plastic and elastic strains in the material. High value of residual stress in construction material can strongly influence overall operational safety and properties of mechanical systems. In general meaning, residual stress is function of the many factors like material structure or type of technological treatment [8]. The paper presents results of the residual stress measurements performed on steel titanium bimetallic plates without and after the heat treatment.

2. Experimental research

Residual stress measurements were performed using the hole drilling method that consists of strain measurements around the drilled hole. Drilling results in a change of the strain state (stress relaxation). Registered change of the stain value is calculated to the residual stresses. The hole drilling method is known as partially destructive method [9]. Re-

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searches were performed on six S355J2+N steel–Titanium Grade 1 specimens (210×180×46 mm) cut out from large (4330×3150×46 mm) bimetallic plates produced in explosive welding technology (Fig. 1). The specimens were taken out from area assigned for certification tests. The specimens were separated into two groups: first group was cut out form large plates just after welding process; second one was collected after the heat treatment and cold rolling. Mechanical properties and chemical composition of joined materials are presented in Tables 1 and 2.

TABLE 1

Chemical composition steel S355J2+N (EN 10025-2:2004) and titanium Grade 1

Steel S355J2						
Chemical element:	C	Si	Mn	P	S	Cu
Maximum content, % weight:	0,22	0,55	1,60	0,025	0,025	0,45
Titanium Grade 1						
Chemical element:	C	Fe	H	N	O	Ti
Maximum content, % weight:	0,10	0,20	0,015	0,03	0,18	99,5

TABLE 2

Mechanical properties of the steel S355J2+N and titanium Grade 1

Material	Mechanical properties					
	R_{eH}, MPa	R_m, MPa	E, GPa	G, GPa	ν, –	A_5, %
S355J2	382-395*	598-605*	206	84	0,27-0,30	24-34*
Grade 1	189-215 (R_{p02})*	308-324*	100	38	0,37**	43-56*

* – manufacturer certificate, ** – own research (titanium after explosive welding

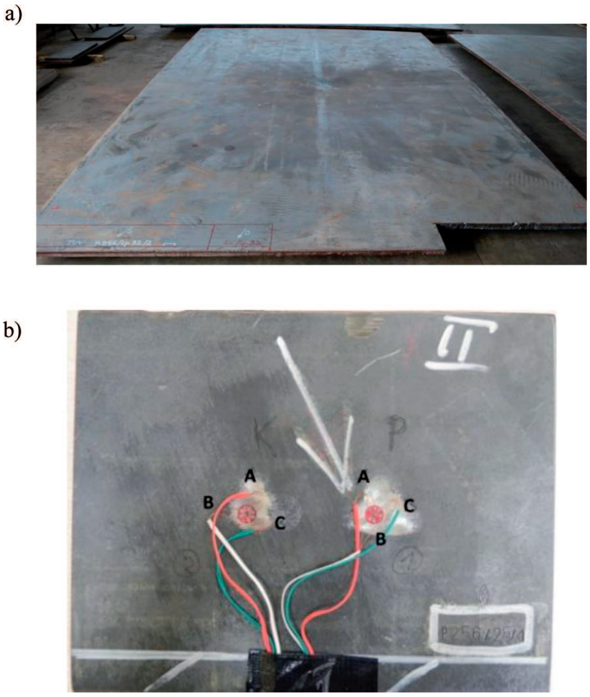
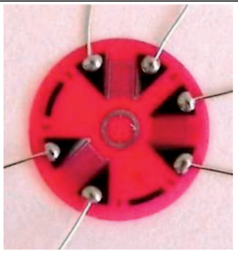


Fig. 1. Example photos of: (a) – the bimetallic plate with visible specimen cut out area (b) the specimen (210×180×46 mm) with the glued strain gauges (plate II without the heat treatment, arrow indicates the detonation direction)

The heat treatment performed on the bimetallic plates consisted of soaking in 600°C for 90 minutes and cooling with furnace to 150°C with 100°C/h cooling rate. Residual stress measurements were performed in two points for each plate in the titanium layer. Experimental setup used in presented research consisted of TML strain gauges (Table 3) connected to National Instruments SCXI-1520 acquisition setup. The holes were drilled using 1.5 mm diameter drill with Proxxon BFW 40/E driller (6000rpm rotational velocity). Strain gauge technical details are presented in Table 3. Distinct strain extremes visible in Fig. 2 indicate the drilling process, but only the stabilized strain values (the flat lines in Fig. 2) were taken into account and used as measured values. Residual stress calculations were performed according to standards developed by strain gauge manufacturer (TML) and ASTM standards separately [9].

TABLE 3

Strain gauge technical data

	Manufacturer: TML TokyoSokkiKenkyujo Co., Ltd. Type:FRS-2 Dimensions : gauge length: 1.5 mm width: 1.3 mm outer diameter: φ9.5 mm Centerline diameter: φ5.14 mm Nominal resistance: 120 ± 0.5 Ω Gauge factor: 2.0

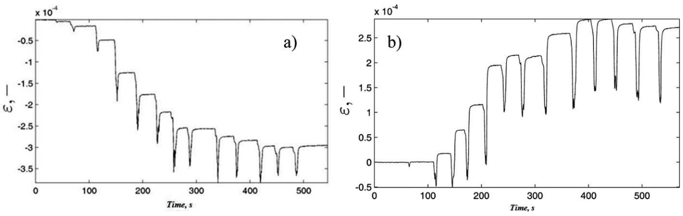


Fig. 2. Example strain history (for single strain gauge) registered in titanium during the drilling process, (a) – the specimen cut out just after explosive welding process, (b) – the specimen after the heat treatment and cold rolling

In order to investigate influence of the detonation wave direction on the maximum principal residual stress direction in bimetal layers angles between A strain gauge and detonation directions were determined for each measurement point (Fig. 3).

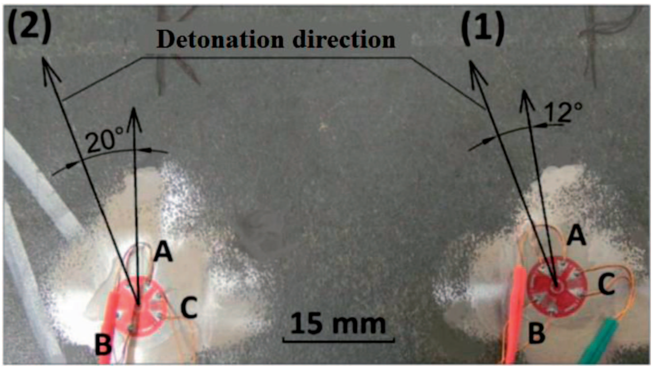


Fig. 3. The specimen with strain gauges (plate I before heat treatment, titanium side), detonation and gauges directions are marked in form of arrows

Example measurement results are presented in form of dependence between the hole depth h and registered stabilized strains in each strain gauge direction: A, B, C (Fig. 4). Characteristic feature of the obtained results is change of the strain sign. The specimens without the heat treatment are characterized by negative strain values indicating tensile residual stresses in the material. In specimens after the heat treatment positive value of measured strain indicated compressing residual stresses.

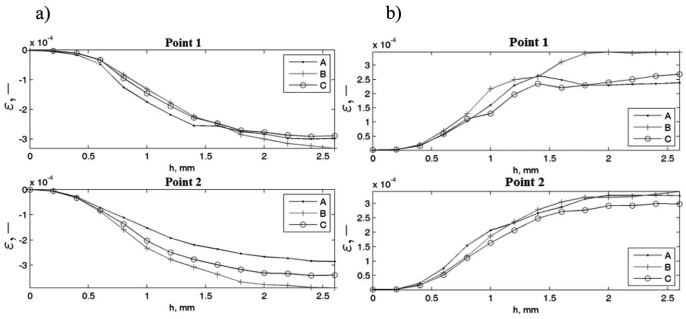


Fig. 4. Measured strain values in titanium layer, registered for A,B,C directions in dependence of hole depth, (a) – plate I without heat treatment and cold rolling, (b) plate I after heat treatment

3. Residual stress calculations according to strain gauge manufacturer's prescriptions

Strain gauge manufacturer TML recommends calculation method based on strain measurement performed for single hole depth equal to 1.2d, where d is the hole diameter. For 1.5 mm drill used in described research calculations were performed using strain (in A,B,C directions) registered for h =1.8 mm hole depth. Assuming uniform residual stress distribution the following computation steps has been done:

$$\theta = \frac{1}{2} a \tan \frac{\varepsilon_a + \varepsilon_c - 2\varepsilon_b}{\varepsilon_c - \varepsilon_a} - \frac{n\pi}{2} \tag{1}$$

where θ is angle defining principal stress orientation measured clockwise from A direction to σ_1; ε_a, ε_b, ε_c are strain measured in A,B,C directions; n =*0* for $\varepsilon_a > \varepsilon_c$; n =*1* for $\varepsilon_a < \varepsilon_c$.

$$\sigma_1 = \frac{\varepsilon_a + \varepsilon_c}{4K} + \frac{\varepsilon_a - \varepsilon_c}{4H\cos(2\theta)}, \quad \sigma_2 = \frac{\varepsilon_a + \varepsilon_c}{4K} - \frac{\varepsilon_a - \varepsilon_c}{4H\cos(2\theta)}, \tag{2}$$

where: σ_1, σ_2 are the principal stresses; K and H are coefficients calculated from the following equations:

$$K = -\frac{(1+\nu)\,d^2}{8ER^2}, \quad H = -\frac{d^2}{2ER^2} + \frac{3(1+\nu)\,d^4}{32ER^4}, \tag{3}$$

where E is modulus of elasticity (E =100 GPa); ν is the Poisson ratio (ν =0.39); d is hole diameter (d =1.5mm); R is the centerline strain gauge radius (R =5.14/2 mm). Tables 4 and 5 contain results of the principal stress calculations and directions of the maximum principal stress σ_1. Results were presented for the specimens without and after the heat treatment.

TABLE 4

The principal residual stresses σ_1, σ_2 computed according to the TML procedure and angles defining the maximum principal stress direction $\theta(\sigma_1)$ and detonation wave direction θ(P) for the specimens without the heat treatment

Plate	Point 1				Point 2			
	σ_1	σ_2	$\theta(\sigma_1)$	θ(P)	σ_1	σ_2	$\theta(\sigma_1)$	θ(P)
I	235	227	-50	-12	269	213	-34	-20
II	243	210	-35	174	373	339	-125	99
IV	313	248	-2	-100	310	220	-43	-130

Where: $\theta(\sigma_1)$ – angle measured clockwise from direction A to σ_1; θ(P) – angle measured clockwise to A direction from detonation direction.

TABLE 5

The principal residual stresses σ_1, σ_2 computed according to the TML procedure and angles defining the maximum principal stress direction $\theta(\sigma_1)$ and detonation wave direction θ(P) for the specimens after the heat treatment and flattening

Plate	Point 1				Point 2			
	σ_1	σ_2	$\theta(\sigma_1)$	θ(P)	σ_1	σ_2	$\theta(\sigma_1)$	θ(P)
I	-194	-194	-45	-97	-239	-260	26	-98
II	-290	-328	-133	93	-310	-335	17	83
III	-310	-337	32	-112	-310	-331	35	-118

4. Residual stress calculations according to the ASTM prescriptions

Residual stress calculation method available in ASTM standards [9] take into consideration strains measured for different hole depths. Therefore the ASTM method is prescribed as more accurate instrument for calculating residual stress under the uniform stress distribution. In the case of a blind hole residual stress calculation procedure is as following:

$$p = \frac{(\varepsilon_c + \varepsilon_a)}{2}; q = \frac{(\varepsilon_c - \varepsilon_a)}{2}; t = \frac{(\varepsilon_c - \varepsilon_a - 2\varepsilon_b)}{2}, \tag{4}$$

where q, p and t parameters are calculated for each hole depth h; ε_a, ε_b, ε_c are strain measurements in A,B,C directions.

$$P = -E\frac{\sum a \cdot p}{(1+\nu)\sum a^2}, Q = -E\frac{\sum b \cdot q}{b^2}, T = -E\frac{\sum b \cdot t}{b^2}, \tag{5}$$

where a and b are constants dependent on hole depth h and ratio between hole and strain gauge spacing diameters (d and *d/(2R)*); ν, E are material constants as previous. Results of the principal residual stress calculations are presented in Tables 6 and 7.

TABLE 6
The principal residual stresses σ_1, σ_2 computed according to the ASTM procedure and angles defining the maximum principal stress direction $\theta(\sigma_1)$ and detonation wave direction θ(P) for the specimens without the heat treatment

Plate	Point 1				Point 2			
	$\sigma 1$	$\sigma 2$	$\theta(\sigma 1)$	θ(P)	$\sigma 1$	$\sigma 2$	$\theta(\sigma 1)$	θ(P)
I	152	143	70	-12	187	133	-33	-20
II	168	132	-38	174	252	212	60	99
IV	227	155	0	-100	218	126	-43	-130

TABLE 7
The principal residual stresses σ_1, σ_2 computed according to the ASTM procedure and angles defining the maximum principal stress direction $\theta(\sigma_1)$ and detonation wave direction θ(P) for the specimens after the heat treatment and flattening

Plate	Point 1				Point 2			
	σ_1	σ_2	$\theta(\sigma_1)$	θ(P)	σ_1	σ_2	$\theta(\sigma_1)$	θ(P)
I	-112	-164	42	-97	-156	-172	20	-98
II	-181	-227	-44	93	-209	-237	17	83
III	-189	-231	29	-112	-195	-229	35	-118

5. Results analysis

Results of measurements and calculations exhibit significant differences in stress states between plates without and after the heat treatment. For the specimens collected just after welding process the calculated residual stresses are in the following range : σ_1 =<235, 373>MPa according to TML and σ_2 =<152, 252>according to ASTM. Both of the used method indicated tensile stresses in material without the heat treatment. In the specimens after the heat treatment and flattening process obtained results are the following: σ_1 =<-194,-337>according to TML and σ_1 =<-164,-237>according to ASTM. Comparison of obtained results is presented in Fig. 5.

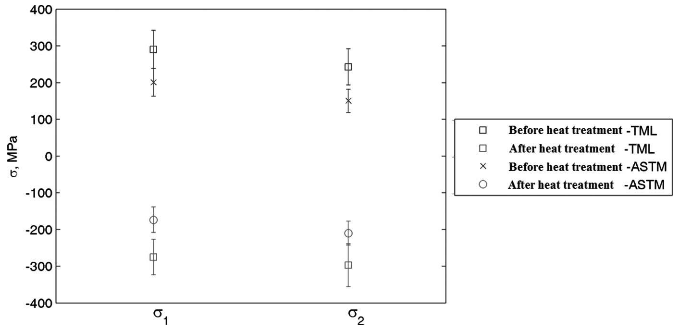


Fig. 5. The mean values of the principal stress σ_1, σ_2 and standard deviations from six measurements (two points for three plates) calculated according to the TML and ASTM prescriptions for the specimens without and after the heat treatment

The tensile stresses in the titanium layer can be explained through the analysis of the layers behavior during detonation process. Pressure (explosive) acting in the direction perpendicular to the titanium surface causes compression in z direction and tension in x direction (Fig. 6). The tensile stresses in the flyer plate (titanium) are introduced during explosion as a reason of standoff distance between the plates (Fig. 6) and high explosion wave velocity. The tensile stresses are catch and blocked by created connection between layers. Compressive stresses in the titanium layer appearing after the heat treatment result from recrystallization of grains in titanium microstructure and different thermal expansion coefficients of welded materials: α_{Steel} =13.0· 10^{-6} 1/K, $\alpha_{Titanium}$ =8.6·10^{-6} 1/K. During the soaking process in furnace the residual stresses existing in titanium are reduced (recrystallization), but in the cooling stage steel and titanium change their volumes differently causing the change of stress state in titanium into compression.

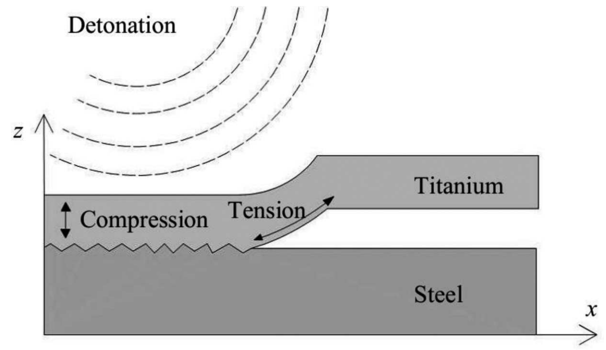


Fig. 6. Simplified detonation process and it influence on the residual stress formation

Differences in obtained residuals stress values for TML (single hole depth and measurement for each point) and ASTM (mean value from fourteen hole depth and measurements for each point) methods indicate heterogeneity of the stress state in investigated material. The assign, by detonation, direction of wave propagation suggests that the maximum principal stress direction will coincide with it. However, the calculated maximum principal stress direction does not overlap with detonation direction. Orientation of the maximum principal stress does not change considerably in the function of the depth of the drilled hole because both used methods indicated the same directions of the maximum principal stress. Direction of the maximum principal stress reveals spread but its mean value differs by 45° if compared to the detonation direction (Fig. 6).

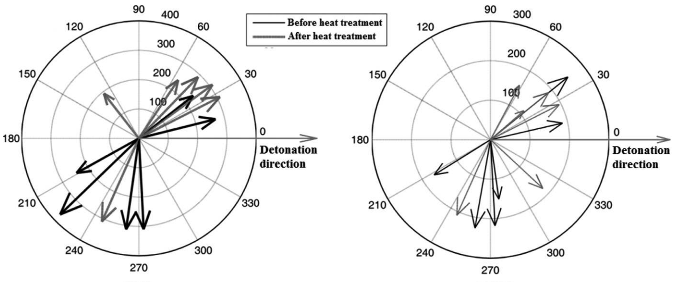


Fig. 7. Directions of the maximum principal stresses related to detonation directions. Calculations according to the TML and ASTM methods

The performed heat treatment has a few beneficial effects on the strength of analyzed bimetallic composite: (i) the compressive residual stresses obtained after the heat treatment enable the cold flattening process without the risk of cracking in titanium layer; (ii) the tensile residual stress weakens the bond between metallic layers, in extreme case – too large tensile stresses, produced during explosive welding, creates shear stresses that exceed the shear strength and the bond is destroyed; (iii) the compressive residual stresses are beneficial in respect to fatigue life.

The residual stresses treated as mean stress component in fatigue loading could be taken into account in fatigue life calculation algorithms according to which the compressive mean stresses increases the fatigue life and strength [10].

6. Summary

Summarizing performed experimental research on explosively welded steel-titanium bimetal the following conclusions are drawn:

1) The heat treatment changes the residual stress state in titanium. The stress state in specimen without the heat treatment is tensile and after the heat treatment is compression.

2) Direction of the maximum principal stress does not coincide with direction of detonation wave.

3) Calculation shows inhomogeneous residual stress state. The stresses change depending on the hole depth.

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