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

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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

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-
searches were performed on six S355J2+N steel–Titanium Grade 1 specimens (210x180x46 mm) cut out from large (4330x3150x46 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 from 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 |
|---------------------------------|---|---|---|---|---|---|
| Chemical element:              | C  | Si  | Mn  | P  | S  | Cu  |
| Maximum content, % weight:     | 0.22 | 0.55 | 1.60 | 0.025 | 0.025 | 0.45 |
| Steel S355J2                   |                |            |              |                  |           |
| Chemical element:              | C  | Fe  | H   | N  | O  | Ti  |
| Maximum content, % weight:     | 0.10 | 0.20 | 0.015 | 0.03 | 0.18 | 99.5 |
| Titanium Grade 1               |                |            |              |                  |           |

**TABLE 2**

| Mechanical properties of the steel S355J2+N and titanium Grade 1 |
|------------------------|---|---|---|---|---|---|---|
| Material               | $R_{H}$, MPa | $R_{m}$, MPa | E, GPa | G, GPa | $\nu$, $\%$ | $A_{5}$, $\%$ |
| S355J2                 | 382-395$^\ast$ | 598-605$^\ast$ | 206 | 84 | 0.27-0.30 | 24-34$^\ast$ |
| Grade 1                | 189-215 (R$_{p02}$) | 308-324$^\ast$ | 100 | 38 | 0.37$^{\ast\ast}$ | 43-56$^\ast$ |

$^\ast$ – manufacturer certificate, $^\ast\ast$ – own research (titanium after explosive welding)

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 |
|----------------------------|
| **Manofacturer:** TML TokyoSokkiKenkyujo Co., Ltd. |
| **Type:** FRS-2 |
| Dimensions : gauge length: 1.5 mm width: 1.3 mm outer diameter: $\phi$9.5 mm Centerline diameter: $\phi$5.14 mm Nominal resistance: 120 ± 0.5 $\Omega$ 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

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

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).
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. The specimens without the heat treatment positive value of measured strain indicated compressing residual strains. The specimens without the heat treatment are presented for the specimens without and after the 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 1.2\( d \), 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 have been done:

\[
\theta = \frac{1}{2} a \tan \frac{\varepsilon_a + \varepsilon_c - 2 \varepsilon_b}{\varepsilon_c - \varepsilon_a} - \frac{m \pi}{2}
\]

where \( \theta \) is angle defining principal stress orientation measured clockwise from A direction to \( \sigma_1 \); \( \varepsilon_a, \varepsilon_b, \varepsilon_c \) are strain measured in A,B,C directions; \( n =0 \) for \( \varepsilon_a \geq \varepsilon_c; n =1 \) for \( \varepsilon_a < \varepsilon_c \).

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

where: \( \sigma_1, \sigma_2 \) are the principal stresses; \( K \) and \( H \) are coefficients calculated from the following equations:

\[
K = -\frac{(1 + \nu) d^2}{8 E R^2}, \quad H = -\frac{d^2}{2 E R^2} + \frac{3 (1 + \nu) d^4}{32 E R^4},
\]

where \( E \) is modulus of elasticity \( (E=100 \text{ GPa}) \); \( \nu \) is the Poisson ratio \( (\nu =0.39) \); \( d \) is hole diameter \( (d =1.5 \text{ mm}) \); \( R \) is the centerline strain gauge radius \( (R =5.14/2 \text{ mm}) \). Tables 4 and 5 contain results of the principal stress calculations and directions of the maximum principal stress \( \sigma_1 \). Results were presented for the specimens without and after the heat treatment.

### 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:

\[
p = \frac{(\varepsilon_a + \varepsilon_c)}{2}; \quad q = \frac{(\varepsilon_c - \varepsilon_a)}{2}; \quad t = \frac{(\varepsilon_c - \varepsilon_a - 2 \varepsilon_b)}{2},
\]

where \( q, p \) and \( t \) parameters are calculated for each hole depth \( h; \varepsilon_a, \varepsilon_b, \varepsilon_c \) are strain measurements in A,B,C directions.

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

where \( a \) and \( b \) are constants dependent on hole depth \( h \) and ratio between hole and strain gauge spacing diameters \( (d \text{ and } d/(2R)); \nu, E \) are material constants as previous. Results of the principal residual stress calculations are presented in Tables 6 and 7.
The principal residual stresses $\sigma_1$, $\sigma_2$ computed according to the ASTM procedure and angles defining the maximum principal stress direction $\theta(\sigma_1)$ and detonation wave direction $\theta(P)$ for the specimens without and after the heat treatment.

### Table 6

| Plate | Point 1 | Point 2 |
|-------|---------|---------|
|       | $\sigma_1$ | $\sigma_2$ | $\theta(\sigma_1)$ | $\theta(\sigma_2)$ | $\theta(P)$ | $\theta(\sigma_1)$ | $\theta(\sigma_2)$ | $\theta(P)$ |
| 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|

The principal residual stresses $\sigma_1$, $\sigma_2$ computed according to the ASTM procedure and angles defining the maximum principal stress direction $\theta(\sigma_1)$ and detonation wave direction $\theta(P)$ for the specimens after the heat treatment and flattening.

### Table 7

| Plate | Point 1 | Point 2 |
|-------|---------|---------|
|       | $\sigma_1$ | $\sigma_2$ | $\theta(\sigma_1)$ | $\theta(\sigma_2)$ | $\theta(P)$ | $\theta(\sigma_1)$ | $\theta(\sigma_2)$ | $\theta(P)$ |
| 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: $\sigma_1 = <235, 373>$ MPa according to TML and $\sigma_2 = <152, 252>$ 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: $\sigma_1 = <-194,-337>$ according to TML and $\sigma_1 = <-164,-237>$ according to ASTM. Comparison of obtained results is presented in Fig. 5.

![Fig. 5. The mean values of the principal stress $\sigma_1$, $\sigma_2$ 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](image)

![Fig. 6. Simplified detonation process and it influence on the residual stress formation](image)

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. Compresive 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: $\alpha_{\text{Steel}} = 13.0 \cdot 10^{-6}$ 1/K, $\alpha_{\text{Titanium}} = 8.6 \cdot 10^{-6}$ 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.

### Table 6

| Plate | Point 1 | Point 2 |
|-------|---------|---------|
|       | $\sigma_1$ | $\sigma_2$ | $\theta(\sigma_1)$ | $\theta(\sigma_2)$ | $\theta(P)$ | $\theta(\sigma_1)$ | $\theta(\sigma_2)$ | $\theta(P)$ |
| 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|

**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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REFERENCES

[1] G. Young, Welding, Technical Growth and Commercial History, Stainless Steel World, 6 (2004).
[2] T.J. Lienert, Welding Fundamentals and Processes, 1st ed. 3, ASM International (2011).
[3] S.L. Semiatin, ASM Handbook: Volume 14B: Metal Working; Sheet Forming. ASM International (2006).
[4] S.A.A. Akbari-Mousavi, L.M. Barrett, and S.T.S. Al-Hassani, Explosive welding of metal plates, Journal of Materials Processing Technology 202, 1-3, 224-239 (2008).
[5] A. Karolczuk, K. Kluger, M. Kowalski, F. Zok, and G. Robak, Residual Stresses in Steel-Titanium Composite Manufactured by Explosive Welding, Materials Science Forum 726, 125-132 (2012).
[6] A. Karolczuk, M. Kowalski, R. Bansk i, and F. Zok, Fatigue phenomena in explosively welded steel-titanium clad components subjected to push–pull loading, International Journal of Fatigue 48, 101-108 (2013).
[7] A. Karolczuk, M. Kowalski, G. Robak, Modelling of titanium-steel bimetallic composite behaviour under mechanical cyclic loading, Solid State Phenomena 199, 460-465 (2013).
[8] G.E. Totten, Handbook of Residual Stress and Deformation of Steel. ASM International (2002).
[9] ASTM E837-08, Standard test method for determining residual stresses by the hole drilling strain gauge method. West Conshohocken: American Society for Testing and Materials (2008).
[10] A. Karolczuk, E. Macha, Critical planes in multiaxial fatigue, Materials Science Forum 482, 109-114 (2005).