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FATIGUE TESTS AND METALLOGRAPHIC OF EXPLOSIVELY CLADDED STEEL-TITANIUM BIMETAL

BADANIA ZMĘCZENIOWE I METALOGRAFICZNE BIMETALU STAL-TYTAN ZGRZEWANEGO WYBUCHOWO

The paper contains a description of fatigue life tests of titan-steel bimetal. The study involved specimens made of bimetal which was a combination of S355J2 steel and SB G1 265 titanium, which was imposed in the material by explosive cladding method. The research shows that the fatigue life of specimens made of native material, derived from clad plate is less than the life of specimens of titanium-steel bimetal.

Keywords: Fatigue life, explosive cladding, explosive welding, clad

W pracy zawarto wyniki badań zmęczeniowych i metalograficznych bimetalu będącego połączeniem stali S355J2 z tytanem SB265G1 przy pomocy technologii zgrzewania wybuchowego. Analiza wyników badań dowodzi, że proces zgrzewania wybuchowego i obróbki cieplnej mają wpływ na trwałość zmęczeniową materiału. Ponadto stwierdzono, że w procesie projektowania elementów narażonych na zmienne obciążenia należy uwzględnić własności wszystkich materiałów wchodzących w skład plateru.

1. Introduction

Explosive materials can be applied for mineral crushing, demolition of buildings, fire suppression (blowing the flame away), stretching the belts and filling the airbags, shooting rackets or rescue cartridges, treatment of metallic and non-metallic materials. Intense energy released in a short time in explosion act gives a possibility of realization of technological processes which could not be obtained in typical conditions. The mentioned technologies using the explosion force have one common feature – suitable application of extreme values of velocity and pressure accompanying the explosion [1-2]. Explosive cladding allows joining materials with completely different properties which are difficult to obtain by means of other methods of joining [3]. Such clad obtained with this method are materials of strong gradient properties and they have complex joining zones. The clad materials are often applied in processing apparatus (chemical and power industries). Wide application of titanium and its alloys in power engineering (condensers, steam condensers, heat exchangers and steam turbines in power plants and thermal-electric power stations) causes that the problem of fatigue life of bimetallic clads, for example, those of steel-titanium type, becomes more and more important. As for many applications, fatigue life of clads is the most important parameter. Performed tests meet suitable standards, but also were modified in order to fit into the special character and dimensions of material used for testing. This paper is a continuation of the previous work con-

cerning strength of clad materials [1,4] with special attention paid to fatigue life of these materials [5,6,7,8,9].

2. Experimental

This paper presents results of the fatigue tests of the clad material being a joint of steel S355J2+N with titanium SB265G1 under pendulum bending for two different bending configurations (perpendicular and parallel) and under three-point bending.

Fatigue life characteristics of bimetal and native materials (titanium and steel under pendulum bending) were obtained. Thickness of the overlaid material (titanium) was 6 mm, so the specimens of untypical, determined with FEM, shape and dimensions were used for fatigue tests. Afterwards the specimens microhardness and fracture was tested.

Investigations were carried out on the specimens in state before and after the heat treatment. Applied annealing was performed at the temperature of 600°C for 90 min with cooling in furnace to 300°C and in air to room temperature. The heat treatment conditions were discussed in cooperation with Explomet company, were investigated bimetal was produced as well.

For pendulum (cyclic) bending, the specimens were prepared and tested as follows. The specimens 100×9×9 mm were tested at the fatigue test stand existing at Department of Me-

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In the tested bimetallic specimens, the bimetal joint was located exactly in a half of their section. Thus, each specimen was divided into two equal parts – steel and titanium (Fig. 1a). Four series of tests were performed. The specimens were subjected to a traditional fatigue test, i.e. alternating bending under sinusoidally changing loading with constant amplitude of bending moment (pendulum bending).

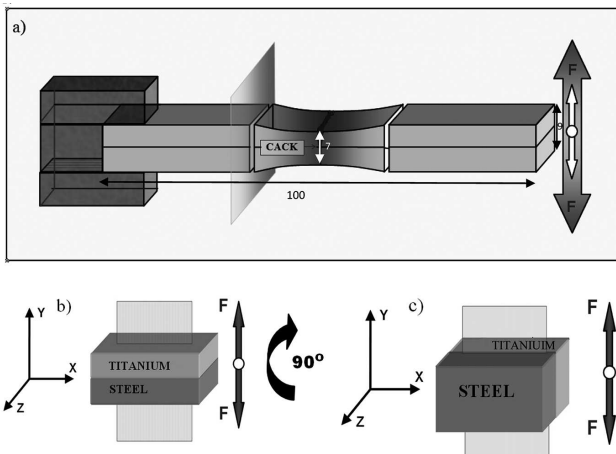


Fig. 1. Scheme of attachment and loading of specimens (a) and a scheme of the loading method depending on the specimen attachment: perpendicular (b) or in parallel (c) [3]

Next investigations were also performed on the bimetal S355J2 explosively welded (cladded) with titanium Grade 1. Titanium was used as a flyer plate due to high corrosion resistance and possibility to cold forming. To investigate fatigue strength of the bimetal, three-points bending test was carried out. Specimens to be tested were cut from the bimetal in parallel direction relative to joining direction, from central part of plates due to avoidance delaminated or weakened interface characterized to the corners of the welded plates. In order to avoid the effect of concentration of the shearing stresses specimens edges were rounded additionally. Specimens dimensions are shown in Fig. 2. and scheme of bending test is shown in Fig. 3.

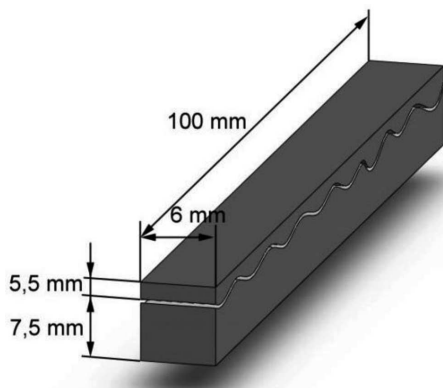


Fig. 2. Dimensions of specimen used in three-points bending test

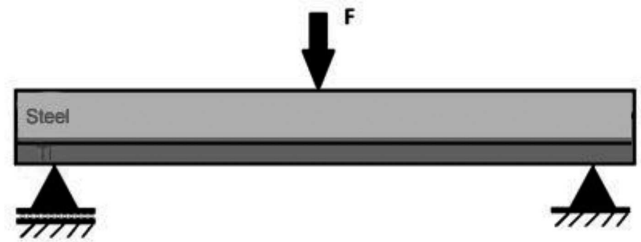


Fig. 3. Scheme of three-points bending test

The three-points bending test results were confronted with the microstructure and microhardness measurements.

Methods used were:

- Metallographic observations of the bimetal;
- Scanning electron microscope observations of fractures resulted from the bending test;
- Microhardness measurements.

To microstructure observation of material before and after the heat treatment, specimens were cut from plate and mounted in resin. At the beginning, the samples were ground and polished using $0.6 \mu\text{m}$ Al_2O_3 powder. To reveal the titanium microstructures, specimens were etched in lactic and nitric acid with hydrofluoric acid and in distilled water solution [11]. Steel microstructures were revealed using the Nital 2% and following oxalic acid solutions in distilled water.

Precise observations of fractographics elements of bond were carried out using scanning electron microscope Hitachi SU-70. Microhardness investigation was performed on specimens used for the metallographic observations. Measurements were carried out in direction perpendicular to the bond both in titanium and steel.

3. Results

3.1. Cyclic bending

In the first series of tests, the specimen was located at the test stand in a way allowing to realize bending according to the scheme (Fig. 1b) on the plane perpendicular to the bimetal joint. In such a case, three fatigue tests were performed. They were presented also in the paper [4], and next seven more tests were realized. The results of those fatigue tests were presented in Fig. 4 for the stress amplitude σ_a depending on a number of cycles N_f . The specimens are shown as loaded perpendicular to the bimetal joint plane.

The next series of tests was performed under different configuration of the clade loading. The specimen was mounted at the stand in the way allowing the vector of the bending force to act on the plane of bimetal joint (Fig. 1c). The test results are presented in Fig. 5 where the specimens are loaded in parallel to the bimetal joint plane. In the third series of tests, the specimens were made of the native material (steel S355J2+N), and they were obtained from the sheets, just like in two previous series, after the explosive welding and heat treatment. The used specimens had the same shapes and dimensions as the specimens tested in the previous series, so it was possible to relate the obtained results to the results of previous tests. These results are presented in Fig. 6.

Fourth and final series for pendulum bending was performed on specimens made of the second native material –

titanium SB265G1. Material was obtained from titanium plate before cladding and any heat treatment. All of the test results are also presented in Tables 1 and 2.

TABLE 1

Fatigue life tests parameters and results for bimetal pendulum bending depending on the specimen attachment perpendicular (a) or in parallel (b) to joint plane:

a) perpendicular				b) parallel			
No.	σ_a , MPa steel	σ_a , MPa titanium	N_f	No.	σ_a , MPa steel	σ_a , MPa titanium	N_f
1	380	266	56000	1	371	185	132000
2	367	257	77000	2	361	180	79000
3	360	252	133000	3	351	175	98000
4	347	243	95000	4	339	169	235000
5	343	240	101000	5	336	168	143000
6	328	230	156000	6	316	157	241000
7	321	225	238000	7	280	140	368000
8	294	206	345000	8	278	139	453000
9	274	192	1760000	9	260	130	5039000
10	287	201	172000	10	259	129	965000

TABLE 2

Fatigue life tests parameters and results for native materials: titanium SB265G1 (a) and steel - S355J2+N (b)

a) Titanium SB265G1			b) Steel S355J2+N		
No.	σ_a , MPa	N_f	No.	σ_a , MPa steel	N_f
I	311	8900	I	329	78000
II	306	14900	II	314	84000
III	283	38100	III	303	156000
IV	262	27800	IV	291	175000
V	245	52100	V	272	165000
VI	235	119400	VI	271	195000
VII	230	491300	VII	253	612000
VIII	228	241800			
IX	214	1227800			
X	201	327800			
XI	196	2262400			
XII	195	3708800			

The fatigue test stand MZGS-100 allows to realize tests under a constant value of the bending moment, so the stress amplitudes used for plotting the presented fatigue characteristics have been determined by means of calculations with FEM, and the linearly-elastic model of the material was assumed.

Fig. 4. presents the fatigue test results obtained for the steel-titanium bimetal, where σ_a is the maximum value of the stress amplitude, and N_f is a number of cycles to the fatigue crack initiation under loading on the plane perpendicular to the bimetal joint (Fig. 1a – the first series of tests) including the stress amplitude used during the tests, occurring in both

steel S355J2, and in titanium SB265 G1. Drop of the specimen stiffness by 30% was assumed as the main criterion of the fatigue crack initiation. Fig. 5. shows the fatigue test results for the steel-titanium bimetal under loading on the plane parallel to the bimetal joint (Fig. 1c – the second series of tests) including the stress amplitude applied in tests, occurring in both steel S355J2 and titanium SB265 G1. The double-logarithmic curve shown in Fig. 6. presents the fatigue test results exhibiting dependence between the stress amplitude σ_a (in steel) and the fatigue life N_f for two kinds of the clad material loading and the native material together with characteristics. Scatters of results are very important for fatigue tests and they also occur for homogeneous materials. In the case of bimetallic materials clad with the explosive method we have heterogeneous structure of the material, and differences in the test results can be much larger even for similar loadings.

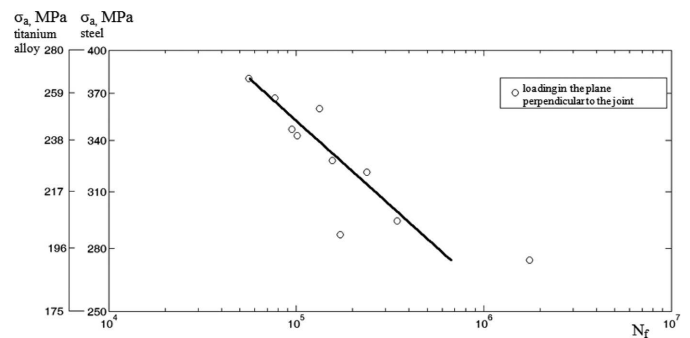


Fig. 4. Graph of dependence of the stress amplitude (σ_a) on number of cycles N_f occurring in steel and titanium

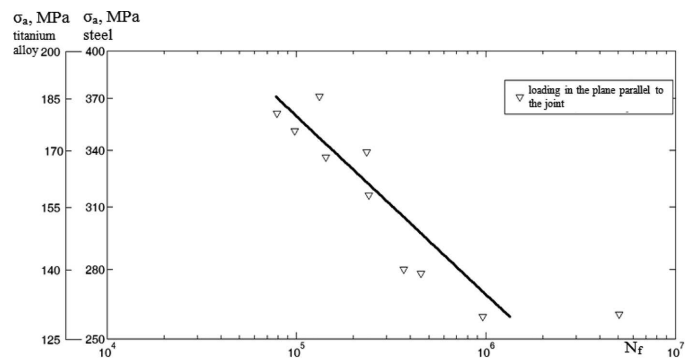


Fig. 5. Graph of dependence of the stress amplitude (σ_a) on number of cycles N_f occurring in steel and titanium

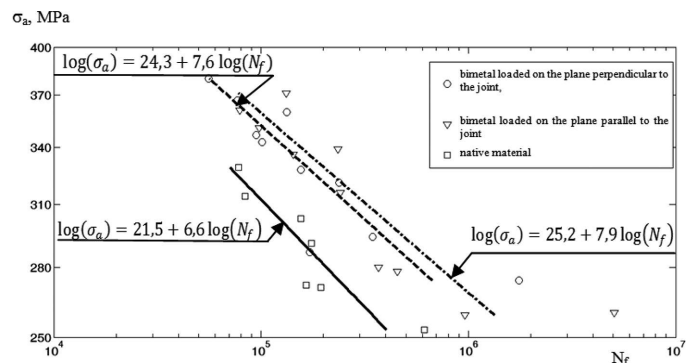


Fig. 6. Graph presenting dependence of the stress amplitude (σ_a) on number of cycles N_f for steel-titanium and native steel specimens in logarithmic scale

Fatigue life testes of titanium specimens are presented in Figure 7. The results for both native material and bimetallic specimens were taken under consideration. For bimetallic specimens only those loaded in parallel to the bimetal joint plane showed tendency to initiate cracks in both materials.

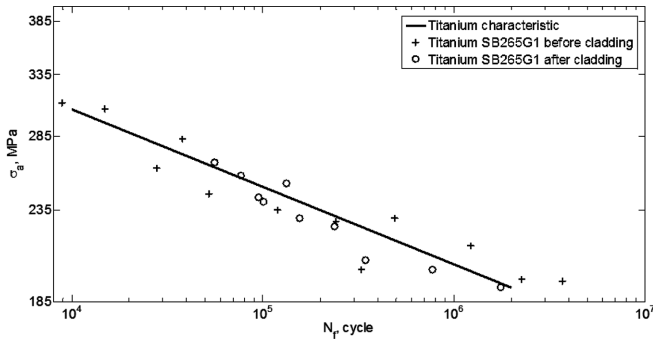


Fig. 7. Graph presenting dependence of the stress amplitude (σ_a) on number of cycles N_f occurring in titanium

The final graph, Fig. 8., for pendulum bending contains results from all four series. Because there was no significant difference in fatigue life for first two series (bimetal loaded parallel and perpendicular to the joint plane) one characteristic was used to describe their fatigue properties.

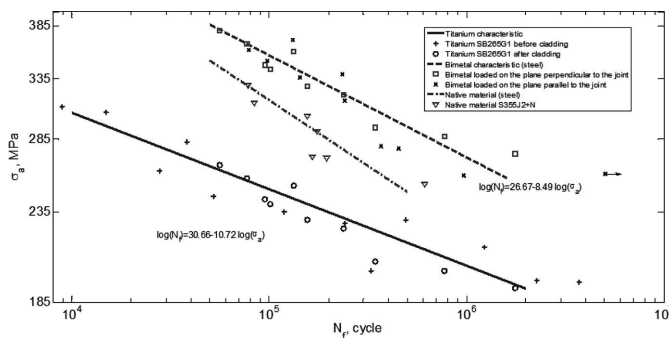


Fig. 8. Graph presenting dependence of the stress amplitude (σ_a) on number of cycles N_f for bimetallic specimens (stress in titanium part) and native titanium

3.2. Bond microstructure

Process of explosive welding performed with the proper conditions is always associated with presence of wavy bond, which were observed in carried out metallographic observations shown in Figs. 9,10. Metallographic investigations revealed that microstructure of steel after the explosive welding is similar to the one characteristic for rolling process. This is associated with the presence of deformed and elongated grains in parallel direction to the bond. Microstructure of explosively welded steel S355J2 in state after the heat treatment is shown in Fig. 9a. Results revealed significant influence of heat treatment on microstructure and mechanical properties of the bimetals. Microstructures characterized for rolling process were due to plastic deformation generated through the detonation of explosive. Elongated grains of steel could be observed both in bimetal in state before and after the heat treatment. In area adjacent to interface on width 150 μm decarbonization of steel was observed. Phenomenon of decarbonization was

a result of carbon diffusion into bonding zone during heat treatment. Steel decarbonization is related with presence of brittle TiC phases in the bonding zone, which was previously observed by Y. Morizono et al [15]. Fig. 9b revealed the presence of melted zone inside the wavy structure and directly on the bond. Molten region revealed a swirl microstructure like the contrast inside the inclusion indicating phase intermixing. Moreover, the melted zone is surrounded by recrystallized steel grains. Presence of melted areas and recrystallized steel grains around them indicate on thermodynamic mechanism of bond creation. Creation process of melted vortex zones was described by I.A.Bataev et al [16].

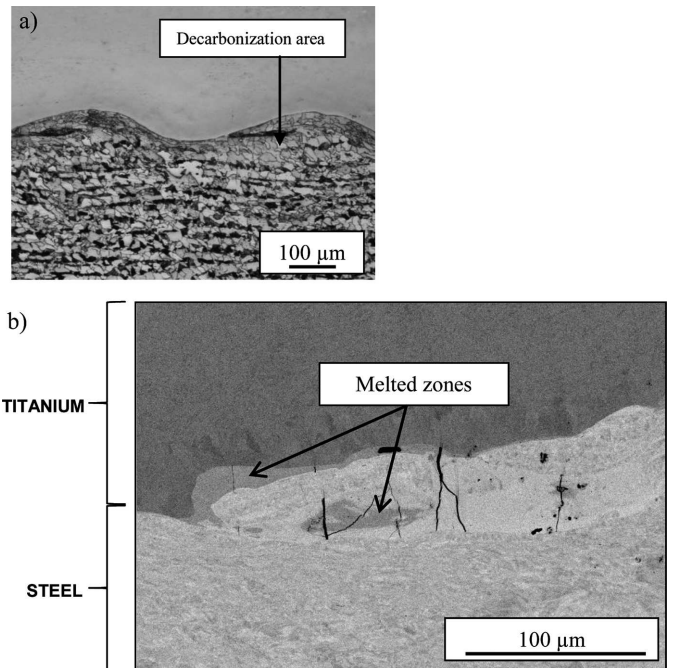


Fig. 9. Microstructure of explosively welded steel S355J2. Specimen after the heat treatment, (a) decarbonization area, (b) melted zones

Microstructure of explosively welded titanium in state after the annealing is shown in Fig. 10. Titanium microstructure observed near the bond and in greater distance revealed typical, equiaxed grains. Average size of the grains near the bond was 18.4 μm , while during increasing the distance from bond average size of the titanium grains increased also, reaching 50.2 μm at the distance of 6 cm from the interface. Influence of post heat treatment on titanium microstructure related to used temperature was described by C. Prothe et al [17]. Prothe results compared to presented one revealed no titanium grains recrystallization after the heat treatment at 600°C. Difference in microstructure is a result of different cladding process parameters what cause another degree of strain hardening.

Microhardness test results plotted as a graph in Fig. 11 revealed significant reduction of microhardness near the bond area, particularly at the steel side. Lower microhardness in the bond area in comparison to the greater distance is associated with decarbonization of steel observed in area adjacent to interface on width 150 μm . Phenomenon of decarbonization was a result of the performed heat treatment. Moreover, applied annealing contributed to the stress relaxation what is associated with significant changes in microstructure like recrystallization of deformed grains.

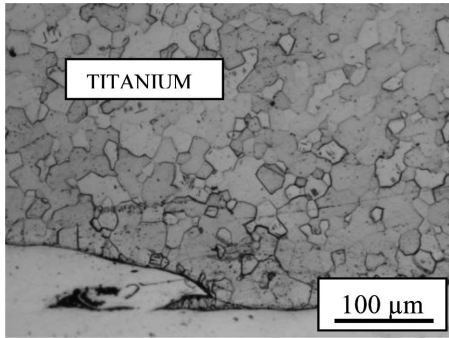


Fig. 10. Microstructure of explosively welded titanium Grade 1. Specimen after the heat treatment

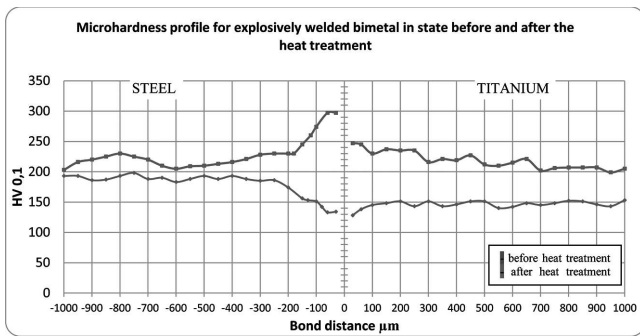


Fig. 11. Microhardness profile for explosively welded bimetal in state before and after the heat treatment

Base on the fractures obtained during three-points bending tests, fractographic investigations were performed. Results showed in Fig. 12. revealed that cracks propagations were always initiated on the sides of the specimens, despite the fact that the edges of all specimens were rounded. It was also observed that the area of the crack initiation was characterized

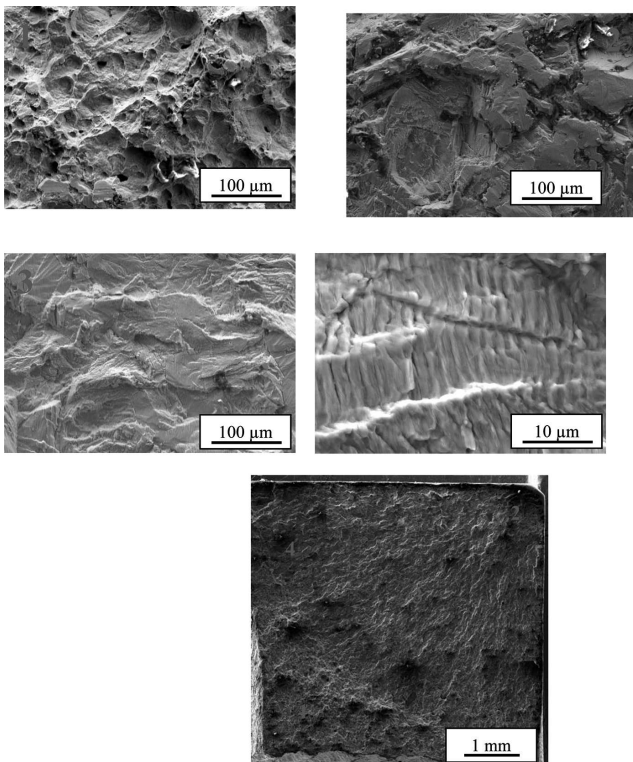


Fig. 12. Fracture of the specimen after the three-points bending test

for plastic fracture. Detailed observations revealed the presence of microcracks in that area, which were connected with each other and propagated farther as a main crack.

3.3. Three-point bending

In order to relate microstructure observations with mechanical properties, three points bending tests were carried out. In literature exist few information about the carried out three-point bending tests [10,11,12]. However, due to the different dimensions of the specimens used in bending test by different researchers it is difficult to compare the test results. The divergence in carried out bending tests comes from absence of appropriate standards concerning the mechanical tests of explosively welded bimetals. Available standards do not provide a fully accurate descriptions and recommendations for testing. In this case, researchers develop own criteria for testing or benefit from the experience of other research centers. However, there is no information about fatigue (cyclic) bending tests referred to post heat treatment. Investigation revealed the growth of fatigue strength in bimetal in state after the heat treatment what is shown as a plotted graph in Fig. 13 and included in Table 3. Blue line shown in the graph represents bimetal in state before annealing, while red line corresponds to the state after the heat treatment. Growth of fatigue strength was observed both for small loads and high loads.

TABLE 3

Results of three-points bending tests, S355J2+SB265G1

Load, kN	S355J2+SB265G1			
	Number of cycles to specimen damage, N_f			
	Specimen No 1	Specimen No 2	Specimen No 3	Average
4	4000000	–	–	4000000
5	15000000	–	–	15000000
6	4000000	3149399	4000000	3716466
7	566599	436799	271399	424932
8	356599	230599	205799	264332
9	93799	87599	96799	92732
10	51399	44599	64599	53532

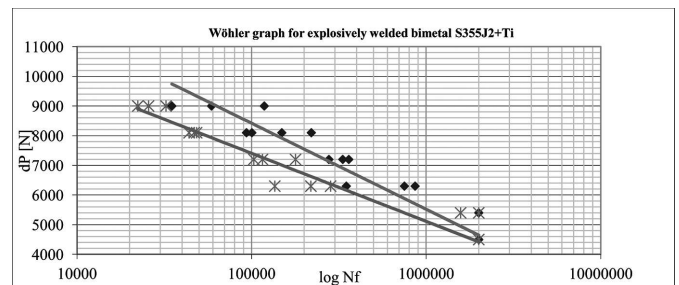


Fig. 13. Wöhler graph for explosively welded bimetal S355J2+Ti

4. Conclusion and acknowledgements

The experiment performed on bimetallic specimens loaded on the plane perpendicular to the joint allowed to conclude

that the crack initiation occurred mostly in titanium SB265 G1. In spite of great difference in Young modulus of the joined materials, determining a lower stress value, titanium has a lower fatigue life. On the other hand, in the case of specimens subjected to bending on the plane parallel to the joint plane, the crack initiation occurred in the steel layer of the bimetal. Thus, we can state that for a given specimen shape, loading by alternating bending and the resulting stress distribution, the fatigue life of both materials is similar, and the final life is influenced by different random factors determined by the technology of materials joining (inclusions, heterogeneity of the joining cone etc.). Thus, while designing of machine elements made of bimetals the fatigue characteristics including fatigue properties of the basic material and the overlaid material should be taken into account [4,10]. The Wöhler's curve for the considered material (see Fig. 4) is an example of such characteristics. The expected fatigue life of both steel and titanium should be checked, and the lower fatigue life should be assumed as the life of the element.

If the tested specimens are loaded in parallel to the joint plane, the difference of stress amplitude occurring in steel and titanium is greater, so the crack initiation process will proceed in the steel layer at first. Moreover, the fatigue life of the specimens made of the native material obtained from the clad is lower than the fatigue life of steel-titanium specimens. Fatigue tests of bimetallic and titanium specimens show no significant difference in fatigue life of titanium SB265G1 before and after cladding and heat treatment.

Basing on the results from three-points bending test in relation to microstructural and microhardness measurements it may be concluded that fatigue strength of bimetal S355J2+Ti Grade 1 obtained by explosive welding method is related with increased ductility due to annealing.

Acknowledgements

The Project was financed from a Grant by National Science Centre (Decision No. DEC- 2011/01/N/ST8/06904).

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