Crack growth of explosive welding zirconium-steel bimetal subjected to cyclic bending

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ABSTRACT. The paper presents the fatigue test results including the cracks growth in the composite zirconium-steel subjected to oscillatory bending. Specimens of square cross-section without melted layer and with a melted layer were tested. In the specimens the net ratio of thickness of steel to zirconium layers was $h_1 : h_2 = 2.5 : 1$. It was observed that a higher fraction of the intermetallic inclusions near the interface increase the fatigue life. Two different interaction mechanisms between a crack and interface were observed.

KEYWORDS. Explosive welding; Bending; Fatigue crack growth; Joint.

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INTRODUCTION

Modern equipment in key branches of industry, like power industry, requires reliable structures. One of the most important element of the construction is the selection of the suitable material, whose task is to ensure durability in an aggressive environment [1]. However, the cost of the production of the working machines is getting significantly higher due to the material price. In order to lower the costs of the materials that are resistant to corrosion and durable in an aggressive environment, there are being created composites combining, for example, titanium or zirconium with steel obtaining the material with the demanding properties [2, 3]. Since the differences in mechanical properties of the materials are big, there are some issues with combining them. One method of bonding those kinds of materials is explosive welding. In which the base plate (steel) and the clad plate are set in specified distance called stand-off distance. The distance between both plates before joining is selected to assure suitable collision velocity. Parameters of the detonation system must ensure a suitable detonation velocity and a required amount of energy necessary for the sheet joining [4-7]. The explosive material is uniformly distributed on all the zirconium (titanium) sheet surface [7]. If the joined plates are parallel, the collision velocity is equal to the detonation velocity and equals from 2000 to 3500 m/s, depending on the joined metals. The stand-off distance between the sheets is dependent on the joined materials, their physical and mechanical properties and properties of the applied explosive material. The detonation velocity and the distance are the main parameters of the detonation system influencing a high quality of the obtained joint. The detonation velocity depends on a kind and amount of the applied explosive material per unit surface. This velocity should allow to obtain the

required energy of detonation. The distance between the sheets is chosen for a given detonation velocity in order to obtain the required collision velocity. The mentioned parameters are calculated separately for each system.
Although the phenomena taking place in layered materials have been dealt with earlier, interest in them is still growing [2-4].
The aim of the paper is to investigate a fatigue crack growth under bending in zirconium-steel bimetal.

EXPERIMENTAL PROCEDURE

Material and specimen

The zirconium-steel bimetals were tested. P265GH normalized carbon steel plate of 20 mm thickness was the base material [8, 9] and Zr 700 zirconium plate of 3.175 mm thickness was the clad material. Basic mechanical properties of both materials before joining (according to the certificate of the manufacturer) are presented in Tab. 1.

Materials	σ_y (MPa)	σ_u (MPa)	E (GPa)	ν	A_5 (%)
Zr 700	143	300	100	0.35	31
P265GH	311	467	210	0.30	33

Table 1: Mechanical properties of Zr 700 and P265GH steel.

Metallographic examination appeared that microstructure of the steel P265GH consists of ferrite grains (bright) and pearlite grains (dark) with typical for materials, after hot working, band arrangement of the grains (see Fig. 1 below the interface line). Steel structure was characterized by ferrite grains of the diameter from 10 to 20 μm and pearlite grains of the diameter from 4 to 11 μm. The clad material (zirconium) contains grains made of oriented packages of phase α of dimensions 70–170 μm (Fig. 1 over the interface line). The zirconium-steel bimetal plates were manufactured from plates of dimensions 300 x 500 mm. The processes were performed at the same initial stand-off distance 4.5 mm between plates and different detonation velocities 2000 m/s (with melted layer) and 2200 m/s (without melted layer). In the case of clads, metallographic specimens were cut out the section perpendicular to the plate surface, and parallel to the direction of propagation of the explosion wave. The metallographic specimens were grounded by abrasive papers and diamond pastes with decreasing grain size. Next, they were polished and subjected to electrolytic etching at the polishing machine LectroPol 5 using the electrolyte made by Struers.

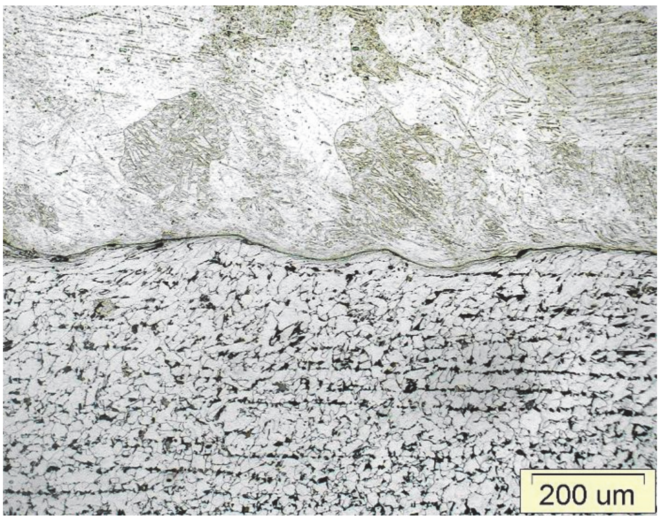

Figure 1: The microstructure of zirconium-steel joint without melted layer.

Fatigue specimens with net square cross-sections of 7 mm thickness, 7 mm width and length 90 mm were tested (Fig. 2). Those were cut off the sheet with a thickness of 23 mm parallel to the detonation direction. Each specimen had an external notches with a root radius R = 22.5 mm. The specimen surfaces have been obtained by milling followed using polishing with progressively finer emery papers. A final average roughness 0.16 μm has been obtained. In the specimens the net thickness ratio of steel/zirconium layers was $h_1 : h_2 = 2.5 : 1$.

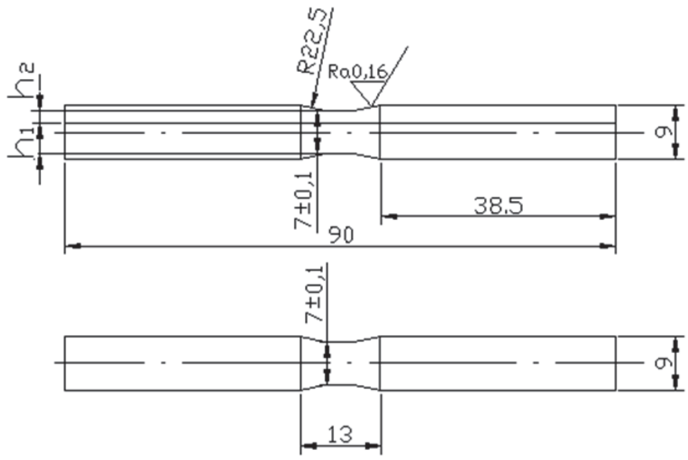

Figure 2: Shape and dimensions of specimen (in mm).

Fatigue tests

The tests were performed on the fatigue test stand MZGS – 100 [10, 11] (Fig. 3), which allows to perform cyclic bending, torsion and synchronous bending with torsion [12]. The tests were conducted under controlled force (in the considered case, the amplitude of bending moment was controlled) with the loading frequency 28.4 Hz. The theoretical stress concentration factor in the specimen under bending $K_t = 1.045$ was estimated according to Ref. [13]. The bending moment was generated by force on the arm 0.2 m in length. Fatigue tests were performed in the low cycle fatigue (LCF) and high cycle fatigue regime (HCF). Unilaterally restrained specimens were subjected to cyclic bending with the constant load ratio $R = M_{min} / M_{max} = -1$ and amplitude of bending moments M_a = 12.28, 14.21, 17.18, 19.41 N·m, which corresponded to the nominal amplitude of normal stresses $\sigma a_{(steel)}$ = 261.4, 302.5, 365.7, 413 MPa and $\sigma a_{(Zr)}$ = 160, 185.5, 224.2, 253.3 MPa [14] for the net section before crack initiation, respectively. The shear stress at the specimen coming from bending takes very small values, below 3% of the maximum applied bending stress and it is neglected in further considerations. Fatigue crack growth on the specimen surface was observed with the portable optical microscope with magnification of 20 times. The fatigue crack increments were measured with the micrometer of accuracy up to 0.01 mm with the corresponding number of loading cycles N.

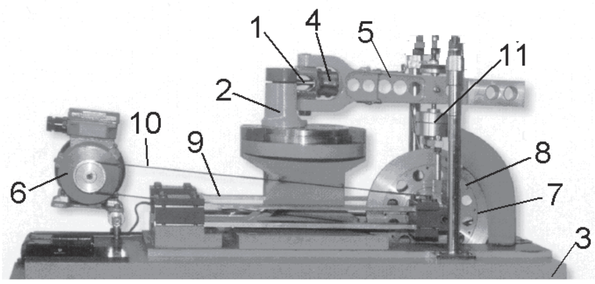

Figure 3: Fatigue test stand MZGS-100 where: 1 – specimen, 2 – rotational head with a holder, 3- bed, 4 - holder, 5 - lever, 6 - motor, 7 – rotating disk, 8 - unbalanced mass, 9 – flat springs, 10 – driving belt, 11 – hydraulic connector.

EXPERIMENTAL RESULTS AND DISCUSSION

A detailed description of the joint boundary was based on measurements of the basic parameters, i.e. the wave length n and the wave height H. In both cases a wavy character of joints were obtained (Fig. 1), however, in the case of a higher detonation velocity the joint boundary was homogeneous, and in the case of lower velocity formation of joint penetration areas were observed. From mechanical properties point of view such areas are unfavourable in the bimetal (Fig. 4). For a higher detonation velocity (without melted layer), the mean wave height H = 53 μm and length n = 409 μm were obtained. A drop of 10% in detonation velocity caused increase of the wave parameters by about 100% and it was for the wave height H = 116 μm and the length n = 725 μm. The coefficient of the equivalent melt thickness (RGP) [7, 9], which is the joint quality assessment factor, determining the fraction of the penetrated layer also increase from 0.02 to 10.98.

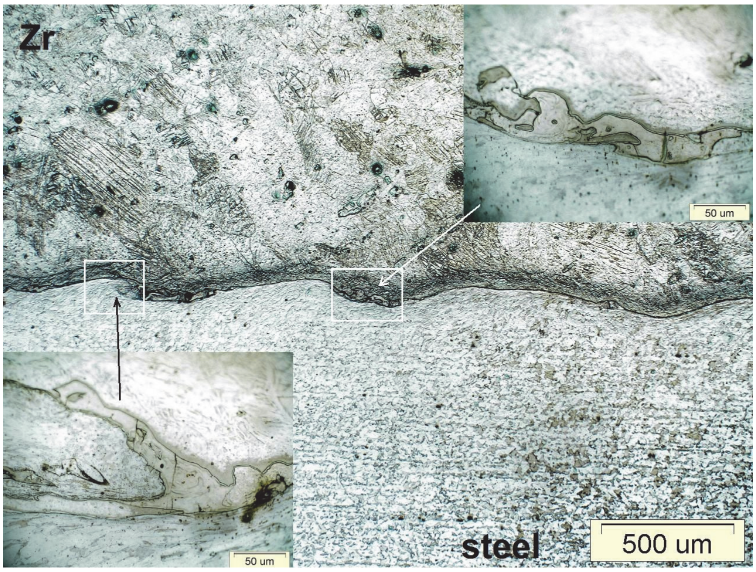

Figure 4: The microstructure of the bimetal joining zone with melted layer - crest of wave.

The Vickers method was chosen to measure microhardness in vicinity of an interface layer. The test was performed using a LECO MH 200 microhardness tester with 50g load on sections parallel to the direction of the detonation wave movement, and the result revealed non-uniform distribution of microhardness values. The highest values of microhardness were measured at the interface layer and range from 571 to 839 $HV_{0.05}$ (Fig. 5), whereas microhardnesses of both materials are much less and is equal to 277 $HV_{0.05}$ for steel and 225 $HV_{0.05}$ for zirconium. The microhardness values of basic materials near the interface layer have also increased compared to the microhardness of these materials prior the joining process (steel 175 $HV_{0.05}$ and zirconium 188 $HV_{0.05}$ [9]).

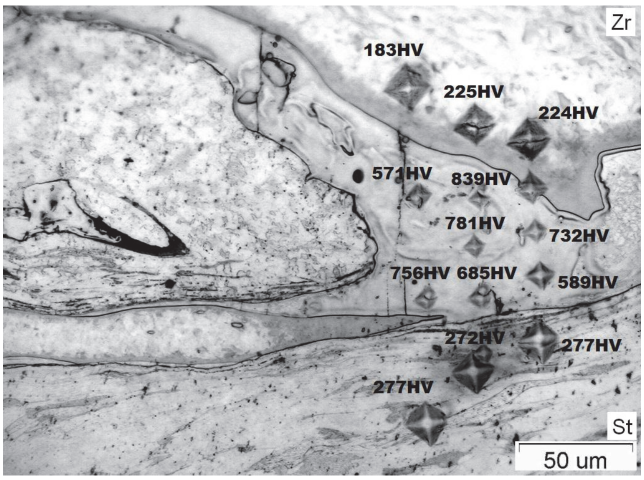

Figure 5: Joint microstructure of the zirconium-steel bimetal together with results of microhardness.

Fatigue test proved much longer fatigue life specimens made with bimetal with melted layer, for example, 2 times longer for amplitude of the bending moment M_a = 14.21 N·m, and about 1.5 for M_a = 12.28 N·m than that of the specimens without melted layer and about 2.6 and 3 times lower than the steel specimens, respectively. Fig. 6 shows graphs of the number of cycles N vs. cracks length a obtained during oscillatory bending.

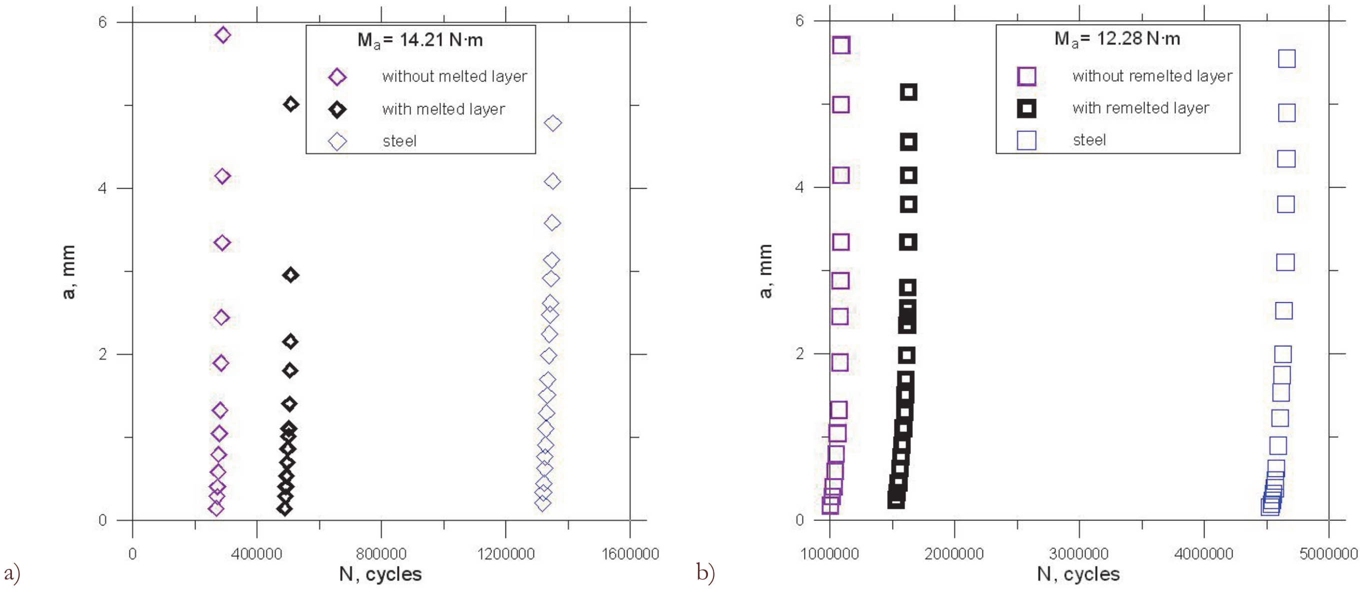

Figure 6: Cracks length vs. number of cycles for amplitude of bending moment: a) 14.21 N·m, b) 12.28 N·m.

Fatigue crack growth initiated in steel and propagated toward zirconium in both cases. Two different interaction mechanisms between a crack and an interface were observed. In case of bimetal without melted layer crack penetrated interface (Fig. 7a) and propagated in zirconium.

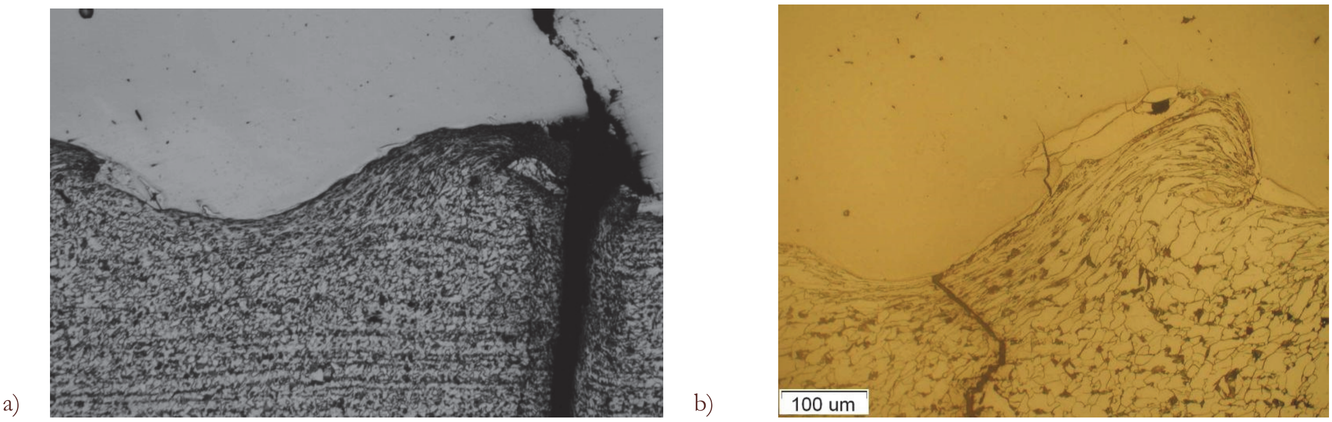

Figure 7: Fatigue crack paths of the in zirconium-steel joint a) without melted layer, b) with melted layer.

Whereas in other case the branching of interfacial crack was observed (Fig. 7b). The crack from the steel side developed in parallel and then kinked in the direction of the interface line and developed in the joint. The crack growth in the interface line to extended the fatigue life.

CONCLUSIONS

The following conclusions have been made on the basis of the obtained results:

- Detonation velocity in the explosive welding process strong influence on interface shape and the microhardness in the vicinity of the joint.
- The melted layer caused increase of the fatigue life and changed the mechanism of crack growth.

- Two different interaction mechanisms between a crack and interface were observed.

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NOMENCLATURE

a	crack length
A_5	elongation
E	Young's modulus
K_t	theoretical stress concentration factor
M_a	amplitude of bending moments
N	number of cycles crack growth
R	load ratio
ν	Poisson's ratio
σ_a	amplitude of nominal stress
σ_u	ultimate tensile stress
σ_y	yield stress