Crack paths in steel-titanium explosive cladding

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ABSTRACT. *The paper presents fatigue crack paths formed during cyclic plane bending of the steel-titanium clad metals obtained as a result of explosive welding. Two kinds of specimens with rectangular cross sections were tested. In the specimens the net thickness ratio of steel and titanium layers was $t_1 : t_2 = 2.5 : 1$ and $1 : 1$. Each specimen had an external notches with a root radius $\rho = 22.5$ mm. In the specimen with the ratio $t_1 : t_2 = 2.5 : 1$ the crack paths were dominating in the steel, and in the case of the ratio $t_1 : t_2 = 1 : 1$ the cracks were initiating and growing in the titanium. Transcrystalline cracks are dominating at the clad metal fractures.*

INTRODUCTION

At present, the materials cladded by means of the explosive method are more often applied in various fields of industry. Application of titanium for constructional steel coating decreases the costs of apparatus requiring high corrosion resistance or temperature resistance. This material is widely applied for construction of processing apparatus in chemical industry, or for heat exchangers in power industry. Tanks of heat exchangers, pressure vessels, electrolytic tanks are other examples. Explosive welding and its parameters are shown in Fig. 1. The thin titanium plate is put on the basic steel plane. The distance between both plates is determined in a special way – the titanium plate must collide with the base plate at a suitable velocity v_P. Parameters of the detonation system must ensure a suitable detonation velocity v_D and a required amount of energy necessary for the sheet joining [1, 2]. The explosive material in form of a granulated product is uniformly distributed on all the titanium sheet surface, and it is limited by the frame placed around the edge of the put on plate. The system is lighted in a suitable point by means of the detonator of high velocity of detonation.

The aim of the paper is to investigate a crack path development under cyclic bending in two-layer cladders.

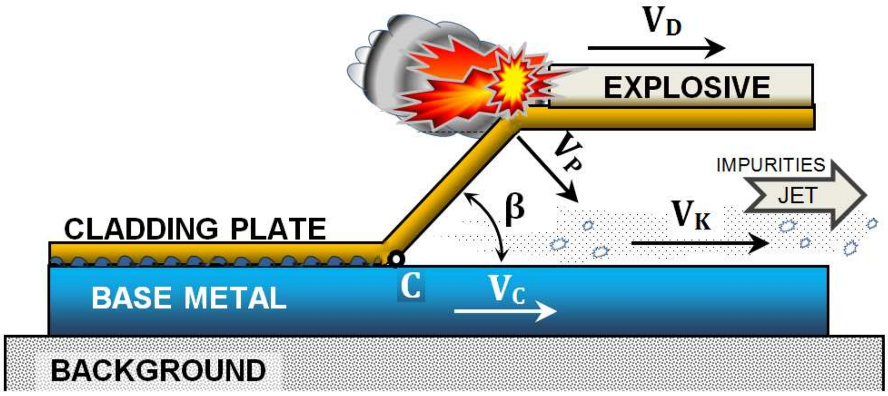

Figure 1. Illustration of explosive welding process and its parameters.

EXPERIMENTS

Specimens with rectangular cross-sections and dimensions: length l = 90 mm, thickness t = 9 mm and width w = 9 mm were tested (see Fig. 2). Those were cut from the sheet with a thickness of 46 mm parallel to the propagation of detonation and prepared in accordance with ASTM D 3165-95. Each specimen had an external notches with a root radius ρ = 22.5 mm. The specimen surface have been obtained by milling followed using conventional polishing with progressively finer emery papers. A final average roughness 0.16 µm has been measured. Two kinds of specimens were tested, where the net ratio of steel height to titanium thickness was $t_1 : t_2 = 2.5 : 1$ and 1 : 1. Some mechanical properties of the tested steel are given in Table 1.

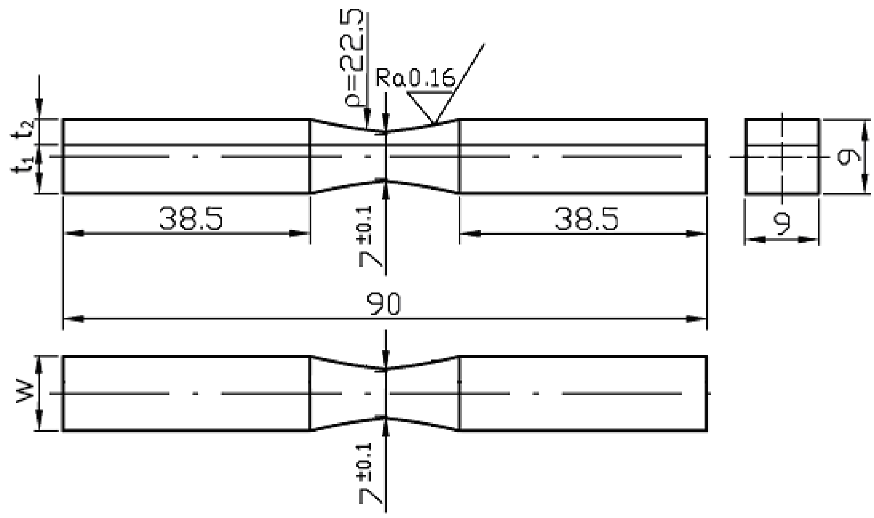

Figure 2. Specimen for tests of fatigue crack growth, dimensions in mm.

Table 1. Mechanical properties of materials before cladding

Materials	Yield stress σ_{YS} (MPa)	Ultimate stress σ_U (MPa)	Elastic modulus E (GPa)
Ti Gr.1	193	308	104
S355J2+N	368	578	210

The cyclic properties for joining of steel-titanium were obtained from the tests done at the laboratory of Opole University of Technology, Poland. The tests were performed on the fatigue test stand MZGS – 100 (Fig. 3) [3]. This machine allows to perform cyclic bending with torsion. The tests were conducted under controlled force (in the considered case, the amplitude of bending moment was controlled) with frequency 29.3 Hz. The theoretical stress concentration factor in the specimen under bending $K_t = 1.045$ was estimated with use of the model presented in paper [4]. The bending moment was generated by force on the arm 0.2 m in length. The shear stress at a fatigue test stand MZGS – 100 coming from bending takes very small values, below 2% of the maximum applied bending stress. 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 moment $M_a = 14.2$ N·m, which corresponded to the nominal amplitude of normal stress $\sigma_{a(steel)} = 314.3$ MPa and $\sigma_{a(Ti)} = 198.2$ MPa (for $t_1 : t_2 = 2.5 : 1$), and $\sigma_{a(steel)} = 299.2$ MPa and $\sigma_{a(Ti)} = 208.4$ MPa (for $t_1 : t_2 = 1 : 1$) for the net section before crack initiation.

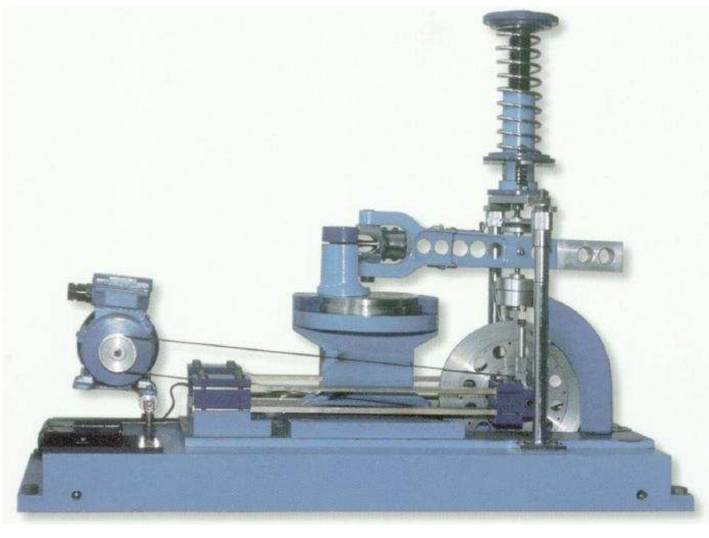

Figure 3. The MZGS-100 fatigue stand.

Fatigue crack growth on the specimen surface was observed with the optical method. The fatigue crack increments were measured with the micrometer located in the portable microscope with magnification of 20 times and accuracy up to 0.01 mm. At the same time, a number of loading cycles N was recorded.

THE TEST RESULTS AND THEIR ANALYSIS

Fig. 4 presents a cross section of two joined sheets (magnified 50x) where the titanium structure is at the top, and the steel structure is at the bottom. The joint has a characteristic wavy structure with a small number of remelted areas, microcracks and microvoids. In a consequence of calculations of position of the neutral axis, it can be found that for the ratio of the specimen thickness $t_1 : t_2 = 2.5 : 1$, the axis occurs in the steel at the distance 3.08 mm from the base (Fig. 2). For the ratio $t_1 : t_2 = 1 : 1$, the neutral axis occurs in the steel at the distance 2.91 mm.

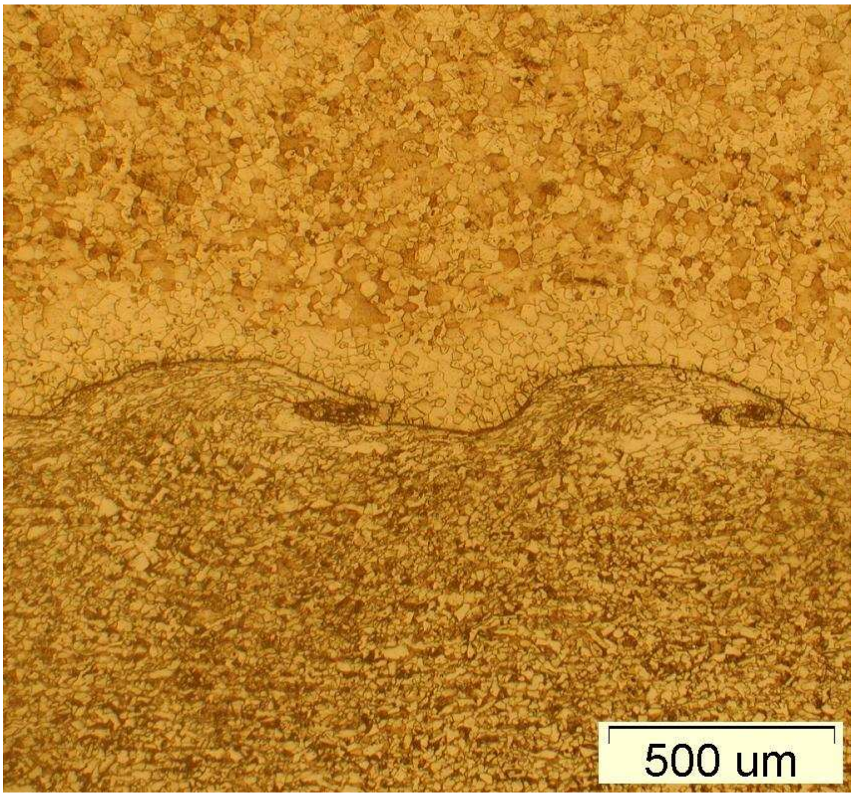

Figure 4. The zone of titanium-steel clad joints.

In the specimens, the crack increase was uniform at both sides of lateral surfaces [5]. In two kinds of specimens crack lengths in the initial period are measured as the growth of particular cracks for mode I as far as the interface line. Next, the crack increased along the interface line, or directly crossed the interface line increasing in the other material of the composite (Fig. 5a). The crack along the interface line (mode II) developed for some time, and next it went into the other material (see Fig. 5b).

(a) (b)

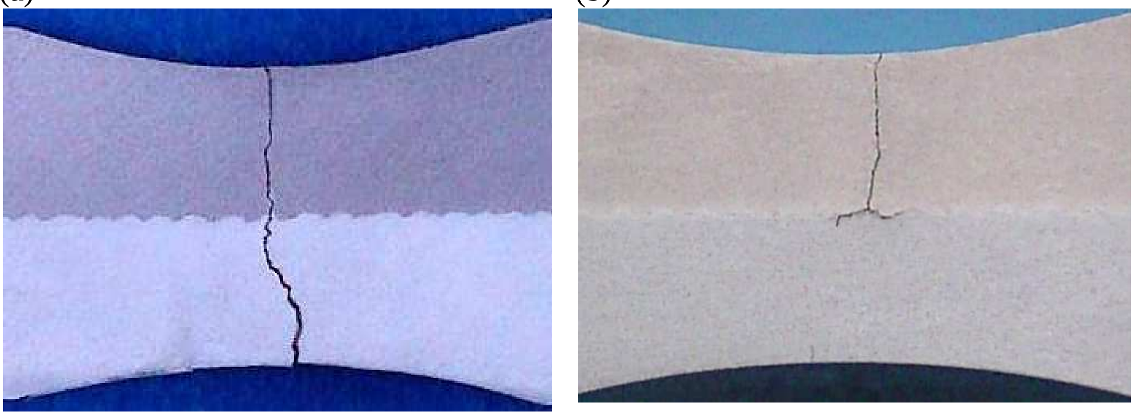

Figure 5. The fatigue crack path for ratio $t_1 : t_2 = 1 : 1$: (a) crossing interface line, (b) path increase along the interface line.

Fig. 6a shows an exemplary surface of the composite specimens with the ratio $t_1 : t_2 = 2.5 : 1$. Fig. 6a allows to observe the fatigue crack growth from the steel side. The main crack developed on the planes of the maximum normal stresses. From the Fig. 6b it appears that the situation is inverse for $t_1 : t_2 = 1 : 1$. Initiation and fatigue crack growth in the composite usually proceeded from the titanium side, although there were some cases of crack growth from the steel side. The course of crack growth was similar as in the case of specimens with $t_1 : t_2 = 2.5 : 1$.

(a) (b)

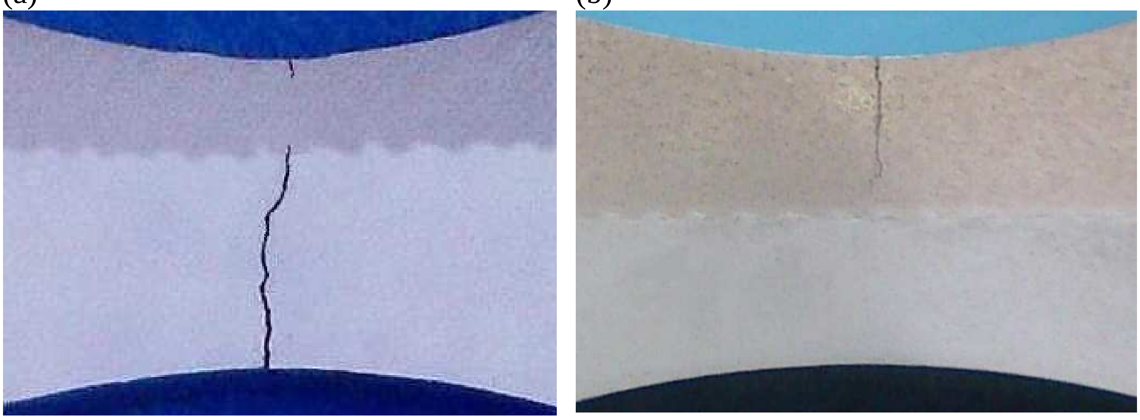

Figure 6. Crack path in titanium-steel joint for): a) $t_1 : t_2 = 2.5 : 1$, b) $t_1 : t_2 = 1 : 1$.

In structure of the S355J2+N steel we can see visible transcrystalline microcracks in grains of ferrite and pearlite in the axial section of the specimen. At the fractures in titanium Gr.1 transcrystalline cracks through grains of the phase α were dominating but cracking along the grain boundaries was also observed.

Different kinds of the metallographic network of both materials and bonds between the atoms in the solid material or the joint can be a reason of such behaviour. In the points where the bonds are weaker, the crack growth can be seen. The main cracks propagated in the direction parallel to the loading action and they did not include secondary cracks. The crack shown in Fig. 7 developed in the plane of the highest normal stresses in the steel and passed into titanium. The crack developing in the steel reached the interface line, and next it was running along that line (in parallel to the specimen length) in two directions. Next, the crack passed from the interface line and developed in titanium from two sides. The crack growth in titanium is similar to propagation in the steel. In the steel there is one main crack developing in a transcrystalline way with visible separations along the grain boundaries. In titanium two cracks developing in a transcrystalline way through grains of the phase α with visible separations along the grain boundaries can be observed. The separation is especially visible at the left side of the propagating crack in titanium, where at the half of the crack length an additional crack is developing; this additional crack deviates along the grain boundaries to the left.

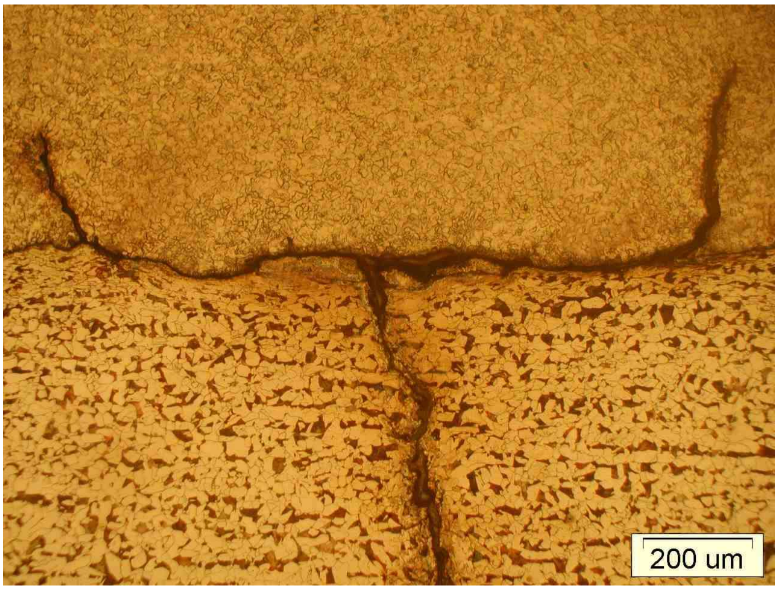

Figure 7. Crack path in titanium-steel joint for $t_1 : t_2 = 2.5 : 1$.

CONCLUSIONS

The presented results of the fatigue crack growth in the specimens subjected to bending loading allow to formulate the following conclusions:

1. For the specimen height ratio $t_1 : t_2 = 2.5 : 1$ initiation and fatigue cracks growth were observed mainly in the steel. In the case of $t_1 : t_2 = 1 : 1$ the cracks growth proceeded in titanium.
2. Crack growth in the clad proceeded through the cross section of the specimen and in the interface line of the bimetal.
3. In both steel and titanium transcrystalline cracks are dominating, but cracks along the grain boundaries are also observed.

Acknowledgements

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