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Crack growth rate under cyclic bending in the explosively welded steel/titanium bimetals

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ABSTRACT

The paper presents the results of the tests on fatigue crack growth in a steel/titanium composite under oscillatory bending. Two kinds of specimens of rectangular cross sections were tested. In the tested specimens, the ratio of heights of basic and overlaid materials was h_1:h_2 = 2.5:1 and 1:1. In the specimens, the fatigue crack growth was parallel to the applied loading and its direction changed at the interface line. Next, the crack growth along the interface line or the crack growth passing through the interface line were observed. When the crack growth passed along the interface line, decrease of the crack growth rate took place. The specimens have the uniform crack growth at both sides of lateral surfaces. At the composite fractures in the steel and titanium, transcrystalline cracks are dominating.

1. Introduction

The cladders obtained by explosive welding are composite materials composed of two or more different metals permanently joined with use of energy of detonation of the explosive material [1]. The explosion welding process proceeds with high velocities under very high pressures [2–4]. Generation of cladders allows to obtain the required properties, such as corrosion resistance, increased hardness, resistance to high temperature, suitable frictional properties or special electrical properties. Application of cladding technologies allows to reduce material costs. Practical properties of the cladder are evaluated according to resistance of the applied layer and they are the same as properties of the homogeneous (monolithic) material. A cheaper material is usually applied as the base material. Depending on a cladder type and its assignment, thickness of the laid layers can vary from 1.5% to 15% of the base thickness – in practice such layers have some or several mm. Explosive welding is usually applied for metal sheet cladding [5]. The explosive welding process and its parameters are shown in Fig. 1. The thinner titanium plate h_2 is bonded on the parallel steel base plate located at a certain distance H_1 over the basic plate. The distance is selected to assure that the titanium plate collides with the base plate after acceleration to suitable collision velocity v_P. The distance H_1 is maintained by support spacers which cannot disturb the plate bonding. Parameters of the detonation system are selected to assure the suitable detonation rate v_D and obtain the required amount of energy necessary for plate bonding. The explosive being a granulated product is uniformly distributed on all the titanium plate surface at the height H_2 and it is limited by the containment frame placed around the edges of the cladding metal plate. This system is ignited at a predetermined point with a detonator of high velocity rate. The detonation front moves from the initiation point through all the plate surface to its edge, and lines of the detonation front form circles. The gas expansion of the explosive detonation accelerates the cladding plate at the interval of H_1 and results in an angular collision β at the collision velocity v_P. In the collision point C very high pressure is generated, it causes that the bonded sheets are pressed down. Any oxides and other impurities are removed from these surfaces by the air stream ejected from among the bonded plates with the subsonic speed v_K. In the collision point C, metallically pure surfaces are pressed down by pressure of the order of some GPa, and in a consequence we obtain a high-quality steel-to-titanium joint without material remelting. Suitable collision parameters for the given connection are dependent on types of the joined metals, their thickness and mechanical properties. Selection of proper collision parameters influences quality of the obtained joint. Collision parameters and relation between them are expressed by the following equation [6]:

$$v_P = 2v_C \sin(\beta/2). \quad (1)$$

If the joined plates are parallel, the collision velocity v_C is equal to the detonation velocity v_D. The detonation velocity v_D is dependent on the joined metals and equals from 2000 to 3500 m/s. The impact angle β is a dependent variable and it results from the detonation velocity v_D and the distance between the sheets. This angle is included in the range from 5° to 25°. The velocity v_C in the collision is usually from 250 to 500 m/s and it is dependent on the joined materials, their physical and mechanical properties and

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Nomenclature

a	crack length (m)
A	area of melted surface (m^2)
A_5	elongation (%)
da/dN	fatigue crack growth rate (m/cycle)
E	Young's modulus (GPa)
E_k	explosion energy (J)
g	specimen thickness (m)
h	specimen height (m)
h_0	amplitude range (m)
h_1	steel height (m)
h_2	titanium height (m)
h_i	layer height (m)
H_1	standoff distance (m)
H_2	explosive height (m)
K_t	theoretical stress concentration factor
l	specimen length (m)
L	interface line length (m)
M_a	amplitude of the loading moment (N m)
M_{max}	maximum amplitude (N m)
M_{min}	minimum amplitude (N m)
N	number of cycles (cycles)
N_f	number of cycles to failure (cycles)
R	stress ratio
v_C	collision velocity (m/s)
v_D	detonation velocity (m/s)
v_K	jet velocity (m/s)
v_P	plate collision velocity (m/s)
ΔK	stress intensity factor range (MPa $m^{1/2}$)
$\Delta\sigma$	stress range (MPa)
β	impact angle (°)
λ	wave length (m)
σ_y	yield stress (MPa)
σ_u	ultimate stress (MPa)
ρ	notch tip radius (m)
ξ	neutral axis

Abbreviations

ND	normal direction
RD	rolling direction
RGP	coefficient of equivalent thickness melted
SIF	stress intensity factor

Subscripts and others

a	amplitude
f	failure
i (i = 1, 2, 3)	individual components in composite
max	maximum value
min	minimum value
Δ	range

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 H_1 is chosen for a given detonation velocity in order to obtain the required collision velocity. The mentioned parameters are calculated separately for each system. Thickness of the overlaid material and mechanical properties of both joined materials are critical elements in the calculations. Amount of the explosive material (kg/m^2) is a function of explosion energy E_k and the coefficient R_0 dependent on physical and mechanical properties of metals. The coefficient R_0 determines the weight ratio of the explosive material and the overlaid material. The collision velocity is expressed by the following function [7].

$$v_P = f(E_k, R_0). \tag{2}$$

The distance and the above parameters of the system determine velocity of the overlaid plate in the collision point C.

In such a generated cladder, namely in its cross section we can distinguish an area hardened by force of the joined sheet collision, and the zone of the joint (see Fig. 2). It is assumed that a correct joint should be characterized by structure of a certain waviness and a suitable amplitude range h_0 and a wave length λ, without or with a small number of melted areas A and discontinuous areas (microvoids, microcracks). If the selected welding parameters are not correct, large melted areas can occur in the joint, and they influence strength of all the cladder [5,8]. The ratio of an area of the melted surface A to the interface line length L is determined by the coefficient of the equivalent thickness melted (RGP), and its value should not exceed 10.

$$\mathrm{RGP} = \frac{A}{L}. \tag{3}$$

From the previous tests it results that the cladded joint is subjected to hardening at all the joint section (Fig. 2) [8], and properties of the made cladder differ from properties of the applied materials.

The cladders made in such a way can be used for production of many advanced structures, such as columns of chemical reactors,

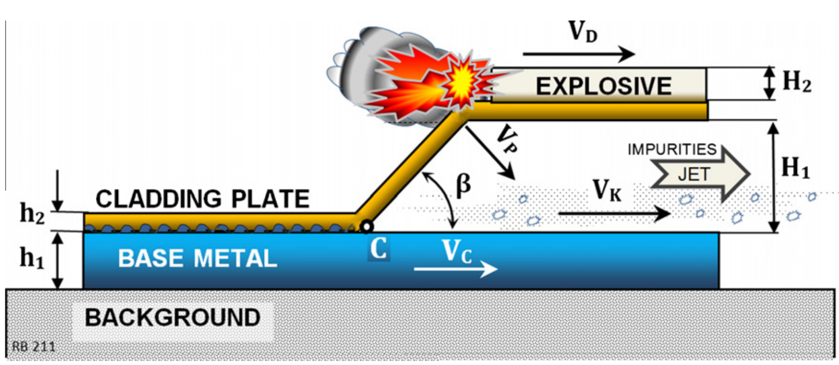

Fig. 1. Explosive welding process and its parameters.