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Testing of explosive welding and welded joints. The microstructure of explosive welded joints and their mechanical properties

Bogumił Wronka

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Abstract The present essential models and some theories were applied to explain the wavy phenomenon, microstructure and mechanical properties of the characteristic joint area. Two phenomena occurring in the plate collision zone during welding were carefully tested. These phenomena were connected with forming the wavy joint surface and the interpass. The available data referring to forming the interpass were further developed.

Introduction

The products of the explosive welding technology are effectively functioning in the power industry, petrochemical industry and the electrical industry. The companies which produce clad plates are among others the NOBELCLAD in France and the Polish firm EXPLOMET.

In this paper was presented the explosive welding with participation of two phenomena in the collision area. Those phenomena referred to mechanical forming the wavy joint surface and the interpass.

To describe forming the joining waves, the essential models and some theories were applied. Some of those theories also included acoustic waves. Conditions and the course of forming the interpass were carefully analysed. The presence of the interpass microstructure was connected with the joint strength. Explosive welded joints were tested in respect of material microstructure in joint area and mechanical properties. For this wave joints in initial state, i.e. without heat treatment were used.

The good knowledge of presented phenomena, microstructures and mechanical properties leads to final improvement of the welded joints quality and the final products as well.

B. Wronka (✉)
Faculty of Civil Engineering, Mechanics and Petrochemistry, Institute of Mechanical Engineering, Warsaw University of Technology, ul. Lukasiewicza 17, 09-400 Plock, Poland
e-mail: wronkab@pw.plock.pl

Stages of welding process

The basic facts about such a welding process can be found in Refs. [1–5]. The typical course of welding is shown in Fig. 1. In the plate collision zone occurs the pressure impulse within the range of a dozen or so GPa. This process consists of the loading and unloading stage. During a loading process occurs the wavy joint surface and the interpass. The results of unloading are wavy tensile stresses in the plate material and in the joint as well.

The both stages influence configuration of joint area. The joint area in the wave joint consists of wave joint surface, interpass and adjoining strain layers of bonded materials. For the joints in initial state those layers are strengthened.

Forming of joint waves

The basic condition of getting the joint is creating the plastic zone in the collision area of welded materials [5]. In this zone are formed joint waves whose courses were modelled. Coordinated model groups refer to: pressure changes [4], penetration with a jet [4, 6], instability of a flow [7] and a flow around the roadblock [8]. Let us consider the first two useful groups and add some supplements to them in order to know this phenomenon much better.

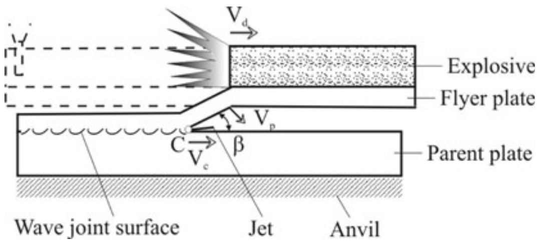

Fig. 1 The course of the welding process at the skew collision of plates: V_p is the flyer plate velocity, C is the collision point, V_C is the collision point velocity, V_d is the detonation velocity and β is the collision angle

The joint waves describe the acoustic waves in accordance with the harmonic movement [5]. Such a process course results from the periodic change of collision pressure p

$$p = A\sin\left[kc_0\sqrt{1 - V_C^2/c_0^2}\,t + \frac{kV_C(x - x_0)}{c_0\sqrt{1 - V_C^2/c_0^2}}\right] \times Z_\nu(kr)\sin(\nu\theta + \alpha); \quad (1)$$

$$tg\theta = \frac{y\sqrt{1 - V_C^2/c_0^2}}{x - x_0}; \quad r = \left[\frac{(x - x_0)^2}{\sqrt{1 - V_C^2/c_0^2}} + y^2\right]^{1/2}$$

where A is the pressure amplitude, Z_ν is Bessel's function of order ν, α and k are unspecified constants, x_0 is the beginning of the coordinate system x, y in which the collision point is included, t is time and c_0 is the mean sound velocity in welded materials.

Stress waves reflected from the free plate surfaces do not interfere with the incident wave in the collision point C, because $V_C < c_0$ [4].

The oscillator of harmonic vibrations around the point C is the collision area with the radius R [9]

$$R = \frac{2}{\pi}\sqrt{1 - V_C^2/c_0^2}\,\frac{2g_1g_2}{g_1 + g_2}\sin^2\frac{\beta}{2} \quad (2)$$

Those vibrations have their own frequency ν and the period T

$$\nu \cong c_0R; \quad T \cong 2\pi/c_0R \quad (3)$$

The acoustic waves were applied to describe periodicity of the joint wave λ [10, 11].

$$\lambda = 0.5A\left\{g_1\sin^2[0.5\beta - \arcsin m] + g_2\sin^2[\arcsin m]\right\} \times \left\{\left[1 - \left(\frac{V_C}{c_1}\right)^2\right] + \left[1 - \left(\frac{V_C}{c_2}\right)^2\right]\right\} \quad (4)$$

$$m = \frac{z_2(z_1 - z_3)\rho_1g_1V_p}{2z_1(z_2 + z_3)(\rho_1g_1 + \rho_2g_2)V_C} \quad (5)$$

where A is constant; z_1, z_2, z_3 are acoustic impedances of the flyer plate material, parent plate material and the anvil; ρ_1, ρ_2, g_1, g_2, c_1, c_2 are accordingly densities, thicknesses and velocities of acoustic waves in the material of the flyer plate and the parent plate.

It also exists the simplified relationship for the wave length in the welded joint [5]

$$\lambda = 26g_1\sin^2\frac{\beta}{2} \quad (6)$$

The acoustic unloading wave in the flyer plate is an additional impulse to cause the joint waves [5]. That is why waving starts in the distance l from the initial collision point

$$l = 2g_1\frac{V_C}{c_0}\left(1 - \frac{V_C^2}{c_o^2}\right)^{1/2} \quad (7)$$

In the collision area occur pressures above which metals behave as viscid and inviscid liquids [4]. It refers to zones which together with the pressure gradient cause periodicity of waves, their asymmetry and the vortexes.

Waviness of the joint results from the periodic change of angle β and velocity V_C [4, 5]

$$V_C = \frac{V_p}{\sin\beta} \quad (8)$$

The angle change results from the periodic outflow of the material of the plastic zone and it is caused by penetration of the flyer plate into the parent plate [7].

The evaluation of this structure and material properties under the influence of dynamic loads was presented in Ref. [12].

The interpass in wavy joints

The interpass results from the jet (Fig. 1) removing oxides and pollutants from the welded joints. The welded joints can be achieved also without the jet. In the wavy joints acts the mass jet instead of the continuous jet close to the cumulative jet. It is the jet of separate, dispersion particles coming from the surface layers of welded plates [5]. The mechanism of forming these two jets is the same. Increase of velocity V_C results in increasing velocity of a cumulative jet V_k. Here it is convergence of thickness changes of the interpass and the cumulative jet and at the same time the mass jet.

The periodic outflow of the plastic zone material forms the wave convex top. It overtakes the collision point C and basically consists of the parent plate material. In accordance with Eq. 8 at V_p = const., the minimal angle β produces the temporary maximum velocity V_C. At that time the jet reaches the maximum thickness and velocity V_k. The larger part of this jet jumps out of the recess beyond the wave top. Thus, the front vortex is created, but the back vortex is left at the opposite top side. Only the larger velocities V_C create chances of existing both vortexes. Intensity of vortexes λ_w is formulated with a function graph of the same type like the wave length λ in Eq. 6, i.e.

$$\lambda_w = 21 g_1 \sin^2 \frac{\beta}{2} \quad (9)$$

The front and back vortex in range of intensity are nearer than the adjacent wave tops. That is why in accordance with (9) the result of coefficient value is 21, then $\lambda_w < \lambda$.

Let us show better physical vortex mechanism against a background of the interpass. The description of forming the vortex zones is based on the analogy with behaviour of liquid particles. In particles of swirled liquid the core as the central part of this vortex rotates with the constant angular velocity ω. Linear velocities of particles v_i, v_o inside and outside the core equal to $v_i = \omega\, r$ and $v_o = K/r$ (Fig. 2).

The jet forming the vortex consists of material particles of various sizes. The impulse collision time of several microseconds allows to accept the same and constant velocity ω for each particle. Within the range $R \geq r > 0$ the centrifugal force W acts on the particle with a mass m

$$W = m\omega^2 r \quad (10)$$

If $W =$ const., then for the free vortex increase of m decreases r and vice versa. In welding conditions the vortex is limited by particles friction against both plates material. Thus, particles of various sizes have in general accidental distribution in the interpass (Fig. 3c).

For $V_C = V_f$ in spite of the jet existence occur wave joints without any interpass (Fig. 3a). Then the thin jet is removed outside. At the little greater velocities V_C exist small sections of the interpass from the back vortex (Fig. 3b). The further increase V_C starts up both vortexes which form the interpass on both sides of the wave top (Fig. 3c). The large steel inclusions and the fine-grained matrix come from the mass jet.

At velocities $V_C \rightarrow c_o$ occurs the continuous interpass dividing both welded materials (Fig. 4). The back part of the vortex levels the steel wave top. It is the case close to forming the flat joint with the continuous interpass.

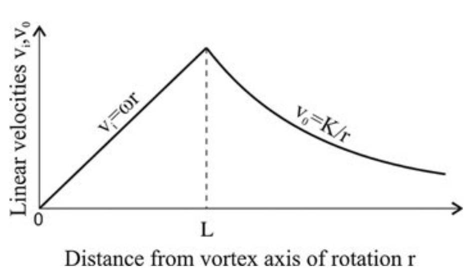

Fig. 2 Linear velocities v_i, v_o in the distance function r from the core axis: L is the core radius and K is the vortex intensity

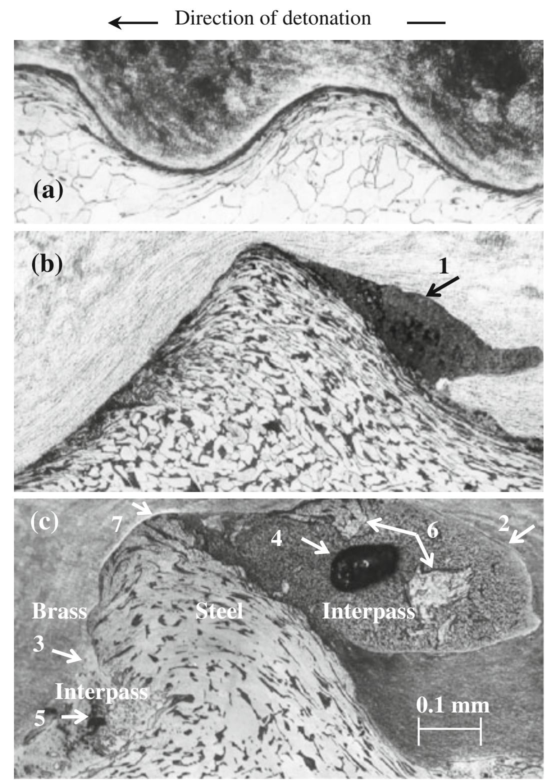

Fig. 3 Carbon steel–brass wavy welded joints, obtained at various velocities V_C: without the interpass at $V_C = V_f$ (**a**); with the section of the interpass 1 from the back vortex at $V_C > V_f$ (**b**); with sections of the interpass *2*, *3* from the back and front vortex at $V_C \gg V_f$ (**c**); the single circular blowhole *4* and oval one *5*, large inclusions of non melted steel *6* and wavy inclined top *7* with elongated grains of ferrite and pearlite in steel after plasic strain

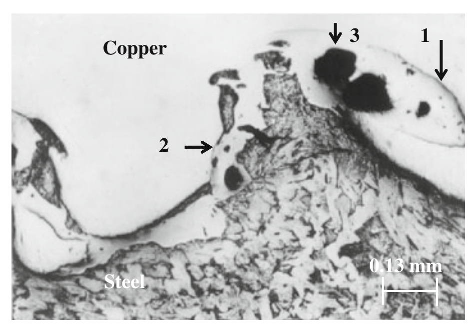

Fig. 4 Carbon steel–copper wavy welded joint obtained at great velocities V_C: the continuous interpass from the back vortex *1* and the front vortex *2* and blowholes *3* of various sizes

Separate sections of the interpass meet the welded materials, which have the role of chills. These conditions do not favour forming of contraction cavities and porosities which come from the casting. When the temperature increases, dissolved gases on the surface and in the interpass grains are emitted. In the time of welding process it is possible to intercept and trap the external air by the vortex. That is why the spherical or oval voids of the small surface

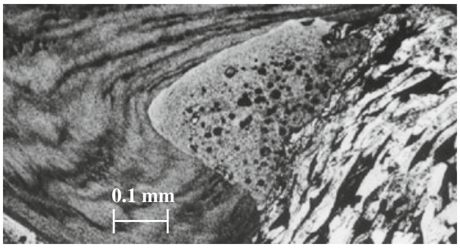

Fig. 5 Carbon steel–brass wavy welded joint with groups of blowholes in the interpass

roughness are blowholes. The variations of single blowholes and their groups are presented in Figs. 3c, 4 and 5.

Microstructure and mechanical properties of welded joints

Actions of both phenomena in the collision area decide about the specified microstructure and mechanical properties of welded joints. The wave length λ stands for the measure of the material plasticity in the collision area and determines the joint strength. At V_C and $\beta = \text{const.}$, the plastic zone can be changed with the thickness of parent plate g_2 [11].

Mechanical properties represented by peel strength $\sigma 1$ and shear strength $\sigma 2$ for initial joints are the increasing functions of thickness g_2 and at the same time the wave length λ in the joint (Fig. 6). Test results referred to wave joints without interpass or with minimal quantity of it (Fig. 3a, b). The increase of joint strength is caused by the increase of material strain hardening which is the result of

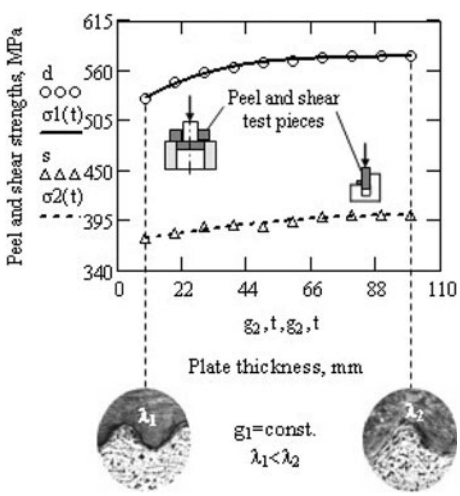

Fig. 6 Relationship between strengths $\sigma 1$, $\sigma 2$ and the wave length λ created by the change of parent plate thickness g_2 for carbon steel–brass wavy joints: $\sigma 1$ is peel strength and $\sigma 2$ is shear strength; t is a program step (1×10^{-3})

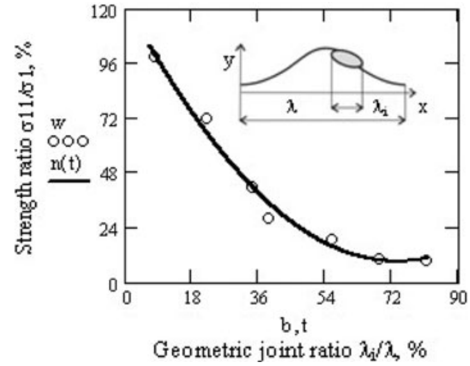

Fig. 7 Relationship between strength ratio $\sigma 11/\sigma 1$ and geometric one λ_i/λ for carbon steel–brass wavy joints: $\sigma 11$ is the peel strength for joints with sections of the interpass λ_i and $\sigma 1$ is the peel strength for joints without interpass

plastic strain and sometimes a phase change in the joint area. The shearing test was conducted in accordance with General Specification NC 501, ASME SA 264.

Peel strength $\sigma 11$ for interpass joints with different length λ_i and peel strength $\sigma 1$ for joints without interpass were tested too. Longer sections of the interpass λ_i occurring at wave lengths λ (Figs. 3c, 4) decrease the joint strength. This is testified by functional course of ratios $\sigma 11/\sigma 1 = f\ (\lambda_i/\lambda)$ showed in Fig. 7. The less joint strength results from negative properties of the interpass and is caused by unfavourable structure with a big heterogeneity, discontinuity (Figs. 3c, 4) and frequent brittleness.

Conclusions

Analysis of test results facilitated presentation of these conclusions.

- Joint waves and the interpass occur in the collision zone as two combined phenomena.
- Acoustic waves model the course of joint waves in the form of periodic pressure change. This phenomenon confirms the model of wave periodicity caused by changes of velocity V_C and angle β.
- Acoustic waves initiate joint waves too and are used to describe the wave length λ which detects thickness of welded joints and the anvil.
- Together with waviness forms the interpass in places of vortex zones. At the angle $\beta = \text{const.}$, the amount of the interpass and its distribution depends on velocity V_C.
- The vortex zones are developed by the mass jet, i.e. the jet of dispersing particles coming from surface layers of welded plates. The particles of various sizes have in general accidental distribution in the interpass.
- The formed spherical and oval voids in the interpass are blowholes and not comes from the casting. They are

made by emitted gases during shaping the interpass and intercepted and next trapped external air by vortex.

- Effects of both phenomena in the form of adequate joint wave length and the amount of the interpass have influence on mechanical properties of welded joints.
- The peel strength and shear strength for initial joints without interpass are the increasing functions of the wave length λ in the joint. Strength increase is caused by the increase material strain hardening in the joint area of welded joints.
- The wave joints with interpass have less strength. Unfavourable structure with a big heterogeneity, discontinuity and frequent brittleness is the cause of that state.

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