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Energy balance during explosive welding

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ABSTRACT

The determination of the energy balance in explosive welding is an important scientific task because information on the itemized expenditure of the energy given off during an explosion makes it possible to manage energy release items and, consequently, to effectively control the structure and properties of the composite materials produced. In the general case, the energy liberated during an explosion is used for the interaction of welded plates: it is spent on the acceleration of the flyer plate and is also wasted on the dispersion of explosion products. A calorimetric method was used to determine the portion of the energy transferred to the flyer plate by detonation products. It was determined that the amount of energy does not exceed 1% of the total energy of the explosion. It was also shown that during the collision of explosively welded plates, a portion of the kinetic energy of the flyer plate transforms into other types of energy and is also released as heat; this energy was measured using the calorimetric method. The heat is given off in the weld joint area as a result of the shock wave action, which crushes the microrelief of the welded surfaces, plastically deforms the metal in the collision area (shear and wave formation) and leads to dissipative losses throughout the metal body of the welded plates. A method is proposed to determine energy losses occurring in the system of colliding plates. This method is based on laminated models and makes it possible to determine a quantitative relation between energy losses on the jet, on the one hand, and the kinematic parameters of explosive welding, on the other. The contribution of explosive welding parameters to the amount of energy spent on the plastic deformation of metal in the collision zone is analysed. The results obtained make it possible to evaluate the explosive welding efficiency required for explosive welding: the efficiency is determined by the specific energy of an explosive converted to the energy spent on the plastic deformation of metal in the weld joint zone. It is shown that the efficiency varies from 0.5 to 3%, depending on the welding regime.

1. Introduction

In explosive welding, metals are joined as a result of deformation processes that occur due to high pressure in the collision point area. The time interval of these processes is very short ($\sim 10^{-6}$ s); as a result, diffusion processes in the contact zone of the metals do not develop, and the bonding is formed in the solid phase. This feature of explosive welding makes it possible to use the process for manufacturing metallic laminated composites of dissimilar metals and alloys. The resulting composites possess high strength and are used in numerous applications.

In explosive welding, the schematic of which is well known, metal plates are placed parallel to each other with a stand-off between them. An explosive charge is placed on the top of the flyer plate and set off with a detonator. The detonation front travels along the charge at speed D (detonation velocity). The high pressure of the detonation expansion products accelerates the flyer plate to velocity V_i (impact velocity in the vertical direction) on the order of several hundred meters per second, and the flyer plate collides with the base plate at angle γ (collision angle). The apex of the angle (collision point or line) travels along the base plate at the collision velocity V_c (horizontal collision point velocity) in the direction of the detonation. Around the collision line, metal bonding conditions develop, and a jet is formed ahead of the collision point. The jet results in the break-up and effacement of the plate surfaces where the metal is intensively deformed, and a deformation asperity is formed. The deformation asperity travels at a great velocity to the surface of the opposite plate and forces another asperity away from the plate. Sometimes this process results in wave formation in the interface. Beyond the collision point, the deformation process continues for some time, thus increasing the amount of plastically deformed metal and the sizes of the waves, if they have been generated.

The power source of explosive welding is an explosive; the energy, W_E, released during an explosion participates in the process of the interaction of the welded plates (W_p), including the

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acceleration of the flyer plate (W_0). Part of the released energy W_E is wasted on the dispersion of explosive fragments (W_d), and part is used to form a weld joint.

Hakamoto et al. (1993) suggested the following formula to evaluate the loss of the kinetic energy, ΔKE, stored by the flyer plate during explosive welding:

$$\Delta\mathrm{KE} = \frac{m_D m_C V_p^2}{2(m_D + m_C)} \tag{1}$$

where (using the authors' designations) m_D and m_C are specific masses of the colliding plates and V_p is the impact velocity.

Manikandana et al. (2008) showed that ΔKE is an important explosive welding parameter and that it influences the quality of welded joints, in particular, the sizes of the waves formed in the bonding area. Researchers have not specified how the portion of the kinetic energy that is lost in the system of welded plates after the plate collision is spent.

However, Petushkov et al. (1995), in an earlier paper, hypothesized that the difference between the flyer plate kinetic energy W_0 and the energy W_1 (kinetic energy of the composite plate) spent on the explosively welded composite is also spent on metal plastic deformation in the collision point zone (W_2) and on jet formation (W_3). They wrote down the energy balance in the following form:

$$W_0 = W_1 + W_2 + W_3 \tag{2}$$

where

$$W_0 = \frac{m_1 V_i^2}{2}, \tag{3}$$

$$W_1 = \frac{m_1^2 V_i^2}{2(m_1 + m_2)}, \tag{4}$$

$$W_2 = \frac{m_1 m_2}{2(m_1 + m_2)} V_i^2 \left[1 - \left(\frac{V_c}{c_0}\right)^2\right], \tag{5}$$

$$W_3 = W_2 \frac{V_c^2}{c_0^2 - V_c^2} = \frac{m_1 m_2}{2(m_1 + m_2)} V_i^2 \left(\frac{V_c}{c_0}\right)^2 \tag{6}$$

m_1 and m_2 are the specific masses of the flyer and base plates, respectively, and c_0 is the sonic speed in metal.

The aim of the present paper is to calculate a complete energy balance of the explosive welding process to improve control over the properties of the resulting weld joints.

Based on the collision kinematics and physical nature of the process under study, the expenditure of explosive detonation product energy W_E can be expressed in a complete form as follows:

$$W_E = W_p + W_d = (W_h + W_b + W_{dE}) + W_1 + \left(W_{2c} + W_{2p} + W_{2d}\right) + (W_{3k} + W_{3t}) + W_d, \tag{7}$$

where W_p represents the energy losses in the system of the welded plates; W_d is the energy wasted on the dispersion of explosive detonation fragments; W_h is the energy lost by heating the flyer plate via detonation products; W_b is the energy spent on plate double plastic bending; W_{dE} represents dissipative losses in the plate after the detonation product impact; W_1 is the residual kinetic energy in the system of the welded plates; W_{2c} is the energy spent crushing the microrelief of colliding surfaces; W_{2p} is the energy spent on metal plastic deformation in the collision zone (wave formation and shear); W_{2d} is the energy spent on dissipative losses in the shock wave accompanying the collision; and W_{3k} and W_{3t} are, respectively, the kinetic and thermal components of the jet energy.

Analytic and experimental methods were used to estimate the energy balance in the system of two explosively welded colliding plates.

2. The energy transferred by explosive detonation products

The input energy W_E can be calculated as the complete ideal work of an explosion using the following equation, which was suggested by Baum et al. (1959) and which relates this work to the specific heat of the explosion and the pressure in the detonation wave front:

$$W_E = Q\left[1 - \left(\frac{p_0}{p_H}\right)^{(k-1)/k}\right] \tag{8}$$

where Q is the specific explosion heat (calculated per 1 kg of explosive); p_0 and p_H are the initial (equal to atmospheric) and final (in the detonation wave front) detonation product pressures, respectively; and k is the polytropic index.

For many explosives and explosive compounds used in explosive welding, the explosive heat Q is within the range of 3.7 to 4.3 MJ/kg; the polytropic index is within the range of 1.5 to 3, depending upon the initial density of the explosive, its chemical composition, the degree of chemical transformation completeness and the explosive charge height.

Calorimetric measurements were used for several types of explosives to experimentally determine the total specific energy expenditures due to heating the flyer plate with the detonation products W_h, the energy W_b spent on the double plastic bending of the plate, and the dissipative energy losses in the plate due to the shock wave W_{dE}. With this aim, only a 5-mm-thick low-carbon steel flyer plate was used; the explosive was placed on the surface of the plate.

With this, the specific heat Q_E (per unit area of the plate), transferred to the flyer plate by the detonation products, was determined. The results are shown in Table 1. For reference, the table contains estimated values of the specific explosion work W^*_E (per unit area of the flyer plate) and the pressure in the detonation wave front p_H, calculated using the equation suggested by Baum et al. (1959):

$$p_H = \frac{\rho_0 D^2}{k+1} \tag{9}$$

where ρ_0 is the initial density of the explosive.

In addition, the share of the heat Q_E from the specific work of the explosion W^*_E was estimated.

Currently, it is impossible to break down the heat input transferred to the flyer plate by the energy released after the explosive detonation W_h, the plate double plastic bending W_b and the energy dissipation $W_{d\times E}$. The reason for this is the fact that, at present, there are no reliable analytical and experimental methods to evaluate heat transfer processes that accompany detonation loads. The absence of these methods also makes it impossible to evaluate metal strength properties for high velocity detonation loads.

It should be noted that there exists a good correlation between the amount of specific heat transferred to the flyer plate by the detonation products, Q_E, and the detonation wave pressure, p_H. The correlation indirectly proves that the shock wave dissipative losses of energy prevail in the heat transferred to the flyer plate.

Thus, the conclusion can be drawn that energy losses in the flyer plate metal during acceleration can be measured and are on the order of 0.18 to 1% of the explosion energy (see Table 1).

3. The energy released by the welded plates upon their collision

When explosively welded plates collide, a portion of the flyer plate kinetic energy is converted into other types of energy and released in the form of heat. The calorimetric method was used to determine the amount of heat that accumulates in the package of