CLEANING AND ACTIVATION OF WELDED SURFACES DURING EXPLOSION WELDING

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Absence of the cumulative effect in explosion welding of large-sized samples and commercial size plates in the modes used in commercial production is experimentally proved. The mechanism of cleaning and activation of surfaces ahead of the contact point is proposed, based on the hypothesis of formation of thin layers of low-temperature plasma in the welding gap on the interface between the shock-compressed gas and surfaces being welded. It is suggested than formation of strong bonds between atoms of the joined metals in explosion welding should be regarded as a three-stage process.

Keywords: *explosion welding, welded surface, oxides and contamination, cleaning, activation, cumulative jet, plasma flows, contact point, three-stage process*

For explosion welding, similar to any other solid-phase pressure welding process, the most important is the condition of materials being welded, which depends on mechanical and chemical properties of the base and cladding layers, quality of preparation and roughness of surfaces being welded.

In keeping with the currently accepted theory of joint formation in explosion welding, it is believed that under the conditions of slanting collision self-cleaning occurs, as a rule, as a result of cumulative jet formation [1–3], which removes a layer of metal from the surfaces being welded together with the oxides and contamination, and carries them out of the welding gap in the form of a cloud of dispersed particles. Then the juvenile surfaces are compressed under the impact of the detonation products up to formation of a metal bond. The process of metal joining in explosion welding is accompanied by an abrupt increase of temperature in the joint zone, which is indicated by the presence of «cast structures» — zones, in which material melting occurs during welding. It should be noted that the cumulative jet proper was observed only during special experiments in the modes, markedly different from those applied in explosion welding of steels. It was not possible to obtain a cumulative jet experimentally, even at a symmetrical schematic at a low angle of collision (20° for steel, and 30° for aluminuim), and the presence of a cloud of dispersed particles in front of the contact point was recorded in the photos [4], and a wavy joint line was formed.

A doubt as to the determinant role of cumulation in joint formation in explosion welding is expressed in [5, 6]. In [4] a conclusion was made about «...formation of a reverse mass flow (cumulation) is not a mandatory condition for joint formation in explosion welding, and, similar to wave formation, it is only indirectly related to it». Explosion welding is considered to be solid-phase pressure welding, and metal adhesion — a particular case of topochemical reactions in pressure welding, which are characterized by a three-stage nature of the process of formation of strong bonds between the atoms of the joined metals; establishing physical contact; activation of contact surfaces; volume development of interaction. Authors of [7] state that explosion welding is characterized by a two-stage nature of the process of joint formation — physical contact and activation of contact surfaces due to plastic deformation. However, despite the doubts as to existence of the reverse flow under explosion welding conditions, the process of joint formation, as well as the energy balance, are considered allowing for the presence of the cumulative effects.

This paper deals with the issue of existence of the cumulation process, and in its absence — issue of existence of mechanisms, which can lead to cleaning and activation of the surface to be welded.

Processes occurring in front of the contact point were studied using the method of traps: a trap consisting of two pre-scraped steel sheets, assembled at an angle with an initial gap equal to welding gap, was mounted on large-sized samples and sheets of commercial size (Table 1) from the end face, opposite to the start of the process. The above method allows recording on samples and sheets of commercial size the presence of particles flying out of the welding gap with shock-compressed gas (SCG), without changing the explosion welding conditions. This method was successfully applied in investigation of processes running in the welding gap in welding titanium to titanium [8] and titanium to steel [9].

Before the start of experiments, published experimental and theoretical data of various authors were used to determine the anticipated thickness of the coating on one of the trap plates in the presence of the cumulation process (see Table 1). Calculations were performed proceeding from the condition that material, removed by the cumulative process from the surface of the plates being welded, is deposited on the trap surface without taking into account the lateral projection of particles:

$$h = \frac{h_{\mathrm{rem}}\, S_{\mathrm{sheet}}}{S_{\mathrm{trap}}}, \qquad (1)$$

Table 1. Thickness of coating layer on the surface of one of the traps

Welded material (atmosphere)	Sample size, mm	Trap size, mm	Calculated data, μm			Experimental data
			[9]	[5]	[10]	
Steel–steel (air)	500×1200	250×500	48	528	192	Absent
Steel–titanium (air)	500×1200	250×500	48	528	192	20–80 μm
Steel–steel (air)	1400×5900	250×1400	236	2600	944	Absent
Steel–titanium (argon)	2700×2800	250×2700	112	1232	448	Same

where h_{rem} is the thickness of metal removed from the welded sheet surface, μm; S_{sheet} is the sheet area, mm^2; S_{trap} is the trap area, mm^2.

At equal width of the sheet being welded and the trap this ratio becomes

$$h = \frac{h_{rem}\, l_{sheet}}{l_{trap}}, \qquad (2)$$

where l_{sheet} is the sheet length, mm; l_{trap} is the trap length, mm.

At calculation of the thickness of the layer which should be deposited on the trap plates, experimental data of [4, 10] were taken as the basis, and at the same time assessment by the hydrodynamic cumulation theory was performed [11].

Calculations of the anticipated coating thickness showed that in explosion welding of large-sized samples and sheets of commercial dimensions, coating thickness should be 48–2600 μm (see Table 1).

Experimental investigations by trap method showed that in steel welding to titanium in air a deposited layer of 20–80 μm thickness is present on the plate surfaces, which consists of a mixture of partially melted titanium oxides. However, experiments did not reveal on the trap surface the presence of particles, flying out of the welding gap in welding of large-sized sheets and samples of steel to steel and of steel to titanium in argon.

Thus, results of the conducted experiments showed that no cumulative effect was recorded in explosion welding of steel to steel and to titanium in argon in welding modes accepted in commercial production of bimetal.

During explosion welding, a SCG region forms in the welding gap ahead of the contact point. Let us consider its thermal impact on the surfaces being welded at a distance from the beginning of plate collision by a procedure described in [12]. Thermal flow from gas to plate surface has the following form:

$$q = \mathrm{St}\rho u c_p (T_{SCG} - T_0), \qquad (3)$$

where St is the Stanton number; ρ is the gas density; u is the mass velocity of gas beyond the shock wave front; c_p is the gas heat capacity; T_{SCG} is the SCG temperature; T_0 is the initial temperature (293 K).

Stanton number at turbulent flowing of the gas flow around the plates is equal to

$$\mathrm{St_t} = \frac{1}{8\left(2\lg\dfrac{a_p}{k} + 1.74\right)^2}, \qquad (4)$$

where a_p is the distance between the plates (welding gap), mm; k is the average size of surface roughness, mm.

At a constant thermal flow from gas into metal the plate surface is heated by the following law:

$$T_s = \frac{q}{2\lambda}\sqrt{6at} + T_0, \qquad (5)$$

where λ, a are the heat conductivity and thermal diffusivity of welded plate material; t is the time.

Calculations made for welding steel (contact point velocity v_c = 2500 m/s; a_p = 8 mm; k = 0.08 mm) showed that the maximum temperature to which the metal surface is heated under the condition of an infinite length of 1 m wide sheet is not higher than 600 °C. Therefore, impact of only the SCG on the surfaces being welded is insufficient for their cleaning and activation.

In this connection, we considered the processes of cleaning and activation by analogy with metal rolled stock cleaning by plasma based on the following hypothesis: thermal ionization of gas with formation of thin layers of low-temperature «cold» plasma occurs on the interphase ahead of the contact point in the welding gap at supersonic (5–6 Makh) flowing of SCG over the surfaces being welded [13].

Under the impact of the plasma flow all the known metal oxides and other chemical compounds dissociate, ionize and evaporate (sublimate) from the surface being welded. Positive ions of metals, formed as a result of dissociation of oxides and their ionization, return to the cleaned surface, and oxygen atoms form the simplest gaseous compounds of O_2, CO_2 and H_2O, which are removed from the welding gap. Note that scale and rust are not the cleaning byproducts, these are exactly the gasified carbon dioxide gas and water molecules. Oxide dissociation results in an abrupt improvement of activation of the surfaces being welded ahead of the contact point.

Similar processes occur in plasma-arc cleaning of metal rolled stock (Table 2). At energy density of $1\cdot10^3$ W/m^2 the thermal flow will be equal to $1\cdot10^3$ J/(m$^2\cdot$s), and the temperature will reach (5–10)$\cdot10^3$ K, here the cleaning speed will be 4.5 m/min [12]. By the data of [13], the heat flow from gas into metal in explosion welding is equal to $1\cdot10^8$–$1\cdot10^9$ J/(m$^2\cdot$s) at brightness temperature of (5–8)$\cdot10^3$ K in the welding gap, depending on welding mode, and by the data of [15] — from 1.3–$1\cdot10^9$ to 4.1–$1\cdot10^{10}$ J/(m$^2\cdot$s). Evidently, plasma-arc cleaning speed is incommensurably lower than at explosion welding, but the thermal flow in the latter case is

Table 2. Calculated parameters of plasma cleaning of metal rolled stock

Cleaning method	$T\cdot10^{-3}$, K	Energy density, W/m^2	Time of plasma action, s	Thickness of removed layer, μm
Plasma-arc [14]	5–10	$1\cdot10^3$	5–10	200–300
Shock plasma [12]	5–8	$1\cdot10^8$–$1\cdot10^{10}$ [12, 15]	$2.4\cdot10^{-5}$–$1.12\cdot10^{-4}$ (at detonation rate 2000–2500 m/s)	5–7 [10, 16]

$1\cdot10^6$ times greater, and the removed layer thickness is just 5–7 μm.

In [10, 16] by measuring the mass loss it was established that for modes usually applied in commercial production of bimetal, a layer of 5–7 μm thickness is removed from each of the welded surfaces. If we consider the area of the real surface along a line enveloping the microroughnesses at abrasive cleaning HR_z 40, the surface size will increase several times. Quantitative assessment of the real surface area along the microroughness envelope was performed proceeding from the average step of microroughness S_m and its profile height R_z according to GOST 2789–73. Therefore, at loss of a layer of 5–7 μm thickness, a layer not more than 0.3–0.5 μm thick is removed from a unit of the real surface, which is equal to thickness of films on the metal surface, removal of which through dissociation ensures cleaning and activation of the surface.

Conducted investigations and calculations allow suggesting the following mechanism of joint formation in explosion welding. After SCG has reached certain points on the surface to be welded, material heating and formation of «cold» plasma at supersonic flowing begin, and cleaning from oxides and contamination and surface activation occur under the cold plasma impact. Proceeding from the dimensions of SCG region the time of plasma impact is equal to approximately $1\cdot10^{-6}$ s. Clean and active surfaces come into contact in the collision point and form a joint, its formation going on beyond the contact point and being accompanied by intensive plastic deformation.

Thus, explosion welding is characterized by running in the above-mentioned sequence of the three-stage process of formation of strong bonds between the atoms of metals being joined: cleaning and activation of contact surfaces ahead of the contact point in SCG region under the impact of a plasma flow; formation of physical contact in the collision point; volume interaction and joint formation beyond the contact point.

Explosion welding quality is determined primarily by processes running ahead of the contact point, namely cleaning and activation of the surfaces being joined.

The proposed hypothesis led to an important conclusion, namely, in order to produce a strong joint at the start of the explosion welding process, prevent formation of initial lacks-of-penetration and regions of lower strength, it is necessary to provide the required SCG parameters and formation of a plasma layer for cleaning and activation of the surfaces being welded.

CONCLUSIONS

1. It is shown that at explosion welding as a result of the impact of a plasma flow cleaning of the surfaces being welded from oxides and organic contamination and their activation ahead of the contact point occur through oxide dissociation, sublimation of contamination and ionization. Positive ions of metals formed as a result of oxide dissociation, partially come back to the cleaned surface, and atoms of oxygen, nitrogen, and carbon form the simplest gaseous compounds of CO_2 and H_2O type, which are removed from the welding gap by SCG.

2. The following sequence of the three-stage process of formation of strong bonds between the atoms of the joined metals in explosion welding is suggested: cleaning and activation of contact surfaces by SCG and thin plasma flows; formation of physical contact in the collision point; volume interaction with joint formation and plastic deformation beyond the contact point.

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