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ENHANCEMENT OF EXPLOSIVE WELDING POSSIBILITIES BY THE USE OF EMULSION EXPLOSIVE

ROZWÓJ MOŻLIWOŚCI ŁĄCZENIA WYBUCHOWEGO PRZEZ UŻYCIE EMULSJI WYBUCHOWYCH

Explosive welding is an effective method of joining of various metals and alloys. However, when the materials with very different strength and thermo-physical properties are welded or thin-layer cladding is performed, the difficulties occur which call for extra investigations. In the present paper, with the couples of steel / carbide composite and copper / hardened steel used as examples, under study were the peculiarities of bonding formation by the explosive welding of metals with highly differing properties. The experiments were carried out with emulsion explosive containing hollow micro-spheres and detonating in thin layers with the low (2 – 3 km/s) detonation velocity. Obtained results show that the emulsion explosives enable to extend the explosion welding potentiality.

Keywords: explosive welding, emulsion explosive, carbide composite, bonding formation

Połączenie wybuchowe jest wydajną metodą łączenia silnie zróżnicowanych metali i stopów. Jednakże, pojawiają się realne trudności w łączeniu, gdy jeden z materiałów posiada bardzo odmienne właściwości wytrzymałościowe lub termo-fizyczne bądź też wytwarzane jest połączenie bardzo cienkich folii. W niniejszej pracy, badano przykładowe: stal/węglik oraz miedź/stal hartowana, jako układy materiałów o silnie zróżnicowanych własnościach spajanych z wykorzystaniem metod wybuchowych. Badania eksperymentalne wykonano z użyciem emulsji wybuchowych zawierających wydrążone mikrosfery oraz układy złożone z cienkich warstw. Proces łączenia wykonywano z wykorzystaniem małych prędkości detonacji (2-3 km/s). Otrzymane rezultaty pokazują, że zastosowanie emulsji wybuchowych znacznie poszerza potencjalny zakres możliwości wykorzystania techniki spajania wybuchowego.

1. Introduction

As a technological process, the explosive welding (EW) is widely utilized in bimetals production. EW is based on the phenomena of bond formation during the oblique collision of two metal surfaces. High explosives (HE) are used in order to accelerate one metal plate against another and provide the collision conditions needed for bonding. Detailed description of EW process can be found in [1] therefore we don't go into smallest details here.

The highest production level falls on such couples as steel-titanium, steel-aluminum, steel-copper, and to the junction of common structural steels with stainless steels. Sometimes in the industry, especially when new equipment is being developed, there is the need to connect low-ductile alloys with ductile ones, or to clad some articles with thin protective or function layers from special alloys. Thin coatings are rather frequently needed on un-massive or thin-walled articles which may be defected by explosion of too big high explosive charge. In these cases, the difficulties arise due to the fact that the utilized industrial HE cannot detonate steadily in thin (below 8-10 mm) layers with the low (2-3 km/s) detonation velocity needed for the EW. It makes researches seek for new explosives. For example, in [2] they studied the detonation characteristics of fine PETN mixtures with baking soda. In this paper, the approach lies in the idea that the powerful and sensitive HE (PETN) detonating in the thin layer is mixed with an inert admixture (soda) in order to reduce the detonation velocity. In the present work, the utilized explosive is prepared in a different way; hollow micro-spheres are added in the low-power emulsion explosive in order to increase its sensitivity [3]. With such an explosive, it is possible to reduce the working charge of HE needed for the EW and hence reduce significantly the residual deformation in the produced bimetal [4]. That is why we refer the EW with above mentioned emulsion explosive the "delicate explosion welding" (DEW).

The present paper deals with the problems related with the welding of materials with highly differing properties. The bonding of copper with a hardened steel, and stainless steel with a carbide composite with the use of DEW was performed.

2. Peculiarities of the explosion welding of dissimilar materials

From the viewpoint of practical applications, layered composite materials containing metals and alloys with highly

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differing physical and mechanical characteristics are the most interesting. But the welding of such materials causes the most serious difficulties. In such combinations as high-strength steel and aluminum or a carbide composite and copper, the melting point may differ from 2 to 3 times, the hardness – from 5 to 10 times. As a rule, the alloys with high strength feature low ductility, whereas less strong metals and alloys have the low melting point. Essential difference in properties complicates the theoretical definition of the welding parameters since they highly depend on the hardness and thermo-physical properties of the material. It is generally accepted that the key parameters in the explosion welding process are the angle of collision of the welded plates γ and the contact point velocity V_c (the velocity of collapsing of the initial gap between the plates [5]). It is illustrated by Fig. 1, wherein it is evident that the EW window in the classical $V_c - \gamma$ diagram depends significantly on the so-called low and upper boundaries. The points (V_c, γ) between line 1 (low boundary) and line 2 (upper boundary) in Fig. 1 correspond to collision parameters $V_c$and γ providing successful welding of collided plates. Points (V_c, γ) above line 2 and below line 1 correspond to the absence of welding. More details concerning EW window are presented in [1, 6, 7].

The low boundary of EW window is calculated by the formula [6]

$$\gamma = k\sqrt{\frac{H_V}{\rho_m V_c^2}} \tag{1}$$

where ρ_m is the plate material density, $H_V$is the material Vickers hardness, k is the factor depending on oxide and other contaminations film thickness on the welded surfaces. This dependence is found as a relation $k = 5.5{\cdot}\xi^{0.18}$, where ξ is the surface film thickness divided by the flyer plate thickness [8]. In real practice, k normally varies from 0.6 to 1.2, for the materials with natural oxide films $k = 1.14$. By the way, not only in EW but also in explosive compaction of powdered materials the surface films on powder particles have an influence on their consolidation [9].

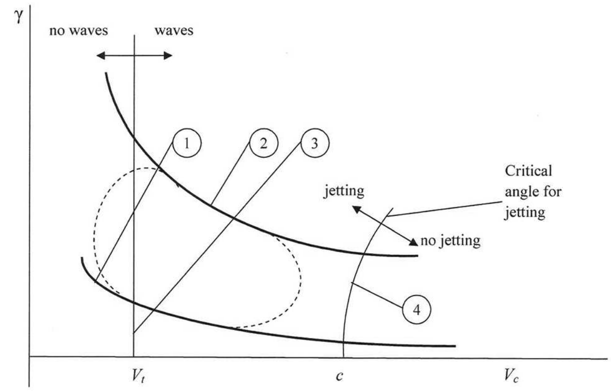

Fig. 1. Explosive welding window on the $V_c - \gamma$plane: 1 – low boundary (calculated by (1)), 2 – upper boundary (calculated by (2)), 3 – the boundary $V_c = V_t$ between the ranges of smooth and wavy shape of the bonding zone in the welded couple (V_t is detected experimentally), 4 – the boundary between the ranges of occurrence and absence of cumulative jet at the collision of flyer and base plates (jetting does not occur if V_c exceeds c); V_c – contact point velocity, γ – collision angle, c – compression wave speed ($c^2 = K/\rho_m$, K-bulk modulus, $K = E/3(1\text{-}2\mu)$, E – Young modulus, μ – Poisson ratio). Broken curves and the lines 1, 2 circumscribe the typical experimental area where reliable welding is achieved

The higher is the melting temperature and melting heat of material, the higher is the upper boundary of EW window. The upper boundary is calculated by the formula [6]:

$$\sin(\gamma/2) = 14,7 \cdot V_c^{-5/4}\sqrt{\frac{T_m\lambda/a}{\rho_m\frac{\delta_2}{\delta_1+\delta_2}\delta_1^{1/2}}} \tag{2}$$

where T_m is the melting point, λ – thermal conductivity, a – thermal diffusivity, ρ_m – density of the metal, δ_1 – thickness of the thinner plate, δ_2 – thickness of the thicker plate.

Note that the low and upper boundaries of EW window approximately correspond to some constant velocities of the flyer plate. The straight line $V_c = V_t$ in Fig. 1 separates the range $V_c > V_t$ where contact surface of welded plates is wavy and the range $V_c < V_t$ where contact surface is plane. The V_t value can be found experimentally. The right boundary of the theoretical EW window (line 4 in Fig. 1) is calculated proceeding from the impossibility of cumulative jet formation if V_c exceeds the sonic velocity of compressed material in the neighborhood of collision point. The formation of jet is considered to be the necessary condition for bond formation. Additional information on EW at collision parameters close to the upper boundary can be found in [10]; and the questions concerning straight and wavy interface are considered in [11, 12].

Generally speaking, the flows and processes passing in the interface of colliding plates depend not only on V_c and γ, but on the other technological parameters. For example in [13] the effect of the size of initial gap between the welded plates on the interface structure was observed. Nevertheless, V_c and γ remain to be the main and key parameters influencing the EW process.

If the properties of the welded materials differ significantly, their EW windows may not cross, or cross to a low degree. Thus, reasoning from the classical concepts of EW window plotting, some couples of materials either cannot be welded at all, or the welding modes lie within a narrow range on the plane of $V_c - \gamma$.

Experimental investigations however show that the low boundary of the EW area for dissimilar materials can be found on the base of less strong material strength (as a rule, this material is more ductile at the same time). It can be also assumed that, to realize the conditions needed for bonding, it is enough to provide the start of the deformation process and then to generate a disperse particles jet from the material of one of the welded plates. High-speed jet flow of the softer plate material results in the removal of surface films from the harder plate surface and deformation of its surface layers [14, 15]. For example when aluminum is welded to steel, high deformation level in the aluminum plate causes the high temperature of the particles in the jet. The jet mainly consists of aluminum particles. As a result, as the flow interacts with steel, the steel surface must be heated, and its strength decreases. Upon such an action, the steel surface gets behind the collision point into the high-pressure area and is already prepared to the following process of bond formation. When collision angle is high the jet gets solid and moves along the steel surface scrubbing it like a blade. This process is strikingly illustrated by Fig. 2, where appearance of solid jet during the welding of aluminum with steel was shown experimentally. In the presence of jet flow, on the base of the hydrodynamic approach, the increased "effective time of joined surfaces interaction" can be suggested [15]. From the viewpoint of the energy approach, each specific couple of welded materials has its characteristic critical energy value of plastic deformation W, at which the strong joint is realized [16]. When welding dissimilar materials, W occupies the position approaching the deformation energy value of the milder metal. Evident that both hydrodynamic and energy approaches applied to the dissimilar materials welding process give quite similar results.

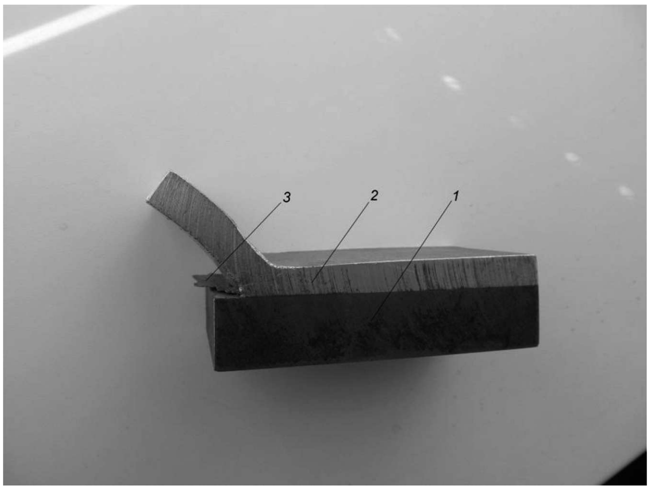

Fig. 2. The bimetal made by explosive welding: 1 – steel plate, 2 – aluminum plate, 3 – aluminum jet coming out of collision point

During the EW process most of the kinetic energy of the flyer plate is consumed for the deformation flows in the bonding zone and hence on the material heating in this area. As the flyer plate speed rises, the flat boundary of the contact area transforms into the wavy one. Further increase of the speed results in vortexes on wave crests, with typical melt zones. The same is observed as the thickness (mass) of the flyer plate increases at the same speed. From the practical viewpoint, it is advisable to perform the welding with the minimal possible energy release in the contact area. It can be reached via, for example, drive of low-thickness plates by small explosive charges; the above-mentioned emulsion explosives fit well to this purpose.

3. Experimental

In order to clarify the DEW potentiality, welding of materials with highly differing properties was studied experimentally. The parameters of cladding plate drive were chosen in such a way to make the collision process pass near the low boundary of the EW window; the position of this boundary was calculated on the base of the less strong material characteristics.

It is known that, when welding the materials with highly differing strength properties, the thicknesses of the layers involved in the plastic flows are inverse dependent on their strength. It causes the concentration of the thermal energy released due to the plastic deformations in the narrow near-joint zone of the stronger material and hence it potentially causes liquation of the less strong material (due to this heat) which as a rule has the lower melting point [17]. To avoid the melting, it is necessary to choose the welding modes with the minimal achievable heat release in the collision area. It can be reached by the reduction of the collision velocity, but the successful bonding is still achievable because of the following reasons. When welding materials with similar strength characteristics, both metals make roughly similar contribution into the preparation of the conditions needed to start the bonding process. The areas enveloped by the significant plastic deformations will be comparable in these materials. As any differences in the strength characteristics of the welded materials occur, the importance of the less strong material in the preparation-to-bonding process will increase. Above all it is valid for the deformation processes in the collision zone and for the particles flow appearing in the welding gap, since this flow will clean up the contacting surfaces. In this situation, the higher is the difference in the welded materials strength, the higher is the stronger component hardness, the more is the dependence of the preparation level of both welded surfaces to the bonding on the deformation processes in the less strong material. The higher is the stronger material hardness, the smaller is the zone in it involved in the plastic deformations. It may result in the reducing energy consumptions for the welded surfaces preparation to the bonding process. That is why, as the initial hardness of the stronger metal rises, the energy consumptions for the preparation process may not increase. Hence it follows that, with the rather big difference in the welded materials hardness, the variations of the harder material do not influence the process of connection, all other conditions being equal.

It is not that easy to prove the above concepts experimentally. In particular, the difficulties are related with the influence of the stronger material surface roughness on the processes occurring. In [18] it is shown that the minimal collision velocity needed to produce a strong bonding is much lower for the polished samples than for the coarse samples with bigger surface micro-imperfections. Detailed results were obtained in [19, 20], too. These data are valid for the welding of materials of quite similar strength characteristics. This trend remains valid when dissimilar materials are welded, but the stronger material surface roughness imposes the most serious effect on the produced bonding quality.

In the first series of tests, under study was the effect of the stronger material hardness on the forming of copper-steel bonding; before the welding, the steel samples (23×25×125 mm) underwent mechanical treatment in order to reduce the welded surfaces roughness to R_a = 0.32-0.16 μm. A copper plate of 1.5 mm thick was driven on 3 steel samples with different hardness: H_1 = 130 – 160 HB; H_2 = 32 – 34 HRC; H_3 = 44 – 46 HRC. Schematic of the experiment is shown in Fig. 3.

In such an experiment the collision conditions can be assumed similar for all steel samples. Above mentioned emulsion explosive with hollow micro-spheres was utilized as a charge. The first test was carried out at the drive parameter R = 0.5, which corresponds to the collision angle $\gamma \approx 7°$, the contact point velocity was V_c = 2.6 km/sec. As a reminder, the commonly accepted in the EW drive parameter R presents the ratio of the explosive charge mass to the flyer plate mass per unit area, whereas the contact point velocity in the case of parallel positioning of the flyer and base plates coincides with the explosive detonation velocity. The collision angle is calculated by the formula [6]:

$$\gamma = \left(\sqrt{\frac{n+1}{n-1}} - 1 \right) \frac{\pi}{2} \cdot \frac{R}{\left(R + 2.71 + \frac{0.184}{y} \right)} \qquad (3)$$

where n – detonation products polytropic index, y – – dimensionless parameter equal to distance of acceleration divided by explosive charge thickness.

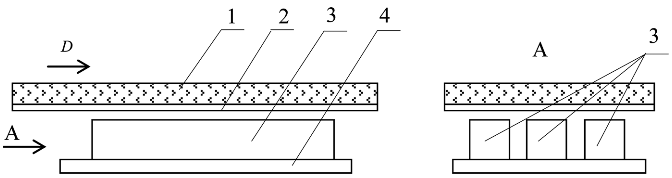

Fig. 3. Schematic of the experiment on copper plate drive on the steel samples with different hardness: 1 – explosive charge, 2 – copper plate, 3 – steel samples, 4 – base plate, D – detonation velocity

At the given collision parameters, the corresponding point on the $V_c - \gamma$ diagram is located near but above the lower boundary of the EW window which is calculated on the base of the copper hardness. The tests showed that copper was welded similarly well to every sample. Evident, that the difference in the strength characteristics of the steel samples does not influence the connection process at such collision parameters. In the next test, due to reduced explosive charge, the drive parameter was reduced to R = 0.3, the collision angle decreased to $\gamma \approx 5°$. As the contact point rate is V_c = 2.6 km/sec, the collision parameters coincide, or are located a bit lower than the lower boundary of the EW window. In this case it is visible that the welding took place on all three samples. The tests with copper layer peeling showed that on the samples with the hardness of H_1 = 130 – 160 HB; H_2 = 32 – 34 HRC, strong bonding took place on more than 95% of the samples area. On the sample with the hardness of H_3 = 44 – 46 HRC, the copper plate separated from about 25% of the area in the place of welding process ending. On the peeling site, the steel surface retained a thin copper layer, which proves that the bonding process took place indeed.

We believe that the described tests vindicate that, as the pressure in the collision zone exceeds the copper strength, and the deformation processes develop extensively in this area, varying hardness of the steel sample does not influence significantly on the welding process.

Fig. 4 shows the schematic of the next tests series; a stainless-steel plate of 0.8 mm thick was driven onto a copper matrix with a plate of carbide composite MC 221 pressed inside. The composite MC 221 based on tungsten, titanium, and tantalum carbides was chosen to provide the maximum achievable difference in the welded materials hardness. The composite consists of 82% WC; 3% TiC; 7% TaC; 8% Co. Stainless-steel hardness was 150 HB, copper 70 HB. The hardness of the composite MC 221 reached 89 HRA, which is much higher than the strongest steels have.

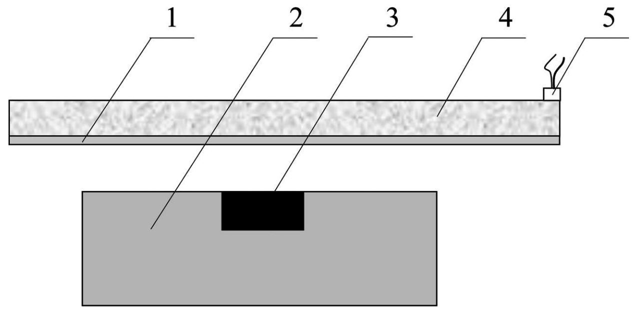

Fig. 4. Experimental layout for stainless steel welding with copper and carbide composite MC 221: 1 –stainless-steel plate; 2 – copper matrix; 3 – carbide composite insert; 4 – explosive charge; 5 – detonator

According to our evaluations, to start the connection process on the copper – stainless steel interface at V_c = 2.6 km/sec, the minimal necessary collision angle is $\gamma = 8°$, whereas on the carbide composite – stainless steel, this angle must be $\gamma = 11°$ [18]. Taking into account almost complete absence of carbide composite plasticity, the shock action must be minimal to avoid cracking. In these very cases, EW is not applicable, and positive results can be achieved with the DEW.

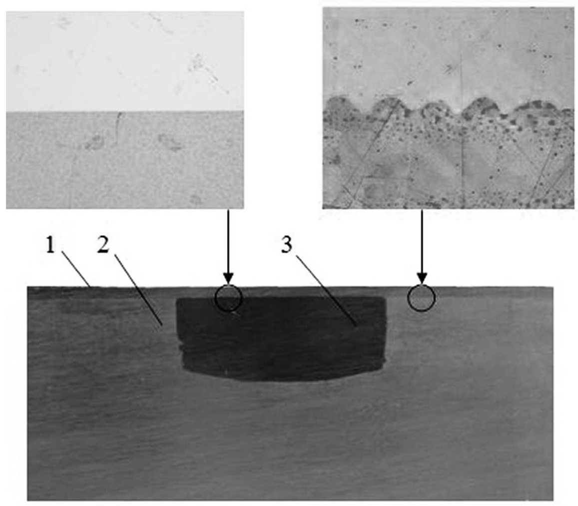

Fig. 5. The composite resulting from the explosion welding: 1 – stainless-steel plate; 2 – copper matrix; 3 – carbide composite

In the first experiment, the drive was initiated by the emulsion explosive charge, its thickness was 7.5 mm, density of explosive ρ_e = 0.63 g/cm^3, detonation rate $D = V_c$ = 2.6 km/sec. At such parameters, R = 0.75, the collision angle $\gamma \approx 10°$. These values of γ and V_c guarantee the presence of the point $(V_{c,}\gamma)$ inside the EW window for the couple stainless steel / copper. As for the area of the stainless steel and carbide composite, the point under consideration (V_c, γ) falls on the lower boundary of the EW window if it is calculated on the base of the stainless steel hardness. The obtained composite sample is shown in Fig. 5. On the copper / steel interface one can see the waves typical for the explosion welding, whereas the interface of the stainless steel and carbide composite is flat, there are no waves, which is natural for the welding of the materials with highly differing strength parameters. This experiment demonstrates that, aside for naturally predicted welding on the copper / steel interface, the connection also took place on the carbide composite / steel interface.

The 2nd experiment was organized in the same way, its parameters were the following: detonation velocity $D = V_c$ = 2.6 km/sec, R = 0.6, γ = 8.5°. In this case, the point (V_c, γ) lies almost on the lower boundary of the EW window calculated by the copper hardness. The welding took place over the stainless steel / copper interface, whereas, opposite to the 1st experiment, there was no connection on the carbide composite / stainless steel interface.

To be sure that the start of the bonding process in the 2nd experiment depended on the level of deformation processes development on the copper surface, the following experiment was carried out. The copper matrix was replaced with a steel plate quenched to the hardness of 46 HRC. The rest test parameters coincided with the test No. 2. As was expected, there was no welding on the stainless steel / quenched steel interface. The signs of bonding on the stainless steel / carbide composite area are missing, too.

In [17] it is shown that the bonding can occur at the collision angles γ = 3 – 4°, if the colliding surfaces are "specially" prepared, and the welding is performed in vacuum. Such γ correlate with the collision velocity of 120 – 150 m/sec. The experimental data presented in [18] show that the deformations on the interface at low collision velocities are minimal, and the deformation character is similar to the ones in the stronger materials, when the materials of different strength characteristics are welded. In [16] they say that in low-intensive collision modes, which result in the primary bonding, cumulative processes are not developed yet. In our case, however, if we base on the copper strength, the studied collision modes cannot be referred to low-intensive. It can be suggested that the role of the "special" preparation of the welded surfaces is played by the deformation processes occurring in the less strong material. The hardness of the stronger material is not of essence providing that its surface roughness influence is minimal.

It follows from the above that it is quite an attainable task to choose such welding parameters for the metals with highly differing characteristics, when the bonding is provided, and excessive heat release in the connection area is minimized. For additional verification of this concept the experiment on explosive welding of aluminum with a carbide composite were performed. For this couple, the hardness difference exceeds 20 times, density difference is 5 times, the aluminum melting point is about two times lower than the carbide composite's one, and nevertheless, the bonding was obtained.

4. Conclusions

The low boundary of the explosive welding window for materials with highly differing properties can be found on the base of less strong material strength. To realize the conditions needed for bonding, it is enough to provide the well-developed deformation process and intensive material flow in only one of the collided plates.

Utilization of the low-detonation-velocity emulsion explosive, which steadily detonates in thin layers, permits extending the capabilities of explosive welding in production of new composite materials. The best effect can be expected if high-strength low-ductile alloys are welded with ductile metals.

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