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Bonding and Wave Formation at the Explosive Welding of Low-Plastic Materials

Boris Zlobin[*], Alexandr Shtertser[*], Victor Kiselev[*], and Andrey Plastinin[**]

[*]*Design & Technology Branch of Lavrentyev Institute of Hydrodynamics SB RAS*

[**]*Lavrentyev Institute of Hydrodynamics SB RAS*

Novosibirsk, Russia

*asterzer@mail.ru

Objective

Sometimes it is necessary to weld low-plastic materials such as high-strength steels, titanium and molybdenum alloys, cast irons, brittle composites, etc. To make it, an intermediate layer of an elastic material can be used, however the problem of cracking at the explosive welding remains urgent.

Crack formation results from the deformation processes occurring at plates collision, and from the wave forming in particular.

The purpose of this work is to consider some peculiarities of bond and wave formation during the explosive welding of low-plastic materials including welding with the use of ductile intermediate layer.

Jet flow and bond formation

It is shown in [1] that plate cleaning needed for the bonding results from the jet flow (particle flow), and its (jet) source is at least one of the welded materials, or the intermediate layer of a ductile material placed on the initial collision section. The jet flow results from the localization of deformation near the joint area. The cleaning process is of dual character: 1) first, the jet itself forms from the surface particles carried away into the gap; 2) second, high-speed particles act on the plate surface ahead of the contact point, clean and heat it. Extra cleaning may take place due to the rotational components of deformation in the conditions of the intensive gradient flows localized in the joint area [1, 2].

1. A.A. Shtertser, B.S. Zlobin. Flows, strains, and formation of joints in oblique collision of metal plates // Journal of Applied Mechanics and Technical Physics. 2015. vol. 56, No. 5. P. 927-935.

2. A.A. Shtertser. Rotational components of deformation in metal bodies under dynamic loading // Combustion, Explosion, and Shock Waves. 1998. vol. 34, No. 2. P. 235-238.

Schematic of the glancing collision of plates

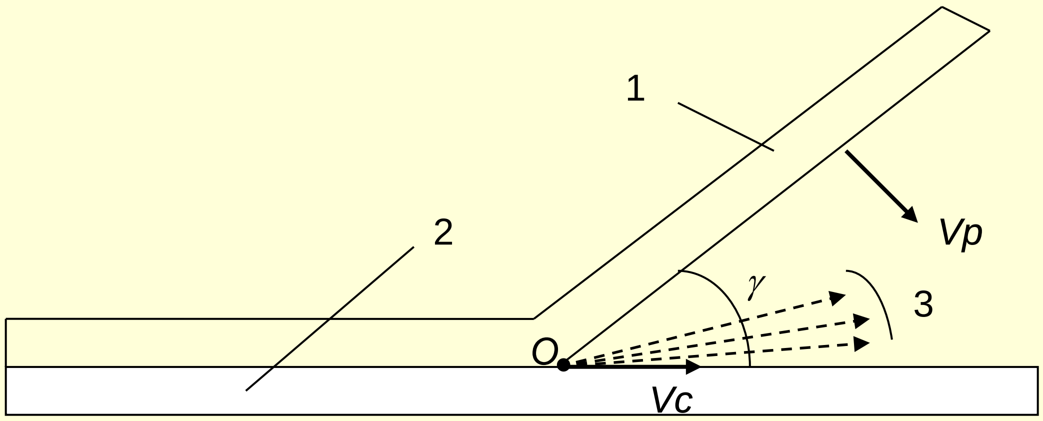


Fig. 1. Glancing collision of plates: 1 – flyer plate, 2 – fixed plate, 3- cumulative jet (particle flow), *Vp* – flyer plate velocity, *Vc* – contact point velocity, γ - collision angle, *O* – contact point.

At the explosive welding of the materials with essentially different strength, the main input in the creation of the bonding conditions is made by the less strong and usually more ductile material. It is the main source to form the jet which then acts on the surface of the stronger material and prepares it for bonding.

The copper jet provides steel-to-steel welding

To reveal intrinsically the degree of jet action on the bond formation, we have performed experiments on explosive welding of hard steels (Fig. 2). The steel plate 3, hardened up to the hardness 42 HRC (423 HV), was first clad by a copper band of 0.8 mm thick. Then the copper cladding 2 was milled to the thickness of 0.3 mm. In the central part of the plate, the copper layer was completely removed (see Fig. 2). Then the steel plate 1 with a hardness of 32 HRC (311 HV) was thrown onto this prepared bimetal plate. The welding mode was calculated on the copper strength base (120 HV). **The flyer steel plate was welded to the copper-covered surface and to the steel base between zones A and B. At the same collision parameters, the direct welding of the steel plates fails.**

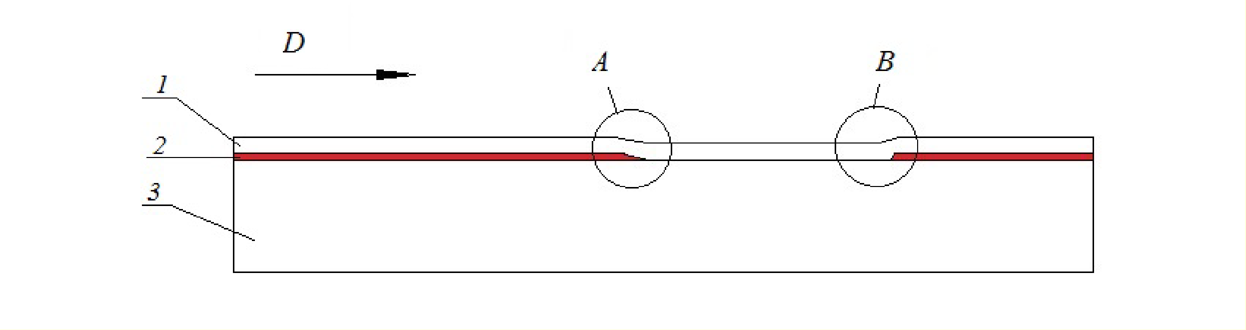


Fig. 2. The sample of joint “steel-copper-steel” and “steel-steel”: 1- steel layer with the hardness 32 HRC, 2- copper intermediate layer, 3 – steel substrate with the hardness of 42 HRC.

Formulas

$$V_p = 2DSin(\beta/2); \quad \beta = \left(\sqrt{\frac{n+1}{n-1}} - 1\right)\frac{\pi}{2}\frac{R}{(R + 2.71 + 0.184/y)}; \quad \gamma = \beta + \gamma_0; \quad V_c = D \cdot \frac{Sin\beta}{Sin\gamma}$$

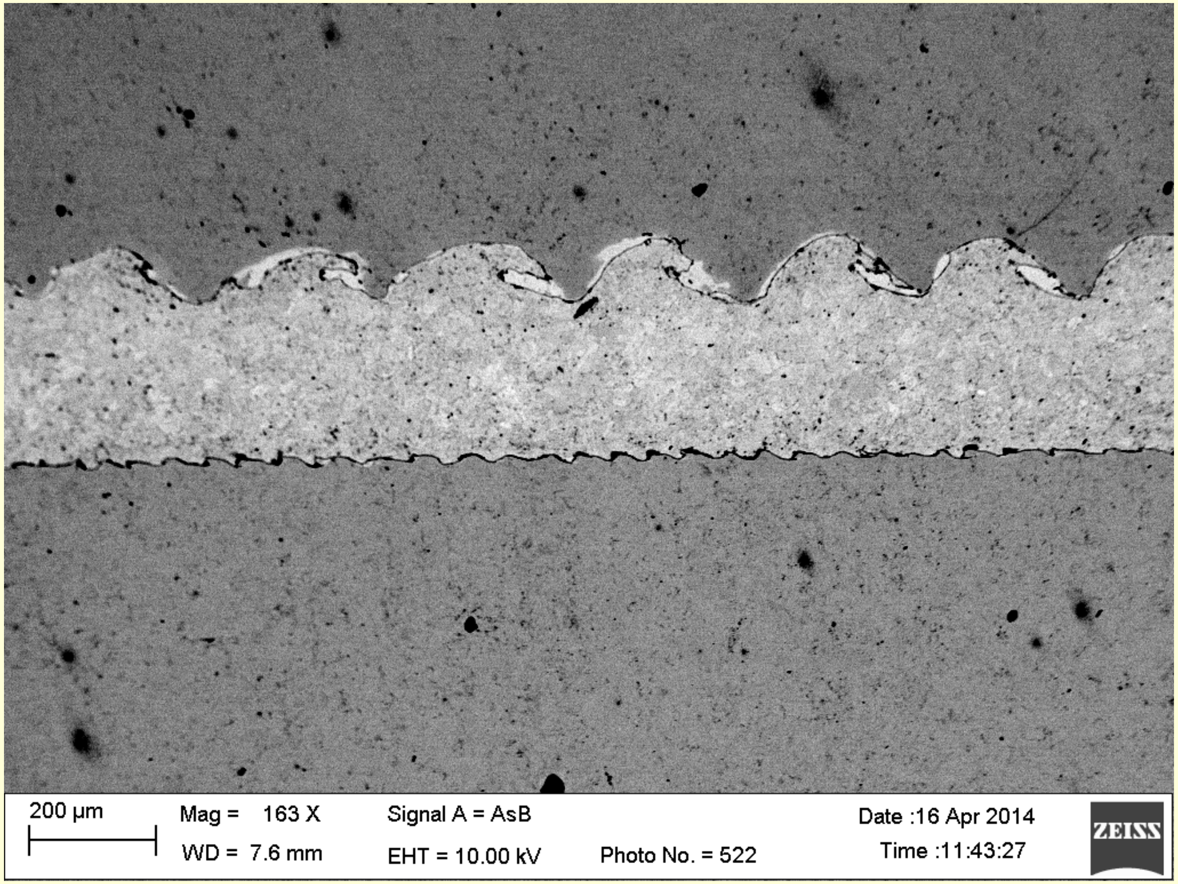
The low boundary of EW window: $$\gamma = k\sqrt{\frac{Hv}{\rho_m V_c^2}}$$

The upper boundary of EW window: $$\sin(\gamma/2) = 14.7 \cdot V_c^{-5/4} \cdot \sqrt{\frac{T_m \lambda / a}{\rho_m \frac{\delta_2}{\delta_1 + \delta_2} \delta_1^{1/2}}}$$

V_p – flyer plate velocity, V_c – contact point velocity, D – detonation velocity, n – detonation products polytropic index, *$y = h/\delta_e$, h –* gap, *δ_e – explosive charge thickness, HV - Vickers hardness, 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.*

$k = 5.5 \cdot \xi^{0.18}$, where $\xi = \delta_s/\delta$ (δ_s is the surface film thickness, δ - flyer plate thickness)*. In real practice, k normally varies from 0.6 to 1.2, for the materials with natural oxide films k = 1.14.*

The zone of the steel-copper-steel weld left from the A area



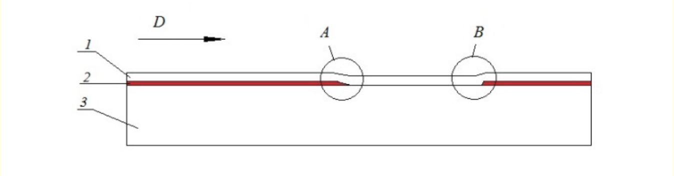


Fig. 3. The joint boundary is of evidently wavy character

The weld in the A area

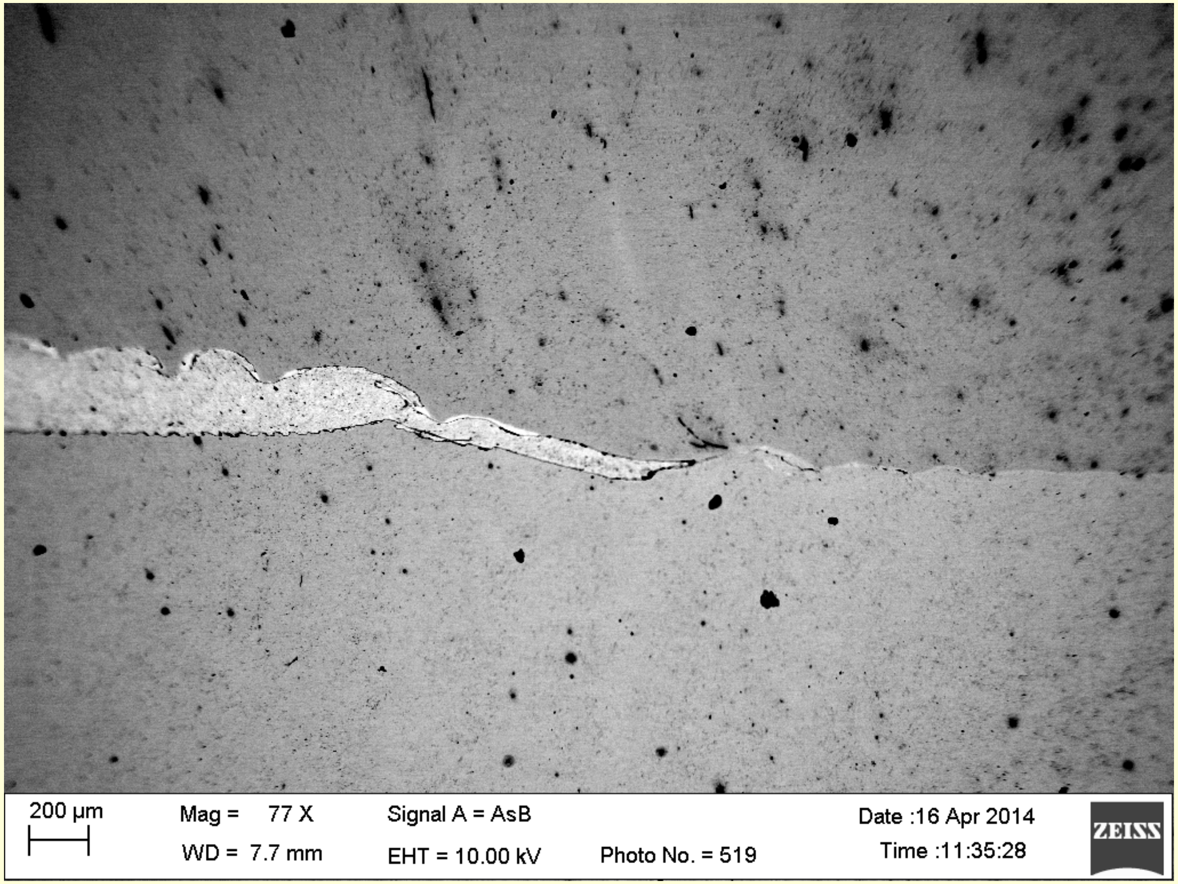
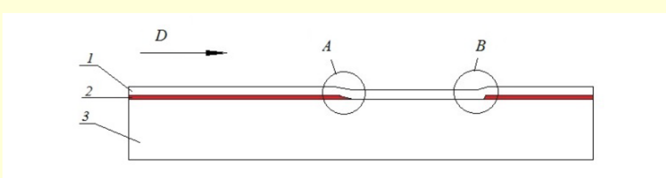


Fig. 4. The copper intermediate layer extends highly toward the moving contact point. The thickness of the copper intermediate layer decreases gradually in the A area, then the intermediate layer fragments and forms a particle cloud. In the A area, on the “steel-steel” boundary, there are regions with copper content from16 to 23 weight%*



*Scanning electronic microscope MERLIN Compact with an X-ray analizer INCA X-mas (Oxford Instruments)

The steel-steel weld between the areas A and B

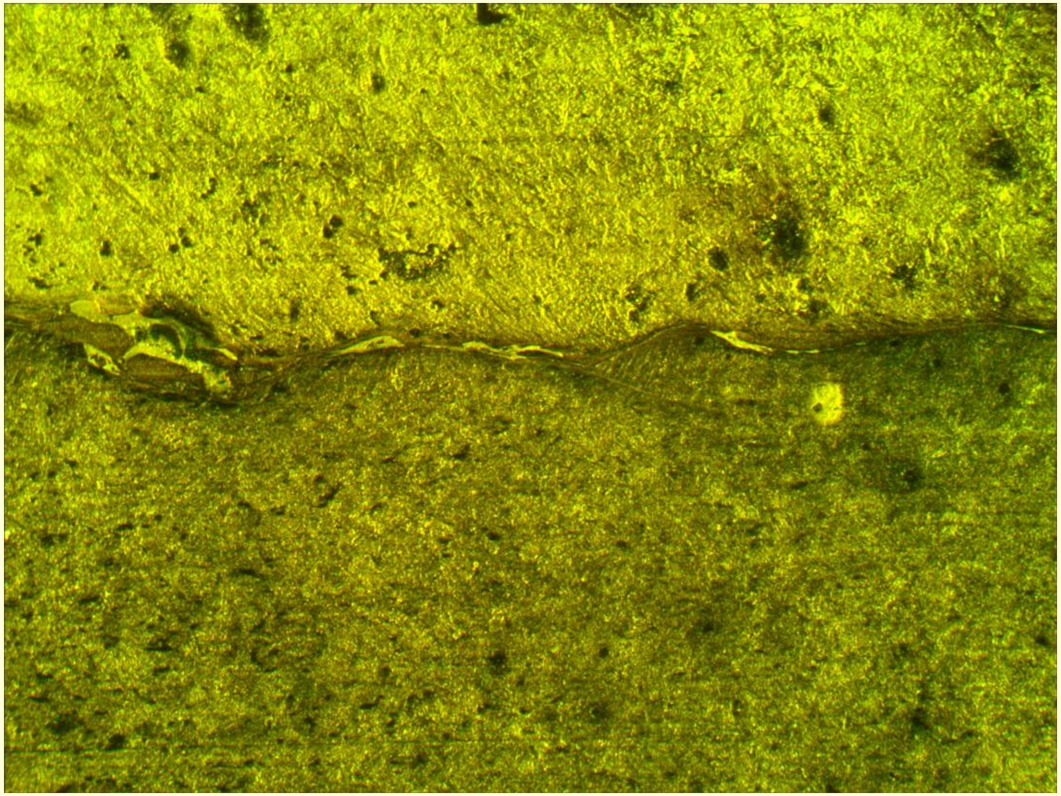
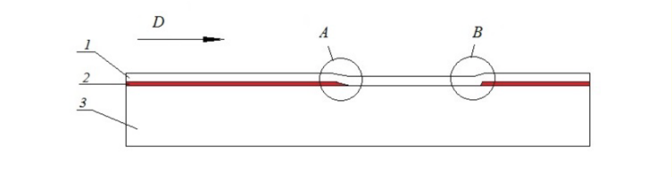


Fig.5.Between the areas A and B in the steel-steel weld, copper content is 1.5 – 3.0 weight %



The weld in the B area

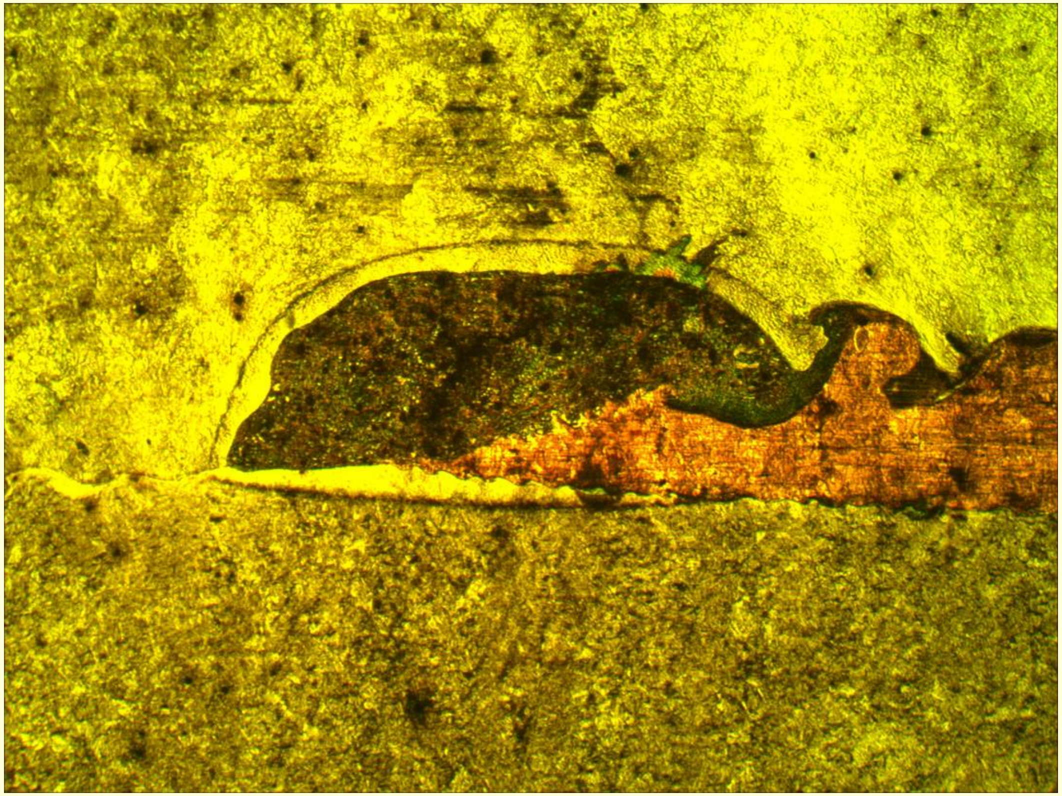
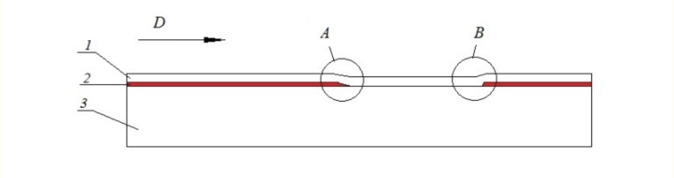


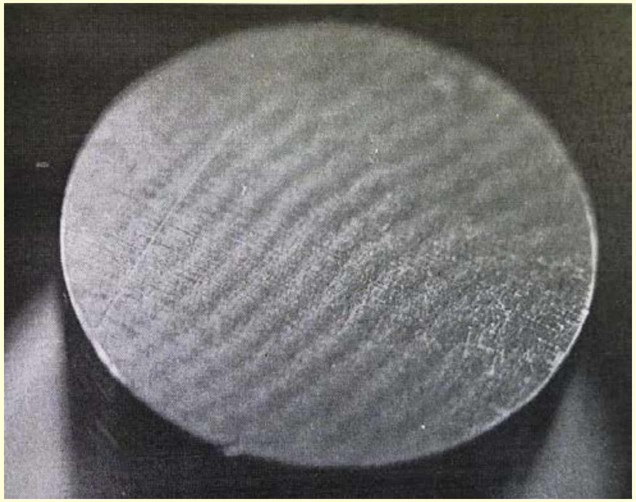
Fig. 6. In the B area, the end face of the copper intermediate layer acts like a trap for the copper particle flow. Ahead of this trap, a mixing zone (like a pocket) of steel and copper occurred where the copper content varies from 60 to 76 weight %



Conclusion: The jet of copper particles provides formation of the strong bond between the plates of a high-strength steel in the low-speed collision mode.

There are always waves in a bonding zone

It is known that welding boundary can be wavy or even. We can see it in a microsection of welded metal layers. But the waveless welding boundary does not mean the absence of periodical oscillations of the parameters governing the bonding and wave formation processes(pressure, mass velocity). **When we can not see waves in a microsection, this only means that the wave amplitude is too small.** For example, when steel and aluminum are welded, in spite of the even boundary, we can perceive the waves in their first stages (in embryo). Fig. 7 presents the plan view of welded steel and aluminum sample which was ruptured during the tensile test by the joint boundary. The welding was carried out at the minimal collision parameters near the lower boundary of the welding area. The strength of the resulting joint was low. On the surface of both steel and aluminum parts of the sample, the signs of the start of bond formation process are seen by the naked eye and through the microscope.



Waves on the steel-aluminum boundary

Fig. 7. The outlook of the steel surface with the signs of the starting process of jointing to aluminum

Wave formation and cracking

During the explosion welding of the materials with different strength, **the main input in the creating bonding conditions is made by the less strong material**, **the start of this process depends on its properties. At the same time the start of wave formation and wave size (amplitude) depends, despite the collision parameters, on the physical and mechanical characteristics of the stronger material.** Welding of low-plastic metals and alloys faces the difficulties related with shear crack occurrence on the joint boundary. Cracks normally start from the joint area, from the places with maximal plastic deformations. At the wavy shape of the joint boundary, these places are wave crests as is shown in Fig. 8 [3].

3. I.D. Zakharenko, B.S. Zlobin. Effect of the hardness of welded materials on the position of the lower limit of explosive welding // Combustion, Explosion, and Shock Waves. 1983. vol. 19, No.5. P. 689-692.

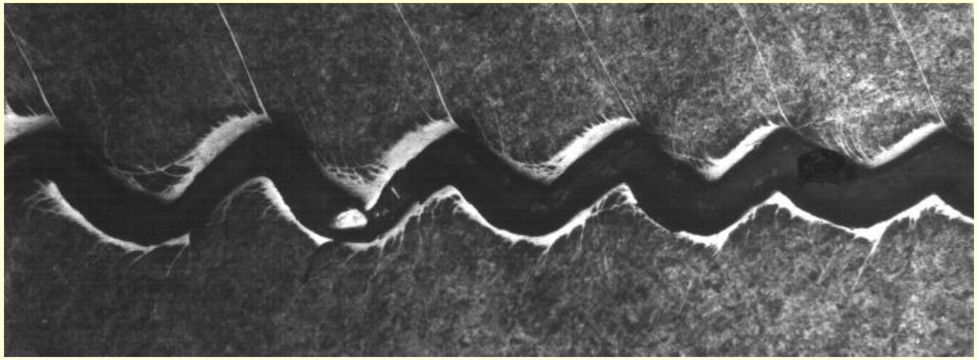


Fig. 8. Cracks on wave crests

Waves generate cracks

Crack occurrence makes difficult producing composite multi-layer materials by the explosive welding when using such low-plastic metals as molybdenum and titanium alloys, high-strength steels, etc. It is possible to prevent cracking on the joint boundary via reducing the wave size.

Wave formation regularities

The wave formation process on the joint boundary is under study since the explosion welding permitted having first bimetal samples. The results of these investigations are described in many works reviewed in [4]. Several models of wave formation are proposed [5], but there is still no consensus about it.

In this work we consider the parameters influencing the wave size and the possibility to reduce wave amplitude within the range of angles $\gamma = 5° - 20°$ typical for the explosion welding.

In early works it was assumed that the wave size is a certain function of the geometrical parameters of the collision. According to the experimental data from [6], the authors of [7] suggested that for the similar metals, the ratio of the wave amplitude to its length could be treated as a constant value on the first approximation

$$a/\lambda \approx 0.19$$

$$0.14 \leq a/\lambda \leq 0.3$$

$$\lambda/\delta = 26 \sin^2(\gamma/2)$$

a – wave amplitude, λ – wave length, δ – flyer plate thickness, γ – collision angle.

Thus, there are no physical and mechanical properties of materials in the final formula.

4. I.V. Yakovlev, V.V. Pai. Explosive welding of metals. Bibliographic index. - Novosibirsk: Publishing House of SB RAS, 2013 (in Russian)
5. I.V. Yakovlev, G.E. Kuz'min, V.V. Pai. Wave formation at glancing collision. – Novosibirsk: Publishing House of the Institute of Discrete Mathematics and Informatics (in Russian)
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7. A.A. Deribas, V.M. Kudinov, F.I. Matveenkov, V.A. Simonov. Simulation of the process of wave formation in explosive welding // Combustion, Explosion, and Shock Waves. 1968. vol. 4, No.1. P. 59-63.

Wave formation regularities

Most authors neglect strength characteristics in the explicit form when considering the wave formation process. There are not so many data on the effect of the strength characteristics on the wave size. The reason is that, apart from the geometrical parameters and strength characteristics, the density of the jointing materials ρ [8], roughness of collided surfaces [9], and welding scheme influence the wave size. There are works experimentally demonstrating that the wave size can be influenced by the type of the base on which the explosion welding is carried out [10] and by the acoustic impedance of the materials ρc [8].

8. H. Hampel, U. Richter. Formation of interface waves in dependence of the explosive welding parameters // Proceed. of the 2-d Meeting on Explosive Working of Materials. Novosibirsk, September 8-10, 1981. Published by Lavrentyev Institute of Hydrodynamics. P. 251 – 262.
9. Dobrushin L.D. On the question of low boundary at the explosive welding // The Paton Welding Journal. 1979, No. 6.
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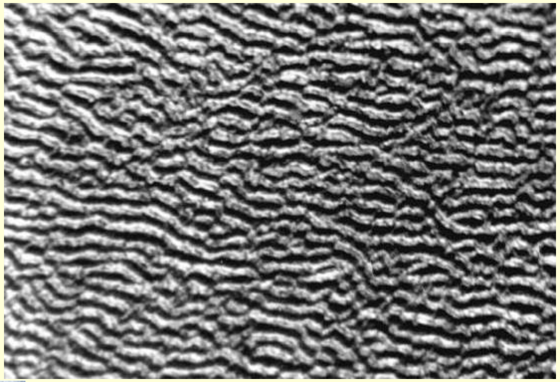
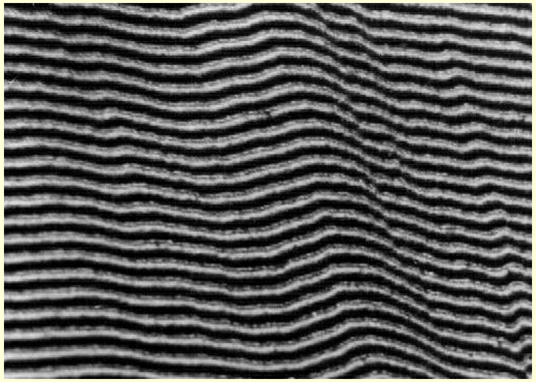


a



b

Fig.9. Surface roughness effect on wave formation
a – Rz = 100; b – Rz = 10

Effect of strength on wave formation

During the welding of the materials with close physical and mechanical characteristics, sizes of the zones undergoing strong plastic deformations are approximately equal in the colliding materials. But when dissimilar metals are welded, the relative sizes of the zones undergoing the strong plastic deformations are inversely dependent on their strength [11]. In this case the wave formation process becomes more complicated. In [12], when the metals with highly different physical and mechanical properties are welded (lead and steel) it was found that the lengths of the waves on the boundary are 2 – 3 times smaller than the wavelength calculated by the formula $\lambda/\delta = 26 \sin^2(\gamma/2)$.

In order to study the effect of hardness of the stronger material on the wave size, we have performed the following experiments. Three steel samples with different hardness (H1=130-160 HB; H2= 32-34 HRC; H3 = 44-46 HRC) and one aluminum sample 23x25x125 mm, were clad by a copper plate of 1 mm thick, its hardness was 70 HB in accordance with the schematic shown in Fig.10.

11. V. I. Lysak and S. V. Kuz'min, Explosion Welding. Mashinostroenie-1, Moscow, 2005 (in Russian).
12. V.I. Mali. Peculiarities of glancing collision of plates made of dissimilar metals // V Symposium on Explosive working of metals, Gottwaldov, Czechoslovakia, October 12-14, 1982. – C. 53 – 59 (in Russian)

Schematic of experiment

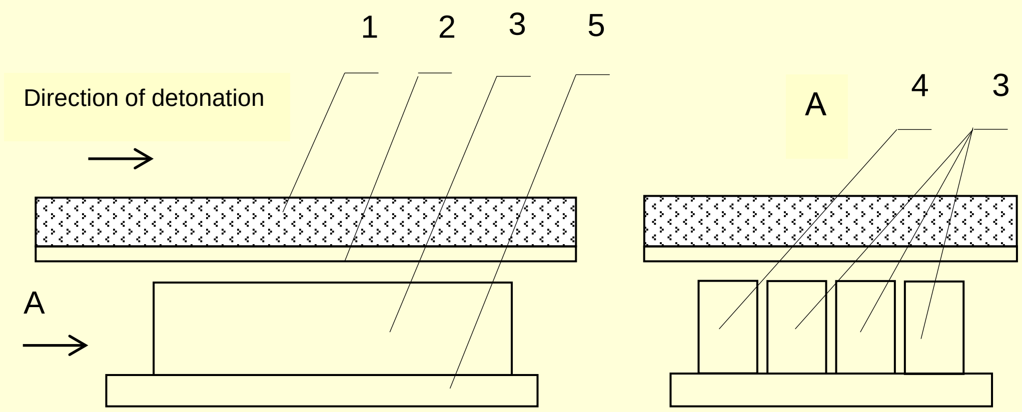


Fig. 10. Welding of a copper plate with the materials of different hardness: 1– explosive charge; 2 – copper plate; 3 – steel samples; 4 – aluminum sample; 5 – base

In this experiment the collision conditions are evidently similar on each sample. Before the welding, the roughness of the welded surfaces was made to be Ra = 0.16 - 0.32 micrometer. The measured detonation velocity was D = 2.8 km/s, the calculated collision angle γ =12°. After the welding, micro-slices were made from the resulting bimetal samples. Wave size was measured in three zones within 20 mm, in the center, and 10 mm from the sample edge. Measurement results are presented in the Table.

Table

Hardness	Section 1		Section 2		Section 3		Average	
	λ	*a*	λ	*a*	λ	*a*	λ	*a*
HRC45	0.302	0.071	0.283	0.071	0.267	0.071	0.28	0.07
HRC 33	0.38	0.114	0.401	0.114	0.362	0.114	0.38	0.11
HB 145	0.457	0.157	0.485	0.157	0.442	0.157	0.46	0.16

Note: values of λ and a are shown in millimiters

Effect of strength on wave formation

As is seen from the Table as the hardness of the steel samples rises, the wave size decreases. Note that the varying hardness makes the strongest effect on the wave amplitude. When hardness rises from a softer to harder steel sample by about 3 times, the wave length changed by 1.6 times, whereas the amplitude changed by 2.2 times.

When the hardness of materials differs by more than 10 times, the boundary is waveless [13]

13. B. Zlobin, V. Sil'vestrov, A. Shtertser, A. Plastinin, V. Kiselev. Enhancement of explosive welding possibilities by the use of emulsion explosive // Archives of Metallurgy and Materials. 2014, vol. 59, p.1599-1604.

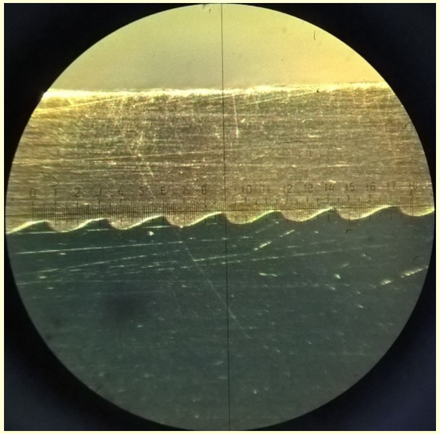


Fig. 11. Macrosection of the copper-steel weld. The steel hardness is HRC 45

Effect of density on wave formation

The hardness of the steel sample is HRC 45, the hardness of the aluminum sample is HB 40. Thus, the samples differ in hardness by 10 times, by density about 2.8 times. The joint area on the copper-steel interface is of evidently wavy character (Fig. 11), but there are no waves on the copper-aluminum interface. It means that the density of the welded metals influences significantly the character of the deformation processes and wave size on the joint boundary.

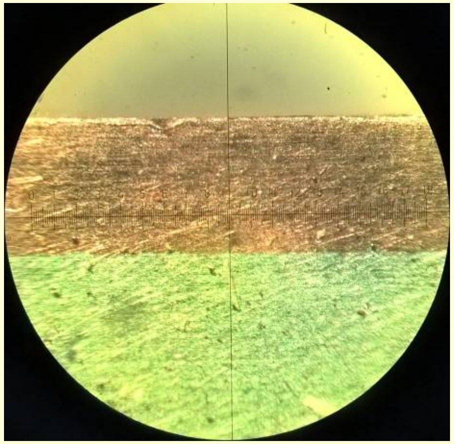


Fig. 12. Macrosection of the copper-aluminum weld. The aluminum hardness is HB 40

Welding with the intermediate layer

For the successful explosion welding of two metals with high strength and low plasticity, usually an intermediate layer of a more ductile material is used. The most common explosive welding with a technological sub-layer is made in the following way. On the 1st stage, a thin sub-layer is welded to the thicker (massive) plate. Often thin copper foil or band is used. Then the steel plate covered with the technological sub-layer is clad by the main flyer sheet. At the cladding sheet of big thickness, the waves may be big since the size of the waves depends on the thickness of the flyer plate. Fig.13 presents the micro-section of the welding area in a layered composite made by the described procedure. There are cracks starting from the wave crests.

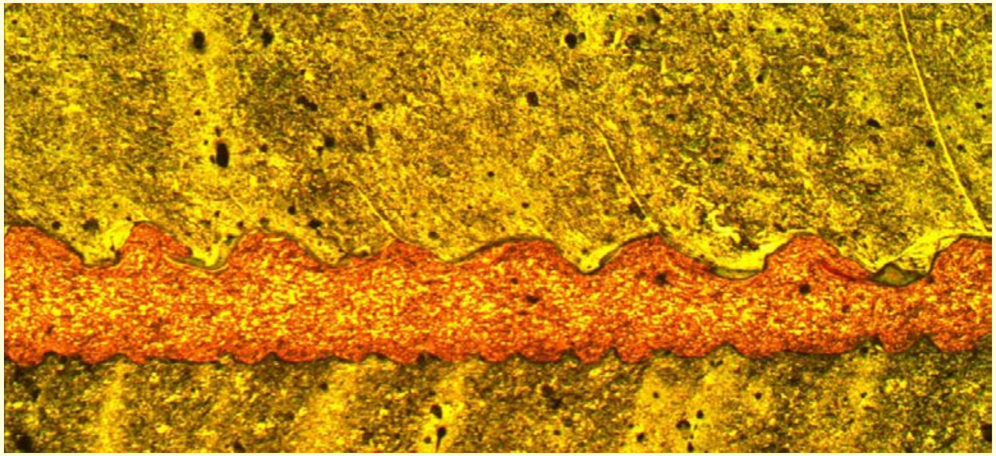


Fig. 13. The waves and cracks on the steel-copper boundary

Welding with the intermediate layer

Interesting peculiarities of the wave formation are noticed in the experiments of welding of the same plates but in another succession. At the 1st stage, the steel plate of 3 mm thick, hardness HRC 45, was clad by the copper foil of t = 0.3 mm. Then this bimetal plate was thrown on the steel sample (t = 25 mm, hardness HRC 42-43). It was found that the wave size in this case depends only on the copper interlayer thickness (Fig.14) and. Hence the waves are smaller than in previous experiment and no cracking is observed.

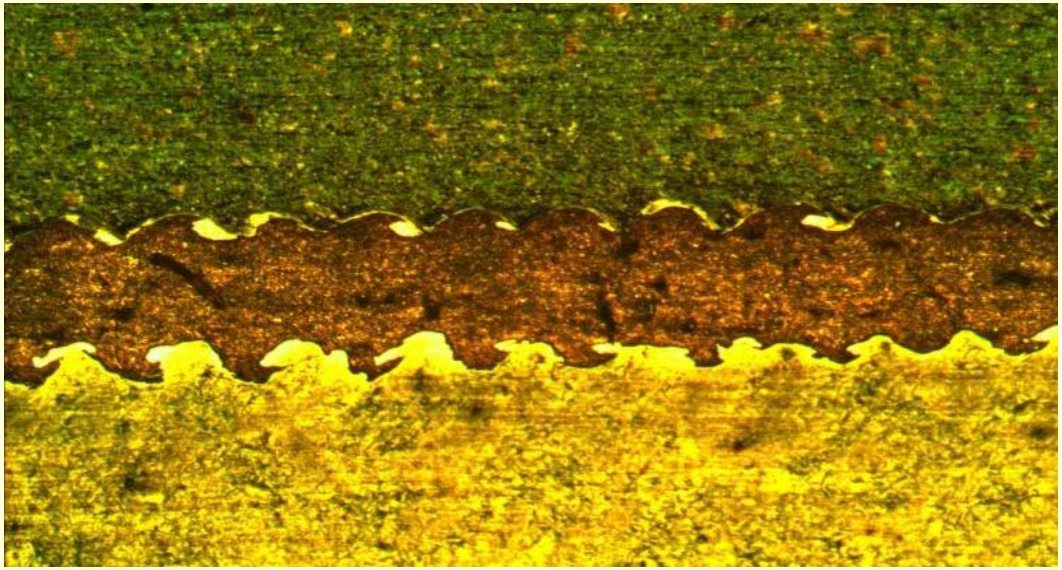


Fig. 14. The waves on the steel-copper boundaries at the explosion welding of hardened steel plates in the case of bimetal flyer plate.

Summary

1. The jet of copper particles provides formation of the strong bond between the plates of a high-strength steel in the low-speed collision mode. This confirms that the main input in the creating bonding conditions is made by the less strong material, which is the source of jetting.
2. There are always waves in a bonding zone, their amplitude decreases and even tends to zero when the difference in strength and density of welded materials increases.
3. At the explosive welding of high-strength metal plates through a thin ductile interlayer, the wave size on the joint boundary can be reduced if interlayer on the first stage of process is welded to the flyer plate and then the bimetal flyer plate is welded to the thick base plate. This is a way to avoid cracking.

References

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