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EXPLOSIVELY WELDED MATERIALS BOND ZONE: MORPHOLOGY AND CRYSTALLOGRAPHY

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Abstract. The physical nature of the wavy interfaces formation under extreme dynamic loading conditions typical for explosive welding was established using the example of copper-copper bimetallic joint structure. It was shown that such surfaces occur in a complex hierarchical subordination of the shear and rotational modes of metal plastic flow, both realized at the macro-, meso-, and micro- levels.

1. INTRODUCTION

One of the urgent problems of modern physics of strength and plasticity is to understand the elementary mechanisms of metals plastic flow under extreme loading conditions. In this connection, great attention is paid to explosive welding. It is believed that the plastic flow particularity in a narrow bond zone (NBZ), formed during dynamic impacting of two flat metal plates, and structural features determine the weld joints quality and mechanical properties [1–3].

Based on the general physical concepts, we can assume that when two crystalline solids are impacted, the plastic flow in a narrow bonds zone (NBZ) should appear on three different deformation (macro-, meso-, and micro-) levels [4,5]. On the macro-level covering hundreds of microns or more the plastic flow of metal, except shear, should include large-scale rotational modes, which cause characteristic vortices forming [6,7]. On the meso-level, ranging to a few microns, fragmentation should be observed [5–9] as well as plastic flow must be realized due to rotational-shear processes localized at the boundaries of the fragments. On the micro-level (~ 100 nm) translational shears are realized by individual lattice dislocations moving.

The aims of the present study are a) a systematic investigation of the defect structure by means of complementary methods such as optical metallography, scanning (using EBSD-analysis) and transmission electron microscopy **at the same area of narrow bond zone (NBZ)**; b) proving experimental evidence for structural deformation levels (macro-, meso-, and micro-) and identifying plastic flow features on each of them.

2. MATERIAL AND METHODS

In this paper we have studied a model explosive welding copper-copper joint, obtained under following conditions: plate collision velocity at the impact point was V_c = 500 m/s, impact point velocity was V_p = 2120 m/s, impact angle was γ = 13,4°, top (cladding) and bottom (base) plate thicknesses are 3 mm. NBZ metallographic structure was studied on optical microscope Axio Observer A1m (Carl Zeiss). EBSD maps were performed and analyzed

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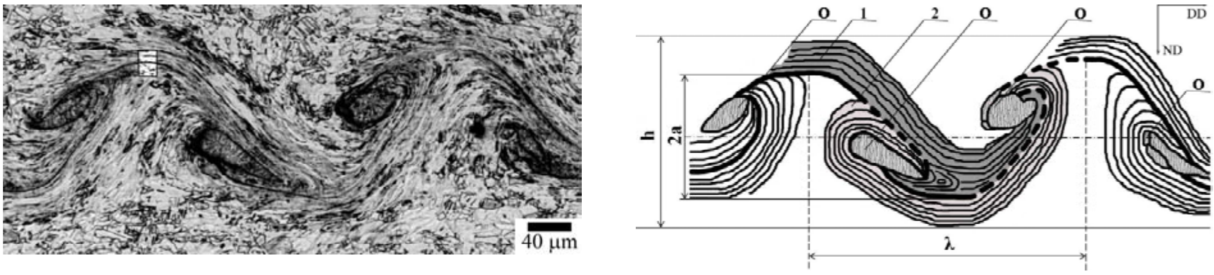

Fig. 1. a – metallographic structure of NBZ of a longitudinal section of bilayer copper-copper plate (area investigated by EBSD-analysis and TEM is marked by a bright rectangle); b – scheme of the plastic stream typical structure element (top (1) and bottom (2) plates are marked with a tone); areas where the interface line (marked with bold line) is lost are marked with a dotted line; *O* – melting area; *h* – NBZ width; 2a – wave height, λ – wavelength, DD – detonation direction, ND – normal direction.

in a scanning dual beam electron-ion microscope Quanta 200 3D FEG, equipped with a Hikari EBSD Detector. The fine structure was investigated in a transmission electron microscope Tecnai S-Twin G2 30 using an accelerating voltage of 200 kV. The specimens for the study were prepared by a specially developed method described in [10].

3. RESULTS AND DISCUSSION

3.1. Macro-level

The metallographic structure of a weld joint of a longitudinal section of bilayer copper-copper plate is shown in Fig. 1. The interface trace in the section plane is a line with an evident periodicity, which in the first approximation we can describe with the wavelength λ = 285 µm and the amplitude a = 60 µm. Each wave hump has a characteristic form, which can be described as a “cap” of a “mushroom” bulged in the detonation direction (DD). Two areas of melting metal with a characteristic dimension of 40 mm are periodically located under each “cap” (Fig. 1a). Obviously, these interface features are due to the heterogeneity of plastic deformation.

The metallographic structure far from the interface (both at top and bottom plates) is slightly different from the initial structure typical for well annealed copper and consists of a recrystallization twins of sizes between 15-20 µm. The weak distortion of twin boundaries indicates that the major part of the plate material undergoes a small (ε ~ 0.1) plastic deformation during explosive welding.

The material is anomalously strong deformed in narrow bond zone (NBZ), adjacent to the interface. Thickness of this zone h = 180 µm is about 1.5 times exceeds the value of 2a. Plastic deformation is so strong that the original metallographic structure inside NBZ seems to be completely destroyed. Grain boundaries (recrystallization twins) have disappeared. Unsystematically located dispersed crystallites with size of 4-6 µm are just observed, which probably correspond to the initial grains parts (recrystallization twins), milled during severe plastic deformation.

A more detailed observation of NBZ structure found that the material plastic flow within the NBZ is not homogeneous over its volume and is localized at specific extensive areas directly adjacent to the interface line and repeat its shape with their curved trajectories. They are discrete and have finite length approximately equal to the wavelength λ (~300 µm). Their width is not constant and varies from 30 to 60 µm. Let us call these unusual macrostructure elements **plastic streams**.

Plastic streams in the top plate are generated over the wave hump, fall down along the right side of the bulged “cap” reaching its end and branch. One part of the stream screws under the “cap” and forms a vortex there (Fig. 1b). In the center of the vortex, where the intensity of plastic flow reaches a maximum, the heat is sufficient for local metal melting, evidenced by the coarse crystallite areas appeared during the subsequent crystallization in these places. The second part of the plastic stream goes up to the rising branch of the next wave hump and form the next vortex under the left part of the bulged “cap”, where the following melting area is formed. The development of the plastic stream is stopped at this stage. The next top plate plastic stream are generated over the next wave hump and then the process described above is repeated cyclically.

Plastic streams in the bottom plate are generated under wave trough lower part, as if they squeezed original material during its formation, then move upward and form the “stipe”. As we can see from Fig. 1, each “stipe” is formed by two streams

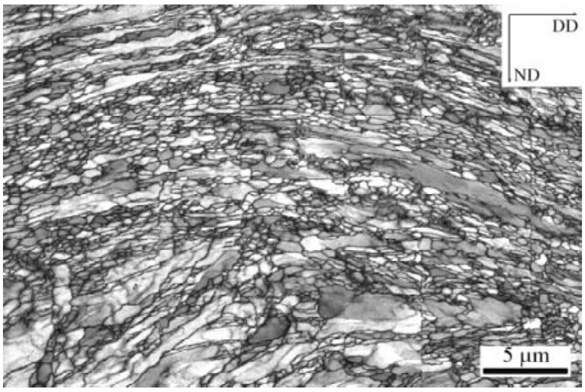

Fig. 2. Misorientation map of crystalline micro-regions (fragments) distributed in the plastic stream (EBSD-analysis is from the area marked by a bright rectangle in Fig. 1a): DD – detonation direction, ND – normal direction.

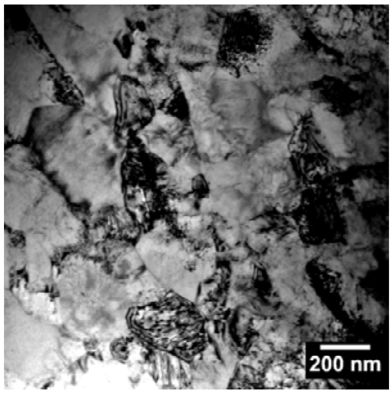

Fig. 3. TEM observation of typical microstructure of the plastic stream in the area marked by a bright rectangle in Fig. 1a: DD – detonation direction, ND – normal direction.

approached from two adjacent wave troughs. Then the streams climb up, met with the top plate material, spread sideward forming the bulged cap. The details of the processes described above are visualized in Fig. 1b.

What is the physical nature of the origin of plastic streams? If we stay within the bounds of the well-known Bahrani model [11] or close to the hydrodynamic models [1-3], the structural features discussed here should be interpreted as a visualization of compressed reverse cumulative jets between cladding and base plates. It should be kept in mind that the origin and the development of the reverse cumulative jet is possible if the mechanical behavior of metal is similar to a liquid-like or an amorphous material behavior. Therefore if the hydrodynamic models are correct: 1) the inverse cumulative jet should be separated with a abrupt boundary from the surrounding material, maintained the crystal structure during the co-deformation process; 2) the material structure inside the inverse cumulative jet must carry features of crystallization processes, which occur during amorphous metal cooling and the crystalline phase formation.

However, the presented observation shows that it is not so. First, plastic streams, observed in our experiments, originate and finished in a deformed material of cladding and base plate continuously and don't have distinguished boundary which separate them from the surrounding material. Second, there are unambiguous indications that the metal flow inside the plastic stream is not homogeneous, as for an amorphous or liquid-like material, but discrete, which is typical for a crystalline solid. Indeed, in Fig. 1, shows that plastic streams consists of a set of parallel and thin deformation bands (up to 20 in each stream), a thickness of 2 - 5 microns. In order to determine the nature of these and other structural features of plastic streams in more detail, it is necessary to switch to the meso-level observations.

3.2. Meso-level

The orientation map obtained by EBSD-analysis of polycrystalline regions in the plastic stream area, framed by a bright rectangle in Fig. 1a, is shown in Fig. 2. The area is located approximately at the top of the wave hump and captures top and bottom material of the plates. Analyzing the presented EBSD map, we should recognize that the plastic stream body consists of many very small, slightly elongated in interface line direction crystallites, and having mostly misorientation angles of more than 15 degree (the high angle boundaries fraction is 83%). The transverse dimension of the crystallites is about 200 nm with grain shape aspect ratio of 0.3. The elongation direction is parallel to the interface line. The crystallites are not chaotically distributed, but combine in bands to a thickness of 10-30 pieces. The length of these bands is 20 -50 μm. These bands structure are similar to the classic deformation bands at the stage of developed plastic deformation [5]. Their thickness, length and direction correspond to structural units identified in the plastic streams (Fig. 1a).

The experimental evidence referred above indicates that we deal with the classical crystal fragmentation during developed (severe) plastic deformation [5]. Therefore, crystallites are fragments formed during the plastic deformation and high angle boundaries are boundaries which have their origination in deformation but not recrystallization.

3.3. Micro-level

In order to obtain direct evidence that we deal with fragmentation, developed at a certain stage of dislocation structure evolution, we have analyzed the structure of the crystallites formed inside the plastic streams by transmission electron microscopy. Let us refer for this purpose to Fig. 3, which shows that the microstructure is typical for the area investigated above (Figs. 1a and 2). It is a classic fragmentation structure, corresponding to developed stages of plastic deformation of crystalline solids [5]. The transverse dimension of the crystallites is about 200 nm. They are elongated along the plastic shear directions. High density of dislocations is observed within the fragments boundaries. Dislocation density does not exceed 10^{10} cm^{-2} in the volume of fragments. Fragments exhibit misorientation angles of more than 15 degrees.

4. CONCLUSION

The physical nature of the wavy interfaces formation under extreme dynamic loading conditions typical for explosive welding was established for the first time in this research. It was shown that such surfaces occur in the complex hierarchical subordination of the shear and rotational modes of metal plastic flow, both realized at the macro-, meso-, and micro- levels.

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