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MICROSTRUCTURE FORMATION DURING INHOMOGENEOUS DYNAMIC DEFORMATION PRODUCED BY STEEL PLATES BONDING

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Abstract. With the electron backscattered diffraction (EBSD) technique the non-uniform microstructure forming under conditions of inhomogeneous dynamic deformation were investigated by the example of explosively bonded steel plates. The layers with fine-grained recrystallized structure as well as deformation-induced fragmented structure are distinguished within the narrow interface zone undergone intense deformation. The study was focused on the mechanism of the fragmented structure formation. Within the layers subjected to mediate deformation, the deformation-induced branching boundaries, along which the misorientation gradually changes from the angles above 30° to the ones below a tolerance angle of 2°, have been examined. The development of such boundaries was shown to demonstrate early stage of the fragmentation process.

1. Introduction

The development of materials for advanced structural applications is now shifting from the optimization of bulk materials to the synthesis of compounds that contain metallurgical joints. Strength properties of the joints are controlled by the microstructure forming within narrow interface zone. Hence, the design of such metallic compounds must be built on a detailed microstructure-oriented understanding. Nevertheless, there is only limited literature data dealing with the microstructural formation occurring close to the bonding interface.

The interface formed during explosive bonding generally has more or less wavy relief and a large plastic deformation is concentrated in the interface zone [1-5]. Recently, the deformation structures typical for this zone have been studied by the example of copper/copper cladding [6-8]. Using optical metallography, elements called plastic streams were identified, which structure is produced due to the macroscopic shear instability. At the smaller scale these plastic streams consist of highly misoriented (“fragmented”) microstructure formed by deformation-induced boundaries (DIBs) and deformation twins.

Sharp strain gradient occurring across the interface zone gives an opportunity to investigate the evolution of deformation structure with increasing strain on a single explosive bond. In the present work, such a study has been carried out by the example of steel/steel cladding. Special attention is attracted to a mechanism of the fragmented structure formation near the interface.

2. Experimental

The explosive bonding of steel plates (low carbon steel Fe-0.18C-0.21Si-0.33Mn with average ferrite grain size of 15.1 μm) has been performed using the impact angle 12.6° and the detonation velocity 2420 m/s. The thickness of the steel plates was 2.5 mm.

Metallographic examination was carried out using the optical microscope Axio Observer A1m (Carl Zeiss). Light optical image (Fig. 1) shows the formation of wavy interface of the explosive joint. It is seen that every plastic stream gradually develops spreading along the interface, but in a certain moment converts in a vortex, inside which a local melting of metal occurs.

The specimens for microstructure analysis were cut from regions near the wavy interface in a plane parallel to the detonation direction and normal to the plane of cladding. After a proper polishing, they were studied using a Quanta 200 3DFEG scanning electron microscope equipped with EBSD facility with OIM software. Orientation mapping involving automatic beam scanning was used with a scan step size of 0.05 μm. Since the experimental accuracy of the EBSD method does not exceed 1° [9], the subboundaries below 2° were excluded from the consideration. Besides, tolerance angle of 3° was used for misorientation angle histograms in order to avoid too high low-angle peak.

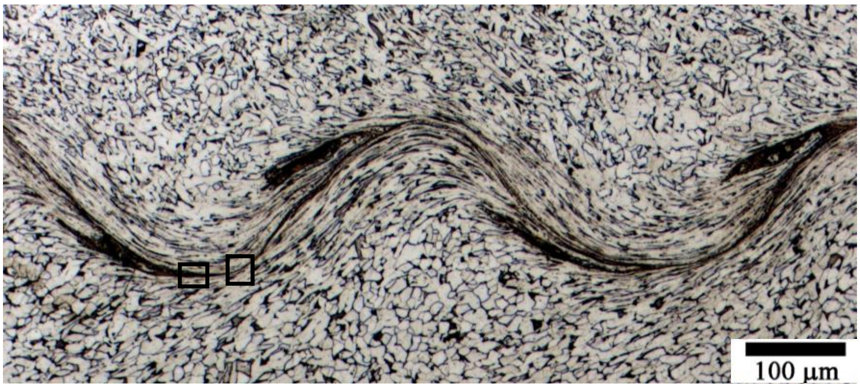

Fig. 1. General view of the wavy interface of the joint (the top plate is the flyer plate and the direction of detonation is from left to right). Rectangular frames indicate regions, from which specimens 1 (right) and specimen 2 (left) for microstructure investigation have been cut.

3. Results

Figure 2 shows EBSD boundary maps of the specimens examined. While the microstructure of interface zone is strongly non-uniform, three types of microstructure can be discriminated according to their morphological features. The domains with a single-type structure are denoted as D1, D2 and R in Fig. 2.

Within the domains D1 initial grain boundaries are well distinguished, while a deformation substructure formed inside the grains mostly consists of low-angle boundaries. It is seen that the most developed DIBs are extended in the line of grain elongation (some of them are indicated in Fig. 2 by arrows). The initial grains are elongated along the bonding interface, therewith their thickness is about 5 μm. As average initial grain size is 15 μm, a local true strain in these domains can be roughly estimated as ~1.

Alternatively, initial grains are hardly distinguished within the domains D2. Here, the most of DIBs are high-angle and extended along the bonding interface. This structure is morphologically similar to the fragmented band structure of severely deformed metals [10, 11]. Thus, relatively large local strain, considerably larger than 1, can be expected in this region.

The microstructure of domains R as compared with domains D2 consists of more equiaxed crystallites, and at that the majority of low-angle boundaries are disappeared. These are apparent morphological features of continuous recrystallization (this phenomenon sometimes is referred to as “recrystallization in situ”), which was observed earlier in metals subjected to large plastic strain [12]. One can note inside the domain R of specimen 2 regions, whose structure keeps deformation band morphology demonstrating thereby very early stage of recrystallization.

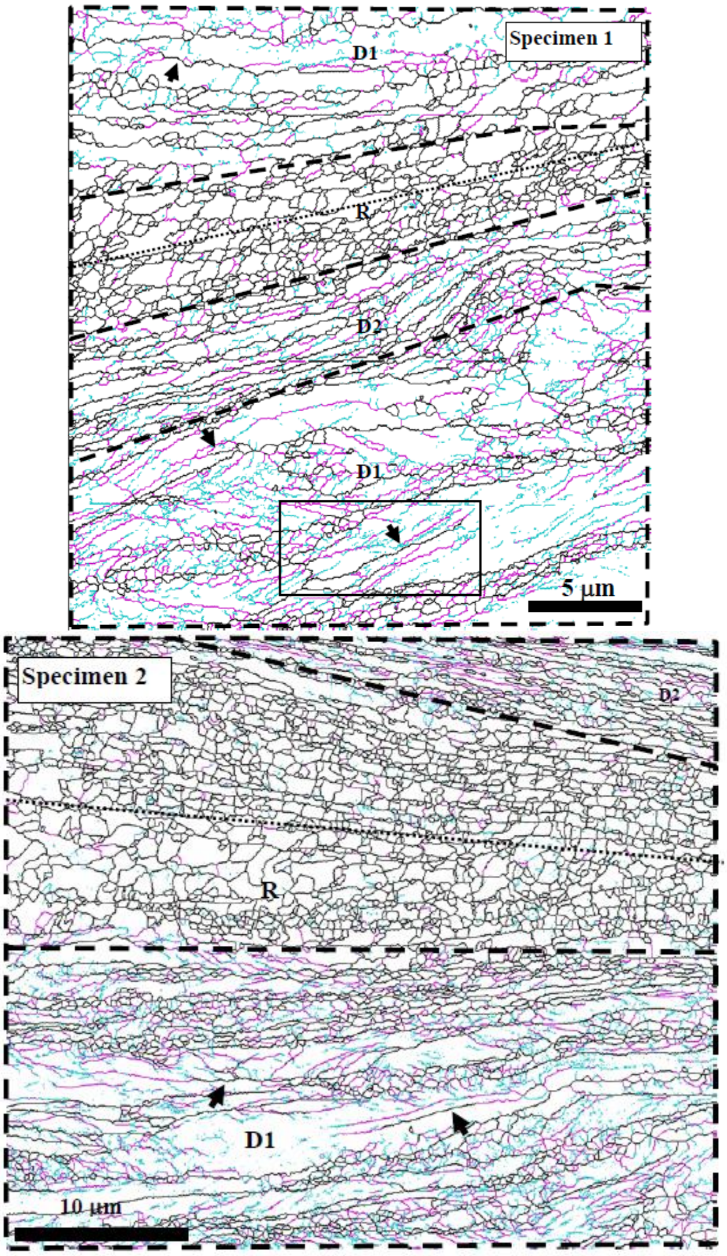

Fig. 2. EBSD boundary maps of the interface zone regions. Domains experienced mediated deformation, large deformation and recrystallization are denoted as D1, D2 and R, respectively. The cyan, magenta and black lines indicate the boundaries with misorientations $2 < \theta < 5°$, $5 < \theta < 12°$ and $\theta > 12°$, respectively. Dotted line shows hypothetical location of a bonding interface.

The bonding interface seems to be located just within this layer of extremely fine grained structure, though its apparent indication are not detectable.

The misorientation distributions obtained for the domains examined (Fig. 3) support above conclusions based on the microstructure morphology consideration. At that, domains of the same type demonstrate similar distribution character. In particular, low-angle peak is predominant for the domains D1. It has a shape typical for a DIBs misorientation distribution developing at small to mediate strain [13]. For the domains D2 the second, high-angle, peak becomes stronger in accordance with considerable increase of local strain level. When shifting from the domain D2 to R, this high-angle peak retains without significant changing its shape (increased frequency near 60° may be due to annealing twin boundaries appeared in the course of recrystallization), while the low-angle peak mainly disappears in accordance with the supposition concerning a recrystallization.

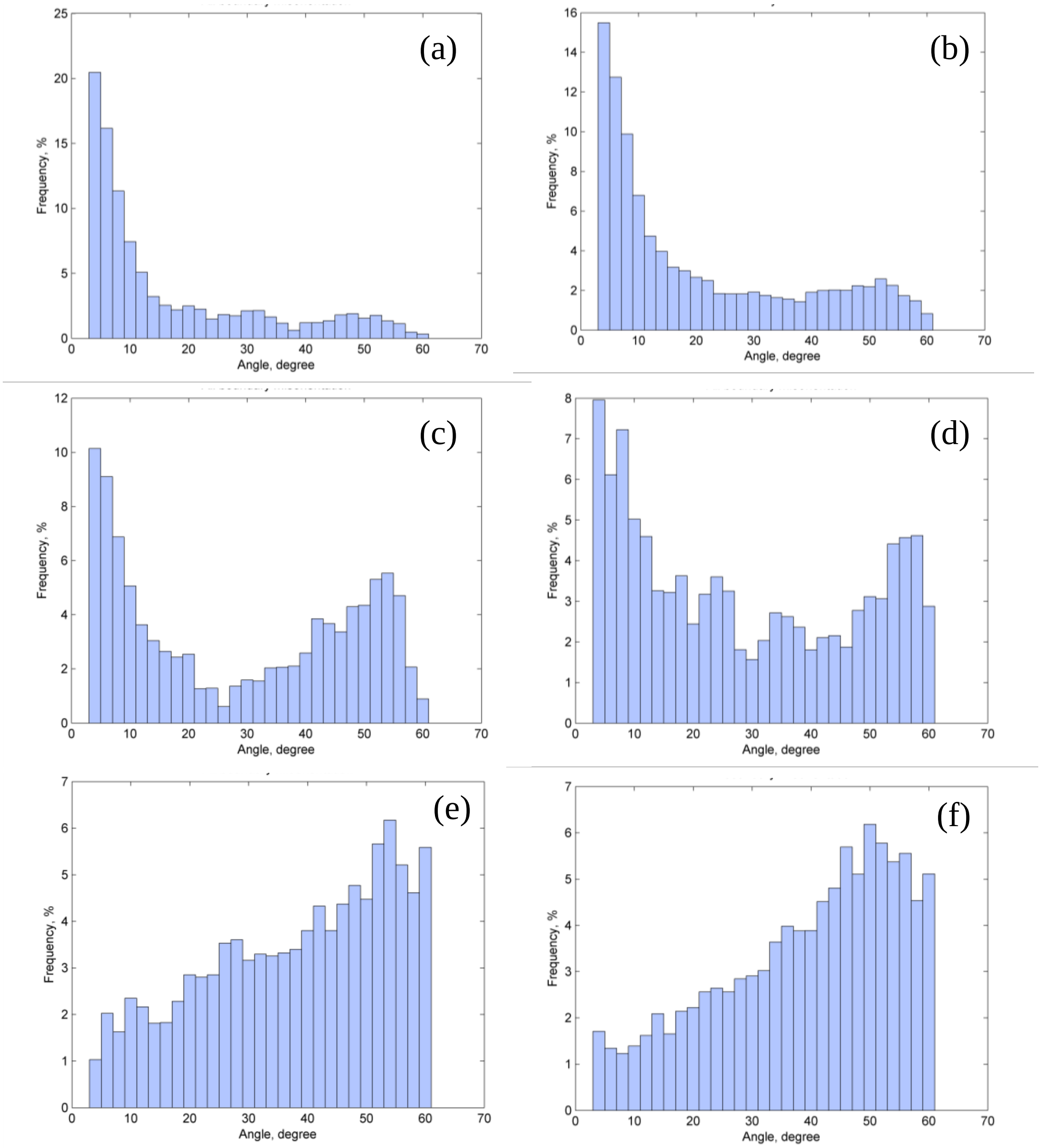

Fig. 3. Misorientation distributions obtained for domains D1 (a,b), D2 (c,d) and R (e,f) separated in Fig. 2 in specimen 1 (a,c,e) and specimen 2 (b,d,f).

4. Discussion

Comparison of microstructure examined by EBSD technique with the light optic image shown in Fig. 1 enables us to suggest that the zone of fine grain microstructure (domains R) corresponds to the interface between explosively welded plates. Since plastic deformation is expected to reach its maximum just at the interface, the recrystallization is developed here due to adiabatic character of high strain rate deformation [2]. When shifting from the interface the plastic strain decreases and becomes insufficient to provide driving force for recrystallization. Notice that regions of fragmented microstructure (domains D2) cannot be clearly distinguished on each side of the interface. At that, such a region is observed above recrystallized zone in the specimen 1, but below it in the specimen 2. That indicates complex strain distribution within the plastic stream.

As it was mentioned above, the significant strain gradient occurring across the interface zone makes it possible to investigate the development of fragmentation process. Actually, while strongly fragmented structure takes place in domains D2, one can find evidence of an earlier stage of the fragmentation in the domains D1. Multiple pieces of low-angle boundaries are observed in the latter (notice that only the pieces with misorientation θ>2° are shown in the maps). They compose common deformation substructure of band-like or irregular morphology, depending on the grain orientation [10, 14]. At the same time, some DIBs (marked by arrows in Fig. 2) stand out because of their rather high misorientations. These boundaries are generally conjugated with initial grain boundaries and extended along the direction of the grains elongation. Besides, they often appear by pairs and, in fact, demonstrate initial stage of the formation of the highly misoriented band structure, which then reaches a developed state in the domains D2.

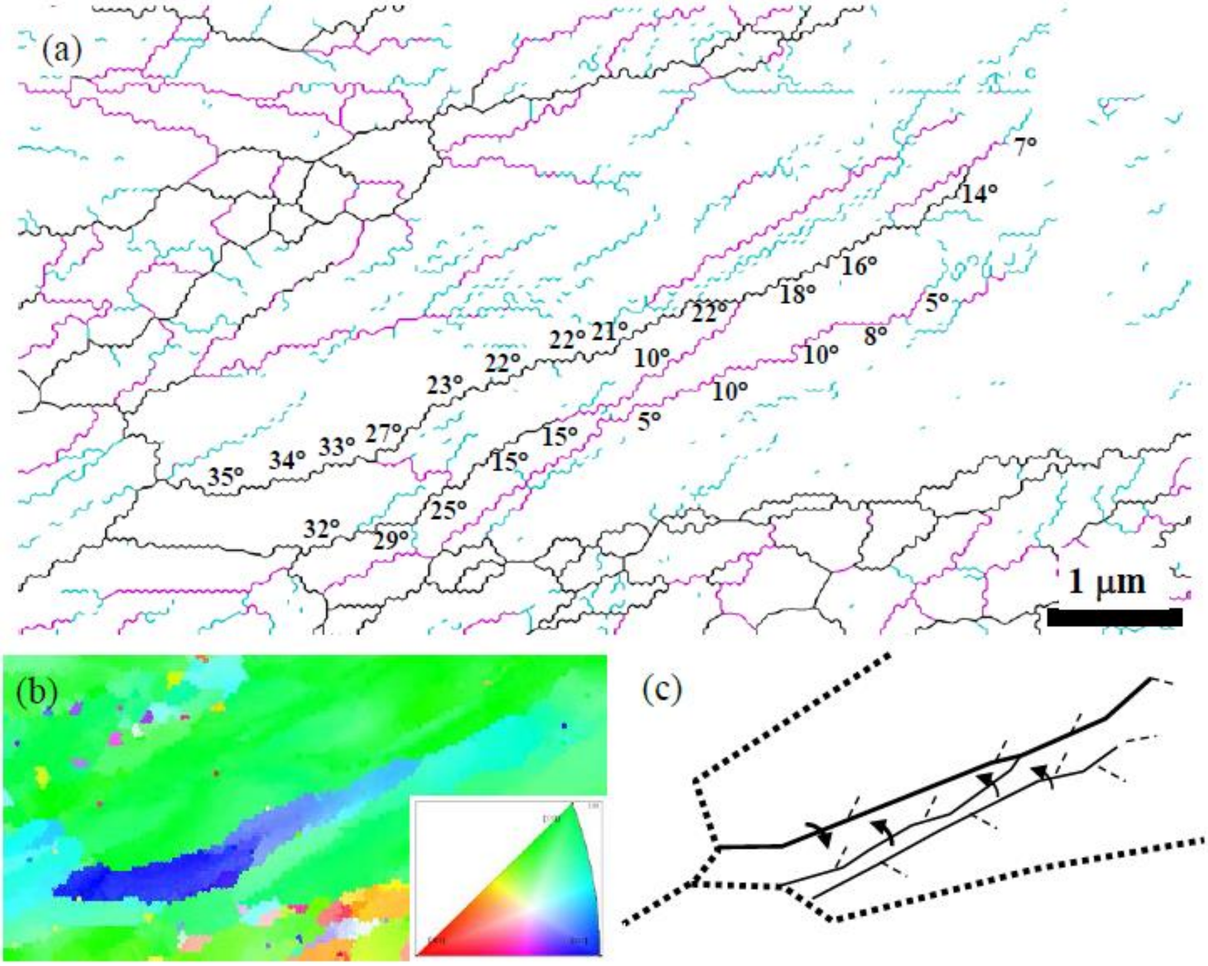

Fig. 4. Magnified image of the region selected in the domain D1 of specimen 1 in Fig. 3: a – boundary map showing local misorientations along some DIBs; b – IPF orientation map; c – scheme of the structure arrangement. Grain boundaries are shown by dotted lines and DIBs by full lines. Directions of rotation at the DIBs are indicated. Assumed subboundaries with misorientation <2° not shown on the map are drawn by thin dashed lines.

An example of such a structural evolution with local misorientations determined along DIBs is shown in Fig. 4. Here, the boundary map with local misorientations indicated along some DIBs is supplemented by an orientation map and a scheme. The upper, more developed, DIB is shown by thicker line at the scheme, Fig. 4c. It has a high angle misorientation on a major part of its visible length. At that, the misorientation gradually decreases with displacing from the initial grain boundary. In much the same manner the misorientations change at the lower DIBs, but with approximately alternative direction of rotation resulting in the appearance of the band-like fragment as it is seen in the orientation map, Fig. 4b. The change of misorientation along a boundary is realized through branching low-angle subboundaries, some of which can be found in the map, Fig. 4a. However, overwhelming majority of these subboundaries have misorientation angles lower than 2° and therefore they are not shown in the map.

The branching boundaries with gradually changing misorientation were observed already in early studies of the fragmentation using the transmission electron microscopy technique [15]. Recently, DIBs of this kind has been demonstrated by means of the EBSD technique in deformed titanium [16]. According to the approach described in Ref. [8], their development is associated with the existence of nonclosed (“terminating”) subboundaries. The latter appear particularly near the grain boundary junctions or ledges, where junction disclinations can be formed under plastic deformation [17]. The power of junction disclination permanently increases in the course of deformation resulting in the increasing internal stress, which relaxation, in its turn, leads to a growth of misorientation along the nonclosed subboundary. This growth is limited, however, by the fact that the misorientation near a “terminating line” cannot differ substantially from ~1° by energy reason. Once it becomes higher, a primary nonclosed boundary branches and a side branch splits out of it. In this way, the nonclosed DIS with gradually lowering misorientation and side branches forms. Under certain conditions considerably different combinations of slip systems become to operate at either side of the boundary leading to accelerated increase of its misorientation as well as accelerated propagation of the boundary into the grain volume. This process appears to be energetically favorable if another DIS with alternating misorientation is generated nearby. The example shown in Fig. 4 seems to be the result of just such structure evolution.

It is worth noting, that while multiple subboundaries occurring inside deformed grains contribute to the low angle peak (angles $< 20°$) of the misorientation distribution, the DIBs similar to those considered above provide enhanced fraction of the misorientation angles of 20…30° in the domains D1, Fig. 2a,b. With increasing strain and developing fragmentation these DIBs increase their misorientation and, as the result, the misorientation distribution evolves to the form observed in the domains D2, Fig. 2c,d.

5. Conclusions

The EBSD technique has been employed to study the microstructure near bonding interface of steel/steel joint developed under conditions of highly inhomogeneous dynamic deformation. The following conclusions can be drawn.

1. The near-bond layers of parent plates underwent intense plastic deformation during formation of the wavy bonding interface. The macroscopic characterization allows to describe this deformation as the development of plastic streams, which, on the smaller scale level, have a complex misoriented structure.
2. The layer with strongly fragmented deformation band structure as well as the layer with fine-grained recrystallized structure can be distinguished within the interface zone based on the results of EBSD analysis.
3. When shifting from the interface, the layers undergone mediate deformation can be observed. Within these layers, the deformation-induced branching boundaries, along which

misorientation gradually changes from the angles above 30° to the lowest ones, have been found and examined. Such boundaries often constitute dipole configuration showing early stage of the formation of the fragmented band structure.

Acknowledgments

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