

Orientation changes near the interface of explosively bonded (carbon steel)/Zr700 sheets

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Abstract. The microstructure and texture of explosively welded carbon steel (base) and Zr700 (flyer) plates were characterized by means of scanning electron microscopy equipped with a high resolution electron backscattered diffraction facility. The orientation maps demonstrate that the deformed zones near-the-interface are composed of several layers, the width of which depends on the applied bonding parameters. For both metals, the very thin layer of ultra-fine grains directly adheres to the interface. In the areas more distanced from the interface, the structure evolution depends on the plate material. In the case of a Zr 700 sheet the second layer is formed by highly dislocated (sub)grains, which progressively evolve, towards the structure composed of only lightly deformed grains. In the case of a carbon steel sheet, the second layer near the interface was composed of flattened grains.

1. Introduction

The mechanism responsible for the creation of a high strength bond during explosive bonding is a major unresolved problem. Explosive bonding is the process of metal joining as an effect of a collision of plates at high velocities by a controlled detonation of an explosive charge which propel a flyer plate towards a fixed metal base plate [1-3]. At the 'collision point', the perfectly clean surfaces are brought together under very high pressure. The high velocity oblique collision will 'produce' a *high temperature* and a *severe shear deformation* near the collision line in a very short time. This causes a local melting of the bonded metals, simultaneously with the severe plastic deformation of the interfacial layers, e.g. [1-7]. The plastic deformation leads to important structural and textural changes in the subsurface areas of the bonded plates and strongly affects the properties of the clad. The literature data on the cladding of steels with the use of zirconium and its alloys is very limited and only contributory works referring to selected aspects of the problem can be found, e.g. [7-9]. Therefore, the purpose of the present work is to identify the microstructure features and the corresponding texture changes occurring during dynamic loading in the clad (carbon steel)/(zirconium alloy)-type. We provide micro-scale analyses in the layers directly adhering to the interface. The basic research technique employed local orientation measurements based on scanning electron microscopy (SEM) equipped with the electron backscattered diffraction (EBSD) facility.

2. Experimental

The sheet of carbon steel (type P355NL2), 22 mm thick, as the base plate and the sheet of a Zr 700 alloy, 3.15mm thick, as a flyer plate were used for the clad preparation. A system of



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parallel arranged plates was applied to manufacture two-layered clads. The sizes of the plates were 300 x 500 mm². The clads were manufactured with two initial stand-off distances between the sheets ($h = 3$ and 4.5 mm) and at two detonation velocities ($V_D = 2000$ and 2200 m/s). All the samples were cut-off from the 'properly' bonded clad (in the 'as-bonded' state). The characteristic of the interfacial microstructure and the texture was performed by means of SEM, with the use of Zeiss Supra 55VP, equipped with a field emission gun and the EBSD facility. The orientation maps were created in the beam-scanning mode with the step size ranged between 50 nm and 100 nm in the ND-ED section (where: ND and ED are the normal and explosive directions, respectively).

3. Results and discussion

A detailed characteristic of microstructure in layers near-the-interface was performed against the background of the orientation maps displayed as a 'function' of the IPF colour code as well as the band contrast, as presented in Figs. 1a and b, respectively. The corresponding particular areas textures are presented in Fig. 1c and d, for the zirconium and carbon steel plates, respectively. The structure of the base plate (carbon steel) near-the-interface was composed of a very thin layer (1-2 μ m in thickness) of fine equiaxed grains and a broader layer of flattened grains. The dimension of the flattened grains in the ND is at least one order smaller than that along the ED and TD. They were bent in the direction of the collision point (line) movement and their curvature reflects the operation of the shear stresses in near-the-interface layer. However, this directionality in the grain geometry was lost as the distance from the interface increased. In the areas distanced about 100 μ m from the interface, nearly globular grains were observed, but still with an increased density of the dislocations (marked as low angle grain boundaries) inside the grains' interior. In the case of the flyer plate (Zr 700) the maps show a fine-grained layer, directly adhering to the melted zone. Those equiaxed grains (identified by the system as zirconium) form a layer of 5 – 20 μ m in thickness (Fig. 2). However, a layer of flattened and/or bended primary grains was not observed in the zirconium plate.

The band contrast map revealed areas of a lower quality of the Kikuchi patterns (as darker areas) occupied by a melted zone and macroscopic shear bands. In the case of the melted zone, the low quality of the diffraction patterns results from the amorphous and/or ultra-fine-grained structure as well as the non-equilibrium chemical composition of the phases that are formed [4, 5, 7]. In the areas occupied by the melted zone, the layer of a very low band contrast is composed of a mixture of amorphous and (ultra-fine-grained) crystalline phases, as presented in [4 - 8].

The formation of the fine-grained structure near the interface is a common characteristic observed in both welded plates. The strongly refined structure is especially well-visible inside the wave crest. This area was always composed of very thin (with the thickness below 200 nm) and elongated grains, separated by large angle grain boundaries [6]. These thin grains were strongly curved and imitated well the rotational character of the material displacement during the wave formation, i.e. reflecting the non-homogeneous flow near the interface [6 - 8].

The flattened grains in the base plate form a layered structure which constitutes the background for the macro- shear bands (SB) formation. The shear banding process results from the operation of shear stresses (due to the oblique collision of plates) in the near-the-interface layers. The most important deformation mechanisms observed in the near-the-interface layers of the Zr 700 alloy plate are twinning and shear banding. Twins were observed also in the structure of the initial material and in the layers distanced ~ 1 mm from the interface. However, their density significantly increases as the distance from the interface decreases. With a contrast used, a rotation of the twins outside the SB and a displacement of their fragments within the band are clearly visible. The strong rotation within the shear bands is responsible for the fragmentation of twins. This leads to an ultra-fine-grained structure inside the well-developed SB. The internal structure of SB changes with the distance from the interface. The parts of the SB placed near the interface are composed of very fine (sub)grains elongated along the shear direction, whereas the parts of them more distanced from the interface are only bent. At the shear band boundary, the twin-matrix

layers usually change the inclination, indicating a gradual incorporation of the layers into the SB area. Moreover, in the sheared layers near the interface, one of the twinning systems very often takes a position nearly parallel to the shear band plane. This can support the strain accommodation in the macro-scale.

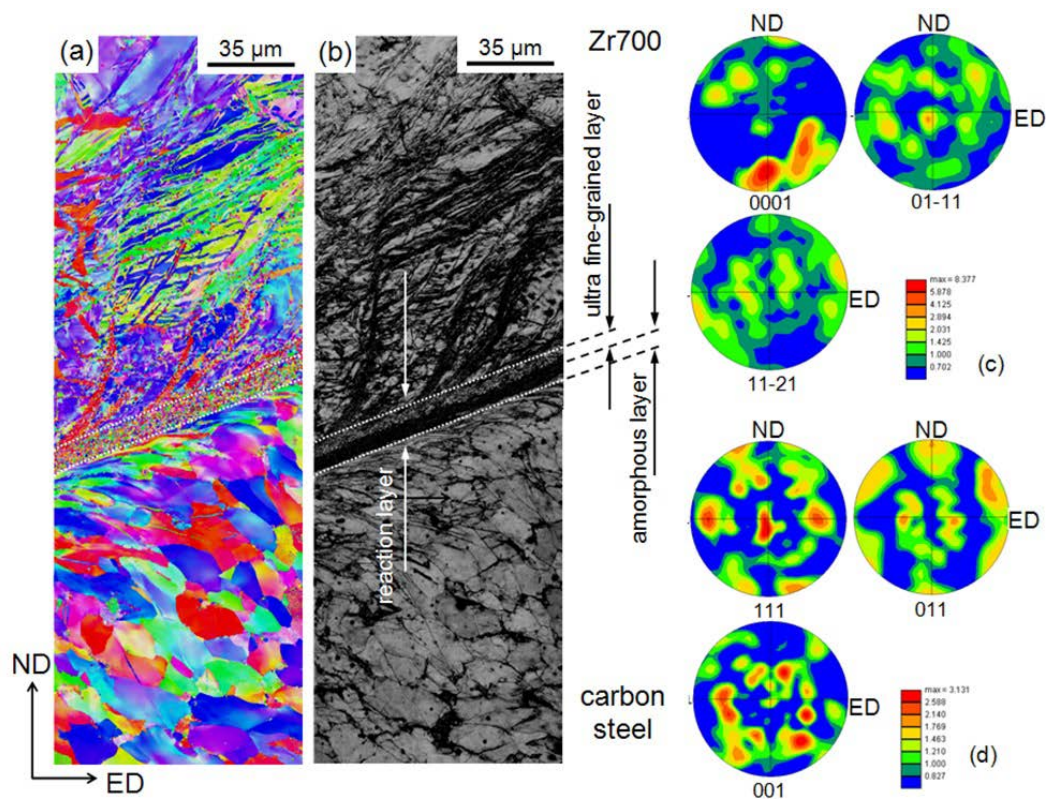


Fig. 1. Microstructure of near-the-interface layer. The orientation map displayed as a 'function' of the IPF colour code (a) and band contrast (b). (c) {0001}, {01-11} and {11-21} pole figures corresponding to the area of Zr 700 and (d) {111}, {011} and {001} pole figures corresponding to the area of carbon steel sheets. ND-ED section.

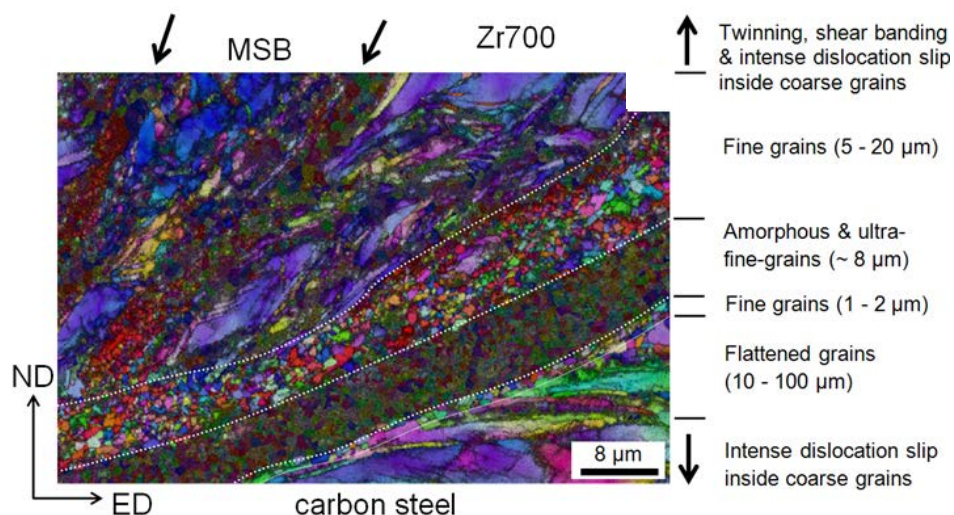


Fig. 2. Near-the-interface area showing formation of fine-grained layers in Zr 700 and carbon steel sheets. SEM/EBSD local orientation measurements with the step size of 100 nm. ND-ED section.

In the case of the carbon steel plate, the flattened grains also showed that a well-defined crystal lattice re-orientation occurred in some grains situated within the area of the broad

macro-SB, although those grains initially had quite a different crystallographic orientation. Their crystal lattice rotated in such a way that one of the {110} slip planes became nearly parallel to the plane of the maximum shear. Moreover, one of the slip direction of the <111>-type, which is lying on this plane, is parallel to the shear direction. A natural consequence of this rotation is the formation of a specific macro-SB texture, which facilitates the slip propagation across the grain boundaries along the shear direction, without any visible variation in the slip direction. It was thereby established that the shear banding occurred across the grain boundaries by the continuity of the slip direction, although the slip plane did not coincide exactly in the adjacent grains.

4. Summary

This work describes the SEM/EBSD investigation of the microstructure and texture changes that occur in the interfacial layers of explosively welded sheets. Clads based on carbon steels as the base plate and Zr 700 as the flyer plate were analysed. The following detailed conclusions can be drawn.

- During the bond formation, the layers of the parent sheets near the interfaces underwent intense plastic (shear) deformation. The effect of the grain refinement was clearly observed in zirconium. The carbon steel deformed more uniformly in the significant part of the sheet, except for a very thin layer near the interface.
- In the case of base plate (carbon steel), the maps revealed a very thin layer (1 - 2 μm in thickness) of fine grains and a broader layer of flattened grains. In the case of the flyer plate (Zr 700), the maps show a thin fine-grained layer of 5 – 20 μm in thickness. However, a layer of flattened and/or banded primary grains was not observed. Both fine grained layers directly adhered to the melted zone.
- The most important deformation mechanisms observed in the near-the-interface layers of the Zr700 alloy plate are twinning and shear banding. In the case of the carbon steel plate, the flattened grains showed that a well-defined crystal lattice re-orientation occurred in some grains situated within the area of the broad macro-SB.
- ‘Metallurgical bonding’ was achieved by way of melting explosively welded sheets. The above proves that the proper explosive welding always incorporates the melting of thin surface layers of joined materials.

Acknowledgments

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