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High cooling rates and metastable phases at the interfaces of explosively welded materials

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ABSTRACT

During an explosion, the interfaces of welded materials experience fast heating due to high strain rate severe plastic deformation. This leads to the formation of local zones, where melting and mixing of welded materials is observed. These zones are frequently referred to as vortexes, eddies or swirls, due to the specific rotational movement of materials during mixing. This study is primarily devoted to the discussion of the structures that appear in these zones. Simple approaches to estimate the heating and cooling rates at the interfaces between explosively welded materials were proposed. It was concluded that the heating rate at the interfaces was of the order of 10^9 K/s, while the cooling rate achieved 10^7 K/s. Several combinations of explosively welded alloys (steel/steel, Ti alloy/steel, Zr/Cu, Zr/Ni, Ta/Cu, Al/magnesium alloy and Cu/brass) were thoroughly analyzed using scanning electron microscopy, transmission electron microscopy and energy dispersive X-ray spectroscopy. In most of these combinations, metastable crystalline, quasicrystalline or glassy phases were observed. The formation of different types of metastable phases is discussed with respect to the compositions of the welded alloys. It was concluded that solidification conditions at the interfaces of explosively welded materials are similar to those during rapid solidification. Thus, the results of numerous experiments on rapid solidification of alloys could be applied to analyze the structures that appear in mixing zones.
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1. Introduction

Explosion welding is one of the most common techniques for the fabrication of bimetals and multilayer composites, consisting of dissimilar alloys. The highspeed oblique collision of workpieces caused by the detonation of explosive materials occurs during the welding process. If the collision angle and velocity are chosen correctly, the conditions for metallurgical bond formation are provided at the contact point [1]. It is typically assumed that surface contaminations and thin oxide films are effectively removed from the surface of welded materials due to the formation of the so-called “jet” [2], which moves ahead of the contact point. This process improves the welding tendency of materials. It is widely considered that virtually all combinations of metallic alloys can be explosively welded. Thus, the range of explosively welded bimetals is much larger compared to the range of bimetals that can be produced by roll bonding, diffusion welding or various types of fusion welding.

A distinctive feature of explosively welded joints is the waveform of an interface. At the crest and trough of an interface, the formation of local areas of material mixing is frequently observed. These zones are typically called vortices, eddies or swirls due to the specific rotational movement of the materials at these areas. It should be noted that the interfaces do not necessarily have a waveform. Under certain impact conditions, nearly flat interfaces between the welded plates may appear. In this case, the formation of a continuous mixing layer or discontinuous mixing zones can be observed along the interfaces. The mechanical properties of explosively welded composites often depend on the structure of the alloys that appear at the mixing zones. Selection of the explosion welding conditions is particularly difficult for those materials, where vortices consist of brittle phases.

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Despite the widespread application of explosion welding in industry and its indispensability for joining certain dissimilar alloys, only a few research studies have been devoted to the microstructures at the interfaces of explosively welded materials. In particular, there is a limited amount of data on the metallurgy of the mixing zones.

In many previously published studies, the mixing zones were analyzed using light microscopy or scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDX). Although they provide important information on the chemical composition and morphology of vortices, these characterization techniques do not give unambiguous information about the atomic structures of the phases formed at the interfaces. Several detailed reviews devoted to this topic can be found in the works of Crossland [3], Deribas [4] and Zakharenko [1]. It should also be noted that the formation of the structures at the interfaces during explosion welding occurs under conditions that are far from equilibrium. Due to the rapidity of the collision process, precipitations of nanoscale metastable phases are often observed at the interlayer boundaries. Thus, the application of equilibrium phase diagrams to identify the phases in the mixing zones may frequently lead to misleading results. Due to this reason, diffraction studies have become especially important for the characterization of the interfacial structures.

In the last two decades, the amount of research on the phase composition of mixing zones has significantly increased, which is probably due to the spread of transmission electron microscopy (TEM) and improvements in sample preparation techniques. Several recently published research studies with significant contributions to this field should be noted. Nishida and Chiba [5] observed the formation of a Ti_2Ni phase, a high-temperature TiNi phase, icosahedral quasicrystals and an amorphous phase during explosive welding of Ti and Ni. Fronczek et al. [6] and Bazarnik et al. [7] studied Ti/Al and Ti6Al4V/Al interfaces using TEM, X-ray diffraction, and synchrotron radiation diffraction. They observed the formation of $TiAl_3$, $TiAl_2$, TiAl and Ti_3Al in the mixing zones. In TEM studies of Ti/steel clads, Song et al. [8] observed the formation of TiFe and metastable $Fe_{9.64}Ti_{0.36}$. Metastable phases at Ti/steel interfaces were also observed by Chiba et al. [9,10]. Zu et al. [11] observed a metallic glass structure in explosively welded Ti/Cu bimetals. Amorphous structures in explosively welded materials were also observed by Paul et al. [12] using TEM studies of Ti/steel, Ta/steel, and Zr/steel bimetals. In recently published research, Bataev et al. observed the formation of metallic glasses at the interface of austenitic stainless steel and niobium [13], and the precipitation of decagonal quasicrystals and metastable Ni_2Al_9 crystals at the interface of explosively welded Al and Ni [14]. The formation of these types of structures was explained by high cooling rates, which are achieved during the welding, and by a specific combination of chemical elements in the vortexes, which promoted the formation of glassy or quasicrystalline structures. Lazurenko et al. observed the formation of several metastable crystalline phases and a glassy phase at the interface of explosively welded Ti and Al-1Mn, the mixture of which is a weak glass former.

The phenomenon of metastable phase formation in explosively welded materials was observed even earlier. For example, Crossland, in his monograph published in 1982, mentioned the formation of metastable structures during explosion welding, but no data about the exact type of the observed phases was reported [3].

Currently, no systematic analysis of vortex structures with respect to the composition of the welded materials has been reported and the phenomenon of metastable phase formation has not been discussed in sufficient detail. In addition, there exist only a few studies that are devoted to the estimation of heating and cooling rates at the interfaces of explosively welded materials. One of the rare discussions of this topic was again completed by Crossland [3]. It should be noted that it is a combination of two factors, material composition and its temperature history, which determine the formation of metastable phases. Due to these reasons, in this study, significant attention is paid to the estimation of heating and cooling rates, as well as to thorough TEM analysis of vortex structures for some explosively welded combinations. The objective of this study is to show that solidification conditions at the interfaces during explosive welding are similar to those during different techniques of rapid solidification of molten metals. Thus, in most cases, one can expect the formation of metastable structures at the interfaces of explosively welded alloys.

2. Materials and methods

Several different combinations of alloys were welded to estimate the influence of chemical composition on the possibility of metastable phase formation in the vortex zones. All samples could be divided into the following groups:

- Flyer and base plates with the same chemical composition. Low carbon steel to low carbon steel clad was used as an example of this group. The low carbon steel contained 0.17% C, 0.49% Mn, 0.22% Si, 0.019% P and 0.007% S.
- Materials of plates that are immiscible with each other. Ta (99.9%) and Cu (99.95%) were used as an example of this combination.
- Materials of plates that are perfectly miscible with each other. This group was represented by a combination of Cu (99.95%) and α-brass (~37% Zn, ~63% Cu, <0.2% impurities).
- Mixing of alloys of flyer and base plates, leading to the formation of intermetallic compounds at equilibrium conditions. This group included the largest number of samples due to several reasons. First, materials of this group are particularly prone to form metastable phases. Second, most explosively welded bimetals produced in industry belong to this group. Zr/Cu (Zr 99.8%, Cu 99.9%), Zr/Ni (Zr 99.8%, Ni 99.8%), Al/magnesium alloy AZ31 (Al 99.9%) and Ti alloy/low carbon steel (Ti alloy − 4% Al, 3.4% V, 1.2% Mo, 0.5% Cr, 0.3% Zr, low carbon steel 0.17% C, 0.49% Mn, 0.22% Si, 0.019% P, 0.007% S) combinations were studied.

Several types of explosive materials and welding schemes were used to produce the samples studied in the present work. Basic information regarding the experimental conditions is summarized in Table 1 and Fig. 1. Prior the experiments all materials were ground with 1000 grade SiC emery paper and degreased with acetone. All explosions were carried out in specialized chambers. It should be noted that the welding parameters were deliberately chosen to ensure the formation of mixing zones at the interfaces.

The structures of the samples were studied by light microscopy using a Carl Zeiss Axio Observer Z1m metallographic microscope, SEM using a Carl Zeiss EVO 50 XVP microscope, EDX using an Oxford Instruments X-ACT analyzer and transmission electron microscopy (TEM) using a FEI Tecnai G2 20 microscope at 200 kV.

The samples for light microscopy and SEM were prepared according to a standard procedure, which included the cutting of samples using a SiC disc, mounting the samples in phenolic resin, grinding the sample using SiC grinding papers and polishing the samples using a diamond suspension to gradually decrease the grain size from 9 to 1 μm. Samples containing Ta, Ti, Zr, and Al were polished using colloidal silica to receive a mirror finish.

The average composition of the mixing zones was measured using EDX analyzer coupled with SEM. High purity elements provided by Micro-Analysis Consultant Ltd. were used as standards to calibrate the equipment. The value of the electron beam current needed for quantitative analyses was found by measuring high

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