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Residual stresses distribution, correlated with bending tests, within explosively welded Ti gr. 2/A1050 bimetals

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ABSTRACT

Synchrotron radiation and XRD^2 method were used to investigate the residual stress distribution before and after three point bending tests within an explosively welded composite composed of two light metals, namely: Ti gr. 2 and A1050. The analysis has shown that the bimetal is slightly affected by the explosive welding process since negative sign values of stress tensor were detected only in the immediate vicinity of interface of Ti gr. 2 characterized by a width of about 0.25 mm. Upon bending higher negative compression stresses are detected in this area as the σ_{11} value changes from −500 MPa to −1200 MPa. Additionally, the analysis of microstructure has revealed significant changes in twins morphology with primary and conjugate twinning before and after bending, respectively. However, the compressive twinning was the dominant system in both cases. Bending has changed the initial bimodal texture developing more spread basal components towards the transverse direction. The sample surface has been also significantly affected as the presence of compressive residual stress (−500 MPa) after bending was measured.

1. Introduction

In recent years detailed study of technological parameters and development of 'welding window' diagrams [1–6] succeeded in joining of various bimetals such as W/Cu [3], Inconel 625/steel [5], Ti/Al [7,8], Ti/steel [9] or steel/stainless steel [10] and multilayered materials e.g. Ti/Al [11–14], Al/Mg [15], Al/Cu [16] or Ni/Al [4] by an explosive welding (EXW) method. However, as in the case of other welding processes such as friction stir welding [17], gas tungsten arc welding [18] or electron beam welding [19], residual stresses are observed after EXW [20–29]. The residual stresses evolve within ingoing metals due to temperature gradients observed at the bonding surface and much lower within the clads [28,30,31]. Through-depth residual stress can be observed within composites manufactured by EXW due to different linear expansion coefficients of each element [23,32]. Depending on stress distribution and their interaction with external forces, they can influence both the mechanical properties and lifetime (e.g. compressive residual stresses can delay fatigue cracking or induce plastic deformation) [33]. In other words, residual stresses are one of the key parameters determining the structural and functional properties of the materials. They may affect the composites integrity, thus a comprehensive study of the residual stresses profile is of great interest. There are few reports concerning the problem of residual stress distribution within explosively welded metals, where various measuring methods

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were applied: layer removal method using inherent strain [20], successive milling technique [21], hole-drilling method [23,24,26], neutron diffraction measurement by using residual stress instrument [25], X-ray diffraction (conventional X-ray) with use of the $\sin^2\psi$ method [27,28] and X-ray diffraction (synchrotron radiation) with use of the XRD^2 method [29].

Explosively welded titanium/aluminum composites in as-welded and as-annealed states were well described in literature in terms of microstructure [7,8,13,14,34], chemical composition of the interface [7,8,34,35] or mechanical properties [35–41]. Much attention has been paid to these materials due to their low density and unique properties suitable for advanced engineering applications in defense, automotive or aerospace industry. This material can be used as different parts of ballistic personal or vehicle protection systems, ballistic shields, partitions or protective panels [40,42]. Nevertheless, the problem of residual stress has never been analyzed.

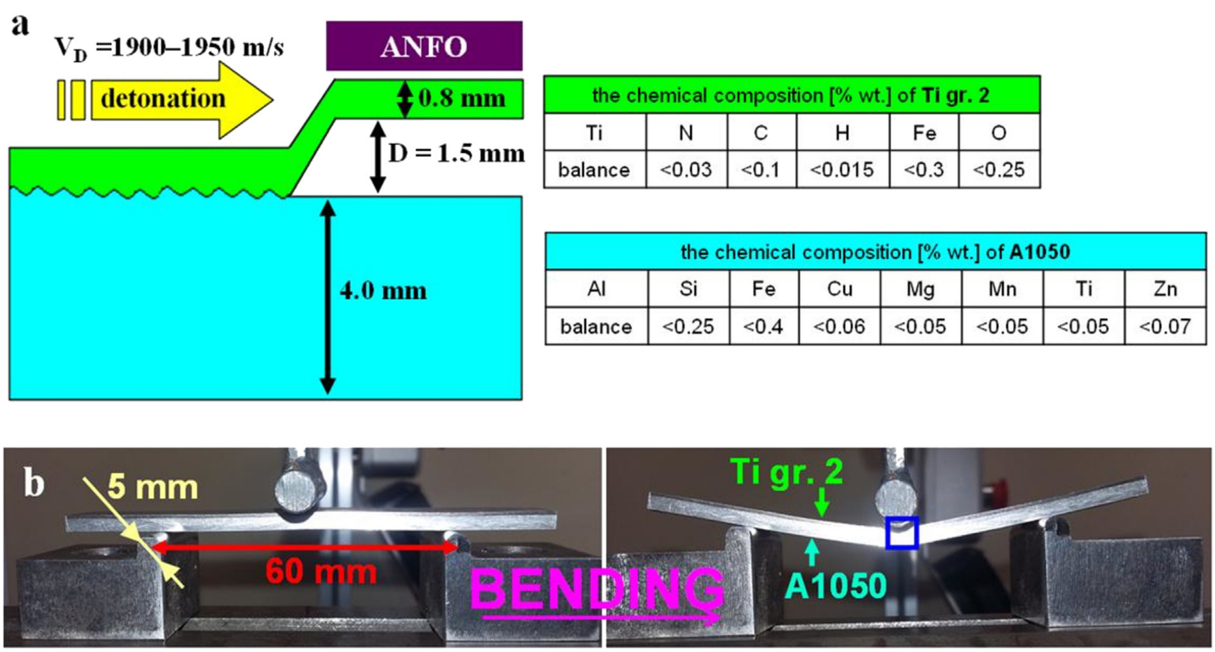
Therefore, the current work attempts to describe residual stress distribution within explosively welded titanium/aluminum bimetals. A relatively novel approach of the two-dimensional method using non-destructive X-ray synchrotron radiation, which takes into account the real width of the interface, for evaluating the stress gradients across the lightweight composites was applied. Moreover, to understand the failure behaviour of multi-layered composites microstructural and textural evolution in as-welded and as-bent states were studied.

2. Material and Methods

To study the residual stress distribution in correlation with three point bending tests of explosively welded sheets of titanium gr. 2 (flyer plate, 140 mm × 460 mm × 0.8 mm) with aluminum A1050 (base plate, 140 mm × 460 mm × 4 mm) synchrotron radiation was used. Experimental set-up and applied parameters of EXW process, which allowed to obtain bimetals of good quality were presented in Fig. 1a. Specimens were cut from the corners of the clad. Sample preparation for scanning electron microscopy (SEM) of both backscattered electron (BSE) and electron backscatter diffraction (EBSD) modes and pole figures were described in [7,8,11]. The boundaries with a misorientation angles larger than 2° were included in calculations.

In order to define the flexural strength, three-point bending tests were conducted according to PN-EN ISO 6892-1 Standard on samples of dimensions 100 mm × 15 mm × 9 mm. Mechanical testing under static load was carried out using a MTS servo-hydraulic test machine with a maximal load capacity of ± 5 kN (Fig. 1b). Rolls of 5 mm in diameter were installed with a distance of 60 mm to each other (Fig. 1b). The tests were performed with deformation controlled by the displacement of actuator. The displacement was increased at a constant rate of 0.10 mm/min according to ASTM C1018.

Samples of dimensions 2 mm × 2 mm × 4.8 mm, dedicated for synchrotron measurements, were cut from the interface region in as-explosively welded and as-bent specimens (marked with a blue square in Fig. 1b) by wire-electro discharge machining process. To determine the phase composition and residual stress distribution a hard X-ray micro-diffraction experiment was performed at the beamline I15 at the Diamond Light Source (electron storage ring operating at an energy of 3 GeV with beam current ~300 mA operating in top-up mode). During the experiment, monochromatic synchrotron radiation of photon energy of 76.01 keV (λ = 0.01631 nm) was applied. The beam of photons was firstly focused by compound refractive lenses down to the size 100 μm and then collimated to a spot size on the sample of diameter 20 μm. With a narrow X-ray beam the specimen was scan along a well-defined trajectory which allows to obtain crystallographic information from small material volume (0.0006 mm^3). Tilt and rotation angles φ and ψ were fixed to 0°. Samples were scanned along two perpendicular faces for ω = 0 and 90° (Fig. 2a). The materials were scanned discretely with equidistance along a straight path (yellow circles path marked in Fig. 2b) of total length 1.8 mm by 10 μm step. During each step, the sample was illuminated by highly intense X-ray beam for 8 s. The resulting 2D XRD patterns were recorded using a Perkin Elmer 1621 detector. The recorded XRD patterns were then processed using the Fit2D software [43] and algorithm implementing XRD^2 method for internal strain/stress determination developed under the MATLAB environment. The interplanar spacing used for the stress calculations of the hexagonal close-packed (hcp) α-Ti and face-centred cubic (fcc) Al were collected in Table 1. For the elastic residual stress analysis, the Debye-Scherrer rings of (110) Ti and (220) Al were chosen because of easy separation from others reflections and similar interplanar distance. The rings were radially integrated $I(2\theta,\gamma)$ with 1° γ steps over the whole azimuthal range (0–360°). The d values were calculated from $I(2\theta,\gamma)$



the chemical composition [% wt.] of Ti gr. 2					
Ti	N	C	H	Fe	O
balance	<0.03	<0.1	<0.015	<0.3	<0.25

the chemical composition [% wt.] of A1050							
Al	Si	Fe	Cu	Mg	Mn	Ti	Zn
balance	<0.25	<0.4	<0.06	<0.05	<0.05	<0.05	<0.07

Fig. 1. (a) Experimental setup of explosive welding process. (b) Three point bending test of explosively welded bimetal Ti gr. 2/A1050 on MTS servo-hydraulic test machine. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)