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Deformation and fracture of explosion-welded Ti/Al plates: A synchrotron-based study

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ABSTRACT

Explosion-welded Ti/Al plates are characterized with energy dispersive spectroscopy and x-ray computed tomography, and exhibit smooth, well-jointed, interface. We perform dynamic and quasi-static uniaxial tension experiments on Ti/Al with the loading direction either perpendicular or parallel to the Ti/Al interface, using a mini split Hopkinson tension bar and a material testing system in conjunction with time-resolved synchrotron x-ray imaging. X-ray imaging and strain-field mapping reveal different deformation mechanisms responsible for anisotropic bulk-scale responses, including yield strength, ductility and rate sensitivity. Deformation and fracture are achieved predominantly in Al layer for perpendicular loading, but both Ti and Al layers as well as the interface play a role for parallel loading. The rate sensitivity of Ti/Al follows those of the constituent metals. For perpendicular loading, single deformation band develops in Al layer under quasi-static loading, while multiple deformation bands nucleate simultaneously under dynamic loading, leading to a higher dynamic fracture strain. For parallel loading, the interface impedes the growth of deformation and results in increased ductility of Ti/Al under quasi-static loading, while interface fracture occurs under dynamic loading due to the disparity in Poisson's contraction.

1. Introduction

Multilayered composites, such as mollusk shells in nature, usually possess unique mechanical and chemical properties [1–3]. Man-made jointed Ti/Al has been widely used in aerospace and automobile industries, for its high specific strength and considerable ductility [4–6]. Impact is commonly encountered in such applications, and dynamic deformation and failure of Ti/Al bimetal plates are thus important for better structural design and safe guarding [7–11].

Ti and Al are dissimilar metals, and are difficult to be jointed through conventional welding methods such as diffusion bonding, cold rolling and pressure welding [12]. Explosive welding has shown its strong capability in joining a variety of dissimilar metals, including Ti and Al [13–16]. Moreover, explosive welding can produce joints with high bond strength over large welding areas, and minimal distortion of parent metals. Extensive studies have been devoted to microstructural characterization of welding interfaces, e.g., wavy patterns, intermetallic compositions and defects [14,15,17]. Three-dimensional x-ray computed tomography (XCT) has been widely utilized as a powerful, non-destructive, tool in microstructure characterization of various materials, e.g., composites, foams, granular materials and similar welding metals, with μm spatial resolution [18–22]. However, XCT characterization of the weld between dissimilar metals has been scarcely reported.

Dynamic mechanical properties of explosion-welded Ti/Al plates have been rarely investigated. For dynamic tension loading, split Hopkinson tension bar (SHTB) has been widely used [23–25]. Strain gages are effective for obtaining bulk, rather than mesoscale, responses. Local deformation dynamics can be characterized with 2D strain field mapping, using optical digital image correlation [26,27] or x-ray digital image correlation (XDIC) [24,28,29]. XDIC is advantageous for the penetration capabilities of x-rays,

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and relies on images acquired with such techniques as x-ray phase contrast imaging [21,30,31], particularly useful in resolving damage and cracking of low-Z, optically opaque, materials [25,30]. Weld or bimetal interface may play a key role in material performance. For example, formation of brittle intermetallic phases may degrade mechanical properties of welding materials [32–34]. However, in situ measurements on dynamic strain distributions across the interface with high-speed XDIC are extremely rare. Mesoscopic deformation dynamics of explosion-welded bimetal plates including Ti/Al subjected to impact loading, is essentially untouched.

In the present study, XCT and energy dispersive spectroscopy (EDS) are utilized to characterize the initial microstructures of explosion-welded Ti/Al interface. A mini split Hopkinson tension bar (SHTB) and material test system (MTS), implemented with in situ, high-speed XDIC, are used to obtain multi-scale responses of Ti/Al bimetal plates under dynamic and quasi-static loading, respectively. Stress–strain curves are measured, together with strain fields of deforming Ti/Al samples loaded either parallel or perpendicular to the interface. The x-ray imaging and strain field mapping demonstrate pronounced anisotropy in deformation and fracture mechanisms of Ti/Al samples. This study also provides insights into strain-rate effects, strength and ductility of Ti/Al bimetal plates, and likely, other layered composites.

2. Experimental

2.1. Materials

Ti plates are TC4 titanium alloy (Ti6Al4V), and Al plates are LY12 aluminum alloy (AlCu4Mg1). Ti/Al bilayer plates are manufactured by explosive welding, as schematically illustrated in Fig. 1. Ti and Al plates are set parallel to each other with a stand-off between them. An explosive charge is placed on the surface of the flyer plate (Ti), and is set off with a detonator. After detonation of the explosive charge, a detonation front travels along the charge at a velocity of V_D. The detonation wave propels the flyer plate to impact on the base plate (Al) at a velocity of V_p. The impact velocity V_p and collision angle β determine the normal and shear stress at the welding zone, which have significant influence on the morphology of the welding interface [35,36].

Composition and morphology of the Ti/Al interface are examined with EDS. The EDS map (Fig. 2(a)) shows no obvious pores or cracks across the interface. A small piece of Ti (the arrow) protrudes into the Al matrix, probably due to rapid pressure boost and intense plastic deformation during welding [37]. Such island morphology is widely observed when the detonation force and metal vortex flow are high [15]. The amplitude of the saw-tooth features of the Ti/Al interface is about 3.67 μm, much smaller than those reported in other explosive-welding materials (~100 μm) [15,38]. The amplitude of the wavy interface structure is directly related to the collision angle [35]. The x-ray tomography (Fig. 2(b)) obtained at the beamline 2-BM of the Advanced Photon Source, and the topography reconstructed from the tomography, reveal 3D nature of the Ti/Al interface (Figs. 2(c) and (d)). The maximum height difference of the interface is 19.52 μm, and the root mean square height difference or roughness [38] is 2.68 μm, consistent with the EDS result (Fig. 2(a)).

2.2. Loading setups

We implement mini SHTB (dynamic) and MTS (quasi-static) loading devices along with a high-speed x-ray imaging system at the beamline 32-ID of the Advanced Photon Source, and the schematic setups are shown in Fig. 3(a). Relevant experimental details have been presented elsewhere [24,28,30,39]. The launch tube of a conventional SHTB is modified (Fig. 3(b)) for synchrotron radiography test. In the conventional design [23], a ring striker is in direct contact with the incident bar, which may pull the incident bar and the sample out of the field of view during launch due to friction. Thus, a sleeve (B) is used to physically separate the incident bar (A) and striker (C) to prevent pre-movement of the bar and sample. A Teflon ring (D) is installed to support the striker and seal gas inside the launch tube (E).

As shown in Fig. 3(a), a Ti/Al sample (4) is held between two steel collets (6). Two kinds of samples are prepared for loading applied either parallel (Ti/Al-0) or perpendicular (Ti/Al-90) to the Ti/Al interface. The samples are dog-bone shaped, with gauge lengths of 3 mm and 2 mm for Ti/Al-90 and Ti/Al-0, respectively; the thickness along the x-ray direction is 500 μm. The striker (2), incident bar (1), and transmission bar (5) are all made of high-strength steel, with a diameter of 6 mm. After the gas gun is fired, the striker impacts the flange fixed to the incident bar end and generates an elastic tensile wave propagating through the incident bar along the x-direction. When the incident wave arrives at the interface between the incident bar and sample, it is partially reflected owing to impedance mismatch, while the rest is transmitted into the transmission bar. The high-speed camera (9) is triggered by the strain gages attached to the incident bar upon arrival of the incident wave. During loading, the x-rays transmitted through the Ti/Al sample form images on the scintillator (8) which are captured by the high-speed camera (9) as image sequences. The transmitted waves are recorded by strain gages attached to the transmission bar. The incident and transmitted waves are used to derive the stress $\sigma_s(t)$, strain $\varepsilon_s(t)$ and strain-rate $\dot{\varepsilon}_s(t)$ histories of the sample with following equations [40]:

$$\sigma_s = E_t \varepsilon_t \frac{A_t}{A_s}, \tag{1}$$

$$\dot{\varepsilon}_s = \frac{2C_0}{L_s}(\varepsilon_t - \varepsilon_i), \tag{2}$$

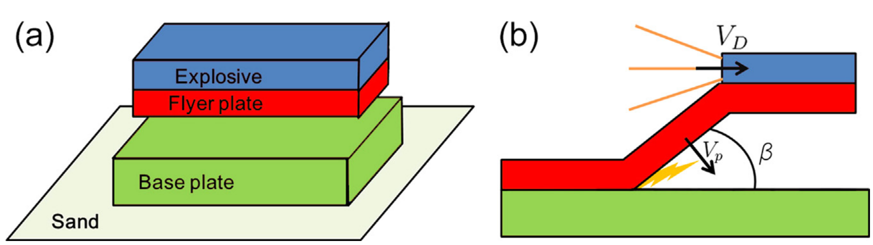

Fig. 1. Schematic illustration of setup (a) and process (b) of explosive welding. In (a), Ti and Al plates are set parallel to each other with a stand-off between them. An explosive charge is placed on the surface of the flyer plate (Ti). In (b), V_D is the velocity of detonation front, V_p is the impact velocity of flyer plate, and β is the collision angle.