

Experimental and numerical analysis of the formation behavior of intermediate layers at explosive welded Al/Fe joint interfaces

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ABSTRACT

The microstructural characteristics and formation mechanism of intermediate layers at the explosive welded Al/Fe wavy interface were investigated by experimental and numerical analyses. Two types of intermediate layers were obtained at the wavy joint interface produced at an impact velocity of 750 m/s and an impact angle of 15°. The layer that was formed in the tail-side included the area showing a dendritic structure consisting of Al_3Fe and Al_5Fe_2 . This indicated that local melting occurred in the area. In contrast, the layer that was formed in the front-side showed no evidence of melting. The formation behavior and temperature change at the Al/Fe interface formed by an oblique collision were simulated by the smoothed particle hydrodynamics (SPH) method. The simulation results revealed that on the tail-side, a mixture of Al and Fe particles formed and a large local temperature increase exceeding the melting temperature of Fe and Al occurred. The front-side showed a small temperature increase. The composition ratio of Al and Fe, and the temperature distribution at the joint interface calculated by the SPH simulation provided plausible explanations for the formation of two types of intermediate layers in each position.

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1. Introduction

Much attention has been paid to joining dissimilar metals. In particular, Al/Fe joining is important for fabricating multi-component structures used in cars and ships. However, fusion welding cannot always be used for Al/Fe joining because a layer of brittle intermetallic compounds ($\text{Al}_{13}\text{Fe}_4$, Al_5Fe_2 , Al_2Fe , FeAl , and Fe_3Al) is formed at the joint interface [1–4]. Solid-state welding methods, such as friction stir welding, and impact welding, have attracted attention as alternative methods. Explosive welding is a type of impact welding. A schematic of explosive welding is shown in Fig. 1. Fig. 1(a) shows two parallel metal plates separated by a gap. The upper and lower plates are called the flyer plate and parent plate, respectively. An oblique collision between the plates is induced by detonating an explosive (Fig. 1(b)) and joining is complete in several microseconds. Metal jet emission occurs from the collision point, and thus the joint interface shows a characteristic wavy pattern [5–7].

The explosive welded Al/Fe clad shows good bonding strength. However, an intermediate layer is observed at the Al/Fe

explosive joint interface, similar to that in fusion welding [8]. It is widely known that the intermediate layer consisting of brittle intermetallics results in poor bonding strength of the joint. Therefore, it is of interest to reveal the reason why the explosive welded Al/Fe joint shows good bonding strength. The character of the intermediate layer formed at the explosive welded interface is considered to be one of the possible reasons. Peculiar microstructures are often observed at the explosive welded joint interface. Li et al. used scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to observe the intermediate layer in explosive welded Al/Fe. The layer contains many kinds of intermetallics in amorphous, microcrystal, and quasicrystal states [9]. Han et al. used TEM to show that the intermediate layer of Al/Fe in explosive welded clads is FeAl_3 [10]. Sun et al. discussed the effect of interface morphology on bonding strength. The clads with poor bonding strengths had thicker transition zones at the Al/Fe interface than those with good bonding strengths [8]. Li et al. used X-ray diffraction to identify the intermediate layer obtained by explosive welding of Al to steel with dovetail grooves as Al_5Fe_3 and Al_2Fe [11].

Numerical analysis of impact welding by smoothed particle hydrodynamics (SPH) has been used to reveal the formation mechanism of the wavy interface during impact welding [12–18]. The temperature change at the explosive welded interface has also

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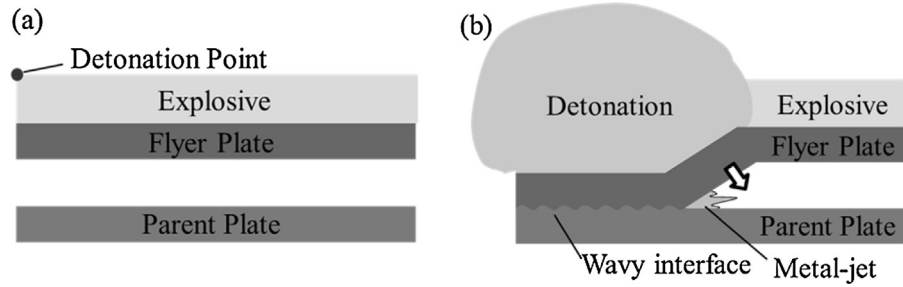


Fig. 1. Schematic of explosive welding (a) before welding and (b) after detonation.

been examined by simulations. Li et al. numerically analyzed the temperature change at an explosive welded steel/steel interface and the temperature distribution suggested that local melting may occur [16]. Nishiwaki et al. investigated the temperature change at the explosive welded Al/Cu interface [19,20]. The deformation and collision behavior of the plates by explosive detonation was simulated by the Euler/Lagrange coupling model, and the collision velocity and collision angle were determined. SPH analysis of the oblique collision behavior of Al and Cu plates was performed by using the impact velocity and angle conditions to reproduce the wavy interface formation. Good quantitative agreement between the experimentally observed wavy interface morphology and the simulation was obtained. They also reproduced the temperature distribution at the joint interface by the SPH method. The localized high temperature zones at the joint interface in the simulation agreed well with the areas in which the intermediate layer formed at the explosive welded interface [19]. These results prove that the numerical analysis is a powerful tool for studying the formation mechanism of the intermediate layer at impact welded interfaces.

Development of wavy joint interface in the impact welding has been simulated by using SPH method in some previous works [12–18]. Microstructural and chemical analyses for the intermediate layer formed at the explosive welded wavy interface were also performed by many researchers so far [9–11]. However, a trial to integrate these two approaches has never been done so far.

The purpose of the present study is to predict the position and chemical composition of the intermediate layer forming at the wavy joint interface by numerical analysis. The obtained simulation results are compared to those of the actually formed intermediate layer formed at the explosive welded Al/Fe interface.

2. Experimental procedure

Commercial purity aluminum plate (A1100) and low-carbon steel (SPCC) plate were used. They are referred to as the Al and Fe plates hereafter. The plate size was $300 \times 300 \times 2$ mm. The Al flyer plate and Fe parent plate were set parallel on a steel anvil. An explosive was mounted on the Al plate with a detonator on one end of the plate. The Al plate deformed and collided with the Fe plate, welding the plates by the explosive detonation and forming the Al/Fe joint.

Experimental conditions of explosive welding were determined by the following process. An optimum combination of several factors (plate thickness, a gap between two plates, explosion velocity of gun powder etc.) providing a target impact velocity (V) and a target impact angle (α) was searched by using a simulation as shown later (Fig. 2(a)). We repeated one trial and error after another to find the optimum combination. Preparation of gun powder and practice of explosive welding were made by a licensed chemical company with reference to the simulation results. Validity of this method was confirmed in the previous work by the present authors. Good quantitative agreement in wave morphology was obtained

between experimental results and simulation results [19]. It should be mentioned that a detailed explanation about explosive and plate setting condition was restricted from the company.

The specimen for microstructure observation was collected 200 mm away from the detonation point. The central cross-section of the specimen was polished and mirror-finished. The microstructure observation was made by optical microscopy and SEM-backscattering electron imaging (BEI) at an acceleration voltage of 20 kV. The chemical composition of the intermediate layer was determined by electron probe microanalysis (EPMA) (15 kV). Precise microstructure observations and crystal structure analysis of the intermediate layer were obtained by TEM (300 kV) for the thin film collected from the position marked in the intermediate layer with a focused ion beam (FIB).

3. Numerical analysis

ANSYS AUTODYN was used for the present simulation. AUTODYN is a software for analyzing high-velocity impacts, explosions, and shock waves. At first, the Euler/Lagrange coupling model was used to simulate the explosive welding and obtain impact velocity and angle during oblique collision during explosive welding. Then, the wavy interface formation process and temperature distribution at the joint interface was simulated by SPH method based on the obtained collision conditions (impact velocity and angle).

3.1. Equation of state (EOS) and constitutive model

In the ANSYS AUTODYN, materials can be modeled by using equation of state (EOS) and constitutive model. The Euler processor, which is used to model gas and liquid, was applied for simulating the air and explosive. The ideal gas EOS was chosen for air, and the JWL EOS was used for the explosive. The Jones–Wilkins–Lee (JWL) EOS (Eq. (1)) was used for the explosive, and the ideal gas EOS (Eq. (2)) was chosen for air [21].

Where p : pressure, ρ : density, e : specific internal energy, η : p/p_0 (initial density) and γ : C_p (specific heat at constant pressure)/ C_v (specific heat at constant volume).

$$p = A \left(1 - \frac{\omega\eta}{R_1} \right) \exp \left(\frac{R_1}{\eta} \right) + B \left(1 - \frac{\omega\eta}{R_2} \right) \exp \left(\frac{R_2}{\eta} \right) + \omega\eta\rho_0 e \quad (1)$$

$$p = (\gamma - 1) \rho e \quad (2)$$

A , B , R_1 , R_2 and ω are constants of explosive. In this study, these parameters were calculated by using Kihara–Hikita–Tanaka (KHT) equation.

The Lagrange processor, which is used to model solids, was applied to simulate the flyer plate, parent plate, and anvil. High speed collision generates a shock wave in materials. The continuity of material properties is lost before and after the shock wave front. This makes the numerical analysis based on the continuum mechanics difficult, and so we need a measure to solve this problem. The Rankine–Hugoniot equations (Eqs. (3)–(5)) are used to relate

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