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A predictive and reliable Eulerian model to compute the interface kinetics of magnetic pulse welding

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Abstract

This work aims to investigate the formation and evolution of the interfacial features which occur during a high-speed impact welding using numerical simulation. A robust numerical modelling based on Eulerian technique is developed to predict the interface kinetics of magnetic pulse welding (MPW). The model has been originally validated for similar material welding and in this study we extend the investigation to an aluminum/copper welding. Results of the kinetics along the welding interface including metal jet emission, wake, vortex, and wave formation are successfully predicted, and the predictions are in good agreement with the experimental observations. Moreover, the metal jet was mainly composed of the lower density metal, i.e. aluminum. It was also observed that the combination of impact velocity and impact angle affects the interface instabilities. The Eulerian model demonstrates its ability to predict the complex interfacial behaviors and the corresponding thermomechanical interactions during the magnetic pulse welding process.

1. Introduction

Multi-material assemblies are growing in popularity due to their various applications in transportation, aerospace and energy industries [1]. Therefore, exploring a suitable method for joining dissimilar metals could help to accelerate their application in those industries. Magnetic pulse welding (MPW), one form of impact welding, is a promising method to join dissimilar metals as it can minimize the formation of intermetallic compounds (IMC) at the interface [2]. Thus, the technique has recently gained a tremendous attention to cater the process of joining different combination of materials in various industrial applications.

MPW works on the principle of electromagnetic forces being produced by the inductive coil combined with a fieldshaper unit and applied on a flyer part to accelerate the flyer to impact onto the inner part. The process is completed within 100 μs and the interface involves high speed collision (100s of m/s) and large plastic deformation [3].

Therefore, the interface is subjected to various instabilities such as jetting, wave, wake, vortex, internal cavities and microporous architecture as reported during MPW process [4, 5].

The impact welding processes have been investigated using numerical simulations to predict the interfacial kinetics. Numerical simulations performed using Lagrangian and Arbitrary Lagrangian-Eulerian (ALE) formulation cannot successfully capture all the details in morphological transitions and successive jet formation owing to poor mesh quality under the large shear deformation [6-7]. Jetting and wavy morphology was captured using smooth particle hydrodynamics (SPH) computation [8]. However, this meshless method has the “zero dissipation” scheme when capturing a shock [9] that makes it unsuitable to simulate the MPW process due to the physical phenomenon requiring dissipative terms.

Eulerian method was regarded as a promising approach to predict reliable interface behaviors and having the modeling capabilities of material flow during the collision process follow a fluid-like behavior [10]. Based on our previous studies [3, 4, 7, 11], a numerical model based on a Eulerian technique has been successfully used to predict the interface kinetics of MPW for similar material welding. The objective of this study is to extend the investigation to an aluminum/copper welding. The interface morphologies are also compared with the experimental observations.

2. Materials and method

The schematic illustrations in Figure 1 show the detail of the numerical model used in this study. The simulations were performed using an equivalent 2D model, which employs a volume of fluid (VOF) algorithm to track the weld interface. Figure 1(a) and (b) were used to simulate the interface and the results were compared with experimental observations. A dedicated small size model was used to predict the interface kinetics under various impact angels (α) between the flyer and inner rod, as presented in Figure 1(c). A linear distribution velocity V_y normal to the interface was imposed to the flyer. Physical and mechanical parameters of the materials used in this study are available in our previous work [5, 11]. For the experiment, Al6060-T6 and commercially pure copper were used for flyer tube and inner part, respectively. The Al tube has an inner diameter of 19.22 mm and the Cu rod a diameter of 15.94 mm. The welding tests were carried on tubular assemblies using a PULSAR MPW welding device with a discharging energy of 12.4 kJ. The interface morphology was observed by a scanning electron microscope (SEM).

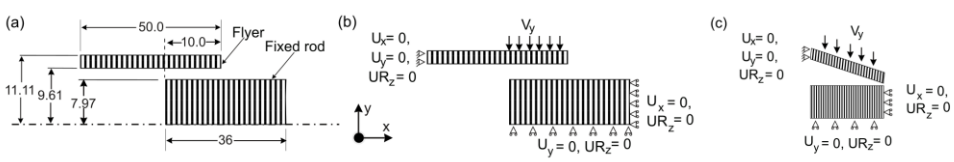

Figure 1. Model setup (a), boundary conditions (b), and small size model used to investigate the impact angle and impact velocity (c)

3. Results and discussions

Interface features obtained from experimental observations are shown in Figure 2(a). The interface morphology reveals various characteristics, viz. wave, wake and discontinuous IMC that demonstrate the collision process and the existence of kinetic instabilities. The linear velocity, V_y = -300000 - 70000X, was used in the simulation model (Figure 1a) to investigate the interface kinetics (where V_y is the impact velocity along the y direction in *mm/s* and X is the distance from the top edge of the flyer along the welding direction in *mm*). The simulated interface successfully reproduced the wavy patterns which are in good agreement with the experimental results.

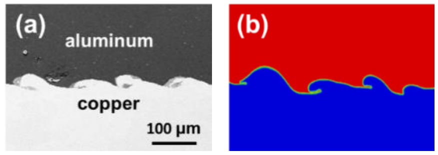

Figure 2. SEM image of weld interface (a) and predicted interface via Eulerian model (b)

Figure 3(a) presents the temperature distribution at the interface zone, the maximum temperature reaches almost 1150°C due to the excessive shear deformation. The local interfacial heating and rapid cooling support the formation of IMC, observed in Figure 2(a). The interface and wavy zone clearly indicate the variation in plastic strain between 0.5 and 13.8 (Figure 3b). Moreover, the plastic strain in the downward region (in Cu) is higher than in the upward region (in Al) leading to higher shear stresses in the downward region. This phenomena demonstrates the irregularities in the instabilities which are in agreement with the experimentally observed irregular interface (Figure 2a).

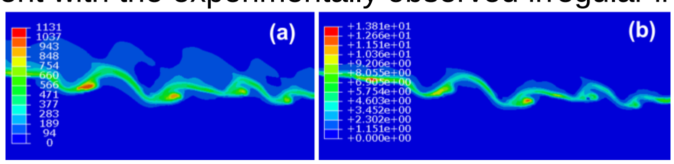

Figure 3. Temperature distribution in °C in (a) and plastic strain in (b) from simulation

Distinct kinetics along the welding interface including jetting, wake, vortices and wave formation are successfully reproduced via Eulerian computation during MPW under the combination of impact velocity of 900m/s and impact angle of 20°, as shown in Figure 4. At onset welding, the flyer with the large impact velocity impinges onto the rod and generates the downward jetting which combines with the upward jetting produced by the strong shear induced by the collision point velocity resulting in the wavy morphology. Subsequently, the wave experiences further instability and shear stress differences between the front and back produce a wake feature. The entrapment of the forward jetting becomes deflected in the upward direction by the impact pressure and shear stress with the advancement of the collision process inducing the formation of vortices.The advancing impact point has a high pressure and large plastic strain, which induces a prominent swirling flow and the vortices roll up at the interface to become a spiral shape. The metal jet was formed due to the local collision pressure that exceeds the dynamic elastic limit of the material [12]. It is also noticed that aluminum mainly formed the jet composition.

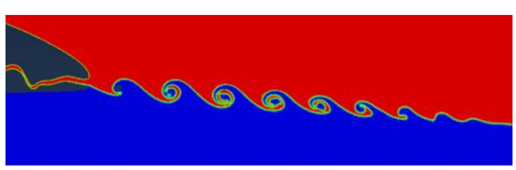

Figure 4. The complex interfacial kinetics produced via Eulerian method.

4. Conclusions

Based on the Eulerian simulation, the interface kinetics of MPW of Al/Cu joint are investigated. The wave and irregular interface observed in experiment are favored by the large plastic strain which is produced by the impact velocity and collision point velocity at the confined interface region. The interface temperature reaches almost 1150°C at some places which provide the favorable condition for the formation of IMC. The actual kinetics of the metal jet emission, wave, wake and vortex formation are related to the shear stress, local pressure and temperature which are influenced by the welding parameters. Therefore, the model will be used to further identify the suitable weldability window under the various welding conditions.

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