Published in the Proceedings of the 16th International Aluminum Alloys Conference (ICAA16) 2018
ISBN: 978-1-926872-41-4
by the Canadian Institute of Mining, Metallurgy & Petroleum

# FORMATION MECHANISM AND CONTROL OF IMPACT WELDED INTERFACE IN DISSIMILAR METAL JOINTS

*Shinji Kumai and Junto Nishiwaki

*Tokyo Institute of Technology*
*2-12-1 O-okayama Meguro-ku, Tokyo, 152- 8552, Japan*
*(*Corresponding author: kumai.s.aa@m.titech.ac.jp)*

## ABSTRACT

Mechanical and physical properties of the impact welded dissimilar metal joints are controlled by joint interface morphology. An intermediate layer (IML) is often formed at the joint interface and this deteriorates the interface quality in some metal combinations. Numerical and experimental studies were performed in order to examine the formation mechanism of the wavy interface and intermediate layer for explosive welded Al/Cu dissimilar metal joints. The impact welding process consists of (1) high-speed oblique collision of metal plates, (2) metal jet emission and large deformation and temperature increase at collision point and (3) rapid cooling at the joint interface. Euler-Lagrange coupling method, smooth particle hydrodynamic (SPH) method and modified laplacianFoam (LF) method were linked together to simulate a series of processes from (1) to (3), and the final interface morphology including the formation of IML was reproduced. The wavy morphology (wave-height, wavelength) and the position and composition of IML formed at the joint interface of Al/Cu joints were quantitatively in good agreement with those reproduced by numerical analysis. Our simulation results are useful for the control of the interface morphology, reduction of the amount of IML, and improvement of the mechanical properties of the impact welded dissimilar metal joints.

## KEYWORDS

Numerical analysis, SPH method, Al/Cu joint, Explosive welding, Joint interface, Cooling process, Intermediate layer, Mechanical properties

## INTRODUCTION

Impact welding is a kind of solid state joining method providing extremely high joint strength for both similar-and dissimilar metal combinations. Explosive welding and magnetic pulse welding are representative methods to achieve the impact welding. By a high-speed oblique collision between two metal plates, a metal jet is emitted from the collision point. The metal jet can remove any oxide films and contaminations on the plates and produce an active refreshed surface. Consequently, good metallurgical bonding can be achieved even for dissimilar metals (Crossland, 1982). Solid metals deform like fluids under the high pressure condition at the collision point and characteristic wavy interface is formed. In addition to the wavy interface, an intermediate layer (IML) is often formed at the joint interface in some metal combinations. Elimination or reduction of the amount of IML at the joint interface is desired since the excessive IML formation along the joint interface causes a large reduction in physical and mechanical properties. Formation of IML is considered to result from characteristic thermal history at the joint interface including partial melting due to the local temperature increase and successive rapid cooling behavior at the joint interface. In order to control the IML formation at the joint interface, it is necessary to reveal both heating and cooling processes at the joint interface. However, it is impossible to observe the phenomenon occurring at the joint interface and also difficult to investigate the temperature change at the joint interface directly during the impact welding. Therefore, simulation or numerical analysis is indispensable to overcome this problem. In the present study, the explosive welded Al/Cu joint, which is prone to form IML at the joint interface, was selected for the research. By using a newly developed numerical analysis method, not only the formation process of wavy interface, but also the local temperature increase and successive temperature decrease at the joint interface were reproduced. The formation process of IML was investigated by using both numerical analytic and experimental results.

## EXPERIMENTAL PROCEDURE

Figure 1 shows the schematic diagram of experimental setup for explosive welding. A pure Al (A1050 hereafter Al) was used as a flyer plate. A pure Cu (C1020 hereafter Cu) was used as a parent plate to fabricate Al/Cu joint. Low detonation speed explosive based on ANFO was used for explosive. The flyer plate and the parent plate were set in parallel with a small gap. The amount of explosive and the gap were altered to control welding conditions. The explosive was set on the top surface of the flyer plate. The detonation progressed from the detonator installed on the explosive. After explosive welding, a specimen was collected and provided for microstructure observation. The joint interface was observed by using an optical microscope and a scanning electron microscope backscattered electron image (SEM-BEI). An electron micro-prove analysis was also performed for chemical composition analysis at the joint interface.

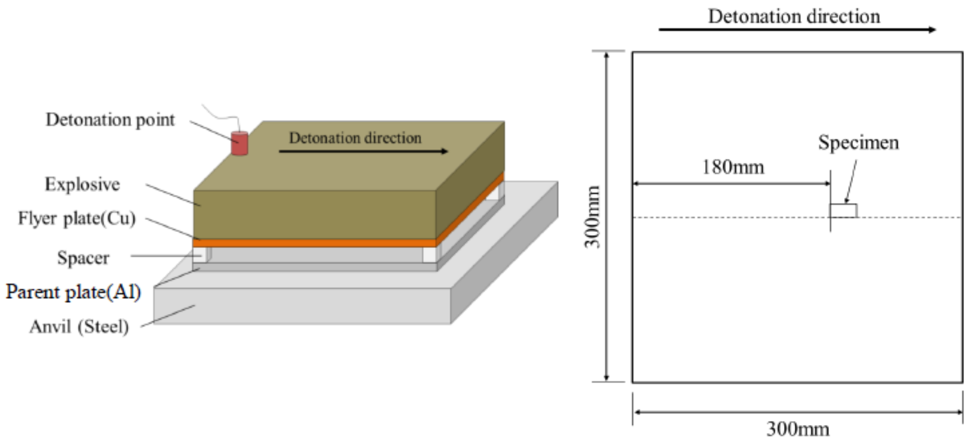


Figure 1. Explosive welding setup and sampling position of the specimen for microstructural observation

## NUMERICAL ANALYSIS PROCEDURE

### A Series of Processes Resulting in Characteristic Explosive Welded Interface

The explosive welding process or impact welding process consists of (1) high-speed oblique collision of metal plates, (2) metal jet emission and large deformation and temperature increase at collision point and (3) rapid cooling at the joint interface. More precisely, as shown in Figure 2, this can be divided into five processes: (I) high speed collision between two plates, (II) metal jet emission from the collision point and formation of wavy interface, (III) temperature increase due to high pressure and heavy plastic deformation, (IV) cooling process, and (V) alloyed region and/or IML formation process. It is important to numerically analyze the series of processes to reproduce the explosive welding behavior. However, for the time being, there is no analytic method that can deal with them all together consistently. Therefore, in the present study, three models were devised and the models were linked together to simulate a series of processes from (1) to (3), and the final interface morphology including the IML was reproduced.

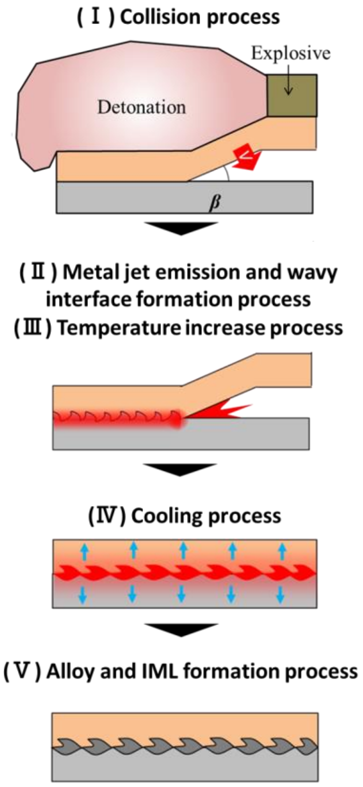


Figure 2. Explosive welding process consisting of five processes from (I) to (V)

Model 1 was used for analyzing (I) collision process. Detonation of explosive and the subsequent oblique collision between two plates were simulated by using Euler-Lagrange coupling method, and collision velocity, $V$, and collision angle, $\beta$, were obtained (Figure 3). The purpose of Model 2 was to reproduce (II) and (III) (Nishiwaki and Kumai, 2016). Smooth particle hydrodynamic (SPH) method was used as a solver. SPH method is suitable for high-speed severe deformation problem. The obtained $V$ and $\beta$ by Model 1 were used as initial conditions. Metal jet emission, mixing behavior of materials and temperature distribution at the joint interface were reproduced by Model 2 (Figure 4). Model 2 cannot reproduce the heat diffusion between materials. In contrast, the commercial OpenFORM can analyze the thermal diffusion equation by lapracianFoam (LF). Accordingly, Model 3 based on the modified LF method was devised and applied to reproduce (IV) and (V) (Figure 5) (Nishiwaki and Kumai, 2017). The material distribution and temperature distribution obtained by Model 2 were used as the initial conditions of Model 3. In Model 3, the cooling process of the joint interface was analyzed and final interface morphology including the formation of IML was reproduced.

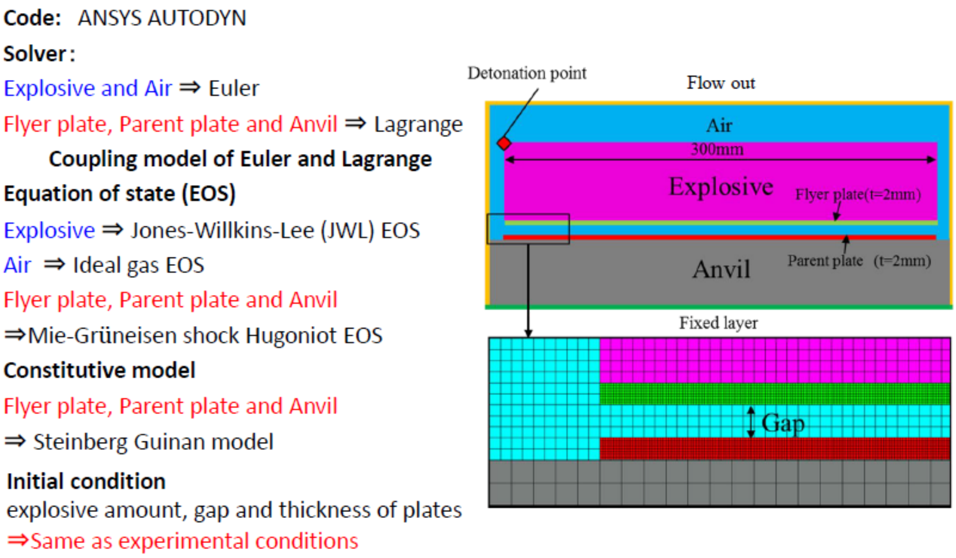


Figure 3. Model 1 to reproduce the process (I) in Figure 2

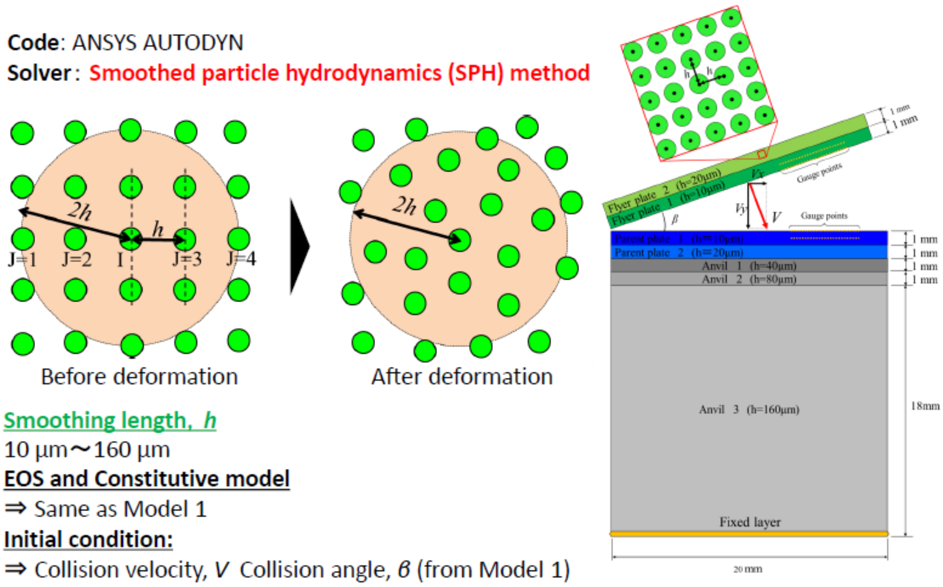


Figure 4. Model 2 to reproduce the processes (II) and (III) in Figure 2

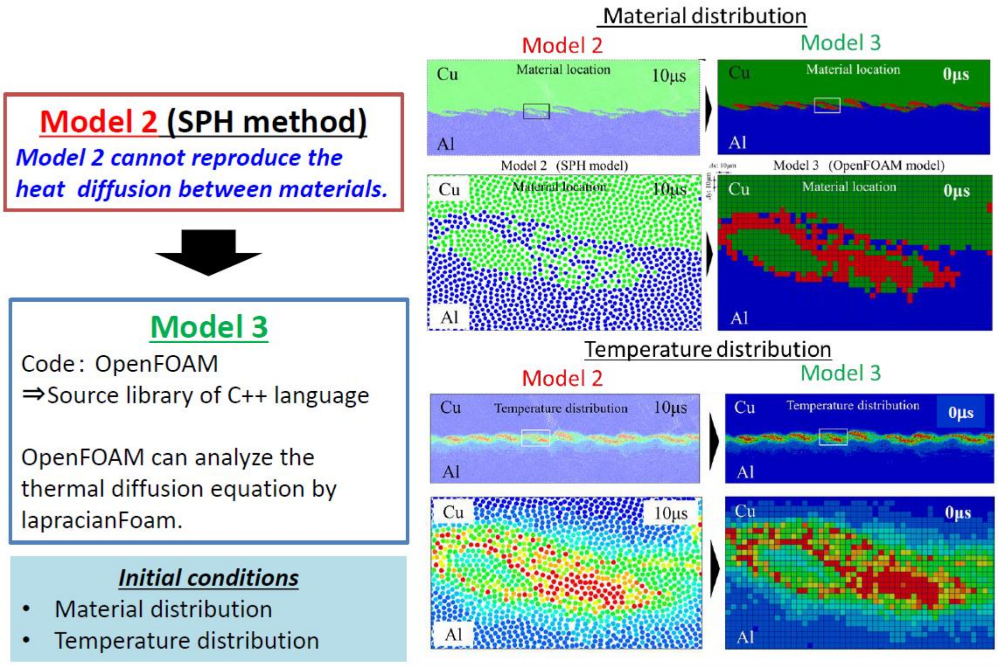


Figure 5. Model 3 to reproduce the process (IV) and (V) in Figure 2

## RESULTS AND DISCUSSION

### Microstructure of Explosive Welded Al/Cu Interface

Figure 6 (a) shows the joint interface of explosive welded Al/Cu. A trigger-like wavy interface was observed. Furthermore, an intermediate layer (IML) was formed along the interface. The IML contains cracks and voids. As shown in the close-up of the IML (Figure 6 (b) SEM-BEI), the IML shows a medium contrast between Al and Cu and contains the solidified structure characterized by dispersed dendrite crystals. These findings suggest that local melting took place at the joint interface.

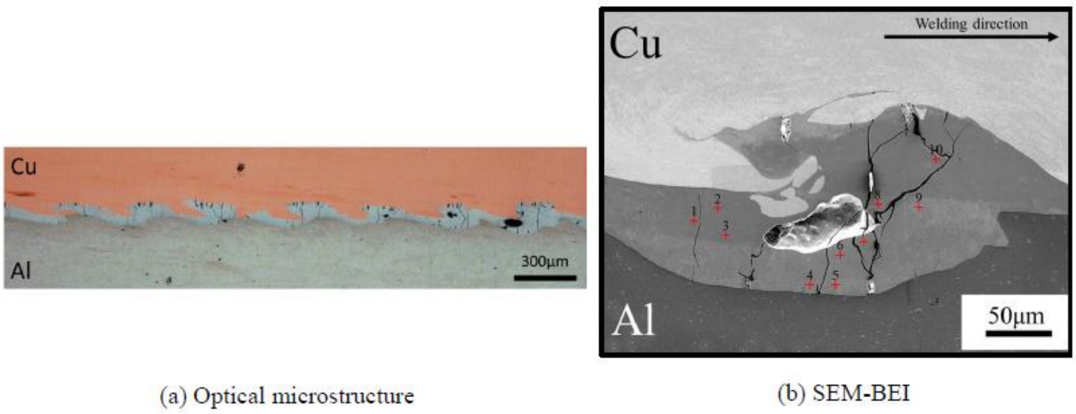


Figure 6. Microstructure of the joint interface of explosive welded Al/Cu

### Formation Process of Wavy Interface Represented by Simulation

Figure 7 shows the formation process of wavy interface simulated by SPH method. The following analytical results were obtained. The metal jet was emitted from the collision point. The metal jet mainly consisted of Al particles and the metal jet was emitted almost parallel to the Cu surface. A characteristic trigger-like way interface was formed behind the collision point and a vortex zone was formed at the top of each wave.

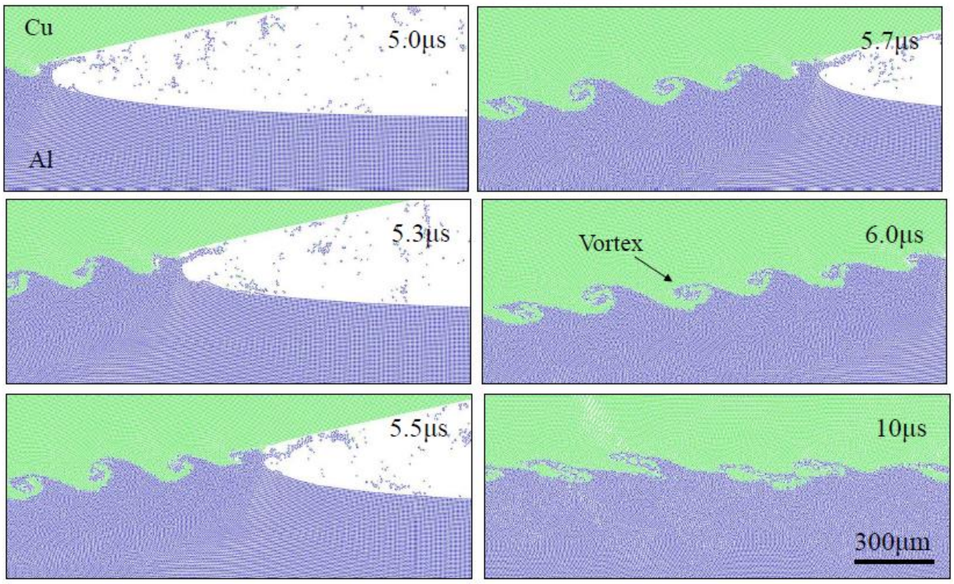


Figure 7. Formation process of wavy interface simulated by SPH method

### Temperature Distribution at the Joint Interface and Location of Local Melting Zone

Material distribution, temperature distribution and the estimated location of local melting zone (LMZ) are reproduced by the SPH method. The results are shown in Figure 8. A temperature increase occurred near the joint interface and vortex zone. However, this temperature increase hardly occurred away from the joint interface in the base metals. LMZ was mainly formed at the vortex zone.

### Cooling Process at the Joint Interface Reproduced by Simulation

The ultimate temperature at the joint interface and vortex zone was high, and it exceeded the melting temperature of Cu. However, the high temperature area was localized, and the temperature increase was negligibly small in the area several hundred μm away from the interface. A large temperature gradient between the joint interface and base metals resulted in extremely rapid cooling at the joint interface. The cooling rate at the local meting zone was estimated to be between $10^6$ to $10^7$ K/s. The obtained cooling rates showed a good agreement with those estimated based on the microstructure change at the explosive welded interface (Crossland, 1982).

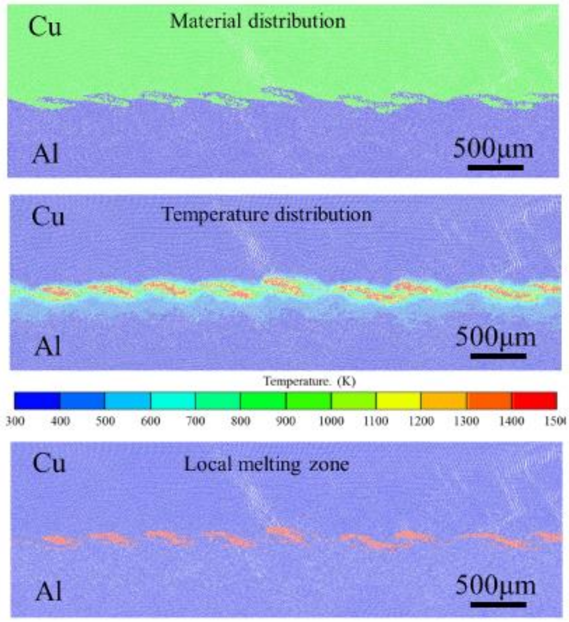


Figure 8. Material distribution, temperature distribution and the estimated location of local melting zone (LMZ) at Al/Cu joint interface reproduced by SPH method

**Formation process of IML at the joint interface and comparison with experimental result**

Comparison of simulation results and experimental results is shown in Figure 9. The wavy morphology (wave-height, wavelength) and the position of IML formed at the joint interface of Al/Cu joints were quantitatively in good agreement with those reproduced by numerical analysis. It was confirmed by both experimental and numerical analyses that morphology and amount of IML at the joint interface changed depending on $\beta$ under the fixed $V$. Chemical composition of IML also changed depending on the welding conditions. At low $\beta$, a large amount of continuous IML was formed and this reduced the strength of the Al/Cu joint significantly. In contrast, at high $\beta$, only a small amount of discontinuous IML was formed at the vortex region of each wave. High joint strength was obtained in this case. It was found that the interface morphology and the amount of IML can be controlled by using the simulation results. This finding is useful to improve the mechanical properties of the impact welded dissimilar metal joints.

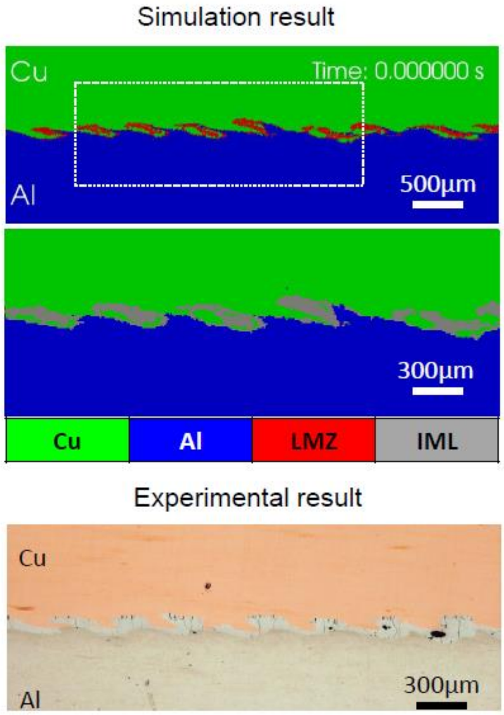


Figure 9. Comparison of simulation results and experimental results

## CONCLUSIONS

The interface morphology of dissimilar metals has an influence on the physical and mechanical properties of the impact welded joint. In the present study, the explosive welding process was divided into five processes. The welding behavior was investigated by using the coupled numerical analyses combining three models. The wavy interface morphology formed at the joint interface and the location of IML reproduced by simulation showed a good quantitative agreement with the experimental results. The estimated cooling rate at the joint interface was also reasonable to explain the microstructure after welding. The newly devised simulation models in the present study were effective to reveal the formation mechanism of characteristic joint interface morphology and IML. This suggests that the control of the interface morphology, reduction of the amount of IML, and improvement of the mechanical properties of the impact welded dissimilar metal joints can be achieved by using the simulation results.

## ACKNOWLEDGMENTS


A part of the present work was supported by JSPS-KAKENHI (JP16K06742) and the Light Metal Educational Foundation, Inc. Their supports is deeply acknowledged.


## REFERENCES


Crossland, B. (1982). Explosive Welding of Metals and Its Application, Oxford Series.

Nishiwaki, J., Kumai, S. (2016). Simulation of local melting zone formation in Cu/Al explosive welded joint. *Quarterly Journal of the JWS*, 34(4), 274–284.

Nishiwaki, J., Kumai, S. (2017). Simulation of cooling and intermediate layer formation at explosive welded Cu/Al interface. *Quarterly Journal of the JWS*, 35(3), 111–121.