Interfacial Morphology Prediction of Impact Welding by Eulerian Method

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Abstract

In this paper, results from LS-DYNA numerical simulations are presented with respect to the interfacial morphology of an impact weld of dissimilar sheet materials, i.e., Cu110 (flyer) and CP-Ti (base), both 1 mm thick. These materials were selected as the workpieces since vortices are known to occur at the interface during experimental welding of this material combination. But a conventional Lagrangian numerical method is not capable of capturing this phenomenon due to large element distortions at the interface. Thus, a numerical simulation with the Eulerian method was used to investigate this local, large plastic deformation of materials at high strain rate. Unlike the Lagrangian method, the surrounding air is modelled in the Eulerian method, with a 5 by 5-micron element size in this research, to capture the vortices at the interface. A Johnson-Cook material model, which is widely used for deformation processes at high strain rates, was used for both flyer and base workpieces. Also, a Mie-Grueneisen's equation of state (EOS) was defined to describe the variation in pressure based on the dynamic condition of materials.

Keywords

Impact welding, Interfacial morphology, Eulerian method, Vortices

1 Introduction

Multi-material welding has become increasingly important for lightweight designs in the automobile and aerospace industries in order to reduce fuel consumption and emissions. But conventional welding processes are not able to meet the requirements of this particular welding because of differences in thermal properties of the two welding partners and the potential for undesirable intermetallic compounds being created. Thus, alternative joining methods must be developed for multi-material welding.

Impact welding is one such solid-state process used for dissimilar materials joining. There exists several impact welding processes including: explosive welding, laser ablation welding, magnetic pulse welding, and vaporizing foil actuator welding (Zhang, 2010). All of these welding technologies show the formation of metallurgical bonds with minimal to no heat affected zone between the two welding partners, which are called the base and the flyer workpieces. The flyer is first rapidly accelerated to a high velocity and then collides with the stationary base at an impact angle. Another advantage of impact welding is that the material surfaces do not need to be prepared. A jetting phenomenon occurs during the welding evolution that removes any oxide layer and/or surface containments in the weld area (Shribman, 2018).

A wavy interface morphology may occur during the impact welding process with an appropriate impact velocity and impact angle. **Figure 1** shows examples of wavy interface morphologies, with wave vortices occurring for certain welding pair combinations (see **Fig. 1a**). Further studies are required in order to determine the fundamental rationale for why vortices exist for such material pairs.

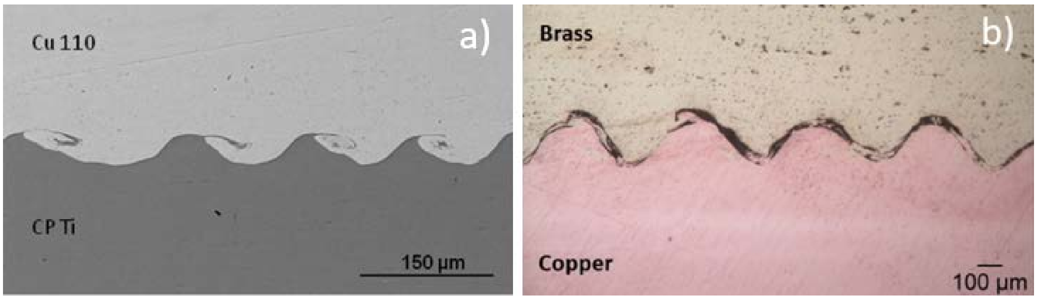

Figure 1*: Wavy interface morphology a) wave with vortices (Vivek et al., 2013), b) wave without vortices (Nassiri et al., 2015)*

Finite Element Analyses (FEA) for impact welding processes are very challenging because of the large deformations that occur near the weld region at the interface. Therefore, it is impossible to obtain the interface morphology with the conventional Lagrangian method due to the excessive distortion of elements that terminates the numerical calculation (see **Fig. 2**). Researchers have investigated how to overcome this difficulty. Nassiri et al., (2015) used the Arbitrary Lagrangian-Eulerian (ALE) method for the same material combination of Al6061-T6 in ABAQUS/EXPLICIT. In this method, a remeshing technique is enabled to perform node relocations that maintain the mesh quality and result accuracy throughout the simulation. However, ALE is unable to predict the complex wavy interfacial morphology with vortices nor the jetting phenomenon. Recent investigations also considered using the Eulerian method to reproduce the wavy interfacial morphology. Some authors were able to reproduce a weak interfacial morphology on dissimilar material combinations, i.e., AA6061 T6 and AISI 1045 (Sun and Xu, 2016), while others used the same material combination of AA 6060 T6 (Raoelison et al., 2016). The Smoothed Particle Hydrodynamic (SPH) technique is another widely used numerical method for processes with large local strain. This is a meshless method where a collection of particles represents the continuum body. Wang et al., (2015) used this method to simulate the wavy interfacial morphology for a laser ablation impact spot welding process, while Nassiri et al., (2017) depicted Ti/Cu interface welded by a vaporized foil actuator welding process by the SPH method. Both wavy interfacial morphology and jetting phenomenon can be predicted by this technique, but this method is considered less accurate than the Lagrangian FEA method. In particular, when the material is in a tensile stress state, the particle may become unstable (Abaqus Manual, 2014).

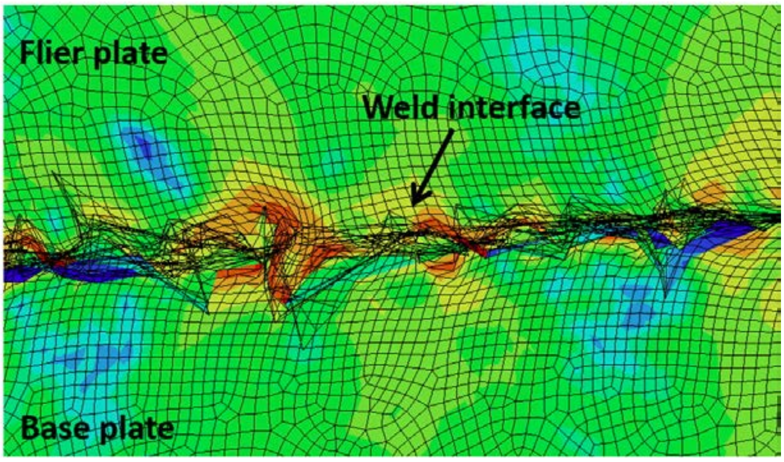

***Figure 2**: Inability of Lagrangian method for impact welding numerical simulations due to excessive element distortions (Nassiri et al., 2015)*

In this study, the Eulerian method is used in LS-DYNA to predict the complex wavy interfacial morphology with vortices as well as the jetting phenomenon during impact welding for the multi-material combination Ti/Cu.

2 Numerical simulation

2.1 Eulerian theory

In the Eulerian method, the time dependent state variables are described by solving the conservation equations of mass, momentum and energy (Raoelison et al., 2016). The variables evolution in time is calculated in a fixed meshing grid. The conservation equations are formulated in terms of the spatial coordinate and time. Thus, the description of motion in the Eulerian method only contains variables or functions with instantaneous significance in a fixed spatial region. This allows an easy management of complex material motion and overcomes the difficulties caused by excessive distortion of the finite element mesh.

The Eulerian method in LS-DYNA first utilizes Lagrangian computation in which the mesh deformed corresponding to the material behaviour due to the high strain rate dynamic constitutive law. The state variables of the deformed material configuration then are advected onto the initial reference mesh, which is called the Eulerian step (Aymone et al., 2001). The Van Leer second order algorithm is used to calculate the new values of state variables for each element from the previous time step configuration.

2.2 Numerical model

One point multi-material Eulerian solid elements were used for the entire model. Each element can have either one or more materials or void space that is defined as air. For the element that contains multi-materials, the stress is calculated based on the volume-fraction-weighted average stress of each material's stress. The 2D model is shown in **Fig. 3**. Both flyer and base have 1 mm thickness and 10 mm length. The angle between the flyer and base was set to 14° and an initial vertically velocity (600 m/s) that drove the flyer was defined (see **Fig. 3**). In order to capture the interfacial morphology, a fine mesh is required at the interface. In this study, an element size of 5x5 μm was used over the entire model, and the simulation time was specified as 3.5 μs. Automatic slip Eulerian boundary conditions were defined to let the materials flow through the fixed mesh. The Johnson-Cook constitutive model was used to describe the high strain rate material deformation:

$$\sigma = (A + B\varepsilon_{eff}^{n})(1 + C\ln\varepsilon)(1 - \frac{T - T_{room}}{T_{melt} - T_{room}}) \tag{1}$$

where σ is the flow stress, ε_{eff} is the effective plastic strain, T is the temperature, and A, B, C, n, and m are material constants. The material parameters for Cu110 and commercially pure Titanium used in this model are given in **Table 1** (Seo et al., 2005, Meyers et al., 1995). Furthermore, the materials were defined as isotropic. The Mie-Grueneisen equation of state (EOS) was defined to explain the pressure based on the thermodynamic condition of the materials. To keep the advection process stable, the difference between the previous and new configurations has to be small, which means that a small time increment is required even though the computational cost increases.

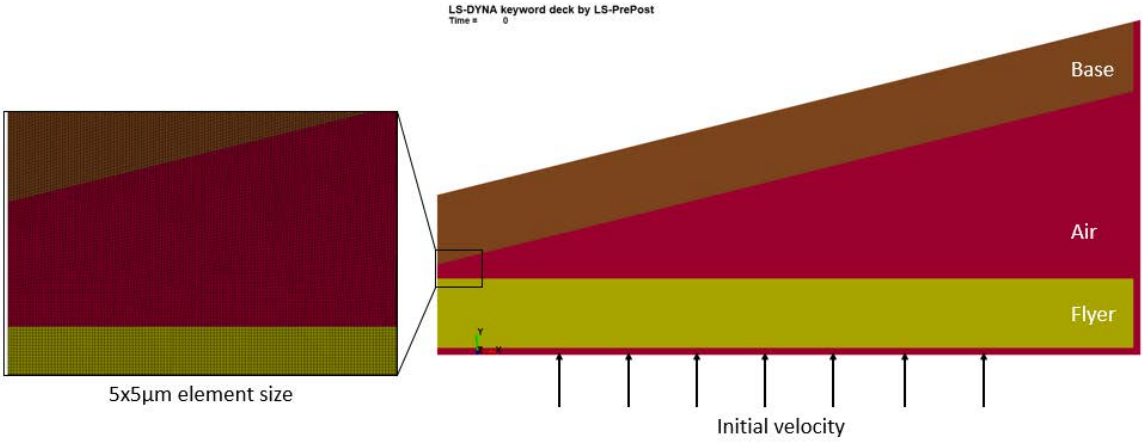

***Figure 3**: 2D Eulerian model*

Materials	**Young's modulus (GPa)**	**Density (kg/m^3)**	**Poisson ratio**	**Shear modulus (GPa)**	**Thermal conductivity (W/mk)**	**Specific heat (J/kgK)**
Cu110	117	8960	0.33	44	390	385
CP-Titanium	105	4510	0.37	45	16.4	523
Materials	**A (MPa)**	**B (MPa)**	**n**	**C**	**m**	**T_{melt} (K)**
Cu110	90	292	0.31	0.025	1.09	1356
CP-Titanium	359	668	0.49	0.0194	0.58	1938

Table 1: *Material parameters used in numerical simulations (Seo et al., 2005, Meyers et al., 1995)*

A structural-thermal coupled analysis was conducted in LS-DYNA in order to predict the change of the temperature at the interface. This is an important parameter to indicate the location of the voids, imperfections, and melting spots in the weld region (Raoelison et al., 2016, Nassiri et al., 2017, Nassiri et al., 2015). A transient thermal analysis was used as this study is a high strain rate dynamic problem. The fraction of mechanical work converted into heat was set to 0.9 as a constant even though it can be strongly correlated to the strain and strain rate (Ravichandran et al., 2002). Mass scaling was not used in this model.

3 Numerical result

The numerical result clearly shows the wavy interfacial morphology for the Cu/Ti material combination (see **Fig. 4**). The collision point propagated from left to right in the figure. The interfacial instability started upon impact and caused the interfacial morphology to evolve from flat to a wavy pattern. As the collision point progressed, larger wave length and amplitude values as well as vortices are produced, but eventually these subside. The jetting phenomenon was also predicted by the Eulerian method, which removed a thin layer of material for both welding partners. The prediction of these experimental observations affirmed the physical abilities of the Eulerian method when simulating impact welding processes.

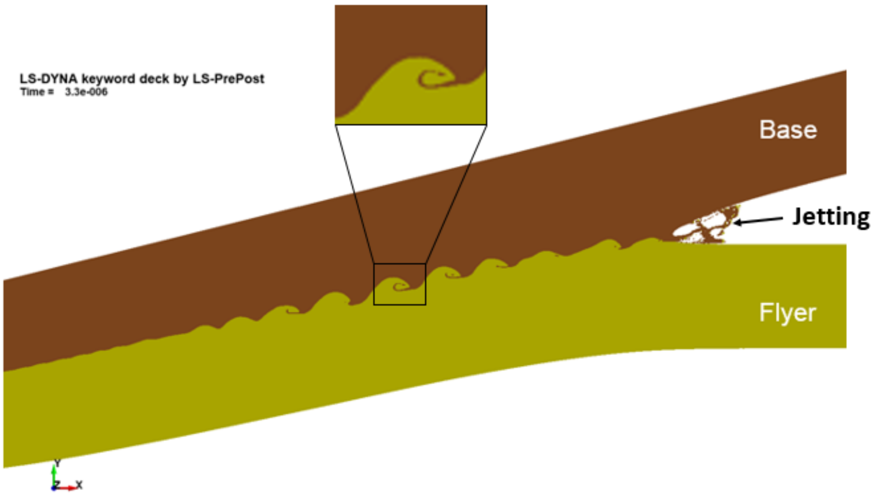

***Figure 4**: Interfacial morphology during weld with jetting indicated*

Figure 5 gives the temperature distribution prediction at the interface during impact welding. The temperature increases from the flat interface to the wavy pattern regions. The highest temperature is around the melting point of CP-Titanium, which occurred near the vortices. At this location, significant plastic work caused by the formation of the vortices promoted an increase of the temperature. This could result in local melting, which could soften the materials and produce potential defects (Vivek et al., 2013, Raoelison et al., 2016, Nassiri et al., 2017).

Based on the aforementioned features and material behaviours given by the numerical result, the complex wavy interfacial morphology of the Cu/Ti material combination during impact welding was able to be predicted with the Eulerian method in LS-DYNA using multi-material elements. The results are consistent with experimental observations (see **Fig. 6a**) and numerical simulations using other solution methodologies (see **Fig. 6b** (Nassiri et al., 2017).

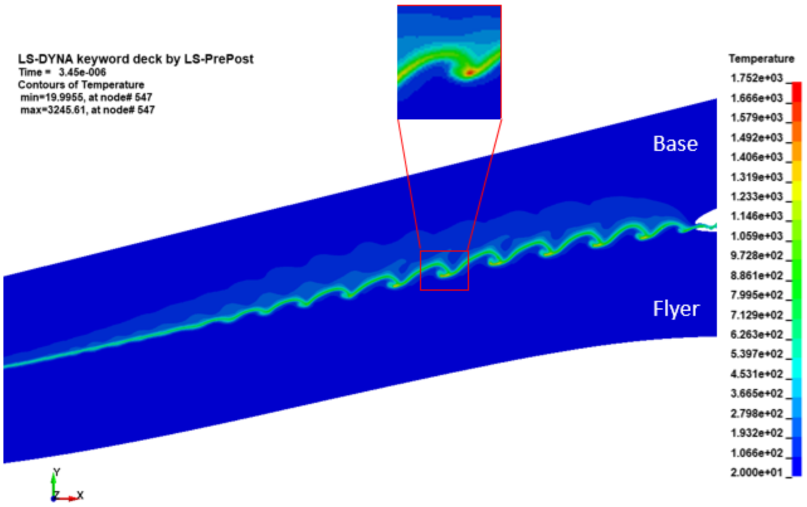

***Figure 5**: Temperature distribution of interfacial morphology during weld*

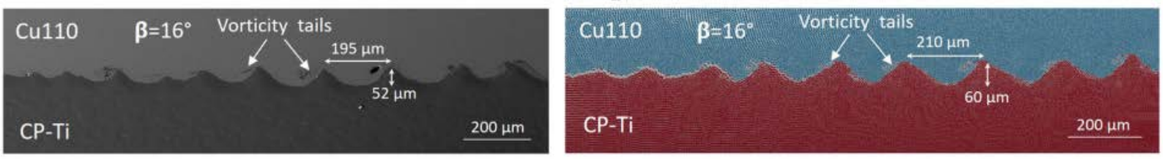

***Figure 6**: Interfacial morphology comparison between experiment and SPH method (Nassiri et al., 2017)*

4 Conclusion

Numerical simulation using the Eulerian method in LS-DYNA successfully reproduced the key parameters at the interface of impact welding processes, which would be impossible to simulate with the classic Lagrangian method. The temperature prediction also provided physical evidence of the realistic material behaviour shown in other studies (Vivek et al., 2013, Nassiri et al., 2017). Thus, the Eulerian method is considered to be an accurate numerical technique for impact welding processes.

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