Journal of Manufacturing Processes 35 (2018) 169–189

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Investigation of explosive welding through whole process modeling using a density adaptive SPH method

Z.L. Zhang[a], D.L. Feng[b], M.B. Liu[a,c,*]

[a] BIC-ESAT, College of Engineering, Peking University, Beijing 100871, China
[b] Institute of Fluid Mechanics and Environmental Physics in Civil Engineering, Leibniz Universität Hannover, Appelstraße 9a, 30167 Hannover, Germany
[c] State Key Laboratory for Turbulence and Complex Systems, Department of Mechanics and Engineering Science, Peking University, Beijing 100871, China

ARTICLE INFO

Keywords:
Smoothed particle hydrodynamics
Explosive welding
Wavy morphology
Numerical weldability window
Effective explosive charge

ABSTRACT

Explosive welding (EXW) involves processes like the detonation of explosive charge, impact of metal structures and strong fluid-structure interaction with complex features such as interfacial waves and jet generation. The whole EXW process has not been well modeled before due to the large deformation and moving interfaces while the associated mechanisms inherent in EXW are also not well understood. In this paper, the whole EXW process is simulated using a density adaptive smoothed particle hydrodynamics (SPH) model, in which a density adaptive algorithm is used to treat variable large density ratio in EXW and the kernel gradient correction (KGC) is used to improve computational accuracy of SPH. The mechanisms in EXW are investigated, and typical phenomena including the wavy interface, jet formation, interfacial temperature and pressure distribution as well as melting voids are examined. The mechanisms of wave formation are studied while two existing mechanisms, namely, the Jet Indentation Mechanism and the Vortex Shedding Mechanism are revealed with the present SPH simulations. It is demonstrated that with proper amount of explosive charge and initial welding angle, the present SPH method can well reproduce the morphology evolution of the welding interface from straight to wavy and further to wavy with vortex shedding. Furthermore, based on comprehensive numerical data from SPH simulations, two types of numerical weldability windows for EXW are presented together with discussions about different welding limits and effective explosive charge.

1. Introduction

It was occasionally found during the Second World War that pieces of shrapnel might be bonded tightly together after the detonation of explosives. Based on such observation, ideas of welding two or more kinds of metals together by using the explosion of explosives were developed to design new composite plates with controllable thermal conductivity and electric conductivity, good welding property and even better erosion resistance than a plate with single material. In EXW process, the detonation of explosive accelerates the flyer plate to impact onto the base plate at a high velocity, which promotes the two plates to be welded together (shown in Fig. 1). Explosive welding causes high pressure around the collision region and produces severe and localized plastic flow at the welding interface. One of the greatest contributions of the EXW technique is that it allows very large surface areas of similar or different metals to be bonded, while this is usually difficult for conventional fusion welding [1].

Wave formation at the material interface is usually an important sign of a successful explosive welding [2,3]. Hence the mechanism of wavy interface formation in EXW has always been the interest to researchers. Basically, there are four different explanations in literatures: (a) the Jet Indentation Mechanism, presented by Abrahamson [4] and later enriched by Bahrani et al. [5]. According to Bahrani et al. [5], when two plates collide at a high velocity, the flyer plate produces a re-entrant jet and a salient jet by the stagnation point S (illustrated in Fig. 2). The interaction between ejected material and the re-entrant jet as well as the hump results in the formation of wavy interface and vortices. (b) the Vortex Shedding Mechanism [6,7], in which the formation of wavy interface is somewhat similar to the formation of von Kármán vortex street produced by a viscos flow over an obstacle at high Reynolds number. (c) the Flow Instability Mechanism [8,9], in which the re-entrant jet plays a key role during the formation of wavy interface. When the re-entrant jet meets the base plate, these two parts have different horizontal velocities under high pressure. Hence the instability, similar to the Kelvin-Helmholz instability, happens. (d) the Stress Wave Mechanism [10], in which the successive interference from

* Corresponding author at: BIC-ESAT, College of Engineering, Peking University, Beijing 100871, China.
E-mail address: mbliu@pku.edu.cn (M.B. Liu).

https://doi.org/10.1016/j.jmapro.2018.08.004
Received 19 June 2018; Received in revised form 29 July 2018; Accepted 2 August 2018
1526-6125/

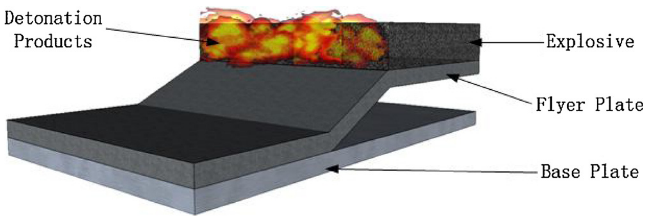

Fig. 1. 3D schematic diagram of explosive welding.

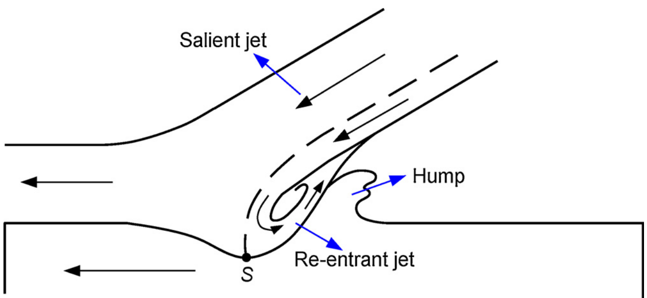

Fig. 2. Illustration of the wave formation according to the Jet Indentation Mechanism.

rarefaction waves in both plates may be responsible for the generation of wavy material interface. Among these wave formation mechanisms, the Jet Indentation Mechanism and the Vortex Shedding Mechanism are frequently accepted when the welding angle is not very large [11]. In contrast, the Flow Instability Mechanism cannot explain the wave produced by symmetrical impact welding and the Stress Wave Mechanism is not able to explain jet formation. Hence further study of the wave formation mechanism becomes important for better controlling the welding quality.

The welding quality in EXW is strongly influenced by process parameters including plate separation or stand-off distance, the amount of explosive or the ratio of explosive to flyer plate and so on. These parameters are mainly selected according to the mechanical properties such as the density and shear wave velocity of the materials [12–14]. Optimal operational parameters are needed for providing ideal bonding conditions of the plates in EXW. Weldability windows with respect to different parameters such as welding velocity - impact angle or flyer plate velocity – impact angle are useful for visually describing the bonding conditions. Fig. 3 shows a classical weldability window with different upper and lower welding limits [1,15].

The existing weldability windows are mainly obtained from experimental approaches [16–18]. For example, Nassiri et al. [17] presented the weldability window for Al6061-T6 experimentally. Vivek et al. [18] obtained the weldability window for commercially pure titanium and copper according to experimental studies as well. However, large quantities of trial-and-error experiments are needed in order to determine the weldability region for the EXW. Moreover, it is also difficult to accelerate the flyer plate to a very high velocity due to the limited experimental conditions, while this often leads to the incomplete weldability windows obtained by limited experimental data. As pointed out in Ref. [18], there are some empty or transitional areas due to the large intervals of collision velocity data. It is attractive to develop reliable numerical methods, which can model the whole process of EXW with major physics well reproduced. As such, after validation with experimental data, numerical methods can minimize the number of experiments and can also overcome difficulties in experimental setup. However, due to the large deformation and moving interfaces, the whole EXW process has not been well modeled before using conventional grid-based methods, which are usually not able to effectively model the explosion of explosive and capture the transitions of the interfacial morphology (from no bond to wavy interface), interfacial melting zones and jet formation. That is why there are rare numerical simulation works on modeling the whole process of EXW, and also that is why rare weldability windows are obtained from numerical approaches.

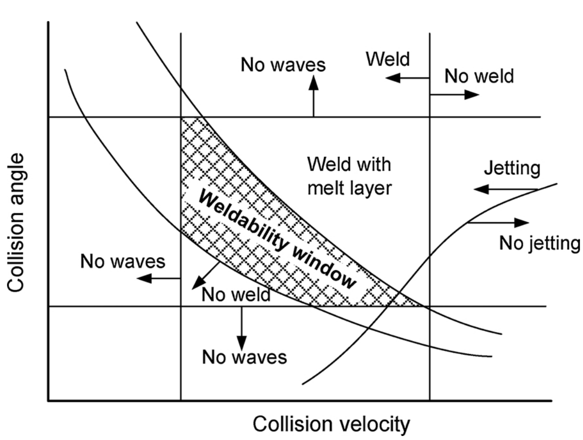

Fig. 3. Generic weldability window with the definition of different welding limits given by [15].

In reality, the EXW process completes in a very short duration along with complex phenomena including chemical reactions (e.g., detonation of explosives) and physical processes (e.g., the driving of explosive explosion on flyer plate, phase transition and large plasticity deformations of the metal structures). It is very difficult to capture such coupled complex processes experimentally or using highly simplified analytical methods such as the Gurney formula [19]. Recently, more and more researchers tend to numerically study EXW as numerical modeling provides an alternative to explore the inherent physics with greatly reduced costs. In most of the existing numerical models, however, the process of EXW is simplified as the impact of the flyer plate onto the base plate at a high velocity. This is usually referred to *high velocity impact welding* (HVIW) since the detonation of explosive together with its driving effect on the flyer plate are ignored. It is clear that numerical results from EXW models are naturally more realistic than those from simplified models (such as HVIW) as more physical effects as well as multi-phase effects are considered. At present, there are only very few reports truly modeling the whole process of EXW including the explosion of explosive and its driving effects [20,21]. However, some important characteristics in EXW such as the wavy interface and the jetting were not well captured by aforementioned approaches. It is thus necessary to develop advanced numerical methods to model real EXW process rather than using simplified models.

Lagrangian grid-based methods suffer from mesh distortion which may abort the computation when the large deformation of the materials becomes serious. Despite the defects, this kind of method can predict the waveless interface and detect the onset of jetting phenomenon, but they are not suitable for predicting the wavy interface pattern, just as mentioned in Ref. [22]. To overcome the mesh distortion problem, the Arbitrary Lagrangian-Eulerian (ALE) method can be adopted in modeling EXW problems while treating large deformations [17,22,23]. However, it can be observed in ALE simulations from these literatures, the mesh deformation at the welding interface is not explicitly evidenced and the jetting cannot be well reproduced [24]. Eulerian grid-based methods have also been used to model EXW, but the Eulerian simulations are only able to capture weak wavy shape, just as pointed out in Ref. [22]. In contrast, meshfree particle methods are more attractive and can capture more physics due to the ability in modeling problems with large deformations and rapidly moving interfaces [24–27].

The smoothed particle hydrodynamics (SPH) method is a truly meshfree and particle-based method which was originally invented for modeling astrophysical problems in three-dimensional open space