

Numerical simulation of explosive welding using Smoothed Particle Hydrodynamics method

J Feng, P Chen*, Q Zhou, K Dai, E An, Y Yuan

State Key Laboratory of Explosion Science and Technology,
Beijing Institute of Technology, China

ABSTRACT

In order to investigate the mechanism of explosive welding and the influences of explosive welding parameters on the welding quality, this paper presents numerical simulation of the explosive welding of Al-Mg plates using Smoothed Particle Hydrodynamics method. The multi-physical phenomena of explosive welding, including acceleration of the flyer plate driven by explosive detonation, oblique collision of the flyer and base plates, jetting phenomenon and the formation of wavy interface can be reproduced in the simulation. The characteristics of explosive welding are analyzed based on the simulation results. The mechanism of wavy interface formation is mainly due to oscillation of the collision point on the bonding surfaces. In addition, the impact velocity and collision angle increase with the increase of the welding parameters, such as explosive thickness and standoff distance, resulting in enlargement of the interfacial waves.

1. INTRODUCTION

Explosive welding is well known for its capability to directly join a wide variety of both similar and dissimilar combinations of metals, which are difficult to be bonded using conventional methods [1,2]. It is generally regarded as a solid phase process, in which the bonding is achieved by the oblique high-speed collision between the flyer plate and the base plate through explosive detonation [11,12]. This technique enables to clad very large section of plates in a single operation and allows us to fabricate large scale composite laminates. Until now, many material combinations, including Al-Cu, Ti-steel, Cu-steel, W-Cu and even multi-layers of metals such as Mg-Al-Ti-Cu-Mo have been welded together using this method [3-7]. However, due to its fast welding characteristic, it is difficult to directly observe and measure the process of explosive welding. Therefore, it is distinctly meaningful to study the process of explosive welding through numerical simulation.

In recent years, a few attempts to numerically model and simulate explosive welding have been reported in the published literatures. Mousavi et al. [8,9] studied the impact process using Euler method. The materials at the collision point were considered to behave like a liquid, the straight or wavy interfaces and jetting phenomena were modeled, and the magnitude of the waves and velocity of jet were predicted. Wang et al. [10] used the material point method to simulate the process of explosive welding. The main physical phenomena and some parameters for the explosive welding were well captured in his simulation. However due to the limitation of the particle size, the interfacial waves and jetting phenomena could not be observed. Li et al. [11] investigated the impact process using the

*Corresponding Author: pwchen@bit.edu.cn

smoothed particle hydrodynamics (SPH) method and concluded that explosive welding can also be regarded as diffusion welding, fusion welding and pressure welding. Wang et al. [12] also simulated the impact process by SPH method, and confirmed that explosive welding is more likely to be a solid state welding. Chen et al. [13] simulated atomic diffusion behavior using molecular dynamics, and demonstrated a hybrid method of calculating the diffusion layer. Although all of these simulations can help us to understand explosive welding, the mechanism of explosive welding and wave formation still remains controversial.

In this paper, the complete process of explosive welding is simulated using Smoothed Particle Hydrodynamics method. Based on the simulation results, the process of explosive welding and wavy interface formation are discussed. In addition, the influences of the welding parameters are studied.

2. NUMERICAL SIMULATION

Numerical simulations of the explosive welding were carried out using SPH method in ANSYS/AUTODYN software [14,15]. SPH method is a Lagrangian technique which has the potential to be both efficient and accurate in modeling material deformation. SPH is also a gridless technique, so it does not suffer from the normal problem of grid tangling in large deformation problems [16]. Therefore, it has been applied to various fields, such as hypervelocity deformation, detonation, and fluid dynamics.

Fig. 1 illustrates the initial configuration of the simulation. Aluminum plate and magnesium plate were respectively selected as the flyer plate and the base plate and parallel configuration was used. ANFO explosive was used to accelerate the flyer plate to impact the base plate and the location of initiation of explosives is located on the left side of the explosive charge. The particle size plays a vital role in visualizing the jetting phenomenon and wave formation of explosive welding. The ANFO explosive, aluminum plate and magnesium plate were modeled with a particle size of 0.05 mm. The sizes of the aluminum plate and magnesium plate were both 2 mm in thickness and 80 mm in length. A steel anvil with transmit boundary was placed under the base plate. Different welding parameters including explosive thickness and standoff distance were considered, which are listed in Table 1.

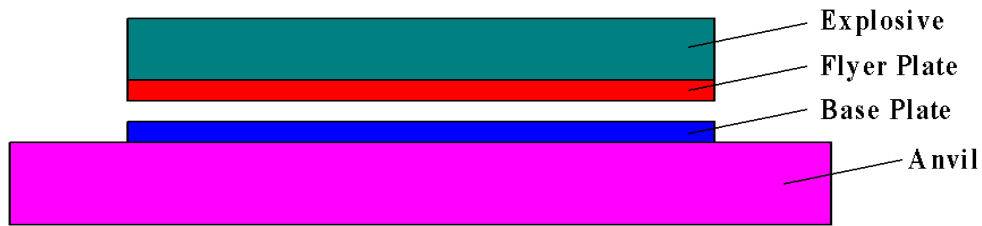


Figure 1: Schematic view of explosive welding.

The JWL EOS is used as the equation of state for ANFO explosive, which can be represented as follows,

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

where p is the pressure, V is the initial relative volume, A , B , R_1 , R_2 and w are constants. JWL EOS parameters for ANFO explosive are shown in Table 2.

Table 1: Explosive welding with different parameters

No.	Flyer plate	Base plate	Explosive thickness (mm)	Standoff distance (mm)
#1	Aluminum	Magnesium	5	0.1
#2	Aluminum	Magnesium	5	0.5
#3	Aluminum	Magnesium	5	1
#4	Aluminum	Magnesium	5	2
#5	Aluminum	Magnesium	5	5
#6	Aluminum	Magnesium	9	0.1
#7	Aluminum	Magnesium	9	0.5
#8	Aluminum	Magnesium	9	1
#9	Aluminum	Magnesium	9	2
#10	Aluminum	Magnesium	9	5
#11	Aluminum	Magnesium	13.5	0.1
#12	Aluminum	Magnesium	13.5	0.5
#13	Aluminum	Magnesium	13.5	1
#14	Aluminum	Magnesium	13.5	2
#15	Aluminum	Magnesium	13.5	5

Table 2: JWL EOS of ANFO explosive

Material	ρ (g/cm ³)	A (kPa)	B (kPa)	R_1	R_2	w	V_{CJ} (m/s)	E_{CJ} (kJ/m ³)
ANFO	0.931	4.946×10 ⁷	1.891×10 ⁶	3.907	1.118	0.3333	4.16×10 ³	2.484×10 ⁶

* V_{CJ} and E_{CJ} are detonation velocity and energy, respectively.

The Shock EOS is used as the equation of state model for both aluminum plate and magnesium plate. It is convenient to establish a Mie-Grüneisen form of equation of state based on the shock Hugoniot. This equation of state is widely used and can be represented as

$$P = P_H + \Gamma \rho (e - e_H). \quad (2)$$

where it is assumed that $\Gamma \rho = \Gamma_0 \rho_0 = \text{const}$, and

$$P_H = \frac{\rho_0 c_0^2 \mu (1 + \mu)}{[1 - (s-1)\mu]^2} \quad (3)$$

$$e_H = \frac{1}{2} \frac{P_H}{\rho_0} \left(\frac{\mu}{1 + \mu} \right)$$

where Γ_0 is the Grüneisen coefficient, $\mu = \left(\frac{\rho}{\rho_0}\right) - 1$, ρ is the current density, ρ_0 is the initial density, and c_0 is the bulk sound speed.

The Johnson-cook strength model is used as the strength model for the flyer and base plates. This constitutive model aims to model the strength behavior of materials subjected

to large strains, high strain rates and high temperatures. The model defines the yield stress Y as:

$$Y = [A + B\varepsilon_p^n][1 + C \log \varepsilon_p^*][1 - T_H^m] \quad (4)$$

where ε_p is effective plastic strain, ε_p^* is normalized effective plastic strain rate, n is work hardening exponent, T_H is homologous temperature, $T_H = (T - T_{room}) / (T_{melt} - T_{room})$, A , B , C , and m are constants.

The parameters of equation of state model and strength model of the flyer and base plates are listed in Table 3:

Table 3: Parameters of Johnson-Cook models and Shock EOS for the plates

Material	ρ (g/cm ³)	Γ	C1	S1	A	B	n	C	m
Aluminum	2.77	2.00	5.328×10^3	1.338	3.37×10^5	3.43×10^5	0.41	0.01	1.00
Magnesium	1.78	1.54	4.520×10^3	1.242	1.90×10^5	1.10×10^3	0.12	0.015	1.60

* C_1 and S_1 are sound velocity and slope, respectively.

3. RESULTS AND DISCUSSION

Fig. 2 shows the results of simulation No. 14, from which the whole process of explosive welding can be clearly observed. The detonation of ANFO explosive accelerates the aluminum flyer plate to a high velocity to impact with the magnesium base plate. With the movement of the explosive detonation wave, the collision point between the flyer plate and the base plate moves forward, and jet gradually appears. With the continuous movement of the collision point, wavy interface is observed progressively, and more jet is ejected. After the explosive detonation, the aluminum and magnesium plates are joined together.

3.1 Welding characteristics

The distribution of velocity, pressure, temperature, effective plastic strain and strain rate in the flyer and base plates in simulation No. 14 are plotted in Fig. 3. As shown in Fig. 3(a), a typical wavy interface with vortex is formed at the bonding interface. The simulated morphology of the interfacial wave is in good agreement with our previous experimental results which is shown in Fig. 6(f). For explosive welding, it is generally accepted that the jet phenomenon is an essential condition. In practice, the surface contaminant, oxides and impurities can be stripped away by the high-speed jet, which contributes to the tight joining of the flyer and base plates. As shown in Fig. 3(a), the jet is ejected in front of the collision point. It is also shown that the jet comes from both the flyer (aluminum) plate and the base (magnesium) plate. The ejected jet moves forward with a velocity of higher than 6000 m/s. Apart from the jet, the highest velocity can be observed at the collision point (Fig. 3(b)), which is approximately equal to the detonation velocity of ANFO explosive.

Due to the drastic collision between the flyer and base plates, high pressures and temperatures are generated near the impact region, as shown in Fig. 3(c) and (d). In order to form the bonding between the flyer and base plates, the atoms from each bonding surfaces must be brought together at atomic scale. The generated high pressure at the collision point will help to bring and keep the atoms together. With the movement of the collision point, the pressure at the welded region will quickly decrease (Fig. 3(c)). However, a thin high

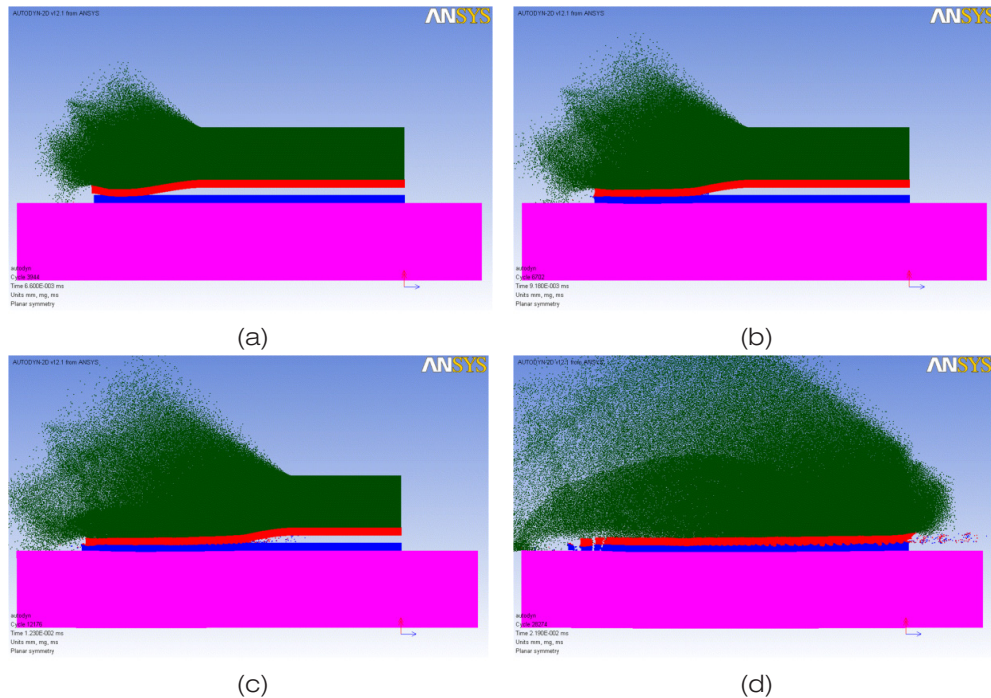


Figure 2: The process of explosive welding in #14.

temperature layer, whose temperature is much higher than the melting points of the welding plates (923 K and 933 K respectively for aluminum and magnesium), will be formed at the welded surface (Fig. 3(d)). In our previous experiments, a thin elemental diffusion layer with a thickness of approximately 3-5 μm was generated on the bonding interface [17]. It can be interpreted that the formation of elemental diffusion layer is mainly due to the accumulated high temperature during high velocity impact of the flyer plate with the base plate.

A plastic strain of more than 2 and a plastic strain-rate of $1 \times 10^4 \text{ s}^{-1}$ were predicted in the collision zone (Fig. 3(e) and (f)), indicating that drastic plastic deformation takes place near the bonding interface. Drastic plastic deformation was also observed in our previous experiment, resulting in the hardening phenomenon and the presence of fine grains near the bonding interface due to dynamic recrystallization [17].

3.2 Wave formation

Fig. 4 illustrates the formation process of interfacial waves in our simulation. At first, the collision point moves towards the base plate (Fig. 4(a)). Drastic collision causes the formation of a hump ahead of the collision point (Fig. 4(b)), and the hump grows in size and moves upwards (Fig. 4(c)). Then, the hump intercepts and blocks the jet, causing the formation of a vortex at the back of the hump (Fig. 4(d)). In addition, a trunk is generated in front of the collision point (Fig. 4(e)). The trunk moves downstream to form an integrated wave (Fig. 4(f)).

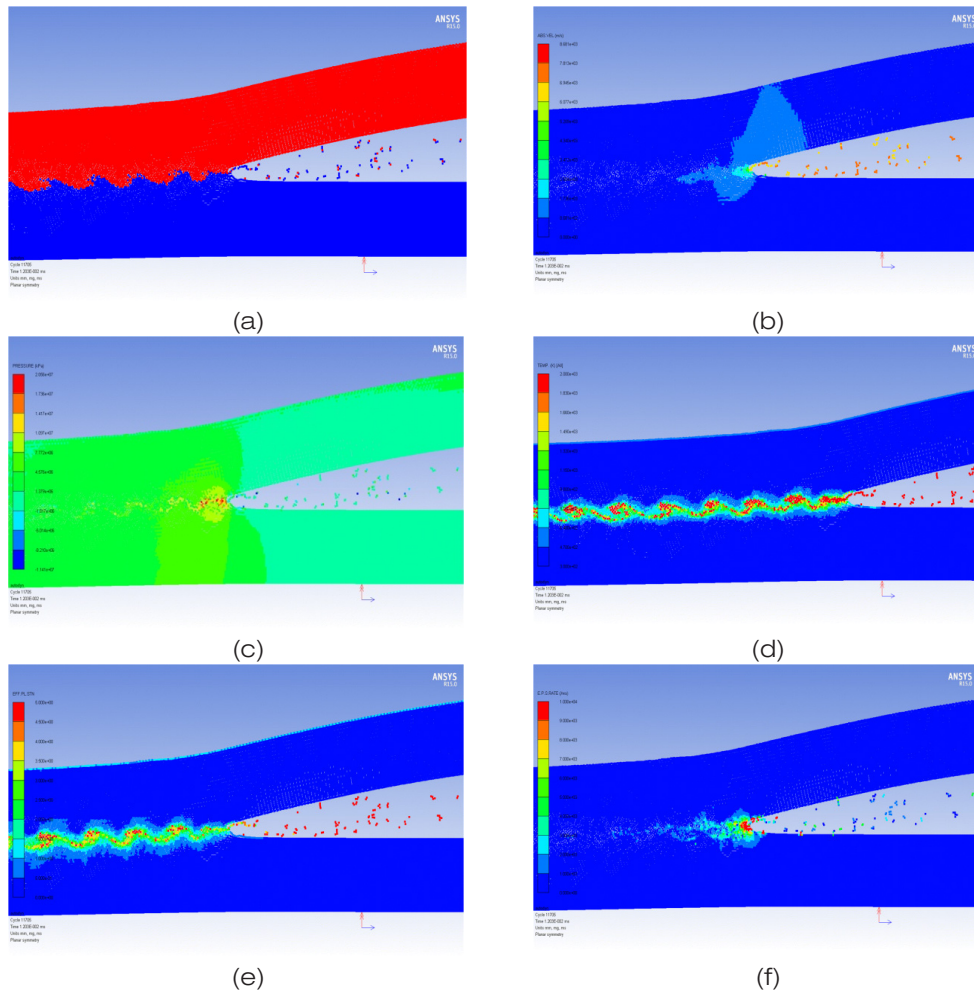


Fig. 3. Numerical simulation of explosive welding in #14: (a) material location, (b) velocity contour, (c) pressure contour, (d) temperature contour, (e) effective plastic strain contour and (f) strain rate contour.

Based on the simulation results, we can summarize the mechanism of wave formation. It is mainly due to the oscillation of collision point on the bonding surfaces. It should be mentioned that, during high speed collision of the flyer and base plates, high pressures and temperatures will cause the materials near the collision point to become fluid state. When the collision point meets the base plate, the base material in front of the collision point will be forced to move upwards and subjected to shear deformation. Thus the sheared material will tend to accumulate as a hump ahead of the collision point, and the hump will grow in size and move upwards due to the deformation of the base material. Ultimately the hump will intercept the jet and completely block the jet. The trapped jet will move backwards to form a vortex at the back of the hump. In this region, phase change or local melting is likely to take place due to the high temperature generated. When the jet is completely obstructed, the collision point

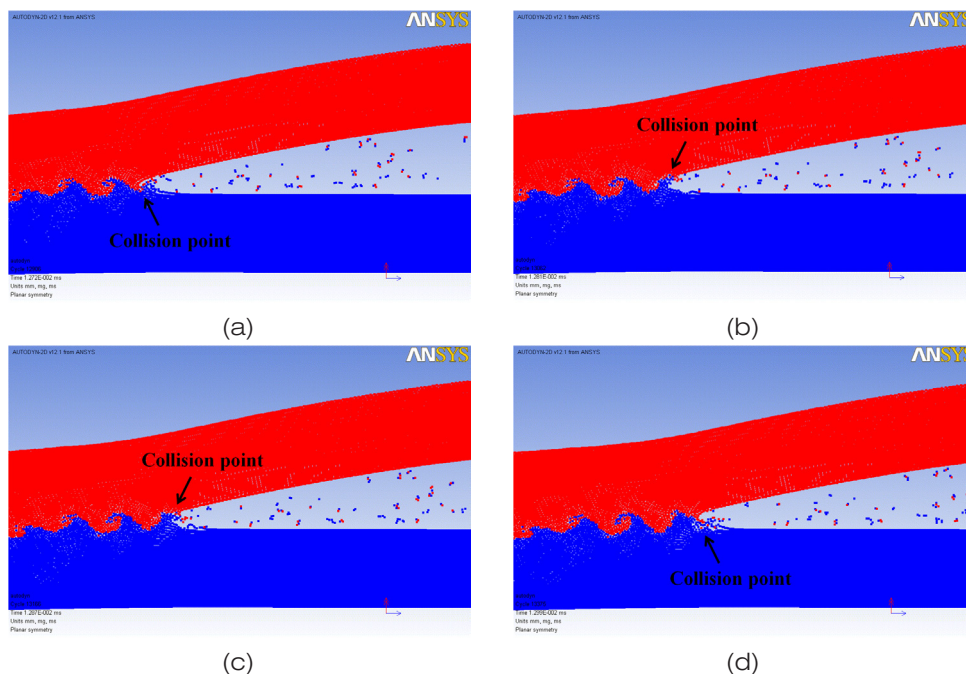


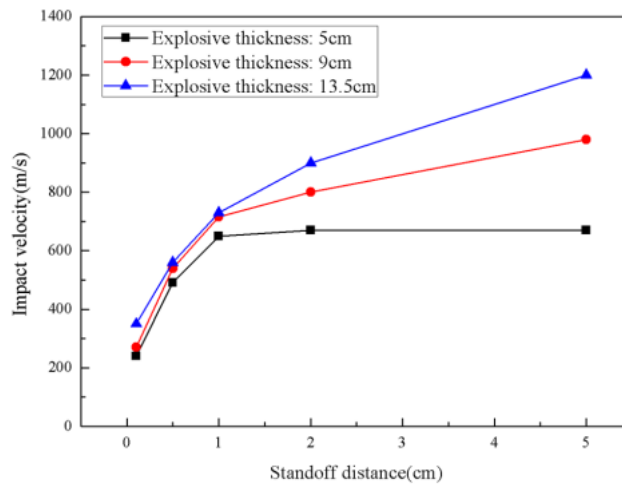
Figure 4: The process of wave formation in #14.

will move from the trough to the crest. At this moment, the collision between the flyer plate and the hump will depress and elongate the hump to form a trunk. The formed trunk will move downstream to collide with the base plate. After collision, an interfacial wave is generated at the bonding interface. Compared with the mechanisms of wave formation [18-21], our results are in accordance with the mechanism proposed by Bahrani et al [18].

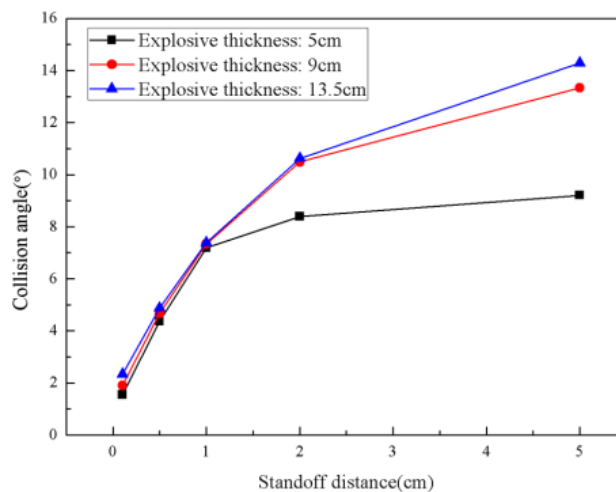
3.3 Influences of welding parameters on the wave formation

It is well known that the welding quality of the composite plates mainly depends on the collision angle and the impact velocity. Fig. 5(a) and (b) summarize all the impact velocities and collision angles obtained in our simulations. The impact velocities are acquired based on the velocity curves from the bonding interface of the flyer plate, and the collision angles are directly measured between the inclined angle of the flyer plate and the base plate. The results demonstrate that increasing the standoff distance or the explosive thickness, the impact velocity and collision angle tend to increase. However, when the standoff distance is less than 1 mm, the increase of the explosive thickness does not significantly increase the impact velocity and the collision angle, which can be explained as that when the standoff distance is small (less than 1 mm), it cannot offer enough space for the flyer plate to accelerate to a higher velocity. When the standoff distance is larger than 2 mm, the increase of the explosive thickness causes both the impact velocity and collision angle to grow distinctly. Similarly, when the explosive thickness is smaller than 5 mm, the increase of the standoff distance from 2 mm to 5 mm will cause a slight increase of the collision angle, while the impact velocity remains nearly unchanged, which can be explained as that detonation of thin-layer explosive cannot offer enough energy for the flyer plate to accelerate to a higher velocity.

Fig. 6(a)-(d) shows the bonding interface with different welding parameters. At a smaller explosive thickness (5mm) and standoff distance (0.1mm), a smooth interface appears at the bonding interface and no jet is ejected due to a smaller impact velocity (240 m/s) and collision angle (1.55°) (Fig. 6(a)). With the increase of the standoff distance to 2 mm, a wavy interface appears and a little jet is ejected (Fig. 6(b)). With the further increase of welding parameters (#9 and #15), more jet will be ejected, which can be attributed to higher impact velocities and larger collision angles. In addition, higher impact velocities will enlarge the magnitude of interfacial waves (Fig. 6(c) and (d)). Fig. 6(e) and (f) show the bonding interface of Al/Mg composite plates obtained in our previous experiments [17]. The experimental results also demonstrate that the size of the interfacial waves tend to increase with increasing the welding parameters.



(a)



(b)

Figure 5: The impact velocities and collision angles of the flyer plate.

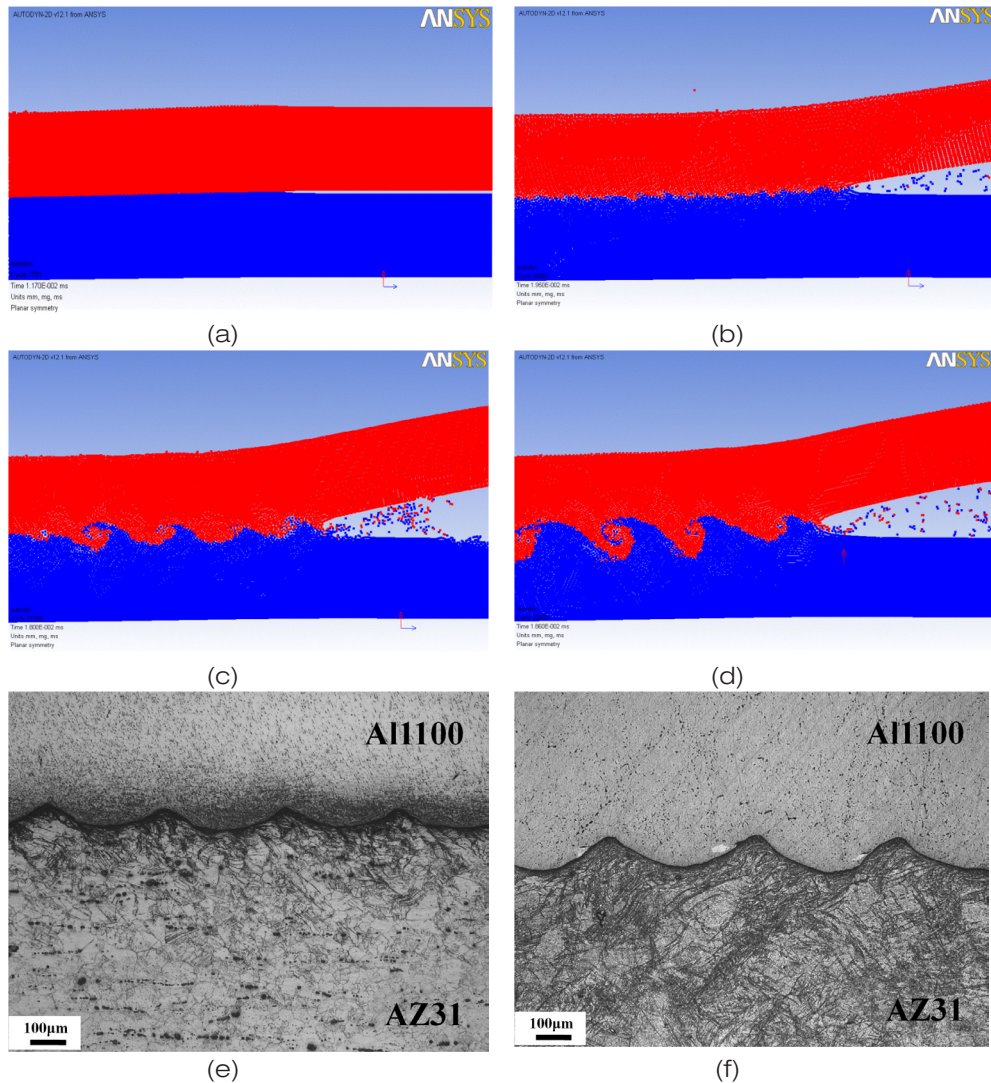


Fig. 6. The bonding interfaces of Al/Mg composite plates: (a) simulation in #1 (impact velocity 240 m/s, collision angle 1.55°), (b) simulation in #4 (impact velocity 670 m/s, collision angle 8.39°), (c) simulation #9 (impact velocity 800 m/s, collision angle 10.49°), (d) simulation #15 (impact velocity 1200 m/s, collision angle 14.29°), (e) and (f) are the real microstructures of the interfacial waves obtained in our previous experiments [17].

5. CONCLUSIONS

Smoothed Particle Hydrodynamics proves to be effective to simulate the process of explosive welding. The whole process of explosive welding, including acceleration of the flyer plate driven by explosive detonation, oblique collision of the flyer and base plates, jetting phenomenon and the formation of wavy interface, can be successfully reproduced using the SPH method. Explosive welding is mainly due to the drastic collision of the flyer

and base plates which generates high pressure, temperature and high strain rate to join the plates together. The simulated morphology of the interfacial wave is consistent with our previous experimental results, and the formation of wavy interface is mainly due to the oscillation of the collision point on the bonding surfaces. This method can also be used to obtain and optimize the parameters of explosive welding practice. By increasing the welding parameters, the impact velocity and collision angle will increase, and the magnitude of interfacial waves will enlarge.

ACKNOWLEDGEMENTS

The authors would like to express their thanks for the financial support of National Natural Science Foundation of China under grant No. 11521062 and 11472054.

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