Numerical Simulation of Explosive Welding of Marine Aluminum Steel Transition Joint Based on AUTODYN

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Abstract. The finite element analysis software AUTODYN is used to simulate the processing process of marine Aluminum-steel transitional explosion joints, and the jet, spallation and waveform distribution in the process of explosive welding are obtained. Comparing the numerical simulation results with the experimental phenomena, the correctness of the simulation results is verified. The effects of the impact velocity of the cladding, the collision angle, etc. on the welding results were further analysed. It provides a reference for studying the formation of jet phenomena in explosive welding and the selection of explosion parameters during actual welding.

Keywords: Aluminum-Steel composite plate; explosion welding; numerical simulation; jet

1. Introduction
Aluminum has been widely used as the main material for ship superstructure construction in recent years because of its low density, high strength, good plasticity and toughness, good thermal conductivity and electrical conductivity, and strong corrosion resistance. The use of the Aluminum alloy structure can reduce the weight of the ship, increase the longitudinal strength, and improve stability. The connection between the traditional Aluminum alloy superstructure and the steel ship main body is riveting, which has been gradually replaced by explosive welding in recent years.

Explosive welding is a technique in which explosives are used as an energy source[1], and the huge energy generated by the explosion of explosives is used to push the composite plate to move, and the composite plate and the substrate are strongly collided to by plastic deformation. Compared with the traditional riveting and bolting, the process of explosive welding is good, and the hardness and fatigue strength of the joint surface are higher. And it is more widely used and can achieve a wide range of dissimilar metals. Marine explosive composite joints are generally Aluminum-Steel joints or Aluminum-Titanium-Steel composite joints. For multi-layer explosive composite joints, one-time welding or multiple welding can be used. The joint performance of multiple welding is better. In this paper, the Aluminum-Steel welding process is studied, and several conclusions are proposed to provide reference for the actual welding parameters selection.

2. Basic theory of SPH
In this paper, the AUTODYYN module in the finite element software ANSYS was used to simulate the welding process by using Smooth Partical Hydrodynamic (SPH). Using this method, the jet phenomenon at the joint interface and the waveform interface morphology can be well observed, and the pressure and plastic deformation at the joint are analysed[2].

SPH is a Lagrange-based meshless calculation method. Its advantage is that it can overcome the shortcomings of the Euler method that is difficult to track structural deformation and can not identify
the interface of the material in the simulation deformation, and there is no Lagrange mesh deformation problem. The SPH method treats continuous objects as interacting particles, and motion passes between the particles. To represent the interaction between particles, the concept of a "smooth kernel" function is introduced.

\[ f(x) = \int_\Omega f(x') \delta(x - x') dx' \]  

Where \( f \) is a function of the three-dimensional spatial position vector \( x \).

By replacing the Dirac function \( \delta(x - x') \) with the smooth function \( W(x - x') \), the expression can be written as:

\[ \langle f(x) \rangle = \int_\Omega f(x') W(x - x') dx' \]  

The smooth kernel function \( W \) should satisfy the following conditions:

1. Regularization conditions (normalization conditions):
   \[ \int_\Omega W(x - x', h) dx' = 1 \]  

2. The Dirac function property when the smooth length tends to zero:
   \[ \lim_{h \to 0} W(x - x', h) = \delta(x - x') \]

3. Tight support conditions:
   \[ W(x - x') = 0, \text{ when } |x - x'| > \kappa h, \kappa \text{ is a constant related to the smooth function at point } x \]

3. Numerical simulation parameters and models

3.1 Model material and parameters

In order to observe the occurrence of jet phenomenon better, the density of the substrate should be less than that of the composite plate because the substrate material is the main source of jet phenomenon \[3\]. Therefore, Al5083H116 plate (10mm×2mm) is selected as the substrate material, and the double plate is SS304 steel plate (11mm×1mm),its length slightly larger than the substrate to ensure complete bonding, the interval is set to 1mm. The chemical composition of these two materials is shown in Table 1 and Table 2.

| Table 1. Chemical composition of Al5083H116 (mass fraction, %) |
|-----------------|-------|-----|-----|-----|-----|-----|-----|
| Si   | Fe   | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  |
| 0.4  | 0.4  | 0.1 | 0.4-1.0 | 4.0-4.9 | 0.05-0.25 | 0.25 | 0.15 |

| Table 2. Chemical composition of SS 304 (mass fraction, %) |
|-----------------|-------|-----|-----|-----|-----|-----|
| Mn  | Si   | C   | Cr  | Ni  | S   | P   |
| 2.0 | 1.0  | 0.08 | 0.05 | 8.0-10.0 | 0.03 | 0.045 |

3.2 Collision angle and impact velocity of the composite plate

The impact velocity of the composite plate and the collision angle are all important factors affecting the welding effect\[4\]. If the collision angle is too small, the substrate and the composite plate cannot be well combined, and no jet phenomenon will occur. And if he collision angle is too large, it will cause over-melting. Therefore, after consulting the relevant literature, we determine the collision angles are 10°, 15° and 20°.

The formation of jets is the most basic condition for explosive welding, because in the process of explosive welding, the free jet will clean the interface to be combined, which is convenient for better combination. Therefore, the collision speed between the superstrate and the substrate must be greater than the critical speed to produce a jet phenomenon. Many scholars have done a lot of research on the lower limit of welding, and also put forward the corresponding theory. We use the formula proposed by Deribas et al to determine the minimum collision speed\[5\].

\[ V_{pmin} = K \frac{H_v}{\sqrt{\rho}} \]  

Where: \( H_v \)—Vickers hardness of the material; \( K \)—constant, and the value is 0.6-1.2.
The Vickers hardness of AL5083H116 material is 96 MPa. Taking a K value of 0.6, the minimum collision speed $V_{pmin}$ obtained is 360m/s.

Therefore, in order to investigate the impact of the impact angle and the impact velocity of the composite plate on the welding results, the two influencing factors were combined and nine operating conditions as shown in Table 3 were set. The collision angles are 10°, 15° and 20°, and the impact speeds are 600 m/s, 800 m/s and 600 m/s.

| Working condition number | collision angles (°) | impact speeds (m/s) |
|--------------------------|----------------------|---------------------|
| 1                        | 10                   | 600                 |
| 2                        | 10                   | 800                 |
| 3                        | 10                   | 1000                |
| 4                        | 15                   | 600                 |
| 5                        | 15                   | 800                 |
| 6                        | 15                   | 1000                |
| 7                        | 20                   | 600                 |
| 8                        | 20                   | 800                 |
| 9                        | 20                   | 1000                |

Set the particle size to 0.02mm and the established numerical model is shown in Figure 1.

4. Numerical simulation results analysis

4.1 Analysis of welding simulation phenomena

By analysing the results under different working conditions, the main phenomenon in the explosion welding process are the waveform of the joint surface and the generation of the jet phenomenon. As shown in Figure 2(a), the main source of material for the jet is Aluminum, because the material density and hardness of the Aluminum sheet is less than that of the composite.

Zoom in on the waveform of the joint surface, as shown in Figure 2(b). In the early collision area, the waveform and amplitude are not obvious, and with the transition of the position, the waveform of the joint surface is gradually stable and exhibits a periodic trend, which is consistent with the actual experiment.

Comparing the welding profile with different impact velocities at the same impact angle, as shown in Figure 3, it can be seen that the impact velocity has a very significant effect on the welding effect. At a speed of 400 m/s, the jet phenomenon is not obvious and the cross-section thickness at the joint surface is small. However, when the speed is 800 m/s, there is a phenomenon that the impact force is
too large and cracks occur in the intermediate region substrate (layer cracking phenomenon). The spallation is related to the reflection phenomenon of stress waves. During the explosion welding process, when the pressure pulse is reflected into the tensile pulse on the free surface of the plate, it will likely cause a relatively high tensile stress somewhere near the free surface. Most engineering materials are able to withstand relatively strong compressive stress waves without damage, but cannot withstand tensile stress waves of the same strength. However, due to the weak strength of the welded joint during the explosion welding process, the interface of the just welded joint is easily pulled apart under the tensile stress, resulting in failure of the welding of the composite plate within a certain range, and the superposed plate due to the tensile stress. Figure 4(c) shows the spallation phenomenon that occurs during welding.

4.2 Welding simulation numerical analysis

4.2.1 Joint surface pressure analysis. The pressure cloud diagram and the pressure-time curve at the joint face is shown in Figure 5(a). It can be clearly seen that the maximum pressure is the position of the current collision point and moves with time. In order to accurately analyse the pressure of the contact surface, 20 measuring points are evenly distributed on the substrate, and the pressure–time curve of the measuring point is shown in Figure 5(b). At an impact velocity of 600 m/s, the welding effect is best, the maximum pressure at the joint reaches 30GPa, the average maximum pressure is 15 GPa, and the maximum pressure duration is short.

Extracting the average maximum pressure under all conditions, as shown in Table 4. It can be found that the average maximum pressure decreases as the collision angle increases and the impact speed decreases.

| Collision angle (°) | 400   | 600   | 800   |
|---------------------|-------|-------|-------|
| Impact speed (m/s)  |       |       |       |
| 400                 |       |       |       |
| 600                 |       |       |       |
| 800                 |       |       |       |
4.2.2 Substrate speed analysis. In the existing literature analysis, most of them focus on the response speed of the composite plate under the impact of explosives. This paper analyses the feedback speed of the substrate as shown in the figure. It can be seen that in the same direction, the velocity curve of the substrate exhibits the same trend as the pressure curve, and its variation with the impact velocity and the collision angle is also the same as the pressure variation. This is because the speed of the substrate is due to the strong action of the composite plate, and the substrate material collides with the composite plate to cause severe plastic deformation, which is reflected in the simulation is the change in the velocity of the substrate particles.

(a) Collision angle: 10; Impact speed: 400m/s.
(b) Collision angle: 10; Impact speed: 600m/s.
(c) Collision angle: 15; Impact speed: 600m/s.

5. Conclusion
The experimental results show that: (1) By simulating the welding process under different impact speeds, it is found that there is no obvious jet phenomenon when the impact velocity is small, and the welding effect of the joint surface is not ideal. When the impact velocity is too large, the cracking phenomenon may occur near the bonding surface of the substrate due to the excessive impact force. Under this experimental condition, 600 m/s is a suitable impact velocity.(2) By simulating the welding under different impact angles, it is found that the average maximum pressure between the substrate and the composite plate decreases with the increase of the collision angle, but the tightness of the welding increases and the spallation phenomenon decreases.(3) In actual manufacturing, it is necessary to select the appropriate impact speed and collision angle to achieve the best welding results.

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