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ARTICLE

Numerical Simulation and Boundary Effect of Explosive Welding of Copper/Steel Composite Pipe

Yang Haijuan[1], **Liu Cuirong**[1,2], **Zhang Wenbin**[1], **Li Yan**[1,2]

[1] School of Material Science and Engineering, Taiyuan University of Science and Technology, Taiyuan 030024, China; [2] Modern College of Humanities and Sciences, Shanxi Normal University, Linfen 041000, China

Abstract: With copper/steel composite pipe as research object, two-dimensional numerical simulation of explosive welding process was conducted through AUTODYN finite element software with SPH and ALE methods. The dynamic welding process and boundary effect were analyzed, and the explosive welding tests of copper/steel composite pipe were conducted. Results indicate that under the action of detonation waves, the composite pipe obliquely collides with the base pipe. The pressure in the collision zone remains stable at the order of 10^7 kPa, and a plastic deformation band appears near the collision zone. The shear stresses have opposite directions on the base pipe and composite pipe, and the interface morphology changes from straight line to wavy shape with the propagation of explosion wave. This result is consistent with the actual interface morphology of the T2/316L bimetal composite pipe in experiments, indicating that this finite element model can effectively simulate the explosive welding process of bimetal composite pipe. During the numerical simulation process, the dynamic parameter values at the edges are all smaller than the normal values, leading to boundary effects. Increasing the length of composite pipe and explosive can eliminate the boundary effect.

Key words: explosive welding; numerical simulation; dynamic parameter; boundary effect

Explosive welding of metals involves metal physics, explosion, and welding technique, which can achieve high-quality solid metallurgical combination of different metal pipe combinations. Currently, explosive welding technique can achieve welding of similar or different metals and alloys of more than 260 types, which has been widely used in the engineering field[1–3]. Numerical simulation is a convenient method to investigate the effect of process parameters during explosive welding process, therefore reducing the experiment cost[4]. Miao et al[5] found that the Lagrangian method is more concise than most modeling methods, and the SPH-FEM coupling method requires much longer simulation calculation time than other methods. The collision velocity obtained by different algorithms has the error of 0.9%–5.3% from the theoretical calculation values. Cao et al[6] used the LS-DYNA software with ALE method to effectively simulate the composite process of the underwater explosion of bimetal pipe, but the waveform of the bonding interface could not be obtained. Ding et al[7] proposed the dynamic self-constrained explosive welding of copper/steel bimetal pipes without outer film and analyzed the mechanical balance of the self-constrained process with three-dimensional numerical simulation, thus eliminating the requirements of explosive welding of composite pipes on the mold.

In the actual production, the edges of products manufactured by explosive welding may be unwelded or torn, namely the explosive welding boundary effects, which affects the quality of welding products and wastes metal material. Zhang et al[8] prepared Q235/T2 composite pipe and 1060/T2 composite rod in a single test by new dolly-type explosive welding method, but the welding quality of the resultant top area of 1060/T2 composite rod was inferior. Miao et al[9–11] found that although the severity of explosive welding boundary effect is different by changing the types of cladding plates and explosives, the boundary effect exists in all cases. The lower the ultimate tensile strength of cladding plates or

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Corresponding author: Li Yan, Ph. D., Associate Professor, School of Material Science and Engineering, Taiyuan University of Science and Technology, Taiyuan 030024, P. R. China, E-mail: yanli1988@tyust.edu.cn

the higher the explosive detonation speed, the more serious the boundary effect phenomenon. The existence of sparse waves in explosives causes the boundary effects. However, the methods to eliminate the boundary effect of composite pipes are rarely investigated.

Copper, as a traditional thermal conductive rolling material, has been widely used in the metallurgy, power, and chemical industries. Stainless steel has the advantages of fine corrosion resistance, high strength, good fatigue resistance, good pressure resistance, and relatively low cost. Therefore, the copper/stainless steel composite pipes have wide application prospects due to their high thermal conductivity, fine corrosion resistance, and good mechanical strength. Based on AUTODYN software, a two-dimensional explosive welding model of copper/steel bimetal pipe was established through SPH and ALE algorithms in this research to simulate and analyze the explosive welding process of copper/steel composite pipe. The process parameters, such as velocity, pressure, and effective plastic strain, were discussed, and the simulated and experimental interface morphologies were compared to verify the accuracy of numerical simulation. Normally, the explosive welding causes boundary effect. In this research, the length of the composite pipe and explosive was increased to decrease the boundary effect. Numerical simulation and corresponding analyses of this new model were conducted, and the boundary effect of the composite pipe was studied.

1 Numerical Simulation of Explosive Welding

1.1 Model

The calculation process of explosive welding of copper/stainless steel pipe was simulated by AUTODYN software. Combined with the physical process of explosive welding, the two-dimensional model used SPH method to effectively and accurately simulate the steel pipe and copper pipe, avoiding the grid distortion. ALE method was used to simulate the explosives and moulds. ALE method could adaptively adjust and maintain high-quality grids, which was suitable for fluid structure coupling problems[12]. The initiation point was set at the center of the explosive edge; 14 gauge points were spaced with equal distances between the lower surface of the composite pipe and the upper surface of the base pipe, as shown in Fig.1. Table 1 lists the geometric parameters of the two-dimensional model. The spacing between the composite pipe and the base pipe was 0.6 mm. The particle size in SPH method was crucial. If the particle size was too large, the model could not accurately simulate the wave interface. If the particle size was too small, the computational cost was high and the material stiffness reduced[4]. In this research, the particle size was 15 μm in SPH method. The model contained 52 000 particles. The ALE grid size was 0.1 mm, and the unit system in the model was mm-mg-ms.

1.2 Explosive model and state equation

Jones Wilkins Lee (JWL) state equation was selected as the state equation of explosives, which is a semi-empirical state equation without detonation products by chemical reaction. This state equation could accurately describe the process of expansion-driven work produced by detonation[13]. JWL state equation is shown in Eq.(1), as follows:

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E_0}{V} \qquad (1)$$

where P is the pressure of the detonation product; V is the relative volume of the detonation product; E_0 is the initial specific internal energy; e is the initial internal energy; A, B, R_1, R_2, and ω are related parameters. The state equation can describe the relationship between various physical quantities (pressure, specific volume, temperature, internal energy) in the detonation system after explosion. Thus, it is often used in the explosive welding simulation. Combined with the theoretical value of explosive welding window[14], JWL state parameters of explosives are shown in Table 2.

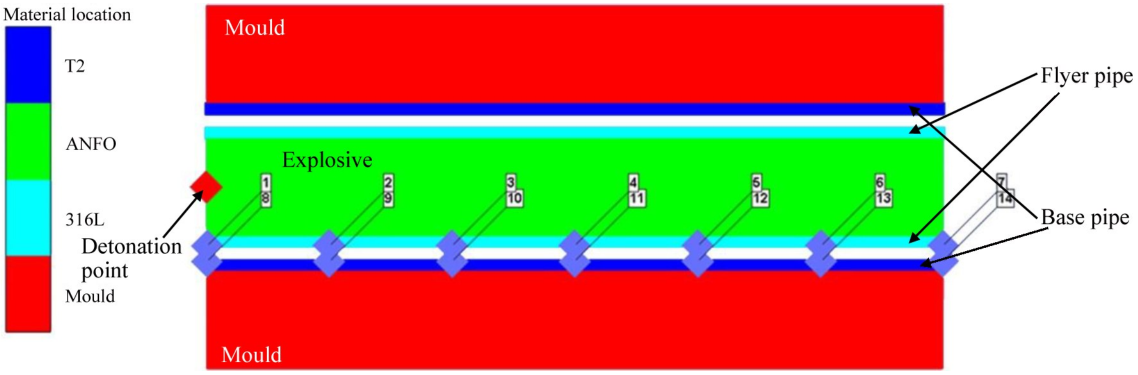

Fig.1 Two-dimensional model of explosive welding of T2/316L composite pipe

Table 1 Geometry parameters of two-dimensional model of explosive welding for T2/316L composite pipe (mm)

Material	Length	Height
316L	30	0.4
T2	30	0.4
ANFO	30	2.8
Mould	30	3.0

Table 2 JWL state parameters of explosives

Relative volume of detonation product, V/m·s^{-1}	Density, ρ/kg·m^{-3}	Initial specific internal energy, E_0/GJ	A/GJ	B/GJ	R_1	R_2	ω
3750	900	2.48	49.46	1.89	3.91	1.11	0.33

1.3 Base and composite pipe models and state equation

Shock state equation is suitable to characterize the dynamic behavior of materials under severe deformation. Mie-Gruneisen state equation was selected to simulate the steel pipe and copper pipe and to describe the basic relationship between particle velocity and impact velocity of SPH algorithm. The expression of this state equation[15–16] is shown in Eq.(2–6), as follows:

$$p = p_{\mathrm{H}} + \Gamma_{\rho}\left(e - e_{\mathrm{H}}\right) \tag{2}$$

with

$$\Gamma_{\rho} = \Gamma_0 \rho_0 \tag{3}$$

$$p_{\mathrm{H}} = \frac{\rho_0 c_0^2 \mu\left(1 + \mu\right)}{1 - (s - 1)\mu^2} \tag{4}$$

$$e_{\mathrm{H}} = \frac{p_{\mathrm{H}}\mu}{2\rho_0\left(1 + \mu\right)} \tag{5}$$

$$\mu = \frac{\rho}{\rho_0} - 1 \tag{6}$$

where Γ_0 is the Gruneisen coefficient; Γ_ρ is a constant; ρ_0 and ρ are the initial density and current density of the material, respectively; p and p_{H} are the material impact pressure and current pressure, respectively; e_{H} is the material impact internal energy; μ is the compression ratio; s is the material constant; c_0 is the volume sound velocity of the material. The parameters of the Mie-Gruneisen material model used in this research are shown in Table 3.

Johnson-Cook constitutive equation can accurately describe the relationship between stress and strain and that between strain rate and temperature under large deformation. Thus, Eq. (7) was selected to simulate the constitutive equation of copper pipe and steel pipe, as follows[17]:

$$\sigma = \left(A + B\varepsilon_{\mathrm{p}}^{n}\right)\left(1 + C\ln\varepsilon_{\mathrm{p}}^{*}\right)\left(1 - T^{*m}\right) \tag{7}$$

where σ is flow stress for Von Mises; A is the initial yield stress; B is the hardening constant; ε_{p} is the equivalent plastic strain; $\varepsilon_{\mathrm{p}}^{*} = \frac{\varepsilon_{\mathrm{p}}}{\varepsilon_0}$ is the equivalent plastic strain rate; n is the hardening index; C is the strain rate constant; m is the thermal softening index; $T^{*} = \frac{T - T_{\mathrm{room}}}{T_{\mathrm{melt}} - T_{\mathrm{room}}}$ is a dimensionless temperature; T_{melt} and T_{room} represent the melting temperature of the material and room temperature, respectively. The Johnson-Cook material model parameters are shown in Table 4.

2 Results and Discussion

2.1 Explosive welding process

Fig. 2 shows the explosive welding process of copper/steel composite pipe (the explosive and mold parts are hidden), which is similar to the welding process of clad plate[12]. The composite pipe is accelerated to bend under the action of explosives, then collides with the base pipe, and ultimately forms a composite material. The inner diameter becomes larger under the action of explosives.

2.2 Velocity distribution

Fig. 3a shows the interface morphology of explosive welding model. Fig. 3b shows the relationship between Y velocity and time of the composite pipe in the model. Fig.3c$_1$–3c$_6$ show the interface waveforms of the regions in Fig.3a. In the numerical simulation, the Y velocity of the base pipe determines the collision velocity between the composite pipe and the base pipe, as well as the waveform formation during interface bonding. According to Fig.3b, the feature point 1 is at the starting position. In the beginning, the explosive energy is insufficient, resulting in the lower velocity of production and no binding occurs at the interface, as shown in Fig.3c$_1$.

With the stable detonation of explosive, the interface presents a flat and straight interface in Fig.3c$_2$. The Y velocity increases sharply and the maximum value is 1420 m/s. Then, it decreases to about 80 m/s to maintain stability. The interface is transformed from the flat interface to the small wavy interface[18] (Fig. 3c$_3$), the periodic smooth wavy interface (Fig.3c$_4$, wavelength of 0.16 mm, amplitude of 0.12 mm), and the vortex wavy interface (Fig. 3c$_5$, wavelength of 0.27 mm, amplitude of 0.18 mm). Finally, under the action of the

Table 3 Mie-Gruneisen material model parameters

Material	Gruneisen coefficient, Γ_0	Volumetric sound velocity, c_0/m·s^{-1}	Constant, s	Initial temperature, T_r/K
316L	2.17	4569	1.49	300
T2	1.99	3940	1.49	294

Table 4 Johnson-Cook material model parameters

Material	Density, ρ/kg·m^{-3}	Initial yield stress, A/MPa	Hardening constant, B/MPa	Hardening index, n	Strain rate constant, C	Thermal softening index, m	Melting temperature, T_{melt}/K
316L	7980	280	1250	0.76	0.021	0.82	1680
T2	8930	90	292	0.31	0.025	1.09	1356
Mould	7896	350	275	0.36	0.022	1	1811

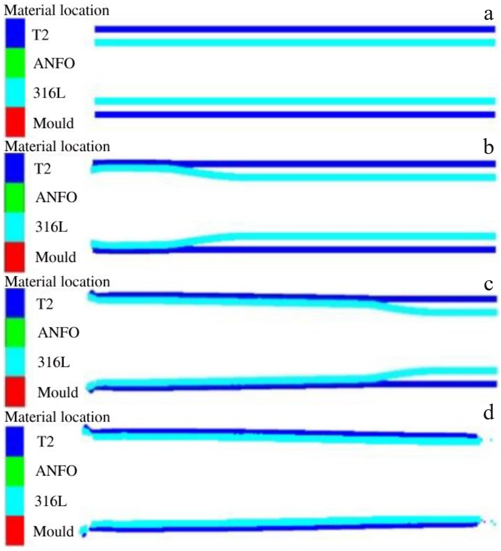

Fig.2 Simulated explosive welding process: (a) 0 ms, (b) 2.73×10^{-3} ms, (c) 6.15×10^{-3} ms, and (d) 8.96×10^{-3} ms

rarefaction wave of explosive[19], the maximum velocity of feature point 7 is smaller than that at the middle position, and the interface becomes a straight interface again (Fig.3c_6).

2.3 Pressure distribution

When the composite pipe collides with the base pipe, huge pressure is generated at the collision point. During explosive welding of copper/steel composite pipe, the pressure distribution at 3.77×10^{-3} ms is shown in Fig.4a. The maximum pressure occurs in the collision point area. The pressure-time curve of the characteristic points on the base composite pipe is shown in Fig. 4b. The pressure at feature points 1 and 8 near the initiation point is extremely low. With propagating the detonation wave, the pressure at feature points 3 and 10 shows a pulse-like upward trend, and the pressure curves of these two points coincide, indicating the combination of the two impact points. Then, the pressure gradually decreases from peak to zero within 1.3×10^{-3} ms[12].

The pressure-time curve of the feature points in the middle part of the composite pipe shows the similar variation: the peak pressure value has the order of magnitudes of 10^7 kPa. The collision pressure at the interface is much greater than the yield strength of the material. In the end, due to the sparse wave of the explosive, the pressure is relatively low.

2.4 Effective plastic strain and shear stress distribution

The materials near the interface produce serious plastic deformation during explosive welding, thus forming plastic deformation zone. A clear narrow plastic deformation band appears near the collision zone. The effective plastic strain cloud map at 3.77×10^{-3} ms is shown in Fig. 5a. The effective plastic strain curves of the feature points on the base pipe in the model are shown in Fig. 5b. The feature points 5 and 12 undergo plastic deformation simultaneously, and their maximum deformation amount is 1.5 and 1.6, respectively. The plastic strain remains stable after reaching a certain value. Plastic deformation is usually irreversible, resulting in uneven

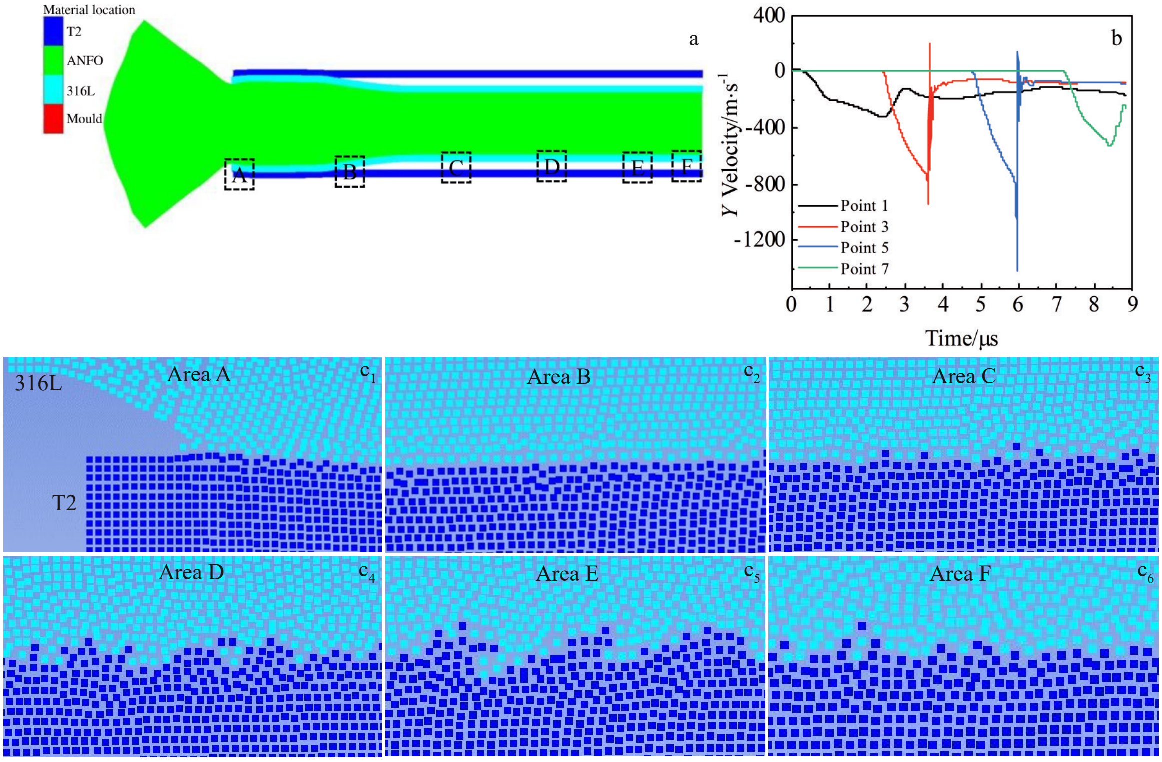

Fig.3 Simulated interface morphology of explosive welding process (a); relationship between Y velocity and time of different feature points (b); enlarged morphologies of unwelded area A (c_1), straight area B (c_2), wave area C (c_3), smooth wave area D (c_4), vortex wave area E (c_5), and straight area F (c_6) in Fig.3a

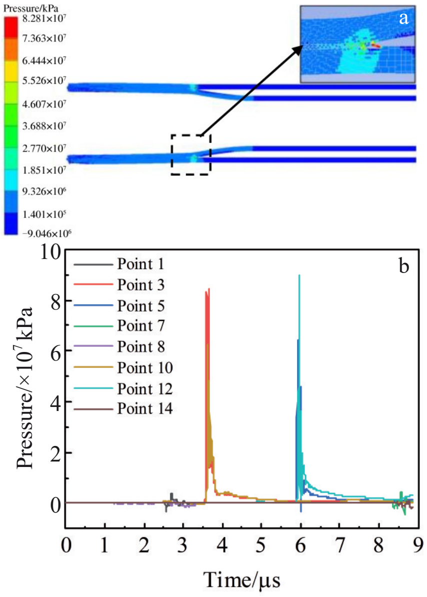

Fig.4 Pressure distribution on copper/steel composite pipe at 3.77×10^{-3} ms (a); relationship between pressure and time at feature points (b)

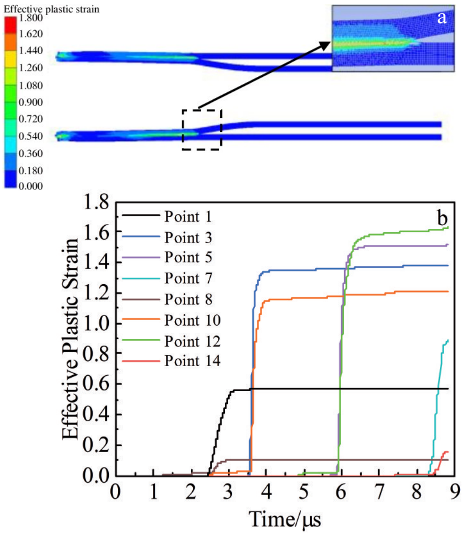

Fig.5 Distribution of effective plastic strain at 3.77×10^{-3} ms (a); relationship between effective plastic strain and time at different feature points (b)

surface. This phenomenon can ensure that the two metals can be successfully welded[4]. Severe plastic deformation is usually accompanied by the grain recrystallization and the formation of intermetallic compounds. However, due to restriction of AUTODYN software, the severe plastic deformation cannot be achieved in current simulations[12].

The distribution cloud diagram of shear stress in copper/steel composite pipe at 3.77×10^{-3} ms is shown in Fig.6. It can be seen that the shear stress on the composite pipe has opposite direction to that on the base pipe. The shear stress on the composite pipe is negative, whereas that on the base pipe is positive. The shear stress is unevenly distributed on the base pipe and composite pipe. Mousavi et al[21] found that the composite pipe can be achieved only when the base pipe is subjected to the opposite shear stress during the explosive welding. In addition, the material properties lead to the higher shear stress value of the composite pipe, compared with that on the base pipe[22].

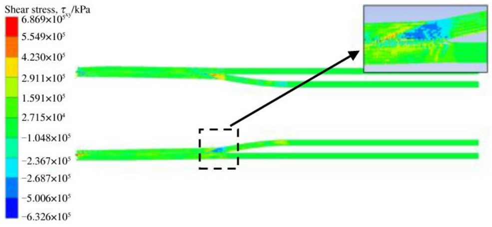

Fig.6 Shear stress nephogram of copper/steel composite pipe

2.5 Boundary effect of controlled explosive welding

Fig.7 shows the composite interfaces at the starting position and ending position after explosive welding. It can be seen that the composite pipe is tilted at the beginning, and the bonding interface at the end changes from the wavy interface to the flat surface. Based on the analysis of velocity and pressure, it can also be seen that these two parts of the composite pipe are not fully bonded, resulting in the boundary effect. Moreover, the boundary effect at the starting position is more severe than at the ending position. The existence of the boundary effect undoubtfully reduces the quality of the entire composite pipe, which not only causes material waste, but also requires additional operation procedures to remove the unbounded parts at the edges, thus increasing the manufacturing cost of the composite pipe.

The boundary effect is caused by not only the insufficient energy generated by explosive detonation at the initial stage and ending stage, but also the effect of explosive rarefaction wave. To eliminate the boundary effect, the composite pipe, explosive length (extending of 5 mm at both ends), explosive initiation position, and other unchanged model parameters should be added into the original model, as shown in Fig.8a.

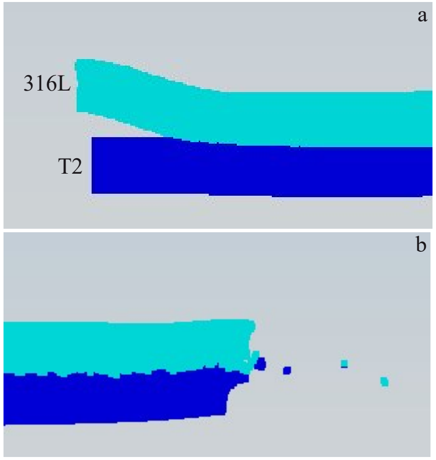

Fig.7 Boundary effect at starting position (a) and ending position (b)

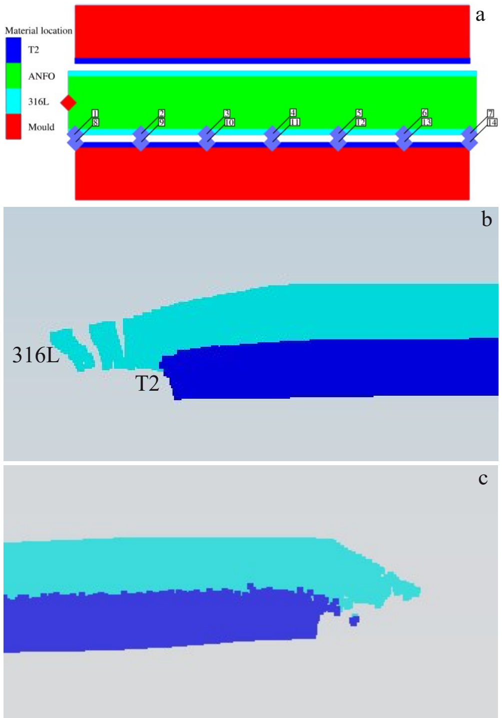

Fig.8 Boundary effect in extended copper/steel composite pipe model: (a) overall model; (b) starting position; (c) ending position

The simulation results of this method at the edges are shown in Fig. 8b–8c. Compared with Fig. 7, it can be seen that this method can avoid the generation of boundary effect, and good combination of pipes can be achieved at the edge of base pipe.

The properties of the extended model are shown in Fig.9. It can be seen that the *Y* velocities at feature points 1 and 7 at the edge increase to 820 and 950 m/s, respectively, and the order of magnitudes of the pressure is 10^7 kPa. Compared with Fig.3 and Fig. 4, it can be seen that the pressure value at the edge greatly increases, which is similar to that at the middle feature points. These results indicate that the combination energy at the edge increases and the edge is well combined, eliminating the boundary effect.

3 Experiment

To conduct the explosive welding experiment of copper/steel composite pipe, the geometric parameters of copper/steel composite pipe are 10 times larger than those of the numerical simulation parameters, as shown in Table 5. Ammonium oil explosive with density of 900 kg/m^3 and detonation velocity of 3750 m/s was selected for edge center initiation. Fig. 10a shows the welded composite pipe. The wire cutting method is used to cut the composite pipes A, B, and C at three positions. The cut samples are shown in Fig. 10c, and each sample has the size of 10 mm×5 mm×8 mm. Grind and polish the sample, and observe the interface morphology of the sample under a VHX-2000 ultra depth of field three-dimensional microscope.

The detailed waveform at area A–C in Fig. 10a is shown in Fig. 11a–11c, respectively. The smooth wave length in Fig. 11b is 203 μm and the amplitude is 59 μm. The vortex wave length in Fig. 11c is 227 μm and the amplitude is 75 μm. Compared

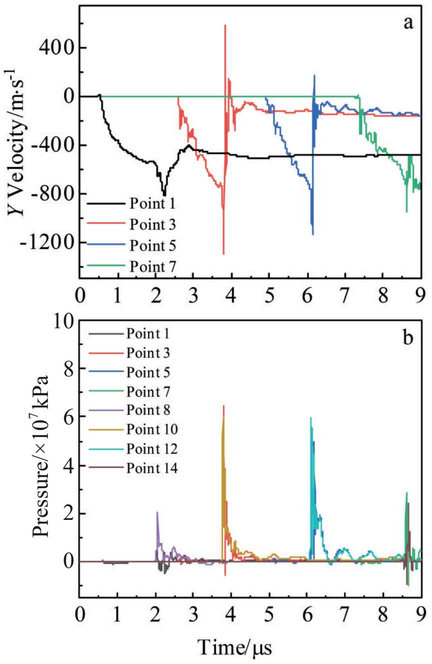

Fig.9 Relationship of *Y* velocity (a) and pressure (b) with time of different feature points

Table 5 Base pipe parameters (mm)

Material	Length	Inside diameter	Thickness
316L	300	28	4
T2	300	48	4

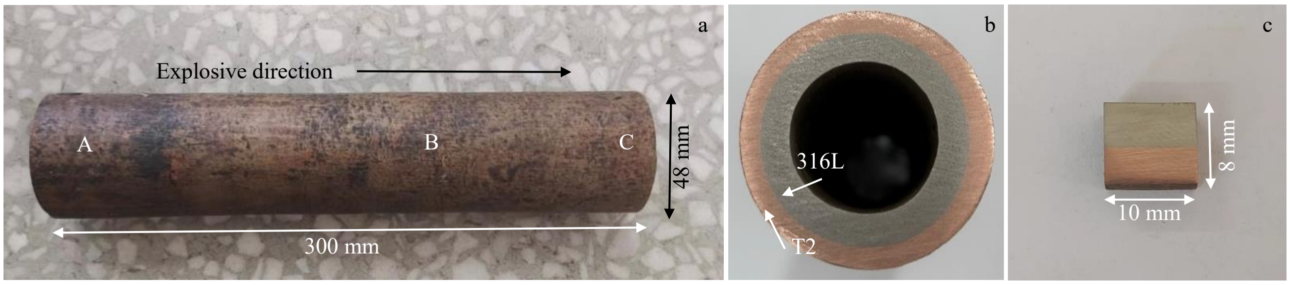

Fig.10 Appearances of copper/steel composite pipe: (a) side appearance; (b) cross-section appearance; (c) longitudinal-section appearance

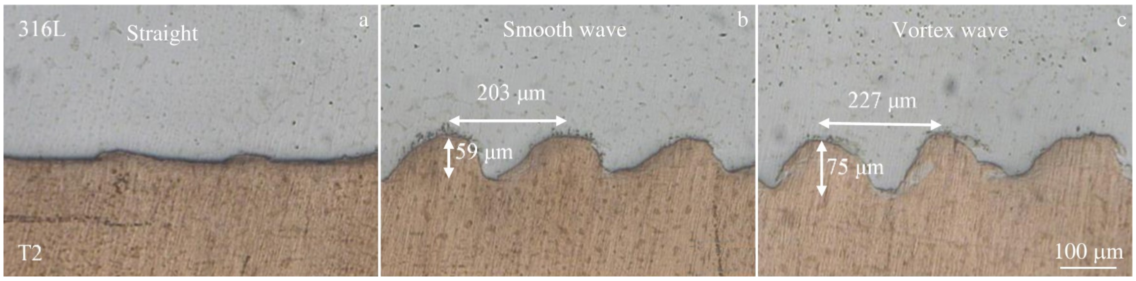

Fig.11 Interface morphologies of waveform at area A (a), area B (b), and area C (c) in Fig.10a

with the simulated interface morphologies in Fig. 3, in the initial stage of explosion, the junction surface is flat, and the periodic smooth waves and vortex waves are formed with the detonation of explosives proceeding[23]. The simulated and experimental shapes of the junction surface are consistent, which verifies the accuracy of the numerical model of explosive welding.

4 Conclusions

1) Under the action of explosive detonation waves, the copper/steel composite pipe is accelerated and collides obliquely with the base pipe. When the explosive explodes stably, the pressure is at the order of magnitude of 10^7 kPa, which is much greater than the dynamic yield strength of copper and steel materials. A clear narrow plastic deformation band appears near the collision zone, and the shear stresses on the base and composite pipes have opposite directions.

2) The velocity, pressure, and effective plastic deformation at the initial position and end position of the explosion are all lower than the normal values. Besides, boundary effect exists in the explosive welding. The boundary effect can be eliminated by extending the composite pipe and explosive, which increases the binding energy at the edge.

3) The established numerical model of explosive welding is reasonable and reliable to simulate the explosive welding process of copper/steel bimetal pipe. In the simulation, the interface morphology changes from straight line to wave shape with the propagation of the explosion wave, which is consistent with the actual interface morphology of the T2/316L bimetal composite pipe after explosive welding.

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铜/钢复合管爆炸焊接数值模拟及边界效应

杨海娟[1]，刘翠荣[1,2]，张文斌[1]，李　岩[1,2]

(1. 太原科技大学 材料科学与工程学院，山西 太原 030024)

(2. 山西师范大学 现代文理学院，山西 临汾 041000)

摘　要：以铜/钢复合管为研究对象，利用AUTODYN有限元软件SPH和ALE法对爆炸焊接过程进行二维数值模拟，分析了焊接动态过程和边界效应问题，并对铜/钢复合管进行了爆炸焊接试验。结果表明，在爆轰波作用下，复管与基管发生倾斜碰撞，碰撞区域压力稳定在10^7 kPa的数量级，在碰撞区附近出现1条塑性变形带，且复管和基管上的剪切应力相反，界面形态随着爆炸波的传播从直线变为波状，这与试验中获得的T2/316L双金属复合管的实际界面形态一致，说明有限元模型能够有效模拟双金属复合管爆炸焊接过程。数值模拟过程中边缘动态参数值均小于正常值，存在边界效应，增加复管和炸药的长度可以消除边界效应。

关键词：爆炸焊接；数值模拟；动态参数；边界效应

作者简介：杨海娟，女，1998年生，硕士生，太原科技大学材料科学与工程学院，山西 太原 030024，E-mail：S202114210133@stu.tyust.edu.cn