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EFFECT OF CONE SIZE ON THE BONDING STRENGTH OF BIMETALLIC COMPOSITE PIPES PRODUCED BY DRAWING APPROACH

The effect of cone size on interfacial bonding strength of bimetallic composite pipe manufactured by drawing approach is studied on base of the plane strain assumption and ideal elastic-plastic model, a simple expression for the effect of cone size on the bonding strength of bimetallic composite pipes is proposed. The agreement of the predicted results with the experimental results shows the reliability.

Keywords: bi-metallic composite pipe, drawing approach, cone size, interfacial bonding strength, ideal elastoplastic

1. Introduction

So far, the main mode of oil and gas transportation is still pipeline one. Pipeline transportation is widely used as transportation equipment of gas, liquid and powder in petroleum, chemical industry, metallurgy, electric power and city gas, heating and water supply system. In addition, the technical requirements of the pipeline is getting higher and higher with the continuous development of the national economy and the improvement of people's living standards, and growing of industrial construction and housing construction. However, the inevitable corrosion of pipeline is the potential problem to restrict the safe operation of pipeline.

Bimetallic composite pipe (hereinafter referred to as the composite pipe) is a new type of pipe composed of two different metallic pipes closely. It is composed of an inner pipe with corrosion resistance, and the outer pipe bearing load. The combining of the interface between the both pipes is through a variety of deformation and metallurgical technologies tightly. Both the inner and outer pipes deform together in loading status and the interface is not separated. The design principle of the bimetallic composite is: the outer pipe is to bear the mechanical load, and the lining pipe is to meet requirements of corrosion resistance or wear resistance as well as other performance. Therefore, compared with a single metallic pipe, the composite pipe can take full characteristic advantage of the base pipe and liner; it not only has high strength, but also the excellent corrosion resistance, wear resistance and other performance. In addition, it could reduce production costs, saving the rare and precious metals, etc. Therefore, the bimetallic composite pipe can be widely used as a transportation pipe in the fields of petroleum,

chemical industry, nuclear industry, medical treatment, food, construction, fire fighting and so on.

Typically, the composite pipe forming method can be divided into plastic forming method and non-plastic forming method [1-7]. The plastic forming technology is the use of plastic deformation in pipe locally or as a whole, so as to achieve a close combination of the inner tube and the outer tube; the process is with simple forming equipment and high efficiency. It has been widely used worldwide. The main plastic forming methods include mechanically drawing approach, hydraulic bulging method, rolling method, and the explosion forming method, etc.

Mechanically drawing approach is an important method of bimetallic composite production process with the lowest cost of production. It is practical significance to analyze the stress and deformation of bimetallic composite pipe in the process of mechanical drawing production process so as to optimize the processing technology rationally and improve product quality effectively.

However, it is a little bit difficult to analyze the stress status since the plastic deforming process of the drawing progress for bi-metallic composite pipe manufacturing is rather complex. Both physical non-linear and geometric nonlinearity are contained, in addition to the complex boundary conditions [8-10], which makes it difficult to establish a rigorous theoretical analysis for drawing forming of bimetallic composite pipe. Some researchers employed finite element simulation to perform relevant analysis [11-13], good results are obtained; In 1976, an analytical solutions of the residual contact pressure for expanding pipe was proposed by Krips [14,15], he assumed an ideal elastic-plastic material model, and both the elastic modulus of tube and

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sheet material is the same. The process of expanding pipe in a sheet of a heat exchanger is analyzed by Krips. While in 1982, Masashi Takemoto gave the relationship between the expanding pressure P_i and the contact pressure P_c by assuming Tresca yield criterion and ideal elastic-plastic material model [16]. In 1988, Yan proposed an equation of residual contact pressure for heat exchanger without considering strain hardening [17].

Actually, the above residual contact pressure formulas are valid in the expansion process of tube to sheet for heat exchanger, which defers from the forming process of bimetallic composite pipe. Therefore, the theoretical formulas for tube and sheet expansion for heat exchanger don't hold for the case of plastic forming process of bi-metallic composite pipe integration as a whole.

Wang et al studied the hydraulic expansion process of bi-metallic composite pipe [18], the principles of graphic method was employed. But his prediction doesn't agree with his experimental data reasonably.

Recently, the plane strain assumption and the ideal elastic-plastic model are used to simplify the forming process of the bimetallic composite pipe in hydraulic bulging process by us [19]. The relationships between the internal pressure and deformation of the bimetallic composite pipe prepared by hydraulic method, and the internal pressure and interfacial residual stress, are established. The comparison of the predicted results with the experimental results shows its reliability [19].

In this article, the plane strain assumption and the ideal elastic-plastic model are employed as well. The effect of the cone-head size of the drawing approach manufacturing bimetallic composite pipe on the interfacial bonding strength is studied.

2. Outline of the main results in hydraulic bulging forming composite tube

In [19], the initial state of the composite pipe is shown in Fig. 1. In the initial state, the inner and outer radius of the lining pipe are a and b; the inner and outer radius of the outer base pipe are c and d, respectively. The wall thickness of the lining pipe is t. Before the composite process, $c > b$, i.e. there is a gap between the lining pipe and the outer tube.
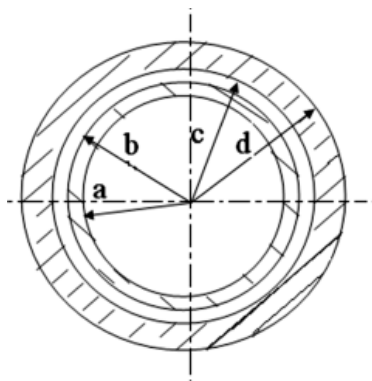

Fig. 1. Initial state of bi-metallic composite pipe

Fig. 2 shows the stress state. The lining pipe expands gradually due to the action of the inner pressure, and contacts with the outer tube finally.

According to elastic-perfectly plastic material model and plane strain assumption, the liner pipe deforms plastically and there is no contact pressure occurring yet till it just contacts with the outer base tube. According to Tresca's plastic yielding criterion, the internal pressure inside the liner pipe in such condition is [19]

$$P_{10} = \frac{2(b-a)\sigma_{s1}}{b+a} = \frac{2t\sigma_{s1}}{b+a} \tag{1}$$

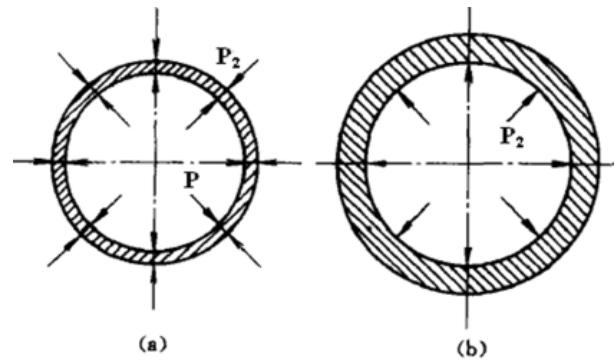wherein σ_{s1} is the yield strength of the liner material.

Fig. 2. Stress status of the bi-metallic composite pipe forming process (a) Liner; (b) Base pipe

There occurs contact pressure between the outer tube and the liner pipe as the inner pipe expands further. Assume the contact pressure is P_2, the internal pressure inside the liner pipe is [20]

$$P = P_{10} + P_2 \tag{2}$$

In the bulging process, as the liner pipe contacts with the base pipe and generates contact pressure, the base tube withstands the action of the contact pressure P_2, the stresses distributions and the displacement at the position of radius r within the base tube are [19],

$$\sigma_r = \frac{c^2 P_2}{d^2 - c^2}\left(1 - \frac{d^2}{r^2}\right), \quad \sigma_\theta = \frac{c^2 P_2}{d^2 - c^2}\left(1 + \frac{d^2}{r^2}\right),$$

$$u = \frac{c^2 P_2}{E_2(d^2 - c^2)}\left((1 - v_2)r + \frac{(1 + v_2)d^2}{r}\right) \tag{3}$$

wherein, E_2 and v_2 are elastic modulus and Poisson's ratio of the base pipe material; u is the displacement at the position of radius r within the base tube, σ_r and σ_θ are stresses of the point r in radial and circular directions, respectively.

In addition, the displacement δ at the inner wall of the base pipe is [20]

$$\delta = u_c = \frac{c^2 P_2}{E_2(d^2 - c^2)} \cdot \left[(1 - v_2)c + \frac{(1 + v_2)d^2}{c}\right] \tag{4}$$

Meanwhile, since the liner pipe expands plastically during expansion, its outer edge reaches to the round of the radius $c + \delta$, its circumference is $w = 2\pi(c + \delta)$.

While, in the unloading stage, internal pressure inside the liner pipe disappears, so the liner pipe will shrinks elastically in unloading, the outer edge of the circumference of the liner pipe will shrink to $w' = 2\pi(c + \delta) \times (1 - \sigma_{s1}/E_1)$, that is, the outer edge of the circumference of the liner pipe will produce the following radial displacement,

$$\gamma = (c + \delta) \cdot \sigma_{s1} / E_1 \approx c \cdot \sigma_{s1} / E_1 \tag{5}$$

wherein, E_1 is elastic modulus of the lined tube material.

The displacement δ at the inner wall of the base pipe in bulging process minus the radial displacement γ of liner pipe due to its natural shrinkage during unloading, will gives an over-matching quantity for the liner and outer tubes in the process of unloading procedure. So the residual pressure at the contact surface in unloading status could be written as [19]

$$P_{rc} = \frac{\left(\dfrac{\delta - \gamma}{c}\right)}{\left\{\dfrac{1}{E_1} \cdot \left[\dfrac{c^2 + (c-t')^2}{c^2 - (c-t')^2} - \nu_1\right] + \dfrac{1}{E_2} \cdot \left[\dfrac{d^2 + c^2}{d^2 - c^2} + \nu_2\right]\right\}} \tag{6}$$

wherein, t' is the wall thickness of the liner pipe after expansion, and it meets to $t' \cdot (c - t'/2) = t \cdot (b - t/2)$ in accordance with volume invariable principle, it yields $t' \approx t \cdot b/c$. Then Eq. (6) becomes,

$$P_{rc} = \frac{\left(\dfrac{\delta - \gamma}{c}\right)}{\left\{\dfrac{1}{E_1} \cdot \left[\dfrac{c^2 + (c - t \cdot b/c)^2}{c^2 - (c - t \cdot b/c)^2} - \nu_1\right] + \dfrac{1}{E_2} \cdot \left[\dfrac{d^2 + c^2}{d^2 - c^2} + \nu_2\right]\right\}} \tag{7}$$

Substituting Eqs. (4) and (5) into (7), it derives,

$$P_{rc} = \frac{\left\{\dfrac{cP_2}{E_2(d^2 - c^2)}\left[(1 - \nu_2)c + \dfrac{(1 + \nu_2)d^2}{c}\right] - \sigma_{s1}/E_1\right\}}{\left\{\dfrac{1}{E_1} \cdot \left[\dfrac{c^2 + (c - t \cdot b/c)^2}{c^2 - (c - t \cdot b/c)^2} - \nu_1\right] + \dfrac{1}{E_2} \cdot \left[\dfrac{d^2 + c^2}{d^2 - c^2} + \nu_2\right]\right\}} \tag{8}$$

And the relationship between the internal pressure P and the interfacial residual stress P_{rc} [19],

$$P = \frac{2t\sigma_{s1}}{b + a} + \left\{P_{rc} \cdot \left\{\begin{array}{l}\dfrac{1}{E_1} \cdot \left[\dfrac{c^2 + (c - t \cdot b/c)^2}{c^2 - (c - t \cdot b/c)^2} - \nu_1\right] + \\ + \dfrac{1}{E_2} \cdot \left[\dfrac{d^2 + c^2}{d^2 - c^2} + \nu_2\right]\end{array}\right\} + \dfrac{\sigma_{s1}}{E_1}\right\}$$
$$\cdot \left\{\dfrac{E_2 \cdot (1 - c^2/d^2)}{[(1 - \nu_2)c^2/d^2 + (1 + \nu_2)]}\right\} \tag{9}$$

The comparison between the predicted results of the above formulas and the experimental results shows its reliability [19].

3. Influence of cone-head size on interfacial bonding strength of bimetallic composite pipe produced by drawing approach

As to the bimetallic composite pipe produced by drawing approach, the bulging process is carried out by the conical head. Therefore, the size of cone head has a direct impact on the interface bonding strength.

The preparation process of bimetallic composite pipe by drawing approach is shown in Fig. 3.
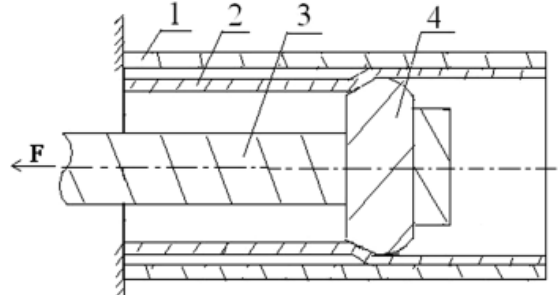
1. Base pipe, 2. Liner pipe, 3. Drawing bar, 4. Cone

Fig. 3. Manufacturing process of bimetal composite pipe by drawing process

As previously stated, the outer diameter of the liner pipe becomes $c + \delta$ at the moment of bulging loading, if the displacement at the liner wall of the outer tube is δ. If the wall thickness of the liner becomes t'', under condition of plane strain the volume-invariant condition at the bulging moment is,

$$t'' \cdot (c + \delta - t''/2) = t \cdot (b - t/2) \tag{10}$$

From Eq. (10), it further derives,

$$t'' \approx t \cdot (b - t/2)/(c + \delta) \tag{11}$$

As to the process of preparing bimetallic composite pipe by drawing approach, its bulging process is carried out by cone head, the cone radius R inside the inner liner pipe should satisfy,

$$R = c - t^2 \tag{12}$$

Combining Eq. (11) with Eq. (12), it derives,

$$\delta = \frac{t(b - t/2)}{c - R} - c \tag{13}$$

Furthermore, by substituting Eqs. (5) and (13) into Eq. (7), it derives,

$$P_{rc} = \frac{\left\{\dfrac{t(b - t/2)}{c(c - R)} - 1 - \sigma_{s1}/E_1\right\}}{\left\{\dfrac{1}{E_1} \cdot \left[\dfrac{c^2 + (c - t \cdot b/c)^2}{c^2 - (c - t \cdot b/c)^2} - \nu_1\right] + \dfrac{1}{E_2} \cdot \left[\dfrac{d^2 + c^2}{d^2 - c^2} + \nu_2\right]\right\}} \tag{14}$$

That is to say, when we use drawing approach with the cone diameter of $2R$ to prepare the bimetallic composite pipe, the in-

ner edge of the outer base pipe will generate a displacement of δ at the bulging moment. At the same time, a compressive stress of P_2 is generated at the interface between the outer base pipe and the inner liner, and an interfacial residual pressure of P_{rc} is generated between the outer base pipe and the inner liner after the unloading. Eq. (14) shows that the interfacial residual pressure P_{rc} between the outer base pipe and the inner liner increases in a hyperbolic form with the cone diameter.

The interfacial residual pressure is an important factor to determine the interfacial bonding strength between the inner liner and the outer base pipe of the composite pipe.

As can be seen from Eq. (14), for the situation of the liner tube and the outer base pipe with given material and geometry, you can adjust the interfacial residual pressure P_{rc} between the tubes by changing the diameter of the drawing cone $2R$, and therefore it induces the change of the interfacial bonding strength between the inner liner tube and the outer base pipe.

Assuming that the interfacial bonding strength Q between the inner pipe and the outer base pipe is linearly related to the interfacial residual pressure P_{rc}, i.e., $Q = A \times P_{rc} + B$, where A and B are parameters, It derives a new formula from Eq. (14),

$$Q = \frac{\alpha}{(c-R)} + \beta \qquad (15)$$

In Eq. (15), the parameters α and β are related to the materials of the inner liner and outer base pipes and the geometrical dimensions of the both pipes.

It can be seen from Eq. (15), that the interfacial bonding strength Q between the outer base and the inner liner pipes increases in a hyperbolic form with the diameter of the drawing cone.

3. Experimental results of interfacial bonding strength of the bimetallic composite pipe produced by drawing approach

3.1. Preparation of bimetallic composite pipe by drawing approach

In recent years, we have studied the preparation of bimetallic composite pipes by drawing approach. The inner liner pipe is stainless steel tube with size of $\phi\,76\times2.4$ mm, outer base pipe is carbon steel pipe with size of $\phi\,89.7\times5$ mm, the gap is $\rho = 1.8$ mm, the length is 2000 mm. The properties of the materials are shown in Table 1.

TABLE 1

Material performance parameters of the both pipes

Name	Liner pipe	Base pipe
Material Grade	0Cr18Ni9Ti	20
Yield strength σ_s (MPa)	210	281
Ultimate tensile strength σ_b (MPa)	520	480
Elastic modulus E (GPa)	210	210
Poisson's ratio	0.3	0.3

The cone is produced by 40Cr steel with quenched and processed treatments. The contact face between the cone and the inner liner pipe is lubricated with the graphite powder. The dimensions of the conical heads were 75.00 mm, 75.20 mm and 75.36 mm, respectively.

3.2. Test of interfacial bonding strength by pull – off method

The testing of the inner liner and outer base pipe interface bonding strength is conducted by using the urban construction standard CJT192-2004. Specific use of the pull-off method is used to test the interface bonding strength, as is shown in Fig. 4 and Fig. 5. The tensile rate of the test is 3 mm/min. Three samples are employed in each group.
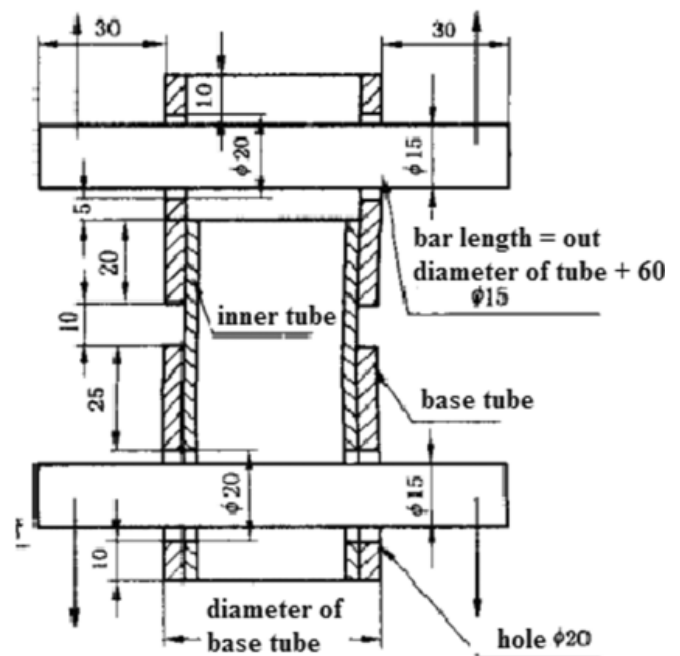
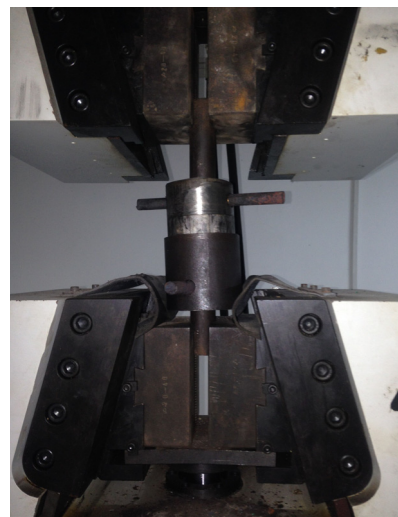

Fig. 4 Pull-off test process for composite pipe

Fig. 5 Actual pull-off test

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The relationship between bond strength and pull-off force is,

$$Q = \frac{F}{\pi D_o H} \qquad (16)$$

wherein F is the maximum pull-off force during the pull-off process in N; D_0 is the outer diameter of the inner liner in mm, H is the effective contact length of the base pipe and the liner pipe in mm, and Q is the interfacial bonding strength of the composite pipe in MPa.

Fig. 6 shows pull-off test curve for the composite pipe produced by drawing approach with cone diameter of 75.20 mm. Table 2 the variation of test results of interfacial bonding strength for the composite pipe with cone size.
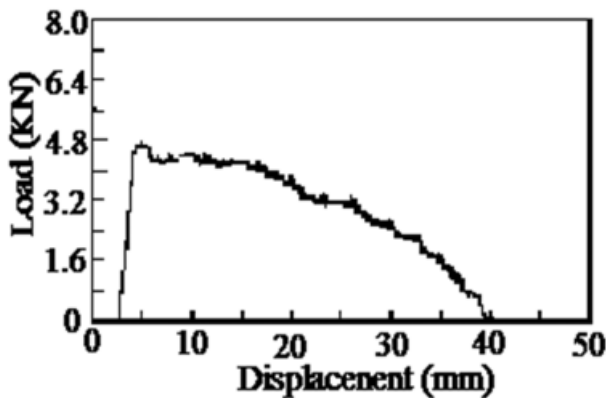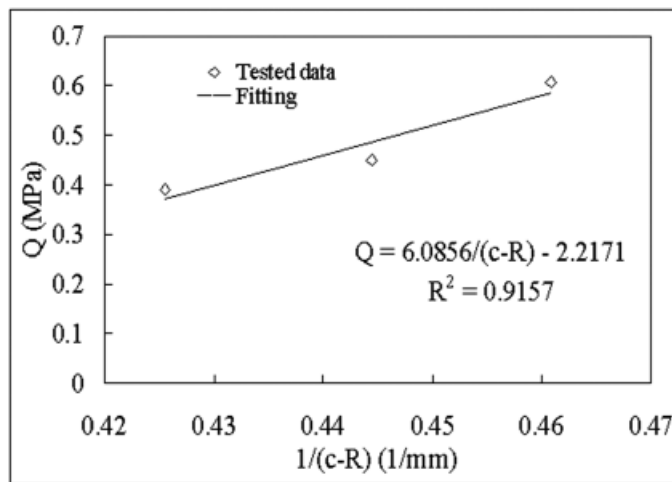

Fig. 6. Pull-off curve of load-displacement

Fig. 7. Variation of Q with R

TABLE 2

Test results of interface strength of composite pipe produced by different sized cone

Cone diameter (mm)	75.00	75.20	75.36
Average bond strength (MPa)	0.39	0.45	0.61

The results of Table 2 are plotted in Fig. 7, and the relationship between the interfacial bond strength Q and the cone size parameter R can be obtained.

From the experimental results in Fig. 6, the relationship between the interface bonding strength Q and the cone size parameter R is given as:

$$Q = 6.0856/(c - R) - 2.2171 \qquad (17)$$

The unit of Q is in MPa, and the units of c and R are in mm. The linear correlation coefficient was 0.9569.

As can be seen from Eq. (17), the interface bond strength Q and the cone size parameter R has a hyperbolic relationship.

4. Conclusion

In this paper, the plane strain assumption and the ideal elastic-plastic model are employed to study the influence of the cone-head size on the interfacial bonding strength of bimetallic composite pipe produced by drawing approach. The comparison between the prediction results and the experimental results shows that the established rule gives a better prediction.

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