Study on Forming Theory of Inner Strong & Outer Weak Strong Bi-metal Pipe

Xianyong Fan*, Xuesheng Wang, Shikuan Zhai, Qingzhu Chen and Jingjiang Yu
School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, China
*Email: 13764928566@163.com

Abstract. As a new type of pipe, bimetallic composite pipe is widely used in various industries in the chemical industry, because its internal and external tubes use different metals, so it can cope with a variety of different working conditions. At present, the application field of composite pipe is mostly inner strong and outer weak strong composite pipe, and this pipe has not been studied accordingly. In this paper, the theory of expansion of inner strong and outer weak strong composite pipe is derived, and a complete set of expansion methods and related parameter calculation formulas are obtained. Abaqus, a finite meta-analysis software, is used to simulate the expansion process and compare it with the theoretical results. The comparative results show that the theoretical formula obtained by derivation has a high degree of credibility, and the results obtained by using this set of theories are close to the results of computer simulation and can be used in industrial production.

1. Inner Strong and Outer Weak Strong Bi-metal Pipe Expansion Process

In the current world of Bi-metal pipe field, the inner weak strong and outer strong composite tube (i.e., lining tube material weaker than the outer base tube) has been the main focus of the manufacturing object, by using the cold hydraulic to complete pipe expansion process[6] is simple, while the application of inner strong and outer weak strong composite pipe is rarely seen even though it has a broader prospect, the main reason is that there is no safe and reliable, expansion method during manufacturing. The cold hydraulic expansion method used in ordinary inner weak strong and outer strong composite pipe cannot be successfully applied in the expansion of inner weak strong and outer strong composite pipes. In the expansion of ordinary inner weak strong and outer strong composite pipes, cold hydraulics can be used to obtain a considerable contact pressure. The inner strong and outer weak strong composite pipe simply cannot use the cold hydraulic expansion process, its specific expansion process as shown in Figure 1.

As shown in the figure, in the cold hydraulic expansion process, the change process experienced by the outer wall of the lining tube is O-1'-2', 2' is the highest pressure point of the outer wall of the inner pipe, and the change process experienced by the outer tube is 1-2, i.e. release pressure at 2. The inner pipe and outer pipe are rebounded at the same time, the inner pipe because its swelling pressure has exceeded the yield limit of its material, so it can only go back to its elastic variables; Because the material strength of the inner tube is greater than that of the outer pipe, its elastic variable is also much larger than the elastic variable of the outer pipe, so the response of the inner tube under cold hydraulic conditions is greater than the response of the outer tube, the internal and external pipes cannot produce effective residual contact pressure, and thus cannot successfully swell.
Figure 1. Diagram of cold hydraulic expansion joint of inner strong and outer weak strong composite pipe

The situation is different if the inner strong outer weak strong compound pipe is used in the hot hydraulic expansion. See Figure 2.

Figure 2. Diagram of hot hydraulic expansion joint of inner strong and outer weak strong composite pipe

In the thermo-hydraulic expansion process, the process experienced by the inner pipe is O-1-2-3-4-6, and the process experienced by the outer pipe is O'3'-4-5. The whole process is divided into three stages: the heating stage of the outer pipe, the expansion stage and the cooling phase of the discharge pressure. First, the external pipe is heated so that it expands in the direction of OO', resulting in a strain caused by the increase in temperature. Because the heat resistance of the air is big, and the inner pipe continues to pass through the circulating cooling water, so the heat transmission in the inner and outer pipe are not considered. When the outer wall of the inner pipe reaches the inner wall of the outer pipe and begins to produce a connection, the inner and outer pipe begin to expand together. When the highest-pressure point 3 (3') is reached, remove the expansion pipe pressure and start to cool down, at this time, because the inner pipe has yielded, its rebound is only its elastic variable, and the outer pipe is still in the elastic stage, so the outer pipe rebounds along its material structure curve, and because of cooling contraction, the inner pipe and the outer pipe reach 4 points at the same time. At
this time the inner pipe has completed the rebound, and the outer pipe has a tendency to shrink due to cooling reasons, so the inner pipe came to 6 o'clock, and the outer pipe reached 5 o'clock, at 5, 6 points, inside and outside the pipe achieved deformation coordination to produce residual contact pressure, compound pipe expansion success.

The figure shows that when the pressure is removed at the yield limit of the outer pipe material, the residual contact pressure obtained can reach the maximum value.

As can be obtained from Figure 1, when the inner pipe outer pipe achieves deformation coordination, the deformation coordination formula can be obtained:

$$\varepsilon_{io} - \varepsilon^*_{io} = \varepsilon_{oi} + \varepsilon_T - \varepsilon^*_{oi}$$

2. Stress Strain State of the Inner and Outer Pipe at Each Stage

Since the lining pipe has reached the yield stage in the process of expansion, it is necessary to consider its strain reinforcement. According to the total strain it produces in the whole process, this can be found on the structure curve of the inner pipe material, and is recorded as $\sigma'_{sl}$, i.e. when the yield strength of inner pipe material reaches the highest pressure point. In this paper, the famous Lame formula and the broad Hooker’s Law are used to calculate the stress strain state of the inner and outer pipe in different states, i.e.:

$$\sigma_r = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} - \frac{(p_i - p_o) r_i^2 r_o^2}{r_o^2 - r_i^2} \frac{1}{r^2}$$

$$\sigma_\theta = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} + \frac{(p_i - p_o) r_i^2 r_o^2}{r_o^2 - r_i^2} \frac{1}{r^2}$$

$$\sigma_z = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2}$$

2.1. Stress Strain State of the Inner and Outer Pipes when the Maximum Pressure Point is Reached

At the highest pressure point 3, according to Tresca yield criteria, the stress state of the outer wall of the lining pipe is:

$$\sigma_{r,io} = -p_c$$

$$\sigma_{\theta,io} = \sigma'_{sl} - p_c$$

$$p_i - p_c = \sigma'_{sl} - \ln k$$

where, $p_c$ —— the highest pressure point of contact pressure between the inner and outer pipe, MPa;

$p_i$ —— the pressure of the expanded tube fluid, MPa;

$k$ —— wall thickness of the inner tube, $k = d_o / d_i$;

$\sigma_{r,io}$ —— axial stress of the inner pipe outer wall contact surface, MPa;

$\sigma_{\theta,io}$ —— circumferential stress of the inner pipe outer wall contact surface, MPa;

According to (2), (3), (4) and the generalized Hooker’s Law, the hoop strain of the outer wall of the inner pipe becomes:

$$\varepsilon_{\theta,io} = \frac{1}{E_i} (\sigma_{\theta,io} - \mu_i \sigma_{r,io})$$

$$\varepsilon_{\theta,io} = \frac{1}{E_i} (\sigma'_{sl} - (1 - \mu_i) p_c)$$

where, $\mu_i$ —— the inner pipe Poisson’s ratio;

$E_i$ —— the MOE (Modulus of Elasticity) of the inner pipe

At the highest pressure point 3’, the stress state of the inner wall of the outer pipe can be calculated by the Lame formula as follows:

$$\sigma_{r,oi} = -p_c$$
According to (7), (8) and the generalized Hooker's Law, the hoop strain of the inner wall of the outer pipe becomes:

\[ e_{\theta,oi} = \frac{1}{E_i} (\sigma_{\theta,oi} - \mu_o \sigma_{r,oi}) \]  

and

\[ e_{\theta,oi} = \frac{1}{E_o} (\frac{K^2+1}{K^2-1} + \mu_i)p_c \]  

Because the pressurized expansion pipe and the pressure protection time is short, and the outer pipe material is in the elastic stage, the process is reversible, so approximately that after the connection were made between the inner pipe and the outer pipe, the heat transfer is 0. i.e, ignore the heat transfer of the inner and outer tube after the connection, and the separate study of discharge phase and cooling phase will not affect the results.

2.2. Stress Strain State of the Inner and Outer Pipes after Unloading

After the pressure of the expansion pipe is removed, the stress state of the outer wall of the inner pipe is:

\[ \sigma^*_{r,io} = -p_c^* \]  

\[ \sigma^*_{\theta,io} = -\frac{k^2+1}{k^2-1} p_c^* \]  

where, the "*" indicates the residual amount after cooling the discharge pressure.

By the formula (11), (12) and the generality of Hook's law, The residual circumferential strain of the outer wall of the inner tube is calculated:

\[ e_{\theta,io}^* = -\frac{1}{E_i} (\frac{K^2+1}{K^2-1} - \mu_i)p_c^* \]  

At the inner wall of the outer pipe, the stress state is:

\[ \sigma^*_{r,oi} = -p_c^* \]  

\[ \sigma^*_{\theta,oi} = \frac{K^2+1}{K^2-1} p_c^* \]  

By the formula (14), (15) and the generality of Hook's law, to get the residual circumferential strain at inner wall of outer pipe:

\[ e_{\theta,oi}^* = \frac{1}{E_o} (\frac{K^2+1}{K^2-1} + \mu_o)p_c^* \]  

The strain \( \varepsilon_T \) caused by temperature is:

\[ \varepsilon_T = \alpha_o \Delta T_o \]  

Bring (6), (10), (13), (16) into (1), we got this:

\[ p_c^* = \frac{p_i}{A} \left( \frac{1}{E_i} + \frac{1}{E_o} \ln k \right) \sigma^*_{si} + \alpha_o \Delta T_o \]  

Where:

\[ \frac{1}{A} = \frac{1}{E_i} (\frac{K^2+1}{K^2-1} - \mu_i) + \frac{1}{E_o} (\frac{k^2+1}{k^2-1} + \mu_o) \]

\[ \frac{1}{B} = \frac{1}{E_i} (1 - \mu_i) + \frac{1}{E_o} (\frac{k^2+1}{k^2-1} + \mu_o) \]

3. Solution of Maximum and Minimum Pipe Expanded Pressure

In order to ensure effective residual contact pressure is generated after the expansion of compound pipe, the expanded pipe pressure \( p_i \) has a minimum value, that is, if less than minimum expanded pressure, then it will not successfully expand the inner strong and outer weak strong composite pipe.
By figure (2) it can be known that when the residual contact pressure is 0, the composite pipe expansion cannot be successful made, and thus the minimum expanded pipe pressure should have the contact pressure greater than or equal to 0, the minimum expanded pipe pressure is when residual contact pressure reaches 0, that is:

\[ p = \frac{B}{E_i} \ln k'_{z_{0i,o}} \]  
(19)

When the pressure of the expanded pipe is too big, it will cause the outer pipe to enter the yield stage, if unload at this time, the internal and external pipe will not be able to produce effective residual contact pressure, so when the elastic strain of the outer pipe reaches the maximum, the expanded pipe pressure reaches maximum, that is:

\[ p = \frac{k^2-1}{2K^2 \sigma_{so}} \ln k_{l,max} \]  
(20)

4. Selection of the Thermal Hydraulic Expansion Temperature

In the thermal hydraulic expansion process, it is important to have a right heating temperature for external pipe. If temperature is too low, it will not cause enough radial strain on the outer pipe. If the temperature is too high, it will change the performance of the material. Since the material properties of carbon steel get changed at around 400°C, so 350°C is the maximum heating temperature. The minimum temperature difference is given by the following:

\[ \Delta T_0 \geq \frac{\sigma_{si}}{E_i} - \frac{\sigma_{so}}{E_o} \]  
\( \alpha_o \)  
(21)

5. Changes in the Expanded Pipe during Heat Conduction between the Inner and Outer Pipe

In the previous inference and calculation, this paper ignores the thermal conduction between the inner pipe and the outer pipe when they get together. When this is taken into consideration, it is hard to determine its thermal conductivity and its effect on the expansion process. Therefore, this graph reveals the change of the inner pipe after heated, as shown in the following figure:

![Figure 3. Diagram of cold hydraulic expansion joint of composite pipe(with heat conduction)](image)

As can be known from the figure, when the inner pipe and outer pipe are connected in thermal conduction, the inner pipe is also subjected to thermal expansion, which causes indentation when cooling, the residual pressure between the inner and outer pipes will be reduced, making the composite
pipe more easily loose. Therefore, in the expansion stage, cooling water needs to constantly flowing into inner pipe to ensure that the inner pipe will not produce too large thermal expansion.

5.1. Model Parameters
The selected simulation material is 316L and L245N, so we selected stronger lining pipe 316L. The specific parameters of the material can be found in the table below.

| Table 1. Material parameters of composite pipe |
|-----------------------------------------------|
| Yang's model (MPa) | Poisson ratio | Yield ultimate (MPa) |
| 316L | 198000 | 0.3 | 387 |
| L245N | 195000 | 0.3 | 317 |

| Table 2. Coefficient of thermal expansion of material |
|------------------------------------------------------|
| Temp (°C) | 316L | L245N |
|-----------|------|-------|
| 20        | 1.64E-05 | 1.09E-05 |
| 40        | 1.65E-05 | 1.11E-05 |
| 60        | 1.66E-05 | 1.12E-05 |
| 80        | 1.67E-05 | 1.13E-05 |
| 100       | 1.68E-05 | 1.14E-05 |
| 120       | 1.69E-05 | 1.16E-05 |
| 140       | 1.71E-05 | 1.17E-05 |
| 160       | 1.72E-05 | 1.18E-05 |
| 180       | 1.73E-05 | 1.20E-05 |
| 200       | 1.74E-05 | 1.21E-05 |

| Table 3. Dimension of model (mm) |
|----------------------------------|
| Outer pipe | lining pipe |
| Outside diameter. | 114 | 47.5 |
| Wall thickness | 8 | 2 |

The model is shown in Figure 4:
5.2. The Numerical Simulation Results are Compared with the Theoretical Calculation Results

According to the formula in the previous section, the maximum and minimum expanded pipe pressure is related to the heating temperature of the outer pipe, because the thermal expansion of the outer pipe is small, the selection of temperature point within the temperature range has few impacts to the minimum expanded pressure. The minimum expanded pipe pressure and the maximum expanded pipe pressure are set between 13MPa-58MPa, and 30MPa is selected as the expanded pipe pressure to explore the changes of residual contact pressure at different heating temperatures of the outer pipe. The residual contact pressure cloud is shown below.

![Figure 5. Residual contact pressure at 160°C](image5)

![Figure 6. Residual contact pressure at 200°C](image6)

![Figure 7. Residual contact pressure at 240°C](image7)

![Figure 8. Residual contact pressure at 280°C](image8)
The numerical simulation results are compared with the theoretical calculation results in the following table:

|       | 160°C | 200°C | 240°C | 280°C |
|-------|-------|-------|-------|-------|
| Theoretical results (MPa) | 6.47  | 8.39  | 10.5  | 12.7  |
| Simulation result (MPa)   | 5.65  | 9.10  | 13.2  | 15.8  |
| Difference                | 13%   | 8%    | 26%   | 24%   |

6. Conclusion

Based on the theory of elastic plasticity, this paper revealed the theory of cold and hot hydraulic forming of inner strong and outer weak strong composite pipes. Through theoretical analysis, comparing the characteristics of cold and hot hydraulics in the formation process of inner strong and outer weak strong composite pipes, from the test results, thermal hydraulics in the formation process of inner strong and outer weak strong composite pipes is relatively better, but its disadvantages are also more obvious, that is, in the actual production process, it is difficult to control the temperature of longer pipe parts. In addition, through numerical simulation, this paper simulates the size of contact surface contact pressure after thermo-hydraulic forming, and compares this value with the theoretical value, which reflects a high accuracy when the temperature is not higher than 200°C, which is a good reference for engineering production.

At present, many of the world's pipeline applications use inner weak strong and outer strong composite pipe, but the pipeline work situation can be described as complex and changeable, a single type of pipeline cannot meet all the conditions of the application. The expansion theory of inner strong and outer strong compound pipe filled the research gap in the field of pipeline, and I believe that in the near future, the application of this kind of pipe will also be spread out and widely used.

7. References

[1] Vedeld, Knut, et al. "Effective axial forces in offshore lined and clad pipes." Engineering Structures 66 (2014): 66-80.
[2] Bian, Kang, Ming Xiao, and Juntao Chen. "Study on coupled seepage and stress fields in the concrete lining of the underground pipe with high water pressure." Tunnelling and underground space technology 24.3 (2009): 287-295.
[3] Limam, A., L-H. Lee, and S. Kyriakides. "On the collapse of dented tubes under combined bending and internal pressure." International Journal of Mechanical Sciences 55.1 (2012): 1-12.
[4] Wang Xin. “Analysis of crack problems in boiler, pressure vessel and pressure pipe inspection.” China Petroleum and Chemical Standards and Quality, 2020, 40 (14): 55-56.
[5] Peng Zai Mei. “Review of the development of bimetallic composite steel pipes and lined composite steel pipes at home and abroad.” World Metal Guide, 2019-11-05 (B10).
[6] Xuesheng Wang, Li Peining, Wang Ruzhu, Xu Weixiong. “Calculation of hydraulic forming pressure of bimetallic composite tubes.” Mechanical strength, 2002 (03): 439-442.
[7] Wei Wei, Xuesheng Wang, Guidong Yan, Zhao Zhang. “Research on the thermal hydraulic process of the new bimetallic composite tube.” China Society of Mechanical Engineering pressure vessel branch, Hefei General Machinery Research Institute. Advanced Technology for Pressure Vessels - 9th National Symposium on Pressure Vessels Paper Collection. Pressure Vessel Branch of the Chinese Society of Mechanical Engineering, Hefei General Machinery Research Institute: Pressure Vessel Branch of the Chinese Society of Mechanical Engineering, 2017:8.
[8] Shu Tonglin, Li Fengbin. “Discussion of the Rame problem in elastic forces.” Sociology and practice. 1991(04)