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Theoretical and experimental study of the thermal strength of anticorrosive lined steel pipes

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Abstract: Bimetallic lined steel pipe (LSP) is a new anti-corrosion technology. It is widely used to transport oil, gas, water and corrosive liquid chemicals. At present, the hydroforming pressure for LSP has been investigated theoretically and experimentally by most researchers. However, there are a few reports on the thermal strength of bimetallic LSP. Actually, the bimetallic LSP will be subjected to remarkable thermal load in the process of three layer polyethylene (3PE) external coating. Reverse yielding failure may occur on the inner pipe of the bimetallic LSP when it suffers from remarkable thermal load and residual contact pressure simultaneously. The aim of this paper is to study the thermal load and strength of the bimetallic LSP. A mechanical model, which can estimate the thermal strength of the bimetallic LSP, was established based on the elastic theory and the manufacture of the bimetallic LSP. Based on the model, the correlation between the thermal strength of the bimetallic LSP and residual contact pressure and wall thickness of the inner pipe was obtained. Reverse yielding experiments were performed on the LSP (NT80SS-316L) under different thermal loads. Experiment results are consistent with calculated results from the theoretical model. The experimental and simulation results may provide powerful guidance for the bimetallic LSP production and use.

Key words: Thermal strength, reverse yielding, mechanical model, lined steel pipe, residual contact pressure

1 Introduction

In the process of oil and gas production and transportation, the corrosive environments to which oil country tubular goods (OCTG) are exposed become more and more complex due to the existence of high levels of carbon dioxide, hydrogen sulfide and sulfur (Chen and Rao, 2005; Eckert et al, 2012; Kermani and Morshed, 2003; Yin et al, 2008; Zhang and Lv, 2008). This makes OCTG more easily corroded and then leads to increasingly serious safety problems (Jiang, 2004; Liu et al, 2004; Zhang et al, 2005). In order to solve the corrosion problem, some methods such as corrosion inhibitor injection, a plastic internal coating, and a use of corrosion-resistant alloy, have been proposed to control corrosion (Aberle and Agarwal, 2008; Ahmad et al, 2011; Pavan et al, 2010; NACE International, 2012; Shouse et al, 2012). Analyses indicate that the bimetallic lined steel pipe (LSP) is more economic and reliable than other anti-corrosion technologies so it has been widely used in the oil and gas industry (Chen and Petersen; 1991; Nikitina, 1998; Reformatskaya et al, 2000; Place et al, 1991; Zhu et al, 2011). A bimetallic LSP consists of an inner pipe and an outer pipe. The outer pipe is an ordinary carbon steel pipe that withstands mechanical loads, and the inner one is a corrosion resistant alloy (CRA) pipe that should prevent the corrosion of steel in the oil and gas environments (Rommerskirchen, 2005; Wang et al, 2004).

It is well known that the bimetallic LSP, which is widely used to transport oil and gas, must be covered with a 3 layer anticorrosive coating of polyethylene (PE) before it is used. The bimetallic LSP will suffer from remarkable thermal load in the process of preheating for the external anticorrosive processing. The yield strength of the inner pipe of the LSP decreases under thermal load (Miura and Sakuraba, 1995). In

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addition, performance indicators and specification calculation method of thermal strength of the bimetalli LSP are not given by the current international standards (American Petroleum Institute, 1998). However, some users and manufacturers only pursue blindly high residual contact pressure between the inner and outer pipes of the bimetallic LSP to prevent the inner pipe from being separated from the outer pipe without considering the thermal strength of the bimetallic LSP. In a sense, the higher the residual contact pressure is, the better the bimetallic LSP is. However, previous research showed that reverse yielding failure occurred easily on the inner pipe when the LSP suffered from additional thermal load and residual contact pressure simultaneously (Zhang et al, 2012; Zheng and Lu, 2010). Namely, the higher the residual contact pressure between the inner and outer pipes of the bimetallic LSP, the easier the inner pipe yields. So it is unreasonable to blindly pursue high residual contact pressure.

The key to solve the problem of blindly pursuing high residual contact pressure is to determine the critical temperature load which makes the inner pipe of the bimetallic LSP yield. As a result, the theoretical and experimental research on the thermal strength of the bimetallic LSP has been done based on elastic theory and the forming principle of the bimetallic LSP (Akisanya et al, 2011; Wang et al, 2002; 2005) and reported in this paper.

2 Analysis of thermal strength of the bimetallic LSP

The bimetallic LSPs are generally manufactured at room temperature but are on service as petroleum pipelines at changing temperature environments, even more than 150 ºC. The inner and outer pipes are bonded together tightly by relatively large residual contact pressure. The inner pipe is a thin-walled corrosion resistant steel pipe and it has a higher coefficient of thermal expansion than the outer one. Therefore, a radial thermal load is applied on the bonding surface due to differences in coefficients of thermal expansion between the inner and outer pipes when the environment temperature changes (Zhang and Jiang, 1997).

In order to facilitate to solve and analyze this mechanical model, some assumptions are made as follows:

1) The LSP is a long thin-walled cylinder, and the axial force caused by temperature is so small that it can be neglected.

2) The inner and outer pipes are ideal cylinders with uniform wall thickness.

3) The mechanical analysis of the LSP under thermal load belongs to a plane strain problem.

2.1 Radial thermal load produced by temperature change

A radial thermal load will be generated on the bonding surface of the bimetallic LSP due to difference in thermal expansion coefficients between the inner and outer pipes, when the surrounding temperature of the LSP changes. Therefore, there are two types of circumferential strain due to the temperature change. One is free expansion strain caused by temperature variation and the other is constrained strain caused by radial thermal load.

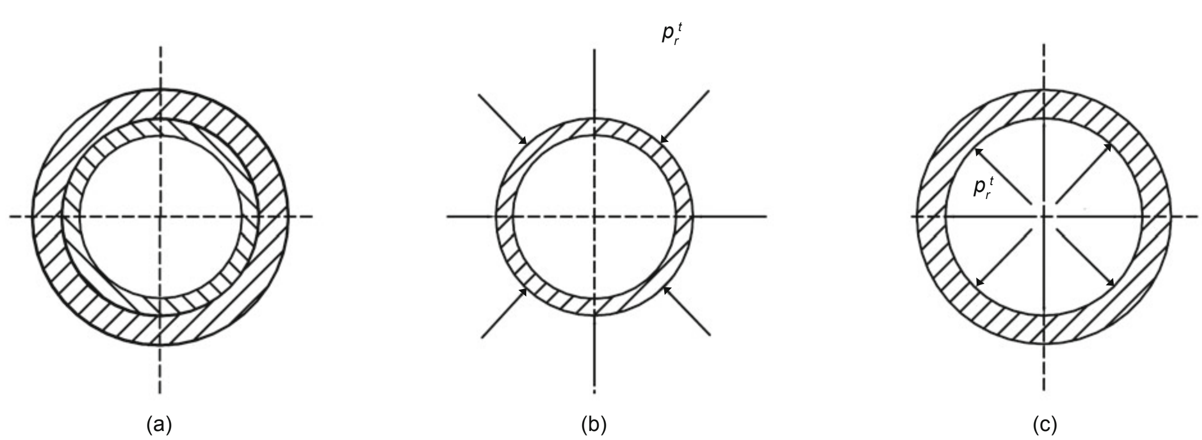
If the radial thermal load caused by temperature change is equal to p_r^t, the inner wall of the outer pipe suffers from an additional internal pressure p_r^t and the outer wall of the inner pipe suffers from the additional external pressure p_r^t, as shown in Fig. 1.

Assume that the inner pipe expands freely in the outer pipe. When the temperature increases from T_1 to T_2, a circumferential strain between the inner wall of the outer pipe and the outer wall of the inner pipe may be generated due to differences in thermal expansion coefficients between the inner and outer pipes:

$$\begin{cases} \varepsilon_{\theta \mathrm{io}}^t = \alpha_\mathrm{i} \left(T_2 - T_1\right) \\ \varepsilon_{\theta \mathrm{oi}}^t = \alpha_\mathrm{o} \left(T_2 - T_1\right) \end{cases} \tag{1}$$

where α_i and α_o are the thermal expansion coefficients of the inner and outer pipes, respectively, ºC^{-1}; T_1 and T_2 are the forming temperature and working temperature of the LSP, respectively, ºC.

According to the Lame formula (Xu, 2006), the thermal stress component at the inner pipe caused by radial thermal load p_r^t can be obtained:



(a) Bimetallic LSP after forming (b) Outer wall of the inner pipe subjected to p_r^t (c) Inner wall of the outer pipe subjected to p_r^t

Fig. 1 Schematic diagrams of the bimetallic LSP suffering from radial thermal load

$$\begin{cases} \sigma^t_{r\mathrm{io}} = -\dfrac{p^t_r k^2}{k^2-1}\left[1-\dfrac{r_\mathrm{i}^2}{r^2}\right] \\ \sigma^t_{\theta\mathrm{io}} = -\dfrac{p^t_r k^2}{k^2-1}\left[1+\dfrac{r_\mathrm{i}^2}{r^2}\right] \end{cases} \tag{2}$$

where r is the radius of the inner pipe; r_i is the inside radius of the inner pipe; k is the ratio of the outer radius r_o to the inside radius r_i of the inner pipe.

From Eq. (2), the thermal stress component at the outer wall of the inner pipe (r=r_o) can be obtained:

$$\begin{cases} \sigma^t_{r\mathrm{io}} = -p^t_r \\ \sigma^t_{\theta\mathrm{io}} = -\dfrac{k^2+1}{k^2-1}p^t_r \end{cases} \tag{3}$$

where $\sigma^t_{r\mathrm{io}}$ is the radial stress component at the outer wall of the inner pipe, MPa; $\sigma^t_{\theta\mathrm{io}}$ is the circumferential stress component at the outer wall of the inner pipe, MPa.

According to the constitutive equations of plane problems, the circumferential strain at the outer surface of the inner pipe caused by the radial thermal load p^t_r can be obtained:

$$\varepsilon^t_{\theta\mathrm{io}} = \frac{1}{E_\mathrm{i}}(\sigma^t_{\theta\mathrm{io}} - \mu_\mathrm{i}\sigma^t_{r\mathrm{io}}) \tag{4}$$

Substituting Eq. (3) into Eq. (4) gives:

$$\varepsilon^t_{\theta\mathrm{io}} = -\frac{1}{E_\mathrm{i}}\left[\frac{k^2+1}{k^2-1} - \mu_\mathrm{i}\right]p^t_r \tag{5}$$

Similarly, according to the Lame formula (Xu, 2006), the thermal stress component at the inner wall of the outer pipe caused by radial thermal load p^t_r can be expressed as follows:

$$\begin{cases} \sigma_r = \dfrac{p^t_r}{K^2-1}\left[1-\dfrac{R_\mathrm{o}^2}{R^2}\right] \\ \sigma_\theta = \dfrac{p^t_r}{K^2-1}\left[1+\dfrac{R_\mathrm{o}^2}{R^2}\right] \end{cases} \tag{6}$$

where R is the radius of the outer pipe; R_o is the outer radius of the outer pipe; K is the ratio of the outer radius R_o to the inside radius R_i of the outer pipe.

From Eq. (6), the thermal stress component at the inner wall of the outer pipe (R=R_i) can be obtained:

$$\begin{cases} \sigma^t_{r\mathrm{oi}} = -p^t_r \\ \sigma^t_{\theta\mathrm{oi}} = \dfrac{K^2+1}{K^2-1}p^t_r \end{cases} \tag{7}$$

where $\sigma^t_{r\mathrm{oi}}$ is the radial stress component at the inner wall of the outer pipe, MPa; $\sigma^t_{\theta\mathrm{oi}}$ is the circumferential stress component at the inner wall of the outer pipe, MPa.

According to the constitutive equations of plane problems, the circumferential strain at the inner wall of the outer pipe caused by radial thermal load p^t_r can be obtained:

$$\varepsilon^t_{\theta\mathrm{oi}} = \frac{1}{E_\mathrm{o}}(\sigma^t_{\theta\mathrm{oi}} - \mu_\mathrm{o}\sigma^t_{r\mathrm{oi}}) \tag{8}$$

Substituting Eq. (7) into Eq. (8) gives:

$$\sigma^t_{\theta\mathrm{oi}} = \frac{1}{E_\mathrm{o}}\left[\frac{K^2+1}{K^2-1} + \mu_\mathrm{o}\right]p^t_r \tag{9}$$

A combination of Eq. (1) and Eq. (5) gives the total circumferential strain $\varepsilon^{tt}_{\theta\mathrm{io}}$ at the outer wall of the inner pipe caused by radial thermal load p^t_r and temperature change:

$$\varepsilon^{tt}_{\theta\mathrm{io}} = \varepsilon^t_{\theta\mathrm{io}} + \alpha_\mathrm{i}\Delta T = -\frac{1}{E_\mathrm{i}}\left[\frac{k^2+1}{k^2-1} - \mu_\mathrm{i}\right]p^t_r + \alpha_\mathrm{i}\Delta T \tag{10}$$

Combining Eq. (1) with Eq. (9) gives the total circumferential strain $\varepsilon^{tt}_{\theta\mathrm{oi}}$ at the inner wall of the outer pipe caused by radial thermal load p^t_r and temperature change:

$$\varepsilon^{tt}_{\theta\mathrm{oi}} = \varepsilon^t_{\theta\mathrm{oi}} + \alpha_\mathrm{o}\Delta T = \frac{1}{E_\mathrm{o}}\left[\frac{K^2+1}{K^2-1} + \mu_\mathrm{o}\right]p^t_r + \alpha_\mathrm{o}\Delta T \tag{11}$$

The outer pipe of the bimetallic LSP can always keep compatibility of deformation with the inner pipe. So the total circumferential strain at the inner pipe of the bimetallic LSP is equal to that at the outer pipe. The compatibility equation of deformation can be expressed as follow:

$$\varepsilon'_{\theta\mathrm{io}} = \varepsilon'_{\theta\mathrm{oi}} \tag{12}$$

Substituting Eqs. (10) and (11) into Eq. (12) gives:

$$\begin{aligned} &-\frac{1}{E_\mathrm{i}}\left[\frac{k^2+1}{k^2-1} - \mu_\mathrm{i}\right]p^t_r + \alpha_\mathrm{i}\Delta T \\ &= \frac{1}{E_\mathrm{o}}\left[\frac{K^2+1}{K^2-1} + \mu_\mathrm{o}\right]p^t_r + \alpha_\mathrm{o}\Delta T \end{aligned} \tag{13}$$

From Eq. (13), the radial thermal load p^t_r can be obtained:

$$p^t_r = \frac{(\alpha_\mathrm{i} - \alpha_\mathrm{o})\Delta T}{\dfrac{1}{E_\mathrm{o}}\left[\dfrac{K^2+1}{K^2-1} + \mu_\mathrm{o}\right] + \dfrac{1}{E_\mathrm{i}}\left[\dfrac{k^2+1}{k^2-1} - \mu_\mathrm{i}\right]} \tag{14}$$

The radial thermal load p^t_r that the inner pipe of the bimetallic LSP suffers from under any temperature environment can be calculated from Eq. (14).

2.2 Reverse yielding of the inner pipe of the bimetallic LSP

Based the hydroforming principle of the bimetallic LSP, it can be known that the inner wall of the inner pipe is subjected to the forming pressure, which make the inner pipe yield and produce plastic deformation in the loading forming process.

The outer pipe is in the elastic deformation under the forming pressure. Residual contact pressure between the inner and outer pipes of the bimetallic LSP is produced because the elastic deformation of the outer pipe is recovered completely while the plastic deformation of the inner pipe cannot be recovered in the unloading process. It is the residual contact pressure that makes the inner pipe bind tightly to the outer pipe of the LSP. Thus the outer wall of the inner pipe is subjected to the residual contact pressure p_c after forming. Therefore, the reverse yielding of the inner pipe is more likely to occur when the radial thermal load p_r^t caused by temperature is applied to the outer wall of the inner pipe.

The stress component at the inner wall of the inner pipe, which is under the residual contact pressure p_c, can be derived from the Lame equation (Xu, 2006):

$$\begin{cases} \sigma_r = 0 \\ \sigma_\theta = -\dfrac{2p_c k^2}{k^2-1} \end{cases} \tag{15}$$

Reverse yielding of the inner pipe occurs under high residual contact pressure p_c because the outer pipe of the bimetallic LSP can always keep compatibility of deformation with the inner pipe. The collapse strength (p_{cimax}) of the inner pipe of the lined steel pipe can be obtained from Eq. (15) and the Tresca yield criterion:

$$p_{cimax} = \frac{\sigma_{-si}\left(k^2-1\right)}{2k^2} \tag{16}$$

where σ_{-si} is the yield strength of the inner pipe considering the Bauschinger effect, MPa; but σ_{-si} is difficult obtained, so the Bauschinger effect of the inner pipe is not considered in general. It is considered that σ_{-si} is equal to the yield strength σ_{si}.

So the reverse yielding of the inner wall of the inner pipe occurs firstly under radial thermal load p_r^t and residual contact pressure p_c between the inner and outer pipes simultaneously. The thermal strength p_{rc}^t (the maximum radial thermal load p_r^t) of the inner pipe can be obtained from Eq. (16):

$$p_{rc}^t = p_{cimax} - p_c = \frac{\sigma_{-si}(k^2-1)}{2k^2} - p_c \tag{17}$$

The thermal strength of the inner pipe of the bimetallic LSP can be obtained when the inner pipe is subjected to different residual contact pressures from Eq. (17). The critical temperature of the inner pipe of the lined steel pipe can be obtained by substituting the value of thermal strength into Eq. (14). To analyze the correlation between the thermal strength of the bimetallic LSP and residual contact pressure and wall thickness of the inner pipe, the thermal strengths of the lined steel pipes (NT80SS-316L) were calculated using Eqs. (16) and (17) and the calculation results are plotted in Fig. 2.

Fig. 2 shows that the thermal strength of the inner pipe decreases with an increase in the residual contact pressure. This indicates that the bimetallic LSP with higher residual contact pressure may not be better than the LSP with lower residual contact pressure. It further proves that blindly pursuing high residual contact pressure to prevent the inner pipe from being separated from the outer pipe is not reasonable. In addition, it can be seen from Fig. 2 that the thermal strength of the inner pipe decreases with a decrease in its wall thickness. This indicates that the wall thickness of the inner pipe should not be too small for safety. So, the reasonable residual contact pressure and the wall thickness of the inner pipe can be determined under the actual working environments by Eqs. (16) and (17), which not only ensures the safety of the bimetallic LSP in service, but also prevents the waste of materials.

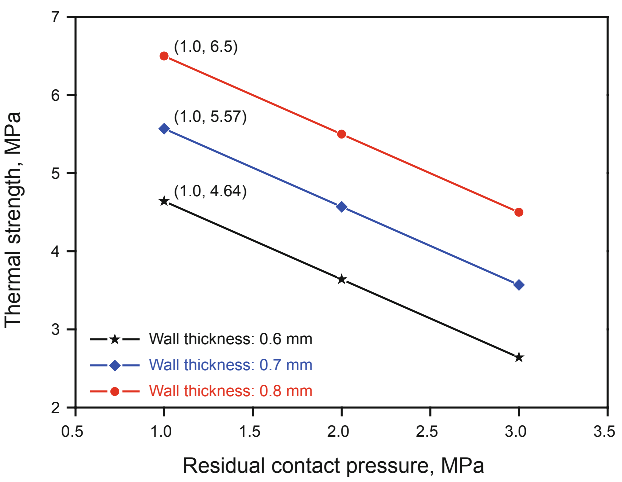


Fig. 2 Correlations between the thermal strength and p_c and wall thickness of the inner pipe

3 Reverse yielding test of the inner pipe

3.1 Experimental

It is known that the inner pipe and outer pipe are bonded together tightly during manufacture by high residual contact pressure. The residual contact pressure is proportional to the shear strength between the inner and outer pipes (Zhang et al, 2012). The higher the residual contact pressure is, the larger the shear strength between the inner and outer pipes. The residual contact pressure and shear strength do not change under relatively low temperatures; and then the reverse yielding of the inner pipe occurs with an increase in temperature, which makes the shear strength decrease with a decrease in the residual contact pressure. So, based on that phenomenon, the critical temperature which makes the inner pipe reverse yielding can be determined.

3.2 Specimen preparation

To validate the accuracy of the theoretical model, one bimetallic LSP with some residual contact pressure was made. The hydroforming test was conducted using a corrosion resistant alloy tube (φ63×0.76 mm) and a oil tube (φ70×3.5 mm), as shown in Fig. 3. The forming pressure and temperature were 48 MPa and 21 °C. The geometric and mechanical parameters of the lined pipe are listed in Table

1. The metallographic micrograph of the inner pipe (316L) is shown in Fig. 4. It can be observed from Fig. 4 that the bar ferrite is dispersed in the austenitic matrix. The chemical composition of the inner pipe (316L) is shown in Table 2.

The collapse strength p_{cimax} of the inner pipe can be calculated with Eq. (16), as listed in Table 1. The difference of thermal expansion coefficients between the inner and outer pipes is 6×10^{-6} °C^{-1} and the thermal expansion of the inner pipe is larger than that of the outer pipe. The test result is shown in Fig. 5.

Based on the calculation method reported by Zeng (2007), the residual contact pressure (3.36 MPa) of the bimetallic LSP was obtained according to the residual circumferential strain in Fig. 5(b). The thermal strength (p^t_{rc}=0.66 MPa) and the critical temperature (T_2=48.6 °C) were also obtained from Eqs. (17) and (14).

3.3 Test procedure

1) The bimetallic LSP was divided into 9 segments by linear cutting, as shown in Fig. 6.

Table 1 The geometric and mechanical parameters of the bimetallic LSP

Bimetallic LSP	Yield strength, MPa	Outer diameter, mm	Wall thickness, mm	Elastic modulus, MPa	Poisson's ratio μ	Collapse strength p_{cimax}, MPa
Inner pipe (316L)	180	63	0.76	1.95×10^5	0.3	4.29
Outer pipe (NT80SS)	551	70	3.5	2.06×10^5	0.3	–

Table 2 Chemical composition of the inner pipe (316L)

Component	Cr	Ni	Mo	Mn	Si	S	C	P
Content, wt%	17.04	11.14	2.16	1.44	0.54	0.012	0.020	0.020

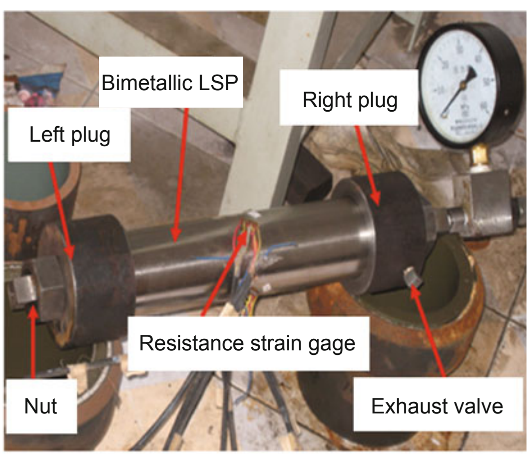


Fig. 3 Equipment for the hydroforming test of the bimetallic LSP

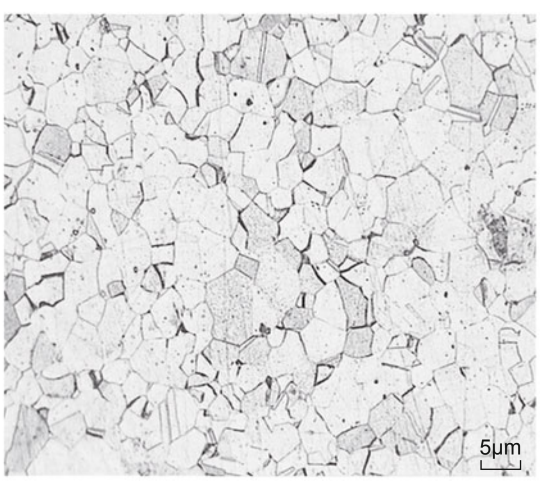


Fig. 4 Microphotograph of the inner pipe (316L)

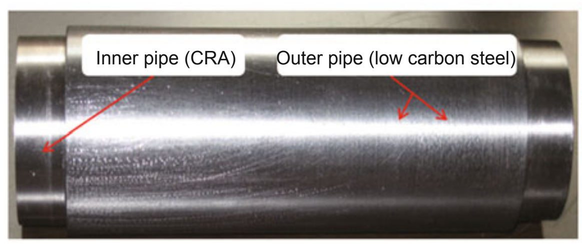


Fig. 5(a) The morphology of the bimetallic LSP after hydroforming

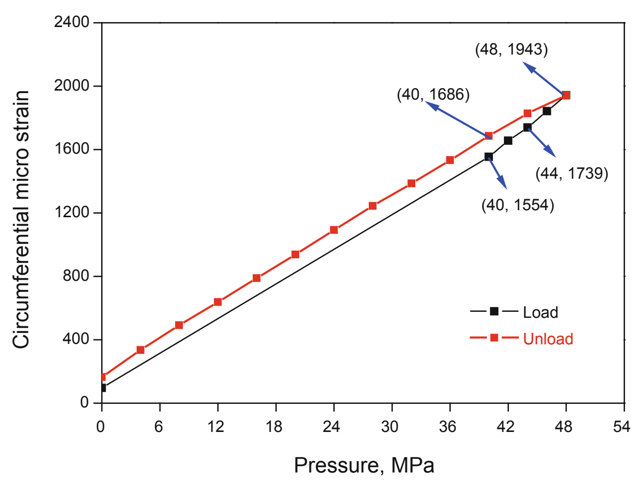


Fig. 5(b) Circumferential strain at the outer pipe in the forming process (0-48 MPa)

2) The 9 samples were put in an oven, and then the oven was heated to the set temperature respectively and maintained for 15 minutes, as shown in Table 3.

3) The samples were taken out and cooled to room temperature in air.

Table 3 Experimental scheme for estimating the reverse yielding of the inner pipe

No.	Sample length l, mm	Heating temperature T_2, °C	Heating equipment	Radial thermal load caused by temperature p_r^t, MPa
1	15	21 (Forming temperature)	—	0
2	15	40	101-2 oven	0.45
3	15	50	101-2 oven	0.68
4	15	60	101-2 oven	0.92
5	15	70	101-2 oven	1.15
6	20	80	101-2 oven	1.38
7	20	100	101-2 oven	1.84
8	20	120	101-2 oven	2.30
9	20	200	Resistance furnace	4.14

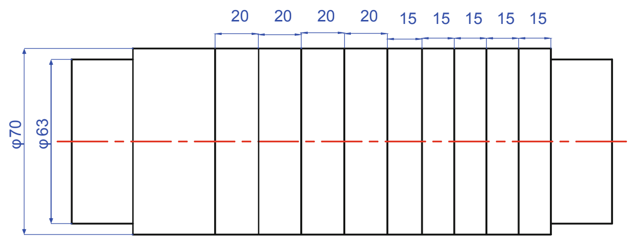


Fig. 6 The sampling method of the bimetallic LSP

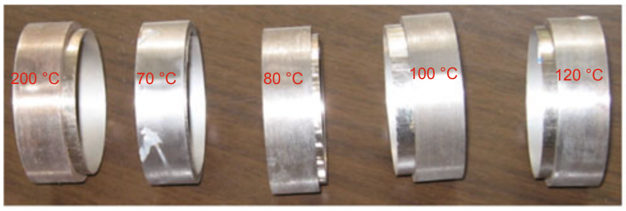


Fig. 7 The appearance of some samples after shearing test

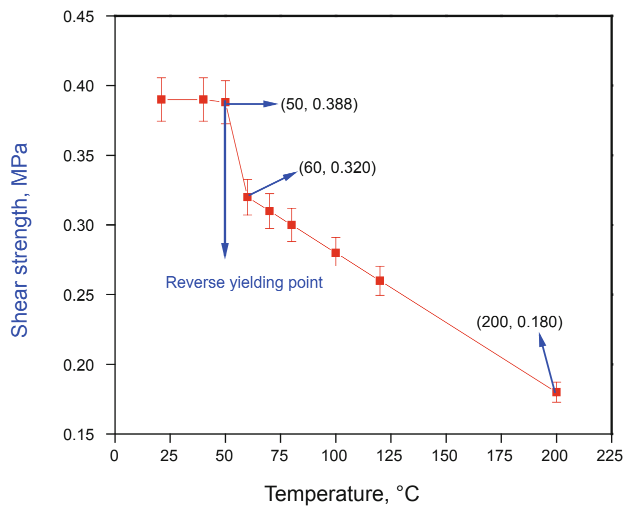


Fig. 8 The correlation between shear strength of the bimetallic LSP and heating temperature

4) Shear tests were conducted on the cooled samples with a MTS testing machine to measure the shear force.

5) The shear strength of each sample was calculated by using the measured shear force and the size of the bimetallic LSP based on the standard method (CJ/T192, 2004).

6) The change of residual contact pressure was analyzed according to the shear strength.

3.4 Test results and discussion

The appearance of some samples after shearing test was shown in Fig. 7. The shear strength of all samples under different temperatures can be calculated by the standard method (CJ/T192, 2004). The shear strengths at different temperatures are plotted in Fig. 8.

Fig. 8 shows that the shear strength (0.39 MPa) of samples after air-cooling basically remained unchanged when the heating temperature was less than 50 °C. This indicates that the shear strength of the bimetallic LSP is 0.39 MPa. The shear strength of samples dropped sharply when the heating temperature was higher than 50 °C. According to the forming principle, it can be known that reverse yielding occurs on the inner pipe when the temperature is 50 °C, the critical temperature (50 °C) and the corresponding thermal strength (0.68 MPa) can be obtained. The test results are very close to the calculation results (the critical temperature and corresponding thermal strength are 48.6 °C and 0.66 MPa respectively) of this mechanical model.

The shear strength of samples decreased linearly with an increase in temperature when the temperature was higher than 50 °C. However, there was still some residual contact pressure between the inner and outer pipes. This indicates that the deformation of the bimetallic LSP under thermal load accords with the assumption of deformation compatibility.

4 Conclusions

1) A mechanical model was developed to calculate the thermal strength of the bimetallic LSP. Its accuracy and reliability was validated by test data. Based on the model, the correlations between the thermal strength of the bimetallic LSP and residual contact pressure and wall thickness of the inner pipe were obtained.

2) Reverse yielding tests were performed on the inner pipe of the bimetallic LSP (φ70×(3.5+0.76) mm). The shear strength of the bimetallic LSP was measured at different temperatures. The critical temperature and its corresponding thermal strength, which made the inner pipe yield, were obtained.

3) Reverse yielding failure of the inner pipe of the bimetallic LSP occurred easily when it was subjected to thermal load and residual contact pressure simultaneously. So, blindly pursuing high residual contact pressure is not reasonable. The manufacturers and users should reasonably determine the value of residual contact pressure of the bimetallic LSP to avoid reverse yielding failure according to the service conditions of the bimetallic LSP.

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