Double-walled Pipe Preparation by Tensile Method and Experimental Verification of Safety

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Abstract

Double-walled metal pipe is a special kind of pipe that maintains both heat transfer function and safety. In this paper, a method of fabricating double-walled pipes using tensile stresses is presented. The residual stress of the experimental sample was measured by X-ray diffraction. The behavior of pre-cracked pipes under axial compression was tested both experimentally and simulatively. The buckling deformation of the pipe causes the outer pipe to bulge up at the crack and separate from the inner pipe. The experimental results demonstrated this method can be used to construct effective double-walled pipes with properties that prevent cracks from penetrating the interface between the two layers of pipe.

Introduction

Double-walled metal pipes provide heat transfer efficiency while ensuring safety by preventing leakage. They are suitable for internal and external heat exchange situations and are widely used in the chemical and electric power industries. Their manufacturing methods include shrink-fitting, explosive forming, and other heat treatment methods, as well as hydraulic forming, cold molding, and other cold treatment processing methods. Different types of double-walled pipes can also be distinguished according to the presence or absence of an inner sandwich. In general, there are a variety of well-established processing methods that output products applicable to various situations ([7]-[20]). The mechanical properties ([22]-[24]) and thermal properties ([25][26]) of double-walled pipes have also received extensive attention.

In this study, we designed a method to prepare double-walled pipes by stretching the outer pipe to make it thinner, and in turn, squeezing the inner pipe to obtain a compacted double-walled pipe. Compared with other preparation methods, this method is simple to prepare and requires less equipment. After preparation, the residual stresses in the pipes were measured by X-ray diffraction to evaluate the extent of their compression. To verify the safety of the double-walled pipe, prefabricated cracks and pressure tests were used. It was found that a crack in the outer pipe could not penetrate the interface, thus causing leakage, due to the buckling effect. These results demonstrate that double-walled pipes can maintain a certain level of safety in hazardous conditions and avoid complete leakage.

1 Double-walled Pipe Preparation By Tensile Method

1.1 Experimental preparation

To execute the tensile method, the outer pipe was stretched and contracted to squeeze the inner pipe, after which the outer pipe maintained a certain degree of shrinkage once unloaded due to plastic deformation. This process formed a double-walled pipe with the inner and outer pipes fitted, as shown in the diagram of Figure 1. These experiments were performed with 316L steel, which has a modulus of 227 GPa and a yield limit of 136.2 MPa. The inner pipe was 140-mm long, which was also the length of the effective tensile section of the outer pipe. The inner diameter of the inner pipe was 18 mm, while the inner diameter of the outer pipe was 23 mm, both with a wall thickness of 2 mm. The pipes were stretched until

the inner and outer pipes were in contact, and then the stretching was continued until a specified length was attained to obtain the finished product. After that, the excess parts at both ends of the finished product were removed by wire cutting to obtain a uniformly stretched middle part, and the residual stress at the section was measured by X-ray diffraction. Figure 2(a) shows an axial force-displacement diagram obtained during the stretching preparation, in which the horizontal axis is the length of the inner and outer pipes that was stretched after contact. Figure 2(b) and (c) show the finished product and the enlarged view of the section wherein the interface between the inner and outer layers can be seen.

1.2 Residual stress measurement by X-ray diffraction and numerical simulation

During the stretching process and after unloading, the inner pipe was compressed and contracted by the outer pipe, and the main residual stress after unloading was the circumferential compressive stress. The simulation and experimental results were used to compare and determine the compression of the inner pipe. For the simulations, the experimentally obtained data were used as material parameters to construct an elasto-plastic model. X-ray diffraction measured the residual strain in the section, which allowed the residual pressure to be calculated. The two results are compared and shown in Figure 3, where it is seen that the actual residual stresses obtained have the same trend as the simulated results, but the values are smaller. This is because the tensile residual stresses in the outer pipe are slightly released when cutting off the excess parts at both ends, which causes the outer pipe to shrink slightly in the axial direction and expand circumferentially, and in turn, the residual stresses between the two pipes are slightly reduced.

2 Numerical Simulation And Testing Of Crack-stopping Capacity Of Double-walled Pipes

2.1 Analysis

The ability of a double-walled heat exchanger pipe to resist liquid leakage is an important feature of the pipe. Even if the pipe is cracked, the crack must be stopped from penetrating the double-walled pipe and causing a liquid leakage accident, instead leaving enough opportunity for repair. Double-walled heat exchanger pipes work under high pressure from both internal and external liquid with both ends fixed. The rapid expansion of an initial crack in such conditions should be avoided. For example, after the crack on the outer pipe expands to the interface, stress concentration may occur there, which may cause cracks to grow on the inner pipe and then penetrate under the action of internal pressure. As previously mentioned, the main residual stress in the inner pipe of the formed double-walled pipe is the circumferential compressive stress, which helps to counteract the tendency for the inner pipe to crack, while the circumferential tensile stress in the outer pipe makes the cracks more likely to grow. However, in practice, the cracking conditions that may happen in double-walled pipes are more complex and require numerical simulations and experimental verification to ensure their ability to stop cracking. As can be expected, the pipe wall will buckle under compression [1][2], and the effect of buckling on crack expansion is one focus

of the present study's experiment. If the two pipes do not buckle in the same way, the interface of the two pipes will separate, which is conducive to hindering the expansion of cracks.

2.2 Simulation and Experimentation

Because the pipe is fixed at both ends during operation and subjected to axial compression at high temperatures, axial compression was chosen as the loading means for the crack expansion test. The pre-crack was set on the surface of the outer pipe and driven to expand by loading to confirm if it would cross the interface between the two pipes. In ABAQUS software, the residual stresses generated during the tensile simulation were used as pre-set stress values, and pre-cracking was set in the outer pipe of the model and axial compression was applied. The results were compared with the corresponding experimental results.

2.2.1 Longitudinal cracks

A 67.5-mm-long section of the prepared sample was cut, and axial cracks of 0.2-mm width and depths of 1 mm and 1.8 mm were prefabricated in the body of the pipe. Axial pressurization experiments and corresponding numerical simulations were performed, and the results were as follows.

The experimentally obtained longitudinal crack extension results can be seen in Figure 4. Figure 4(a) shows the results obtained for three pipes prepared by the tensile method with 1-mm deep vertical cracks and axial pressure. It is apparent that all three pipes buckled near the ends, and the cracks also opened in the buckling. This crack expansion at the location with residual stresses will cause the tensile residual stresses to be released [3], making the cracking of the outer pipe more obvious (compared with oblique cracks). The pipes from left to right in Figure 4(a) were subjected to compressions of 4 mm, 4.4 mm, and 4.8 mm, respectively, and as can be seen, the amount of compression significantly affected the degree of crack opening. Figure 4(b) shows the compression curves corresponding to the different compressions, where the horizontal axis shows the amount of the pipe that continued to be stretched after the outer pipe contacted the inner pipe during the preparation process. The difference in stiffness between the three pipes can be seen in this plot, as well as how the pressure tends to be consistent and smooth after the pipe yields. Figure 4(d) shows the crack extension results obtained from the simulation. Figure 4(c) shows the experimental results obtained under a 1.8-mm deep pre-set crack, in which the crack penetrated through the outer layer as seen in Figure 4(f), where the fracture is visible under the microscope.

Figure 5 examines the section obtained after cutting the sample horizontally, which shows that the buckling of the outer pipe is more obvious than that of the inner pipe due to the pre-cracking, and the inner and outer pipes are shown to be separated at the buckling. In Figure 4(a)(c)(f), there is no obvious crack extension at the unbent area. Therefore, it can be concluded that when the structure of the double-walled pipe is subjected to axial pressure that causes wall buckling and obvious crack expansion, a gap

between the inner and outer pipe will be produced, making it difficult for crack expansion through the inner and outer pipe interface to occur. However, the clearly visible buckling phenomenon alone does not lead to the separation of the two pipes, but instead, the combined effect of both buckling and crack extension leads to the separation and prevents further crack extension. In the case of longer pipe lengths, the pipes may show overall buckling phenomena [4][5][6] that are not closely related to the crack extension discussed here.

2.2.2 Oblique cracking

Simulation results obtained during compression for a model with an axial length of 65 mm are shown in Figures 6 and 7. The crack penetrates the outer layer at pressures above 800 kN, shown in Figure 7(c) and (d), after which it begins to expand toward the ends of the pipe. The inner pipe showed no obvious stress concentration or signs of cracking, indicating that no crack penetration occurs in this state. The later cracking turns into axial development, which is consistent with the use of axial residual stress to prevent it as mentioned before, indicating that the axial residual stress obtained by the tensile method does counteract the cracking.

The results obtained from the experiment are shown in Figure 8. The pipe length was 65 mm long with a 45°-inclined, 1-mm-deep, and 0.2-mm-wide pre-set crack, and subjected to a downward pressure causing a 3-mm length deformation. The change in buckling of the pipe can be seen in Figure 8(a).

As shown in Figure 8(b) and (c), the pre-crack has been extruded and dislocated under extrusion. This is consistent with the dislocation pattern from the simulation shown in Figures 6 and 7. In contrast to the vertical cracks, the oblique cracks become tighter rather than opening due to the axial pressure, causing the residual stresses to be released in a dislocated manner. This also directs the crack expansion in the direction that intersects the crack, developing it inside the outer pipe, as seen in Figures 6 and 7. However, given the limited range of available pressures in the equipment, it was not possible to pressurize to the extent that crack expansion occurred.

Conclusion

In this paper, double-walled metal pipes were prepared using the tensile method. This method does not require a high degree of refinement of the equipment, but does require cutting off both ends of the pipe to obtain the finished product, consuming more material. For these reasons, this method is suitable for using in experiment. After the preparation, X-ray diffraction, crack extension experiments, and simulations were performed. The X-ray diffraction results showed that the residual stresses in the real constructed pipes were comparable to those obtained from the simulations, indicating that the results obtained by the stretching method were as expected. The results of crack extension experiments showed that buckling occurs in the pipe under axial pressure, and only at the buckling is there obvious crack extension. Buckling in turn separates the inner and outer pipe, with the extension of the crack also intensifying this separation. In this way, the crack will not have a chance to penetrate the interface between the inner and

outer pipes, which indicates that the double-walled pipe has the property of preventing crack penetration under axial pressure. In summary, a method for preparing a double-walled pipe has been obtained and its safety has been verified.

Results for crack expansion and buckling of the pipe were obtained; however, a kind of buckling of the pipe axis occurs on longer pipes, which is different from what is discussed in this article, which needs more experimental and theoretical analysis. However, pipes longer than those used in this study do not facilitate axial pressure tests as they are prone to instability. The change of pipe properties and heat transfer efficiency at high temperatures is the focus of subsequent work.

Declarations

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Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Ethical Approval and Consent to participate

Not applicable.

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Be included in the acknowledgement.

Authors Contributions

A fabrication method of double-wall metal tube based on tensile method was proposed and experimentally prepared.

The residual stresses of the tubes obtained by experiment and simulation were compared.

Crack propagation experiments were carried out to verify the ability of the pipe to prevent crack propagation.

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Figures

(a)

(b)

Figure 1

(a) Schematic diagram of the tensile experiment, and (b) photograph of the actual experimental procedure.

(a)

(b)

(c)

Figure 2

(a) Diagram of the axial force-displacement during the stretching preparation. The inflection point of 30 mm is the point at which the outer pipe contacted and started to squeeze the inner pipe. (b) Photograph of the finished product obtained after stretching and cutting. (c) Microscopic image of the cross-section, which shows the interface between the inner and outer layers.

Figure 3

Graph of the comparison of residual stresses in the inner wall of the pipe obtained by simulation and X-ray diffraction.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 4

(a) Photograph of the three results obtained from crack (1 mm) extension experiments; (b) graph of the compression curves; (c) crack extension experiments under deeper (1.8 mm) pre-cracking; (d) simulation results; (e) and (f) photographs of the results in (c) taken under the microscope with depth-of-field extension processing for the unbent and bent-out pre-cracking, respectively, which can be seen in (f) as the crack penetrates the outer pipe.

(a)

(b)

(c)

(d)

Figure 5

(a) and (b) The pipe sample that was cut horizontally after being re-flexed under pressure and undergoing crack expansion, where it is seen that the inner and outer pipes are separated at the crack such that the crack expansion of the outer pipe cannot affect the inner pipe. (a) The 1.8-mm-deep pre-crack, and (b) the 1-mm-deep pre-crack, with the buckling and separation of the inner and outer pipes more obvious in (a), showing that the more serious the crack expansion of the outer pipe is, the more difficult it is to affect the inner pipe, corresponding with the simulation results in (c) and (d).

Figure 6

The pre-crack expansion when the model is subjected to an axial pressure of 200 kN. This crack has just penetrated the outer pipe to expose the inner pipe surface.

(a)

(b)

(c)

Figure 8

The pre-crack expansion for a tilted pre-crack. (a) The experimentally obtained buckling state; (b) and (c) comparison of the pre-crack before and after the experiment, respectively.