Effect of butt fusion welding process parameters on mechanical properties and residual stress of polyethylene pipeline

Zhaopu Li[a], Liang Qiao [b, c], Yi Zhang[1*], Ben Jar[d]

a Department of Engineering Mechanics, College of Pipeline and Civil Engineering, China University of Petroleum (East-China), Qingdao, China

b Shenzhen Gas Corporation Ltd., Shenzhen 518000, China

c Shenzhen Engineering Research Center for Gas Distribution and Efficient Utilization, Shenzhen 518000, China

d Department of Mechanical Engineering, University of Alberta, Edmonton Alberta T6G 2R3, Canada;

Abstract： In the process of production and butt fusion welding, polyethylene pipe will produce some residual stress, and the existence of hoop residual stress will affect the bearing capacity of pipe system and reduce the service life. In this paper, the hoop residual stress of polyethylene tube substrate and welded joint is measured by open ring method and blind hole method, and the finite element model of butt fusion welding with temperature-displacement coupling is established based on elastoplastic constitutive. The results show that the hoop residual stress of the fusion zone of the polyethylene pipe welded joint is slightly less than that of the substrate, and the residual stress of the weld and fusion zone is tensile stress, the tensile stress of the inner wall is greater than that of the outer wall. The residual stress changes from tensile stress to compressive stress at 5mm away from the weld, and the increase of welding temperature and heat-soak time will increase the residual stress value.

Keywords: Polyethylene pipe; Butt fusion welding; Residual stress; Elastic-plastic constitutive

0 Introduction

Currently, the global economy is rapidly advancing, and energy and environmental issues are becoming increasingly critical. Natural gas, as a clean energy source, is widely recognized, and the demand for gas pipelines is continuously rising. Polyethylene pipelines, known for their light weight, high flexibility, corrosion resistance, and oxidation resistance, have been utilized for over 60 years in applications such as natural gas and water transport, as well as nuclear industrial wastewater treatment [1-2]. After years of utilization and development, medium to high-density polyethylene gas pipes now hold a dominant market share of up to 98% in the European plastic gas pipeline market. They have become the primary component of plastic gas pipelines, presenting significant market potential in developing countries as well.

Butt fusion welding is one of the welding methods for polyethylene pipelines. It is widely applied in practical engineering due to its low energy consumption, simplicity of operation, and reliable welding quality. The entire butt fusion welding process can be divided into four stages: preheating, heating, switching, and cooling, as shown in Figure 1. During welding, the PE material at the pipe end is heated to a molten state. Under the influence of welding pressure, the two pipes to be welded are pressed together, and the molten PE material is extruded and cooled to form a welded joint.

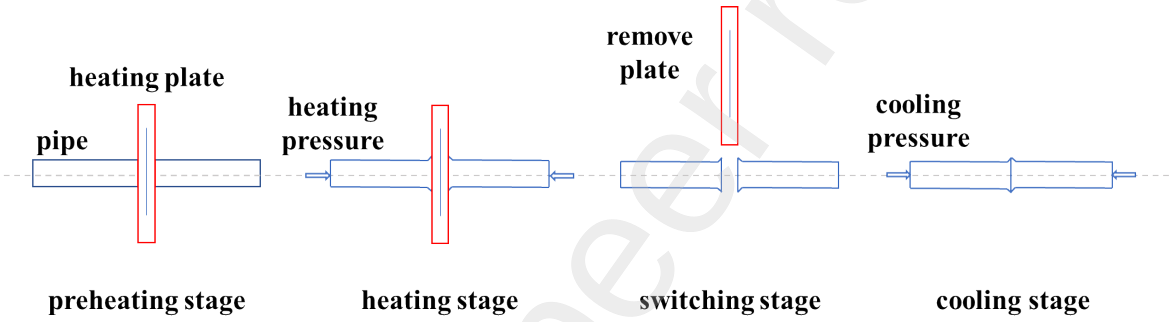

Fig. 1. Butt fusion welding process

The quality of welded joints directly affects the reliability of the entire polyethylene pipeline system. According to investigations by relevant organizations in the United States, 13% of plastic pipeline failures are attributed to joint failures [3]. The performance of welded joints formed after butt fusion welding differs from the pipeline base material [4-7]. Generally, qualified welded joints are required to have mechanical performance differences with the pipeline base material within the allowable range specified by standards. Welding parameters are crucial factors influencing the performance of joints and the entire polyethylene pipeline system, with welding temperature, pressure, and heating time being the most significant [8-9].

Residual stresses in polyethylene pipe material are generated during the production process. The predominant method of processing polyethylene pipes in the current market is extrusion molding. Polyethylene material is first heated and melted, then extruded through a die by a screw, and finally cooled to form [10]. During the cooling and shaping process of the molten polyethylene, the outer surface of the pipe is subjected to water or air cooling, while the inner surface only contacts stationary enclosed air [11]. The significant difference in cooling rates between the two surfaces leads to irregular changes in the density, crystallinity, volume, and other attributes of different parts of the pipe wall, ultimately resulting in residual stresses from processing [12,13]. In addition to thermal residual stresses from uneven cooling, there are also flow-induced residual stresses generated by material compression and constraints, but their values are relatively small and can be neglected in residual stress studies [14].

Research has shown that there are residual compressive stresses in the outer layer of polyethylene pipes and residual tensile stresses in the inner layer [15,16]. Studies, such as those by Frank et al. [17], indicate that residual stresses do not disappear with extended service time, emphasizing the need for a fast and convenient method to measure residual stresses in polymer pipelines for timely assessment of their pressure capacity and lifespan. Poduška et al. [18] proposed an one-slit-ring method based on beam bending theory to calculate circumferential residual stresses in different parts of the pipe wall by measuring the deformation of an open ring. Chen et al. [19] improved the one-slit-ring method and verified its accuracy through numerical simulations. The blind hole method can measure residual stresses without changing internal stresses in materials and has achieved good results in metal fields [20-22]. Kim et al. [23] used both the blind hole and one-slit-ring methods to measure residual stresses in polyethylene pipes, confirming the applicability of the blind hole method to the polymer field.

Residual tensile stress accelerates the initiation and propagation of internal cracks in the pipe wall, affecting the reliability and lifespan of the pipeline [24,25]. Numerous scholars have researched methods to predict the lifespan of polyethylene pipelines. Long-term static hydraulic experiments, such as those conducted by Farshad [26], can establish a relationship curve between stress and lifespan, enabling the prediction of pipeline lifespan. Other common methods include pre-cracking and applying loads. Huang et al. [27] found through experiments that the SCG (Slow Crack Growth) resistance of welded joints in polyethylene pipes is lower than that of the base material. Analyzing the composition of pipeline materials can also be used for lifespan estimation. Hoàng et al. [28] analyzed the chemical composition of PE100 pipes and extrapolated the lifespan of the pipes based on the Arrhenius formula, demonstrating good agreement with static hydraulic test results.

As one of the common failure locations in plastic pipelines, the performance of welded joints has received widespread attention [29]. The butt fusion welding process involves material melting and subsequent cooling, causing changes in crystallinity, crystal shape, and molecular chain arrangement and size [30]. The processing residual stresses of welded joints are released, leading to new welding residual stresses. The distribution pattern of welding residual stresses is not yet clear and cannot be determined using existing experimental methods. Sun et al. [31] obtained the viscoelastic constitutive of polyethylene through relaxation tests, established a butt fusion welding model, and found that welding residual stresses increase with the thickness of the pipe material.

This study conducted multiple sets of butt fusion welding experiments on polyethylene pipes for gas use to explore the effects of butt fusion welding parameters on the mechanical properties of polyethylene pipelines. It summarized an optimal set of welding parameters and used numerical simulation software to study the constitutive relationship of the welded joint, aiming to guide the construction and evaluation of gas pipeline projects. Additionally, existing research indicates that stress conditions significantly impact the lifespan and reliability of pipelines, but the influence of residual stresses on pipelines is rarely considered in current studies. This paper establishes a polyethylene pipe butt fusion welding model, using the residual stresses measured by the one-slit-ring method as the initial stress field and employing the elastic-plastic constitutive obtained from tensile experiments to calculate and analyze the temperature field and circumferential residual stress distribution during the butt fusion welding process.

1 Experiment

1.1 Materials

The experiment selected PE100 DN90 pipes for gas use. A semi-automatic butt fusion welding machine was used to perform butt fusion welding on the pipes at room temperature (25℃). Welded pipes were produced under different welding parameter conditions, and the specific welding parameters are shown in Table 1.

Table 1 Butt fusion welding experiment parameters

Welding temperature T /℃	Heat-soak time t / s	Heat-soak pressure P / MPa	Cooling time t_0 / min	Heat-soak pressure P_0 / MPA
170~270	100	1.5	14	1
230	60~140	1.5	14	1
230	100	0.6~3	14	1

1.2 Tensile test of welded joint

The experimental procedure is as shown in Fig. 2. A tensile specimen is taken from the butt fusion-welded joint, and the dimensions of the tensile specimen follow the GB/T 8804-2003 standard. To better simulate real-world conditions, the welded joint tensile specimen retains the edge of the butt fusion coil for the experiment, and the specimen thickness is the same as the pipe wall thickness. An electronic universal testing machine is used to conduct uniaxial tensile tests on the specimens. Before the experiment starts, the cross-sectional dimensions of the weld at the specimen location are measured. The test is conducted using a displacement-controlled loading method at a constant rate of 50 mm/min until failure. The software records the load and displacement during the entire tensile process.

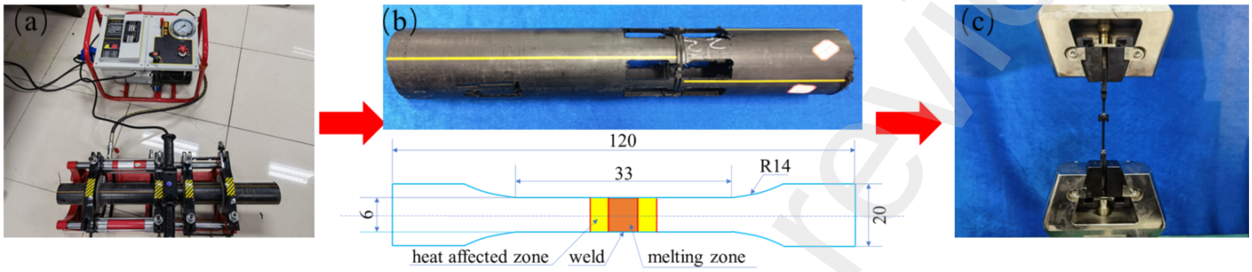

Fig. 2. Polyethylene welded joint tensile test flowchart (a) polyethylene pipe butt fusion welding (b) preparation of tensile specimen (c) tensile test

1.3 Measurement experiment of residual stresses in welded joints

The hoop residual stress in polyethylene pipe material manifests as internal tension and external compression, with the variation trend simplified to a parabolic curve. Based on this pattern and the principles of beam bending theory, the proposed method of the one-slit-ring can rapidly and accurately measure the hoop residual stress in PE pipe material. Firstly, a circular ring is cut from the pipe as a specimen, with the thickness of the ring equal to the wall thickness of the pipe. Using a wire cutting machine, a 120° circular arc is removed from the ring specimen, and the diameter of the remaining semi-circular arc is measured, as shown in Fig. 3.

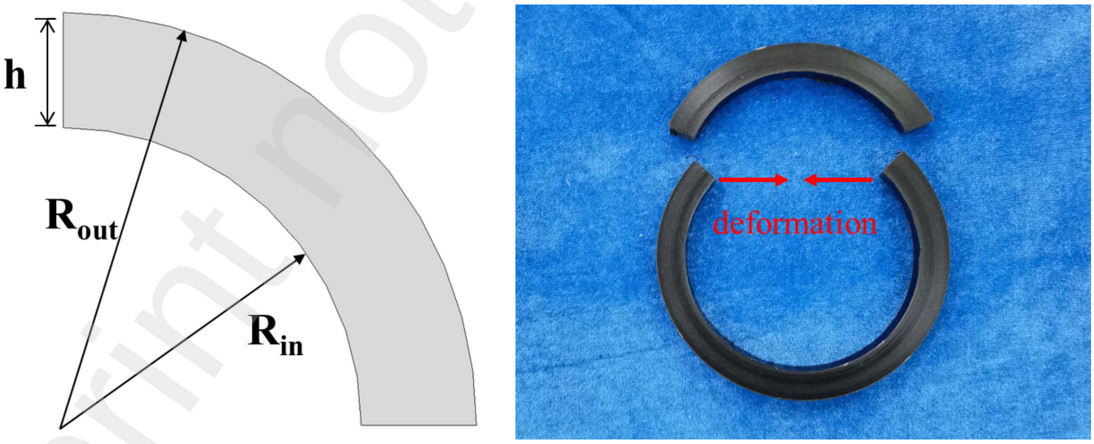

Fig. 3. Polyethylene ring specimen

Due to the viscoelastic characteristics of polyethylene material, after cutting off the circular arc of each ring and allowing it to stand for 1 hour, the diameter is measured using a long-handle vernier caliper. Subsequently, the measured values are substituted into the following formula to calculate the hoop residual stress [13]:

$$\sigma_{res} = C_1 + C_2 e^{3.2x} \tag{1}$$

in the equation, C_1 and C_2 are constants, and x represents the relative wall thickness. The calculation formulas for C_1 and

C_2 are as follows:

$$C_1 = -7.354C_2 \tag{2}$$

$$C_2 = \frac{-\left(D_0 - h - 2R\right)\left(R - R'\right)E}{3.382hR'} \tag{3}$$

in the equation, D_0 is the pipe diameter, h is the thickness of the one-slit-ring specimen, R and R' are the radii of the neutral layer before and after the deformation of the open ring, and the calculation formulas are as follows:

$$R = \frac{R_{out} - R_{in}}{\ln \frac{R_{out}}{R_{in}}} \tag{4}$$

in the equation, R_{out} is the inner radius of the one-slit-ring specimen, and R_{in} is the outer radius of the one-slit-ring specimen.

During the hot welding process, polymer materials undergo heating, melting, and subsequent cooling. The heat history in the heat-affected zone changes, leading to alterations in the distribution pattern of residual stresses. Therefore, the one-slit-ring method is not suitable for measuring residual stresses near the welded joints of PE pipes. In this study, the blind-hole method was employed to experimentally measure surface residual stresses near the butt-fusion welded joints and the base material of PE pipes. Three strain gauges were attached at corresponding positions, following ASTM E837 standards. A 2mm diameter drill bit was used to drill a hole at the center of the strain gauge with a depth of 2mm, as shown in Fig. 4. It is worth noting that due to the heat-soak pressure, the molten material at the welded end of the pipe was extruded to form a welded joint. Additionally, the strain gauge itself has a certain volume. Therefore, the experimentally measured stress value corresponds to a point 6mm away from the weld. To eliminate the influence of the thermoplastic nature of PE materials and ensure the accuracy of the experimental results, the PE pipes were allowed to stand for 24 hours after butt fusion welding. Three strain gauges were uniformly attached to each PE pipe at the base material and the welded joint. The strain gauge readings were recorded every 30 minutes until the strain values no longer showed significant changes. The measured results were averaged for analysis.

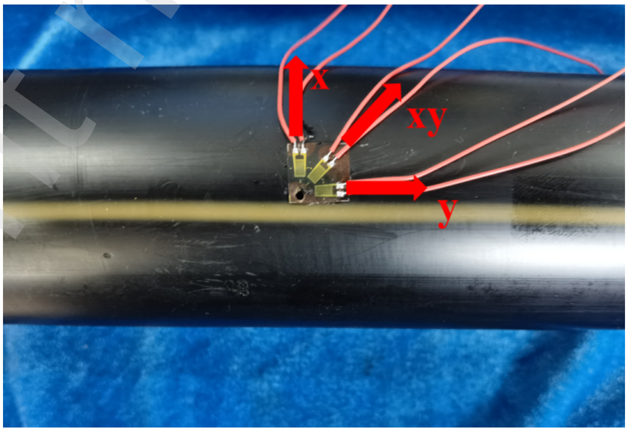

Fig. 4. Schematic Diagram of the Blind-Hole Method

2 Numerical simulation

2.1 Constitutive model of PE

PE material is a typical plastic material that experiences significant thermal expansion and deformation during the heat fusion welding process. However, conventional nonlinear viscoelastic constitutive equations in the past have usually been suitable only for small deformations, failing to accurately represent the deformation process in heat fusion welding. Therefore, this study will adopt the constitutive equations proposed by Kwon [32], which are suitable for describing the large deformation process of polyethylene materials. Specifically expressed as

$$\sigma(\varepsilon)=\begin{cases} 2\dfrac{E}{(1+\nu)}\varepsilon, & \varepsilon\le\varepsilon_y \\ d\left\{\left[a(\varepsilon+b)\right]^{(c-1)}-\left[a(\varepsilon+b)\right]^{(-c)}\right\}+e, & \varepsilon_y<\varepsilon\le\varepsilon_n \\ \alpha k\varepsilon^{N}, & \varepsilon_n<\varepsilon\le\varepsilon_t \\ ke^{M\varepsilon^{\beta}}, & \varepsilon>\varepsilon_t \end{cases} \tag{5}$$

in the equation, σ is the equivalent stress, ε is the equivalent strain, ε_y is the critical strain point from linear elasticity to nonlinear elasticity, ε_n is the initiation point of necking, ε_t is the initiation point of hardening, and a, b, c, d, e, α, k, N, M, β are fitting parameters. These parameters need to be obtained through a combined study and analysis of tensile experiments and simulations

Using ABAQUS finite element analysis software, a three-dimensional model of a butt fusion welding tensile specimen with rolled edges was created. The shape and dimensions of the rolled edge model were obtained through experiments. As shown in Fig. 5, the finite element model of the tensile specimen comprises a total of 46,240 twenty-node second-order hexahedral elements (C3D20R). To accurately calculate the tensile deformation and stress of the specimen, mesh refinement was applied to the neck and weld areas, with the minimum mesh size after refinement approximately 0.4mm. Fixed constraints were applied to one side of the model, and displacement boundary conditions were set on the other side, consistent with the experimental conditions. To enhance the consistency between the simulation and the specimen, the boundary conditions in the finite element model covered the same area as the clamping surface in the experimental setup.

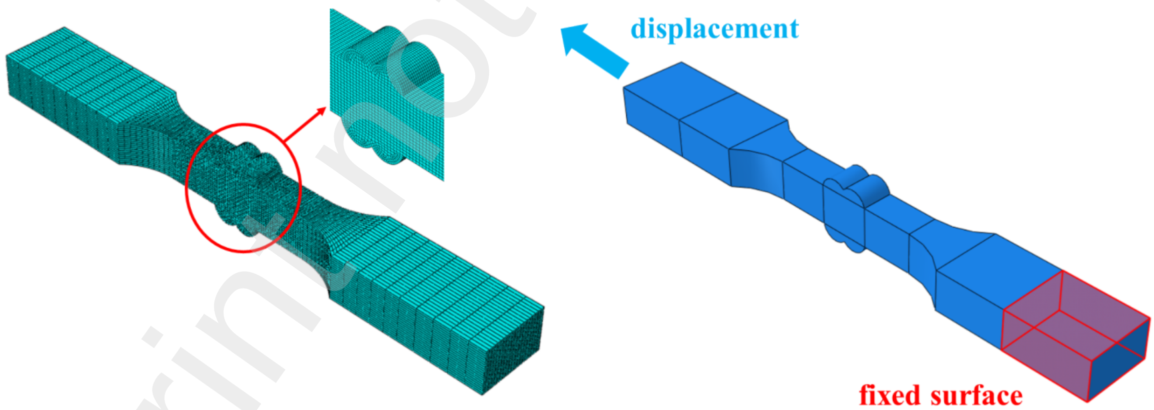

Fig. 5. Finite element model of the tensile specimen with butt-fusion welded joint

2.2 The butt fusion welding process

Using ABAQUS finite element software, a quarter-pipe finite element model was established, with a pipe diameter of 90mm, wall thickness of 6mm, and length of 1500mm, consistent with the specifications of the pipe used in the experiment. The polyethylene pipe itself possesses hoop residual stresses characterized by 'internal tension and external compression.' To account for the influence of these stresses on the residual stresses resulting from butt fusion welding, an initial hoop residual stress field was obtained by defining thermal expansion coefficients with varying thicknesses of the pipe wall. This field was then used as the initial stress condition for simulating the butt fusion welding, as illustrated in Fig.

6. The magnitude of the initial residual stress aligns with the measurement results obtained from the experimental method of the one-slit-ring method.

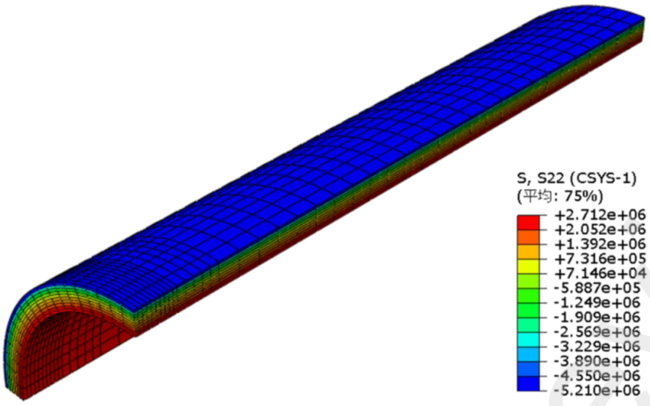

Fig. 6. Initial stress field of the butt fusion welding model

The butt fusion welding simulation employs a temperature-displacement coupled approach, and the calculation process involves thermal physical property parameters such as density, thermal conductivity, thermal expansion coefficient, specific heat capacity, and convective heat transfer coefficient. PE (polyethylene) is a typical polymeric material, undergoing transitions from the glassy state to the high elastic state during the welding heating process, and ultimately transforming into the viscous flow state. The thermal physical properties of PE material exhibit significant differences in different phases. To account for the effects of phase transitions, the finite element model defines material properties under various temperature conditions, with specific numerical values provided in Table 2. Convective heat transfer coefficients for the inner and outer walls of the pipe are calculated separately, with the outer side representing infinite space heat transfer and the inner side representing interlayer heat transfer, having values of 6.609 W/(m^2•°C) and 0.401 W/(m^2•°C), respectively.

Table 2 Parameters of PE

Temperature /°C	Density /Kg•m^{-3}	Thermal conductivity /W• (m•°C)$^{-1}$	Heat capacity /J•(Kg•°C)$^{-1}$
28	980	0.49	1920
125.6	900	0.32	5560
134.7	850	0.31	15510
210	780	0.23	2730

The model employs symmetric boundaries with transverse symmetry conditions and longitudinal boundary conditions separately. During the heating process, the pipe contacts the heat plate, and a temperature boundary condition of 210°C is applied to the welding surface, along with axial constraints. The heat-soak pressure acts on the non-welding surface, with a uniform load of 1.4 MPa applied in the finite element model. During the transition process, the heat plate is removed, and the welding surface is no longer subject to axial constraints; the load on the non-welding surface is set to zero. In the pressure welding cooling process, the two welded pipes are pressed together by the heat-soak pressure, forming a welded joint. Some molten PE material overflows from the pipe wall. At this point, the welding surface in the solid model represents the weld, and axial constraints are applied. The non-welding surface is subjected to a pressure heat-soak pressure of 0.375 MPa. During the free cooling stage, the welded pipe component is allowed to cool, and the non-welding surface is in a state of free deformation. The analysis steps, time, and loading conditions for each stage of the butt fusion welding simulation process are provided in Table 3.

Table 3 The analysis steps and loads in the butt fusion welding simulation

Welding simulation stage	**Analysis step time**	**Welding surface boundary conditions**	**Non-welded surface boundary conditions**
Heating phase	120s	axial constraint,210℃	1.4MPa
Switching stage	5s	unconstraint	unconstraint
Press-welding cooling stage	840s	axial constraint	0.375MPa
Free cooling stage	24h	axial constraint	unconstraint

The model mesh and boundary conditions are shown in Fig. 7. The simulation utilizes C3D20T temperature-displacement coupled hexahedral elements, with each element containing 20 nodes. Deformation and temperature changes in the model primarily occur near the welding surface. To enhance the accuracy of the calculation results, the mesh near the welding surface is refined. The entire model consists of 8200 elements.

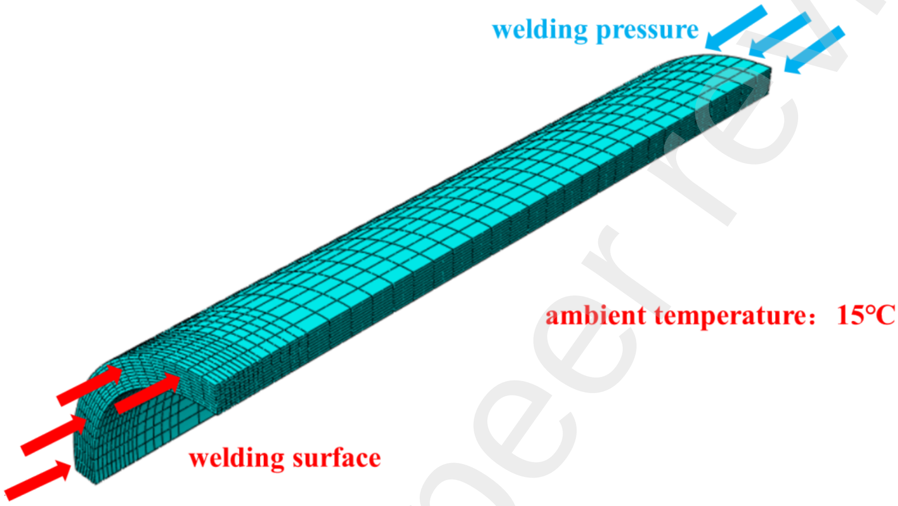

Fig. 7. Load and mesh division of the butt fusion welding model

3 Results and Discussion

3.1 Experiment results

The welding temperature refers to the maximum temperature of the heating plate during the welding process, and its value is much higher than the melting point of high-density polyethylene material (135°C). Fig. 8 shows the relationship between the tensile yield strength of the welded joint and the welding temperature. When other parameters of the butt fusion welding process remain constant, the tensile yield strength of the polyethylene pipe's welded joint of this model reaches its maximum at a welding temperature of 230°C.

The welding temperature during the butt fusion welding process can significantly influence the mechanical performance of the welded joint. During the heating stage, the polyethylene pipe material melts and forms a molten state, with the internal molecular chains continuously undergoing overlapping and entanglement due to heat absorption. When the welding temperature is relatively low, insufficient heating at the pipe end leads to a lack of molecular chain thermal activity in the local area. Activities such as untangling, penetration, and entanglement are not carried out sufficiently. The movement of molecular chain segments adjusting to enter the lattice is inhibited, and the number of bound molecular chains in the amorphous region is relatively reduced [13]. This results in a decrease in material bonding strength, leading to a lower yield strength of the joint. On the other hand, when the welding temperature is too high, material at the end of the pipe may undergo thermal oxidative degradation, molecular chain breakage, disruption of the crystal structure, and the possible release of impurities such as unsaturated hydrocarbons. If these impurities cannot be expelled in a timely manner, they may adsorb near the welded joint. This not only hinders the recrystallization process of polyethylene and reduces the number of bound molecular chains but also creates pore defects that cause stress concentration, significantly lowering the mechanical performance of the welded joint. In summary, selecting an appropriate welding temperature is crucial for butt fusion welding.

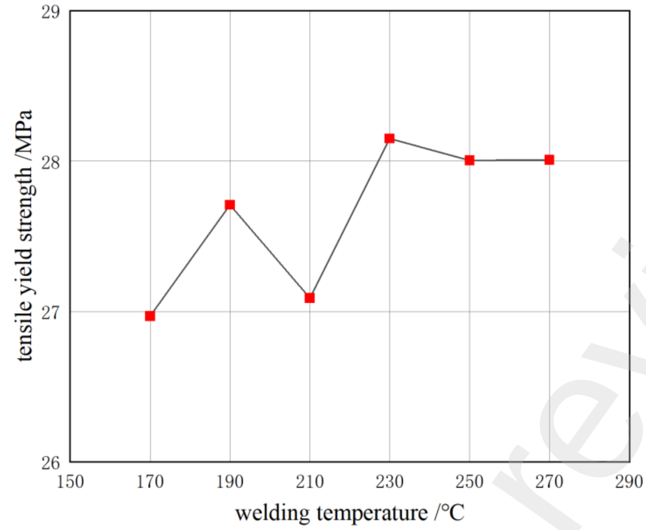

Fig. 8. Effect of welding temperature on tensile yield strength of welded joint

Heat-soak time refers to the time the heating plate is in contact with the end of the pipe. Fig. 9 shows the relationship between the tensile yield strength of the welded joint and the heat-soak time. The performance of the welded joint is optimal when the heat-soak time is 100 seconds. Insufficient or excessive heat-soak time can significantly reduce joint strength. Similar to the principle of welding temperature, when the heat-soak time is insufficient, the polyethylene material does not absorb enough heat, and the depth of the heat-affected zone is too small. There is not enough material to form a molten state, resulting in an unqualified welded joint. Additionally, the molecular chain thermal activity in the deep layer of the pipe wall is insufficient, preventing the formation of a stable structure. Excessive heat-soak time may also increase the likelihood of thermal oxidative degradation. The depth of the heat-affected zone increases, and an excessive volume of molten-state polyethylene material increases the possibility of trapping gas and impurities, leading to pore defects in the welded joint. When extending the heat-soak time, the cooling phase time also needs to be extended. Choosing the appropriate heat-soak time can improve the efficiency of pipeline connection projects.

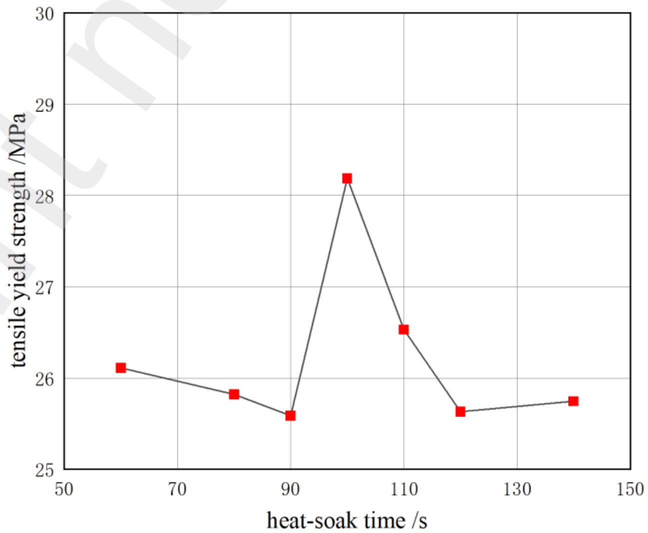

Fig. 9. Effect of heat-soak time on tensile yield strength of welded joint

During the cooling phase, in order to allow the heated and melted ends of two pipes to fit together and cool, forming a welded joint, it is necessary to apply a certain pressure at the other end of the pipe, and this pressure is referred to as heat-soak pressure. The polyethylene material in a molten state at the heated end of the pipe is extruded and overflows from the pipe surface during this process, forming a welded joint after cooling. Fig. 10 illustrates the relationship between the tensile strength of the welded joint and the heat-soak pressure, with the highest yield strength of the joint occurring at a heat-soak pressure of around 2.5 MPa. Improper selection of heat-soak pressure can lead to over- or under-pressure defects in the welded joint. Excessive heat-soak pressure can cause an excessive overflow of molten material, forming a larger volume of rolled edges, while the material in the molten zone inside the pipe decreases. The rolled edge material, influenced by the extrusion, has its molecular chain orientation perpendicular to the direction of the pipe wall and cannot provide sufficient tensile strength. Additionally, after extrusion, the remaining molten zone along the pipe diameter is relatively far from the heat source, with lower temperatures, slower molecular chain thermal movement, and insufficient unraveling and re-entanglement, ultimately resulting in a decrease in the tensile strength of the joint. Too low heat-soak pressure can prevent the molecular chains from having sufficient external force to re-entangle, leading to too little overflow of molten material, and impurities such as gases and dust on the welding surface cannot be expelled from the weld, causing pore defects in the weld and reducing the performance of the joint. Furthermore, material deformation caused by heat-soak pressure, if not compensated for by the cooling-induced deformation, may result in shrinkage holes at the welded joint and the generation of significant residual welding stresses, increasing the risk of structural damage. In comparison to the variation in yield strength of the welded joint, heat-soak pressure has a relatively small impact compared to welding temperature and heat-soak time.

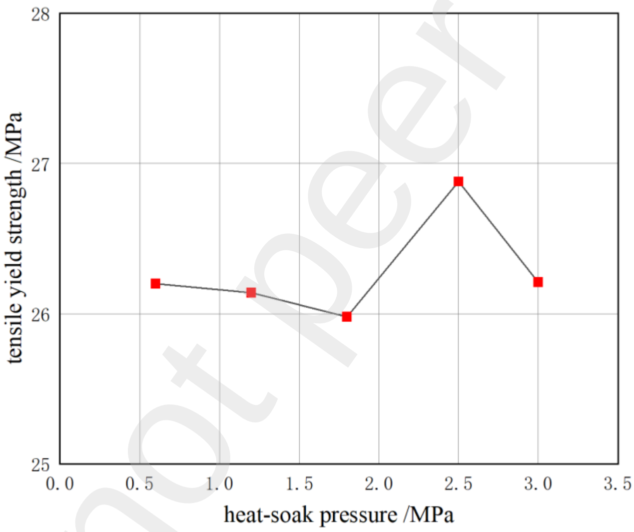

Fig. 10. Effect of heat-soak pressure on tensile yield strength of welded joint

During the entire welding process, the material near the weld seam is heated, melted, and subsequently cooled and solidified. As the molecular chains untangle and re-entangle, the degree of order increases. The appearance of more crystal nuclei enhances the material's crystallinity, consequently boosting the tensile strength of the entire welded joint [14]. It is generally understood that the qualified performance of a welded joint should not be lower than that of the pipe base material. In Fig. 11-a, a comparison is presented between the tensile yield strength of the welded joint and the pipe base material under different welding temperature conditions. It can be observed that when welding process parameters are within specification, the tensile performance of the welded joint surpasses that of the pipe base material. Fig. 11-b illustrates the comparison of the engineering stress-strain curves between the qualified welded joint and the pipe base material. It shows a slightly enhanced capacity of the welded joint to resist tensile failure. However, the ability to resist tensile deformation significantly decreases, with a fracture elongation rate less than half that of the pipe base material.

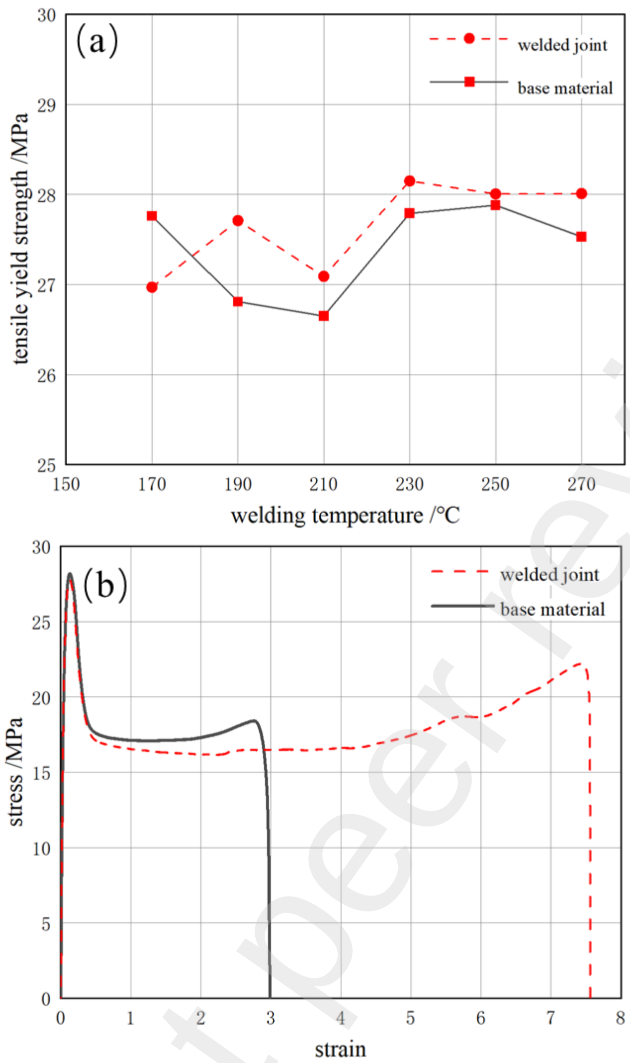

Fig. 11. Comparison of properties of welded joints and pipeline substrates (a) tensile yield strength (b) stress-strain curve

Fig. 12-a shows the specimen after the tensile fracture of the pipeline base material, while image 12-b depicts the specimen after the tensile fracture of the pipeline joint. It can be observed that due to the presence of burrs, the neck of the joint specimen is divided into two parts, resulting in deformation occurring only in half of the specimen. Ultimately, fracture occurs near the weld seam, hence the fracture elongation rate being lower than that of the base material. Polyethylene, being a typical viscoelastic material, exhibits four stages—elastic deformation, yielding, plastic deformation (necking and hardening), and fracture—both in the base material and the welded joint during the tensile process. Additionally, inappropriate selection of welding process parameters might cause distortion in the shape of the welded joint's burrs, leaving gaps on the surface of the pipeline. When subjected to tensile forces during the use of polyethylene pipelines, these gaps at the joints lead to stress concentration, accelerating the initiation and propagation of cracks, thus reducing the overall tensile strength and lifespan of the pipeline.

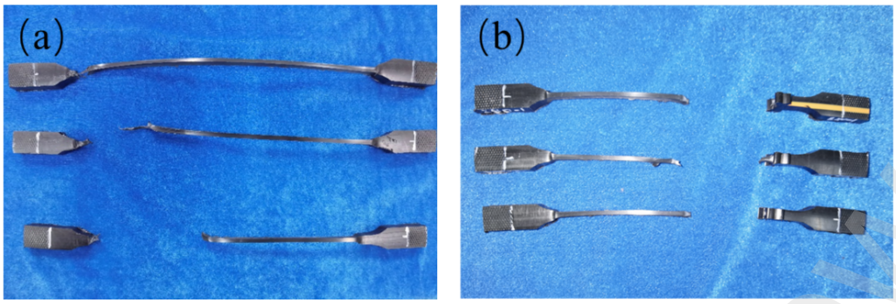

Fig. 12. Tensile fracture sample of welded joint and pipeline substrate (a) base material (b) welded joints

By substituting the values of the one-slit-ring deformation into equations (1), (2), (3), and (4), the hoop residual stresses along the wall thickness of the polyethylene pipes can be calculated, as shown in Fig. 13. It can be observed that the polyethylene pipes exhibit 'internal tensile, external compressive' residual stresses. The maximum hoop tensile stress is distributed along the inner wall of the pipeline, approximately 2.5 MPa, while the maximum hoop compressive stress is distributed along the outer wall of the pipeline, approximately -7.5 MPa. More than 60% of the hoop residual stresses in the pipe wall are tensile stresses, which are not conducive to the long-term use of the pipeline.

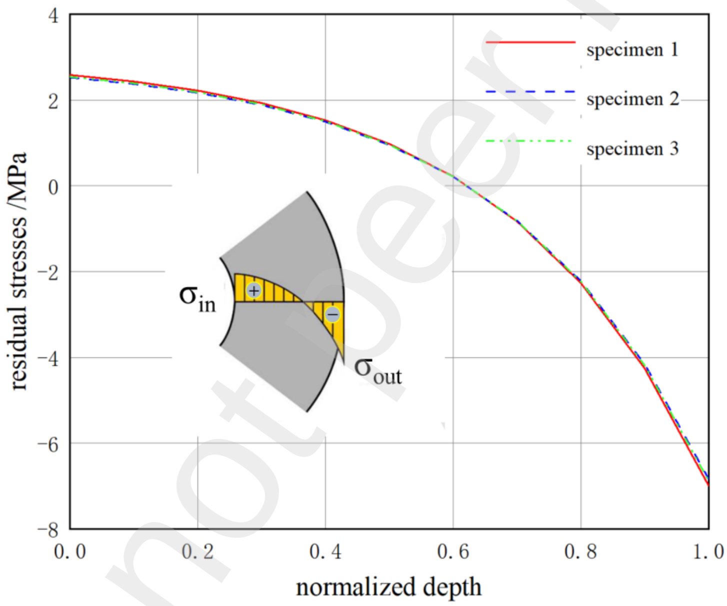

Fig. 13. Measurement results using the one-slit-ring method

In accordance with ASTM E837 standards, the strain gauges were used to measure deformation, which was then calculated as residual compressive stress with the stress direction being compressive. Due to factors such as raw materials, production processes, and transportation conditions, the residual stress levels in each base material of the PE pipes vary. Therefore, when comparing the residual compressive stresses in different welded joints, it is necessary to simultaneously consider the magnitude of residual stress in the base material before welding. The results of measuring the residual compressive stress at the base material and welded joint of PE pipes using the blind hole method are shown in Fig. 14. Axial residual stresses are released during the welding process, resulting in a generally lower residual stress magnitude at the welded joint compared to the base material. When the welding temperature is in the range of 190 to 250°C, the most significant changes in residual stress values occur at 190°C and 230°C, reducing by 0.67 MPa and 1.18 MPa, respectively, compared to the base material. The changes in residual stress values are smaller at 210°C and 250°C, reducing by 0.16 MPa and 0.37 MPa, respectively. It is generally believed that the smaller the performance gap between the welded joint and the base material, the better the stability of the material structure. Since the blind hole method can only measure the surface residual stress of PE pipes, this study used the one-slit-ring method to measure the residual stress in the base material to verify the accuracy of the blind hole method's measurement data. The specific experimental results of the blind hole method and the one-slit-ring method are compared in Fig. 15, indicating that the residual stress values measured by the two methods are close, and any small discrepancies may be attributed to variations in the position of the measured PE pipes.

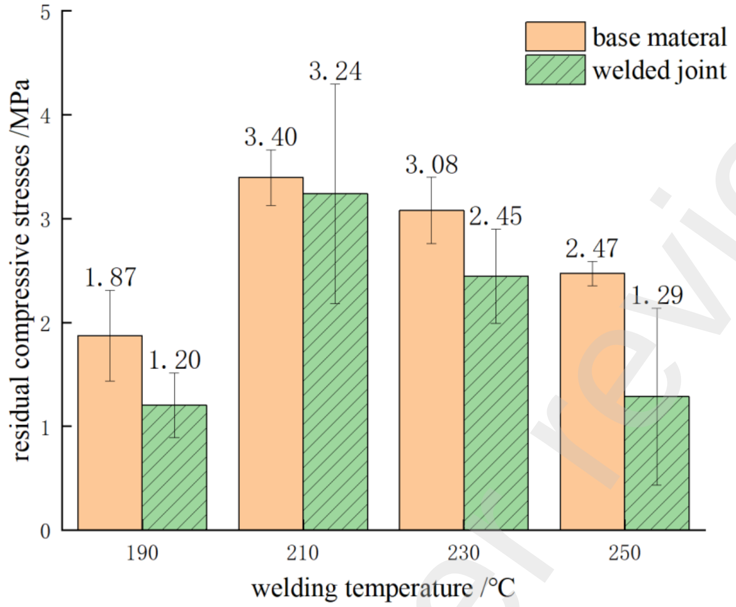

Fig. 14. Comparison of residual compressive stresses in the base material and weld seam of PE pipes

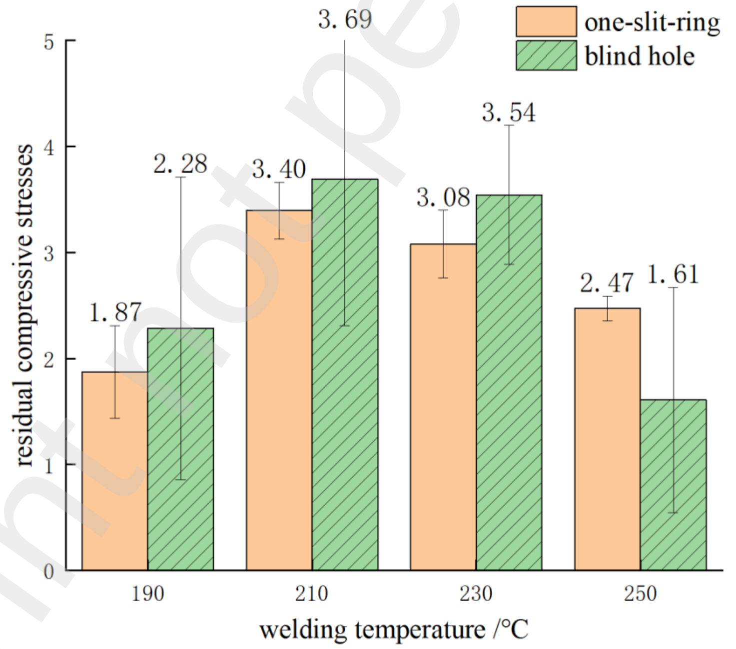

Fig. 15. Comparison of residual stress testing methods

3.2 Numerical simulation results

During the uniaxial tensile test, the strain in polyethylene material can reach 2.0 or higher. However, traditional nonlinear viscoelastic constitutive equations in the past were typically suitable for smaller deformations and couldn't accurately characterize the stretching deformation process. The reaction forces at the fixed constraint points of the model and the displacements in the region where boundary conditions were applied were derived to synthesize the force-displacement curve of the finite element model during the stretching process. This curve was then compared with the experimental curve obtained. By adjusting the fitting parameters of the constitutive model, the force-displacement curve obtained from the simulation was modified to match the experimental curve, as shown in Fig. 16. Once the simulated curve matched the experimental curve, the parameters of the constitutive equation could be determined. This led to the establishment of the constitutive model for the test material, as depicted in Fig. 17.

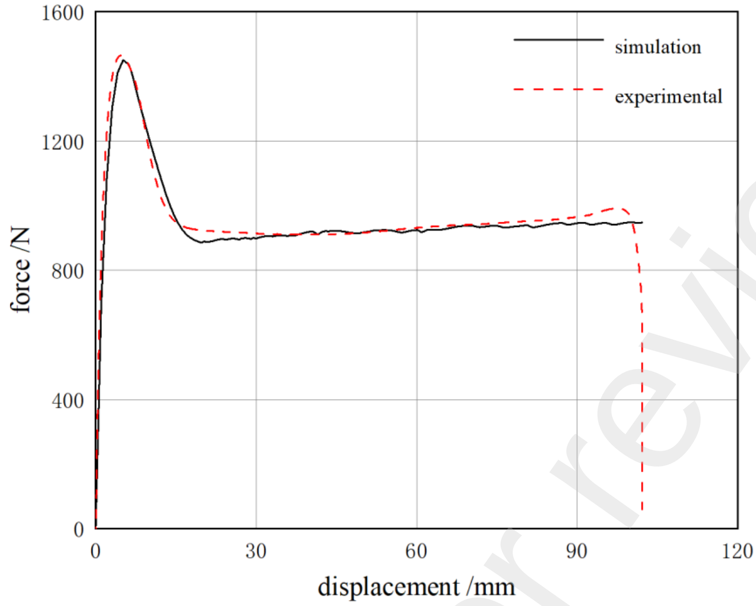

Fig. 16. Comparison between finite element simulation results and experimental results

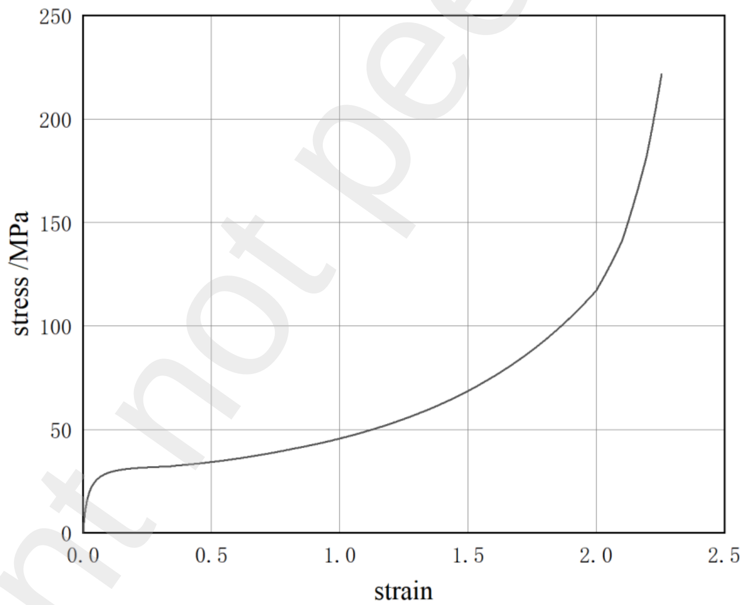

Fig. 17. Constitutive model of PE

The simulation results show that the stress value on the outer wall of the pipeline at a distance of 6mm from the weld is -3.66MPa, which is approximately equal to the -3.24MPa result from the blind hole experiment. This demonstrates the high accuracy of the model, making it suitable for analyzing the stress and temperature field distribution during the welding process. In the butt fusion welding process, different parts of the pipe wall experience varying levels of heat-soak and deformation, leading to the generation of non-uniform residual welding stresses, with the hoop residual stress directly affecting the pressure-bearing capacity of the pipeline, exerting the greatest impact on its lifespan. In this study, the focus is on two key regions: the outer wall of the pipeline (path 1) and the inner wall of the pipeline (path 2). The research analyzes the distribution and variation of the temperature field and hoop residual stress field along the axial direction of the pipeline during the butt fusion joint. Additionally, the study explores the influence of butt fusion welding process parameters on the distribution of these factors.

The distribution of the butt fusion welding temperature field is depicted in Fig. 18. During the heat-soak phase, heat flows axially along the pipeline from the heat-soak end towards the remote end, causing a continuous increase in the thickness of the melted material. At the end of the heat-soak phase, the melting thickness at the weld end of the pipeline approaches 2mm, consistent with the melting thickness observed in the butt fusion welding experiments. Due to a switching time of only 5 seconds, there is no significant impact on the temperature field distribution of the pipeline. During the cooling phase, the heat source is removed, and the pipeline undergoes convective heat transfer with the surrounding air. As the convective heat transfer rates differ between the inner and outer walls of the pipeline, the cooling rate of the outer wall is greater than that of the inner wall. At this point, the temperature at the welding end remains higher than that of the pipeline base material, allowing some heat to continue transferring axially within the pipeline wall.

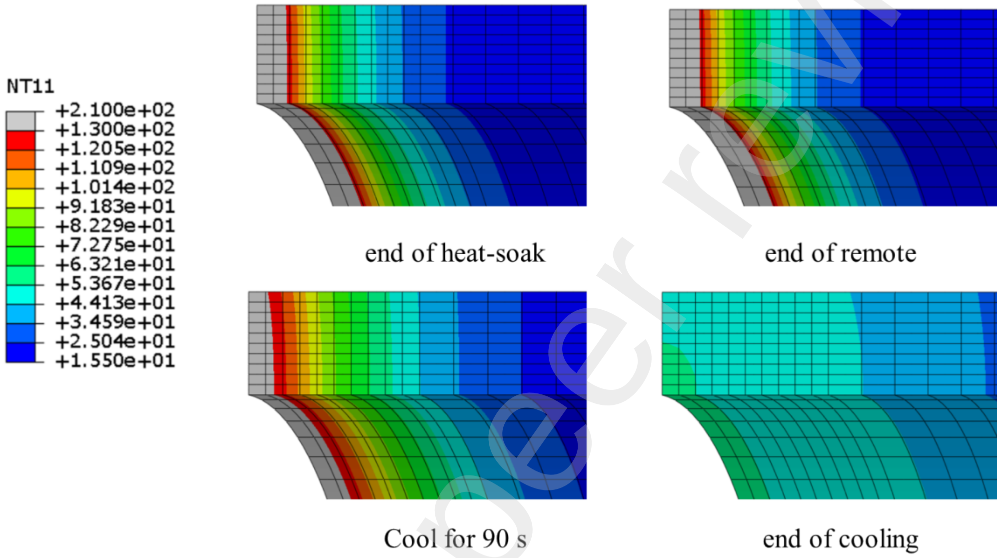

Fig. 18. Distribution of temperature fields at various stages of butt fusion welding

Both the magnitude of welding temperature and the duration of heating directly impact the distribution of the pipeline temperature field. This study investigated the effects of these two welding process parameters on the pipeline temperature field distribution, as depicted in Fig. 14. The research identified the region within the pipeline where the temperature exceeds the material's melting point as the molten layer. In the graph, the horizontal dashed line represents the melting point of high-density polyethylene material, and the abscissa of the intersection between the curve and the dashed line indicates the thickness of the pipeline's molten layer under that condition. From Fig. 19-a, it's observed that with a constant heat-soak time of 100 seconds and an increase in welding temperature, the thickness of the molten layer significantly increases. At welding temperatures of 170°C, 210°C, and 250°C, the pipeline's molten layer thickness measures 1.25mm, 1.96mm, and 2.44mm, respectively. Variations in welding temperature mainly affect the temperature field distribution around the weld and the fusion zone (within 5mm from the weld). The impact on the heat-affected zone farther from the weld is less significant due to limitations in the heat transfer properties of high-density polyethylene material. Within a certain time frame, the pipeline's heat transfer capacity is limited, and higher temperatures cannot be efficiently transferred over longer distances. Fig. 19-b illustrates that with a constant welding temperature of 210°C and an extension in heat-soak time, the thickness of the molten layer slightly increases. For heat-soak times of 60 seconds, 100 seconds, and 140 seconds, the pipeline's molten layer thickness measures 1.56mm, 1.96mm, and 2.28mm, respectively. The influence of heat-soak time on the depth of the molten layer is relatively minor compared to the impact of welding temperature. Changes in heat-soak time exert a broader influence on the temperature field; within 15mm from the weld, the temperature increases with longer heat-soak times. In summary, the thickness of the molten layer in butt fusion welding is primarily influenced by the welding temperature, while the length of the butt fusion joint is mainly associated with the heat-soak time.

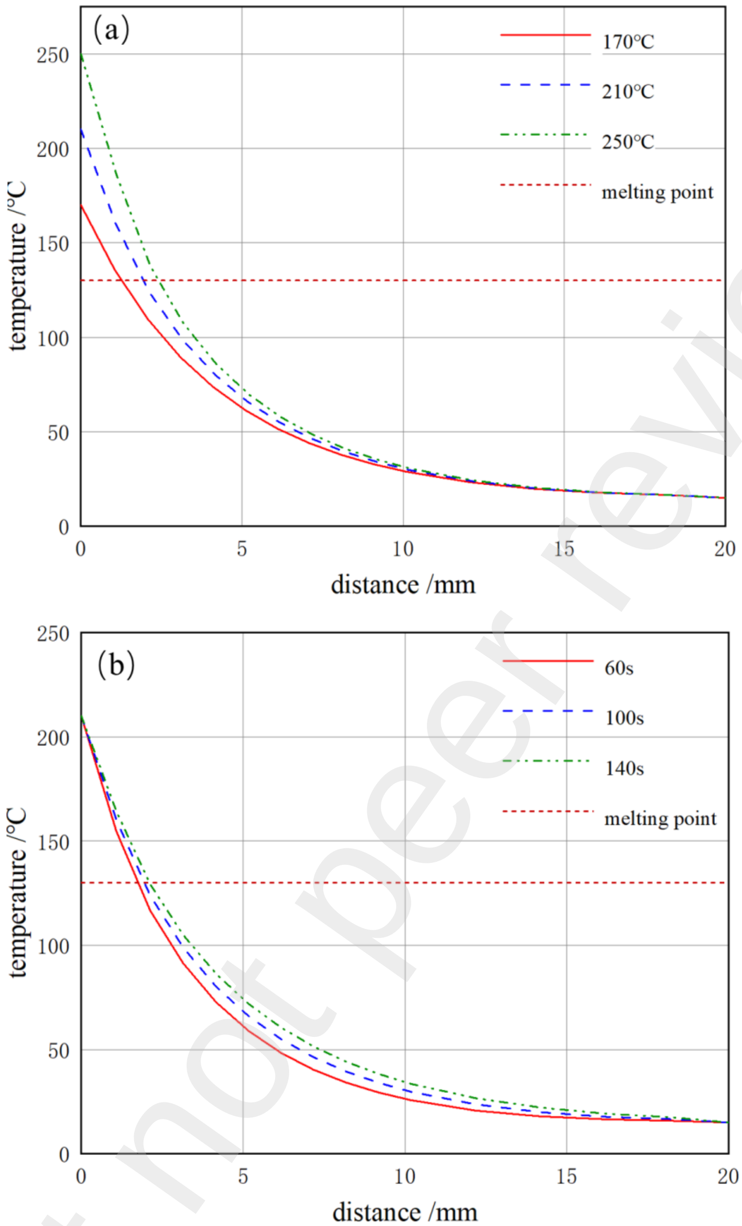

Fig. 19. Influence of butt fusion welding parameters on the axial temperature field distribution of the pipeline (a) welding Temperature (b) heat-soak Time

In the process of butt fusion welding, different parts of the pipe wall experience varying degrees of heat-soak and deformation. This generates uneven residual welding stresses at the butt fusion joint, where the hoop residual stresses directly impact the pressure-bearing capacity of the pipeline, exerting the greatest influence on its lifespan. This study focuses on the outer wall of the pipeline (path 1) and the inner wall (path 2) as the key research areas. It analyzes the distribution and variations of hoop residual stress fields along the axial direction of the pipeline at the butt fusion joint and explores the impact of butt fusion welding process parameters on the stress field distribution. Simulation results indicate that at a distance of 6mm from the weld, the stress value on the outer wall of the pipeline measures -3.66MPa, which is approximately equal to the -3.24MPa observed in the blind hole experiment. This similarity validates the reliability of the model's results.

Fig. 20 illustrates the distribution of hoop residual stress on the outer wall of the pipeline. From the Fig.20, it is evident that the hoop residual stress on the outer wall of the pipeline is maximized near the fusion zone, manifesting as tensile stress. The material in the fusion zone and its vicinity experiences the highest temperature and undergoes the greatest deformation due to thermal expansion, thus exhibiting higher stress values. The magnitude of hoop residual stress initially rises briefly along the axial distance, then significantly decreases. It becomes zero at a position approximately 5mm away from the weld seam and gradually transitions to compressive stress. Hoop residual compressive stress continues to increase along the axial distance, reaching its maximum value at a distance of 7 to 10mm from the weld seam, then decreases and gradually stabilizes. The final value is slightly smaller than the residual stress in the base material.

The distribution of residual stresses in the butt fusion welding process is related to the welding temperature field and the applied load. Therefore, variations in the butt fusion welding process parameters will affect the magnitude of hoop residual stress during welding. According to Fig. 20, an increase in welding temperature results in an increase in hoop residual stress, and the peak compressive stress occurs farther from the weld seam. Extending the heat-soak time leads to a slight increase in the magnitude of hoop residual stress, while an increase in heat-soak pressure causes a reduction in hoop residual stress, although the magnitude is small and can be neglected. Analyzing the temperature field, it is evident that an increase in welding temperature mainly affects the temperature rise in the vicinity of the weld seam. Consequently, there is a larger variation in tensile stress near the weld seam, while the variation in compressive stress at the distant end is smaller. Prolonging the heat-soak time mainly changes the temperature in the rear part of the heat-affected zone, resulting in variations primarily in the compressive stress portion of residual stress. Heat-soak pressure does not affect the temperature field, and since the force direction is perpendicular to the hoop direction of the pipeline, its influence on hoop residual stress is not significant.

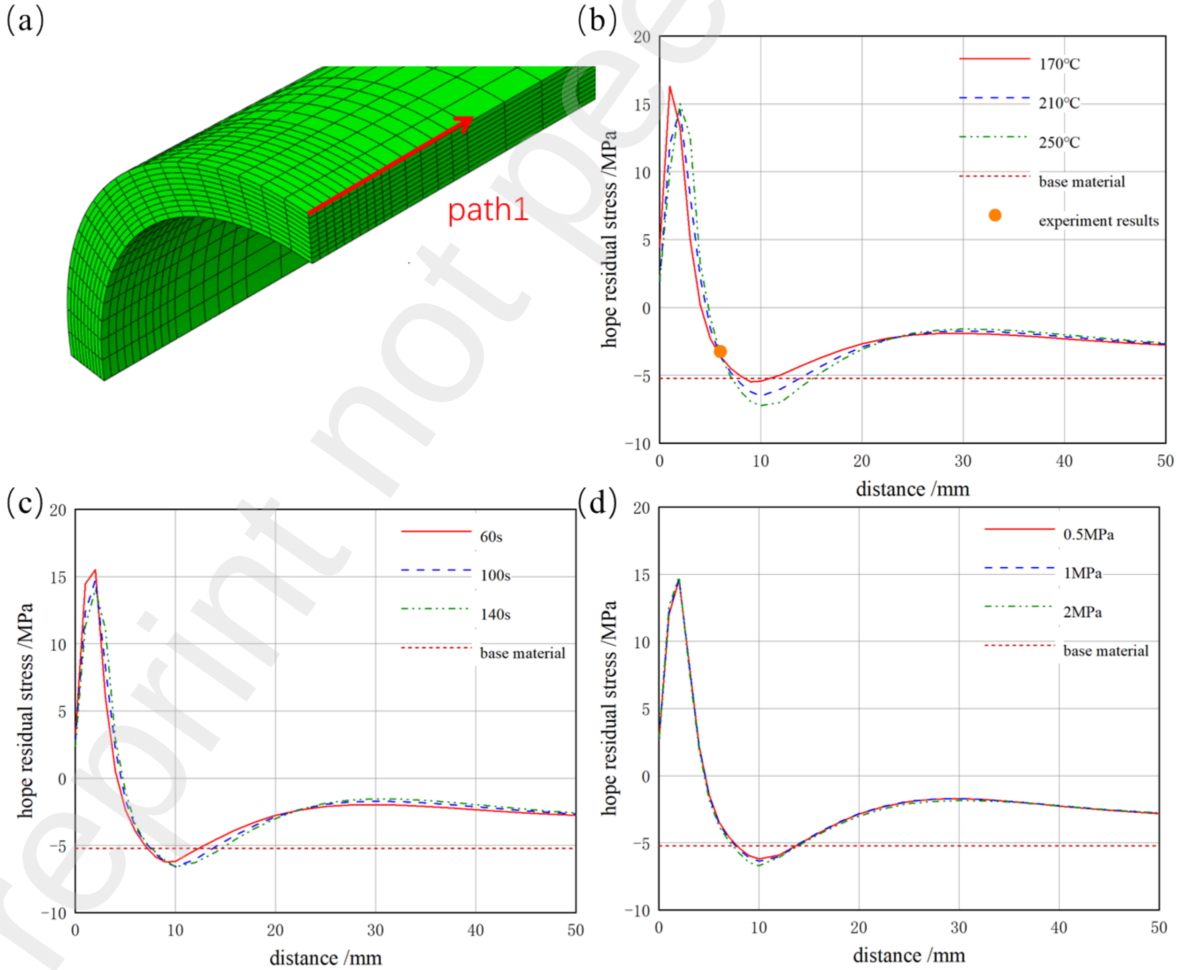

Fig. 20. Influence of butt fusion welding parameters on the distribution of hoop residual stress on the outer wall of the pipeline (a) schematic diagram of the path (b) welding temperature (c) heat-soak time (d) heat-soak pressure

The Fig. 21 depicts the distribution of hoop residual stress within the inner wall of the pipeline. It can be observed that the trend of stress variation between the inner and outer walls is consistent, but the stress values differ. At a greater distance from the fusion joint, the stress values gradually revert to the magnitude of the base material's residual stress. The reason for the aforementioned scenario is that both the inner and outer surfaces of the pipeline experience similar constraints, and the efficiency of heat transfer in the axial direction is also comparable, as the heat is uniformly supplied by the heating plate. Additionally, the inner wall of the pipeline is in contact with enclosed stagnant air, while the outer wall is in direct contact with the external atmosphere. The inner wall exhibits significantly lower heat transfer efficiency compared to the outer wall. This leads to a rapid increase in material temperature and slower heat dissipation, resulting in a relatively greater thermal expansion effect. Consequently, the peak residual stress in the inner wall surpasses that of the outer wall. This also implies that the inner surface of the pipeline's fusion joint is more prone to failure.

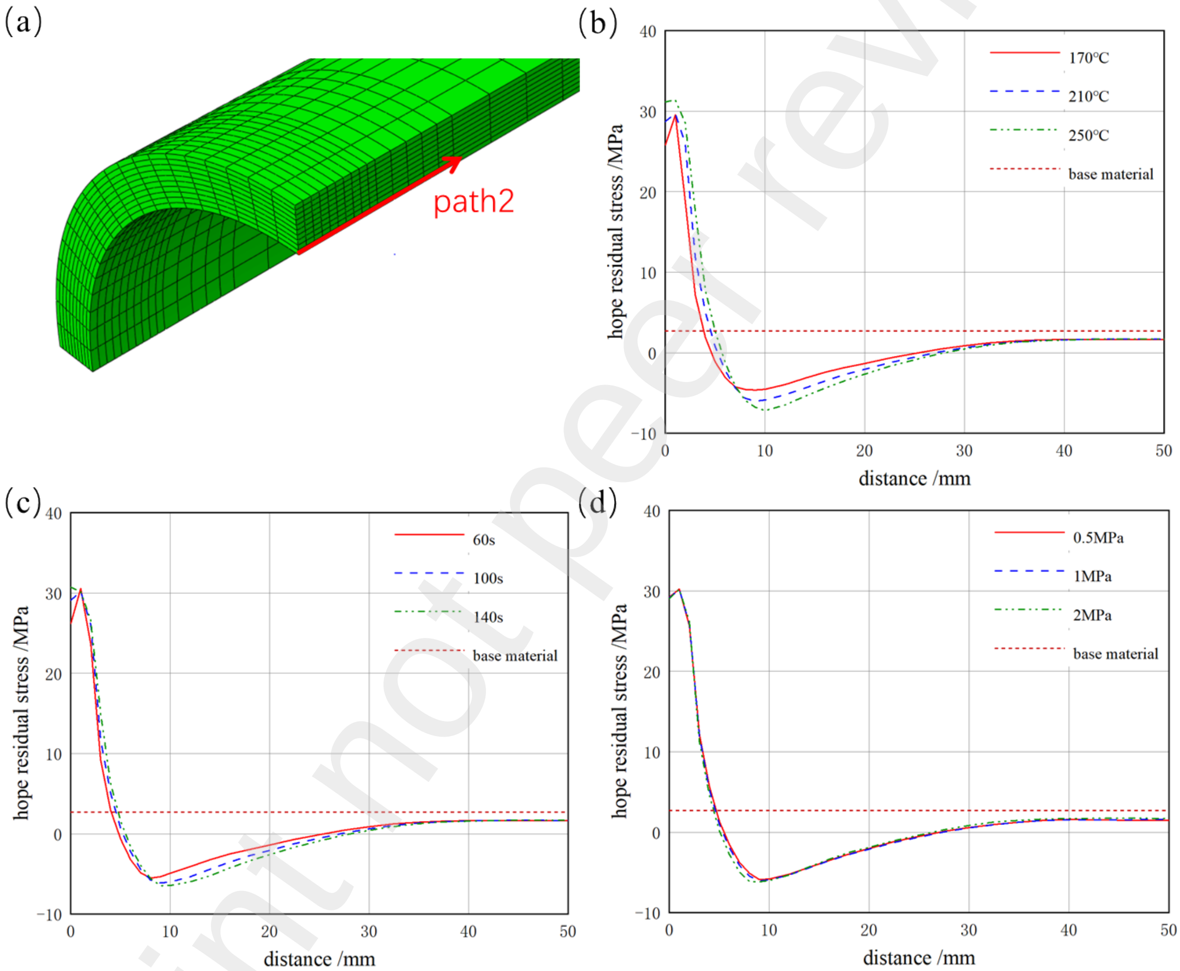

Fig. 21. Influence of butt fusion welding parameters on the distribution of hoop residual stress on the inner wall of the pipeline (a) schematic diagram of the path (b) welding temperature (c) heat-soak time (d) heat-soak pressure

This butt fusion welding model adopts a plastic constitutive model. In comparison to models employing thermal viscoelastic constitutive models, the residual welding stress does not exhibit significant changes with the elongation of the pipeline's idle time. This model aligns more closely with experimental measurement results, providing crucial guidance for practical engineering applications. There are significant hoop tensile stresses near the inner and outer surfaces near the weld seam in the vicinity of the pipeline weld. Improper operation leading to defects such as bubbles or gaps near the weld seam of the butt fusion joint can easily result in the failure of the joint. To ensure the overall reliability of the pipeline, the welding end surface of the polyethylene pipeline should be kept smooth and clean during butt fusion welding. It is essential to prevent impurities from entering the joint, which could lead to stress concentration. When inspecting and predicting the lifespan of in-service pipelines, particular attention should be given to the butt fusion joints and the weld seam area.

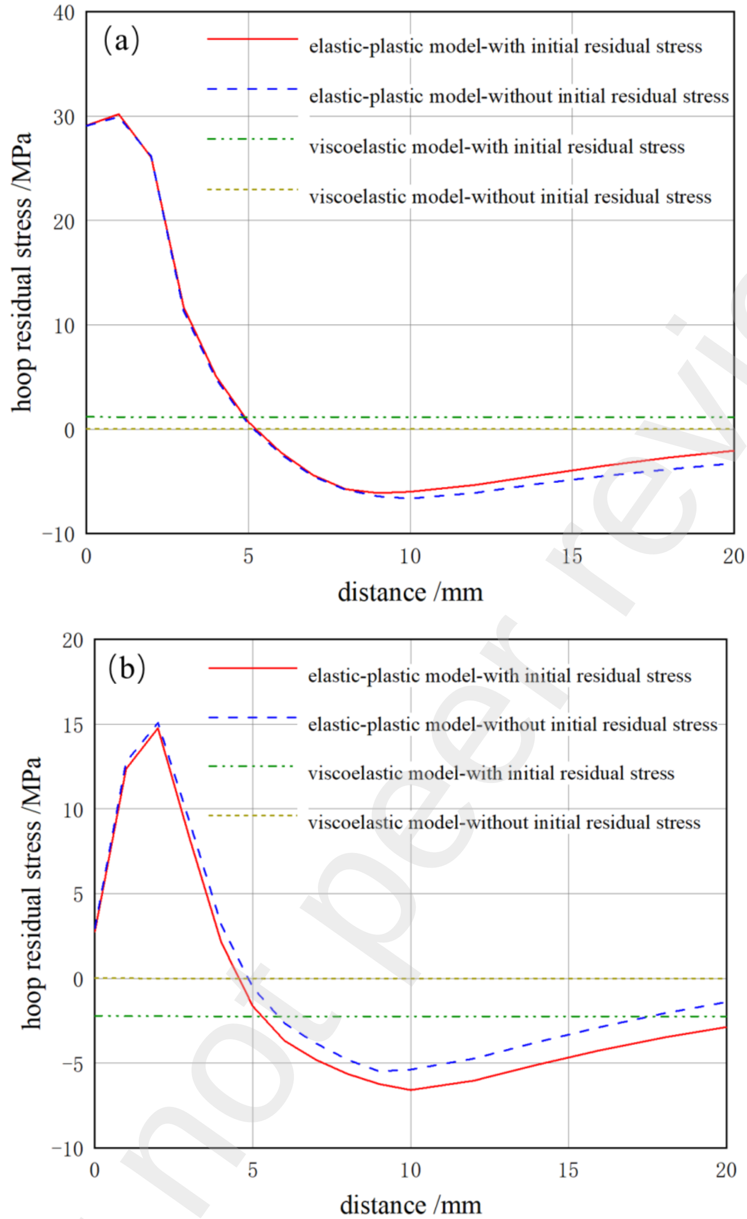

Fig. 22. Comparison of results from the butt fusion welding model (a) inner surface (b) external surface

Fig. 22 depicts a comparative illustration of results from different butt fusion welding models. It can be observed that when the model does not consider initial residual stress, there is no significant change in the results near the weld seam. However, the stress field values in the heat-affected zone are relatively small and tend to approach 0 away from the welding end, which is inconsistent with reality. When the model adopts the viscoelastic constitutive obtained from creep experiments, the residual stress near the butt fusion joint is the same as that of the pipeline base material after 24 hours of cooling. The stress on the outer surface is 1.15 MPa, and on the inner surface, it is -2.23 MPa, which deviates significantly from the experimental results. Without considering initial residual stress, the stress field values after cooling and static settling are approximately 0. In comparison, the results of the butt fusion welding stress field obtained by using the plastic constitutive model are more accurate.

4 Conclusions

This article investigates the effects of welding temperature, heat-soak time, and heat-soak pressure on the mechanical properties of polyethylene pipeline butt fusion joints. A combination of the one-slit-ring method and blind-hole method was employed to measure the residual stresses in both the polyethylene pipeline base material and the butt fusion joint. Additionally, a temperature-displacement coupled butt fusion welding finite element model was established to explore the influence of butt fusion welding parameters on the temperature field and residual stress of the butt fusion joint.

The tensile strength of the polyethylene pipeline butt fusion joint is slightly higher than that of the pipeline base material. The tensile performance increases initially and then decreases with the increase in welding temperature, heat-soak time, and heat-soak pressure. Among these factors, welding temperature and heat-soak time have a more significant impact on joint performance, while heat-soak pressure has a relatively minor effect.

The results obtained from the one-slit-ring method and blind-hole method are approximately equal. The average hoop residual stress at the polyethylene pipeline base material is measured experimentally to be 2.78 MPa. Near the butt fusion joint, the average value is 0.65 MPa smaller than that of the base material.

A numerical model based on elastic-plastic constitutive behavior for butt fusion welding was established. The model simulates the temperature field and residual stress distribution during the polyethylene pipeline butt fusion welding process, taking into account the influence of production residual stress. Compared to traditional models, the results from this model are more accurate.

An increase in welding temperature and prolonged heat-soak time leads to an increase in the thickness of the molten layer in the pipeline. Changes in welding temperature primarily affect the temperature field in the weld and fusion zone, while changes in heat-soak time primarily influence the temperature in the heat-affected zone and the length of the butt fusion joint.

Residual stresses are smaller farther from the weld seam, and in the heat-affected zone, they transition from tensile to compressive stresses. The numerical values of residual stresses increase with higher welding temperatures or longer heat-soak times, and the influence of heat-soak pressure on residual stresses can be considered negligible.

Author contributions statement

Zhaoupu Li: Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft. Liang Qiao: Writing – review and editing, Funding Acquisition; Project Administration. Yi Zhang: Writing – review and editing; Supervision; Data curation. Ben Jar: Writing – review and editing; Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (11802343) and Jiangsu Province Quality and technical supervision Bureau project (KJ2023005).

References

[1] Ruminski A. Failure analysis of a low-temperature carbon steel pipe from a nuclear power station cooling water system[J]. Journal of Failure Analysis and Prevention, 2015, 15: 534-540.

[2] Schulte U, Hessel J. Remaining service life of plastic pipes after 41 years in service[J]. 3 R INTERNATIONAL, 2006, 45(9): 482.

[3] Plastic Pipe Database Committee. Plastic Pipe Database Collection Initiative Status Report [R]. Washington D C: PPDC, 2017.

[4] Leskovics K., Kollár M., Bárczy P.. A study of structure and mechanical properties of welded joints in polyethylene pipes[J]. Materials Science and Engineering: A, 2006, 419(1-2): 138-143.

[5] Shim D.-J., Krishnaswamy P., Focht E.. Comparison of Parent and Butt Fusion Material Properties of High Density Polyethylene[C]. Proceedings of the ASME 2009 Pressure Vessels and Piping Division Conference. Prague, Czech Republic: ASMEDC, 2009, 1301-1308.

[6] Fatima Zohra Talhi, Mohamed Tahar Benaniba, Naima Belhaneche-Bensemra, et al. Comparison of material properties in butt welds of used and unused polyethylene pipes for natural gas distribution[J]. Journal of Polymer Engineering, 2017, 37(3): 279-285

[7] Belaziz A, Mohamed M. Experimental study of the weld bead zones of a high-density polyethylene pipe (HDPE)[J]. Journal of Failure Analysis and Prevention, 2018, 18(3): 667-676.

[8] Pathak S, Pradhan S K. Experimentation and optimization of HDPE pipe electro fusion and butt fusion welding processes[J]. Materials Today: Proceedings, 2020, 27: 2925-2929.

[9] Riahi M, Arab H, Ghanati M F. Analysis of pressure exertion's effect on electrofusion welding process of polymer pipes[J]. The International Journal of Advanced Manufacturing Technology, 2011, 57: 183-188.

[10] Poduška J, Hutař P, Kučera J, et al. Residual stress in polyethylene pipes[J]. Polymer Testing, 2016, 54: 288-295.

[11] Jonson L E. Plastics Pipes for Water Supply and Sewage Disposal. Borealis[J]. CIRCULAR UNDERGROUND PIPE STABILITY ANALYSIS Vasil'ev AI, Golyshev AI Institut Prirodoobustroystva im. AN Kostyakova, Moscow During, 1996: 1913-2013.

[12] Janson L E. Plastics pipes for water supply and sewage disposal[M]. Borealis, 1995.

[13] Clutton E Q, Williams J G. On the measurement of residual stress in plastic pipes[J]. Polymer Engineering & Science, 1995, 35(17): 1381-1386.

[14] Douven L F A, Baaijens F P T, Meijer H E H. The computation of properties of injection-moulded products[J]. Progress in Polymer Science, 1995, 20(3): 403-457.

[15] Williams J G, Hodgkinson J M, Gray A. The determination of residual stresses in plastic pipe and their role in fracture[J]. Polymer Engineering & Science, 1981, 21(13): 822-828.

[16] Clutton E Q, Williams J G. On the measurement of residual stress in plastic pipes[J]. Polymer Engineering & Science, 1995, 35(17): 1381-1386.

[17] Frank A, Pinter G, Lang R W. Prediction of the remaining lifetime of polyethylene pipes after up to 30 years in use[J]. Polymer Testing, 2009, 28(7): 737-745.

[18] J. Poduška, J. Kučera, P. Hutař, et al., Residual stress distribution in extruded polypropylene pipes[J]. Polymer Test, 2014, 40: 88–98.

[19] Chen B, Jar P Y B, Mertiny P, et al. A Refined One-Slit-Ring Method to Quantify Residual Hoop Stress in Chlorinated Polyvinyl Chloride Pipe—Application to Specimens After Immersion in Primer[J]. Polymer Engineering & Science, 2019, 59(s2): E296-E309.

[20] Beghini M, Bertini L. Recent advances in the hole drilling method for residual stress measurement[J]. Journal of Materials Engineering and Performance, 1998, 7: 163-172.

[21] da Silva D S, Lutckmeier F, Diehl I L, et al. Hole-Drilling Method for Deep Residual Stress Measure in Tensile Armour Wires[J]. Experimental Mechanics, 2023, 63(1): 29-42.

[22] Ammar M A, Shirinzadeh B. Evaluation of robotic fiber placement effect on process‐induced residual stresses using incremental hole‐drilling method[J]. Polymer Composites, 2022, 43(7): 4417-4436.

[23] Kim J S, Yoo J H, Oh Y J. A study on residual stress mitigation of the HDPE pipe for various annealing conditions[J]. Journal of Mechanical Science and Technology, 2015, 29: 1065-1073.

[24] Chaoui K, Chudnovsky A, Moet A. Effect of residual stress on crack propagation in MDPE pipes[J]. Journal of materials science, 1987, 22: 3873-3879.
[25] Hutař P, Ševčík M, Frank A, et al. The effect of residual stress on polymer pipe lifetime[J]. Engineering Fracture Mechanics, 2013, 108: 98-108.
[26] Farshad M. Two new criteria for the service life prediction of plastics pipes[J]. Polymer Testing, 2004, 23(8): 967-972.
[27] Huang B, Li X, Zeng Z, et al. Study on viscoelastic behavior during slow crack growth of medium density polyethylene pipes[J]. Transactions of the Indian Institute of Metals, 2016, 69: 1257-1265.
[28] Hoàng E M, Lowe D. Lifetime prediction of a blue PE100 water pipe[J]. Polymer Degradation and Stability, 2008, 93(8): 1496-1503.
[29] Shim D J, Krishnaswamy P, Focht E. Comparison of parent and butt fusion material properties of high density polyethylene[C]//ASME Pressure Vessels and Piping Conference. 2009, 43697: 1301-1308.
[30] Dai H, Peng J. The effects of welded joint characteristics on its properties in HDPE thermal fusion welding[J]. Modern Physics Letters B, 2017, 31(15): 1750185.
[31] Sun Y, Jia Y F, Haroon M, et al. Welding residual stress in HDPE pipes: measurement and numerical simulation[J]. Journal of Pressure Vessel Technology, 2019, 141(4): 041404.
[32] Kwon H. J., Jar P. Y. B. On the application of FEM to deformation of high-density polyethylene[J]. International Journal of Solids and Structures, 2008, 45(11-12): 3521-3543.