Study on CTOA evolutions during dynamic crack propagation of pipelines

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Abstract

:Crack Tip Opening Angle (CTOA) is considered and has been attempted to be used as a fracture parameter to describe the crack arrest toughness of ductile steel gas pipelines. However, its evolution and influencing factors during pipeline dynamic crack propagation are still unclear, and its use as a crack arrest toughness parameter similar to the Charpy impact toughness also lacks theoretical support. In view of the above problems, this paper reproduces the full-scale test with the help of the numerical simulation method for pipeline dynamic crack propagation. Comparing the numerical simulation results with the experimental ones, it is proved that the numerical model is reliable in studying the pipeline CTOA evolutions. On this basis, this paper systematically studies the evolution laws of CTOA in the process of dynamic crack propagation and arrest for natural gas pipelines, and clarifies the effects of the following factors on CTOA values, including the design factor, geometric dimensions, inertia backfill effect and material property of pipeline steel, et al. The results show that the critical CTOA (CTOA $_{C}$) of a pipeline is independent of the design factor, the pressure decompression, and the large change in the crack velocity, and is also not sensitive to the pipe strength, pipe wall thickness, and the inertial effect of soil, but only related to the pipe diameter and pipe toughness. The above conclusions show that it is reasonable to use CTOA as the crack arrest toughness parameter and has laid a foundation for the subsequent establishment of the crack arrest control method for natural pipelines based on CTOA $_{C}$.

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Abstract: Crack Tip Opening Angle (CTOA) is considered and has been attempted to be used as a fracture parameter to describe the crack arrest toughness of ductile steel gas pipelines. However, its evolution and influencing factors during pipeline dynamic crack propagation are still unclear, and its use as a crack arrest toughness parameter similar to the Charpy impact toughness also lacks theoretical support. In view of the above problems, this paper reproduces the full-scale test with the help of the numerical simulation method for pipeline dynamic crack propagation. Comparing the numerical simulation results with the experimental ones, it is proved that the numerical model is reliable in studying the pipeline CTOA evolutions. On this basis, this paper systematically studies the evolution laws of CTOA in the process of dynamic crack propagation and arrest for natural gas pipelines, and clarifies the effects of the following factors on CTOA values, including the design factor, geometric dimensions, inertia backfill effect and material property of

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Keywords: crack tip opening angle (CTOA), natural gas pipeline, arrest toughness, ductile fracture

Nomenclature	**Nomenclature**		
BTCM	Battelle two-curve model	P_0	initial pressure, MPa
CTOA	Crack Tip Opening Angle, °	Pa	pressure at the current crack tip, MPa
$CTOA_C$	critical CTOA, °	q_1, q_2, q_3	material damage parameters
D	pipe diameter, mm	S_N	standard deviation
DF	design factor	t	the wall thickness of the pipe, mm
DWTT	Drop Weight Tear Test	μ	Poisson ratio
E	Young's modulus, GPa	x	the distance between the key point used for CTC
f_0	initial void volume fraction		
f_C	critical void volume fraction	ϵ_N	average equivalent plastic strain
f_F	void volume fraction at failure	σ_ψ	yield stress, MPa
f_N	nucleation phase particle volume fraction	Δa	propagation length of the crack, mm
GTN	Gurson-Tvergaard-Needelman	ρ	density, kg/m^3

1. Introduction

As the second line of defense to prevent catastrophic accidents of pipeline ductile fracture[1], crack arrest control is of great significance to ensure the safe transmission of energy. Battelle two-curve model (BTCM) which is based on Charpy impact toughness is the most representative and industrialized technology for fracture control of pipelines[2]. However, the original BTCM does not apply to X70 and the above high-toughness pipeline steel. Although a series of correction models[3, 4] appeared subsequently, the deviation of BTCM when it is used for high-grade pipeline steel is not fundamentally solved.

The essential reason for the limitation of BTCM is that the Charpy impact specimen is small, and the predicted Charpy absorbed energy mainly represents the resistance to plastic deformation rather than crack propagation[5]. Pre-crack DWTT(Drop Weight Tear Test) absorbed energy has been proposed as a better indicator to express resistance to fracture propagation, as the similar fracture morphology of running ductile fracture in pipeline and DWTT is observed and the thickness of DWTT is equal to the pipe thickness[6]. However, DWTT absorbed energy includes the energy for crack initiation, the plastic deformation and the movement of specimens. Therefore, it is not universally recognized that it is included in the traditional model as crack arrest toughness[7]. With the upgrading of pipeline steel grade, the crack arrest toughness predicted by the crack arrest control method based on Charpy impact toughness or DWTT energy becomes more and more uncertain.

A variety of laboratory tests show that the Crack Tip Opening Angle (CTOA) always maintains a constant value during the crack propagation of pipe steel specimens, indicating that it is only related to the stable crack propagation stage, and is expected to overcome the fundamental defects of Charpy impact toughness and DWTT energy[8]. In order to fully demonstrate the feasibility of CTOA characterizing the ductile fracture arrest toughness of natural gas pipelines, researchers made several attempts to measure CTOA in high-pressure natural gas pipeline burst tests in the 1980s and 1990s[9-11]. However, the test results are not ideal, and the experimental data of CTOA is highly dispersive, which may be related to the low accuracy of the measuring instruments at that time. Subsequent researchers have designed different laboratory specimens

with different geometries, sizes, and loading modes for CTOA tests[12-14], so that they have similar constraints and plastic zones with pipelines as much as possible. Although some useful conclusions have been obtained, it is not clear whether there are relevant laws in CTOA for high-pressure natural gas pipeline.

In 2018, Shibanuma et al. [15] of Tokyo University carried out a full gas burst test using STPG 370 steel pipe and recorded the entire test process with a high-speed camera. The test proved for the first time that the CTOA value remains constant during crack propagation in the pipeline despite the large changes in the crack velocity, which provides strong proof that CTOA can be used as the pipeline fracture criterion. Compared with full-scale burst tests, the finite element numerical simulation is more convenient for systematically studying the effect of different factors on CTOA evolutions of pipelines. Shibanuma et al. studied the CTOA values under various conditions using the simulation method based on the local fracture strain criterion. The results showed that the $CTOA_C$ depends only on the pipe diameter, and is nearly independent of the crack velocity, initial pressure, pipe strength, and ratio of diameter to thickness. However, this simulation method fails to reproduce the phenomenon that CTOA remained constant during stable crack propagation. Xue et al.[16] found that CTOA depends on the pipe geometry based on their numerical research, especially the pipe diameter. But in their simulation, CTOA also did not reach a steady state. Although this reference[16] suggests that the crack propagation will reach a stable state after the crack length exceeds four pipe diameters, the CTOA values of the platform are unrealistic (30°~50°). Zhu et al.[17]used CZM to simulate the evolution process of CTOA during crack propagation of buried pipeline and found that the $CTOA_C$increases with the increase of internal pressure, which is inconsistent with Shibanuma's conclusion. Bassindale et al.[18]proved that CTOA has nothing to do with the inertia effect caused by soil backfilling through the simulation of crack propagation in large plates, but the crack velocity range studied is far less than that of the pipeline, so it is not clear whether pipeline CTOA has the same conclusion.

To sum up, although a test proving that CTOA remained constant during the stable crack propagation of a pipeline, it is unclear whether this conclusion is broad. Researchers have carried out some research on influencing factors of pipeline CTOA with numerical simulation methods, but there are still some problems. On one hand, the existing numerical simulation methods are difficult to obtain a steady state of CTOA evolutions; on the other hand, the influencing factors studied are not comprehensive even some studies have come to the opposite conclusions. In view of the above problems, this paper reproduced the constant CTOA in the full-scale burst test carried out by Shibanuma with the help of the numerical simulation method proposed by the author earlier. On this basis, the evolutions of CTOA during the dynamic crack propagation and arrest of natural gas pipelines were systematically studied, and the effects of design factors, pipeline geometric dimensions, backfilling effects, pipe properties, and other factors were clarified, which provided more supports for characterizing the pipeline fracture toughness with CTOA.

2. The simulation of pipeline CTOA

2.1 Simulation method of dynamic crack propagation in natural gas pipeline

In the author's previous work, a simulation method for dynamic crack propagation in natural gas pipelines with the real-time prediction of crack tip position was proposed[19, 20]. In this method, the dynamic crack propagation of pipelines was achieved by element deletion with the Gurson-Tvergaard-Needleman (GTN) model, the decompression behavior of natural gas after the pipeline cracking was described by the gas decompression model which was fitted based on full-scale burst test data. An iterative loading method incorporating real-time prediction of crack tip position was proposed to realize the interaction between crack propagation and gas decompression. It was verified by the pipeline burst test that the proposed simulation method can approximately realize the multi-field coupling of gas decompression, pipeline deformation, and crack propagation. The simulated fracture parameters and pipeline deformation were in good agreement with the experimental results. Since the CTOA data are not collected in the mentioned test for the simulation verification, it was impossible to prove whether the evolution law of CTOA can be accurately described.

Therefore, this simulation method was used to reproduce the full gas burst test carried out by Shibanuma, and the simulation results should be systematically compared with the experimental results to prove its ability for studying the CTOA evolutions and their influencing factors.

The test[15] was conducted as a full gas burst test using a single pipe with a total length of 5, 000 mm. The diameter and the wall thickness of the pipe were 356 mm and 9.5 mm, respectively. The grade of the tested pipes was classified as STPG370 with a yield strength of 344 MPa and a tensile strength of 540 MPa. The true stress-strain curve of the pipe steel is shown in Fig. 1. In the test, pure nitrogen (N_2) was used as the internal blasting gas, and an axial surface notch with a length of 300 mm was processed in the center of the pipe through a linear shaped charge cutter. Under the drive of internal pressure, the crack started from the surface notch and expands to both sides.

The finite element model established according to the real test pipeline was meshed by elements of C3D8R. Along the crack propagation path, element sizes of 0.5 mm and 0.25 mm were employed in the axial and circumferential direction considering the grid dependence. The transitional grid technology was used to realize the gradual decrease of the element size along the axial and circumferential directions. Finally, 410, 744 elements and 502, 049 nodes were generated. Fig. 2 shows the FE mesh used in the present effort. The Young's modulus, Poisson's ratio, and density of the material were set as $E = 206.04$ GPa, $\mu = 0.3$ and $\rho = 7860$ kg/m^3, respectively. As the GTN parameters of STPG 370 pipe steel were not provided in that literature, they were determined by trial calculations. It was found that when the values of the damage parameters were set as shown in Table 1, the simulation results were most consistent with experimental ones. The pipeline was loaded by the iterative loading method[21], which incorporated the real-time prediction of the crack tip position, combined with the two-dimensional exponential gas decompression model. The initial pressure $P_0$was set as 16.5 MPa, which did not remain constant during the loading history, but exponentially reduced according to the pressure transducer data recorded during the burst test.

2.2 Comparison of simulation and experimental results

The simulation and experimental results of crack tip position and crack velocity are shown in Fig. 3. It shows a slight difference in simulation and experimental crack tip position as a function of time. The simulation results are a little bigger than the experimental data throughout the crack propagation and the maximum error is less than 10%. In terms of crack velocity, the results show downward trends as loading time increases which means the pipeline cracks tend to arrest. The maximum crack velocities obtained from the simulation and test are both about 200 m/s.

The definition of CTOA in a pipeline is illustrated in Fig. 4, where$x = 5$ mm[19]. The simulation and experimental CTOA evolutions for the pipeline are shown in Fig. 5. As the high-speed camera failed to effectively record the blunt phenomenon in the initiation stage of crack, the CTOA history obtained from the test was in the stable stage. In the later stage of the test, the CTOA appear an upward trend as the crack was close to the restraint end and the pipe was bent. The numerical simulation can capture the evolution of CTOA in the process of full crack propagation, which consists of an initially high CTOA region that transitions into a constant CTOA region soon after cracking. The critical CTOA ($CTOA_C$) is defined as the average value during stable crack propagation. The $CTOA_C$obtained from the test and simulation is 13.2° and 12.39° respectively, and the difference between them is only 6.1%.

To sum up, the good correspondence between the numerical and experimental crack tip position, crack velocity profiles and CTOA evolutions indicates that the simulation method used in this paper can effectively reflect the fracture behavior of the real cracked pipeline.

3. Analysis of influencing factors on pipeline CTOA evolutions

In this part, the effects of design factors, pipeline geometric dimensions, backfilling effects, pipe properties, and other factors on the evolutions of CTOA during pipeline crack propagation were systematically studied by the numerical simulation technology verified above.

3.1 Effects of design factor

As mentioned above, the current research conclusions about whether the applied internal pressure (i.e. pipeline design factor (DF)) has an effect on the pipeline CTOA are inconsistent. In order to reveal its effect, the CTOA evolutions of the X80 pipeline with a diameter of$D = 1422$ mm and wall thickness of $t = 27.7$ mm were studied when the design factors were 0.8, 0.72, 0.56, and 0.43, respectively. The detailed setting of the numerical model of the cracked pipeline, including the meshing, boundary conditions, and model validation were all published in the previous work. The specific calculation conditions are listed in Table 2, in which the GTN parameters used are provided in Section 3.4.

The evolution histories of CTOA for the X80 pipeline with different design factors are shown in Fig. 6, where P a refers to the pressure at the crack tip. It can be seen that all the CTOA-*[?]a*curves enter into stable states when the crack length reaches $0.2D$, except for the condition for DF = 0.43. At the same time, CTOA always remains constant even though the pressure at the crack tip decreases linearly. It also can be seen that when DF changes from 0.8 to 0.43, the pipeline $\mathrm{CTOA_C}$ only changed from 10.13deg to 9.49deg, which can be approximately considered unchanged. Therefore, $\mathrm{CTOA_C}$ can be considered independent of design factors and the change of crack tip load.

Fig. 7 shows the relationship between crack velocity and CTOA after pipeline cracking. Combined with Fig. 6, it can be seen that for the condition with a certain design factor, as the crack tip pressure decreases in a nearly linear manner, the crack velocity also decreases gradually while the corresponding CTOA always remains constant. For the conditions with different design factors, it is clear that the higher the design factor is, the greater the maximum crack velocity is, and the slower the crack velocity decreases. The values of $\mathrm{CTOA_C}$change little even though the maximum value and decline of crack velocity are different. Therefore, it can be concluded that pipeline $\mathrm{CTOA_C}$ is independent of the crack velocity, which is consistent with the conclusion obtained from the full-scale pipeline burst test conducted by Shibanuma[15].

3.2 Effects of pipeline geometric dimensions

The relevant tests and research of small-size laboratory specimens show that the experimental $\mathrm{CTOA_C}$ is significantly affected by the in-plane and out-of-plane constraints[22, 23]. However, it is unknown whether there are similar results for pipelines. This paper takes the model numbered T1-T3 in Table 3 as examples to explore the effect of wall thickness on the CTOA evolutions for the X80 pipeline. For the models studied, all the design factors are 0.72 and the outer diameters are 1422 mm with different diameter-thickness ratios of 51.3, 66.4, and 103, respectively.

Fig. 8 shows the effect of pipeline thickness on CTOA-*[?]a* curves. It can be seen that $\mathrm{CTOA_C}$ has only changed 0.45deg while the pipeline thickness changes by two times. This conclusion is not the same as that of the laboratory specimens, which indicates that the thickness is not the main factor affecting the constraint effect of a pipeline.

Shibanuma's research[15] shows that the pipe diameter has a certain effect on CTOA. In order to get more extensive conclusions, this paper takes X80 pipelines with a design factor of 0.72 and a diameter thickness ratio of 66.4 as examples to study the effect of pipe diameter on CTOA evolutions when the diameter changes from 1422 mm to 219 mm. The specific calculation conditions are shown in Table 4.

The effect of pipe diameter on CTOA evolutions is shown in Fig. 9. It can be seen that when D [?] 660 mm, the change of diameter has little effect on $\mathrm{CTOA_C}$. When the pipe diameter decreases further, the

$CTOA_C$ increases with the decrease of pipe diameter. It indicates that there is a critical value for the pipe diameter: when the diameter reaches the critical value, the pipe constraint will also reach the critical state, which will not change with the further increase of the diameter. When the pipe diameter is less than the critical value, the pipe constraint level will decrease with the decrease in the diameter. Therefore, it can be simply considered that $CTOA_C$ is independent of the diameter for large-diameter pipelines. This is not consistent with Shibanuma's conclusion[15], which may be because his conclusion comes from the study of the relationship between $CTOA_C$and fracture strain, rather than the direct study of the effect of diameter on $CTOA_C$.

3.3 Effects of the inertia backfill effect

The inertia effect brought by soil backfilling has a significant effect on the dynamic fracture behavior of pipelines. Bassindale[18] first assessed the effect of inertia on $CTOA_C$ by altering the density of the material used with the tensile plate model and found inertia has no significant effect on the measured CTOA. However, the maximum velocity in the tensile plate is ˜20 m/s, which is far less than those measured in pipe fractures (˜300-400 m/s). Therefore, it is not clear whether the conclusion applies to the pipeline.

According to the method used by Bassindale[18], the movement resistance was increased by scaling the material density in this paper to study the inertia effect on pipeline $CTOA_C$. The X80 pipeline with a diameter of $D = 1422$ mm and wall thickness of $t = 27.7$ mm was used. The design factor was set as 0.72, and the density of pipe steel was set as 7850 kg/m^3(ρ), 11790 kg/m^3 (1.5ρ), and 15, 720 kg/m^3 (2 ρ). The specific calculation conditions are listed in Table 5. The effect of inertia on pipeline CTOA evolutions is shown in Fig. 10. It can be seen that $CTOA_C$ has only changed 0.18° though the pipe material density changes by two times. Therefore, it leads to a conclution that the inertia effect brought by soil backfilling does not affect the fracture toughness of materials.

3.4 Effects of the material property

To study the effect of the strength grade of pipe steel on pipeline CTOA evolutions, X100, X80, and X65 pipelines with a diameter of 1422 mm and thickness of 27.7 mm were selected to analyze the pipeline fracture behavior. The corresponding true stress-strain curves for the three pipeline steel are shown in Fig. 11. Different internal pressures were applied to each model to ensure that the design factor of each pipe was 0.72. The corresponding calculation conditions are listed in Table 6.

The effect of the strength grade of pipe steel on CTOA evolutions is shown in Fig. 12. It can be seen that the corresponding $CTOA_C$ of X100, X80, and X65 pipeline steels are 10.22°, 10.06°, and 10.58°, respectively. The three values are very close with a maximum difference of 0.52°. Therefore, it can be concluded that pipeline $CTOA_C$ is independent of the strength grade of pipe steel.

The research conclusions in the previous paper show that pipeline $CTOA_C$ is independent of the design factor and crack velocity. For large-diameter pipelines, the $CTOA_C$ is not affected by geometry sizes as the pipe wall thickness and diameter, and it is not sensitive to the inertial backfill effect and material strength. Shibanuma's research[15] shows that the $CTOA_C$ is closely related to the material fracture strain, and there is a one-to-one correspondence between them. In this paper, the GTN model was used to describe the mechanical behavior of pipeline steel, which was equivalent to the fracture strain and the toughness of a material. Therefore, the effect of material toughness on pipeline CTOA was studied by adjusting different sets of GTN parameters.

In this section, the GTN parameters (set 1) of X80 pipe steel calibrated in the previous work were taken as reference, and the other three sets of GTN parameters were selected and studied as listed in Table 7. The dynamic crack propagation of pipelines with a diameter of 1422 mm and thickness of 27.7 mm was simulated using the above four sets of GTN parameters in combination with the X80 stress-strain curve. The obtained $CTOA_C$ values for different damage parameters are 10.26°, 8.24°, 6.57°, and 4.36° as shown in Fig. 13, which

demonstrates that GTN parameters, that is, the material toughness, have a significant effect on the pipeline CTOA.

4. Conclusions

To clarify the CTOA evolution and its influencing factors during the dynamic crack propagation for pipelines, this paper conducts a systematic study with the help of numerical simulation technology verified by experiments. The conclusions are drawn as follows:

1. The numerical simulation method used in this paper can effectively reflect the dynamic fracture behavior of the natural gas pipeline, the obtained crack tip position, crack velocity, and $CTOA_C$are verified by a full-scale pipeline burst test. For all cases, the pipeline CTOA evolution consists of an initially high CTOA region that transitions into a steady state soon after cracking.
2. Pipeline $CTOA_C$ is independent of the design factor, the pressure decompression, and the large change of crack velocity, and is also not sensitive to the pipe strength, pipe wall thickness, and the inertial effect of soil, but only related to the pipe diameter and pipe toughness. Moreover, the change in diameter does not affect its value when the pipe constraint reaches the critical state.
3. For large-diameter pipelines, pipeline $CTOA_C$ can be regarded as a material parameter only related to toughness, which lays a theoretical foundation for guiding the crack arrest design of natural gas pipelines.

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