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COMPARATIVE ANALYSIS: FRACTURE TOUGHNESS DEMANDS OF X80 PIPELINE GIRTH WELD UNDER DIFFERENT DESIGN CRITERIA

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Abstract. *Fracture control of girth welds of large-diameter high-grade steel pipes has gradually become research priority with the commissioning of the China-Russia Eastern Gas Pipeline and girth weld fracture accidents occurred in recent years. In this paper, taking the D1219mm with single V-shaped groove and D1422mm with Double V-shaped groove as the research objects, the parametrical 3D numerical models for X80 pipe considering the discontinuous geometric structure and nonlinear material properties were established. Through parallel simulation, the fracture toughness demands of X80 pipe girth weld under different conditions were determined by the 0.9 times minimum yield strength criterion based on stress and the 0.5% strain requirement criterion based on strain, respectively. Research revealed that the fracture toughness demands requirement decreases with the increase of base material' yielding-to-tensile ratio, weld strength matching coefficient and wall thickness. Based on the results, fracture toughness demands of large-diameter X80 pipe were listed, which provide guidance for welding material selection and welding parameter design of large-diameter high-grade steel pipelines.*

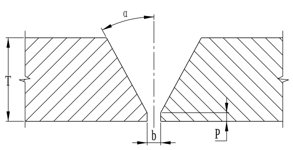
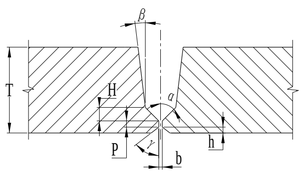
1 INTRODUCTION

The presence of numerous factors affecting the deformation bearing capacity of the pipe girth weld makes the weld a weak link in the pipe [1-7]. Pipeline welding process may appear porous, slag, not weld through, cracking, misalignment and other defects, while the material variability near the girth weld is large, including filler welding, heat-affected zone, root welding, base material and other areas where there are significant differences in material properties [8, 9]. The double discontinuity in the geometry and material of the girth weld easily lead to the formation of stress concentrations at the location of the weld defects, thus reducing the deformation bearing capacity of the girth weld [10]. In order to ensure the safe and smooth operation of pipelines, the risk control of crack expansion stop cracking of high-grade steel pipeline girth welds has gradually become the focus of research, and the determination of girth weld fracture toughness demands has become a key technology to ensure the safety of pipelines. High-grade steel pipeline girth weld fracture failure criterion is the premise and basis of the girth weld evaluation, the root cause of pipeline girth weld fracture failure is the girth weld crack expansion driving force is greater than the apparent fracture toughness of the girth weld. Material fracture toughness characterizes the ability of a material to prevent crack expansion and is a quantitative indicator of how good the toughness of a material is.

Foreign standards have given methods for evaluating the suitability of pipes containing crack defects, among which the failure assessment chart method recommended by BS 7910-2013 [11] and API 579-2007 [12] is the most widely used. Due to the multiple discontinuities in the geometry as well as the material of the girth weld, some existing semi-empirical formulas annot accurately calculate the stresses at the crack surface, which can easily lead to inaccurate results of the applicability evaluation of stress-based failure assessment charts. The Chinese evaluation standards GB/T 19624-2004 [13] and SY/T 6477-2014 [14] for the suitability of oil and gas pipelines containing cracks adopt the evaluation method of API 579-2007 [12], and these evaluation standards fail to accurately consider the effects of weld strength matching and heat-affected zone softening characteristics on the crack expansion driving force of structures containing cracks. In recent years, related scholars at home and abroad [15-20] have conducted a lot of research on fracture assessment of pipelines containing cracks, providing a reference for the safety evaluation of pipelines containing cracked girth weld joints based on fracture mechanics; however, none of these methods are applicable to the fracture of weld cracks at the single V-shaped groove of 1219mm X80 pipeline and double V-shaped groove of 1422mm X80 pipeline.

Therefore, this paper will be based on the nonlinear finite element platform ABAQUS to build a numerical simulation model to consider the complete geometry of the welded joint, a variety of material partitioning cracked high-grade pipe girth weld fracture toughness demands, respectively, based on the stress of 0.9 times minimum yield strength criterion, based on the 0.5% strain requirement criterion to determine different pipe diameter, different groove type, wall thickness, base material yielding-to-tensile ratio, weld The fracture toughness demands of X80 pipe girth weld under different pipe diameters, different groove types, wall thicknesses, base material flexural strength ratios, and strength matching coefficients are determined to provide guidance for the selection of welding consumables and girth weld design in engineering practice.

Table 1: Single v-shaped groove type.

Welding method	Groove form diagram	Detailed parameters
STT/RMD /SMAW+Single welding torch flux-cored wire automatic welding process (FCAW-G)		Joint type: butt joint Groove type: Single V-shaped groove Back cushion: No back cushion Angle of groove: α=22°~25° Blunt edge (P): 1.6±0.4mm End clearance (b): 2.5~4.0mm Misalignment: ≤2.5mm, locally not more than 3.0mm in length≤50mm Reinforcement: Suitable for 0~2.0mm, locally not more than 3.0mm in length≤50mm Surface run weld width: 0.5~2.0mm widening on each side of the groove
Internal welding machine + double torch solid wire welding process (GMAW)		Joint type: butt joint Groove type: Double V-shaped groove Back cushion: No back cushion Angle of groove: β=5°±1.5°, α=45°±1.5°, γ=37.5°±1.5° Blunt edge (P): 1.3±0.3mm Height from blunt edge to variable groove inflection point (H): 2.3±0.3mm Inner groove height (h): 1.7±0.3mm End clearance (b): 0~0.5mm Misalignment: ≤2.5mm, locally not more than 3.0mm in length≤50mm Reinforcement: Suitable for 0~2.0mm, locally not more than 3.0mm in length≤50mm Surface run weld width: 0.5~2.0mm widening on each side of the groove

2 NUMERICAL MODEL OF FRACTURE TOUGHNESS DEMANDS

2.1 Geometric groove form and crack simulation

For X80 steel pipes under D1219mm and D1422mm, single V-shaped groove semi-automatic welding and manual welding method and double V-shaped groove fully automatic welding method are adopted respectively, and the groove forms and dimensional parameters of single V-shaped groove and double V-shaped groove are shown in Tbl.1.

According to a certain diameter 1219mm, wall thickness 18.4mm FCAW process welding single V-shaped groove metallurgical diagram to determine the structural dimensions of the girth weld, for a conservative point of view, considering the existence of the design of the structure allows the maximum misalignment of 3mm [21], considering the existence of the girth weld at the base material (BM), heat-affected zone (HAZ), root-welded material (RW), welding material (WM) and other four material characteristics of the region there are certain differences, to determine the final diameter 1219mm, wall thickness of 18.4mm pipe single V-shaped groove girth weld geometry as shown in Fig.1.

Similarly combined with a certain diameter 1422mm, wall thickness 21.4mm GMAW process welding double V-shaped groove metallurgical diagram to determine the final diameter 1422mm, wall thickness 21.4mm pipe composite groove girth weld geometry chart.

The geometric forms and material area distribution schematics and finite element models of D1219mm single V-shaped groove and D1422mm double V-shaped groove for different wall thickness conditions (32.1mm, 27.5mm, 22.0mm, 21.4mm, 18.4mm) were determined respectively (Fig.1).

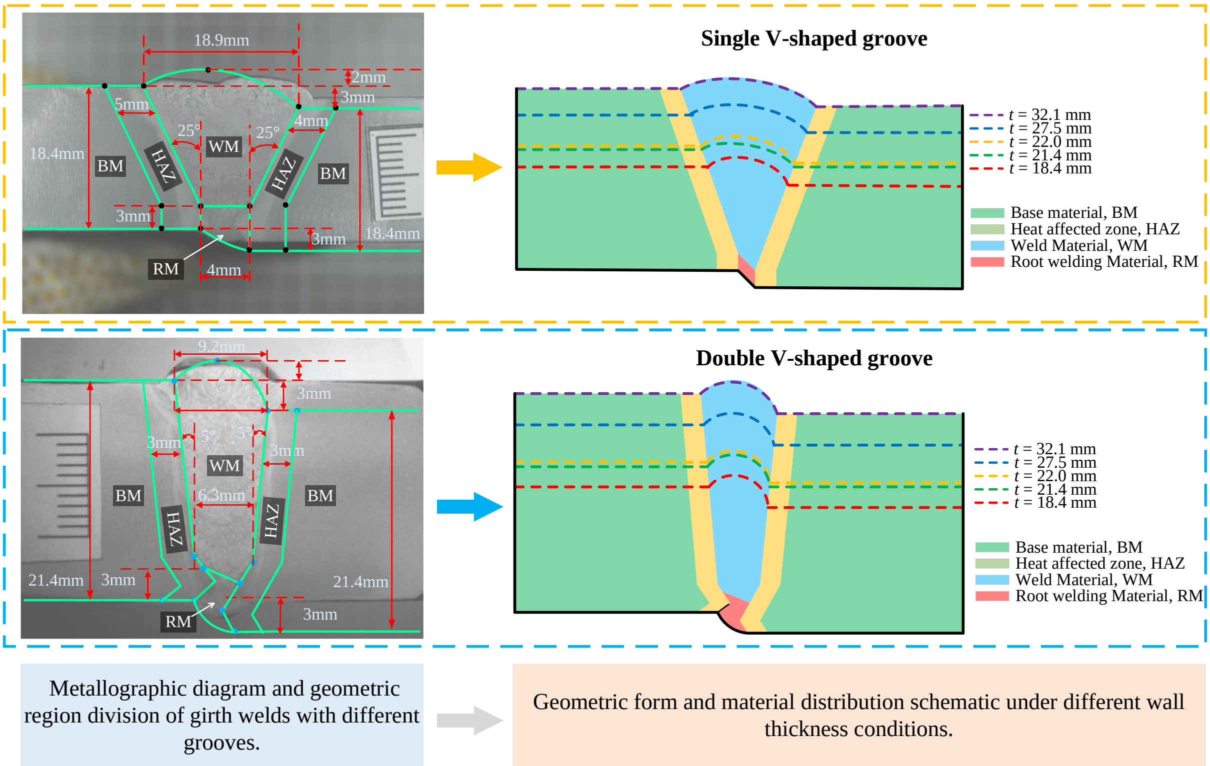
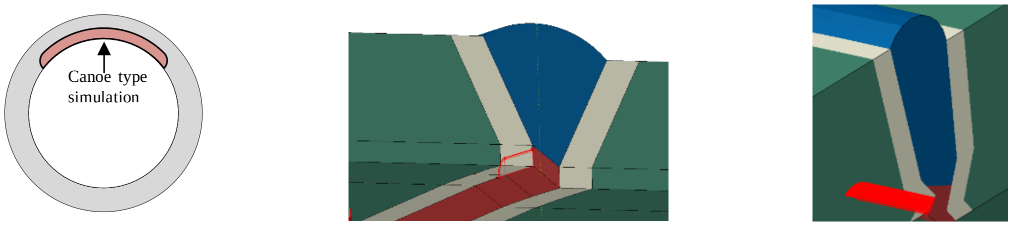


Figure 1: Metallographic region division and finite element model geometry of different groove.

In D1422mm and D1219mm fracture toughness numerical simulation model, are considered root-welded zone and heat-affected zone junction location exists a surface crack type defects (Fig.2). According to the accuracy of nondestructive testing and different welding processes to obtain the actual shape of the welded joint, determine the D1422mm finite element model crack size of 25mm × 2mm (length × depth), D1219mm finite element model crack size of 25mm × 2.5mm (length × depth) [1].

The DNV OS F101 standard [22] suggests that damage models and static cracking simulation methods can be used, and this paper uses the static cracking method to simulate the presence of crack-type defects at the girth weld. This method of calculating crack propagation based on static cracking is used by many standard codes and research institutes. The first is to consider the crack as a semi-elliptical defect, and the other is to consider the crack combination as a canoe type (Fig.2). Some research showed that the Canoe type simulation method is closer to the real situation in engineering. Therefore, this paper adopts the Canoe type method to simulate cracks. According to Appendix B of API 579 [12], the "Key Hole" modeling method is used to describe the process of crack tip passivation [23].



(a) Canoe type crack. (b) D1219mm FEM. (c) D1422mm FEM.

Figure 2: Crack surface of the finite element model.

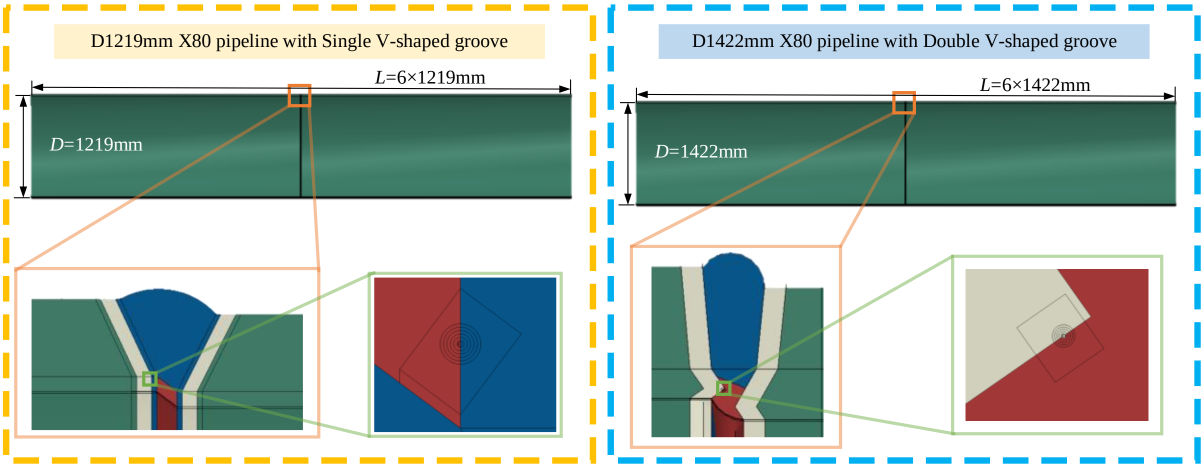


Figure 3: Finite element model of large-diameter high-grade steel pipeline with crack.

According to the finalized schematic diagram of the girth weld geometry and crack simulation form, a finite element model considering the complete geometry of the girth weld was established, and the total length of the pipe in the model was taken as 6 times the diameter to eliminate the effect of the distal boundary effect.

2.2 Constitutive relationship of different material

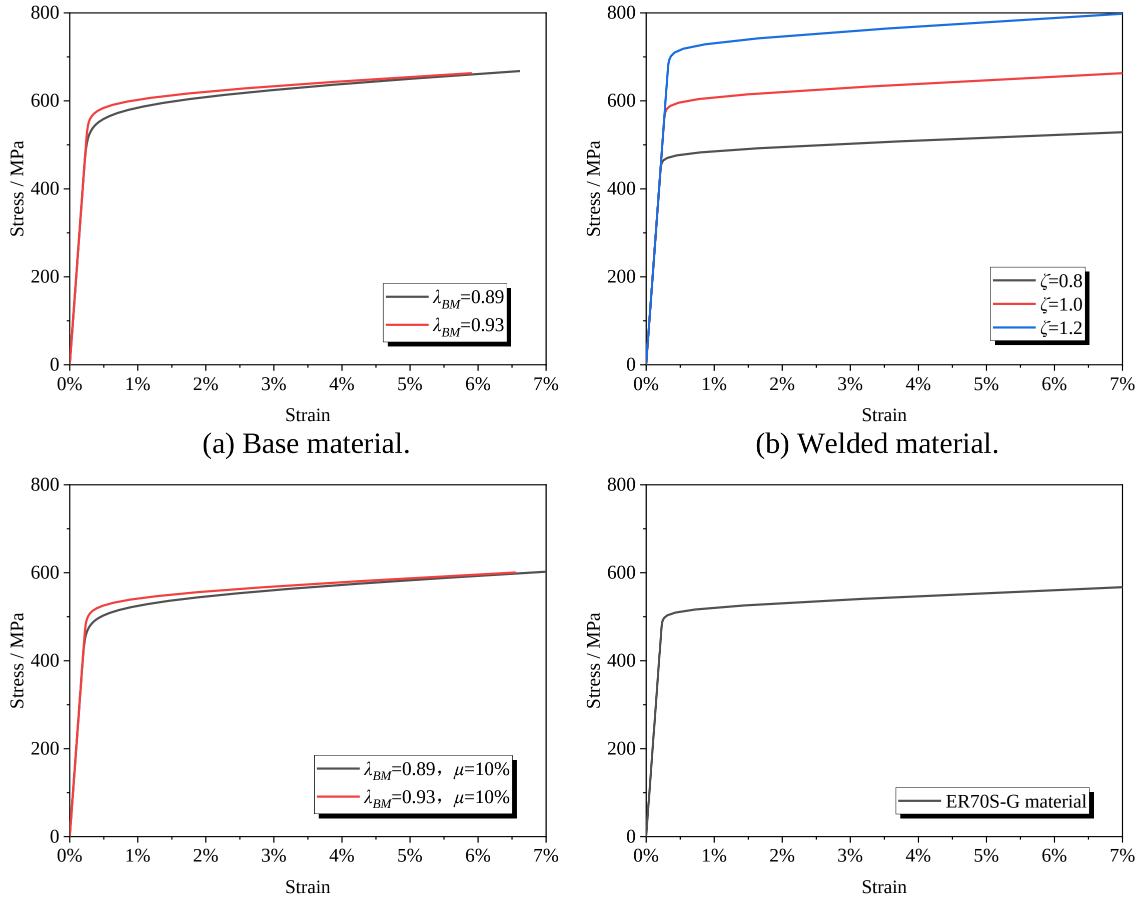
The Ramberg-Osgood equation [24] is widely used to describe the mechanical properties of pipe metals:

$$\varepsilon = \frac{\sigma}{E} + \alpha \frac{\sigma}{E} \left(\frac{\sigma}{\sigma_Y} \right)^{n-1} \tag{1}$$

Where: ε is the strain of the material; σ is the stress of the material, MPa; E is the modulus of elasticity of the material, taken as 2.1×10^5 MPa; λ is the yielding-to-tensile ratio, $\lambda = \sigma_Y/\sigma_T$;

σ_Y is the yield strength of the material, MPa; σ_T is the tensile strength of the pipeline, MPa; n is the stress hardening index of the material, n=3.14/(1-λ); α is the yield offset coefficient.

Based on the above method of determining the stress-strain curve of the base material, the stress-strain curves of the two base materials were finally obtained as shown in Fig.4 (a), considering the two cases of 625 MPa tensile strength of the base material and 0.89 and 0.93 yielding-to-tensile ratio, respectively.



(a) Base material. (b) Welded material.

(c) Heat affected zone. (d) Root-welded material.

Figure 4: The true stress-strain relationship of materials.

In the welded material, the stress-strain relationship (without yield plateau) is calculated based on CRES [25] as follows.

$$\varepsilon = \frac{\sigma}{E} + \left(0.005 - \frac{\sigma_{Y-WM}}{E}\right)\left(\frac{\sigma}{\sigma_{Y-WM}}\right)^{n_{WM}} \quad (2)$$

Where: λ_{WM} is the yielding-to-tensile ratio of welded material, λ_{WM}=0.95; n_{WM} is the stress hardening index of the welded material, n_{WM}=2.58/(1-λ_{WM})^1.17.

After the performance parameters of the base material and the stress-strain curve are determined, the tensile strength of the weld can be determined according to the strength matching. For the weld strength matching coefficient ζ, which is the strength matching of the weld to the base material based on the yield strength, it is defined as follows.

$$\xi = \frac{\sigma_{Y-WM}}{\sigma_{Y-BM}} \quad (3)$$

Where, $\sigma_{Y\text{-}BM}$ is the welded material yield strength. Then, the yield strength, yielding-to-tensile ratio and hardening index of the welding material can be determined according to the above formula, and then the stress-strain curve of the welding material (Fig.4 (b)).

For the heat affected zone, it is firstly considered that the heat-affected zone has the same hardening characteristics as the base material. Depending on the softening rate, the yield strength of the base material is directly multiplied by (1 - softening rate μ) to obtain the yield strength of the heat affected zone, while the yielding-to-tensile ratio of the heat affected zone and the base material is considered to be the same to obtain the material curve of the heat affected zone. Taking the softening rate of 10% as an example, the material stress-strain curve of heat affected zone is calculated as shown in the Fig.4 (c). The definition of softening rate is:

$$\mu = 1 - \frac{\sigma_{Y-HAZ}}{\sigma_{Y-BM}} \tag{4}$$

Where, $\sigma_{Y\text{-}HAZ}$ is the heat affected zone yield strength, $\sigma_{Y\text{-}BM}$ is the base material yield strength.

For the root-welded material, the ER70S-G material (yield strength $\sigma_{Y\text{-}RM}$=509MPa, tensile strength $\sigma_{T\text{-}RM}$=536MPa) was taken for the calculation and the same stress-strain curve equation as for the weld zone [25] was used.

2.3 Boundary conditions and finite element mesh

Considering the pipe subjected to tensile load, a one-half model is established for calculation according to the symmetry of the analytical model, symmetric constraints are applied to the symmetric XY plane of the pipe, reference points are established at the two ends of the pipe, and a kinematic coupling method is used to couple with the end faces of the pipe respectively, and the pipe is simulated to be subjected to tensile action by applying translational displacement boundary conditions to the reference points. The model contains a total of two load steps: the first step is to apply 12 MPa design internal pressure to the pipe pair and keep it constant; the second step is to apply translational simulated tensile load to the reference points.

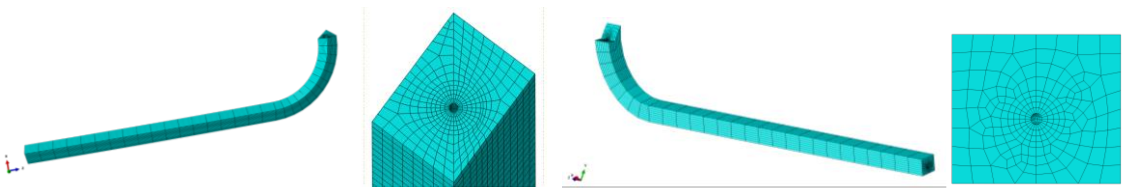


Figure 5: Meshing of the crack tip of the finite element model.

In this analysis, a static cracking method is used to simulate the crack-type defects existing at the girth weld. During the deformation of the girth weld structure by external load, a large plastic deformation is generated near the crack surface area, so the mesh near the crack tip area is locally encrypted. In order to better simulate the passivation process of the crack, the modeling method of circular hole is used in the crack tip part, and the circular hole is divided into 24 cells in the circular direction and four layers in the radial direction. This simulation method for cracks proved to be effective in simulating the passivation behavior of the crack tip during the crack opening process, so that the corresponding fracture parameters, such as J-integral and CTOD, can be accurately obtained, and the mesh of the crack tip region is shown in Fig.5.

For the other areas, a swept or structured grid is used to divide the structure, and the local area of the structure is cut and encrypted to improve the computational convergence and accuracy of the results. Both model meshes use C3D8RH cell to improve the convergence, and C3D8RH cell is usually used for calculation and analysis.

2.3 Model validation based on wide plate tensile test of pipeline girth weld

Based on the digital image correlation method, the author carried out the wide plate tensile test of the crack X80 pipeline girth weld, and the whole test process was accurately inverted by the finite element simulation. Fig.6 demonstrated the comparison of finite element results and test results of relation between crack mouth opening displacement-distal strain. On the whole, the test results are in good agreement with the finite element results, which indicates that the finite element inversion results accurately describe the fracture behavior of cracks. Therefore, it is proved that the finite element modeling and analysis method selected in this paper is accurate and reliable.

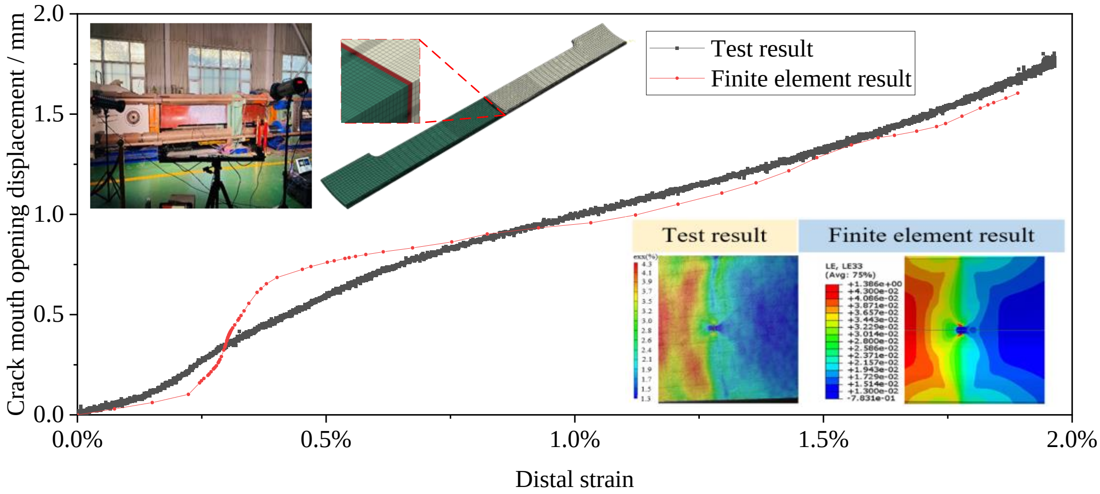


Figure 6: Comparison of numerical and experimental result of wide plate test result.

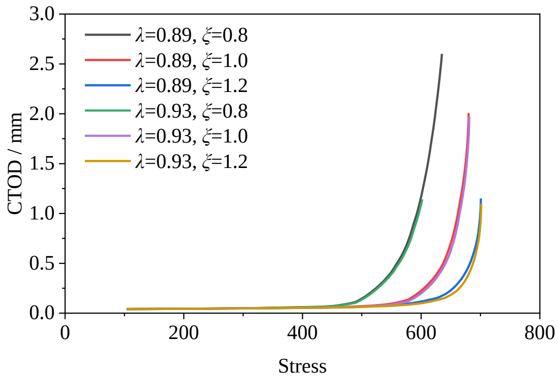
After the completion of the above-mentioned preparatory work, the wall thickness of the computational model for the fracture toughness requirement of girth weld of high steel grade pipe is constructed by changing the nonlinear finite element software ABAQUS to accurately consider the nonlinear geometric partitioning of the girth weld and material properties, and the multi-parameter combination condition parallel calculation and CTOD automatic extraction are carried out by the parametric programming language Python to determine the fracture toughness requirement of girth weld of X80 pipe under different pipe diameter, wall thickness, base material flexural strength ratio and weld strength matching coefficient conditions based on 0.9 times the minimum The fracture toughness requirement of X80 pipe girth weld under different pipe diameter, wall thickness, base material yield to strength ratio and weld strength matching coefficient is determined by 0.9 times minimum yield strength criterion based on stress and 0.5% strain requirement criterion based on strain respectively.

3 ANALYSIS OF INFLUENCING FACTORS

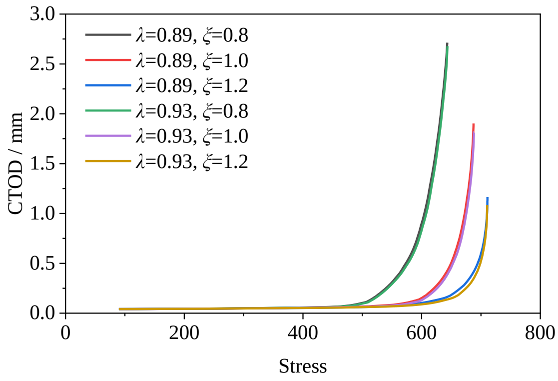
3.1 The 0.9 times minimum yield strength criterion based on stress

Take the case of 1219mm diameter single V-shaped groove containing crack X80 high steel grade pipe girth weld as an example to show the results of analysis of girth weld fracture toughness demands based on 0.9 times minimum yield strength criterion.

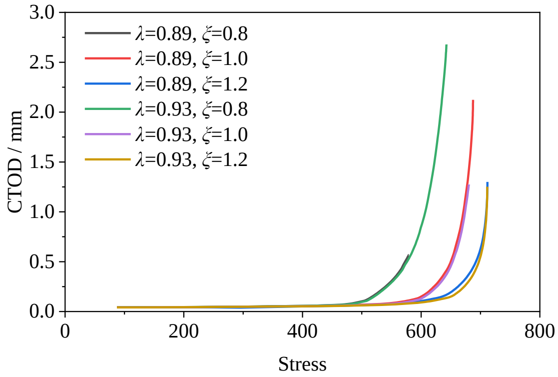
The variation curve of Crack tip opening displacement (CTOD) with axial stress for the case of 1219mm diameter pipe with wall thickness of 32.1mm, 27.5mm, 22.0mm, 21.4mm and 18.4mm single V-shaped groove respectively as shown in Fig.7.



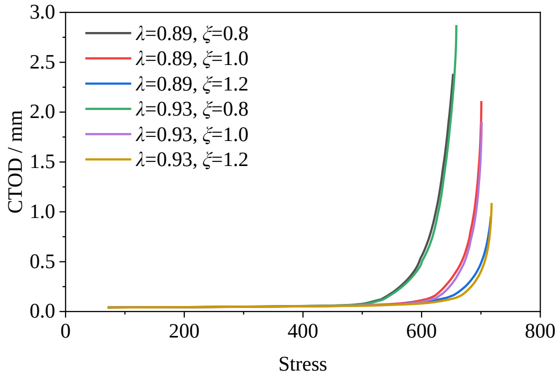
(a) *t*=18.4mm



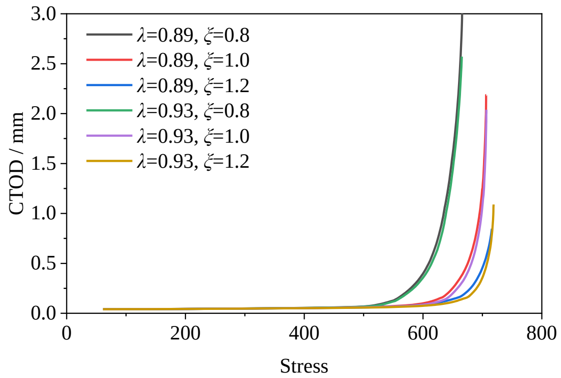
(b) *t*=21.4mm



(c) *t*=22.0mm



(d) *t*=27.5mm



(e) *t*=32.1mm

Figure 7: CTOD-stress curves of D1219mm pipe with single V-shaped groove.

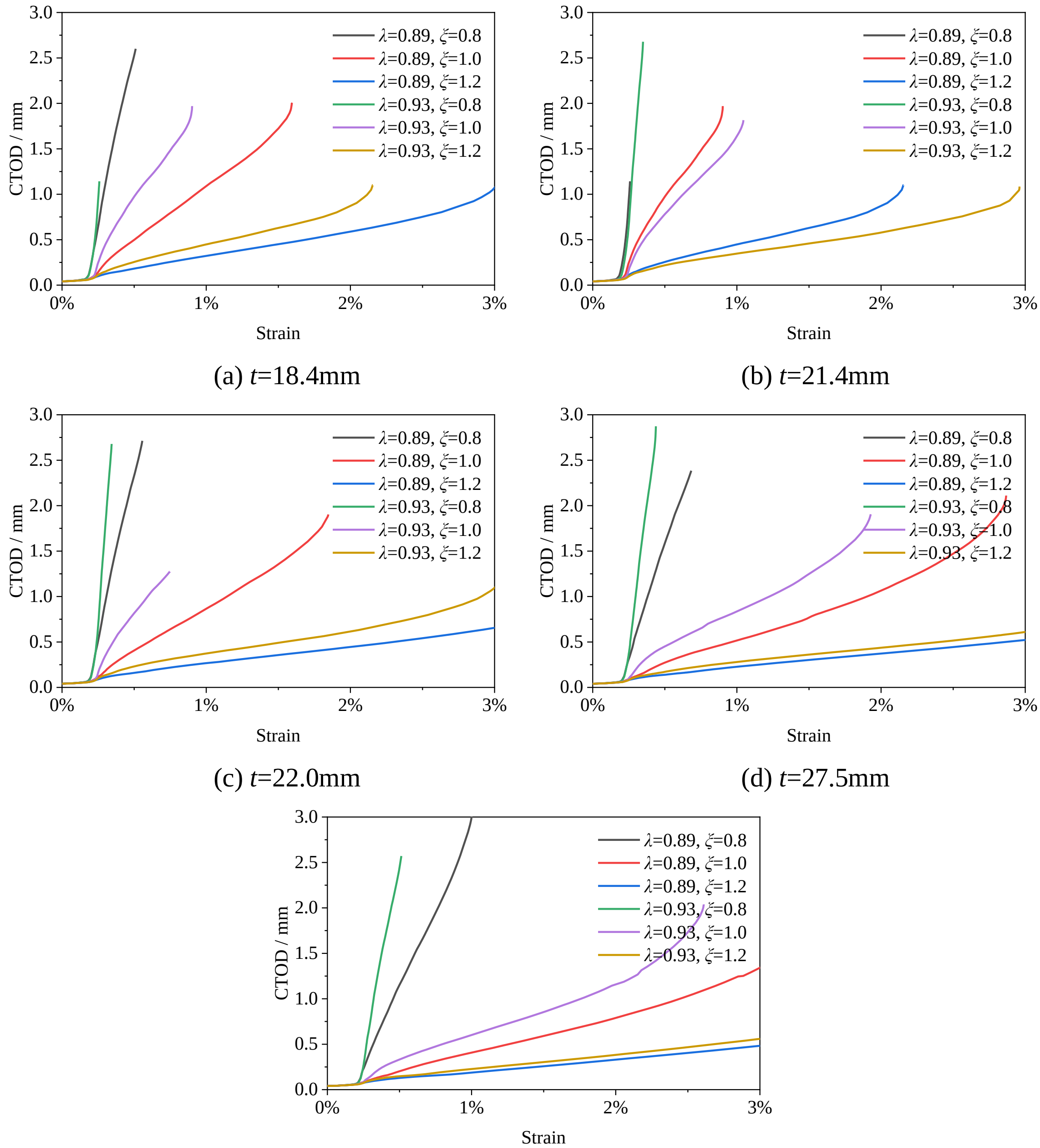
As the tensile strength of the base material is certain, so the greater the yielding-to-tensile ratio, the greater the corresponding yield strength of the base material, the greater the overall strength of the welded joint before the material enters yield, 0.9 times minimum yield strength criterion based on stress of the tube under the axial load conditions corresponding to the smaller the toughness demands. The greater the weld tensile strength matching coefficient, the greater the weld tensile strength must be, the greater the corresponding weld tensile strength, 0.9 times minimum yield strength criterion based on stress of the pipe axial load conditions corresponding to the smaller the toughness demands.

At the same time, it can be seen that the wall thickness increases, the overall reduction of the girth weld toughness demands. Based on the stress of 0.9 times minimum yield strength criterion based on stress guidelines corresponding to the toughness demands are shown in Tbl.2.

3.1 The 0.5% strain requirement criterion based on strain

The results of the analysis of the fracture toughness demands of the girth weld under strain-based 0.5% strain requirement criterion based on strain are shown for the case of a single V-shaped groove containing cracked X80 high-steel grade pipe girth weld with a diameter of 1219mm as an example.

The variation curves of Crack tip opening displacement (CTOD) with strain for the case of 1219mm diameter pipe with wall thickness of 32.1mm, 27.5mm, 22.0mm, 21.4mm and 18.4mm single V-shaped groove respectively as shown in Fig.8.



(a) t=18.4mm

(b) t=21.4mm

(c) t=22.0mm

(d) t=27.5mm

(e) t=32.1mm

Figure 8: CTOD-strain curves of D1219mm pipe with single V-shaped groove.

Table 2: Fracture toughness demands of girth welds under different combination conditions.

Wall thickness (mm)	Base material yielding-to-tensile ratio	Strength matching coefficient	CTOD toughness demands (mm)			
			Single V-shaped groove D1219 X80 pipe		Double V-shaped groove D1219 X80 pipe	
			Based on stress	Based on strain	Based on stress	Based on strain
18.4	0.89	0.8	0.1473	2.5297	0.0562	0.8897
18.4	0.89	1.0	0.0703	0.4983	0.0507	0.2546
18.4	0.89	1.2	0.0656	0.1817	0.0496	0.1765
18.4	0.93	0.8	0.1357	≥ 2	0.0528	1.6056
18.4	0.93	1.0	0.0667	0.9728	0.0498	0.5113
18.4	0.93	1.2	0.063	0.2546	0.0487	0.2683
21.4	0.89	0.8	0.1027	≥ 2	0.0503	0.6273
21.4	0.89	1.0	0.0671	0.4058	0.0497	0.1989
21.4	0.89	1.2	0.0611	0.1596	0.0492	0.1373
21.4	0.93	0.8	0.0959	≥ 2	0.0497	1.2876
21.4	0.93	1.0	0.0645	0.7818	0.0486	0.4773
21.4	0.93	1.2	0.0603	0.2182	0.0485	0.202
22.0	0.89	0.8	0.1024	≥ 2	0.0493	0.3886
22.0	0.89	1.0	0.0688	0.4058	0.0491	0.1859
22.0	0.89	1.2	0.0638	0.1664	0.0488	0.1511
22.0	0.93	0.8	0.0964	≥ 2	0.0491	1.1851
22.0	0.93	1.0	0.0655	0.8192	0.0487	0.391
22.0	0.93	1.2	0.0613	0.2309	0.0486	0.1969
27.5	0.89	0.8	0.077	1.5891	0.0487	0.2942
27.5	0.89	1.0	0.0641	0.2733	0.0486	0.2143
27.5	0.89	1.2	0.0602	0.1392	0.0485	0.1876
27.5	0.93	0.8	0.0725	≥ 2	0.0487	0.7373
27.5	0.93	1.0	0.0618	0.4618	0.0482	0.2521
27.5	0.93	1.2	0.0585	0.1757	0.0482	0.1998
32.1	0.89	0.8	0.0681	1.1537	0.0483	0.2838
32.1	0.89	1.0	0.0629	0.2020	0.0478	0.2039
32.1	0.89	1.2	0.0583	0.1282	0.0476	0.1761
32.1	0.93	0.8	0.0661	≥ 2	0.0481	0.6036
32.1	0.93	1.0	0.0601	0.3404	0.0474	0.2496
32.1	0.93	1.2	0.0570	0.1494	0.0473	0.1946

It can be seen that at strains less than 0.25%, the overall structure is mainly in the elastic phase, and the wall thickness, base material flexural strength ratio, and weld zone strength matching coefficient have less influence on the CTOD value, and the corresponding toughness demands are almost the same under the same strain conditions.

And when the strain is greater than 0.25%, the same heat-affected zone softening rate, the weld zone tensile strength matching coefficient conditions, the greater the base material flexural strength ratio, the same strain conditions the greater the crack tip opening displacement, 0.5% strain requirement criterion based on strain corresponding to the greater the toughness demands.

When the strain is greater than 0.25%, the weld tensile strength matching coefficient of 0.8, its crack extension drive increases exponentially with the increase in strain, 0.5% strain requirement criterion based on strain corresponding to the toughness demands are greater than 1.5mm; this is mainly due to the model takes into account the large misalignment, and the weld is in low matching conditions, the combined effect leads to an exponential increase in crack drive, the distal end loaded tensile deformation is almost entirely taken up by the crack surface. As the strength matching coefficient increases, the growth trend of the crack extension driving force then decreases, and the fracture toughness corresponding to the 0.5% strain requirement criterion based on strain also decreases significantly.

At the same time, it can be found that under the condition of certain material properties, the wall thickness increases and the girth weld fracture toughness requirement decreases. The toughness demands corresponding to the 0.5% strain requirement criterion based on strain based on strain are shown in Tbl.2.

4 CONCLUSION

(1) The 0.9 times minimum yield strength criterion based on stress, strain-based 0.5% strain requirement criterion based on strain under the conditions containing crack X80 high steel grade pipe girth weld fracture toughness demands are with the base material yielding-to-tensile ratio increases, weld strength matching coefficient increases, wall thickness increases and decreases.

(2) D1219mm single V-shaped groove with crack X80 high steel grade pipe girth weld (Case 1), the fusion line (i.e., crack location) and pipe axial (i.e., loading direction) is not 90 ° distribution, cracking form I (open type), fracture toughness demands are less than 0.15mm; D1422mm double V-shaped groove with crack X80 high steel grade pipe girth weld (Case 2), due to the composite groove The fusion line position has a certain angle, crack defects and pipe axial (i.e., loading direction) is not 90 ° distribution, belong to I (open type)-II (slip open type) mixed cracking; under the same load conditions, compared to the I (open type) cracking case, mixed cracking crack tip opening displacement is smaller, fracture toughness demands are less than 0.06mm, significantly smaller than the diameter of 1219mm single V-shaped groove containing cracks X80 high steel grade pipe girth weld case.

(3) The 0.5% strain requirement criterion based on strain, when the base material yielding-to-tensile ratio of 0.93, weld strength matching coefficient of 0.8 conditions, Case1's fracture toughness demands are greater than 2mm, Case2's fracture toughness demands are less than 1.7mm. engineering, in the case of difficult to improve the girth weld fracture toughness demands, to avoid the weld in the low match is an effective way to ensure the strain capacity of the weld.

(4) Based on the derived results, fracture toughness demands of large-diameter X80 pipeline were listed (Tbl.2), which provide guidance for the welding material selection and welding parameter design of large-diameter high-grade steel pipeline.

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