The effect of thickness and crack geometry on material fracture toughness of high-toughness pipeline steels

Huiru Dong[1,2)], Wanlin Guo[1,3)]
1) The State Key Laboratory of Mechanical Structural Strength and Vibration, Xi'an Jiaotong University, Xi'an, 710049, China
2) Engineering College, Engineering University of Air Force, Xi'an, 710043, China
3) Department of Aircraft Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China

Abstract The fracture toughness of all sort of crack forms of a kind of pipeline steel were investigated experimentally by using through-cracked specimens with thickness of 3,6,9,12,15mm, surface cracked panels, single and double corner cracked panels. The coupled effects of specimen thickness and delamination upon fracture toughness and the mechanism of delamination are revealed; the general role of delaminations and geometry configurations on fracture toughness is found out; the initiation stress intensity factors and fracture toughness are determined. It is very dangerous to predict critical load for no-through cracked bodies by using test data from through crack. The initiation stress intensity factors of no-through and through cracks can be unified by the three dimensional fracture theory.

Keywords three-dimensional crack, delamination, constraint, fracture toughness, pipeline steel

1. Introduction

Thick wall and relatively high-toughness pipeline steels are widely used. However, it has been recognized by fracture mechanics community that the fracture toughness curve is not really a material constant, and that its value may decrease with increasing thickness in metal materials [1,2]. On the other hand, most of the existing cracks are not through the pipe wall but in the form of internal or external surface cracks or embedded cracks. In this paper, detailed experimental investigations will be conducted by use of tensile specimens with through cracks of varying thickness, semi-elliptical surface cracks and corner cracks of different configurations. The purposes are to reveal coupled effects of specimen thickness and delamination upon fracture toughness and the mechanism of delamination in part-through cracked pipes, to find out the general role of delaminations and geometry configurations on fracture toughness, and to determine whether the cracking resistance of a no-through crack in pipelines can be predicted by the fracture toughness obtained from through-thickness cracked specimens.

2. Experiments

2.1 specimen preparation and testing

The material pieces were directly cut from a pipe structure with 700mm diameter and 18mm-thick wall. The yield stress of the material σ_{ys}=500MPa, the limit stress $\sigma_u \geq$620MPa, the Young's modulus E=210GPa, the Poisson's ratio is equal to 0.3. CT specimens with width W=60mm are prepared with the crack along the axial direction. Microstructure was found homogeneous along thickness. Mechanical milling thinned the wall pieces and six thicknesses were obtained: 3, 6, 9, 12 and 15 mm. The in-plane geometry is the same as that of the ASTM E561 standard [3] CT specimen; five specimens for each thickness were prepared; the final crack length to width ratio of $a_0/W \approx 0.47$ for each specimen. To simulate the various possible forms of crack in practical pipelines, single edge corner cracked (SECC), double edge corner cracked (DECC) and center surface cracked (CSC) tensile specimens are prepared. The size of the pre-fatigued cracks are given in table 1 where WCSC denotes the CSC from a rib with 10mm-width which leads to a final ratio $c/a \approx 0.2$, and NCSC denotes the CSC from a rib with 6mm-width which leads to a final ratio $c/a \approx 0.3$. All of the pre-fatigue tests were performed on a MTS810 100kN machine.

After fatigue pre-cracking, all the specimens were loaded monotonically to fracture at room temperature on a MTS 810 100kN TestStar controlled fatigue testing system under displacement control mode with a loading speed of 0.05mm/sec. A MTS 633.030-01 COD gauge was used for crack-mouth opening displacement (COD) measurement. Data were captured using the TestStar computer-testing system and were triggered every 0.05mm of displacement.

2.3 Testing Phenomena and analyses

2.3.1 CT through-thickness specimens

(1) Delamination exists in all CT through-thickness specimens. Although no obvious delamination appears in the 3mm-thick specimens, under SEM, small delaminations can also be found in them. Multiple delaminations occur in thicker specimens. As the out-of-plane constraint is highest at the center of the specimen the delaminations in the middle part of all specimens are most severe.

(2) Delamination originates before crack initiates, and with the thickness increases, the size and depth of delaminations at the center of the specimen increase. In the 15mm-thick specimen, a large delamination starts from the initial crack front and grows with crack extension to the final separate point. This implies that the constraint at the growing crack front is like that in two 7.5mm-thick plates. Secondary delaminations turn up at 1/4 thickness from the free surfaces, and similar to the main delaminations in 6mm- and 9mm-thick specimens. The main reason for this phenomenon is that the overall out-of-plane constraint and the size of high constraint zone increases with thickness. The main delamination at the center of thick plate

releases the out-of-plane constraint completely on the middle plane, and the second peak of constraint move to 1/4 thickness with lower levels.

(3) All the delaminated cracks, in spite of the size, are opened and necking occurs between the delaminations. This means that extensive plastic deformation is accompanied the cracking and the delaminations can reduce the out-of-plane constraint effectively. Both necking and delamination will greatly reduce the effect of thickness on cracking resistance.

2.3.2 Part-through thickness specimens

As can be seen in Fig.1, there is no delamination in the first few millimeters crack growth, the initiation of the corner crack occurs at 45^o. However, once the crack grows through the thickness and further expands through the remaining ligament, large delaminations formed at the center of the plate, similar to that observed in CT specimens. The fracture profiles of the DECC is similar to that of SECC in Fig.1.

Typical fracture profiles of the WCSC specimens are shown in Fig.2. It can be seen that the crack grows through the thickness firstly and then expands to two sides as a through crack with company of large delaminations, the initiation the surface crack is at 75^o-90^o to the front surface. In both stages, strong residual deformation has been formed. As all the fracture section except the pre-fatigue cracked area was seriously deformed, it can be deduced that before crack growth, large plastic deformation has occur and the stable crack growth stage is very short. This is in coincidence with the phenomena observed during the test. Large plastic deformation and crack blunting made the final rupture of the specimens insensitive to the existed initial crack.

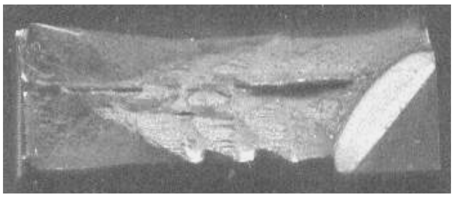


Fig.1 Macro-profile of the fracture surface of a SECC specimen

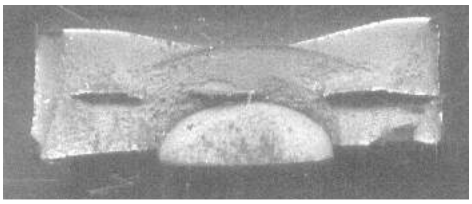


Fig.2 Fracture profile in a WCSC specimen

3. Experimental Results and Analyses

3.1 Load-displacement results

Typical measured load-COD curves for each thickness of CT specimens are plot in Fig.3. Figure 4 shows the effect of crack geometry on the load-COD curves. From the figure

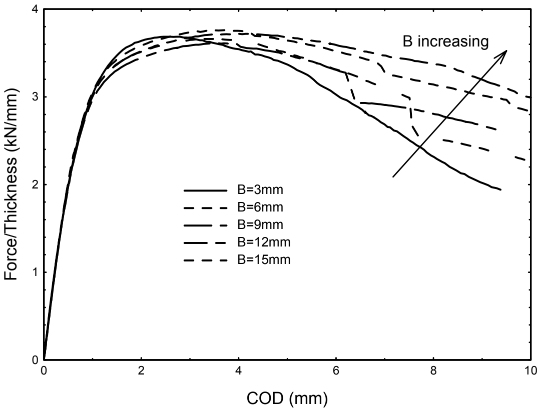


Fig.3 Typical load versus crack open displacement (COD) curves for different thickness of CT specimens

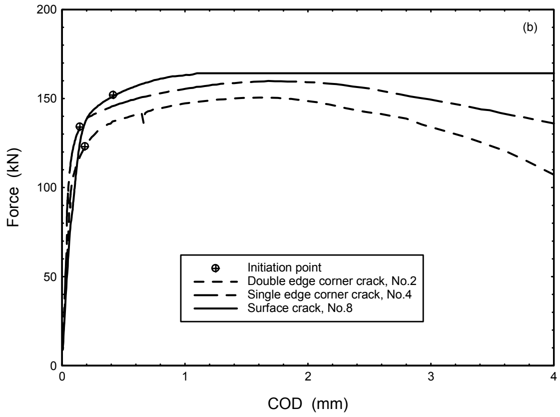


Fig.4 The load-COD curves

it can be found that before crack initiation, plastic deformation is limited. After initiation large deformation occurs before unstable crack growth but the increment of load is relatively small, about 8% to 30% of the initiation load.

3.2 Measurement of critical stress strength

The initial loads and J assessment can be obtained from the load-COD curves. The effective stress strength factor K_e and a J-based SIF $K_J(K_J=(EJ)^{1/2})$ can then be attained in through-thickness specimens. For no-through thickness specimens, the initiation toughness K_i along the crack front and K_{zi} assessed according to the three-dimensional fracture theory[4] are calculated, K_{imax} is the maximum of K_i. They are listed in table 1.

4. Conclusions

(1) Delaminations exist not only in through-thickness specimens but also in no-through thickness specimens; it is characteristics of this material. Delamination originates before crack initiates in through-cracked specimens; however, inverse phenomena appear in others' specimens. Strong coupled effects of specimen thickness and delaminations dominate the fracture behavior of this steel. Formation of delaminations and has close relation to the relative orientation between the directions of crack growth and thickness.

(2) As the out-of-plane constraint keeps low in spite of the specimen thickness B. The conservative plane strain fracture toughness K_{IC} or J_{IC} can not be approached by increase of B as the multi-delaminations will reduce the "effective local thickness" and enhance the nominal toughness. When the through-thickness toughness is used to safe assessment of general 3D cracked bodies, delaminations may be dangerous.

(3) As the out-of-plane constraint keeps higher in the interior of the part-through

cracks, the fracture initiation toughness is much lower than that of the through-thickness cracked specimens. The traditional fracture toughness K_i is not a proper material toughness parameter. The three-dimensional parameter K_{zi} proposed by Guo[5] is proven to be a material constancy independent of geometry configurations. The toughness K_i of part-through cracks can be predicted well by the three-dimensional theory and test data of through cracks provided there is no delamination.

REFERENCES

[1] Schwalbe, K.-H., Influence of stress state on static crack growth in AlZnMgCuO.5, *Engineering Fracture Mechanics*, 1977, **9**, 557-583.

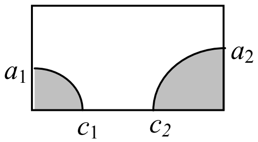
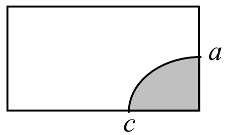
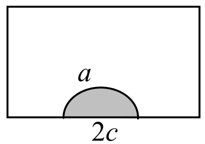
[2] Anderson, T.L., Fracture Mechanics-Fundamental and Application. CRC Press, Boca Raton, 1995.

[3] ASTM E561–81, Test method for determining R curve, 1981

[4] Guo W L, Pitt S D, Jones R. Three dimensional strength assessment for damage tolerant structures, Strength Theory. Science Press, Beijing and New York; 1998: 799

[5] Guo, W., Three dimensional study for the effects of sheet thickness on fracture toughness of materials, *Acta Mechanica Solida Sinica*, 1995, **16**(S.I.), 1-9.

Table 1. Geometry of the specimens and experimental results

Specimen Number	Crack configuration	Crack size mm	Initiation: Initiation load P_i kN	Initiation: K_{imax} MPam$^{1/2}$	Initiation: K_{imax} θ°	Initiation: K_{zimax} MPam$^{1/2}$	Initiation: K_{zimax} θ°	Maximum: Maximum load P_{max} kN	Maximum: K_{cmax} MPam$^{1/2}$	Maximum: K_{cmax} θ°	Maximum: K_{zCmax} Mpam$^{1/2}$	Maximum: K_{zCmax} θ°
No.0	 Double edge corner cracks (DECC)	a_1=6.5, c_1=6.5 a_2=9.5, c_2=10	125	91.2	0	107.8	0	135	98.5	0	116.6	0
No.1		a_1=6, c_1=7 a_2=7.4, c_2=8.5	132	70.3	0	106.6	45	148.75	78.8	0	112.4	45
No.2		a_1=5.5, c_1=6 a_2=7, c_2=8	123	61.2	0	89.2	45	150.78	74.9	0	111.6	45
No.3	 Single edge corner crack (SECC)	a=7, c=7.7	139	68.4	0	100.8	45	164.67	81.0	0	114.5	45
No.4		a=7, c=7.3	134	64.9	0	102.1	45	159.90	77.4	0	110.6	45
No.5		a=7, c=6.4	145	69.5	0	100.6	45	165.66	79.4	0	109.5	45
No.6	 Center surface crack (CSC)	a=3.5, 2c=11	158	49.5	90	106.9	75	180.20	56.5	90	128.6	75
No.8		a=4, 2c=11.5	152	49.8	90	111.5	75	176.84	57.9	90	130.8	75
No.12		a=4, 2c=7.5	151	49.2	0	100.6	80	188.91	61.5	0	116.8	80
No.13		a=4, 2c=8	150	44.9	0	100.9	80	186.95	56.0	0	116.8	80
No.14		a=4, 2c=9	136	41.6	0	100.0	75	178.00	54.4	0	119.7	75