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Study on fracture toughness with different thicknesses CT specimen

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Abstract: The material selected for this study was a WELDOX 900 steel plate. This paper analyzed the size effect of fracture toughness based on experimental results and finite element numerical simulation results. In addition, J-integrals of different thicknesses were investigated and the relational expression between them was acquired in this study. The main conclusions are as follows: Firstly, the formula between the ductile fracture toughness $J_{0.2}$ and the specimen thickness was obtained. It proposed a method for predicting the fracture toughness of plane strain state using thin specimens of several thicknesses based on this formula. Secondly, the fracture toughness values of the materials were obtained by finite element numerical simulation. And it was found that the distribution of stress triaxiality near the crack tip could well explain the variation of fracture toughness with thickness.

Keyword: fracture toughness; J-integral; reverse finite element method; stress triaxiality

1. Introduction

The fracture toughness of materials is an important reference for the safety evaluation of equipment and life prediction. The sample of conventional methods for measuring fracture toughness was required to have larger size specimens. But many in-service equipment couldn't meet this requirement. It is an effective way to make the sample thinner in order to evaluate fracture toughness of in-service equipment. J-integral was an index for fracture toughness, which was used to characterize the stress strain field in the leading edge of crack [1]. Therefore, it is great engineering significance to study the effect of thickness of specimen on J-integral.

The stress triaxial factor represented the triaxial stress state and determined the degree of restraint, which was used by many literatures to explain the influence of size on fracture toughness [2]. The stress state in the front of the crack tip was changed with the thickness. With the specimen size decreasing and reaching to the plane stress state, the fracture toughness would increase [3]. Although the value of the fracture toughness was related to the size of specimen, the fracture toughness could be considered to be dimension independent when the specimen thickness was large enough to reach the plane strain state [4].

2. Experimental procedure

2.1 Material

The materials used in this series of experiments were WELDOX900, which was applied to fan blower compressor. The chemical composition of weldox900 low-alloy high strength steel under investigation in wt% was shown in Table 1. The results were shown that the material met the standard of EN10025. In addition, yield strength and tensile strength of metallic materials were necessary for fracture toughness test, which were acquired by uniaxial tensile test [5] (Table 2).

Table 1. Chemical composition of WELDOX 900 (wt%).

Element	C(max)	Si (max)	Mn(max)	P (max)	S (max)	Cr (max)	Mo(max)
Measured value	0.20	0.21	1.37	0.01	0.002	0.25	0.52
EN10025	0.20	0.51	1.60	0.02	0.01	0.70	0.70
Element	Ni(max)	Al(min)	Cu (max)	V(max)	Ti(max)	Nb(max)	B (max)

Measured value	0.05	0.058	0.01	0.02	0.001	0.017	0.0013
EN10025	2.0	0.018	0.30	0.06	0.04	0.04	0.05

Table 2. Tensile mechanics of WELDOX 900.

No.	$R_{p0.2}$ (MPa)	R_m (MPa)	δ_5 (%)	ψ (%)
1	890.5	947.0	15.78	69.10
2	889.3	949.1	14.56	68.19
3	890.1	948.2	15.23	68.29
Average	890.0	948.1	15.19	68.53

2.2. Experimental methods

In fracture toughness testing, the Compact Tension (CT) specimen that was recommended as one of the standard specimen was adopted in this study [6]. On the basis of the load-displacement curves which were obtained by the experimentation, J-integral was worked out.

In addition, multi-specimen method and single-specimen method were the main methods to determining J resistance curves. Multi-specimen method means a series of specimen of the same size are used to gain different levels of displacement. In contrast, different levels of displacement were acquired by only one specimen for single-specimen method. Single-specimen method was used in this study.

The experimental materials were got from a sheet material whose thickness was 18mm with 240mm width. Sampling direction was shown in Figure 1 which was the same as tensile samples.

The sizes of these specimens were designed as follows: width was invariable which was 50mm and the thickness was set into five levels which were 16mm, 12.5mm, 8mm, 4mm and 2mm (Figure 2).

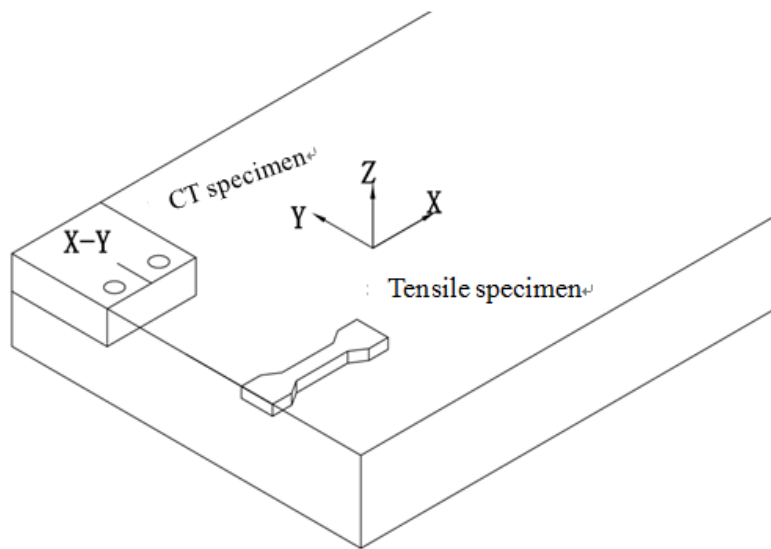


Figure 1. Sampling direction.

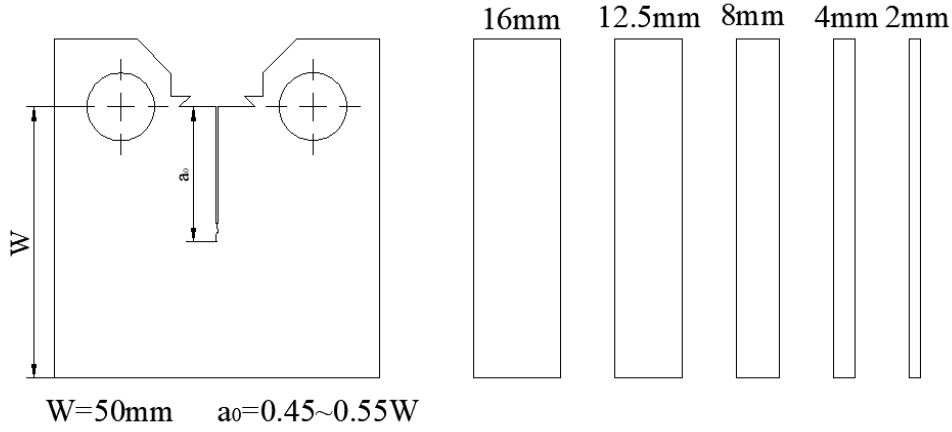


Figure 2. CT samples with different thickness.

2.3. Method of gaining J resistance curves

According to GB/T 21143-2014, J -integral was obtained by the follow formula for CT specimen:

$$J = \left[\frac{F}{(BB_N W)^{0.5}} \times g_2 \left(\frac{a}{W} \right) \right]^2 \left[\frac{(1-\nu^2)}{E} \right] + \left[\frac{\eta_p U_p}{B_N (W-a)} \right] \left\{ 1 - \left[\frac{(0.75\eta_p - 1)\Delta a}{W-a} \right] \right\} \quad (1)$$

$$\eta_p = 2 + 0.522(1 - a_0/W) \quad (2)$$

$$a = a_0 + \Delta a \quad (3)$$

Where n_p was plastic factor. $g_2(a/W)$ could be acquired in GB/T 21143-2014. BN meant the thickness between side groove and here $BN = B$.

The output data of the test machine was the force-displacement curve while using single sample unloading flexibility technology. J -integral was calculated by iterative algorithm.

3. Results and discussion

3.1. Experiment

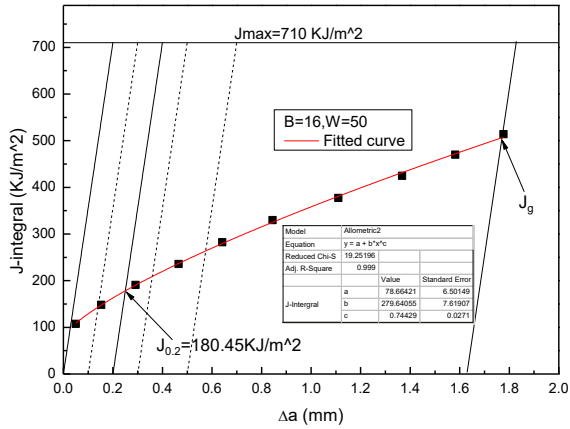
The results of different thickness samples where shown in Table 3 which including initial crack length a_0 , end crack length a_f and fracture toughness $J_{0.2}$. J resistance curves of the samples of different sizes were shown in Figure 3. The results of samples with different thickness were shown in Figure 3(f). Blunting line equation was as follow:

$$J = 3.75 \times 948 \Delta a \quad (4)$$

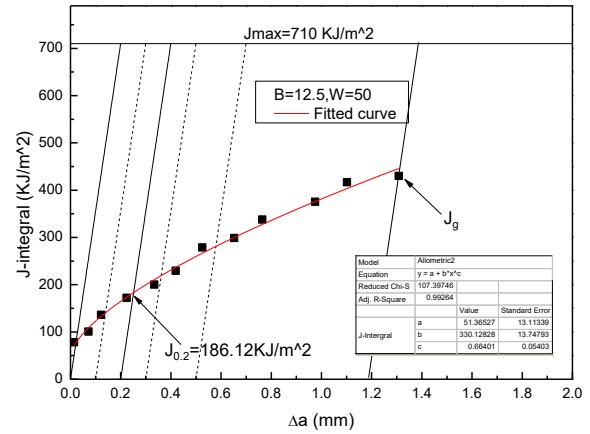
Where Δa was the length of crack propagation.

Table 3. Test data of fracture toughness of CT specimen.

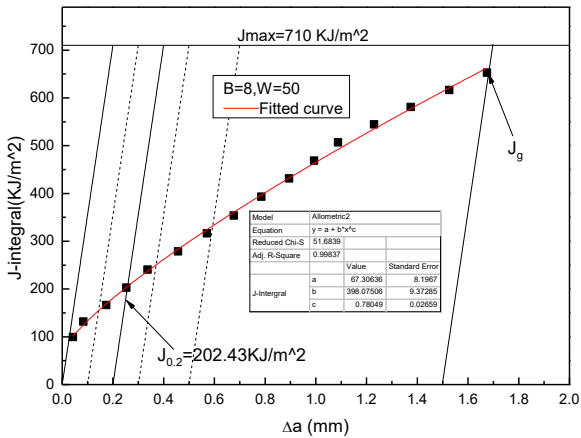
NO.	Thickness /mm	Width /mm	a_0 /mm	a_f /mm	$J_{0.2}$ KJ/m ²	Notes
CT-T16-1	16.00	49.98	24.31	26.33	311.46	Pin bending
CT-T16-2	16.00	50.02	24.30	26.03	175.53	
CT-T16-3	16.00	49.99	24.29	26.25	180.45	
CT-T12.5-1	12.51	50.02	24.38	25.78	186.12	
CT-T12.5-2	12.49	50.02	24.28	25.62	179.61	
CT-T12.5-3	12.50	50.00	24.32	25.71	177.85	
CT-T8-1	7.95	50.01	24.45	26.12	202.43	
CT-T8-2	7.96	50.01	24.51	25.96	196.86	
CT-T8-3	7.98	50.00	24.48	26.07	200.02	
CT-T4-1	3.96	50.01	25.31	26.06	218.57	
CT-T4-2	3.97	50.01	25.02	25.96	220.88	
CT-T4-3	3.98	50.02	25.15	25.89	220.32	
CT-T2-1	1.98	50.01	24.96	26.01	null	Sample distortion
CT-T2-2	1.97	50.01	25.38	26.13	210.56	
CT-T2-3	1.86	50.07	24.61	26.52	211.15	



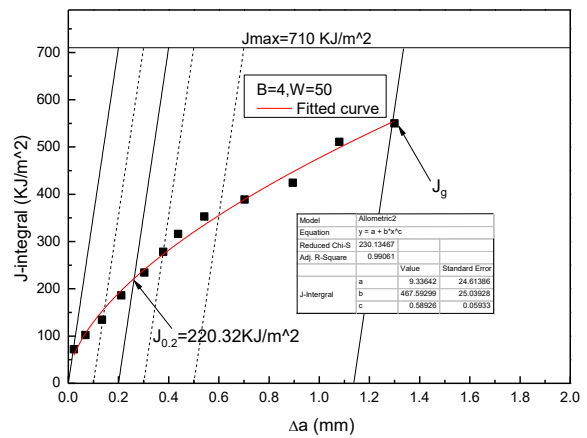
(a) B = 16mm, W = 50mm



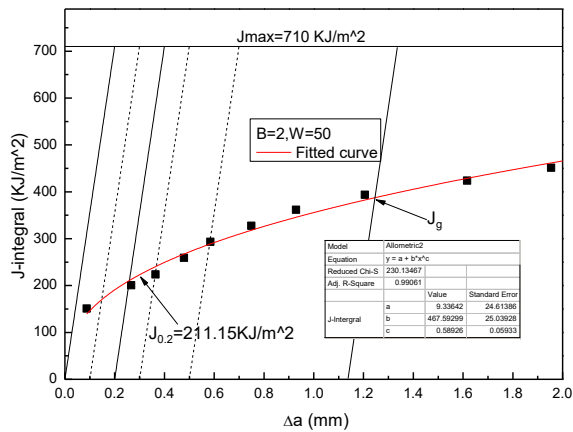
(b) B = 12.5mm, W = 50mm



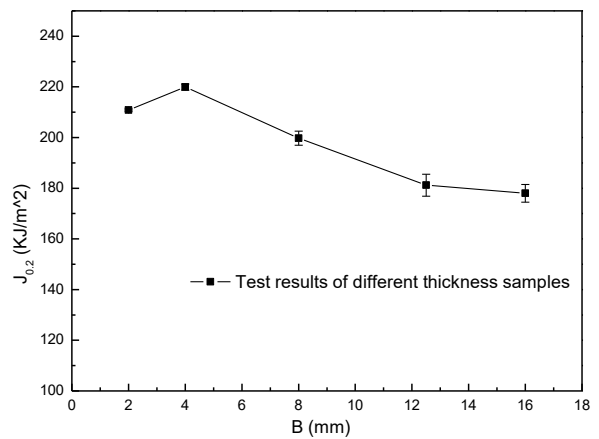
(c) B = 8mm, W = 50mm



(d) B = 4mm, W = 50mm



(e) B = 2mm, W = 50mm



(f) Test results of samples with different thickness

Figure 3. JR curve and J_{0.2} value obtained by single sample method.

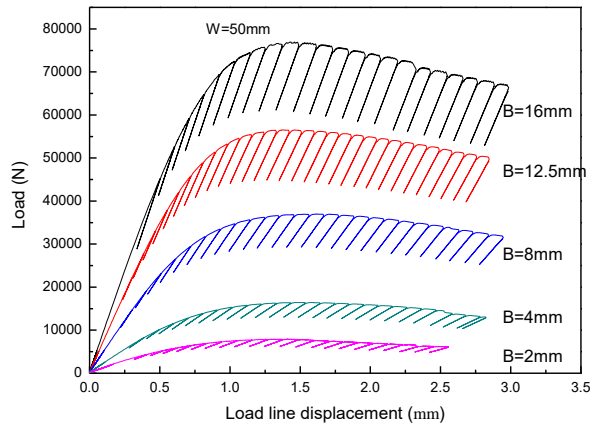


Figure 4. Load and displacement curves of specimens with different thickness.



Figure 5. CT specimens of different thickness after test.

Load and displacement curves of specimens with different thickness were shown in Figure 4. And CT specimens of different thickness after test were shown in Figure 5.

It was shown that increasing thickness resulted in rising fracture toughness, except for the specimen of 2mm. And the results of last two specimens were very close. It is important to note that to calculate the plane strain fracture toughness, the thickness of the sample should be larger while in the case of plane stress fracture toughness test, small thickness of the sample is sufficient. That meant that the process of changing the plane stress state to the plane strain state was relevant with thickness. And finally, the J integral value of fracture toughness was determined and had no relation with thickness when the thickness was larger enough.

The relationship between fracture toughness and thickness of high strength titanium alloy had been researched by Ji [7]. The following formula was given by them.

$$K_c = \xi B^{1/2} e^{-kB} + K_{IC} (1 - e^{-kB}) \quad (5)$$

Where, B was thickness of sample, K_c was stress intensity factor and K_{IC} was stress intensity factor. ξ and k were material constant.

The relationship between J-integral and stress intensity was obtained by many researchers [8].

$$J = \begin{cases} \frac{1}{E} K^2 & \text{plane stress state} \\ \frac{1-\nu}{E} K^2 & \text{plane strain state} \end{cases} \quad (6)$$

On the basis of the two formulas, the following relationship was acquired.

$$J = \alpha B e^{-\beta B^n} + J_{IC} (1 - e^{-\beta B^n}) \quad (7)$$

Where n was used to improve the accuracy of fitting curve.

The result of fitting curve was closed to experimental data and the goodness-of-fit was 0.97195 which indicated that the variation of fracture toughness and thickness of low alloy and high strength steel could be described well by the formula.

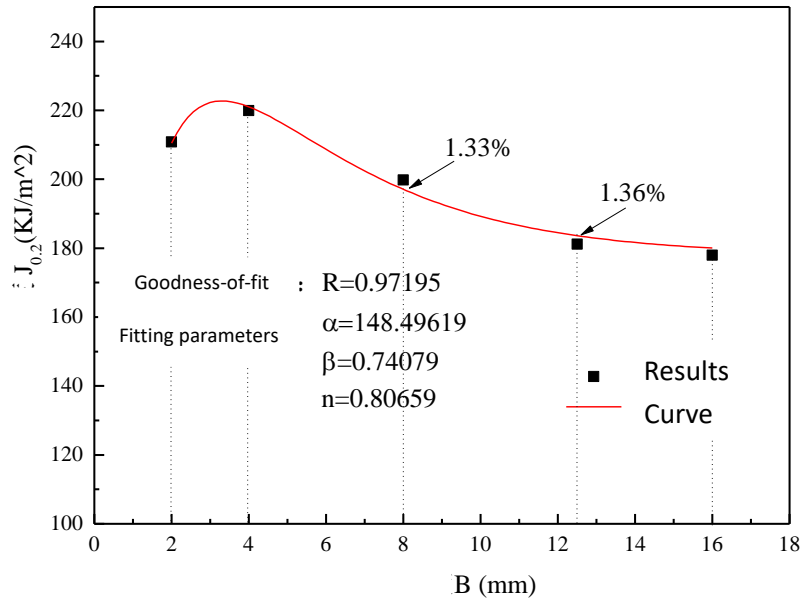


Figure 6. The formulae (3-6) are used to fit the result of the test.

3.2. Simulation

The fracture toughness parameters and true stress strain curve of material were necessary for finite element modeling (FEM). GTN model which was aimed at simulating ductile fracture process was chosen in this study. The parameters of GTN and true stress strain curve were obtained by means of small punch test which was based on inverse finite element [9]. Above results were used to obtain fracture toughness of specimens with different thickness by FEM [10].

Table 4. Fracture toughness of specimens with different thicknesses obtained by FEM.

B (mm)	2	4	8	12.5	16	25
Simulated results $J_{0.2}$ (KJ/m ₂)	207.44	216.97	193.92	174.83	162.82	165.65
Test results $J_{0.2}$ (KJ/m ₂)	210.56	218.57	196.86	177.85	180.45	170.94
Deviation %	1.48	0.73	2.94	1.15	9.78	6.02

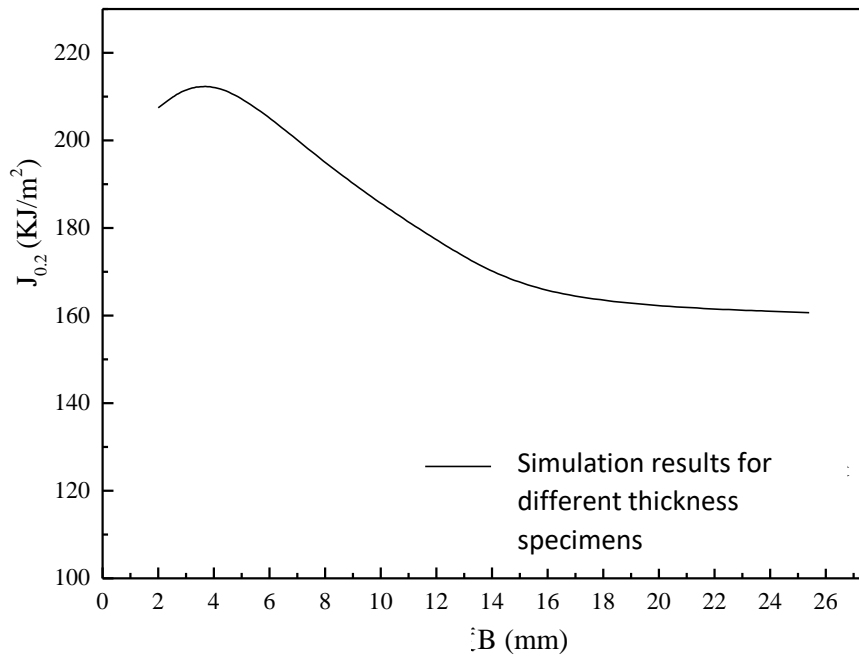


Figure 7. Simulation results for different thickness specimens.

Figure 7 was shown that the simulation results for specimens with different thickness were closed to the results of testing. It was indicated that the backward simulation using FEM which was used to get fracture toughness parameters and true stress strain curve of material was able to simulate the fracture toughness of specimens with different thickness.

In addition, many researchers found that the fracture of ductile material was divided into void-mode fracture and shear-mode fracture [11]. There was a critical stress state between the two kinds of fracture which was represented by stress triaxiality. Fracture morphology of sample was dimple, which was conformed to the characters of stress triaxiality in this study (Figure 8). Furthermore, growth and polymerization of material void were affected by stress triaxiality, which was related to GTN because GTN was based on theory of void damage of materials. Therefore, the relationship between stress and thickness of specimen was discussed in this study.

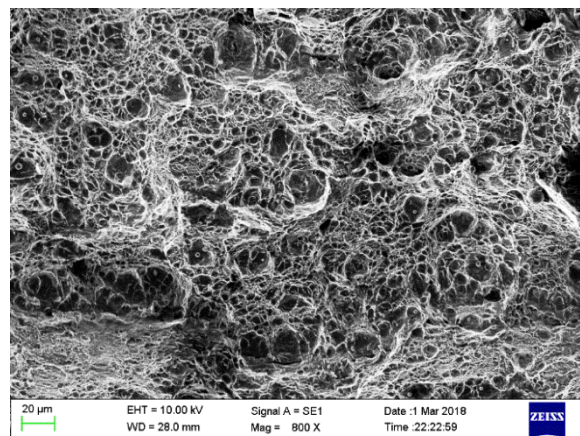


Figure 8. Topography of crack tip extension.

The time of beginning the phenomenon of unit reduction was defined as the rev. crack moment. The distribution of Von Mises stress was shown in Figure 9.

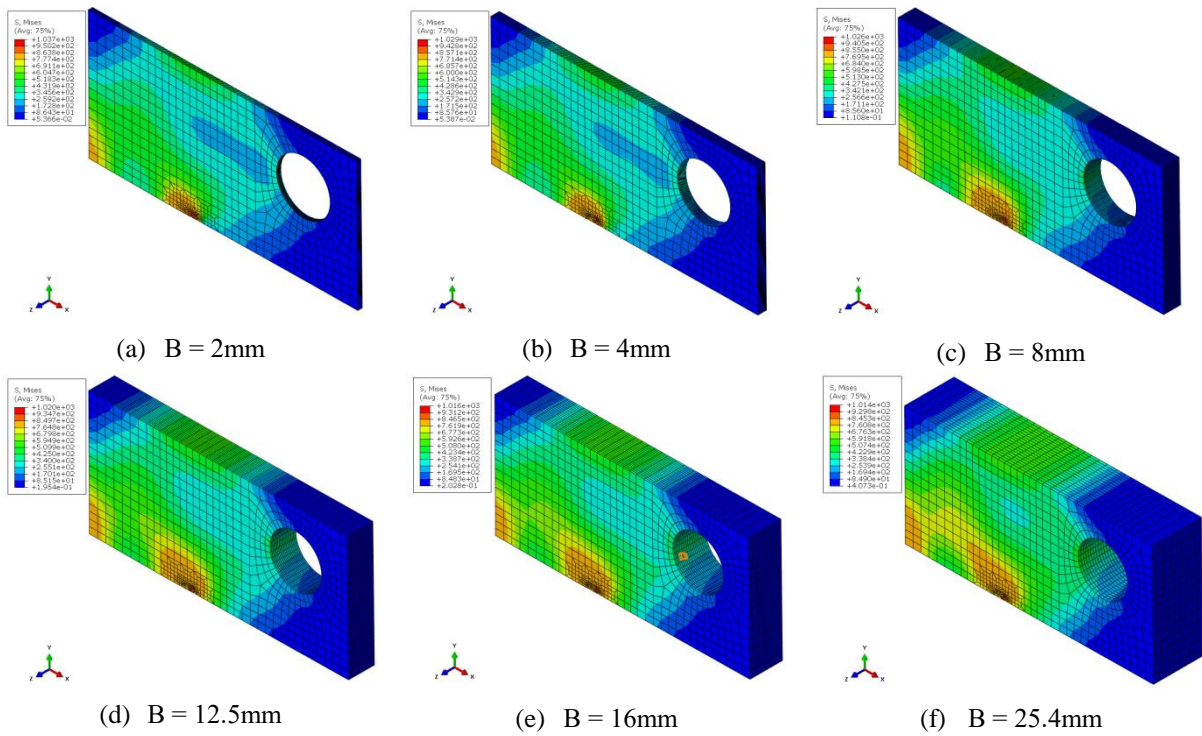
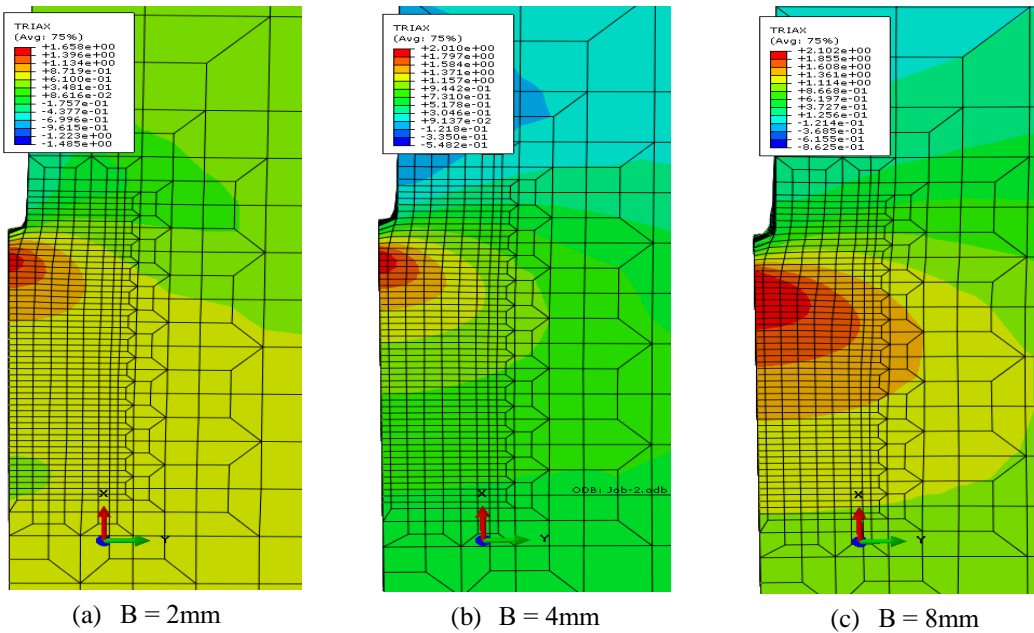


Figure 9. Von Mises stress distribution of samples with different thicknesses.

It was shown that six specimens reached the balance of stress at the rev. crack moment. Von Mises stress was increased slightly with the increase of thickness.



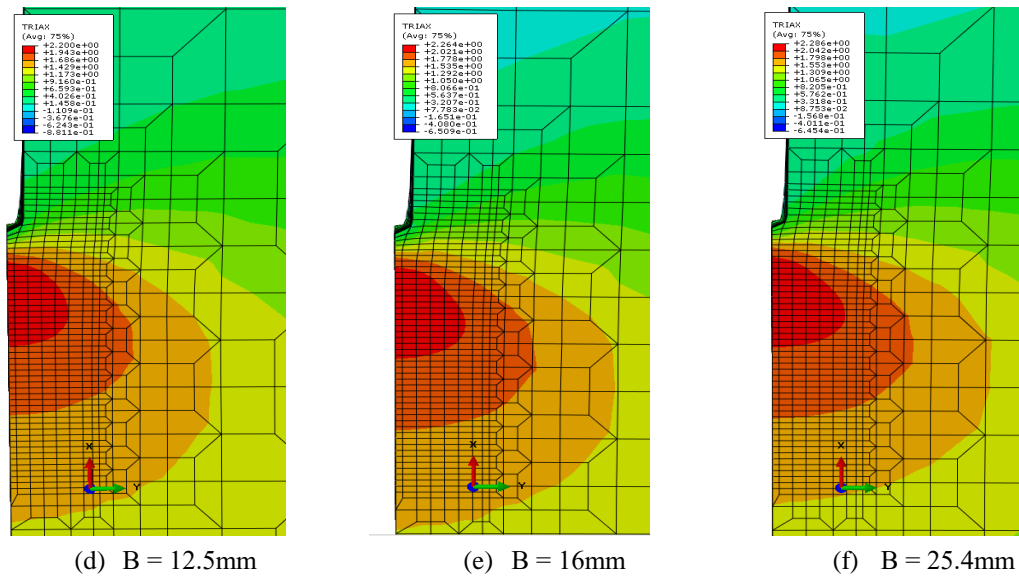


Figure 10. Stress triaxiality distribution of specimens with different thicknesses.

Stress triaxiality distribution of specimens with different thickness was shown in Figure 10. It indicated that stress triaxiality was raised with the increase of thickness and the area of maximum value was also expended.

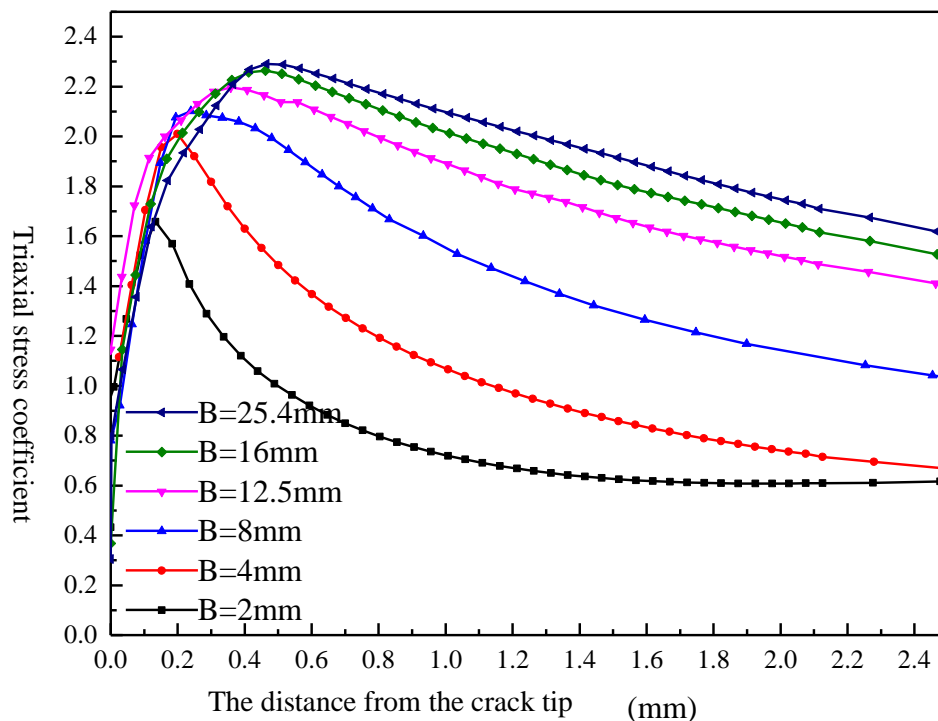


Figure 11. Stress triaxiality distributions in front of crack tips.

Stress triaxiality distribution in the front of crack tips was shown in Figure 11. It revealed that stress triaxiality was higher when the thickness of specimen was larger and the result of specimen with 16mm was closed to 1T, which was illustrated that the specimen with 16mm was more closed to plane strain state.

In addition, the specimen with 2mm was different with others in not only stress cloud charts but curve graphs (Figure 10 and Figure 11). It illustrated that the maximum stress triaxiality couldn't be used to reflect fracture toughness when the thickness of sample was too small to close to plane stress state.

4. Conclusions

An experimental program was carried out to study the fracture toughness and dimensional effect. The results were shown that specimens of different sizes were relevant and guidelines for further practice were proposed. The main outcomes are the following:

- 1) Based on the testing results of samples with different thickness, a larger number of data was obtained and $J_{0.2}$ was calculated by series of formulas. According to the relationship between ductile fracture toughness ($J_{0.2}$) and thickness, the specific mathematical expression was given by derivation and limit analysis which was $J = \alpha B e^{-\beta B^a} + J_{IC} (1 - e^{-\beta B^a})$. The expression could fit the relationship between fracture toughness $J_{0.2}$ and specimen thickness well.
- 2) The fracture toughness values of the materials were obtained by finite element numerical simulation. Compared with the experimental results, it is found that the numerical error of $J_{0.2}$ obtained by reverse finite element method was only 9.7%. That was indicated that the results of tests were valid and the formula that was based on the results was reliable.

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