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DETERMINATION OF FRACTURE TOUGHNESS FROM SMALL PUNCH TEST USING IMPROVED INVERSE FINITE ELEMENT METHOD

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ABSTRACT

Fracture toughness is one of the most significant evaluation factors in the life assessment of the pressure vessels. In conventional sampling process, a large quantity of material from the component is needed to prepare the specimen, which makes it impossible to monitor the status of the in service equipment. Small punch test (SPT) specimen often comes in limited sampling size and it enables material be taken directly from the surface of equipment. Mechanical properties including fracture toughness can be obtained by studying the load-displacement curve of the specimen. By introducing a four-step inverse finite element method (IFEM), the fracture toughness of the investigated material is derived. After that, the influence of friction coefficient and methods of friction measurement are studied. The contact pressure distribution during SPT is firstly studied by means of finite element software. And a method to define the friction efficient using specimen with central hole is proposed. The determination of the friction coefficient improves the accuracy of the inverse finite element method. At the meanwhile, taking A106 steel as an example, several mechanical properties of the material is obtained. The result shows that the deviation of yield strength is 6.3, tensile strength 1.1% and fracture toughness J_{IC} 23.4%

INTRODUCTION

Small Punch Test

Small Punch test uses miniaturized specimen to obtain mechanical properties of the materials, in which little damage is imposed on the equipment while conducting specimen sampling. Small punch test was firstly proposed by Baik et al. (1983), which is mainly used to evaluate the embrittlement of the materials after neutron irradiation. The specimen is mounted in between the upper and lower die. While conducting SPT, a constant loading speed is applied to the centre of the Specimen by a rigid steel ball. The specimen is put between the upper die and the lower die, and is punched in its centre by a steel ball. The load-displacement curve (LDC) of the centre of the lower surface is extracted. The mechanical properties of materials can be obtained by studying the load displacement curve.

Some researchers used the SPT to predict the elastic plastic properties, see Ha et al. (1998), and fracture toughness J_{IC} for the ductile case, see Catherine et al. (1998), or fracture toughness K_{IC} for the brittle case, See Bulloch et al. (1998). Kaishu Guan et al. (2007), obtained total deformation energy by SPT and established the correlation with the fracture toughness J_{IC} obtained by traditional test methods. Foulds et al. (1995), put forward a method to evaluate fracture toughness with finite element numerical simulation.

Inverse Finite Element Method

According to Husain et al. (2004), inverse finite element method (IFEM) may be defined as the reverse of that process, where the time history of a selected system ‘‘output’’ variable is prescribed

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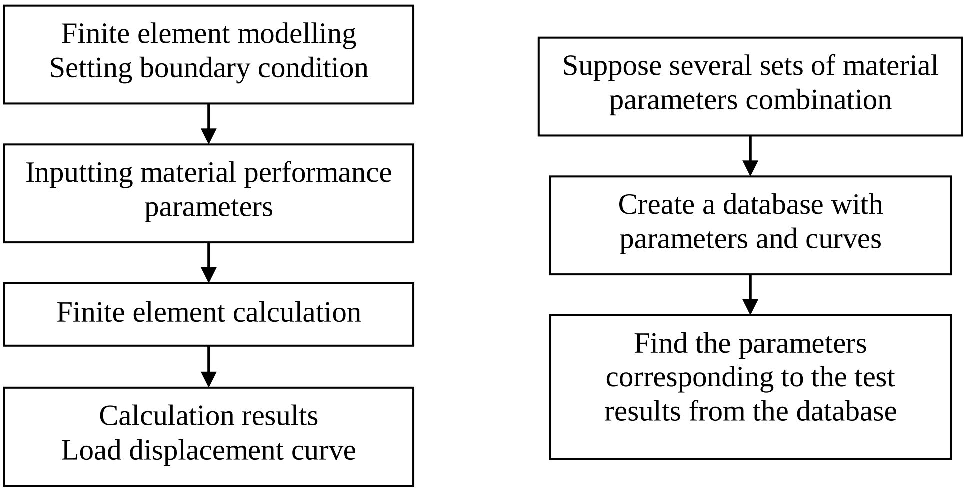
and the inverse simulation algorithm allows the investigator to determine the time history of the corresponding “input’’ variable. IFEM makes it possible to obtain material parameters from LDC, which belongs to the category of reverse engineering.

Conventional FEM can be divided into four steps. The first step is to develop a finite element model and set the boundary conditions. The second step is to input mechanical property parameters of the material. The third step is finite element calculation. The finally step is to obtain a LDC from finite element simulation. This process can be understood with the help of Figure 1(a). The calculation process of FEM is irreversible, which means that the material parameters cannot be deduced from the final results. The pre work of the IFEM is to construct a database containing a lot of material properties and the corresponding finite element simulation results. And the next is to use artificial neural network (ANN) to identify material parameters matched with the test results from the database, which are as the properties of the material sample, as shown in Figure 1 (b).



a) FEM b) IFEM

Figure 1 FEM and IFEM

Determination of Fracture Toughness

Artificial neural network (ANN) plays an important part in the inverse finite element method. ANN is a mathematical model established based on the principle of brain stimulation. ANN possesses self-learning and memorizing ability, and it can build complex nonlinear correspondence without knowing the expression of the correlation function. Based on these characteristics of ANN, The performance parameters of the material can be obtained.by means of the load displacement curve.

The IFEM of small punch test can be divided into four steps, as it is shown in Figure 2.

(a) By assuming a certain parameter sets of one material model, construct the SPT simulation curve with the parameters combination.
(b) Train neural network with the load-displacement curves as input and the material parameter as output.
(c) Conduct SPT and obtain the load-displacement curve. Use the load-displacement curve as the input of the ANN which has been trained in the last step and the output is the corresponding parameter.
(d) Simulate uniaxial tensile test and fracture toughness test using material parameter obtained in the above step to gain strength and fracture toughness property J_{IC}.

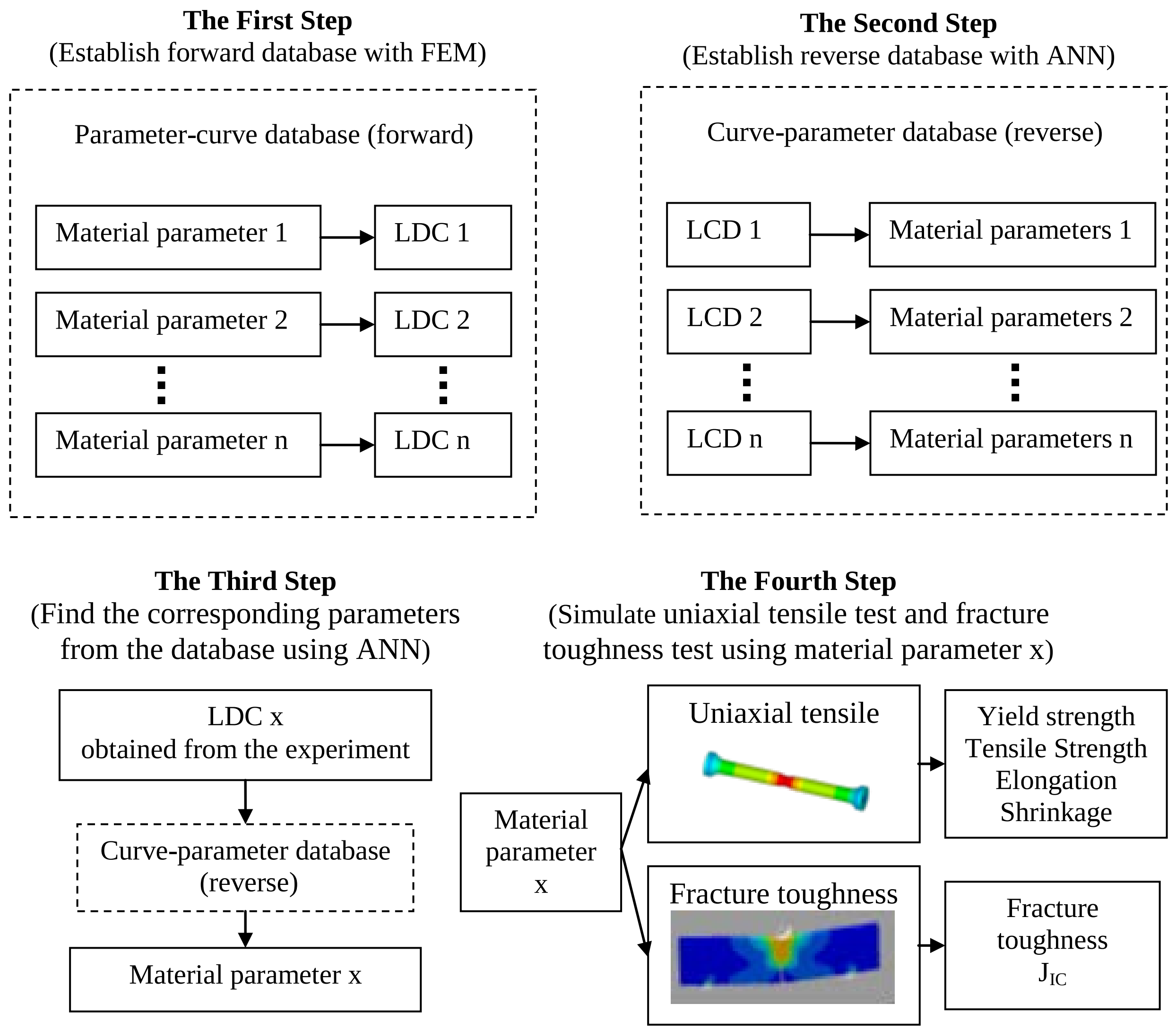


Figure 2 Step of Inverse Finite Element Method

The inverse finite element method is introduced in details in the reference. See Zhang (2014). But there are some crucial problems exist in IFEM. They are the influence of friction coefficient and its measuring method. This paper aims to solve these problems and improve the accuracy of fracture toughness obtained by using IFEM.

INFLUENCE OF FRICTION COEFFICIENT AND ITS MEASURING METHOD

As it was described in the previous section, GTN parameters are obtained from the LCD. There was research shows that the LDC obtained by simulation (when displacement exceeds 0.65mm) is affected by the GTN model parameters and the friction coefficient between the steel ball and the sample. In order to obtain the GTN parameters with better accuracy, it is vital that the friction coefficient be determined and measured. It is necessary to determine the friction coefficient. However, at present, there is still little research on friction coefficient in all articles and research reports. The friction coefficient adopted previously by other researchers is assumed to be a fixed value. See Husain et al. (2004). In this part, the investigation will focus on the variation law of the small punch test friction coefficient. A new method is put forward to measure the friction coefficient.

Determination of Frictional Theory

The coefficient of friction (COF) describes the ratio of the force of friction between two bodies and the force pressing them together. The theory of friction, also called "mechanical friction theory", was first proposed by Coulomb et al.. It was assumed that the two contact surfaces are absolutely rigid, and that the convex and concave of the contact surfaces are inlaid with each other, hindering the sliding of the two contact surfaces. In fact, the stiffness (or hardness) of any metal material is limited. When the contact pressure reach to a certain value, plastic deformation will occur on the contact surface of the low hardness material, and the microstructure of the contact surface will change. In this case, the main reason of the sliding resistance cannot be explained by the mechanical friction theory based on the absolute rigid body assumption.

The steel ball used in the SPT is of great hardness (about 58~65 HRC), while the hardness of the sample is less than 25 HRC. The sample deforms downwards along with the steel ball. At the same time, the sample is continuously extended and deepened. During the experiment, large plastic deformation occurred in the sample, and the contact pressure is very large. The test procedure does not satisfy the assumptions, so the friction mechanism cannot be explained by the mechanical friction theory.

The SPT is essentially the plastic forming process of metal, so some methods used in the metal plastic forming process can be used in SPT to obtain the COF. The common plastic forming system of metal include: roll bending of sheet metal, sheet metal drawing, sheet drawing and pipe hydraulic expansion, and etc. The small punch test is similar to the drawing process of metal sheet The SPT is similar to the non-lubricated drawing process of sheet metal. The steel ball and fixture in SPT are equivalent to the die in plastic forming system, and the sample is equivalent to the plate.

Research shows that with the increase of the contact pressure, there is not a stable relation between friction and contact pressure. Further studies show that the COF decreases with the increase of contact pressure. See Zhao et al. (2006).

Measuring Method of Friction Coefficient in Small Punch Test

In the case of large contact pressure, a large amount of plastic deformation occurs on the contact surface. The COF is not a constant, but a function of the contact pressure. In metal plastic forming process, the size of mould and sample is very large, so that the sensor can be installed on the device to obtain the coefficient of friction during the experiment. But, this method is difficult to achieve in the SPT, because of the small size of the fixture and the sample. In this section, in order to find a new method to solve the COF, we mainly studied the size and distribution of contact pressure in the SPT.

The numerical simulation method is the only way to study it. The finite element analysis software used in this paper is ANSYS 14. The contact pressure of all contact units for each load step is extracted and the averages of the contact pressure are shown in Figure 3. With the increase of displacement, the contact pressure decreases sharply from the maximum value, and stabilizes in a certain range. When the ball just touches the sample, the contact area is small; the contact pressure is very great. With the increase of the load, the plastic deformation occurs and the contact area increases rapidly, and the contact pressure decreases rapidly. When the displacement reaches 0.1mm, there is an inflection point. After that, the contact pressure tends to be a fixed value. This phenomenon can be explained by the change of contact area. The contact area of each load step is extracted from the finite element results, as shown in Figure 4.

The results show that when the displacement is less than 0.65mm, the COF has no influence on the LDC. When the displacement reaches 0.65mm or more, the contact pressure tends to be a steady value which is about 250MPa. Therefore, in order to accurately simulate the SPT (the displacement is greater than 0.6mm), we only need to calculate the corresponding COF when the contact pressure is 250MPa.

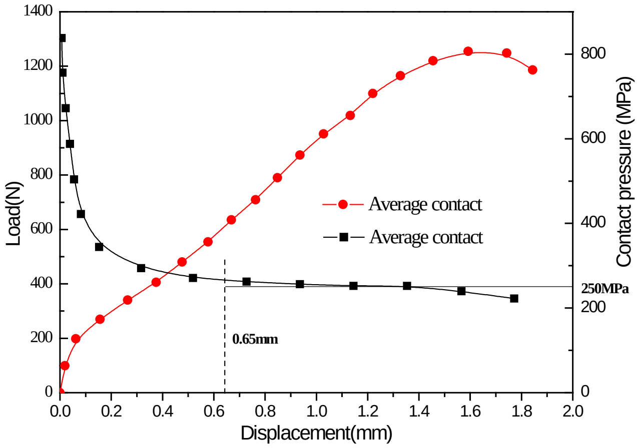


Figure 3 Curve of mean contact pressure

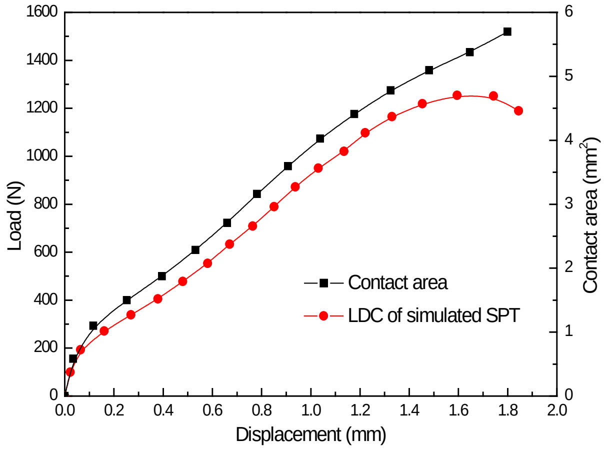


Figure 4 Curve of contact area

Since the size of the specimen and fixture is small, it is almost impossible to measure the parameters related to the coefficient of friction directly from the test by the sensor. If we change the fixture structure and enlarging the specimen size, it is difficult to ensure that the specimen's stress state and the contact conditions in the new system are completely consistent with these in the original SPT. In order to solve this problem, we design a set of COF testing system with fixed contact pressure. The system is based on the small punch test system, and there is only a slight change in the structure of the SPT specimen. Fixture, steel ball and punch are consistent with the original device, as shown in Figure 5. The specimen adopted is machined with a central hold in the middle, as shown in Figure 6. The steel ball is forced to pass through a circular hole, and the contact pressure between the ball and the side wall of the hole can be adjusted through the diameter of the hole. In this way, a new LDC only related to the COF can be obtained by the experiment. Then, we change the COF to get different curves by FEM. The simulation results are compared with the experimental curves. If the two curves are consistent, the COF used in the simulation is the correct COF of the material.

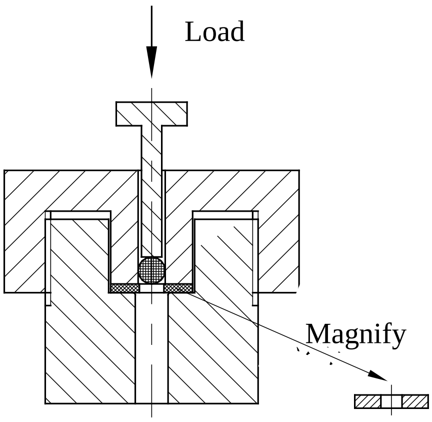


Figure 5 Specimen and fixture

Figure 6 Specimen with central hole

As mentioned earlier, both the friction coefficient and the GTN parameter affect the simulation results. The main task of this part is to determine the COF for establishing the corresponding relationship between the GTN curve and the simulation results. However, the plastic deformation occurs in a certain area around the round hole, which may cause the damage to the material. And GTN parameter is the characterization of material damage. In order to obtain the COF from the LDC of specimen with a central hole, it is necessary to prove that the LDC with a central hole is independent of the parameters of the GTN model. For this reason, the same finite element model is used to carry out the two numerical simulation. One contains the GTN model, and the other includes the GTN model. The calculated results are shown in the Figure 7. The two curves are approximately coincident. On the contrary, with the change of the COF in the finite element software, the change of the curve is very obvious, as shown in Figure 8. Therefore, the LDC of specimen with central hole and the COF have a one-to-one relationship.

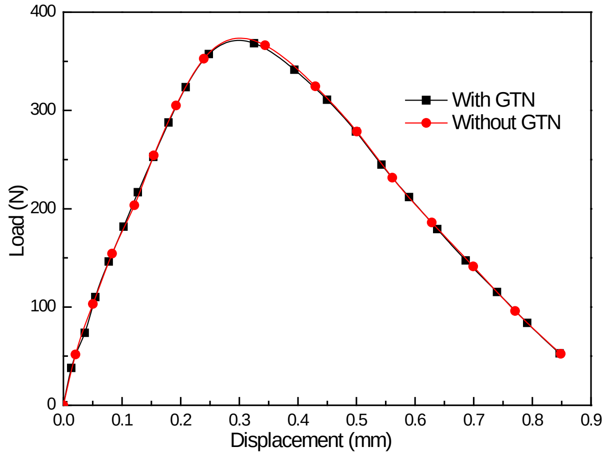


Figure 7 Curve with GTN and without GTN

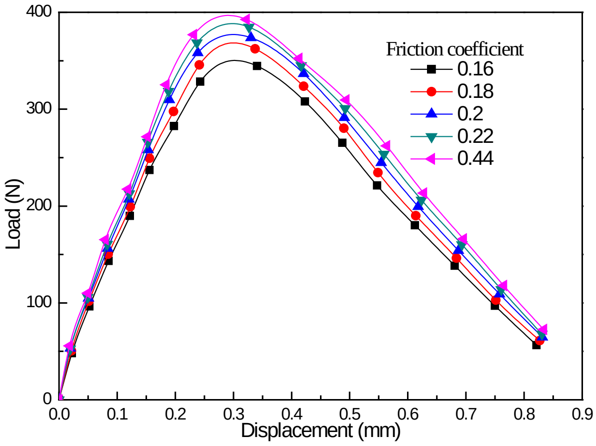


Figure 8 FEM curve with different COF

In order to make the contact pressure between the steel ball and the sample 250 MPa, the finite element numerical simulation is carried out for the samples with different diameters of the center hole. The results show that when the diameter of the hole is 2.42 mm, the average contact pressure between the steel ball and the sample is about 250 MPa. as shown in Figure 9, the LDC is obtained by SPT with the outer diameter of the sample is 10 mm, the center hole diameter is 2.42 mm and the thickness is 0.5 mm.

The finite element model was established according to the size of the test specimen. When the COF is 0.19, the simulation curve is closest to the experimental curve, as shown in Figure 10. On the left side of the highest point, the coincidence of the two curves is poor. The reason may be the dimension error of the sample that the ball and hole are not completely coaxial. On the right side of the highest point, the contact between the ball and the sample is stable, and the contact pressure is maintained at 250 MPa. As long as this part of the curves are coincident, it can be draw that the COF used in simulation is consistent with that in experiment. That is to say, 0.19 is the coefficient of friction of this material in the SPT.

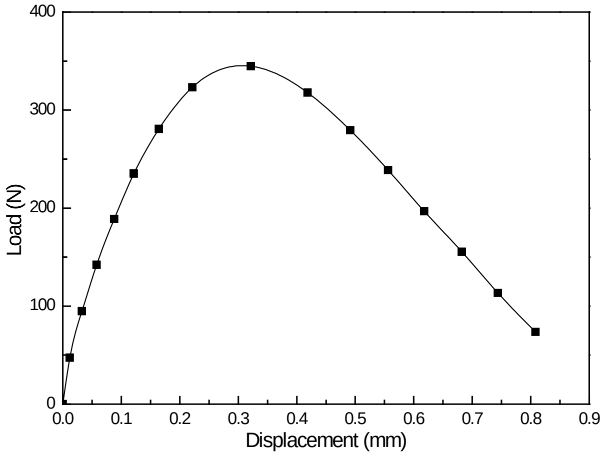


Figure 9 Curve of test

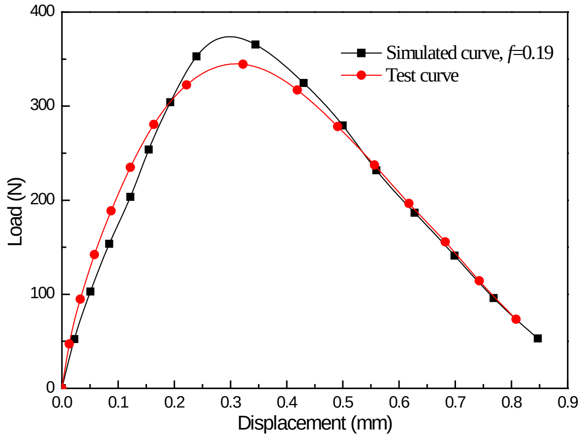


Figure 10 Curve of test and FEM

DETERMINATION OF A106 STEEL'S FRACTURE TOUGHNESS

The test method of the COF has been established, and a specific COF is obtained by this new method. In this part, the fracture toughness of A106 steel is obtained by using the IFEM by taking into account of COF influence. According to the four steps of the inverse finite element method, the solving process of fracture toughness of A106 steel is as follows.

Firstly, we get the LDC of A106 by the SPT, as shown in Figure 11. There is a unique corresponding relation between the true stress-strain curve and small punch load - displacement curve when the displacement is less than 0.65mm. In Figure 12, the LDC obtained from the SPT is compared with that obtained from inverse FEM. The tensile strength and yield strength of A106 steel are shown in Table 1.

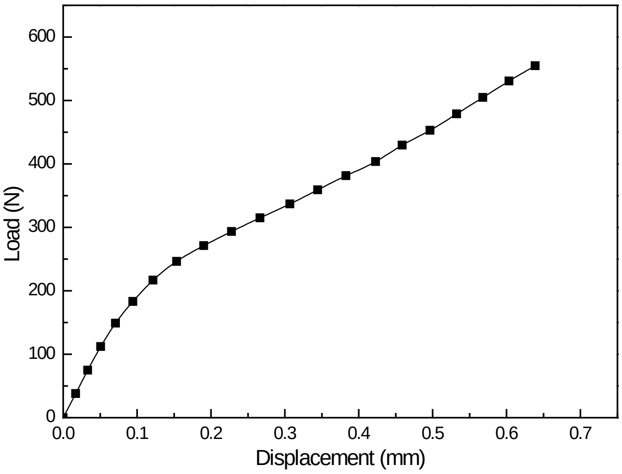


Figure 11 SPT curve of A106

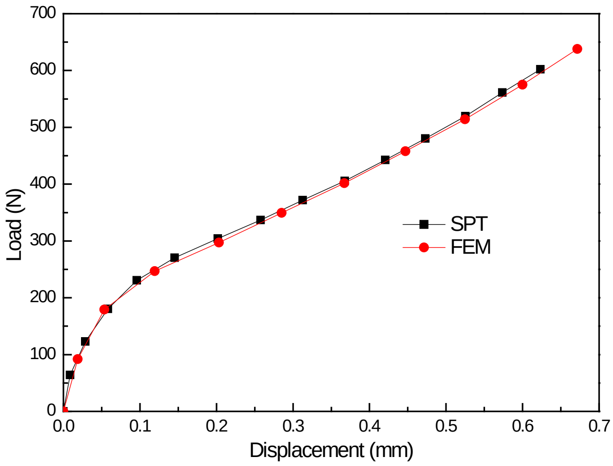


Figure 12 the LDC obtained from SPT and FEM

Table 1 Strength value of A106 steel obtained from IFEM and routine test

Parameter	Results of IFEM	Results of routine test	Error (%)
Yield strength R_{el} (MPa)	299.8	320	-6.3
Tensile strength R_m (MPa)	445	440	+1.1

Secondly, the main task is to derive GTN model parameter by inverse finite element method. When the displacement exceeds 0.65mm, the LDC is affected by the GTN model parameters and the COF. The COF has been obtained by the new measurement method. Therefore, GTN parameters and LDC curves have a one-to-one correspondence. There are 9 parameters in total in GTN model obtained by IFEM, as shown in Table 2.

Table 2 GTN parameter obtained by IFEM

Parameter	f_n	f_c	f_F	q_1	q_2	q_3	f_0	ε_n	S_N
Value	0.0249	0.1082	0.2007	1.5	1	2.25	0.00043	0.3	0.1

Finally, based on the existing parameters, the fracture toughness of A106 steel is achieved by finite element method. It should be noted that the fracture toughness parameter adopted in this paper is J integral. A 3D model of the S (E) B has been created in ABAQUS. The mesh of SEB model and crack tip are shown in Figure 13. The J-integral result was obtained by the method in the reference, See Zhang

(2014). The J integral of test and IFEM is shown in Figure 14. According to the standard GBT 21143-2007, J_R curve is plotted in Figure 15. The apparent crack initiation toughness obtained by inverse finite element method and test method are shown in Table 3. When crack extension is 0.2mm, the J integral is as the J_{IC}.

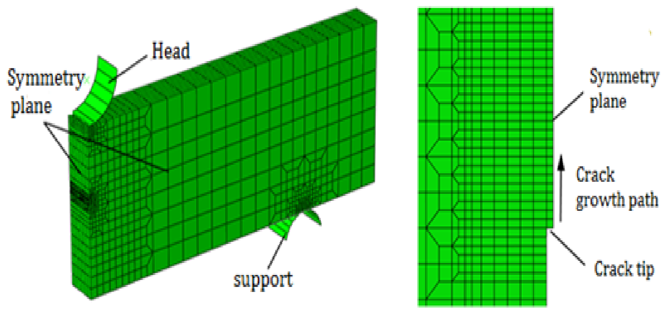


Figure 13 Mesh of crack tip

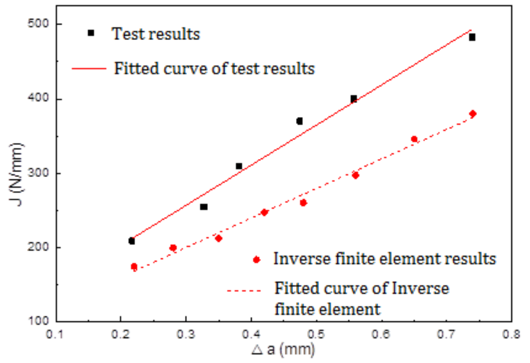


Figure 14 J integral of test and inverse FEM

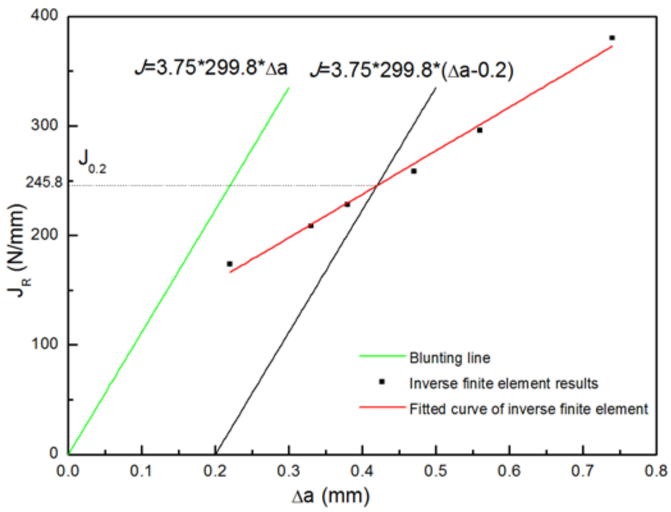


Figure 15 J_R curve by IFEM

Table 3 Error for inverse FEM and test

Initiation toughness	Result of inverse FE	Result of test	Error
$J_{0.2}$ (J_{IC})	245.8	280.58	-12.3%

CONCLUSION

In this paper, a method is presented to acquire the fracture toughness of the material by means of the small punch test and the inverse finite element method. To begin with, the IFEM theory and the procedures were introduced briefly. The influence of the COF and its measuring method are the main part of this paper, which was presented in the second part.

The contact pressure distribution between the steel ball and the specimen is investigated for the first time. The results show that the COF varies with the change of contact pressure. In small punch test, the contact pressure increase sharply after the initial loading, and decrease rapidly afterwards。 Numerical simulation shows that when the displacement goes beyond over 0.65mm, the contact pressure remained a fix value. When the displacement is less than 0.65 mm, the COF has little influence on the load displacement curve. By adopting a modified small punch test specimen, a new COF measurement method was prosed. With the proposed method, the COF was determined as COF=0.19.

The determination of the COF improves the accuracy of the IFEM. As an example, the fracture toughness of A106 steel is determined by the improved finite element method. The fracture toughness value is close to that acquired by the routine test, and the feasibility of the method is verified.

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