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A Simulation Model for Tensile Fracture Procedure Analysis of Graphite Material based on Damage Evolution

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Abstract – *Graphite material is generally easy to be damaged by the widely distributed micro-cracks when subjects to load. For numerically analyzing of the structure made of graphite material, the influences of the degradation of the material in damaged areas need to be considered. In this paper, an axial tension test method is proposed to obtain the dynamic damage evolution rule of the material. Using the degradation rule (variation of elastic modulus), the finite element model is then constructed to analyze the tensile fracture process of the L-shaped graphite specimen. An axial tension test of graphite is performed to obtain the stress-strain curve. Based on the variation of the measured curve, the damage evolution rule of the material are fitted out. A simulation model based on the above measured results is then constructed on ABAQUS by user subroutine. Using this simulation model, the tension failure process of L-shaped graphite specimen with fillet are simulated. The calculated and experimental results on fracture load are in good agreement. The damage simulation model based on the stress-strain curve of axial tensile test can be used in other tensile fracture analysis.*

I. INTRODUCTION

Graphite materials with good high temperature performance, good neutron moderator capabilities and low neutron absorption properties, is a key component of HTR [1] body, its structural integrity is directly related to the core of the integrity and security. Graphite is a quasi-brittle material [2-4], its structural integrity is commonly assessed with the conservative assumption of brittle fracture [5, 6]. The inelastic behavior of graphite is generally treated as negligible [7-8]. Yet post-initiation tension-softening behavior can play an important role in the integrity of components that are made of graphite material. Understanding and quantifying this effect could improve confidence in the safety margins of their structural integrity assessment. IG-11 graphite, manufactured by Toyo Tanso Ltd., Japan, is a fine-grained isotropic petroleum coke-based polycrystalline graphite made by the isostatic pressing method.

The L-shaped specimens were tested to examine the effect on the failure load of the radius in the corner. The corner is subjected to a tensile stress. This is similar to the load in a typical graphite moderated reactor component keyway root.

When components subjected to load, the stress concentration occurred near the fillet root, thereby weakening the strength and stiffness of the components, the carrying capacity of the components is reduced. So the stress concentration is often the starting point for the component damage, stress concentration is the main factor causing tensile fracture of L-shaped components [9, 10].

To study the stress concentration of graphite L-shaped component, the fracture mechanism of graphite the brittle material needs to be analyzed.

II. EXPERIMENT

II.A. Specimen geometry and load

The L-shaped specimens were designed following the recommendations of a recent paper [11]. The dimensions of the specimen are given in Fig. 1. All the specimens were machined to a tolerance of 0.1 mm with a surface finish of 0.01 mm.

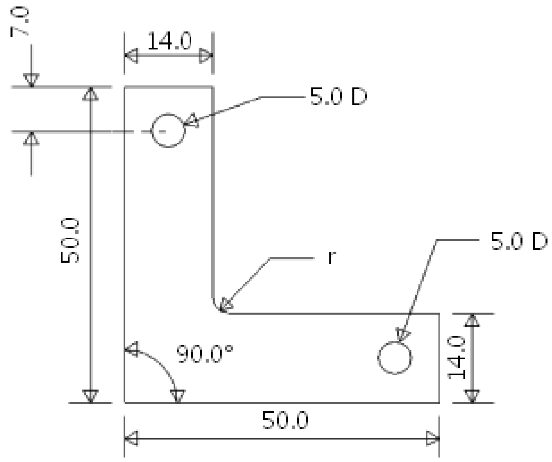


Fig. 1. Dimensions of L-shaped sample (in mm)

Which r = 1, 2, 3 mm, respectively. 10 specimens of each size are performed.

The key to measure the stress concentration coefficient of L-shaped specimens is to obtain specimens in load, due to the artifacts that stress concentration strongly, fracture load is small, so using the MTS Tytron250 (load range of 0 ~ 250 N, load resolution 0.01 N) micro force testing machine for testing.

Because of the brittle characteristics of the graphite and the special shape of L-shaped specimen, the ordinary loading rig of testing machine cannot meet the loading requirements. Therefore, we design a set of special loading rig, as shown in Fig. 2, to L-shaped specimens for clamping.

Fig. 2. The loading rig of L-shaped specimen

The specimens were loaded and supported on rollers. The L-shaped specimens were tested by placing a pin in each hole and attached to a loading rig and hence, the specimens were subjected to a tensile load. In every test the load/displacement curve was plotted and the maximum failure load noted. The experiment overview is shown in Fig. 3.

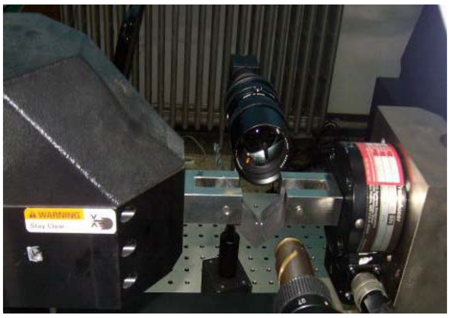


Fig. 3. The experiment overview

The samples were all tested in a MTS Tytron250 testing machine at a constant crosshead displacement rate of 0.05mm/min.

II.B. Experimental results

The typical stress and testing time curve of L-shaped specimen is shown in Fig. 4. Which r = 1mm, and the maximum fracture loads in each experiment are summarized in Fig. 5.

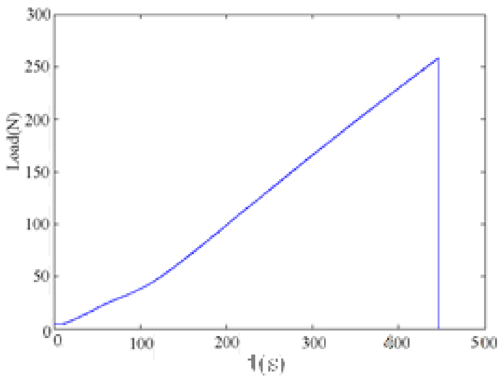


Fig. 4. Stress and testing time curve of L-shaped specimen in r = 1mm

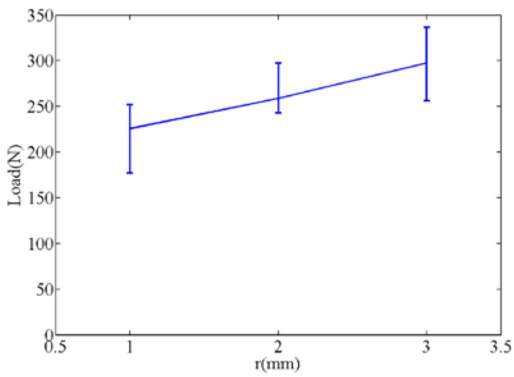


Fig. 5. Maximum fracture loads in each experiment

II.C. Elastic finite element model

As shown in Fig. 6, the L-shaped specimen is studied by finite element model. The finite element model of L-shaped specimen is established by ABAQUS software, as shown in Fig. 6 (right). Considering the symmetry of the specimen, 1/2 component model is taken. According to the actual loading ways of the experimental set boundary conditions:

Left symmetry boundary: X direction displacement symmetrical constraints.

Round hole: along the X axis is concentrated load.

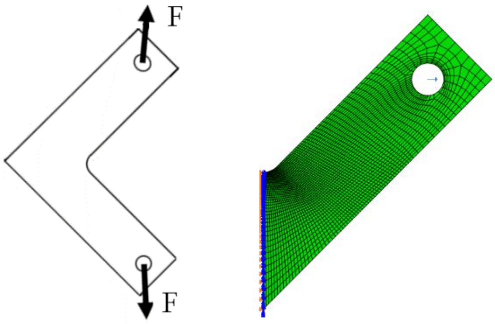


Fig. 6. The finite element model of L-shaped specimen

Graphite material is assumed to be linear elastic constitutive model, its elastic modulus is taken as 9.8GPa, Poisson ratio is taken as 0.14, and tensile strength is taken as 28 MPa [12].

Fillet radii of 1mm, 2mm and 3mm, 10mm thickness of four kinds of components were analyzed, respectively.

When the tensile stress reaches the tensile strength of fillet calculation stops. The load on the reference point of the round hole is recorded as the maximum failure load of the specimen.

II.D. Elastic FEM results

The comparison results of numerical simulation and experimental results are shown in Fig. 7.

Observe and analyze comparison curve in Fig. 7, we find that the numerical simulation results is much larger than the experimental results, and the greater the difference when a small corner radius, indicating that the material damage occurs at the fillet root, the stress is released, so the smaller the measured stress, resulting in the measured ratio of FEM stress concentration factor calculated stress concentration factor is small. When a small corner radius, damage is more serious, leading to the release of more stress, and therefore a greater difference. Then, in the numerical simulation process must consider the impact of material damage to get more accurate results of the L-shaped specimens. FEM method to use to accurately analyze the stress state components, you first need to consider the establishment of damage FEM models and methods, followed by access to the material but also the evolution of damage under stress under consideration, the following were discussed.

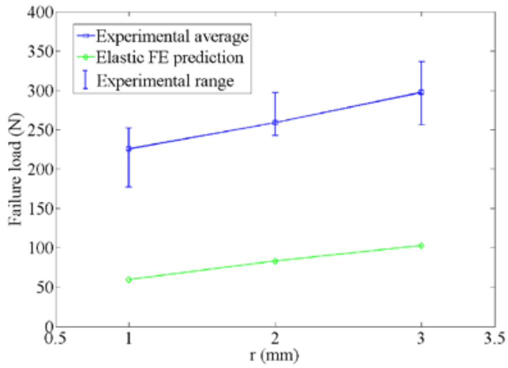


Fig. 7. The comparison results of numerical simulation and experimental results on maximum fracture load

III. METHOD

III.A. Uniaxial tensile experiment

To obtain the damage evolution of graphite, the simple uniaxial tensile experiment is taken. Because of the specimen in the simple unidirectional tensile stress state, it is easy to obtain the damage evolution due to tensile failure.

The uniaxial tensile specimens were designed following the recommendations of JIS7222-1979. The dimensions of the specimen is shown in Fig. 8.

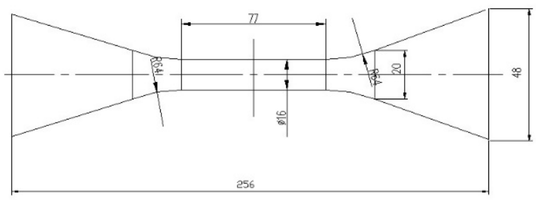


Fig. 8. The dimensions of the specimen (in mm)

The samples were all tested in a MTS testing machine at a constant crosshead displacement rate of 0.5mm/min. In order to ensure a neutral specimen loading, supporting jig is designed, the experiment overview is shown in Fig. 9. And in order to obtain the strain of the specimen, the electrical measurement method is taken. Each specimen is axially posted four strain gauges. 2 specimens are performed. In every test the stress and strain curve was plotted.

Fig. 9. Experiment overview

III.B. Experimental results

A summary of stress and strain curve for the L-shaped specimens is given in Fig. 10. And the average stress-strain curve and the fitting line of the elastic modulus during the period of elasticity are shown in Fig. 11.

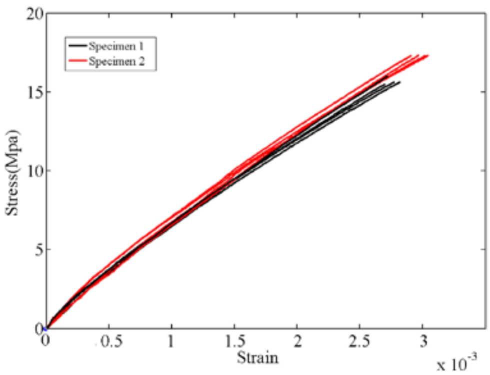


Fig. 10. Stress and strain curve for the L-shaped specimens

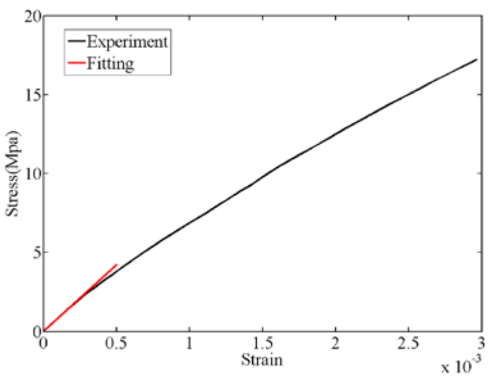


Fig. 11. The average stress-strain curve and the fitting line of the elastic modulus during the period of elasticity

III.C. Tensile failure damage model

During loading, the damage on the stress concentration part of L-shaped graphite components is accumulated, and the property of the volume unit continues to be degraded. Assuming the damage evolution is known as:

$$D = f(\varepsilon)$$

Where D is the damage variable during loading, and ε is the strain during loading.

According to the basic principles of damage mechanics [13] can be expressed as:

$$E = E_0(1 - D)$$

Where E_0 is the elastic modulus of no damage element. Then, the model considering damage of material can be expressed as:

$$\sigma = E\varepsilon = E_0(1 - D)\varepsilon = E_0\varepsilon[1 - f(\varepsilon)]$$

According to uniaxial tensile stress-strain curve, the damage evolution equation is proposed as:

$$D = 1 - \frac{(\varepsilon - \varepsilon_{cr})}{(\varepsilon_c - \varepsilon_{cr})} \times 0.3$$

Where ε_{cr} is the yield strain, and ε_c is the maximum tensile strain. ε_{cr} is approximately equal to one tenth of ε_c.

According to the results of uniaxial tensile experiment, the fitting of damage evolution equation is shown in Fig. 12.

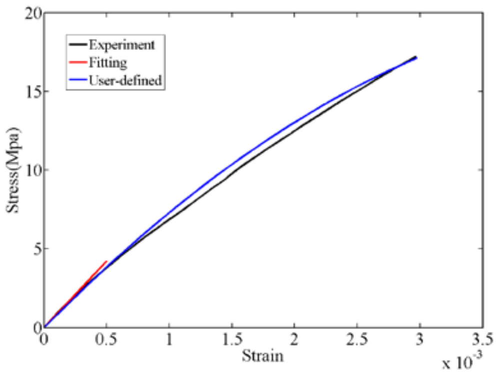
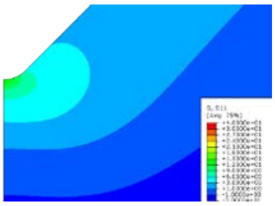
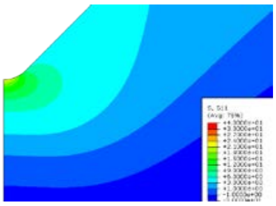


Fig. 12. Damage evolution equation

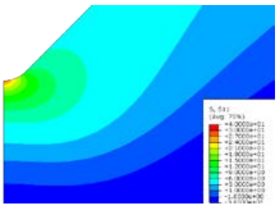
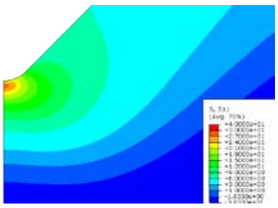
Since own model to ABAQUS does not consider the response of the damage of material, so we need to use the user subroutine included by ABAQUS software for secondary development. User subroutine USDFLD or VUSDFLD is typically used when complex material behavior needs to be modeled and the user does not want to develop a UMAT or VUMAT subroutine. By coding the USDFLD subroutine, the damage model can be added to calculate program.

III.E. Numerical results

The curve of the principal stress of the specimens with the radius of 2 mm and the load process is shown in Fig. 13. From the results we can find that, in the beginning to load, the stress value at the first corner with increasing load increases, after reaching a certain level, stress values began to decrease at the outside corner when the strain values kept increasing, as shown in Fig. 13(d). This is because the damage coefficient at the element of the fillet increase sharply with the increase of strain values, resulting in 38 step reached the maximum strain, the damage coefficient of the element is very close to 1, indicate that the unit almost completely destroyed. In the next step load has reached the maximum tensile strain and the element was fractured, the loading of the load of 246N.

(a) step1 (b) step10

(c) step20 (d) step38

Fig. 13 Principal stress field

Corresponding to loading curve of the L-shaped specimen given before, the numerical load curve the rounded 2mm specimen is also given, as shown in Fig. 14. Can be seen from the results at the start of the load while material internal damage, but the overall load curve of the specimens remains a good linear relationship. When the load reaches 246N, load curve produced bend, and lost the original linear relationship, which marked a qualitative material change. Because the coded secondary development did not consider to have the function of stress redistribution after elements fracture, so the displacement of the load in the next step will also increase, therefore the trend of numerical load curve without rapid drop, this part of the curve can be ignored.

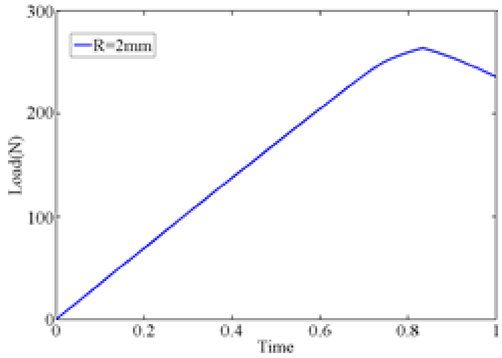


Fig. 14. Load curve

Corresponding to maximum fracture loads of the L-shaped specimen in each experiment given before, the numerical maximum load are also given, as shown in Fig. 15. It can be found that, comparing the calculation results given before using elastic model, the results of considering damage model are very close to the experimental results.

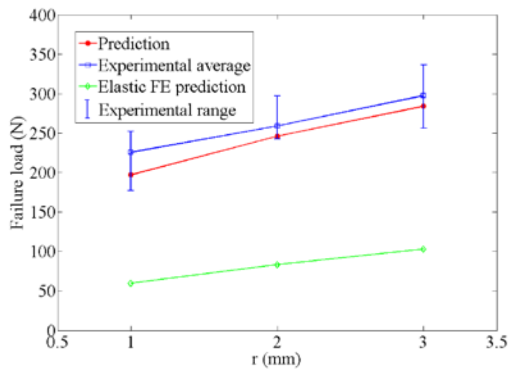


Fig.15. Comparison experimental and numerical results

IV. CONCLUSION

The assumption of elastic modulus for graphite material in the L-shaped specimen tensile experiment is perhaps too simplistic.

The current work provides a fundamental understanding and an easy way to consider material damage.

A deterministic damage model has been developed for graphite materials.

The model can correctly predict the failure behavior for the L-shaped specimens which have different strain gradients, including those with sharp corners.

V. ACKNOWLEDGEMENTS

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II.H. References

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