Mechanical damage behavior of two-phase material with the arbitrary morphology of particles

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1. Abstract

Two-phase materials have significant applications in the engineering field. During service, fracture is one of the most typical failure modes. In this study, the digital image-based technique (DIT), a micro-scale damage cohesive finite element model (CFEM) was employed to reconstruct the microstructures of a compacted graphite iron (CGI) with the arbitrary morphology of graphite particles. The cohesive finite element in this model can make the process of crack initiation and propagation spontaneously.

2. Cohesive model constitutive

With the development of computing technologies , the numerical simulation as a primary tool can provide a chance to predict the performance of materials.

The crack initiation of material is a very complex process. At present, the theory of macroscopic fracture mechanics is not able to provide the evaluation parameters and the theory of prediction within the crack initiation stage. The fracture theory cannot describe the process effectively, so damage theory should be employed. Meanwhile, the ferrite and graphite of compacted graphite iron (CGI) is also very complex. How to construct the model with arbitrary mesoscopic morphology effectively and accurately is the key to the simulation.

From its failure analysis, Cocco et al. studied the damaging micro mechanisms characterization of a ferritic ductile cast iron [1]. Transition of tensile strength and damage mechanisms of CGI with temperature was investigated and the relationship between yield strength of CGI, the strength of matrix as well as the graphite content was established by Qiu et al. [2, 3]. Although those studies mentioned above have a profound guiding significance for design and preparation of CGI [4-7], the experiment is time consuming and its cost is rather expensive. All the studies above focused on the elastic stage, while the intrinsic damage mechanism of materials was not considered.

In this paper the methods based on the DIT and CFEM have been well developed, which could be applied to spontaneously investigate the initiation and propagation of cracks in materials containing two-phases, due to the embedded cohesive element.

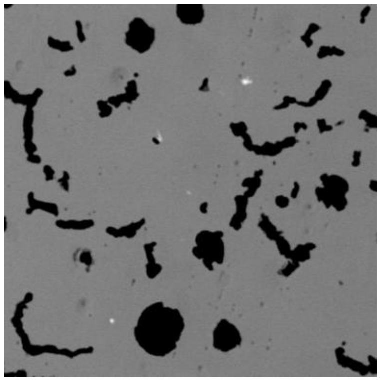

Fig. 1. Micrograph of a two-phase material: compacted graphite iron (ferrous matrix: gray area, graphite particles: black spots)

As an important two-phase material, CGI is widely used in the cylinder head of diesel engine. It mainly consists of two phases, i.e., ferrous matrix and graphite particles as shown in Fig.1

Table 1 . Material properties of CGI and cohesive model constitutive parameters [8]

Phase	Ferrite	Graphite	Interface
Bonding strength(GPa)	$T_{max} = 430$	$T_{max} = 40$	$T_{max} = 300$
Fracture energy (J/ m^2)	$\Phi = 39.71$	$\Phi = 0.029$	$\Phi = 20$
Critical separation (nm)	$\Delta_c = 9.23$	$\Delta_c = 6.04$	$\Delta_c = 3.33$
Fracture toughness (MPa·m^{½})	$K_{IC} = 96.3$	$K_{IC} = 0.7$	
Density(10^3kg/m^3)	$\rho = 7.85$	$\rho = 1.82$	
Young' Modulus(GPa)	$E = 210$	$E = 17$	
Poisson's ratio	$\nu = 0.3$	$\nu = 0.2$	

In this subsection, the digital image-based technique (DIT), a micro-scale damage cohesive finite element model (CFEM) was employed to reconstruct the microstructures of a compacted graphite iron (CGI) with the arbitrary morphology of graphite particles. A kind of CGI was taken to validate the cohesive damage model. Modeling parameters are shown in Table 1. The material parameters include bonding strength $t_{\max}$, fracture toughness K_{IC}, density ρ, Young's modulus E and Poisson's ratio ν of ferrite and graphite, which were referred to [8]. Its fracture toughness was calculated using an empirical relation (Eq. (1)).

$$K_{IC} = 0.79\left[\sigma_{0.2}\left(A_{KV} - 0.01\sigma_{0.2}\right)\right]^{1/2} (MPa \cdot m^{1/2}), \quad (1)$$

$$t = \frac{\partial \Phi}{\partial \Delta}. \quad (2)$$

$$\Phi = \frac{1}{2} t^{\max} \cdot \Delta_c. \quad (3)$$

Where Δ_c is critical separation and A_{KV} is impact energy.

3. Finite element discussions

Since in engineering applications, the compressive and tensile loading is also frequently encountered. To test the present model further, the simulation of uniaxial compression and tension test are employed.

In order to validate current cohesive element method quantitatively, the yield strengths determined by the experimental and computational tensile stress-strain curves are 299 MPa and 278 MPa. Cohesive method has a small error of 6.7%, which indicates an accurate prediction of experiment result and then it validates the reliability of current method. It is clear that current cohesive damage model can precisely predict the mechanical properties of CGI.

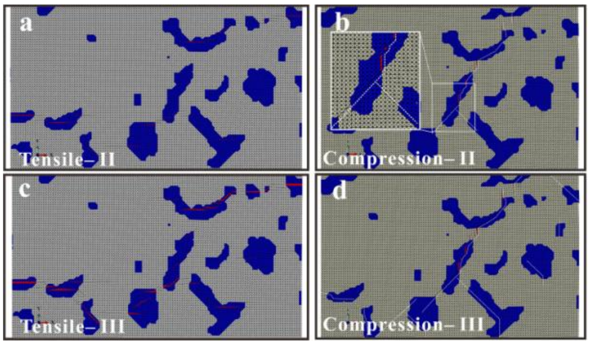

Fig. 2. Microstructure morphology and crack sketches under tensile loading ((a) ,(c)) and compressive loading ((b) , (d)).

Fig. 2b and Fig. 2d show that the fracture mechanism of compressive loading is quite different from that of the tensile loading. The magnified image in Fig. 2b reflects the failure mode of CGI, the red line means the micro-crack, and element distortion and invasion occur in the left of the dash line. At the failure stage, the phenomena of distortion and invasion are more obvious, see the dash line in Fig. 2d. Based on the holistic trend of micro-cracks, the fracture mechanism under compression loading is shear fracture and the opening angle is about 40°.

4. Conclusions

Based on the data reconstruction technique and cohesive element model on the meso-scale, the initiation and propagation of cracks for CGI under tensile and compressive loadings were studied. The conclusions can be summarized as below:

1). By using the CGI as the model material, based on the DIT and CFEM, the simulation of graphite particles with arbitrary morphologies and random distribution was conducted.

2). Based on the embedded cohesive element, the crack initiation and propagation mechanisms of CGI under tensile and compressive loadings were analyzed.

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