Research on Mesoscopic Damage Mechanics Model and Ductile Fracture Criterion of Metal Forming Process

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Abstract: The study of damage and fracture analysis in metal forming by means of mesoscopic damage mechanics has attracted much attention in recent years.Metal fracture and damage is due to the emergence of micropores, expansion and accumulation of the process of development.Therefore, on the basis of micropore mesoscopic damage, the establishment of a certain ductile fracture criterion can effectively predict the occurrence of cracks in metal formation process.In this paper, a brief overview of microdamage mechanics is given at first, and then a series of microdamage models and ductile fracture criteria for metal are expounded according to the evolution process of micropores.

Introduction

Ductile fracture occurs when the metal material is subjected to a certain degree of external force. The formation of micropores degrades the quality of the metal. The development of damage mechanics can make people better judge the ductile fracture of metal in the forming process. There are two research directions of damage mechanics: one is the macroscopic damage mechanics, the other is the microscopic damage mechanics. Next, the microscopic damage mechanics model and the ductile fracture criterion of metal are discussed.

1. Brief description of mesoscopic damage mechanics

Damage mechanics is the study of the law of damage change of various materials under the action of external forces. Continuous damage mechanics is often used to study the strength and service life of material structure. In this paper, mesoscopic damage mechanics is mainly discussed. Mesoscopic damage mechanics is used to study the damage of material based on the microscopic changes of material structure. The research scale of mesoscopic damage mechanics is the combination of medium mechanics and micromechanics.There are many mechanisms of mesoscopic damage, such as microcracks and micropores. Microcrack damage is generally aimed at some composite, ductile materials, such as concrete, tile, etc.However, the ductility of metal materials is relatively good, so its fracture is a process of plastic change, which is commonly referred to as ductile fracture or plastic fracture.

2. Evolution of micropores during ductile fracture of metal

(1) The appearance of micropores. The reason for the formation of micropores is that the microstructure of metal materials is not uniform, often containing some other inclusions, commonly known as the second phase particles. The formation of micropores is closely related to the second phase particles. Generally, the micropores exist in the vicinity of the inclusion, or the fracture of the inclusion itself, or the inclusion falls off from the matrix.

(2) Expansion of micropores. With the continuous action of external forces, the plastic deformation of metal materials around the micro-holes is also increasing, and the micro-holes are also expanding and expanding.

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(3) The aggregation of micropores.When the plastic deformation of the metal material around the micropore reaches a certain amount, the plastic limit of the material is exceeded, and the local connection and aggregation between the micropores will form visible cracks.

3. Micropore mesoscopic damage model

(1) In the early stage of the study of micropore mesoscopic model, the research work of McClintock Rice and Tracey is more classic. Their research object is the ideal plastic material under the condition of single hole, analyzed the micro holes around the material of the plastic limit, and describes the increase as the degree of triaxial stress, the rule of micro size holes has increased rapidly, mainly studies the evolution of the close link between hole and the hole mechanism.

(2) On the basis of the previous research results, gershon constructed an equation to describe the influence of micropores on the plastic change of materials, which made a great breakthrough in the study of pore mesoscopic damage. Formula (1) is as follows

$$\phi(\sigma_e,\sigma_m,\overline{\sigma},f) = (\frac{\sigma_e}{\overline{\sigma}})^2 + 2fcosh\left(\frac{\sigma_m}{2\overline{\sigma}}\right) - 1 - f^2 = 0$$

Where, σ_e is equivalent stress.$\overline{\sigma}$ represents the yield limit of a material under plastic change. σ_m refers to the average stress.f refers to the volume proportion of the micropore.

Gerson is not assuming an infinite matrix material, but a finite one. The matrix material is based on the proposed microvoids. Four kinds of volume cell models were used to describe the volume proportion f of micropores and other microscopic models. The damage characteristics and rules lay a foundation, which facilitates the use of volume averaging to deduce the macroscopic properties of materials.

Tvergaard further improved on the basis of gesen's plastic equation. He added the above equation to the idea of the relation between the holes which are close to the uneven stress of the nearby materials and the reduction of the stress bearing capacity caused by the expansion of the holes, and obtained a new formula (2).

$$\phi(\sigma_e,\sigma_m,\overline{\sigma},f) = (\frac{\sigma_e}{\overline{\sigma}})^2 + 2fq_1\cosh\left(\frac{q_2\sigma_m}{2\overline{\sigma}}\right) - 1 - q_3f^2 = 0$$

q_1,q_2,q_3 are the correction coefficient for equation 1.

The expansion rate of the microporous matrix material is determined by the expansion rate of the matrix material. Tvergaard concluded that there is a critical point of hole volume fraction f in the process from hole formation to hole confluence, which leads to material damage. That is, once the critical value is exceeded, the damage increases sharply.

Based on the characteristics of the evolution process of holes in materials and the influence of the double factors of material stress and material expansion rate on the evolution process of holes, Zheng Changqing et al. put forward the theory of multistage formation of holes under the control of combined work, and further improved the above equation, and established a meso-damage model based on this theory.

Lim proposed a coupled elastoplastic and viscoplastic mesoscopic damage model, which is a kind of metal composite material after particle enhancement. The model is aimed at the effect of particle enhancement state, volume ratio and distribution on material deformation, damage and hole evolution. This model is used to calculate that the pore evolution has a decisive relationship with the volume proportion of the reinforcing particles, and the critical value of the volume proportion f of the pore under the action of stress and deformation is 1/5.

According to Huang's research, the appearance or expansion of pores will cause local stress to exceed a certain value and generate plastic flow, and he also gives a parameter to indicate the influence of the appearance and expansion of pores on local plastic flow. If the size of two-phase particles is large due to the expansion of pores, the appearance of pores is the main factor for the local plastic flow; otherwise, the expansion of pores is the main factor for the local plastic flow. Moreover, Huang concluded from the comparison of experimental data that the stress-induced pore emergence mechanism is more likely to generate local plastic flow under low plastic pressure than the stress-induced pore emergence mechanism.

Thomson established a 1/8 cell cell model, which is to add a set of particles with linear arrangement into the cell of the cell hole, and analyze the damage degree of the particle set to the hole and the material in the plastic material. It is found that the critical stress when the material is completely destroyed is related to the direction of the particle set. When the pores are constantly evolving and polymerization occurs between adjacent pores, the place where the pores evolve changes from within the particle set to between the particle sets, the pore polymerization rate will increase abruptly until the material is completely destroyed.

Bandstra has proved through experiments that the growth of pores is related to the polymerization rate and the distance between pores, that is, the closer the distance between pores is, the faster the evolution of pores will be, and a geometric model will be abstracted. Through the analysis of the geometric model, it is concluded that the expansion rate in the early stage is the same as that in the case of a single hole, but with the gradual evolution of the hole, the expansion rate will increase significantly due to the influence of holes with similar distances.

Mesoscopic damage mechanics model and evolution mechanism of holes, under the excellent expression of micro plastic fracture formation and explain the process of material damage but in practical applications, the mesoscopic damage model need more in a project whether metal materials or other materials before fracture, namely to application in metal material quality inspection, therefore, it is also related to the researchers should pay attention to one direction.

4. Analysis of ductile fracture criterion of metal materials

Because the toughness of metal material has a certain limit, that is, its bearing capacity and the ability to continue deformation is limited, if the metal fracture degree is too high, beyond its toughness limit, it can not continue deformation. In order to control the construction quality by determining when the metal material will fracture before a process is carried out, we need to establish relevant ductile fracture criteria. Above, the mechanism of ductile fracture of metal materials is introduced by micropore damage mechanics. Most ductile fracture criteria are based on the formation, expansion and polymerization of micropores. Relevant researchers have made great efforts in the establishment of ductile fracture criteria. At present, there are numerous data of ductile fracture criteria formed on different foundations, and the following discussion will be made on different ductile fracture criteria.

4.1 Ductile fracture criterion based on stress and strain states

Introducer	Basis	Fracture criterion
Cockroft et al.	They believe that ductile deformation and fracture are mainly caused by the maximum tensile stress, and the fracture occurs when the work done by the tensile stress per unit area reaches a certain value. Therefore, the following criteria are proposed.	Formula（3）
Borrzo	Borrzo believed that the ratio of average stress would slow down or promote the process of material damage, so he proposed the following criteria.	Formula（4）
Mcclintock	It can be seen from the above that the study of damage mechanics of micropores is closely related to the ductile fracture of materials. With the gradual development of mesoscopic damage mechanics,	Formula（5）

	many researchers use the critical points in the evolution process of the emergence, expansion and aggregation of micropores as the basis for the establishment of the toughness criterion.Mcclintock proposed an evolution model of an elliptic cylindrical cavity under radial stress. When the cavity grows and touches the boundary of the element body, the material is considered to be fractured. He proposed the following fracture criteria.	
Oyane	Based on the cumulative damage caused by plastic deformation and the plastic theory of loose materials, the following fracture criteria are proposed	Formula（6）
Zhang Keshi	According to the microscopic observation of the evolution process of the pore, Zhang Keshi et al. believed that the fracture of the material under the microscopic condition was equivalent to the occurrence of the largest first-order pore. Therefore, the conditions for the formation of the largest hole can be used as the criterion of ductile fracture. The appearance of holes is controlled by stress and strain. According to zhang, the material will be damaged when the work density W (the work of deformation and expansion of material per unit volume) of the resultant force reaches a certain critical value	Formula（7）

Table 1. Comparison of several ductile fracture criteria

Formula（3）:

$$\int_0^{\varepsilon_t} \sigma_1 d\bar{\varepsilon} = C$$

The above is formula (3), in which ε_t---Critical strain value at fracture of material; σ_1---Maximum tension stress; C--Material constant.

Formula（4）:

$$W_{vp} = \int_0^t \sinh\left(\frac{0.5\sigma_k}{\sigma_e}\right) dt$$

Formula（5）:

$$\int_0^{\varepsilon_t} \left[\frac{2}{\sqrt{3}(1-n)} \sinh\left\{ \frac{\sqrt{3}(1-n)}{2} \quad \frac{\sigma_1+\sigma_3}{\bar{\sigma}} \right\} + \frac{\sigma_1}{}\right.$$

Among n---Coefficient of hardening

Formula（6）:

$$\int_0^{\varepsilon_t} \left(1+\frac{\sigma_m}{A\sigma}\right) d\bar{\varepsilon} = G, \quad G = \int_0^{\varepsilon_v} \left(f^2\rho^{2n-1}\right) d\varepsilon_v$$

Among ρ---Density of material; A—Stress value correction factor

Formula（7）:

$$W = W_s + F_p W_{vp} = W_F$$

$$W_s = \int_0^t \sigma_e \bar{\varepsilon} dt, \quad W_{vp} = \int_0^t \sinh\left(\frac{0.5\sigma_k}{\sigma_e}\right) \sigma_k \bar{\varepsilon} dt$$

Among $\bar{\varepsilon}$---Equivalent macro. Toughness. Strain capacity; F_p--Reflect the holes in the material. Swelling capacity; W_s、W_{vp}--These are called plastic shapes. Change the work density and the plastic volume. The work density, the elastic volume work density. negligible; W--Material constant。

Through the comparison of the above different fracture criteria (see table 1), it can be found that many fracture criteria are expressed in the form of integral ductile fracture criteria by using the theory that stress and stress force states jointly play a role in material fracture. When the stress is low, the damage in the three dimensions results in a large deformation resulting in plastic flow; when the stress is high, the damage in the three dimensions shows that the material may exist simultaneously with the accumulation and evolution of the holes, or may separate from each other. It depends on the properties of the material. At present, there are still many scholars who compare the predicted results of different fracture criteria with the experimental results of specific plastic processing technology, analyze and summarize the advantages and disadvantages of different fracture criteria, and try to find a more applicable fracture criterion to adapt to different fracture conditions and explain the impact of damage on ductile fracture.

4.2 Application effect of ductile fracture criterion

Venugopal et al. compared the ductile fracture criteria commonly used in the engineering analysis of 10 volumetric forming problems, and evaluated their accuracy and sensitivity (that is, the dispersion of the calculation errors of different deformation methods). Their results showed that these ductile fracture criteria were not accurate enough and were poorly applicable

Komori et al. analyzed several different ductile fracture criteria. Crack propagation in metal drawing process. It turns out that the aforementioned basis. The gesen and Oyane fracture criteria for the mechanism of hole evolution. Axial fracture expansion simulated with other faults. The former is in good agreement with the experimental results.

Fahrettin et al. applied the ductile fracture criterion based on stress and strain state mechanism to describe the forming limit diagram of materials.It is found that the predicted material forming limit diagram is in good agreement with the left part, but there is a big deviation in the right part.He believed that the deviation was due to the neck shrinkage in the right half of the material forming limit diagram, which was mainly due to the expansion and accumulation of holes.Therefore, in order to better match the forming limit diagram predicted by the fracture criterion with the experimental results, it is necessary to consider whether the microscopic damage mechanism and pore evolution of the material fracture formation have effects on the necking, so as to improve the existing fracture criterion.

5. Problems in the study of mesoscopic damage mechanics

The mesoscopic damage model proposed and modified by gershon, Tvergaard and Needleman was introduced earlier, and has been applied in some relevant neighborhood. However, there are still many problems in the development of mesoscopic damage mechanics:

At present, the evolution mechanism of micropores is not fully understood, and there are still some fields that have not been broken, such as how the size, state and distribution of inclusions affect the process of hole formation, expansion and aggregation. Different deformation in different stages will cause the damage of the same factor to the material to be different. (2) In the existing mesoscopic damage model, the microstructure of the material is too simplified and idealized in the assumed conditions. For example, the material parameter is not a specific constant and needs to be determined through a complex experimental process. Therefore, the research in this field should be further developed. (3) There is a lack of a widely applicable and normative ductile damage criterion. At first gershon thought that the material would break if the hole's volume ratio was 100%, but this was not true. Overgaard's determination of critical hole ratio by single direction tensile test is 15%, which is also quite different from the actual situation. Most ductile fracture criteria consider that the fracture of materials has a turning point.

This turning point is considered a material constant. In the case of the actual complex microstructure and the force doing work, this turning point is not so easy to determine in a simple experiment. Because of these conditions, some fracture criteria are only applicable to a specific process scope and do not have good guiding significance to other processes. The critical hole volume ratio is a significant material damage variable, because it can better reflect the change of the hole and the expansion of the material volume. Therefore, the method of function modification can be considered to change the critical pore volume ratio from fraction to a constant, so as to establish a new and meaningful ductile fracture criterion.

6. Brief summary

In a word, with the mesoscopic damage mechanics methods to analyze the micro fracture of metal material is the basis of study the macroscopic properties, and in order to better judgment of ductile fracture of metal conditions, optimizing the metal forming effect, we should promote the development of the study mesoscopic damage mechanics, the change of direction from macroscopic to microcosmic experiment, see the essence through the phenomena. At the same time, a uniform ductile fracture criterion with strong applicability is established.

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