Plastic Damage Evolution in Low-carbon Steels

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ABSTRACT

In this paper, the plastic damage evolution in two chinese low-carbon steels during tensile straining are studied experimentally by using smooth tensile specimens and circumferentially notched specimens. The results show that both stress state and plastic deformation have great influence on the damage evolution, and the internal microvoid damage plays a significant role in ductile fracture. A comparision of the present experimental results with the damage model proposed by Tai and Yang(1986) is made and a good agreement is found.

KEYWORDS

Plastic damage evolution; continuum damage mechanics; mild steel; void nucleation; void growth; void coalescence.

INTRODUCTION

Many investigations have shown that ductile fracture in metals involves three successive damage processes which are the nucleation of microvoids from inclusions, void growth and void coalescence. For a ductile solid containing a macrocrack, the similar damage processes take place in the intensely deformed nonlinear region called "Damage zone" at the crack tip, and the internal damage plays a significant role in ductile fracture and crack initiation. However, the details of the microvoid damage processes are still poorly known because they are often markedly affected by the material structure and the stress state. In addition, it is difficult to make a continuous direct observation of these processes which take place inside a specimen.

In this study, the plastic damage evolution process in low-carbon steels 20 and A3 (chinese steels) are experimentally investigated with the smooth tensile specimens and circumferential notched specimens, by using two kinds of quantitative microscopy methods, and the relationships between the microvoid damage D, the stress triaxiality ($\sigma_m/\bar{\sigma}$) and the effective plastic strain $\bar{\varepsilon}_p$ are obtained, which are approximately agreement with the theoretical prediction by Tai and Yang(1986).

EXPERIMENTAL PROCEDURE

The materials used in this study are two chinese low-carbon steels: 20 and A3. The chemical compositions and the mechanical properties are listed in Table 1 and Table 2 respectively.

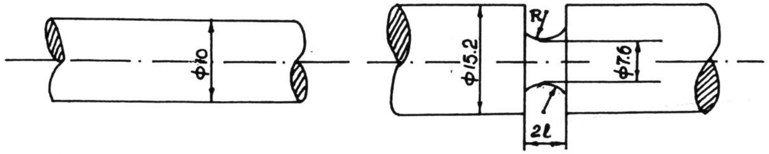
Table 1. Chemical compositions of tested materials

Material	C	Mn	Si	P	S
20	0.20	0.65	0.24	0.035	0.025
A3	0.18	0.60	0.15	0.038	0.024

Table 2. Mechanical properties of tested materials

Material	σ_y(MPa)	σ_b(MPa)	E(GPa)	T.E.(%)
20	279	468	205	26
A3	245	411	200	25

Both smooth cylindrical tensile specimen and circumferentially notched specimen are used and ten groups of specimens with different notch root radius for each material are prepared, as shown in Fig. 1(a,b). The specimens are loaded using a 50KN MTS880 material testing machine with a cross-head speed of 0.4 mm/min at the room tempureture, and the specimens are pulled either to fracture or to different strain corresponding to different degrees of necking.



(a) (b)

Fig. 1. Tension specimens. (a) smooth, (b) notch.

In order to observe the plastic damage processes—void nucleation, void growth and void coalescence, the metallographic examination of the deformed specimens is performed on longitudinal section through the tensile axis and transverse section cross the tensile axis. In the experiments, two types of samples are prepared respectively by mechanical polish method and brittle fracture method (Shi and Barnby, 1984), and metallographic observation on the mechanically polish section and on the brittle fracture section are carried out. The plastic damage behavior under different stress state and different plastic deformation are obtained.

It is found that void nucleation predominantly takes place at the interfaces between inclusions and the matrix in the necked portion of the specimens. Initially, the void is formed at some part of the interface on the inclusion. The deformed matrix is then separated from the inclusion. Then the void grows along the whole surface of the inclusion and grows further with increasing of plastic deformation, until the coalescence between two neighboring voids occurs.

For the smooth tensile specimens, the plastic damage processes are mainly dependent on plastic deformation of the specimens. When the plastic strain $\varepsilon_p \approx 0.12$, only a few voids can be observed and the void area density is very small. As the plastic deformation increases, new voids are appearing and the older ones grow, and the void density increases slowly, approximately linearly with the plastic strain ε_p, until a damage strain threshold ε_0 is reached (e.g. $\varepsilon_p \approx 0.18$). After that, the internal damage is mainly caused by the growth of voids and the void area density increases rapidly. When the plastic strain ε_p reaches a critical value $\varepsilon_c(=0.90-0.95\varepsilon_f)$ the void coalescence is observed, and ductile failure occurs subsequently, as shown in Fig.2(a-d) and Fig.3(a,b).

For the circumferentially notched specimens, the similar damage processes are observed. The results show that both stress triaxiality $\sigma_m/\bar{\sigma}$ and plastic strain $\bar{\varepsilon}_p$ have significant effects on the plastic damage evolution in the materials studied.

EXPERIMENTAL RESULTS

Here, the damage variable used to describing the damage process is defined by(Lemaitre, 1984)

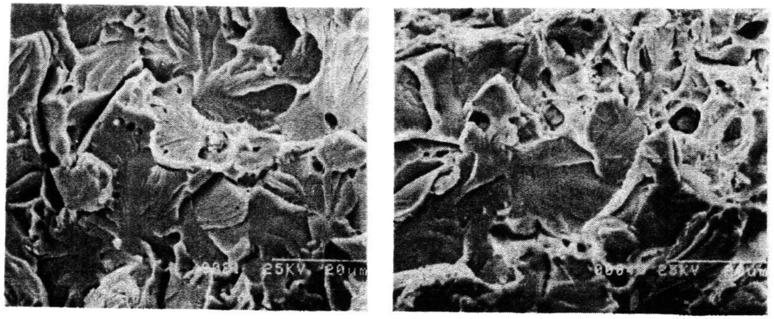
$$D=1-A_{eff}/A=A_v/A \qquad (1)$$

which is identical with the void area fraction in material and is a macroscopic measure of the microscopic geometrical deterioration of the material.

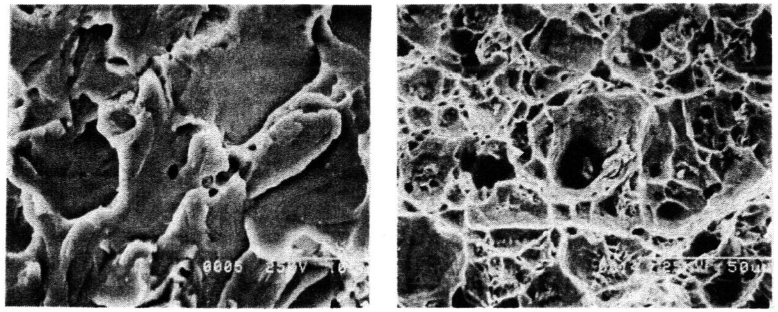
For the smooth tensile specimens of steel 20, the plastic damage D is plotted as function of the plastic strain ε_p in Fig.4, which shows that the plastic damage evolution experiences three damage stages: damage generation, damage growth and damage instability. In stage I the damage is very small and is principally caused by void nucleation. In the stage II the damage is related to void growth and the damage evolution may be expressed as follows:

$$D=D_0\cdot\exp\left[C\cdot(\varepsilon_p-\varepsilon_0)\right] \qquad (2)$$

which is the same as the theoretical equation proposed by Tai and Yang(1986), where D_0 is the initial damage corresponding to the damage strain threshold $\bar{\varepsilon}_0$, C is a material constant. In stage III, the plastic damage evolution is corresponding to void coalescence and the damage varies suddenly. For this reason, it is difficult to make accurate observation of damage evolution in this stage.

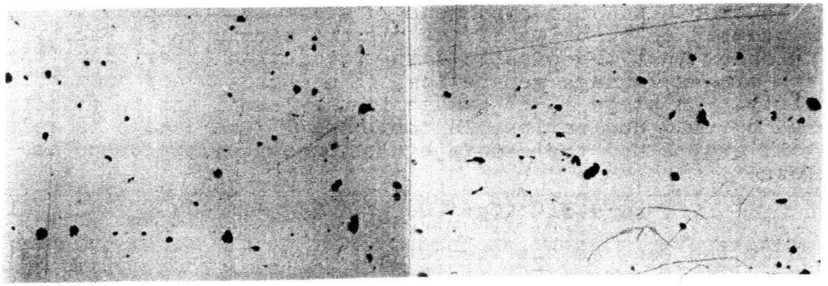


(a) ε_p=0.20 (b) ε_p=0.55



(c) ε_p=1.02 (d) ε_p=1.15

Fig. 2. Scanning electron micrograph of brittle fracture section.
(a) void nucleation,
(b) void growth,
(c) void coalescence,
(d) ductile failure.



(a) (b)

Fig. 3. Optical micrograph of mechanically polished section.

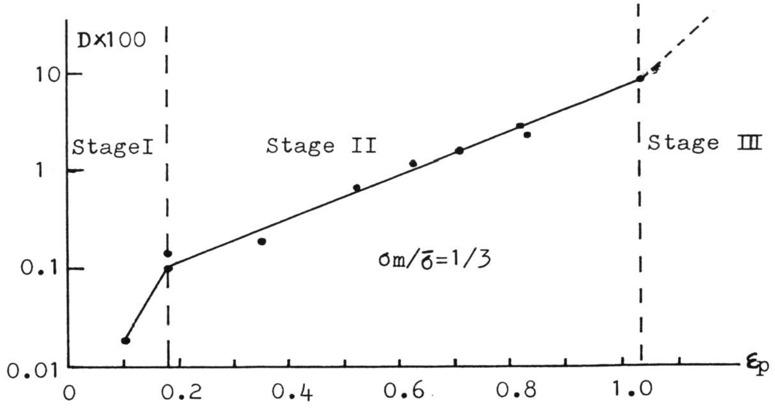
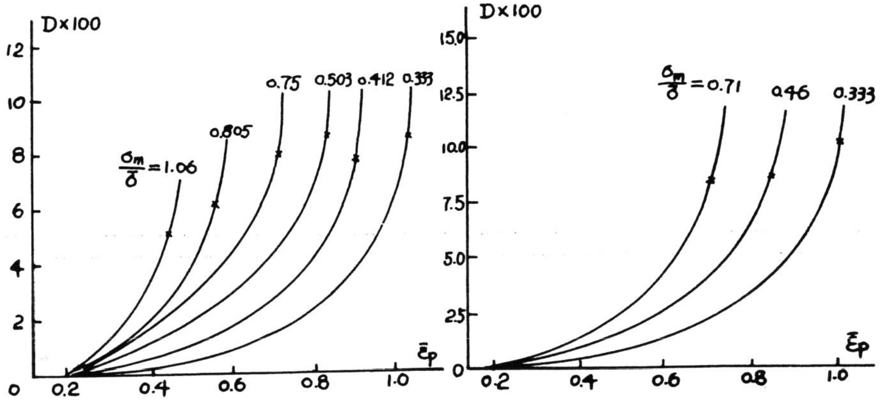


Fig. 4. Damage evolution in the smooth specimens of steel 20.

For the notched specimens of two steels, the measured plastic damage D are obtained as function of the stress triaxiality ratio $\sigma_m/\bar{\sigma}$ and effective plastic strain $\bar{\varepsilon}_p$, as shown in Fig.5(a,b). It is clear that the plastic damage D is greatly affected by stress state. The greater the stress triaxiality $\sigma_m/\bar{\sigma}$ is, the greater the damage will be. The experimental results are in good agreement with the damage evolution equation given by Tai and Yang(1986):

$$D=D_0\cdot\exp\left[C\cdot f(\sigma_m/\bar{\sigma})(\bar{\varepsilon}_p-\bar{\varepsilon}_0)\right] \qquad (3)$$



(a) (b)

Fig. 5. Plastic damage evolution in mild steels (a) 20 and (b) A3.

where

$$C = \frac{1}{\varepsilon_c - \varepsilon_0} \ln({}^{D_c}/D_0) \tag{4}$$

$$f(\sigma_m/\bar{\sigma}) = \frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{\sigma_m}{\bar{\sigma}}\right)^2 \tag{5}$$

ν is the Poisson's ratio.

CONCLUSIONS

1. Ductile failure involves three damage processes which are damage generation, damage growth and damage instability.

2. The plastic damage evolution in low-carbon steels is strongly affected by the stress and strain states.

3. The theoretical damage evolution equation is in good agreement with the experimental one.

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