Three Stages of Ductile Fracture Process and Criteria of Void Initiation in Spheroidized and Ferrite/Pearlite Steels*

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Synopsis

Microscopic investigation of ductile fracture processes has been made in the course of tensile deformation of spheroidized and ferrite/pearlite steels by means of transmission and scanning electron microscopies.

In the beginning of deformation, dislocation tangling occurs in the vicinity of a spheroidal carbide and a cell structure forms around a pearlite nodule. These dislocation structures protect second-phase particles from highly localized stress concentrations and delay the void initiation to a considerably late stage of deformation.

Basing on these observations, criteria for void initiation at both spheroidal carbides and pearlite nodules are discussed. The stresses on the second-phase particles can be estimated by modifying the Fisher-Hart-Pry (FHP) model for dispersion hardening.

In spheroidized steels, the void initiation takes place when the stress on carbides reaches their fracture stress. In ferrite/pearlite steels, the imposed stress on pearlite nodules induces slips of pearlitic ferrite and the secondary stress concentration exerts to cementite lamellae due to the dislocation pile-ups. This secondary stress can be predicted by Ansell-Lenel model and void initiation occurs when the secondary stress overcomes the fracture stress of cementite.

I. Introduction

There has been a large amount of experimental evidence¹⁻⁷⁾ to show that ductile fracture process of materials consists of three stages, *i.e.*, initiation, growth and coalescence of voids, and second-phase particles play an important role as sites of void initiation. Total ductility of materials, therefore, can be expressed as a sum of the ductility of each stage, as schematically shown in Fig. 1.

In 1962, Edelson and Baldwin⁸⁾ found that ductility of material depends primarily upon the volume fraction of second-phase particles.

Following at heel, several models⁹⁻¹⁴⁾ have been proposed to account theoretically for the above-mentioned experimental result. Most of these models, however, deal mainly with the void growth stage (stage II) assuming that the amount of strain before void initiation is negligibly small ($\epsilon_I \doteq 0$).

However, there is considerable evidence^{15,16)} that void formation occurs at sufficiently large strain and total ductility can be no longer discussed without taking the first stage of ductile fracture process into consideration. Despite the importance of the first stage, the mechanisms and criteria for void initiation are far from good understanding.

The present paper describes the details of observation of ductile fracture process, especially focusing on the stage of void initiation, in spheroidized and ferrite/pearlite steels by means of TEM (Transmission Electron Microscopy) and SEM (Scanning Electron Micro-

scopy). In addition, a model and criterion for void initiation are proposed.

II. Experimental Procedure

The chemical composition of materials used in this investigation is given in Table 1. Steels A and B are commercial grade plain carbon steels (JIS S10C and S40C, respectively) and steels D through G are high purity Fe-C binary alloys induction-vacuum-melted as 90 kg laboratory scale heats. All of the steels were hot forged into bar stocks of 13 mm dia. and were subjected to heat treatments to give the spheroidized and ferrite/pearlite structures. To obtain the spheroidized structures, specimens were quenched and tempered for various hours at 700°C. This treatment gives uniformly distributed carbide particles of average sizes ranging 0.3 to 1.9 μm . For ferrite/pearlite structures, steels were austenitized and cooled in air (normalized).

Tensile specimens with gauge section of 7 mm dia. by 25 mm long were machined out of the heat treated bar blanks. The strain was given by an Instron-type tensile tester at cross-head speed of 5 mm/min. In

Fig. 1. Schematic representation of three stages of ductile fracture process. Total ductility or fracture strain (ϵ_f) is a sum of strains of stages I and II, because the strain of stage III being highly localized and having little effect on macroscopic strain.

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Table 1. Chemical composition of steels (wt%)

Steel	C	Si	Mn	P	S	Al	Note
A	0.11	0.20	0.43	0.017	0.018	0.030	Commercial
B	0.40	0.33	0.85	0.016	0.008	0.034	
D	0.39	0.05	0.008	0.007	0.005	0.021	Vacuum-melt Laboratory heat
E	0.58	0.05	0.008	0.009	0.006	0.021	
F	0.72	0.04	0.008	0.007	0.006	0.022	
G	0.91	0.04	0.008	0.012	0.005	0.020	

order to observe the various stages of deformation, tensile test was interrupted at various strains. Thin foils for TEM observations were prepared using an etchant of 7% perchloric acid solution in glacial acetic acid. SEM observations were carried out on the longitudinal sections of fractured tensile specimens varying the distance from fracture surface end. The detail of this technique and analysis of strain at the position of observation have been described in the previous papers.^{18,19)}

III. Experimental Results

1. Observation of Ductile Fracture Process in Spheroidized Steels

1. Dislocation Structure around Spheroidal Carbides

Once plastic deformation begins, spheroidal carbides hinder the motion of dislocations in matrix. Photograph 1 shows a dislocation-carbide interaction at a very beginning of deformation of a spheroidized steel (steel A spheroidized for 30 hr and strained to $\epsilon=0.03$). As the deformation proceeds, and therefore as dislocation density around carbides increases, the tangling of dislocations begins to occur as shown in Photo. 2.

At a larger strain, it can be seen that carbides become surrounded by tangled dislocations, just looking like a cocoon of silkworm, as shown in Photo 3. The cocoon of tangled dislocation protects the carbide particle from the highly localized stress concentration, but it is expected to impose the averaged stress on the carbide particle.

2. Void Initiation at Spheroidized Carbides

As mentioned above, the cocoon of tangled dislocations exerts stress on the whole on the carbide and the stress is expected to be related closely to the density of dislocation around the particle. Therefore, the stress on the carbide increases gradually with increasing the strain of specimen and this stress will be quantitatively discussed later.

The strength of carbide (cementite in this case) is sufficient to sustain the stress without undergoing plastic deformation up to a considerable strain of the specimen. As can be seen in Photo. 3, the contour patterns in carbide indicate that the strain of carbide remains within the elastic limit. At a higher strain of the specimen, as can be seen in Photo. 4, dislocations and slip traces begin to appear in carbide and eventually void initiates at carbide when the stress exceeds the fracture stress of the carbide. The criteria

Photo. 1. Dislocation structure around carbide in steel A, microstrained to $\epsilon=0.03$

Photo. 2. Tangled dislocations around carbides in steel A, strained to $\epsilon=0.05$

Photo. 3. "Cocoon" of dislocation around carbide formed at strain $\epsilon=0.1$ in steel B

of void initiation will be also discussed later.

3. Growth and Coalescence of Voids

In spheroidized steels as stated above, void forma-

tion occurs at so large strain that high density of dislocation makes the TEM observation difficult and obscure. Moreover, it is difficult to distinguish the intrinsic voids from pits introduced during the preparation of thin foil. The observation of the later stage of deformation is carried out by SEM.

Photograph 5 shows the sequences of ductile frac-

Photo. 4. Dislocations introduced in carbide (cementite) at strain $\varepsilon=0.3$ (steel A)

(a) Void initiation ($\varepsilon=0.5$)
(b) Void growth ($\varepsilon=1.0$)
(c) Void coalescence ($\varepsilon=1.3$)

Photo. 5. Sequences of ductile fracture process in the spheroidized steel D observed in SEM

ture process occurring in the spheroidized structure of steel D. Photograph 5(a) illustrates the void initiation to take place at around $\varepsilon=0.5$ and it is noteworthy that voids form both by decohesion of carbide/matrix interface and by cracking of carbide with virtually the same frequency. In the course of deformation, voids grow preferentially in the direction of tensile axis (horizontal direction in Photo. 5(b)), and these voids coalesce and link up each other followed by the final fracture (Photo. 5(c)). The well-known dimples on the ductile fracture surface are formed at this stage, and moreover, it has been clearly demonstrated^{16,17)} that the number of dimples in a unit area of fracture surface corresponds quantitatively to the number of carbide in the structure as can be seen in Fig. 2.

It should be noted from these observations that void initiation occurs at a considerably large strain, *e.g.*, as can be seen in Photo. 5(a) in a 0.39% C steel, void initiation occurs at around $\varepsilon \approx 0.5$ which corresponds to about 40% of the total strain to fracture. This fact strongly suggests the importance of the first stage of ductile fracture. It is also noteworthy that voids grow and elongate preferentially to the direction of tensile axis, especially in a low carbon steel as shown in Photo. 6.

Fig. 2. Relation between dimple density on fracture surface and carbide density in steel B spheroidized for various times ranging 1 to 200 hr

Photo. 6. Highly elongated voids suggesting that growth of void occurs preferentially to the direction of tensile axis (steel A)

2. Observation of Ductile Fracture Process in Ferrite/Pearlite Steels

1. Dislocation Structure around Pearlite Nodules

Regarding pearlite nodules as second-phase particles, ductile fracture process of ferrite/pearlite steels is describable in the analogy with spheroidized steels. Although a pearlite nodule is much larger in size comparing to a spheroidal carbide, it acts as an obstacle against the motion of matrix dislocation in the course of deformation.

Transmission electron microscopic observations reveal that tangling of dislocations begin to appear in the vicinity of pearlite nodule at strain around $\varepsilon \approx 0.05 \sim 0.1$ and well-developed cell structure at around $\varepsilon \approx 0.2$. Photograph 7 shows the cell structure developed around a pearlite nodule in steel E strained to $\varepsilon \approx 0.2$ and it is noteworthy that cells tend to be elongated and curved along the circumference of the sphere of nodule.

2. Void Initiation at Pearlite Nodule

The authors have reported^{18,19)} that, during the deformation of ferrite/pearlite steels, the strain of specimen is expected to partition between the two phases and the partitioning rate is strongly dependent on the volume fraction of pearlite. In the course of deformation of ferrite/pearlite steels, dislocations in

matrix ferrite become operative at first and motions of dislocation follow in pearlitic ferrite (ferrite lamellae in the pearlite nodule). Photograph 8 shows slip traces and dislocations in the pearlitic ferrite in steel E strained to $\varepsilon = 0.1$. As the strain of the pearlitic ferrite increases, the stress concentration on the cementite plate increases and eventually microcracking takes place. Photograph 9 illustrates the cementite plates in pearlite nodule of steel E strained to $\varepsilon = 0.2$, showing that one of the cementite plate has just microcracked and the adjacent cementite plate is about to crack. Once the microcracking occurs at one cementite plate, it tends to propagate successively to the neighboring cementite plate along the slip direction of pearlitic ferrite and results in the alignment of microvoids as shown by the arrow A in Photos. 10 and 11. These aligned microvoids are ready to link up and open up to a void as large as the size of pearlite nodule (arrow B in Photo. 10). Another example of void formation at a pearlite nodule is shown in Photo. 12. In this case, microvoids initiate preferentially at ferrite/cementite plate interface (arrow A in Photo. 12) and aligned microvoids link up by tearing off the cementite to form void (arrow B).

Photo. 7. Cell structure around pearlite nodule in steel E, strained to $\varepsilon = 0.2$. Cells tend to be elongated and curved along the circumference of nodule.

Photo. 8. Slip traces and dislocations in pearlitic ferrite in normalized steel E, strained to $\varepsilon = 0.1$.

Photo. 9. Cementite lamellae just after microvoid initiation in steel E, strained to $\varepsilon = 0.2$.

Photo. 10. Microvoids aligned along the slip direction of ferrite (arrow A) and they link up and open up to void (arrow B). (steel E)

Photo. 11. Microvoids alignment induced in steel E, strained to $\varepsilon=0.2$

Photo. 12. Microvoids occurring at ferrite/pearlite lamellar interface (arrow A) and void formed by tearing off of cementite lamellae (steel E)

3. Mode of Fracture of Cementite Plate

It is reported that cementite in ferrite can plastically deform to a considerable extent,^{20,21)} and the fracture of cementite occurs either in brittle or ductile manner at room temperature.²²⁾ Photograph 13 shows tips of cementite plates at a void formed in steel E strained to $\varepsilon=0.5$. As can be seen here, many slip traces are visible in the cementite plate adjacent to void, and moreover, the fracture occurs preferentially parallel to slip trace. These observations, together with Photo. 11, suggest that cementite lamellae are fractured in a ductile manner.

4. Void Growth and Coalescence in Ferrite/Pearlite Structure

The stages of growth and coalescence of voids associated with pearlite nodules are strongly affected by the volume fraction of pearlite involved. In low or medium carbon steels, the mean ferrite path between pearlite nodules is sufficiently large that voids grow at the expense of ferrite matrix. However as the

Photo. 13. Slip traces in cementite lamellae adjacent to the void in steel E, strained to $\varepsilon=0.5$

Fig. 3. Fracture strain and strain to void initiation as a function of volume fraction of pearlite

volume fraction of pearlite increases, the amount of strain associated with the stage II decreases. Figure 3 shows the fracture strain and the strain to void initiation as a function of volume fraction of pearlite.¹⁸⁾ It is obvious from this result that the strain after void initiation ($\varepsilon_{II} = \varepsilon_f - \varepsilon_I$) decreases with increasing of volume fraction of pearlite.

Photograph 14(a) shows just beneath the fracture surface and Photo. 14(b) indicates the dimples of fracture surface of the normalized medium carbon steel (steel D). It can be seen that voids are formed at pearlite nodules and link up with each other by means of internal necking of ferrite. As shown in Photo. 14(b) the debris of pearlite at the bottom of dimple is surrounded by the high ridge of ferrite in a medium carbon steel. The height of ferrite ridge (or the depth of dimple) decreases with increasing of pearlite volume fraction, and hence, with decreasing of the amount of strain in the second stage of ductile fracture. Photograph 15 shows the low ridge of grain

Photo. 14. (a) Microstructure near fracture surface, and (b) fracture surface showing debris of pearlite at the bottom of dimple (steel D)

boundary ferrite in a steel with nearly eutectoid composition. Furthermore, with increasing of pearlite volume fraction, the manner of linkage of voids changes from the internal necking mode to the shear-like as shown in Photo. 16 in a eutectoid steel.

The mode of linkage is largely affected by the characteristics of the matrix between voids, *i.e.*, the strain hardening exponent (n -value) plays an important role. The smaller the n -value, the more strain tends to localize, and hence the voids may link up by shear to an increasing extent. Since the n -value of pearlite is very small,^{18,19)} it is reasonably expected that the strain of the stage II of a eutectoid carbon steel is extremely small and fracture occurs immediately after the initiation of void, in accordance with the experimental result shown in Fig. 3.

IV. Discussion

1. Void Initiation at Spheroidized Carbide

Once plastic deformation begins, dislocations moving in the matrix are hindered by particles of the second-phase and exert the stress on them. If the particles are strong enough, they sustain the stress up to a considerable extent of strain and void formation eventually occurs when the stress on particles exceeds their fracture stress. According to this model, void initiation criteria will be reasonably derived if the stress on the particles can be appropriately evaluated.

Ansell and Lenel (AL)²³⁾ and Fisher, Hart and Pry (FHP)²⁴⁾ have put forward theories dealing with the stress arising from the interaction between dislocations and obstacles. AL assume dislocation pile-ups

Photo. 15. Shallow dimples surrounded by grain boundary ferrite ridge formed on the fracture surface of nearly eutectoid steel F

(a) Sharp voids immediately underneath of fracture surface
(b) Fracture surface in eutectoid steel G

Photo. 16. Arrows indicate voids introduced just before fracture

against particles whereas FHP consider the dislocation loops around a particle.

Gurland²⁵⁾ and Barnby²⁶⁾ calculated the stress required to initiate voids according to the AL model. However the stress predicted through this model is too small and the strain at void initiation may be within the elastic limit of matrix. Moreover, FHP point out that pile-ups can be formed only by linear obstacles since the by-passing of dislocations occurs and

loops must be left around the non-linear obstacles such as spheroidal particles.²⁷⁾

The stress on the particle due to dislocation loops is given, according to FHP, as

$$\tau = \frac{N\mu b}{2R} \quad \dots\dots\dots(1)$$

where, R : radius of a particle
 N : number of loops
 μ : elastic modulus of matrix
 b : Burgers vector.

In practice, tangled dislocations are found instead of the oversimplified loops in the vicinity of carbide as shown in Photo. 3. Therefore, it is of importance to evaluate N in Eq. (1) as a function of dislocation density. To evaluate N , it is assumed that the stress on particles arises from dislocations, of the average density ρ , lying between R and $(R+r)$ around a particle of radius R , and then the total length of dislocations in this region is given by $4\pi R^2 r \rho$. On the other hand, if the dislocations are replaced by N dislocation loops of radius R , total length of loops being $2\pi RN$. Then we obtain

$$2\pi RN = 4\pi R^2 r \rho \quad \dots\dots\dots(2)$$

or

$$N = 2Rr\rho \quad \dots\dots\dots(2)'$$

Substituting this relation in Eq. (1) gives

$$\tau = r\rho b\mu \quad \dots\dots\dots(3)$$

It is reasonably assumed that the void formation occurs when the stress expressed by Eq. (3) reaches the fracture stress of particles.

On the other hand, dislocation density ρ is related with strain (ε) and available slip distance of dislocation (A) as

$$\rho = \frac{\varepsilon}{Ab} \quad \dots\dots\dots(4)$$

and the available slip distance is assumed to decrease with increasing strain according to²⁸⁾

$$A = \frac{k}{\varepsilon} L \quad \dots\dots\dots(5)$$

where, L is interparticle spacing and k is constant relating to the critical strain at which the constriction of available slip distance becomes clear due mainly to the interaction between dislocations.

Now we obtain the strain to void initiation (ε_1) by substituting Eqs. (4) and (5) in Eq. (3) and putting τ as τ_c , the fracture stress of carbide,

$$\varepsilon_1 = \sqrt{k \frac{L\tau_c}{r\mu}} \quad \dots\dots\dots(6)$$

Equation (6) predicts that void initiation strain increases proportionally to square root of the interparticle spacing and this parabolic law is in good agreement with the experimental result reported in the previous paper.¹⁶⁾ The verification of this equa-

tion will be quantitatively discussed later.

2. Void Initiation in Ferrite/Pearlite Steels

As stated in the preceding section, TEM observation showed that cell structures are predominant around pearlite nodules and they tend to be elongated and curved along the circumference of pearlite spheres (Photo. 7). Then it is assumed, for simplification, that dislocations in the cell are forced to bend at the radius of pearlite nodule and nodules are suffered to stress as a reaction. This stress increases as the all-over strain increases and void formation occurs when the stress on pearlite nodules exceeds their fracture stress. Basing on this model, void initiation strain (ε_1) for ferrite/pearlite steels is given by replacing τ_c in Eq. (6) into the fracture stress of pearlite (τ_p) and can be written as

$$\varepsilon_1 = \sqrt{k \frac{L\tau_p}{r\mu}} \quad \dots\dots\dots(7)$$

Since Eq. (7) is derived in the analogy of spheroidized structure, it is of importance to keep in mind that this equation is only valid for the ferrite/pearlite structure with sufficiently large mean free ferrite path, in other words, up to about 0.6% C steels. The validity of this equation will be also discussed later.

3. Cementite Plate Fracture in Pearlite Nodule

In the course of deformation of the ferrite/pearlite structure, pearlite nodule deforms to the extent in accordance with the strain partitioning. Once pearlite nodule begins to deform, dislocations in pearlitic ferrite become operative and pile up against cementite plates since the cementite plate is regarded as a linear obstacle for moving dislocations. For the stress concentration to the linear obstacle, Ansell-Lenel (AL) model dealing with dislocation pile-ups are applicable and given as

$$\tau = \frac{2S\sigma^2}{\mu b} \quad \dots\dots\dots(8)$$

where, $2S$ is the mean free path of dislocation, corresponding to the lamellar spacing of pearlite and σ is the stress on the pearlite nodule. Putting τ as the fracture stress of cementite, τ_c , σ gives the stress on the pearlite required to initiate voids by rewriting Eq. (8)

$$\sigma = \sqrt{\frac{\mu b}{2S} \tau_c} \quad \dots\dots\dots(8)'$$

Since σ corresponds to fracture stress of pearlite nodule τ_p in Eq. (7), then we obtain the void initiation strain of ferrite/pearlite steels as

$$\varepsilon_1 = \left(k \frac{L}{r}\right)^{1/2} \cdot \left(\frac{b\tau_c}{2S\mu}\right)^{1/4} \quad \dots\dots\dots(9)$$

4. Verification of the Proposed Criteria

In the preceding sections, some equations predicting the stresses on the particles and the strains to void initiation at particles are proposed for spheroidized

and ferrite/pearlite steels. The verification of these equations will be checked using the well accepted material constants; the Burgers vector of iron $b=4\times 10^{-8}$ cm, the elastic modulus of iron $\mu=10^4$ kg/mm², the fracture stress of cementite $\tau_c=10^3$ kg/mm² (after Collins²⁹) and Webb³⁰) and the fracture stress of pearlite nodule $\tau_p=10^2$ kg/mm².^{6,18)}

(1) Equation (3) gives the relation between the stress on the particles and the density of dislocations around the particles. From the photographs, *e.g.*, Photo. 3, it is reasonable to estimate r to be the order of the thickness of cell wall, *i.e.*, $r=0.1$ μ m. Let the stress given by Eq. (3) be equal to the fracture stress of cementite, τ_c , the critical density of dislocation to initiate voids is calculated as $\rho_c=2.5\times 10^{11}$ /cm, which is reasonable enough and is in good agreement with the value predicted in the previous papers.^{16,17)}

(2) Equation (6) predicts the strain to void initiation as a function of interparticle spacing of spheroidized steels, and the result agrees quantitatively with the experimental value^{16,17)} as shown in Fig. 4. (Here we put $k=0.2$ because the remarked restriction of free path of dislocation begins to occur at around this strain.)

(3) Similarly, the strain to void initiation for ferrite/pearlite steel is given by Eq. (7) as $\varepsilon_1=0.71$ for 0.05% C steel ($L=25$ μ m) and $\varepsilon_1=0.45$ for 0.58% C steel ($L=10$ μ m), and these calculated values are in good agreement with experimental values, $\varepsilon_1=0.78$ and 0.38, respectively (See Fig. 3).

(4) For the cementite lamellae cracking, Eq. (8) (or (8)') predicts the fracture stress of pearlite to be $\sigma=115$ kg/mm² (for the pearlite with lamellar spacing of 0.3 μ m), being in accordance with the commonly observed fracture stress of eutectoid carbon steels.

(5) Finally, Eq. (9) predicts the tendency that the strain to void initiation decreases as the pearlite lamellar spacing increases. Although there has been no experimental data showing the relation between pearlite lamellar spacing and strain to void initiation, it is well established that the coarser lamellae are detrimental to the ductility of pearlite.^{31,32)}

V. Conclusions

The ductile fracture process during tensile deformation of spheroidized and ferrite/pearlite steels have been studied by means of transmission and scanning

electron microscopies. As deformation proceeds, spheroidized carbides become surrounded by tangled dislocations, just as the cocoon of silkworm, which prevent particles from premature formation of void due to the highly localized stress concentration. The averaged stress on the particles is evaluated as a function of dislocation density from the modified Fisher-Hart-Pry model.

In ferrite/pearlite steels, cell structures are predominant around pearlite nodules. The stress on the pearlite nodule is also evaluated in the analogy of spheroidized steels.

Under this stress, pearlite nodule deforms according to the strain partitioning and secondary dislocations become operative in the pearlitic ferrite and impose the stress concentration on the cementite plate. The void initiation occurs at pearlite nodule when the stress on the cementite plate reaches its fracture stress. Basing on these models, the criteria for the strain to void initiation are put forward for spheroidized and ferrite/pearlite steels and the verification of the proposed mechanism was carried out. Although in the present models the stress relief³³⁾ and uniformity of Burgers vector of dislocations are not taken into consideration, these models prove to account qualitatively, and to a considerable extent quantitatively, for the ductilities of spheroidized and ferrite/pearlite steels.

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Fig. 4. Variation of strain to void initiation with interparticle spacing in spheroidized steel B. Experimental data are compared with the calculated values by Eq. (6) putting $k=0.2$ (solid line).

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