On Ductile Fracture of Steels Containing the Coarse Second Phase

By Yō TOMOTA**, Yasufumi KAWAMURA*** and Kōshiro KUROKI****

Effects of the strength and microstructure of the coarse second phase on tensile ductile fracture processes were studied. The materials used were 0.16% carbon steel composed of ferrite(matrix) and martensite or pearlite colony(coarse second phase). With an increase in martensite strength which was adjusted by tempering temperature, void formation mode was changed from a fracture of the colony to a decohesion at the interface, and fracture strain($\epsilon_f$) was decreased. This decrease of $\epsilon_f$ was due to a decrease of void initiation strain($\epsilon_{iv}$). In comparison with martensite colony's case, number of voids produced during deformation and $\epsilon_f$ or $\epsilon_{iv}$ relation in ferrite-pearlite material were quite different. The reason seemed to be in the anisotropic fracture strength of pearlite colony.

1. Introduction

When a specimen is subjected to tensile deformation, voids are initiated due to a fracture of the second phase particle or a decohesion at the interface, and then they grow to coalesce themselves, which leads to the final fracture. This is a common feature of the ductile fracture process in various commercial materials\(^1\) -\(^6\). Up to date, many models of the ductile fracture have been proposed, but none of them can explain the experimental results sufficiently\(^6\)\(^-\)\(^3\). The reason seems to lie in that the above process is influenced by various metallurgical factors in a complex manner.

The void initiation has been discussed from the stand point of the energy balance\(^1\) or the stress criteria\(^5\)\(^-\)\(^3\)\(^1\). In such cases, the magnitude of the internal stress caused by a difference in plastic strain between two component phases plays an important role. The internal stress depends not only on the volume fraction, the shape or the size of the second phase\(^1\)\(^-\)\(^2\)\(^1\) but also on the ductility of the second phase\(^1\)\(^4\). The effect of the latter factor on the ductile fracture, however, has not been clarified yet, while the effects of the former factors have been examined well.

If one tries to apply the models of void-coalescence\(^6\)\(^-\)\(^6\)\(^6\), the data concerning

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** Assistant, Dept. of Mech.Engng., Faculty of Engng., Ibaraki University, 4-12-1 Nakanarusawa-Machi, Hitachi 316.  
*** Student of Graduate School of Ibaraki University(now at Nippon Gakki Co., Hamamatsu).  
**** Professor, Dept. of Mech.Engng., Ibaraki University.

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1 The colony of tempered martensite or pearlite is larger in size compared with a small second phase such as inclusions or precipitates. Therefore, to distinguish the former from the latter, the term "coarse second phase" is used in this paper. The coarse second phase is one of the void initiation origins as can be seen in pearlite colony, martensite colony\(^1\)\(^6\)\(^-\)\(^7\), or $\beta$ phase in $\alpha$-$\beta$ Ti alloys. In the case of the coarse second phase, the observation of the voids is easy because large voids are formed.
(i) Austenitizing at 1423 K for 12 h $\rightarrow$ holding at 1003 K for 3 h $\rightarrow$ quenching in water $\rightarrow$ tempering at 473, 573, 673, 773, or 873 K for 1 h $\rightarrow$ quenching in water.

(ii) Austenitizing at 1423 K for 4 h $\rightarrow$ furnace cooling.

The heat treatments were conducted in a vacuum condition (below $10^{-4}$ Pa). The microstructure consisting of ferrite and tempered martensite was obtained by heat (i) and that consisting of ferrite and pearlite by heat (ii). Hence, the former will be called material A and the latter material B.

Figure 2 shows typical micrographs of both materials, where (a) is the case of tempering at 873 K. In material A, the features of optical micrographs, i.e., the volume fraction, size, and shape of the martensite colony did not change but the etching condition was influenced by the change of martensite substructure with tempering temperature.

The volume fraction of the coarse second phase and grain size measured by the linear analysis on optical micrographs are shown in Table 2. Figure 3 shows Vicker's hardness (load 25-200g) of ferrite or of the coarse second phase. The effect of heat treatment on the hardness of ferrite matrix was very small in comparison with that of the coarse second phase. Tamura, et al. (29), have shown that the ratio of hardnesses between two constituents had a close relation with that of the yield strength between two single phase alloys of relevant constituent phases. Thus, these specimens are considered suitable for the purpose of the present study.

The connectivity of the second phase on which Suzuki, et al. (16) stressed was almost isolated.

Tensile tests were carried out by an Instron type and an Amsler type testing machine at a crosshead speed of about 5 mm/min.

Using specimens in Fig. 1(a), the longitudinal sections of fractured specimens which were made by cutting along the tensile direction after Ni plating, were

Table 2 Volume fraction and size of the coarse second phase (colony)

<table>
<thead>
<tr>
<th>Material A</th>
<th>Material B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(martensite)</td>
<td>(pearlite)</td>
</tr>
<tr>
<td>Volume fraction</td>
<td>0.23</td>
</tr>
<tr>
<td>Grain size $\mu$m</td>
<td>31</td>
</tr>
</tbody>
</table>

![Fig. 2 Typical optical micrographs; (a)ferrite-martensite(material A), (b)ferrite-pearlite(material B).](image)

![Fig. 3 Effect of heat treatment on the hardness of the coarse second phase and ferrite matrix; material A(W.Q.) and material B(Ph.C.).](image)

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Table 1 Chemical compositions of specimens (wt %)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16</td>
<td>0.25</td>
<td>0.34</td>
<td>0.018</td>
<td>0.016</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

![Fig.1 Tensile specimens; (a) specimen for measurements of fracture strain ($\epsilon_f$) and void initiation strain ($\epsilon_i$), and (b) specimen for observation of the longitudinal section near the fracture surface.](image)
observed with an optical microscope. As shown in Fig.4, the micrographs at the central part on the longitudinal section within the width of 260 mm, were taken continuously and then the number of voids and the mode of void initiation were checked. Although it was difficult to know the exact values of stress and strain in a necked region of a plain specimen(14), the strain was estimated by the following equation proposed firstly by Inoue and Kinoshita(6):

$$\epsilon(x) = \ln\left(\frac{A_x}{A_0}\right) = 2\ln\left(\frac{d_x}{d_0}\right) \tag{1}$$

where \(\epsilon(x)\) refers to the tensile strain at a point \(x\) (see Fig.4) and \(A_0\), \(d_0\), \(A_x\), and \(d_x\) refer to the initial cross area, initial diameter, the cross area at \(x\) in Fig.4, and the diameter at \(x\), of a specimen, respectively. The value of \(d_x\) was calculated from the value of \(D_x\) in Fig.4 and a projected picture of fractured specimen before cutting. The fracture surface was observed using a Hitachi-Akashe MINI SEM.

3. Experimental results and discussion

3.1 General features of fracture process

When a tensile test was stopped after a plastic instability (starting of necking), voids were often revealed on the longitudinal section of the necked region of a specimen. The voids of the order of the coarse second phase size were also recognized in the brittle fracture surface as can be seen in Fig.5. In this case, the longitudinal plane was prepared by the means of brittle fracture(6), instead of mechanical cutting. The void initiation was believed to occur easily in the central portion of a specimen. In material A, voids were initiated adjacent to martensite colonies(23). Even when isolated voids were observed in ferrite matrix, they were frequently found to be connected with martensite colonies when the observed surface was polished little by little.

In the case of ferrite-pearlite structure, many workers(9)(15)(22) have reported that voids initiated by the fracture of pearlite colonies play a more important role than microvoids due to small particles such as nonmetallic inclusions. The present results concerning material B also support their conclusion.

Figure 6 shows some examples of fracture surface. It is found that large dimples as large as the voids in Fig.5 were scattered among small dimples. Sometimes, particles such as inclusions were observed in the bottom of small dimples.

Summarizing the above observations, a ductile fracture process of the present steels containing martensite or pearlite colonies could be concluded to take place as follows; firstly, voids are initiated due to the coarse second phase; and secondly, a connection of these voids occurs through small voids initiated at inclusions etc.; and finally the specimen separates completely. Such a mechanism has also been proposed by Ohji, et al(22).

Thus, it was decided to pick up only voids formed from the coarse second phase in the later discussions on void initiation strain etc.

3.2 Void initiation mechanism

Two types of void initiation mechanisms, that is, the void initiation by a decohesion at the interface and that by a fracture of the coarse second phase were identified. Typical examples of both mechanisms are shown in Fig.7.

The relationship between the number of voids and
the distance from the fracture surface was measured and whether a void was formed by the decohesion or by the fracture of the coarse second phase was judged in the observed zone on the longitudinal cut section in Fig. 4. The measurements were conducted on six planes in each heat treatment. Figure 8 was obtained by averaging these results where the distance from the fracture surface and the number of voids were respectively converted to strain(s(x)) by Eq. 1 and to the possibility of the coarse second phase with voids (number of the coarse second phase colonies with voids/total number of the coarse second phase colonies in the relevant observed zone (observed zone was divided into 28 intervals of s(x)). From Fig. 8 it is concluded that the decohesion type becomes dominant with a decreasing tempering temperature, i.e., an increasing martensite hardness, while the fracture type does so with an increasing tempering temperature, in material A. On the other hand, in material B, most of voids are initiated by the fracture of pearlite colonies, as stated in the previous reports (4)(22). Comparing Fig. 8 with Fig. 3, the void initiation by the fracture of the coarse second phase is believed to occur more frequently with a decreasing hardness of the coarse second phase. Generally, which type of the void formation occurs is considered to depend on the interface strength (or energy) (3), the fracture strength and shape of the coarse second phase (25).

However, even in the case that one type of void initiation is dominant, the other type is also observed although not so frequently. In such rare cases, the shape of the coarse second phase is mostly unique. For

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*2 This judgement was done by one plane observation. Therefore, some doubts remain; for instance, there is a little possibility that voids judged as the decohesion type may include those formed in ferrite matrix in the vicinity of the interface.
instance, in material A tempered at 473 K where the decohesion type was dominant, martensite colonies elongated along the tensile direction were apt to initiate voids by their fracture. Then, this seems to be ascribed to the effect of the shape of the coarse second phase like the influence of the aspect ratio on the fracture or the pull out of fiber in composite materials.

The decohesion at ferrite-pearlite interface in material B was also observed by Osakada, et al. (27). The actual stress condition in the second phase in plastically deformed specimens is composed of the applied stress and the internal stress caused by the plastic strain gradient (distribution of dislocations). Therefore, the authors believe that the above shape effect is closely connected with the plastic relaxation by dislocation movements in the vicinity of the interface.

3.3 Fracture strain and void initiation strain

The fracture strain \( \varepsilon_f = \ln A_f/A_0 \), where \( A_0 \) and \( A_f \) refer to the cross area of a specimen at the initial state and that at the final fracture state, respectively, and the void initiation strain \( \varepsilon_i \) are shown in Fig.9. The value of \( \varepsilon_i \) was determined as the strain at the end of the region where voids could be observed in Fig.4(5). This strain was estimated using Eq.1.

In material A, \( \varepsilon_i \) was increased when the tempering temperature became higher. The value of \( \varepsilon_i \) in material B shows a good agreement with the data by other workers (24). Kobayashi, et al. have proposed an empirical equation between \( \varepsilon_i \) and metallurgical factors in ferrite-pearlite steels. Figure 9 suggests that taking the strength of the second phase into account is necessary for enlarging the application limit of their equation because the strength of pearlite varies with the cooling speed after annealing.

On the other hand, \( \varepsilon_i \) is also increased with an increasing tempering temperature. A change of tempering temperature is accompanied with complicated phenomena, i.e., a change of void initiation mode, segregation of impurities, etc. Among them, the main reason for tempering temperature dependence of \( \varepsilon_i \), the authors believe, is the strength of martensite. This is because the internal stress due to the inhomogeneity of plastic strain between two components is expected to be reduced by plastic deformation of the second phase. It is interesting to note that the increasing rate of \( \varepsilon_i \) with tempering temperature shows a similar trend to that of \( \varepsilon_f \). When the strain from the first void formation to the final fracture \( \varepsilon_{f1} \) is roughly determined as the differ-

![Graph](image)

**Fig.8 Relations among void initiation rate, void initiation mode and strain.**

- Void initiation by the fracture of the coarse second phase.
- Void initiation by the decohesion at the interface.

\*3 The strength or energy of the interface is strongly influenced by the segregation of impurity elements. Recently, steels containing P as much as that in the present steel have been revealed to show a segregation of P at the prior austenite grain boundaries even at quenched state, in an Auger electron spectroscopy (24). Then, if one uses a steel with little P content, the frequency of the decohesion type void formation in Fig.8 is likely to decrease.
ence between $\varepsilon_1$ and $\varepsilon_0$, the value of $\varepsilon_1$ remains almost constant as shown in Fig.9. The effects of the measuring points of $\varepsilon_1$ and $\varepsilon_0$ and stress-strain distribution were considered important but neglected in this evaluation as first approximation.

In ferrite-pearlite steel, the values of $\varepsilon_1$ which were determined not as the fracture of cementite plates but as the fracture of whole pearlite colony, have been reported to be 0.46-0.54 (0.12% C) \(^{(4)}\), 0.4 (0.17% C) \(^{(28)}\), 0.55 (0.17% C), 0.4 (0.39% C) \(^{(5)}\). Despite dependencies of carbon contents (volume fraction of pearlite), heat treatment (strength of pearlite) and measuring method on the value of $\varepsilon_1$, the present result of 0.40 is close to the above data. Another noticeable point in Fig.9 is that $\varepsilon_1$ of material B is much larger than that of material A as discussed in the following section.

3.4 Comparison between martensite colony and pearlite one

The shape and size of martensite colony in material A are not so different from those of pearlite one in material B in Fig.2. However, comparing material B with material A tempered at 873 K which shows almost identical hardness (see Fig.3) and same trend of void initiation mode, the manner of void coalescence is found different. Namely, as can be known from Fig.9, the value of $\varepsilon_1$ is almost equal in both cases, but the value of $\varepsilon_0$ of material B is quite small. In material B, the voids are initiated at the early stage of deformation, but it takes much strain for them to be connected. Besides, in Fig.6, the fraction of the second phase colony with voids near the fracture surface in material A remains about 1.5% independently of the tempering temperature, while that in material B is more than twice that value.

Next, to study the manner of void connection or coalescence process in detail, an observation near the fracture surface was performed carefully using the specimen of Fig.1(b). The aspects of the longitudinal section after or just before the final fracture, are shown in Fig.10. Figure 11 shows etched patterns with the central part of Fig.10 magnified. Comparing these micrographs, it is well recognized that voids are concentrated near the fracture surface in material A while they are dispersed widely in the necked region in material B. Such a difference is considered to result from the difference in microstructure of the second phase. That is, the morphology of cementite in colonies is quite different in spite of similar hardness. In material A, nearly spherical cementite particles are dispersed uniformly in the tempered martensite colony \(^{18}\). Contrary to this, the pearlite colony has a layer structure of

Fig.9 Effects of heat treatments (material A (W.Q.) and material B (F.C.)) on fracture strain ($\varepsilon_1$), void initiation strain ($\varepsilon_0$), void coalescence strain ($\varepsilon_{10} - \varepsilon_1$), and uniform strain ($\varepsilon_u$).

Fig.10 Comparison of the aspects of longitudinal sections near the fracture portion (part 1); (a) material A tempered at 873 K, (b) material A tempered at 873 K, and (c) material B.
ferrite and plate-like cementite. The cementite plate in the pearlite colony has been found to be broken easily producing microvoids, by only a few percent of plastic strain\(^{(29)}\). By connecting these microvoids, a shear fracture of pearlite colony occurs, so that a large void which is adopted for the determination of \(e_p\) in this study is found. In such a fracture process, the fracture criterion of the pearlite colony is easily supposed to show an anisotropic feature depending on the orientation of cementite plate against the applied stress\(^{(30)}\). In contrast, the fracture of tempered martensite seems to show an isotropic feature. Therefore, in material B, the fracture of a certain pearlite colony occurs early depending on the orientation of its cementite plates, but other colonies in the vicinity of it are estimated to produce voids at the later stage of deformation. Thus, many voids are initiated over the whole necked region of the specimen, but they are relatively difficult to connect together because a large distance between them.

On the other hand, in material A tempered at 873 K, at the time one colony fractures, others around it are considered to be in such a situation that the fracture criterion is almost satisfied. Thus, the connection of voids formed in a limited region could occur easily unlike the case of material B. This suggests the distance between voids is more important than the number of voids in the necked region.

Although the fraction of the colony with voids near the fracture surface in material B is about twice that in material A in Fig.9, one should keep in mind that these data are the averaged value within some distance. The number of voids which form an actual fracture surface seems to be almost identical in both materials, judging from Fig.11. This is ascertained by the fact that the density of the large dimples in material A is not so much different from that in material B (see Fig.6).

In the case of specimens in which the decohesion type void initiation is dominant, e.g., material A tempered at 473 K, the number of voids in the necked region is relatively small because of little possibility of the anisotropic feature for void initiation.

4. Conclusions

The ductile fracture process was observed in detail and the void initiation strain, the initiation mode, the number of voids etc. were studied, using a carbon steel consisting of ferrite matrix and tempered martensite or pearlite. New information concerning the effects of the strength and the microstructure of the coarse second phase was obtained. The main results obtained are as follows:

1) In the case of steels containing a tempered martensite colony, with an increase in the hardness of martensite adjusted by tempering temperature, the void initiation mode changed from a fracture of the colony to a decohesion at the interface. Nevertheless, even when one type is dominant, the other type was observed but not frequently. This is considered to be ascribed to the effect of the colony shape.

2) In the case of the martensite colony which shows no anisotropic feature for the void initiation, the fracture strain is increased with an increasing tempering temperature, i.e., with a decreasing hardness of martensite. This is because the strain for void initiation is increased.

3) On the other hand, in the case of pearlite which shows an anisotropic feature for the fracture, the strain from the first void initiation to the final fracture has to be much larger in comparison with the case of martensite. A large num-
ber of voids are formed widely in the
necked region of a tensile specimen. Com-
paring both cases, it is concluded that
the distance between voids is important
for the connection of voids.

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