Strain Partitioning and Void Formation in Ferrite Pearlite Steels Deformed in Tension*

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Synopsis

A study has been made of the deformation behavior of the pearlite nodules and void formation process in the course of tensile deformation of ferrite-pearlite steels containing 0.05 to 0.91wt% C.

Since the pearlite nodule and matrix ferrite differ in their strengths, the overall strain of a specimen is partitioned between the two phases. The degree of partitioning is largely affected by the volume fraction of pearlite, and the extent of strain partitioned to pearlite nodules tends to increase as the pearlite volume fraction increases. Therefore, the strain of pearlite nodules increases with increasing the volume fraction of pearlite at a given strain of the specimens.

As the deformation of a specimen proceeds, void formation occurs at pearlite nodules, and the strain at void initiation decreases in a parabolic fashion as the volume fraction of pearlite increases. However, the strain of pearlite nodules themselves at this point are approximately equal (ε=0.3) irrespective of the volume fraction of pearlite.

Furthermore, the estimated stress on pearlite nodules at the void initiation falls on almost the same stress level (σ=110~120 kN/mm²) regardless of the pearlite volume fractions of steels.

These results reveal that the void formation in ferrite-pearlite steel occurs when the strain and stress of a pearlite nodule reach to the critical values characteristic to the fracture of the pearlite nodule itself.

I. Introduction

Since ferrite-pearlite is one of the most fundamental structures in steels, it has long been the subject of a great many investigations. A large number of studies have been conducted to understand the strength\(^1\) and toughness\(^6\) of this structure. In addition, the ductility and ductile fracture process of this structure are also interesting and a considerable amount of information is available.\(^1\)\(^1\)\(^5\)\(^6\) However, systematic studies on ductile fracture process of this structure are scarce and the mechanism involved has remained unclear.

It is well established that the ductile fracture process of materials consists of three stages, i.e., the initiation, growth, and coalescence of voids and the second-phase particles play an important role at these stages. Previous studies\(^19\)\(^20\) on steels with spheroidal carbides revealed that voids initiated at carbides. In ferrite-pearlite steels, on the other hand, there is enough evidence to show that a pearlite nodule acts as a site of void initiation.\(^12\)\(^13\) This fact implies that a pearlite nodule can be regarded as a second-phase particle in this structure. However, a distinct difference exists between the two in the manner as second-phase particles, that is, spheroidal carbides can hardly deform itself, while pearlite nodules deform plastically to a considerable extent. Accordingly, the former can be referred to "a hard particle" and the latter to "a soft particle".

In order to understand the ductile fracture process and void initiation stage in a ferrite-pearlite structure, it is of great importance to know the deformation behavior of pearlite nodule in the course of deformation of materials.

The present investigation was intended first to know the deformation behavior or strain partitioning of pearlite nodule and secondly to discuss the void initiation criterion in ferrite-pearlite steels deformed in tension.

II. Experimental Procedure

1. Materials

A series of plain carbon steels containing 0.05 to 0.91wt% C was induction-vacuum-melted as 90 kg heats and the analyses are given in Table 1. All of the steels were hot-forged to 13 mm diameter bars. Steels DF 1 and DF 2 (low carbon steels) were austenitized at 920°C and steels DF 3 to 6 (medium or high carbon steels) at 850°C for 1 h and cooled in air (normalized).

The volume fraction of carbide \((V_j^C)\) was calculated by assuming that all of the carbon was presented as cementite and the volume fraction of pearlite \((V_j^P)\) was estimated as \(8V_j^P\), because the volume ratio of

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>(V_j^P)</th>
<th>(V_j^{11})**</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF 1</td>
<td>0.05</td>
<td>0.06</td>
<td>0.008</td>
<td>0.004</td>
<td>0.007</td>
<td>0.022</td>
<td>0.008</td>
<td>0.062</td>
</tr>
<tr>
<td>DF 2</td>
<td>0.17</td>
<td>0.06</td>
<td>0.008</td>
<td>0.005</td>
<td>0.007</td>
<td>0.022</td>
<td>0.026</td>
<td>0.209</td>
</tr>
<tr>
<td>DF 3</td>
<td>0.39</td>
<td>0.05</td>
<td>0.008</td>
<td>0.007</td>
<td>0.005</td>
<td>0.021</td>
<td>0.060</td>
<td>0.489</td>
</tr>
<tr>
<td>DF 4</td>
<td>0.58</td>
<td>0.05</td>
<td>0.008</td>
<td>0.009</td>
<td>0.006</td>
<td>0.021</td>
<td>0.089</td>
<td>0.712</td>
</tr>
<tr>
<td>DF 5</td>
<td>0.72</td>
<td>0.04</td>
<td>0.008</td>
<td>0.007</td>
<td>0.006</td>
<td>0.022</td>
<td>0.111</td>
<td>0.884</td>
</tr>
<tr>
<td>DF 6</td>
<td>0.91</td>
<td>0.04</td>
<td>0.008</td>
<td>0.012</td>
<td>0.005</td>
<td>0.020</td>
<td>0.140</td>
<td>1.000</td>
</tr>
</tbody>
</table>

* \(V_j^P\): Volume fraction of carbide
** \(V_j^{11}\): Volume fraction of second-phase particle

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cementitic and ferrite is 1:7 in pearlite nodule. \( V_f \) and \( V_p \) of each steel are also listed in Table 1.

2. Tensile Testing

Tensile specimens with gauge sections of 7 mm in diameter by 25 mm long were machined out of normalized steels. Tensile tests were conducted at room temperature on an Instron-type testing machine at a cross-head speed of 5 mm/min.

3. Metallography

Tensile specimens tested to fracture were nickel-plated to protect the fracture surface and sectioned as close as possible to a longitudinal plane containing the central axis (Fig. 1(a) and Photo. 1). Optical and scanning electron microscopical examinations were carried out on the longitudinal section at various distances \( x \) from the fracture surface (Fig. 1(b)). The strain of the specimen at distance \( x \) can be calculated from the measurements of dimensions \( D_0 \) and \( D_x \) as illustrated in Fig. 1(b). Suppose the sectioning was carried out accurately along the central axis of the specimen, \( D_x \) would be directly related to the specimen diameter \( d_x \). In practical sectioning, however, a small deviation from the central axis is unavoidable. In this case, \( d_x \) should be corrected and is related to \( D_x \) as:

\[
d_x^2 = D_x^2 + D_0^2 - 2D_0D_x \cos \theta \quad \text{(1)}
\]

and the strain of specimen at \( x \) can be written as:

\[
\varepsilon_x = \ln \left( \frac{d_x}{d_0} \right)^2 = \ln \left( \frac{D_x^2 + D_0^2 - D_0D_x \cos \theta}{D_0^2} \right) \quad \text{(2)}
\]

where, \( d_0 \) is the initial specimen diameter and \( d_x \) the diameter at the necked region of specimen after fracture.

III. Experimental Results

1. Mechanical Properties

Mechanical properties of each steel are shown in Table 2. The fracture stress \( (\sigma_f) \) and fracture strain \( (\varepsilon_f) \) were defined as true stress and true strain at fracture, respectively. At the same time, tensile test data were converted to the true stress–true strain relation and parameters \( k \) and \( n \) were determined in Hollomon’s equation:

\[
\sigma = k \varepsilon^n \quad \text{(3)}
\]

Furthermore, the hardness of the pearlite nodule in each steel was measured using a micro-vickers tester with 15 g load. These data are listed in Table 2 along with tensile properties mentioned above.

Figure 2 compares the ductility (fracture strain, \( \varepsilon_f \)) of normalized ferrite–pearlite structures with that of spheroidized structures as a function of volume fraction of carbide \( (V_f) \). The spheroidized structures were obtained by quenching and tempering the steels at 700°C for 20 hr. It can be seen in Fig. 2 that ductility decreases with increasing \( V_f \) in a parabolic fashion both in the spheroidized and normalized structures. The spheroidized structures, however,

### Table 2. Mechanical properties of normalized specimens

<table>
<thead>
<tr>
<th>Property</th>
<th>DF 1</th>
<th>DF 2</th>
<th>DF 3</th>
<th>DF 4</th>
<th>DF 5</th>
<th>DF 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS ((\text{kg/mm}^2))</td>
<td>36.9</td>
<td>38.6</td>
<td>51.3</td>
<td>63.3</td>
<td>76.8</td>
<td>93.9</td>
</tr>
<tr>
<td>Elongation ((%))</td>
<td>52.4</td>
<td>50.8</td>
<td>38.4</td>
<td>27.1</td>
<td>19.6</td>
<td>14.0</td>
</tr>
<tr>
<td>RA ((%))</td>
<td>81.3</td>
<td>72.8</td>
<td>57.4</td>
<td>42.6</td>
<td>30.6</td>
<td>19.3</td>
</tr>
<tr>
<td>Fracture stress, (\sigma_f) ((\text{kg/mm}^2))</td>
<td>97.8</td>
<td>93.6</td>
<td>96.8</td>
<td>98.6</td>
<td>104.2</td>
<td>112.7</td>
</tr>
<tr>
<td>Fracture strain, (\varepsilon_f) ((%))</td>
<td>1.664</td>
<td>1.302</td>
<td>0.853</td>
<td>0.554</td>
<td>0.365</td>
<td>0.214</td>
</tr>
<tr>
<td>(\sigma = k \varepsilon^n) (k)</td>
<td>81.05</td>
<td>84.94</td>
<td>101.53</td>
<td>113.88</td>
<td>126.21</td>
<td>133.85</td>
</tr>
<tr>
<td>(\sigma = k \varepsilon^n) (n)</td>
<td>0.370</td>
<td>0.369</td>
<td>0.300</td>
<td>0.243</td>
<td>0.190</td>
<td>0.115</td>
</tr>
<tr>
<td>Vickers hardness of pearlite nodule ((15 \text{ g}))</td>
<td>254</td>
<td>287</td>
<td>274</td>
<td>284</td>
<td>259</td>
<td>271</td>
</tr>
</tbody>
</table>
show higher ductilities than the normalized structures by comparing at the same $V_f$.

As has been previously mentioned, the pearlite nodule seems to act as a second-phase particle in the ductile fracture process in a ferrite–pearlite structure. Fig. 2 can be replotted as a function of the volume fraction of second-phase particles ($V_p$) and the result is shown in Fig. 3. In contrast to the previous result, the replot reveals that the spheroidized structure shows much smaller ductility than the normalized structure at a given $V_p$. This can be attributed to the difference of the nature of the second-phase particle, i.e., the spheroidal cementite is a hard particle while the pearlite nodule behaves as a plastically deformable soft particle. This comparison proves that the information about the deformation behavior of pearlite nodule is indispensable for the better understanding of the ductile fracture process of this structure.

2. Deformation of Pearlite Nodule and Strain Partitioning Behavior

Deformation of pearlite nodules was observed as a function of strain of the specimens. The observations were carried out at various distances ($x$) from the fracture surface on the longitudinal section as illustrated in Fig. 1(a). The strain of the specimen at a distance $x$ can be calculated from Eq. (2) and given in Fig. 4 in each steel. On the other hand, the strain of pearlite nodule must be measured directly at each position. Photograph 2 shows the shape changes of pearlite nodules during tensile deformation. Assuming that a pearlite nodule which is initially an equiaxed sphere changes in shape to an ellipsoid elongated along the tensile axis after deformation, the strain of each pearlite nodule involved is given[21] as:

$$\varepsilon_p = \frac{2}{3} \ln \left( \frac{a}{b} \right) \quad \text{...(4)}$$

where, $a$ and $b$ are major and minor axes of an ellipse appeared on the polished specimen surface, respectively. The mean strain of pearlite nodules ($\varepsilon_p$) was established by measuring of 40 to 100 pearlite nodules randomly selected at a given position of the specimen.

Combining $\varepsilon_p$ with the strain of the specimen at the corresponding position ($\varepsilon_s$) gives the information of the strain partitioning behavior of pearlite nodules in the course of tensile deformation and the result is
shown in Fig. 5. It can be seen here that the strain is partitioned to a decreasing extent to pearlite nodules with a decrease of the pearlite volume fraction and this trend is obvious especially at the early stage of deformation.

3. Void Formation at Pearlite Nodule

In the ductile fracture process of the ferrite–pearlite steel, void formation occurs preferentially at pearlite nodule where the lamellae are aligned parallel to the tensile axis. To elucidate the void initiation stage and to establish the criterion for void formation in this structure, the detailed observations of voids at pearlite nodule were conducted by means of scanning electron microscopy.

Figure 5 shows that the strain to void initiation changes from \( \varepsilon_f \approx 0.8 \) in the lowest carbon steel (DF 1) to \( \varepsilon_f \approx 0.2 \) in the eutectoid steel (DF 6). Furthermore, it can be seen that the amount of strain after void initiation (i.e., \( \varepsilon_f - \varepsilon_i \)) decreases as the volume fraction of pearlite decreases. It is noteworthy that fracture follows immediately after void initiation in a eutectoid steel.

As stated above, voids at pearlite are induced by the slip of pearlitic ferrite and hence by the strain of pearlite nodule. Accordingly, it is expected that void initiation is closely related to the deformation behavior of the pearlite nodule, per se. Then the observed strain of void initiation \( (\varepsilon_f) \) was plotted on the strain partitioning curve illustrated in Fig. 5, and the result is given in Fig. 7. The result offers important information that the strain of specimen at void initiation differs with volume fraction of pearlite, while the strain of pearlite nodule at this point is unaffected by the pearlite volume fraction. Consequently, it is concluded that void initiation occurs when the strain...
of the pearlite nodule reaches a given critical value, which is probably related to the fracture strain of pearlite nodule itself.

In sum, the ductile fracture process of ferrite-pearlite steels can be described as follows. Once plastic deformation begins, deformation proceeds with accompanying the strain partitioning between ferrite and pearlite. The larger the volume fraction of pearlite, the more rapidly the amount of strain of pearlite nodule increases, and eventually void initiation occurs at a pearlite nodule when the strain of the pearlite reaches a critical value. Therefore, the strain at the void initiation in a higher carbon steel is lower than that in a lower carbon steel.

IV. Discussion

1. Strain Partitioning Behavior

The strain partitioning of ferrite-pearlite steels may be governed by the ratio of the internal stress exerted on pearlite nodules to the applied stress on the specimen.

![Fracture strain and strain to void initiation as a function of volume fraction of pearlite](Fig. 6)

The applied stress \( \sigma_i \) and the strain \( \epsilon_i \) of the specimen \( i \) are related as:

\[
\sigma_i = k_i \epsilon_i^{n_i}
\] .............................(5)

Similarly, for the internal stress \( \sigma_p \) and the strain \( \epsilon_p \) of the pearlite nodule,

\[
\sigma_p = k_p \epsilon_p^{n_p}
\] .............................(6)

Introducing the stress concentration factor \( \beta \) as

\[
\beta = \sigma_p / \sigma_i
\] .............................(7)

Equations (5) and (6) give

\[
\epsilon_p = \left( \beta \cdot k_i / k_p \right)^{1/n_p} \cdot \epsilon_i^{n_p/n_i}
\] .............................(8)

If the parameters \( k_i \)'s and \( n_i \)'s in Eq. (8) are available, the strain partitioning behavior, i.e., the relation between \( \epsilon_p \) and \( \epsilon_i \), could be predicted. Parameters \( k_i \) and \( n_i \) for each steel examined here are given in Table 2. Unfortunately, parameters \( k_p \) and \( n_p \) for pearlite
nodule are unknown. However, since the hardness of the pearlite nodule is almost equal in each steel as shown in Table 1, it is reasonably assumed that $k_p$ and $n_p$ are representable by those of eutectoid steel DF 6 ($k_6$ and $n_6$).

The strain partitioning for each steel can be calculated by Eq. (8) using parameters $k$'s and $n$'s in Table 2, and the results are given in Fig. 8 comparing with the observed results. It can be seen that Eq. (8) predicts the strain partitioning behavior with a considerable accuracy especially at the early stage of deformation.

The stress concentration factor $\beta$ changes from unity to about 2.0 at this stage, with an increasing trend with decreasing volume fraction of pearlite. The discrepancy between the calculated and the observed becomes larger at the later stage of deformation. This is presumably ascribed to the stress relief due to the formation of void at pearlite.

2. Stress on the Pearlite Nodule

In the preceding section, it is shown that the strain partitioning behavior can be predicted by introducing the stress concentration factor $\beta$. Comparing the observed with the calculated value, the factor $\beta$, and hence the stress on the pearlite nodule, can be estimated as a function of the strain of each specimen. The estimated stress on the pearlite nodule is given in Fig. 9. The result implies that the stress on the pearlite nodule increases with increasing the strain of specimen and also with increasing the volume fraction of pearlite.

3. Criterion for Void Initiation at Pearlite Nodule

Although a limited number of data are available, as far as is known, no systematized investigation on the strain of void initiation has been reported in connection with the pearlite volume fraction of steels. Barnby showed very small strain ($\approx 4\%$ elongation) for the void initiation in a $0.5\%$ C ferrite–pearlite steel. Clausing observed void initiation at $z \approx 0.4$ in a $0.17\%$ C steel, and Kobayashi, et al., at $z \approx 0.46-0.54$ in a $0.1\%$ C steel. Comparing these data with those of the present investigation, the results of Clausing and Kobayashi appear to be in good agreement, while the strain obtained by Barnby seems to be too small. The disagreement is probably due to that Barnby observed microvoid which is a preliminary stage of void initiation as stated previously.

In the course of tensile deformation of ferrite–pearlite steels, ferrite matrix and pearlite nodules deform to the different extent according with the strain partitioning depending on the pearlite volume fraction. As can be seen in Fig. 6, the strain of the specimen at void initiation depends on the volume fraction of pearlite. The strain of the pearlite nodule, however, is approximately equal at void initiation regardless of the volume fraction of pearlite. Consequently, a possible criterion for the void initiation is that the strain of the pearlite nodule reaches the critical value which is probably related to the fracture strain of the pearlite nodule itself.

Furthermore, the criterion can be considered from the viewpoint of the stress on the pearlite nodule. Void initiation strain ($z_i$) of each steel is again plotted in Fig. 9, and this result that the stress exerted on the pearlite nodule ($\sigma_p$) at void initiation is essentially the same level (110–120 kg/mm$^2$) for all steels investigated. This stress level is very close to the fracture stress of the eutectoid steel (113 kg/mm$^2$ of DF 6) and is in accordance with the reported value. Therefore, from the point of view of stress, the criterion is described as that void initiation occurs when the stress on the pearlite nodule exceeds its fracture stress.
V. Summary

The strain partitioning behavior and void initiation have been investigated during the tensile deformation of ferrite–pearlite steels with a wide range of carbon contents.

The strain of the specimen is partitioned between the two phases, ferrite matrix and pearlite, and the extent of strain partitioned to pearlite nodules increases as the pearlite volume fraction increases. On the other hand, the strain at void initiation increases with decreasing the pearlite volume fraction. Combining these data, it is concluded that void initiation occurs when the strain of the pearlite nodule reaches its fracture strain. Furthermore, the stress consideration gives the criterion that void initiation occurs when the stress on the pearlite nodule reaches its fracture stress.

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