Effect of Microstructural Features on Ductility of Drawn Pearlitic Carbon Steels

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The effect of microstructural features on ductility of cold drawn pearlitic steels containing 0.52–0.92 wt% C was investigated. The relationship between ductility and microstructural features of interlamellar spacing, ferrite thickness and cementite thickness, was closely examined, compared with that with drawing strain. The variations of reduction of area (RA) with drawing strain well reflected the microstructural evolution occurred during wire drawing; RA increased initially with the progressive realignment of randomly oriented cementite, showed a maximum peak due to the completion of the alignment of most cementite, and decreased with thinning or fragmentation of the aligned cementite. Among factors on ductility, cementite thickness was found to be the most dominant microstructural feature for RA of drawn pearlitic wires, regardless of transformation temperature and carbon content in steels. Additionally, the presence of the specific cementite thickness for the maximum RA in drawn steel wires was observed as about 0.006–0.009 μm.

KEY WORDS: pearlite; ductility; wire drawing; cementite; carbon steel.

1. Introduction

Ductility is very important for shaping and forming operations in the industry. Especially, for the wire drawing process, the increment of ductility of wire rods has an advantage of eliminating heat treatment as well as obtaining high strength level. The relationship proposed by Embury and Fisher,\textsuperscript{1)} which has been widely used in the steel wire industries in estimating strength of cold drawn eutectoid steels, also indicates that the increase of the drawing strain by improving ductility is one of the effective ways to increase strength of cold drawn pearlitic steels;

\[ \sigma = \sigma_0 + \left[ k / (2 \lambda_0) \right]^{1/2} \exp \left( \varepsilon / 4 \right) \]

where \( \varepsilon \) is the true drawing strain, \( \sigma_0 \) is the friction stress, \( \lambda_0 \) is the initial interlamellar spacing and \( k \) is the Hall–Petch parameter.

It is generally accepted that interlamellar spacing is one of the suitable factors to control ductility of pearlitic steels. In eutectoid steels, the refinement of interlamellar spacing causes the reduction of cementite thickness. Coarse pearlite deforms inhomogeneously and results in strain localization in narrow slip band.\textsuperscript{2,3)} Thus, thick cementite in coarse pearlite is allowed only limited ductility and then fractures without thinning. These cracks due to shear cracking process subsequently develop into cleavage-type cracks. Meanwhile, fine pearlite containing thin cementite exhibits more uniform distribution of strain during deformation. Thin cementite of fine pearlite appears to be ductile and neck down into fragments, resulting in ductile fracture.\textsuperscript{2–6)} However, when carbon content is varied in pearlitic steels, interlamellar spacing is no more a single proper variable to control ductility since ductility is also affected significantly by the amount of hard phase, \( i.e. \) the volume fraction of cementite. The different carbon content in steels leads to the different ratio of cementite thickness to ferrite thickness as well as the variation of interlamellar spacing. Thus, it seems more reasonable to investigate ductility in relation to the variation of carbon content.

Moreover, microstructural features of drawn pearlitic steel wires are quite different from those of hot-rolled or transformed pearlitic steels. The main features of microstructural evolution during wire drawing strain are a progressive alignment of cementite along the drawing axis, a reduction of interlamellar spacing, a thinning of cementite, a fracture and the dissolution of cementite.\textsuperscript{2–18)} Thus, it is easily expected that the cementite, aligned parallel to the drawing axis, would react in the different way from the randomly oriented cementite during tensile deformation.

According to previous investigations,\textsuperscript{19–20)} a nearly fully pearlitic microstructure in hypo-eutectoid steels can be obtained by controlling several factors related to transformation kinetics, such as austenitizing temperatures and transformation temperatures. Accordingly, the deficiency of carbon contents in the pearlite region induces the formation of ‘degenerate pearlite’. The morphology of cementite in hypo-eutectoid steel is a type of discrete cementite plates. However, these cementite plates are plastically deformed
into the elongated shape along the drawing direction. Subsequently, the fibrous shaped cementite in cold drawn hypo-eutectoid steels can be considered similar to that of cold drawn eutectoid steels. Thus, fully pearlitic microstructures with various carbon contents from hypo-eutectoid to hyper-eutectoid cold drawn steels would be useful in investigating the influences of the carbon content on ductility of cold drawn pearlitic steels.

In view of the foregoing, it is attempted in this work to investigate the effect of microstructural features such as interlamellar spacing, ferrite thickness and cementite thickness on ductility of cold drawn pearlitic steels.

2. Experimental Procedures

The starting materials used in this work were Stelmor-cooled wire rods with the carbon content of 0.52–0.92 wt% C. The rods were austenitized at 1 223–1 423 K for 10 min. followed by quenching in a salt bath set to temperature range of 793–923 K. Especially, to examine the effects of transformation temperatures on ductility of steels with pearlitic microstructure, eutectoid steels were austenitized at 1 223 K and transformed in temperature ranges of 823–883 K. Measured interlamellar spacing and calculated cementite thickness for eutectoid steels are shown in Table 1. The initial interlamellar spacing was measured by a linear intercept method on the colonies oriented nearly perpendicular to the plane of observation in scanning electron microscope (SEM) photographs. The thickness of cementite (t_c) was calculated as follows,

\[ t_c = (\lambda_0 / V_p) \left[ (W_{cem} / \rho_{cem})(W_{cem} / \rho_{cem} + W_{fer} / \rho_{fer}) \right] \] \hspace{1cm} (2)

where \( \lambda_0 \) is the interlamellar spacing, \( \rho_{cem} \) is the density of cementite, \( \rho_{fer} \) is the density of ferrite, \( V_p \) is the measured volume fraction of pearlite, \( W_{fer} \) is the weight fraction of ferrite and \( W_{cem} \) is the weight fraction of cementite, 0.15 (wt% C). The ferrite thickness was obtained by the subtraction of the thickness of cementite (t_c) from the initial interlamellar spacing.

The variation of cementite thickness in the pearlite during wire drawing could be estimated by assuming that both ferrite plates and cementite undergo the same strain. The interlamellar spacing is reduced proportionally to the wire diameter during wire drawing.\(^{11,17,20,21}\)

\[ \lambda(\varepsilon) = \lambda_0 \exp(-\varepsilon/2) \] \hspace{1cm} (3)

Thus, the thickness of cementite plates in drawn steel wires can be obtained by substituting \( \lambda(\varepsilon) \) of the Eq. (3) for \( \lambda_0 \) of the Eq. (2).

The rods were pickled and successively cold drawn at a relatively low drawing speed of 3 m/min, to avoid the dynamic strain aging effect. The average reduction per pass was 20%. After each pass during the drawing operation, samples were taken for tensile tests and the observation of microstructural changes. Tensile tests were carried out at room temperature at the initial strain rate, 3 \times 10^{-3}/s. Ductility of the steels was estimated by reduction of area (RA) from samples fractured in tensile tests.

<table>
<thead>
<tr>
<th>Transformation temperature(K)</th>
<th>Interlamellar spacing(μm)</th>
<th>Cementite thickness(μm)*</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>823</td>
<td>0.125</td>
<td>0.0154</td>
<td>741</td>
<td>1139</td>
</tr>
<tr>
<td>853</td>
<td>0.142</td>
<td>0.0175</td>
<td>695</td>
<td>1123</td>
</tr>
<tr>
<td>883</td>
<td>0.175</td>
<td>0.0216</td>
<td>624</td>
<td>1038</td>
</tr>
</tbody>
</table>

Table 1. Measured interlamellar spacing and calculated cementite thickness for 0.82 wt% C steels.

3. Results and Discussion

3.1. Effect of Transformation Temperature on Ductility of Drawn Eutectoid Pearlitic Steels

Unlike hot-rolled or transformed pearlitic steels, RA of cold drawn steels is significantly influenced by the degree of the realignment of cementite to the drawing axis. As mentioned above, a wire drawing process changes not only the orientation of cementite but also the shape and dimension of microstructural features, such as interlamellar spacing, cementite thickness and ferrite thickness. Thus, these microstructural changes occurred during wire drawing must be closely related to RA of drawn pearlitic steels.

Figure 1 shows the typical microstructural evolution of eutectoid steels occurred during wire drawing. Cementite plates oriented favorably or parallel to the drawing axis are plastically deformed and thinned to a fibrous shape during drawing, while those oriented unfavorably are bent and/or kinked (marked arrow in Figs. 1(b) and 1(c)). Around the drawing of \( \varepsilon = 2.06 \) (Fig. 1(c)), most cementite plates are observed to be aligned along the drawing axis, and the kinked and/or bent cementite plates are rarely found. As shown in Fig. 1(d), further straining results in the alignment of virtually all cementite plates along the drawing axis.

Figure 2 shows the effects of microstructural features on ductility of drawn eutectoid steel wires, austenitized at...
1223 K and transformed at various temperatures. In Fig. 2(a), the variations of RA of drawn wires are plotted as a function of drawing strain, \( \varepsilon \). The value of RA would be strongly related to the characteristics of microstructural features at the corresponding drawing strain. Under the present experimental conditions, RA of all steel wires slightly increases up to about \( \varepsilon /H_{1.1005} = 1.5–2.0 \) and then gradually decreases with increasing strain. The initial increment of RA is attributed to the realignment of randomly oriented cementite and the occurrence of a maximum peak of RA at \( \varepsilon /H_{1.1005} = 1.5–2.0 \) corresponds to the completion of the alignment of most cementite along the drawing axis. The subsequent decrease of RA, after reaching its maximum value, results from the deformation behavior of the aligned cementite such as thinned and/or fragmented cementite.

It is of interest to note that the increase of initial interlamellar spacing due to high transformation temperature causes the shift of the maximum peak of RA to the higher drawing strain as well as decreases RA in drawn eutectoid steels. Since the dimension, the shape and the orientation of microstructural features in pearlitic steels are changed differently according to the initial interlamellar spacing, drawing strain would not adequately explain the behavior of RA of drawn wires. Thus, it is necessary to examine the relationship between microstructural features and RA in drawn pearlitic steels.

The close relationship between RA and interlamellar spacing in Fig. 2(b), confirms that interlamellar spacing is the main parameter to control RA of drawn eutectoid steels. However, at the constant carbon content in the pearlite, the refinement of interlamellar spacing implies the reduction of cementite thickness as well as ferrite thickness at the same rate. Moreover, assuming the axisymmetric deformation in the longitudinal cross-section of wires during wire drawing,\(^{21,22}\) it is easily expected that other microstructural features of ferrite thickness (Fig. 2(c)) and cementite thickness (Fig. 2(d)) also show the equivalent influence on RA of drawn steels.

Meanwhile, the variation of carbon content in pearlitic steels causes the changes in volume fraction and morphology of cementite as well as cementite thickness. Since cementite thickness and ferrite thickness are a function of not only interlamellar spacing but also carbon content in the Eq. (2), cementite thickness and ferrite thickness would vary with transformation temperature at the different rate according to carbon content in steels. When interlamellar spacing of 0.52% C steel transformed at 793 K and that of 0.82% C steel transformed at 863 K are similar as about 0.154 mm, cementite thickness of 0.82% C steel, 0.0214 mm, is much larger than that of 0.52% C steel, 0.0132 mm, due to the larger volume fraction of cementite. Thus, for fully pearlitic steels with the same interlamellar spacing, the increase of carbon content results in the increase of cementite thickness. Accordingly, those various microstructural features would show the different level of influence on RA of drawn pearlitic steels with different carbon content.

3.2. Effect of Carbon Content on Ductility of Drawn Pearlitic Steels

The effects of microstructural features on ductility of drawn steel wires with various carbon content of 0.52–0.92 wt% C are shown in Fig. 3. All steel wires in Fig. 3(a) show the maximum peaks of RA at near drawing strains of
1.5–2.0, in spite of various characteristics due to different
carbon content and transformation temperature. Additionally,
the increment of the carbon content in steel wires induces
the more rapid change of RA with drawing strain as well as
the lower value of RA. The fact that RA of drawn wires
with higher carbon content reacts sensitively to drawing
strain, implies that cementite among microstructural fea-
tures would possibly play an important role for RA of
drawn steel wires.

Unlike drawn eutectoid steel wires, RA of drawn wires in
Fig. 3(b) shows the poor relations with interlamellar spac-
ing. Especially, for steel wires with the interlamellar spac-
ing larger than 0.08 mm, RA varies rapidly with not only in-
terlamellar spacing but also carbon content in steel wires. It
is interesting to note that the maximum peak of RA of
drawn wires shifts to the lower interlamellar spacing as car-
bond content in steels increases. Additionally, for the in-
terlamellar spacing below the maximum peak of RA, all
drawn wires exhibit the similar values of RA. This implies
that RA in each steel wire before the occurrence of the
maximum peak is influenced by the different degree of the
realignment of cementite according to its carbon content
during wire drawing, while after the accomplishment of re-
alignment no difference in RA with interlamellar spacing is
observed in Fig. 3(b). Meanwhile, interlamellar spacing
consists of ferrite thickness and cementite thickness. Since
ferrite thickness is much larger than cementite thickness, the
variation of RA with ferrite thickness in drawn wires,
Fig. 3(c), resembles the relationship between RA and inter-
lamellar spacing. However, the close relationship between
RA and cementite thickness in Fig. 3(d) indicates that RA of
drawn wires is mainly controlled by cementite thickness.

This implies that thinning of cementite thickness as well as
the realignment of cementite would start at low strains of
wire drawing.

3.3. Factors on Ductility of Drawn Pearlitic Steels

To confirm the above results, measured RA data are plot-
ted with microstructural features for all tested steels (Fig.
4). Although Fig. 4(a) represents the typical behavior of RA
with drawing strains, related to microstructural evolution
occurred during wire drawing, scattered data of measured
RA make it difficult to describe the dependence of RA on
drawing strain for all tested drawn wires. Additionally, in-
terlamellar spacing and ferrite thickness in Figs. 4(b)–4(c)
are found inadequate to describe RA of drawn wires.
Meanwhile, the distribution of RA with cementite thickness
in Fig. 4(d) provides the evidence that RA of all tested
drawn wires is closely related to cementite thickness. It is
also obvious that the increased cementite thickness beyond
the maximum ductility deteriorates ductility by decreasing
plastic deformability. Additionally, the reason for the de-
creased RA with the reduction of cementite thickness
below the maximum ductility, would be the lack of de-
formability of the aligned cementite to the drawing axis,
due to necking and fragmentation of the cementite.

It is worth to mention that the maximum ductility is ob-
served at the specific cementite thickness of 0.006–0.009
µm in Fig. 4(d). The authors do not claim the exact value.
But the presence of the specific cementite thickness for the
maximum ductility is evident, and cementite thickness for
the maximum ductility is about 0.006–0.009 µm for all test-
ed drawn steel wires. Additionally, the similar cementite
thickness and values for the maximum RA would imply...
that fine pearlite with thin cementite or small interlamellar spacing would realign faster to the drawing direction than coarse pearlite, regardless of transformation temperatures and carbon content in pearlitic steels. Accordingly, it is expected that in spite of different volume fraction of cementite and drawing strains, the same thickness of cementite would lead to the similar value of RA in drawn wires.

In general, during the plastic deformation of two phase alloys, the initiation of voids occurs by the decohesion of the interfaces or by the fracture of hard phase particles. The interfaces of ferrite/cementite in the pearlite are coherent or semi-coherent boundaries, although high elastic stress occurs at the interfaces due to the accumulation of misfit dislocations during wire drawing.21) Additionally, most cementite plates are realigned parallel to the wire axis during wire drawing. Thus, it is expected that the decohesion of the interfaces along the wire axis hardly occur in drawn pearlitic steel wires. Therefore, it is easily expected that the thickness of cementite plates is closely related to the ductility of drawn pearlitic steel wires.

From the above, it can be concluded that cementite thickness must be the dominant parameter to control RA of drawn pearlitic carbon steel wires.

4. Conclusion

In this work, it is attempted to investigate the effect of microstructural features on ductility of cold drawn pearlitic steels containing 0.52–0.92 wt% C. Thus, the relationship of RA in drawn steel wires was closely examined with microstructural features of interlamellar spacing, ferrite thickness and cementite thickness, compared with that with drawing strain. For drawn eutectoid steels, the variations of RA with drawing strains reflected the microstructural evolution occurred during wire drawing; RA increased initially with the progressive realignment of randomly oriented cementite, showed a maximum peak due to the completion of the alignment of most cementite, and decreased with the further deformation of the aligned cementite such as thinning or fragmentation. However, interlamellar spacing showed the much closer relationship with RA of drawn wires. Thus, interlamellar spacing could be considered as a main parameter to control RA of drawn eutectoid steels. Additionally, ferrite thickness and cementite thickness also showed the equivalent influence to interlamellar spacing on RA of drawn eutectoid steels, since ferrite thickness and cementite thickness reduced their thickness at the same rate to interlamellar spacing during wire drawing.

For drawn pearlitic steels with various carbon contents, it was found that RA of drawn wires would be mainly controlled by cementite thickness among microstructural features, regardless of transformation temperature and carbon content in pearlitic steels. For all tested drawn steel wires, cementite thickness must be the dominant parameter to control RA of drawn wires. Additionally, the presence of cementite thickness for the maximum ductility in all the tested drawn steel wires was observed as about 0.006–0.009 μm for tested steels.
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REFERENCES