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Ductility of hypo-eutectoid steels with ferrite-pearlite structures

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Ductility is very important for shaping and forming operations in the industry. Especially for the wire drawing process, the increment of the total amount of deformation through improving the drawability has an advantage of eliminating heat treatment as well as obtaining a high strength level.

It has been generally accepted that the refinement of grain size in polycrystalline materials improves ductility as well as strength. Recently, ultra-fine grained (UFG) materials with grain size less than 1μm have been studied extensively, since they are expected to provide high strength without the degradation of toughness [1–5]. One of the distinguishing features of UFG materials is the lower ductility than conventional grain sized materials. This unusual behavior can be explained in terms of the transition of deformation mechanisms from dislocation activity to grain boundary-related deformation [6, 7]. Therefore, it is expected that there must be a range of grain size for the maximum ductility in polycrystalline materials.

Meanwhile, a similar behavior of ductility with transformation temperature is often observed in hypo-eutectoid steels with ferrite-pearlite structure. In low carbon steels, the increment of volume fraction of ferrite by decreasing the carbon content is very useful in improving ductility with a resulting loss of strength. However, for a given medium carbon steel the presence of the maximum ductility is often observed at a specific transformation temperature. At a given carbon content of 0.55%C, volume of ferrite can be reduced significantly from 30% to less than 2% by a control of transformation kinetics factors such as transformation temperatures [8–10]. The deficiency of carbon contents in the pearlite region induces the formation of the degenerate pearlite, which is different in morphology and volume fraction of cementite from eutectoid pearlite. Thus, it is anticipated that medium carbon steels, containing ferrite and degenerate pearlite, would show different behavior from annealed steels with ferrite-pearlite structure. Accordingly, it is necessary to investigate the relationship between microstructural features, such as the pro-eutectoid ferrite and degenerate pearlite, and ductility in medium carbon steels, in conjunction with transformation temperatures. Additionally, the comparison of mechanical properties in medium carbon steels with eutectoid pearlitic steels would be useful to understand the role of degenerated pearlite on ductility during tensile deformation.

In view of the foregoing, in the present work, it is attempted to investigate the effect of transformation temperature on microstructural features and ductility in 0.55%C steels, and compare with those in 0.82%C eutectoid steel.

Chemical compositions of steel rods with 12mm in a diameter, used in this work are shown in Table I. The rods were austenitized at 1273 K for 30 min followed by quenching in a salt bath in the temperature range of 773–923 K. Microstructural parameters such as interlamellar spacing and the volume fraction of pro-eutectoid ferrite were measured by linear intercept method and point counting method in scanning electron microscope (SEM) photographs. The interlamellar spacing was an average value of the minimal interlamellar spacing measured by a linear intercept method on the colonies oriented nearly perpendicular to the plane of observation in SEM micrographs. The thickness of cementite (t_c) was calculated as follows,

$$t_c = (s_p/V_p)[(W_{cem}/\rho_{cem})/(W_{cem}/\rho_{cem} + W_{fer}/\rho_{fer})] \tag{1}$$

where s_p is the interlamellar spacing, C is the carbon content, V_p is the measured volume fraction of pearlite and W_{cem} is the weight fraction of cementite, 0.15 (wt%C).

Tensile tests were carried out at room temperature at the initial strain rate, 3×10^{-3}/s. The strain gauge was taken off from the specimens after the occurrence of the peak in engineering stress-strain curves. Ductility of the steels was estimated by reduction of area (RA) from samples fractured in tensile tests.

The variations of ductility with transformation temperature in shown in Fig. 1. RA of 0.55%C steels, steels A and B, increases with increasing transformation temperature and then, decreases after reaching its maximum value, while that of 0.82%C steel, steel C, decreases monotonously. The occurrence of maximum peak of RA would be strongly related to the characteristics of microstructural features at the corresponding transformation temperature. In hypo-eutectoid steels, austenite is decomposed into pro-eutectoid ferrite and then, pearlite during transformation. Therefore, the carbon content in pearlite depends on the pro-eutectoid ferrite content during transformation of steels. The

TABLE I Chemical composition of steels

	C (wt%)	Mn (wt%)	Si (wt%)	Cr (wt%)	S (wt%)	P (wt%)
Steel A	0.551	0.500	0.304	–	0.006	0.017
Steel B	0.550	0.496	0.303	0.198	0.006	0.010
Steel C	0.821	0.498	0.223	–	0.004	0.004

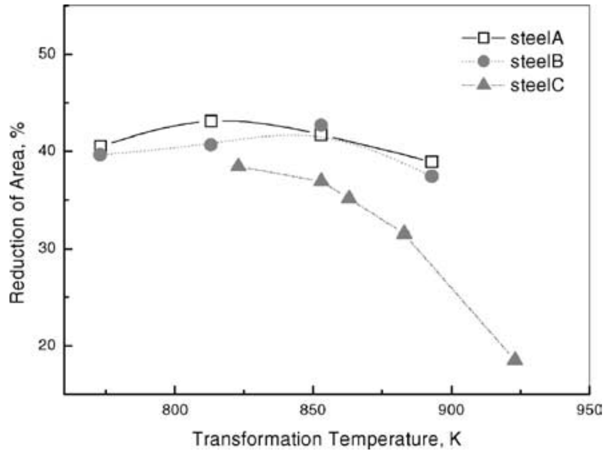

Figure 1 Variations of RA with transformation temperature in steels.

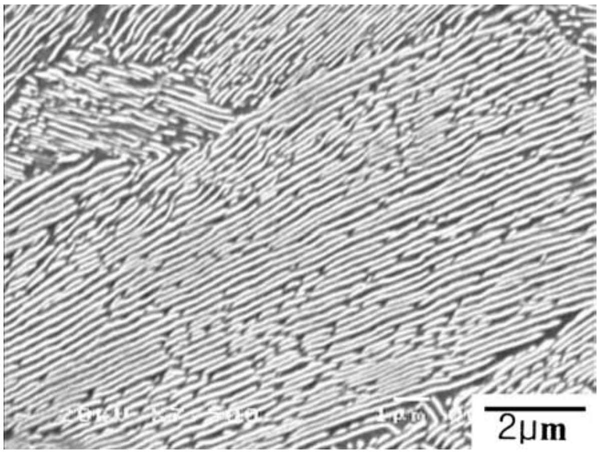

Figure 2 SEM micrograph showing cementite lamellae of degenerated pearlite in steel B, transformed at 813 K.

reduction of volume fraction of pro-eutectoid ferrite with decreasing transformation temperature (Table II), results in the less carbon content in pearlite as well as the increment of volume fraction of pearlite. SEM micrograph in Fig. 2 shows degenerate pearlite, consisting of platelike cementite by its fragmentation and fairly uniform distribution of cementite in the ferrite matrix.

Among microstructural features, volume fraction of pro-eutectoid ferrite, which increases with transformation temperature, would not be adequate for describing the behavior of RA of 0.55%C steels in Fig. 1. Thus, it is necessary to investigate the effect of the characteristics of pearlite on ductility. For eutectoid steels, coarse pearlite deforms inhomogeneously with strain localized in narrow slip band, whereas fine pearlite exhibits a much more uniform distribution of strain during deformation. Thick cementite in coarse pearlite shows only limited ductility and fracture without thinning, whereas in fine pearlite the thin cementite appears to be ductile and is able to neck down into fragment [11–13]. Accordingly, the increase of interlamellar spacing, due to high transformation temperatures, causes the drop in RA for steel C (Fig. 1).

It is interesting to note that the distinction between coarse pearlite and fine pearlite would be drawn on the basis of the measured interlamellar spacing in pearlite. At the constant carbon content in pearlite, the refinement of interlamellar spacing implies the reduction of cementite thickness as well as ferrite thickness at an equivalent rate. However, since cementite thickness is a function of not only interlamellar spacing but also the carbon content in the Equation 1, the thickness of lamellar cementite varies with transformation temperature at the different rate from interlamellar spacing in 0.55%C steels. Thus, the variation of interlamellar spacing can not properly reflect that of cementite thickness in 0.55%C steels. Fig. 3 shows that the single microstructural parameter, interlamellar spacing, cannot adequately explain the behavior of RA in steels.

TABLE II Volume (%) of pro-eutectoid ferrite as a function of transformation temperature

Transformation Temperature, K	Steel A	Steel B
773	1.4	1.2
813	2.6	1.4
853	3.6	3.0
893	5.2	4.7

Considering the combined effect of the ferrite content and interlamellar spacing on ductility in steels, the variation of RA in Fig. 1 can be explained qualitatively as the increased volume fraction of pre-eutectoid ferrite increases RA at low transformation temperatures and the increased interlamellar spacing decreases RA at high transformation temperatures. However, the decreased ductility at high transformation temperatures in Fig. 1, in spite of the increased volume fraction of pre-eutectoid ferrite, indicates that the characteristics of pearlite would be a dominant factor on RA in 0.55%C steels with volume of pro-eutectoid ferrite of less than 6%.

The thickness of lamellar cementite is an important parameter in controlling the characteristics of degenerate pearlite in medium carbon steels, since it controls the deformability of lamellar cementite during tensile deformation and ferrite thickness in pearlite.

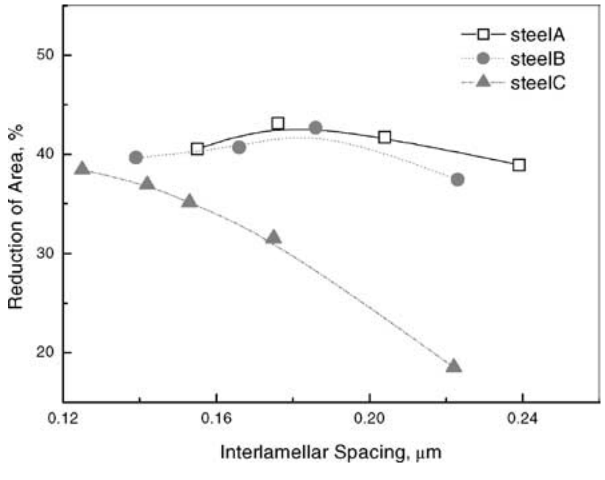

Figure 3 Variations of RA as a function of interlamellar spacing in pearlite.

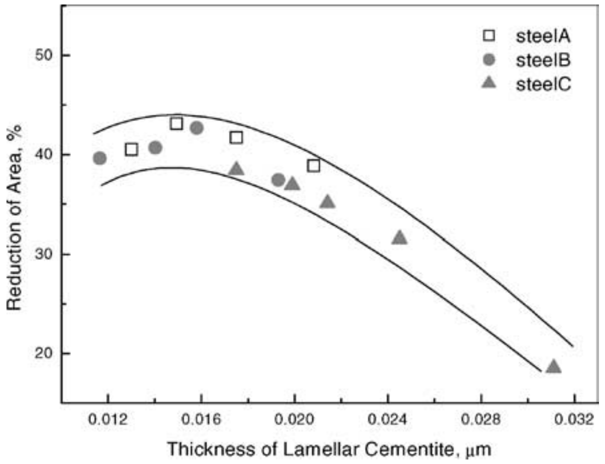

Figure 4 Variations of RA as a function of the thickness of lamellar cementite in pearlite.

The close relationship between RA and cementite thickness in Fig. 4, confirms that the thickness of lamellar cementite is the main parameter to control RA for all tested steels, including eutectoid steel of steel C. It is worthy of note that the maximum ductility is observed at the specific cementite thickness of 0.014–0.016 μm in Fig. 4. Additionally, the calculated interlamellar spacing of 0.12 μm for eutectoid steels, by applying the cementite thickness of 0.015 μm to the Equation 1, almost coincides with the measured interlamellar spacing for the maximum ductility, reported by Houin *et al.* [14]. The authors do not claim the exact value. But they report that the presence of the specific cementite thickness for the maximum ductility is evident, and cementite thickness for the maximum ductility is about 0.014–0.016 μm for tested steels.

From the above, it is obvious that the increased cementite thickness beyond the maximum ductility deteriorates ductility by decreasing plastic deformability. However, the reason of the increased RA with cementite thickness below the maximum ductility is still unclear. Although the authors do not have physical insight at the moment, the change of main controlling factor on ductility from cementite thickness to the thickness of lamellar ferrite for dislocation activity due to the little variation of plastic deformability in thin lamellar cementite, seems most probable.

Therefore, it can be concluded that RA increases with increasing transformation temperature and then, decreases after reaching its maximum value in steels containing pro-eutectoid ferrite less than 6%. The thickness of lamellar cementite was found to be the main factor controlling RA. Additionally, the presence of cementite thickness for the maximum ductility in all the tested steels was observed as 0.014–0.016 μm for tested steels.

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