Mechanism Behind the Onset of Delamination in Wire-drawn Pearlitic Steels

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Fully pearlitic steel was wire-drawn up to a strain of 2.2. Torsion tests were performed using two types of specimens—one was an as-drawn specimen, and the other was aged at 423 K for 3.6 ks. A delamination crack propagated along the longitudinal direction of the wire in the aged specimen, whereas normal fracture was exhibited perpendicular to the longitudinal direction in the as-drawn specimen during torsion tests. Backscattered electron images indicated that the cementite lamellae beneath the delamination crack had vanished, whereas, in the as-drawn specimen, the cementite lamellae beneath the normal fracture surface had rotated until the fracture. Torsion tests with different strain rates indicated an inverse strain-rate dependence of the onset of the delamination, suggesting that the plastic deformability of ferrite and existence of the thermally activated process that controls the cementite dissolution indicate the onset of the delamination. In the present study, the effect of aging and deformability of ferrite on delamination is discussed, suggesting that the delamination crack propagates as a result of the local plastic instability on the scale of several microns.

KEY WORDS: delamination; crack; pearlite; aging; fracture; work hardening.

1. Introduction

Pearlite exhibits a lamellar structure which consists of alternating layers of ferrite and cementite. Pearlitic steel offers superior ductility and work hardenability to other varieties of steels, so it can be used in the manufacturing of high-strength wire.1,2) In the wire manufacturing process, the cementite lamellae are gradually decreased in width, resulting to be hetero-nano structures on the sub-micron scale. The increase in strength obtained during the wire-manufacturing process is explained via the decrease in the lamellar spacing which occurs as the wire is drawn.3) High-strength pearlitic steel has also been developed at the laboratory level, with a tensile strength that reaches 6.3 GPa.4) Wire-drawn pearlitic steels have superior strength and the resistance to delayed fracture;5,6) however, some of them show “delamination”, a particular type of vertical cracking during torsion tests. The resistance to the delamination depends on how to obtain the final strength even though the value of the final strength of the material is the same. For example, it is known that delamination occurs more easily in the sample which was wire-drawn from a high-strength sample with small grains after patenting, comparing to the sample which was strengthened to the same level by wire-drawing from a low-strength sample with large grains after patenting.7) This suggests that deformations of pearlitic steel, i.e., work-hardening, strongly influences the occurrence of delamination. Additionally, strain aging is known to occur owing to the generation of heat during wire manufacturing,8,9) and the existence of a relationship between strain aging and delamination has been identified. Furthermore, through the results of element mapping using 3D atom probes, it has been suggested that the cementite in pearlitic decomposes, and the carbon concentration in the ferrite increases with the increase in drawing deformation.4,10) In fact, the carbon concentration in the ferrite has been reported to reach 4 at% in the segregated parts. Tarui et al.11) focus on the relationship between solid-solution carbon concentrations and delamination, clarifying that in wire manufacturing samples, delamination occurs when the carbon concentration in the ferrite exceeds 1 at%. This suggests that the solid-solution carbon in ferrite affects the occurrence of delamination.

Given this, the authors have conducted microstructural
observations exactly beneath the delamination cracks, and elucidated that the cementite dissolution does occur not only through the progression of the deformation at the wire-manufacturing process, but also occur exactly beneath the delamination cracks.\(^\text{12}\) It is difficult to say that a delamination mechanism has been definitively identified although some controlling factors have been suggested. Therefore, this paper first presents the results of microstructural observations after fracture, using samples in which delamination has and has not occurred during torsion tests. Furthermore, the change in the microstructure due to the delamination is presented. Based on these results, the mechanisms behind delamination are discussed, focusing on the capability of plastic deformation of ferrite in the pearlite structure.

2. Experimental Methods

Factory-produced piano wires were employed as testing material (JIS Standard No.: SWRS82B). The standard composition of the material is shown in Table 1. After hot rolling, the material is reduced to 9 mm in diameter. It is then held in a tubular furnace at 1 223 K for 240 s, then subjected to lead patenting at 833 K for 60 s to obtain a fully pearlite microstructure. This patented material was drawn until it reached a diameter of 3 mm. The final strain after wire-drawing was 2.2 as is given as \(\ln \left( \frac{d_0}{d} \right)^2\) \(^\text{13}\) where \(d_0\) and \(d\) are the diameter before and after drawing, respectively. Delamination is known to be promoted by an increase in the wire-drawing strain, however, as the amount of wire-drawing strain in this study was small, the sample did not exhibit delamination during drawing. Therefore, aging processing was applied to the drawn sample at 3.6 ks and 423 K in order to induce delamination during torsion. The aging temperature and duration time were the lowest temperature and the shortest aging time, respectively, for as-drawn specimens to show delamination, although comprehensive analysis had not been done. So, it is a lower limit condition of delamination for the specimen employed in this study. Torsion testing was conducted using a self-made equipment, in which both ends of the rod material were held by chucks placed at an interval of 160 mm. Then, one side was firmly affixed in a chuck, and the other side was rotated at a fixed speed. The torsion test was conducted at room temperature. The moment applied on the test specimen was recorded using a moment meter mounted to the rotating part, and the number of rotations was calculated from the rotation speed. When the rod specimen was subjected to the torsion test, a large scatter in the onset points of delamination was seen owing to the differences in surface conditions, such as the size of the scratches on the sample surface. In order to control the scatter of crack initiation points in the study, a 0.2-mm-diameter hole was made through the torsion-tested specimens at their centres (80 mm from the grip points) using electrical-discharge machining. The torsion test was conducted 5 times in the study. In all specimens, the delamination cracks always originated from the sides of the hole. As for the torsion speed, the shear strain rate on the outermost surface of the specimen was 0.0015 s\(^{-1}\). In this study, results from two types of specimens—"as-drawn specimen," and "aged specimen" to which aforementioned aging processing applied—were compared.

3. Experimental Results

Figure 1(a) shows the schematic of observed cross sections in the specimens. Hereafter, the sections perpendicular to the direction of wire-drawing are referred to as the "C-sections," while the sections parallel to the direction of wire-drawing are referred to as "L-sections." Figures 1(b) and 1(c) show orientation maps and backscattered electron (BSE) images for ferrite observed from the L-sections of the hot-rolled specimens. The crystallographic orientations are directions normal to the observed surfaces (L-sections). If block boundaries are taken as boundaries with the difference in the orientation for the ferrite crystals of 15° or more, the blocks are roughly equiaxial with a size of approximately 30 μm. The average lamellar spacing was approximately 100 nm in the measured area of 3.3 × 10\(^{-9}\) m\(^2\) although the distribution of lamellar spacing has a certain deviation in a pearlite structure,\(^\text{14}\) where the minimum lamellar spacing was approximately 90 nm. Unlike hot-rolled single-phase ferritic steels, pearlitic steels display a slight change in the orientation within the blocks.\(^\text{15,16}\) This change in orientation also appears as contrasts in colonies of the BSE images as shown in Fig. 1(c).

Figures 1(d), 1(e), 1(f), and 1(g) show crystallographic orientation maps and BSE images for samples in which wire drawing was conducted on hot-rolled material until the drawing strain reached 1.2 and 2.2. An elongation in the block was seen along the drawing orientation (horizontal direction in the diagram) with an increase in the drawing strain. In addition, the lamellar spacing decreased as the drawing strain increased, and its orientation rotated towards the drawing direction. At a strain of 2.2, the minimum lamellar spacing was reduced to be approximately 40 nm. Subsequent results were obtained with samples of the drawing strain of 2.2.

Next, torsion tests were performed on both the as-drawn specimen and aged specimen. Figure 2 displays the moment - shear strain curves from the torsion tests in the as-drawn and aged specimens. In addition, the swing of the curves seen periodically at an interval of approximately 0.05 of strain is the fluctuation of the moment produced from the specimens not being perfectly straight. Here, the horizontal axis of shear strain expresses the shear strain at the outermost surface of the specimen, produced by the added moment, which is given by the following formula:

\[ \gamma = \frac{\theta r}{L} \]

where \(L\), \(\theta\), and \(r\) are the length of the tested specimen, the rotation angle, and the rod diameter, respectively.\(^\text{17}\)

Figure 2 shows that the moment from the as-drawn speci-

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<th>Table 1. Chemical compositions of the employed materials defined in Japanese Industrial Standard (JIS).</th>
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\(2597 \quad \text{© 2020 ISIJ}\)
men increased with a slight amount due to work hardening after yielding, and that the specimen fractured at the strain of 0.34. The elastic limit was increased in the aged specimens compared with that in the as-drawn specimen, which is considered to be due to the aging. The aged specimen displayed almost no work hardening after yielding, and a sudden decrease in moment caused by the occurrence of delamination. The aged specimen fractured at a shear deformation of 0.49, without being destroyed just after the onset of delamination.

Figures 3(a) and 3(b) show optical micrographs of the as-drawn and aged specimens after torsion tests. Figure 3(a) indicates that as-drawn specimen shows normal fracture near the initial hole in the middle of the specimen. The fracture surface is perpendicular to the longer (drawing) direction. In contrast, Fig. 3(b) indicates that delamination occurred as the specimen peeled along the long (drawing) direction from the hole in the centre of the aged specimen. Those indicate that delamination is promoted by aging.

Figure 4(a) shows the fracture surface for the as-drawn specimen. The fracture surface shows elongated dimples. If the normal fractures were produced by the uniaxial tensile load, equiaxial dimples would be seen on the fracture surface. On the other hand, if the principal stress direction is inclined toward the fracture surface, elongated voids which are not perpendicular to the fracture surface would develop.

Fig. 1. (a) Schematic image showing a C-section and an L-section in the specimen. (b), (d), (f) Orientation maps of ferrite observed from the L-section. The crystallographic orientations of the images are those normal to the L-section. (c), (e), (g) Backscattered electron images observed from the L-section. (b), (c) as hot-rolled specimen before drawing, (d), (e) specimen with drawing strain of 1.2, (f), (g) specimen with drawing strain of 2.2. (Online version in color.)

Fig. 2. Moment-shear strain curves from as-drawn and aged specimens, where the drawing strain was 2.2. (Online version in color.)
within the specimen prior to fracture. Then, dimples which inclined with respect to the fracture surface would be seen on the fracture surface, that is, elongated dimples would be seen on the fracture surface. In that case, shear stress is considered to contribute to fracture. The fracture surface with elongated dimples in Fig. 4(a), then, is expected to be created by multi-axial stresses. The origin of the multi-axial stresses is considered to be the tensile stress applied along the longitudinal direction during torsion. If one considers a small square shown in Fig. 7(a) at the initial stage of torsion where the direction of depth is the unit length, a shear stress such as those illustrated in Fig. 8(a) in the torsion deformation is applied on the outer circumference of the test specimen. In the torsion tests, the rotation of a specimen produces the shearing as shown in Fig. 8(b). At the same time, the normal stress is applied in the direction along the axis of rotation (the horizontal direction in the diagram) because the both sides of the specimen are fixed.

Next, Fig. 4(b) displays an SEM image of the fracture surface with delamination in the aged specimen. It is clear that the delamination fracture surface is smooth compared with that of Fig. 4(a), and is the so-called “shear fracture surface” which is accompanied by plastic deformation. As stated previously, the onset of delamination is immediately after yielding, therefore, if the sample is subjected to the plastic deformation in torsion even after the delamination crack initiated, the delamination crack rotates with the specimen until the final fracture. So, it is difficult to elucidate the mechanism behind the delamination using a completely fractured specimen. Thus, we subsequently used an aged specimen for which the torsion test was terminated immediately after the moment drops after yielding (in Fig. 2, at a plastic strain of 0.038), and observations with an optical microscope were conducted with a post-unloaded specimen. Note, specimens observed after torsion tests hardly demonstrated plastic deformation macroscopically except for the area close to the initial hole.

Figure 5(a) shows an optical micrograph of the area surrounding the hole in the sample directly after the occurrence of delamination. It indicates that plastic deformation is concentrated in the area near the initial hole surrounded by dotted lines in Fig. 5(a). In particular, it shows that the hole is sheared in a perpendicular manner toward the longitudinal direction. It is to be noted here that the delamination cracks extended approximately 7.5 mm from the hole parallel to the longitudinal directions. Figure 5(b) shows an SEM image of the C-section near the hole indicated by an arrow A in Fig. 5(a). The delamination cracks also propagated approximately 970 μm from the outer circumference of the specimen to the centre. Those results indicate that the delamination cracks propagated from the surface of the specimen where the hole was created, directly after the beginning of macroscopic plastic deformation, and that the delamination crack propagated along the longitudinal direction of the specimen and parallel with the radial direction. Meanwhile, the crack surface is flat.

Next, in order to elucidate the mechanism behind the delamination, microstructures were observed immediately beneath the normal fracture surface, and beneath the delamination crack. First, a torsion test was terminated just after the drop of moment, and the microstructure just beneath the delamination crack was observed using back scattered electron (BSE). The observed surface was a C-section as shown in Fig. 6(a), the area of which is enclosed by the dotted square in Fig. 5(b). As also shown in Fig. 6(a), the delamination crack propagated both along the longitudinal direction and radial direction of the specimen. Figure 6(a) shows a C-section, so that the drawing direction is the depth direction. The cementite lamellae exhibit complex shapes. Focusing on the cementite lamellae at the wake of the delamination crack, it is to be noted that contrasts from cementite are vanished. TEM observation beneath the delamination crack revealed that the cementite lamellae were actually decomposed during delamination. In addition to that, the decomposition of cementite was observed at the delamination crack tip,
suggesting that the delamination crack extended after the decomposition of cementite. This suggests that the decomposition of cementite is strongly related to the propagation of delamination cracks. In order to elucidate whether the decomposition of cementite in this manner is a phenomenon characteristic only to the area beneath delamination cracks or not, the microstructure beneath the normal fracture surface was also observed.

Figure 6(b) shows a BSE image immediately beneath the normal fracture surface (L-section) outlined by a dotted square in the schematic. The drawing direction which is the longitudinal direction of the sample is left-right, and the left edge of the schematic is the normal fracture surface. Comparing with the area immediately beneath the delamination crack, there are two points of interest; (1) the contrasts of the cementite lamellae keep clear in the whole figure, and there is no decomposition of the cementite immediately below the normal fracture surface; and (2) the cementite lamellae which had lain along the drawing direction (left-right in the image) before the torsion test rotated in the up-down direction. The considerable rotation of the cementite lamellae indicated is considered to be primarily prompted by the plastic deformation of ferrite because the yield stress of cementite is much higher than that of ferrite. These differences observed in the behaviour of plastic deformation in the specimens with the normal fracture and the delamination lead to the following points. In samples with normal fractures, the torsion till the fracture is owing to the plastic deformation with lamellar rotation. In contrast, in the case of the delamination just after yielding, plastic deformation is accompanied by the decomposition of the cementite immediately beneath the delamination crack. Based on these results, we consider the mechanisms behind the delamination in the next section.

4. Discussion
4.1. The Effects of Aging and Drawing Strain (Work Hardening) on Delamination

With respect to the results obtained in this study, aging and drawing strain play an important role on controlling the delamination. To consider these effects, the state of stress which produces normal fracture or delamination must be considered first. When moment is applied to the specimen during a torsion test as shown in Fig. 7(a), shear stress is applied on the outermost surface of the sample as shown in the figure. As shown in Fig. 3(a), the plane normal of fracture surface in the normal fracture is parallel to the longitudinal direction. Therefore, the dominant shear stress acting on the fracture surface is those vertical with respect to the longitudinal direction as shown in Fig. 7(b). On the other hand, the delamination cracks propagate parallel to the longitudinal direction as shown in the schematic in Fig. 6(a). Therefore, the dominant shear stress acting on the delamination cracks is those vertical with respect to the longitudinal direction as shown in Fig. 7(b). On the other hand, the delamination cracks propagate parallel to the longitudinal direction as shown in the schematic in Fig. 6(a). Therefore, the dominant shear stress acting on the delamination cracks is those parallel to the longitudinal direction as shown in Fig. 7(c). Furthermore, as shown in the optical micrographs in Fig. 3(b), the delamination crack demonstrated complex shapes after fracture.

Next, we will consider the effects of the aging and drawing strain. Here, the cementite lamellae in the specimens are oriented in the wire-drawing direction owing to a drawing. In the as-drawn specimens with normal fractures, the lamellae need to keep rotating with plastic deformation to continue rotating the specimen as shown in Fig. 6(b). This rotation is produced by the shear stress generated by moment during rotation. When the moment is applied on the sample, shear stress which is parallel to the longitudinal direction is applied on the lamellae as indicated by the arrows in Fig. 8(a). If the ability of work-hardening of the ferrite is sufficiently high, ferrite deforms plastically under
the shear stress generated by the moment, and the lamellae rotate as shown in Figs. 6(b) and 8(b). When the torsion continues, it leads to the normal fracture as shown in Fig. 3(a). Furthermore, as previously mentioned, dimples are also observed on the normal fracture surface as shown in Fig. 4(a), which indicates that the component of tensile stress applied along the longitudinal direction also contributes to the normal fracture. This is the process of normal fracture.

The primary effect of aging is to lock dislocations in ferrite, which reduces the deformability of ferrite. Although the moment-shear stress of the aged specimen is not significantly different from that of the as-drawn specimen shown in Fig. 2, carbon atoms in the cementite of the aged specimen must have migrated into ferrite to some extent resulting in hardening.\textsuperscript{21) If the plastic deformability of the ferrite becomes low owing to the application of aging and high drawing strain, it is difficult for the lamellae to rotate from the aforementioned plastic deformation. Li\textsuperscript{9} and Takahashi\textsuperscript{10} showed with element maps generated via 3D atom probing that the carbon in the cementite dissolved into the ferrite in the wire-drawing process. When delamination fractures occur as with the aged specimen used in this study, the cementite dissolution is considered to occur locally and dynamically immediately after macroscopic yield. Flow stress in the area in which the cementite dissolves is decreased compared with that of the matrix; thus, the shear deformation is considered to be localised in this area (Fig. 8(c)). In other words, localised unstable deformation under the shear stress parallel to the longitudinal direction progresses in the longitudinal (wire-drawing) direction. This is thought to lead to the propagation of delamination cracks. Furthermore, the area in which the cementite dissolves is within approximately 5 \( \mu \text{m} \) from the delamination crack as shown in Fig. 6(a). It is to be noted that, considering that the average lamellar spacing is approximately 100 nm, the unstable deformation is not occurred at the interface between the cementite and ferrite but in the area which includes dozens of cementite layers.

As stated previously, when the moment is applied on the sample as shown in Fig. 8(a), the shear stress acts equally in the directions parallel and perpendicular to the numerous lamellae lying along the longitudinal direction on the outermost surface of the sample. However, the delamination cracks always propagate parallel to the longitudinal direction. The reason for this can be understood by the followings. First, because many of the cementite lamellae in wire-drawn specimens are parallel to the drawing (longitudinal) direction, the area which serves as the trigger for delamination, where the cementite dissolves, should also be distributed along the longitudinal direction. Therefore, the following three factors are considered to contribute to the propagation of the delamination crack only along the longitudinal direction: (1) the generation of shear stress parallel to the longitudinal (or lamellae) direction due to the macroscopic torsion; (2) the decrease in local flow stress at the area where the cementite decomposed; and (3) the distribution of the cementite-decomposed area which is parallel to the longitudinal direction. It should be noticed here that it can be concluded that the delamination is one of the unstable localised deformation along the longitudinal direction.

Although further study on the cementite decomposition process is necessary, it is pointed that plastic deformation induces the decomposition of cementite. Actually, the cementite decomposition was observed with using atom probes in wire-drawn pearlite steels.\textsuperscript{4,22) It has been demonstrated that carbons segregated at dislocations in ferrite. They suggest that the carbon is more stable being in dislocation cores in the ferrite than bonding to iron atoms in the cementite. They also suggest that the increase in the
number of dislocations in the ferrite with plastic deformation enhances to the migration of carbon atoms from the cementite to the dislocation cores in the ferrite. However, it is possible that the decomposition of the cementite is influenced not only by the plastic deformation of the ferrite but also by the plastic deformation of the cementite itself. This is because if the cementite is decomposed only by the plastic deformation of the ferrite, the delamination should be always observed also in the wire-drawn specimens (non-aged samples) where plastic deformation of the ferrite is sufficiently high enough.

The yield stress of single-phase cementite as a bulk material is significantly higher than that of ferrite. It is estimated to exceed 2.5 GPa at room temperature. The torsion test in this study was conducted at room temperature, therefore, the cementite is not expected to exhibit plastic deformation. However, the cementite in the pearlite was reported to show plastic deformation even at room temperature. Tomota et al. demonstrated in-situ tensile tests in neutron diffraction with pearlitic steels. They unveiled that the stress which the cementite bears reaches to 5 GPa during the plastic deformation in tensile tests. In the torsion deformation, the cementite is expected to bear the same degree of stress, the amount of which is higher than the yield stress of cementite. When dislocations in ferrite are locked either by carbon atoms migrated from cementite during aging, or by other dislocations introduced during wire-drawing, the applied stress distributes to the cementite. It induces the stress transfer into cementite to accelerate the decomposition of cementite, where the stress reduces Gibbs free energy for the decomposition of cementite. In addition to that, plastic deformation of cementite would also accelerate the decomposition of cementite transferring carbons to ferrite along with dislocation cores.

There also must be the critical lamellar spacing which controls the deformability of ferrite and cementite. However, it is to be noted that it contains the effects of work-hardening and deformability of cementite if one makes the specimen with different lamellar spacing by means of wire-drawing. It is necessary to change lamellar spacing without deformation in order to investigate only the effect of lamellar spacing on delamination.

4.2. The Effect of Strain Rate on Delamination

As stated in the previous section, if the cementite decomposition is the trigger for delamination, delamination should be one of thermally activated processes, i.e., the onset of delamination is controlled by the strain rate. Therefore, it is investigated next whether the onset of delamination is dependent or not on the strain rate. As in the former section, samples with a 0.2-mm-diameter hole in the centre were employed for the torsion samples. The aging condition was 393 K for 0.6 ks. Torsion tests were performed at strain rates of 0.00015 s\(^{-1}\) and 0.03 s\(^{-1}\). Figure 9 shows moment - shear strain curves that the drop of moment at a strain of 0.03 due to the onset of delamination in the specimen with the strain rate of 0.00015 s\(^{-1}\). In contrast, moment kept increased in the specimen with a higher strain rate of 0.03 s\(^{-1}\), where delamination was not observed. As the employed samples were both aged, the moment-shear strain curves practically overlap until the onset of delamination at low strains unlike those in Fig. 2. As the generation of delamination is inversely dependent on the strain rate as shown in Fig. 9, it is clear that the onset of delamination is controlled by a thermally activated process.

The difference of delamination and low temperature embrittlement is considered briefly. Brittle fractures are seen at low temperatures or high strain rates in standard steel due to the loss of plastic deformability. In contrast, delamination occurs at low strain rates. Therefore, delamination is not the same as “low-temperature embrittlement”. The propagation of delamination cracks, as stated in the previous section, is localised plastic deformation accompanying cementite decomposition, and considered to be one of unstable deformations. The easiness of delamination depends on the ability for plastic deformation in the ferrite after aging and drawing, however, we conclude that the direct trigger for the delamination is the decomposition of the cementite followed by unstable localised plastic deformation, which means that mechanism behind the delamination is essentially different from that behind low temperature embrittlement.

5. Conclusion

To identify the mechanism behind the delamination of pearlitic steels after wire-drawing, torsion tests were conducted, and observations of fractured specimens were performed. The following conclusions were obtained:

1 In controlling a process involving a thermally activated process, manipulation to lower the strain rate conditions in testing corresponds to a higher testing temperature. The onset of delamination occurs at low strain rates or high temperature in testing. Thus, the delamination fundamentally differs from low-temperature embrittlement.
tion of the specimens. Delamination occurred in the aged specimens, and the plane-normal of the fracture surface was perpendicular to the longitudinal direction.

(2) Lamellae rotated immediately beneath the surface of the normal fracture while cementite lamellae dissolved in the area with the width of several microns immediately beneath the fracture surface of the delamination crack. Cementite lamellae did not rotate in the delaminated specimens. In the as-drawn specimens, plastic deformation of the ferrite was capable, which allows cementite lamellae continue to rotate to the point of normal fracture. In wire-drawn specimens, the cementite lamellae were not able to rotate during the rotation.

(3) An inverse dependence on the strain rate was identified in the occurrence of delamination, which indicates that a type of thermally activated process must contribute to the onset of delamination.

(4) The decrease in deformability of ferrite due to aging or work-hardening (wire-drawing) makes it difficult for lamellae to rotate under the shear stress from the moment. Consequently, immediately after the onset of macroscopic plastic deformation, cementite decomposes locally on the order of several microns. The delamination process is suggested as follows: (i) Plastic deformability of ferrite is reduced by the locking of dislocations in ferrite with carbon atoms migrated from cementite due to aging or work-hardening during the wire-drawing. (ii) The stress intensifies at cementite, which accelerates the decomposition of cementite. (iii) The area where cementite decomposed shows relatively low flow stress, which becomes the initiation site of a delamination crack. (iv) The delamination crack propagates, making another stress intensification ahead of the crack to decompose cementite along the drawing directions. (v) It happens in very short time detected as delamination failure. It is to be noted that the delamination cracks are considered to be the unstable deformation which occurs in the area where the cementite locally dissolves. The unstable deformation is not produced at the single layer of ferrite/cementite interface but is produced in an area with dozens of lamellae.

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