Ductile–Brittle Transition Temperature of Ultrafine Ferrite/Cementite Microstructure in a Low Carbon Steel Controlled by Effective Grain Size

T. HANAMURA, F. YIN and K. NAGAI

National Institute for Materials Science, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047 Japan.

(Received on August 29, 2003; accepted in final form on October 17, 2003)

To analyze the good toughness of ultrafine ferrite/cementite steels, the concept of effective grain size (d_{EFF}) is applied to ductile-to-brittle transition temperature, DBTT, for ultrafine ferrite/cementite (Uf-F/C), ferrite/pearlite (F/P), quenched (Q), and quench-and-tempered (QT) microstructures in a low carbon steel. The d_{EFF} is determined to be 8, 20, 100, and 25 μm for Uf-F/C, F/P, Q, and QT, respectively. In F/P and Q, it is in accordance with the ferrite grain size and the prior austenite grain size, respectively. In QT, the d_{EFF} fits the martensite packet size. In Uf-F/C, the ferrite grain size has a bimodal distribution and the larger grain size corresponds to the d_{EFF} , which is the smallest among the four microstructures. In terms of the relationship between d_{EFF} and DBTT, the Uf-F/C, Q, and QT microstructures can be placed into the same group and the F/P to a different one. Furthermore, the Uf-F/C has the highest estimated fracture stress among the four microstructures. These might be the result of the difference in the surface energy of fracture, namely the former is estimated to have a surface energy of 34.6 J/m² and latter a surface energy of 7.7 J/m². Thus, the excellent toughness of the ultrafine ferrite/cementite steel can be attributed to the small d_{EFF} and the high surface energy of fracture.

KEY WORDS: effective grain size; ductile-to-brittle transition temperature; toughness; fracture strength; low carbon steel; ultrafine grain structure.

1. Introduction

A major concern for structural materials has been the improvement of the trade-off balance between strength and toughness. The balance between yield strength, YS, and ductile-to-brittle temperature, DBTT, has attracted a great attention from an engineering point of view. In this aspect, Pickering¹⁾ derived the balance vectors with respect to the strengthening mechanism from his collected database for low carbon steels with ferrite grain sizes larger than 10 μm , and pointed out the great significance of grain refinement. As shown in Fig. 1, the change of DBTT by a 9.8 MPa increase in YS is +6K in dislocation strengthening, +4K in dispersion strengthening, and –10K in grain-size strengthening.

In ferrite/pearlite, F/P, low carbon steels, DBTT can be determined by the crystallographic ferrite grain size, d , and expressed in the following forms^{1–4)}:

$$\text{DBTT} = A - Kd^{-1/2} \quad \text{or} \dots\dots\dots (1)$$

$$= A - K \ln d^{-1/2} \dots\dots\dots (2)$$

where the constant A contains metallurgical factors other than the grain size and the coefficient K is independent of grain size.

The ultrafine ferrite/cementite, Uf-F/C, steel shows an

excellent balance of high YS and low DBTT as expected. However, the above-mentioned equation is not necessarily applicable⁵⁾ when the ferrite grain size is taken as d . In other words, the value of DBTT varies widely between Eqs. (1) and (2) when a grain size in the range of a few μm and smaller is used. The DBTT estimated with $d=1 \mu\text{m}$ from Eq. (1) is 49K, while that from Eq. (2), based on the extrapolation of the experimental data from reference,⁶⁾ is 104K.

Fig. 1. Relationship between the change in DBTT and the change of 9.8 MPa in yield strength for different microstructural factors, i.e. dislocation strengthening, dispersion strengthening, and grain-size strengthening.

The 9% Ni steel is an excellent material with a good balance of strength and toughness.⁷⁾ The microstructure is a quench and tempered (QT) martensite that occasionally contains a small volume of retained austenite. Its high YS is inherent to the QT martensite, since Ni addition does not increase YS by itself. Hence, the specific effect of Ni is to enhance the toughness of QT steel, whose mechanism is still disputable. In QT steel, the idea of an effective grain size,⁸⁾ d_{EFF} , accounts for the DBTT in the steel (Terasaki *et al.* use the term, unit crack path,⁹⁾ instead of effective grain size).

The Griffith idea says that fracture stress, σ_F , is a function of the surface energy of fracture and an imaginary crack size. The unstable growth of the Griffith crack has been discussed by assuming that the imaginary pre-existing crack interacting with the stress field in the transition temperature range is comparable to the size of the ferrite grain.¹⁰⁾ Under the same stress field in the transition temperature range, plastic deformation prevails over brittle fracture when yielding occurs first or the brittle fracture dominates when the cleavage starts before yielding. Since a criterion to initiate yielding in polycrystalline material is the grain size or slip length, it is simple and reasonable to suppose that the cleavage cracking of a grain is a counter measure to initiate cleavage fracture. However, such a “grain” idea is not always evident in all the steel mi-

crostructures.

The brittle fracture belongs to a similar family of transgranular cleavage in bcc steels. In F steel, its brittle fracture is a typical cleavage of the $\{100\}_\alpha$ plane.¹¹⁾ Furthermore, the cleavage planes have also been identified as $\{100\}_\alpha$ ^{12–14)} in F/P, QT, and Uf-F/C steels. Hence, we can finally understand that d_{EFF} , in which a cleavage crack goes through in a straight fashion, corresponds to the microstructural unit having a specific crystallographic orientation and bounded by high-angle boundaries. In addition, the d_{EFF} can be determined experimentally by fractography.

Flow stress increases at lower temperatures. Fracture stress, σ_F , which is assumed to be equal to the flow stress at DBTT, is believed to be not dependent on temperature. Hence, an increase in flow stress or that in YS increases the temperature at which the flow stress reaches σ_F , or shifts the DBTT to a higher temperature. In addition, a further increase in DBTT may occur when the increase in YS decreases σ_F , as described in Fig. 2(a).¹⁾ Unless the grain refinement increases σ_F significantly, the shifting of DBTT to a lower temperature cannot be accounted for as demonstrated in Fig. 2(b). Thus, the reasons that Uf-F/C can generate the excellent toughness should also be considered in terms of σ_F .

Hence, we fabricated four different microstructures from a single steel with a low carbon content in the present study and extensively examined how DBTT is determined for each microstructure with the aid of an d_{EFF} idea, paying special attention to the excellent toughness of the Uf-F/C steel. Recently, the Uf-F/C has sometimes been shown to have bimodal structures, *i.e.* two peaks exist in the grain size distribution.¹⁴⁾ Hence, it is also interesting to determine which crystallographic unit mainly controls the DBTT in the Uf-F/C structure.

2. Experimental

An ingot was melted in vacuum in a laboratory scale. The chemical composition analogous to the conventional JIS-SM490 is shown in Table 1. The ingot was homogenized for 1 800 s at 1 473 K and hot-rolled to a 23 mm-thick plate. (1) F/P samples were machined from the plate. (2) Uf-F/C samples were made from the plate in the following manner: The plate was heated for 1 800 s at 1 173 K, followed by water quenching, and then caliber-warm-rolled into 12 mm-square and 1 000 mm-long rods by an accumulated area reduction of 85%. (3) Q, designating as-quenched, samples were the Uf-F/C samples annealed for 3 600 s at 1 373 K and water quenched. Finally, (4) QT samples were obtained by tempering the Q samples for 3.6×10^5 s at 723 K.

Cylindrical tensile test pieces were machined from four samples with a gage diameter of 3.5 mm and a gage length

Fig. 2. (a) Schematic relationship among yield stress, fracture stress, and DBTT: in the case, where a further increase in DBTT occurs when the increase in YS decreases σ_F . (b) Schematic relationship among yield stress, fracture stress, and DBTT: in the case, where a further decrease in DBTT occurs when the increase in YS significantly increases σ_F .

Table 1. Chemical compositions of the steel.

	(mass %)						
	C	Si	Mn	P	S	T-Al	T-N
Present	0.148	0.33	1.41	0.001	0.001	0.003	0.0012
SM490	0.15	0.28	1.45	0.005	0.0004	0.031	0.0016

of 25 mm. The direction of the tensile test pieces was parallel to the rod length. Charpy impact test pieces were similarly prepared in a standard 10 mm-square, 55 mm-long, and 2 mm V-notched geometry. The length of the Charpy impact test pieces was parallel to the rod length and the notch was vertical to both the rod length and one of the four flanks of the rod. Tensile tests were performed with a crosshead speed of 0.5 mm/min at room temperature, and Charpy impact tests were conducted in the temperature range between 78 K and 373 K.

Samples from the Charpy impact test were observed with an optical microscope (OM), a scanning electron microscope (SEM), an electron backscatter diffraction measure-

ment (EBSD) and a transmission electron microscope (TEM). The d_{EFF} was determined by measuring the cleavage fracture unit of each sample fractured at 77 K. Each fractured sample was cut in half, embedded into a plastic mold, and observed by SEM.

3. Results

3.1. Microstructure

Figure 3 shows SEM microstructures for all the samples. In the F/P sample, the horizontal and the normal directions are parallel and perpendicular to the hot-rolling direction, respectively. In the other samples, the normal direction is

Fig. 3. Microstructures of (a) ferrite/pearlite (F/P), (b) ultrafine ferrite/cementite (Uf-F/C), (c) as-quenched (Q), (d) quench-and-tempered (QT) steels.

Fig. 4-1. EBSD analysis on the ultrafine ferrite/cementite (Uf-F/C) steel. (a) The ferrite grains manifested by the boundaries with the misorientation above 5 degrees (the difference in crystallographic orientation is 5 degrees and more), (b) the grain size and misorientation distribution calculated on the analysis.

Fig. 4-2. EBSD analysis on the quench-and-tempered (QT) steel. (a) The ferrite grains manifested by the boundaries with the misorientation above 5 degrees (the difference in crystallographic orientation is 5 degrees and more), (b) the grain size and misorientation distribution calculated on the analysis.

identical to the caliber-rolling direction or the cross sectional area is shown.

The F/P (a) consists of ferrite and pearlite. White parts correspond to the pearlite and gray parts to the ferrite. The average ferrite grain size is 20 μm .

The Uf-F/C (b) consists of equiaxed ultrafine grain microstructures and finely dispersed cementites, according to SEM observations. White dots correspond to the cementites and gray parts to the ferrite. The ferrite grains were elongated to some extent in the longitudinal direction. On the other hand, the EBSD analysis also characterized the grain boundaries in the Uf-F/C sample, as shown in **Fig. 4-1**. In this figure, the ferrite grains are manifested by the boundaries with the misorientation above 5 degrees. There are two kinds of characteristic ferrite grains with a peak area fraction in the microstructure, *i.e.* the fine ones (about 1.6 μm), and the coarse ones (about 8 μm).¹⁵⁾ The average grain size determined by grain area averaging, including the two kinds of characteristic grain sizes, is 2.7 μm .

The Q (c) has a structure mostly consisted of martensite, while the QT (d) has a structure mostly consisted of tempered martensite. The large unit corresponds to the prior austenite grain. The prior austenite grain size for both samples is determined to be about 100 μm . The EBSD analysis cannot be applied to the Q sample because of the large strains in the matrix that prevent precise EBSD measurements. On the other hand, the detailed microstructure of the

Table 2. Properties of the steel with different microstructures, *i.e.* ferrite/pearlite (F/P), ultra-fine ferrite/cementite (Uf-F/C), as-quenched (Q), and quench-and-tempered (QT) steels: YS (yield strength), TS (tensile strength), T.El. (total elongation), and U.El. (uniform elongation).

Sample	YS(MPa)	TS(MPa)	T.El.(%)	U.El.(%)
F/P	261	463	35	16.0
Uf-F/C	536	612	21	9.5
Q	619	1027	4	2.9
QT	548	676	17	7.4

QT shows the interior of the prior austenite grain, where the fine martensite laths and fine cementite particles can be seen. The EBSD analysis also characterized the grain boundaries in the QT sample, and the grains are manifested by the boundaries with the misorientation above 5 degrees, as shown in **Fig. 4-2**. There are grains with a peak area fraction in the microstructure with a size of about 25 μm , which corresponds to the packet size.

3.2. Charpy Impact Property

YS, TS, total elongation, T.El., and uniform elongation, U.El., for each structure are listed in **Table 2**.

The Charpy impact absorbed energy as a function of test temperature for the four samples is plotted in **Fig. 5**. The Q

sample shows the poorest impact properties among them. The upper shelf energy cannot be determined even at 373 K. The QT shows improved properties of 240 K for the absorbed energy transition temperature and 240 J for the upper-shelf energy. The F/P shows a lower absorbed energy transition temperature and a higher upper-shelf energy than those of the QT. The Uf-F/C has the best impact properties, having the lowest absorbed energy transition temperature of 160 K and maintaining the high upper-shelf energy level of 300 J down to 230 K.

The change of crystallinity, or the area percent of brittle fracture on the fracture surface, measured by fractography is plotted as a function of temperature in Fig. 6. DBTT is defined as the temperature having 50% crystallinity. The DBTT for the four samples is as follows: 53 K for Uf-F/C, 223 K for F/P, 253 K for QT, and 378 K for Q samples.

Figure 7 shows the SEM image of the side view of the

Fig. 5. Charpy impact absorbed energy as a function of test temperature for ferrite/pearlite (F/P), ultra-fine ferrite/cementite (Uf-F/C), as-quenched (Q), and quench-and-tempered (QT) steels.

fracture surface for each sample tested at 77 K. The crack path is from the right to the left, with the V-notch at the right end. Therefore, the fracture surface is observed as a line at the top-edge side view of the sample. d_{EFF} is determined to be 8, 20, 100, and 25 μm for Uf-F/C, F/P, Q, and QT, respectively. In F/P and Q, it is in good accordance with the ferrite grain size and the prior austenite grain size, respectively. In QT, the d_{EFF} of 25 μm fits with the martensite packet size in the tempered structure. The reason why the d_{EFF} value is different between Q and QT might be due to the relaxation of strain and the rotation of crystallographic grain direction because of annealing. The d_{EFF} of 8 μm for Uf-F/C corresponds to the larger grain size in the bimodal distribution.

Figure 8 shows the relationship between the d_{EFF} and DBTT, including the literature data for QT steels,⁹⁾ F/P

Fig. 6. Crystallinity after Charpy impact test as a function of test temperature for ferrite/pearlite (F/P), ultra-fine ferrite/cementite (Uf-F/C), as-quenched (Q), and quench-and-tempered (QT) steels.

Fig. 7. SEM micrographs of cleavage fracture unit for ferrite/pearlite (F/P), ultra-fine ferrite/cementite (Uf-F/C), as-quenched (Q), and quench-and-tempered (QT) steels.

Fig. 8. Relationship between effective grain size and DBTT for the steels in this study, M and M+B steels⁹⁾ and a F/P steel.^{10,16)}

steels (0.15C–0.26Si–1.44Mn),¹⁰⁾ and another F/P steel (SM490: 0.15C–0.48Si–1.48Mn).¹⁶⁾ The F/P steel of Ref. 16) had an average grain size of 7 μm and a DBTT of 200 K. Here, the data of two F/P samples with different grain sizes of 12 and 16 μm were also added. These two samples were prepared by heating the Uf-F/C sample at different temperatures in the austenite phase region and then by cooling them in the ferrite/pearlite structure. In this figure, two groups seem to exist, a group belonging to the F/P microstructure and the other to the Q, QT, and Uf-F/C microstructures. The important points in this figure are that the smallest d_{EFF} of Uf-F/C results in the lowest DBTT in the latter group. Furthermore, the Uf-F/C shows a lower DBTT at a given d_{EFF} than the F/P group.

Accordingly, when d in Eq. (2) is replaced by effective grain size, d_{EFF} , DBTT can be expressed by the following equation:

$$\text{DBTT} = A - B \cdot \ln(d_{\text{EFF}}^{-1/2}) \quad (3)$$

Here, A and B are 1279, 203 for the Q, QT, and Uf-F/C group and 836, 108 for the F/P group. The unit is K for DBTT and m for d_{EFF} .

In Fig. 8, the estimation on the change of DBTT by d_{EFF} is also superimposed using Eq. (1) by Pickering¹⁾:

$$\begin{aligned} \text{DBTT} = & 254 + 44(\text{Si}) + 700(\text{N}_f)^{-1/2} \\ & + 2.2(\text{Pearlite}) - 0.36d^{-1/2} \quad (4) \end{aligned}$$

with Si=0.3%, $\text{N}_f=0\%$, Pearlite=20%. Finally A becomes 311.5 and B 0.36 in the form of Eq. (1). Here, (Si) and (N_f), are the mass percentages of Si and N in the matrix, respectively. (Pearlite) is the volume percent of pearlite. The unit of d is m. The estimated curve is close to the F/P group data in the present study. However, the extrapolated curve shows that the DBTT of F/P is lower than that of the present study, suggesting that the Pickering's estimation is applicable only in the range around 10 μm . For grain sizes be-

Fig. 9. Relationship between flow stress and σ_F as a function of temperature based on experimental data for different microstructures.

tween 100 and 7 μm , the equation obtained in this study along with the data from Refs. 10) and 16), e.g. Eq. (3) with $A=836$ and $B=108$, agrees better with the presented data.

4. Discussion

4.1. Estimation of Fracture Stress

Fracture stress is a function of the surface energy of fracture, γ , and the crack size, r , according to the Griffith equation¹⁷⁾ when considering an infinite cracked plate with a central transverse crack of length r :

$$\sigma_F = (4\gamma E/\pi)^{1/2} \cdot r^{-1/2} \quad (5)$$

Here we replace r by d_{EFF} :

$$\sigma_F = (4\gamma E/\pi)^{1/2} \cdot d_{\text{EFF}}^{-1/2} \quad (6)$$

On the other hand, when we assume an infinite plate with a penny shaped crack of diameter r in the bulk center, the fracture stress is expressed like the following¹⁷⁾:

$$\sigma_F = (\pi\gamma E/(\nu-1)^2)^{1/2} \cdot r^{-1/2} \quad (7)$$

Here we replace r by d_{EFF} :

$$\sigma_F = (\pi\gamma E/(\nu-1)^2)^{1/2} \cdot d_{\text{EFF}}^{-1/2} \quad (8)$$

When we assume that σ_F is independent of temperature and becomes equal to the flow stress at DBTT, we can estimate the σ_F by taking the YS as the flow stress at DBTT as described below.

According to N. Tsuchida *et al.*,¹⁸⁾ the thermal component of flow stress is independent of ferrite grain size while the athermal component increases with decreasing grain size. Therefore, in Fig. 9, the change of flow stress by temperature obtained by Tsuchida *et al.* is adopted and drawn parallel to each sample as each curve has the YS determined at three different temperatures, i.e. 77, 293, and 323 K. However, in the sample Q, the curve is offset to higher temperature regions to fit the experimental data of YS. This is done by assuming that the change in YS for sample Q has the same shape as those of F/P samples, except with a different temperature, at which the curve changes its inclination. The marks, ■, ●, ◆, ▲ stand for the YS for F/P, Uf-F/C, Q, and QT, respectively. The large meshed diamond (◆) is the YS at DBTT for each sample,

or in other words the estimated σ_F . The horizontal line shows the σ_F vs. temperature curve for each sample.

The difference between σ_F and YS for each microstructure is 440 MPa, -18 MPa, and -90 MPa at room temperature for Uf-F/C, Q, and QT, respectively, while F/P is taken as the reference. This clearly shows that Uf-F/C has the largest difference between σ_F and YS among the four microstructures. Hence, the earlier speculation that the grain refinement increases the σ_F significantly is proved.

4.2. Estimation of Surface Energy of Fracture

Using Eqs. (6) and (8), we can also estimate the surface energy of the fracture for each sample with the estimated σ_F and the experimentally determined d_{EFF} . In this estimation by using Eqs. (6) and (8), E is taken as 2.06×10^2 GPa and ν is taken as 0.293 as for steel.

When σ_F determined by Eq. (6) is plotted against d_{EFF} , and we can find three groups similarly as in Fig. 8. The slope of each group shows the surface energy of fracture. The first group consists of only F/P samples with the lowest estimated surface energy of 7.7 J/m^2 , the second group of Uf-F/C and QT with an estimated surface energy of 34.6 J/m^2 , and the third group of Q with a surface energy of 150.9 J/m^2 . σ_F determined by Eq. (8) can also be used to estimate the surface energy of each sample, and we can find three groups. In this case, the first group consists of only F/P samples with the lowest estimated surface energy of 1.5 J/m^2 , the second group of Uf-F/C and QT with an estimated surface energy of 7.0 J/m^2 , and the third group of Q with a surface energy of 29.7 J/m^2 .

The surface energy of ferrite iron is presented to be

Fig. 10. σ_F as a function of the inverse square root of effective grain size for different microstructures.

Table 3. Properties of the steel with different microstructures, i.e. ferrite/pearlite (F/P), ultra-fine ferrite/cementite (Uf-F/C), as-quenched (Q), and quench-and-tempered (QT) steels: d_{EFF} (effective grain size), unit determining the d_{EFF} , YS (yield strength), σ_F (fracture strength), DBTT (ductile-to-brittle transition temperature), and γ (surface energy).

Sample	d_{EFF} (μm)	Unit determining d_{EFF}	YS(MPa) Experimental	FS(MPa) Estimated	DBTT(K) Experimental	γ (J/m ²) Estimated
F/P	20	Ferrite grain	261	351	223	7.7
Uf-F/C	8	Bigger part in grain clusters	536	1066	53	34.6
QT	25	Martensite packet	548	620	253	
Q	100	Prior-austenite grain	619	619	378	150.9

4.52 J/m^2 by A. Kelly *et al.*¹⁹⁾ T. Yokobori *et al.*²⁰⁾ reported that an experimental value of effective surface energy is 100 J/m^2 . In Fig. 10, σ_F determined by Eq. (6) is plotted against d_{EFF} , together with lines constructed using the value of surface energy of Refs. 19) and 20). The surface energy together with d_{EFF} , the unit of structure determining the d_{EFF} , YS, σ_F , and DBTT are listed in Table 3.

Interestingly Uf-F/C is concluded to have a higher surface energy than F/P. This means that Uf-F/C can have a lower DBTT than F/P due to its higher surface energy of fracture and the resultant higher fracture stress when Uf-F/C has the same d_{EFF} as F/P.

Accordingly the excellent toughness or a very low DBTT of Uf-F/C can be attributed to its small d_{EFF} and high surface energy of fracture.

4.3. Bimodal Distribution of Grain Size in Uf-F/C

There are three kinds of grain sizes in the present Uf-F/C, i.e. 1.6 and $8 \mu\text{m}$ for the peaks of distribution, and $2.7 \mu\text{m}$ for the area average determined by EBSD. One way to determine the grain size of a microstructure is by the linear intercept method based on OM or SEM images. Another way is grain area averaging based on the EBSD images using different angle values of grain boundaries. Among the high angle grain boundaries, those with boundary angles equal to or above 5 degrees are said to be effective for the clarification of grain sizes.^{21,22)} In the Uf-F/C, the larger grain cluster, i.e. the $8 \mu\text{m}$ grain cluster, corresponds to the d_{EFF} .

Tsuchida *et al.*²³⁾ reported that YS is estimated to be 551 MPa for $1.6 \mu\text{m}$, 464 MPa for $2.7 \mu\text{m}$, and 342 MPa for $8 \mu\text{m}$ when Uf-F/C is annealed after caliber rolling. Yin *et al.*¹⁴⁾ considered the effect of average dislocation density and the dislocation interaction parameter on YS, and concluded that the dislocation contribution is estimated to be 115 and 52 MPa in the as-rolled and as-annealed conditions, respectively. Based on this, the dislocation density contribution without annealing is estimated to be 63 MPa. When this value of 63 MPa is subtracted from the YS data for the present Uf-F/C, the corrected YS value for the annealed one becomes 473 MPa. This is in good agreement with the above-mentioned value of 464 MPa because the grain size is supposed to be $2.7 \mu\text{m}$.

Therefore, the grain size determining YS is the average grain size for the Uf-F/C, although the d_{EFF} determining the DBTT corresponds to the larger size in the two-grain clusters. This result might be very much disputable; however,

more improvement in the YS-DBTT balance can be expected from the present results. Further detailed studies are required for this purpose.

5. Conclusions

To investigate the excellent toughness of ultrafine ferrite/cementite steels, the concept of effective grain size (d_{EFF}) is applied to ductile-to-brittle transition temperature, DBTT, for four different microstructures in one composition of low carbon steel. The microstructures are ultra-fine ferrite/cementite (Uf-F/C), ferrite/pearlite (F/P), quenched (Q), and quench-and-tempered (QT). The following conclusions are obtained.

(1) For Uf-F/C, F/P, Q, and QT, the d_{EFF} is determined to be 8, 20, 100, and 25 μm , respectively. In F/P and Q, the d_{EFF} is in accordance with the ferrite grain size and the prior austenite size, respectively. The d_{EFF} for QT corresponds to the martensite packet size. In Uf-F/C the ferrite grain size has a bimodal distribution and the larger grain size matches the d_{EFF} , the smallest among the four microstructures.

(2) The relationship between d_{EFF} and DBTT reveals that the Uf-F/C microstructure belongs to the same group composed of Q and QT microstructures, and F/P belongs to a different group.

(3) The estimated fracture stress shows that Uf-F/C has the highest fracture stress among the four microstructures.

(4) The difference in DBTT and σ_F among the four microstructures is estimated to be the difference in the surface energy of fracture. The group of Uf-F/C and QT has a much higher surface energy value than that for the F/P group.

(5) The excellent toughness of the ultrafine ferrite/cementite steel can be attributed to its characteristic small d_{EFF} and high surface energy of fracture, compared to those of other structures.

Acknowledgments

The authors thank Dr. Kaneaki Tsuzaki, Dr. Shiro

Torizuka, Mr. Hiroshi Nakajima, Mr. Nobuo Sakuma, Mr. Masashi Saito, Mr. Katsuya Ohnishi, Mr. Tohru Awane, Mr. Takaaki Hibar, Ms. Tomoko Nozawa, Ms. Lan Huang, and Ms. Elena Bulgarevich for their technical help and scientific discussions.

REFERENCES

- 1) F. B. Pickering and T. Gladman: *Iron Steel Inst. Spec. Rep.*, (1963), No. 81, 10.
- 2) A. H. Cottrell: *Trans. Metall. Soc. AIME*, **212** (1958), 192.
- 3) N. J. Petch: *Philos. Mag.*, **3** (1958), 1089.
- 4) A. N. Stroh: *Adv. Phys.*, **6** (1957), 48.
- 5) T. Hanamura, T. Hayashi, H. Nakajima, S. Torizuka and K. Nagai: Second Int. Conf. on Processing Materials for Properties, ed. by B. Mishra and C. Yamauchi, TMS, Warrendale, PA, (2000), 206.
- 6) W. C. Leslie: *Metall. Trans.*, **3-5** (1972).
- 7) J. M. Hodge, R. D. Manning and H. M. Richhold: *Trans. AIME*, **185-233** (1949).
- 8) S. Matsuda, T. Inoue and M. Ogasawara: *Trans. Jpn. Inst. Met.*, **9** (1968), 343, **11** (1970), 36.
- 9) F. Terasaki and H. Ohtani: *Tetsu-to-Hagané*, **58** (1972), 436.
- 10) F. Terasaki and H. Ohtani: *Trans. Iron Steel Inst. Jpn.*, **12** (1972), 45.
- 11) C. D. Beachem: *Metall. Trans.*, **4** (1973), 1999.
- 12) S. Matsuda, T. Inoue, H. Mimura and Y. Okamura: *Trans. Iron Steel Inst. Jpn.*, **12** (1972), 325.
- 13) C. D. Beachem: *Fracture*, Vol. I, Academic Press, New York and London, (1968), 305.
- 14) F. Yin, T. Hanamura, T. Inoue and K. Nagai: Seventh Workshop on the Ultra-Steel: Requirements from New Design of Constructions, NIMS, Tsukuba, (2003), 288.
- 15) F. Terasaki and H. Ohtani: *Tetsu-to-Hagané*, **58** (1972), 1067.
- 16) K. Nagai and O. Umezawa: Report of Study Committee on Effect of Impurities due to Scrap on Steel Products, Materials Science of Tramp Elements, ISIJ, Tokyo, (1997), 70.
- 17) A. A. Griffith: *Philos. Trans. R. Soc. (London) A*, **A221** (1920), 163.
- 18) N. Tsuchida, Y. Tomoda and K. Nagai: *ISIJ Int.*, **42** (2002), 1594.
- 19) A. Kelly *et al.*: *Philos. Mag.*, **15** (1967), 567.
- 20) T. Yokobori: *Tech. Rep. Tohoku Univ.*, **29** (1964), 167.
- 21) H. Yagi, N. Tsuji and Y. Saito: *Tetsu-to-Hagané*, **86** (2000), 349.
- 22) A. Ohmori, S. Torizuka, K. Nagai, K. Yamada and Y. Kogo: *Tetsu-to-Hagané*, **88** (2002), 857.
- 23) N. Tsuchida, Y. Tomoda and K. Nagai: *Tetsu-to-Hagané*, **89** (2003), 1170.