Brittle Fracture Initiation and Propagation-arrest Characteristics in Ferritic-Pearlitic Steels*

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Synopsis

The effects of the microstructure and the alloying elements on the initiation and the propagation-arrest properties of brittle fracture in ferritic-pearlitic steels were investigated by means of COD (Crack Opening Displacement) and tapered DCB (Double Cantilever Beam) tests.

It was recognized that in both cases the temperature at which the brittle fracture was initiated or arrested at a given toughness was linearly related to the inverse square root of the mean pearlite colony diameter. This implied that the pearlite colony which lay in the plastic zone in the vicinity of the fatigue crack tip or the propagating main crack tip was cleaved by the applied stress, and that the critical condition whether this pearlite crack cleaved the adjacent ferrite to become Griffith's flaw dominated the initiation or the propagation-arrest properties of the brittle fracture.

The difference between the result of the static COD and that of the tapered DCB test appeared to exist mainly in the strain rate, the strain rate at the tip of the advancing cleavage crack for the DCB test being much larger than that of the fatigue crack tip for the COD test.

It was also confirmed that the addition of nickel greatly improved the low temperature toughness for the tests with high strain rates.

I. Introduction

The problem of brittle fracture in steels has been treated from both the engineering and the metallurgical points of view, the former based on macroscopic fracture mechanics, while the latter tackling the problem in terms of microscopic dislocation theory. Although either approach has made great progress independently in recent years, it cannot be said that the mutual relationship between them has been fully understood.

There are also some terminological differences between those approaches. In microscopic treatment,¹⁾ the initiation of brittle fracture is defined as the stage at which a crack nucleus of atomic dimensions is formed, and the extension of it to critical dimensions of grain size order is termed growth. In this case, the propagation of brittle fracture is the stage at which catastrophic failure occurs with overcoming the potential barrier for the critical crack size.

Whereas, in macroscopic fracture mechanics, the initiation characteristics are referred to as the condition to produce a cleavage fracture from a critical crack, which may be a pre-existing one or an extending fibrous crack. Thus this corresponds to the condition for crack propagation in microscopic sense. On the other hand, brittle fracture propagation can be stopped by the change of environmental condition in the vicinity of crack tip, such as the decrease in the stress intensity factor (K -value) at the crack tip and the increase in the critical stress intensity factor (K_{IC} -value) of the material with raising temperature. This

is referred to as the propagation-arrest of brittle fracture.

The microscopic investigations of brittle fracture have shown that a stable ferrite microcrack²⁾ or a brittle second phase crack itself such as a crack in grain boundary cementite film^{3,4)} can be the critical crack leading to complete fracture. In the previous work,⁵⁾ in which fracture behaviour of some ferritic-pearlitic steels was examined by means of low temperature tensile tests, it was shown by the authors (Y.O. and F.T.) that a pearlite colony crack can act as the critical crack which will practically determine the subsequent crack propagation characteristics in microscopic sense.

The aim of the present study is to reveal the effects of microstructure and alloying elements on the initiation and the propagation-arrest characteristics of brittle fracture in some ferritic-pearlitic steels by means of COD (Crack Opening Displacement) test with fatigue crack and DCB (Double Cantilever Beam) test.⁶⁾

II. Experimental Procedure

1. Materials and Heat-treatments

The chemical compositions of the steels studied are shown in Table 1. The materials were received as 25 mm thick hot-rolled plates, and the following three different heat-treatments were carried out to obtain the large varieties in ferrite grain and pearlite colony sizes:

- 1) Furnace-cooled after austenitizing for 1 hr at 1200°C
(The average cooling rate between 800° and 500°C is 50°C/hr)
- 2) Furnace-cooled after austenitizing for 1 hr at 900°C
(The cooling rate is the same as above)
- 3) Air-cooled after austenitizing for 1 hr at 900°C.

Table 1. Chemical composition of materials used

Steel	C	Si	Mn	P	S	Ni	Al
270	0.10	0.26	0.62	0.008	0.007	0.03	0.045
271	0.10	0.26	1.02	0.008	0.008	0.04	0.044
272	0.11	0.25	1.38	0.009	0.008	0.04	0.041
273	0.10	0.26	0.62	0.007	0.007	1.02	0.047
274	0.10	0.24	0.60	0.008	0.006	2.48	0.046

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2. Examination of Microstructure

The microstructures of the steels were revealed by etching in 2% nital and were examined by optical microscope. The mean linear intercepts for ferrite grains and pearlite colonies were determined by lineal analysis.

3. Determination of Initiation Characteristics of Brittle Fracture

In order to determine the initiation properties of brittle fracture in macroscopic sense, the bending COD tests were carried out. The dimensions of a specimen with a fatigue notch are shown in Fig. 1. The static three point bending test with a span of 40 mm was conducted by a tensile machine, and the crack displacement was measured by a clip-gauge. While the dynamic COD test was accomplished by means of a standard Charpy impact machine together with a displacement gauge specially designed to meet the purpose.⁷⁾ The critical COD-value (δ_c) was determined by the following equation:⁸⁾

$$\delta_c = \frac{V_c}{1 + \frac{Z+C}{r(w-C)}}$$

where, $r=0.3$; V_c , the crack displacement; Z , the clearance of the displacement gauge over the specimen surface; w , the height of the specimen; and C , the crack length; all as indicated in Fig. 1.

In addition to the tests described above, the unit crack path (L_c),⁹⁾ which is the mean linear intercept of individual cleavage microcracks, was determined by means of scanning electron microscopy for each fracture surface of static COD specimen.

4. Determination of Propagation-arrest Characteristics of Brittle Fracture

For direct evaluation of the propagation-arrest characteristics of brittle fracture, Robertson test¹⁰⁾ or Double Tension test¹¹⁾ is commonly used, but such a large scale test is quite expensive and impractical for metallurgical study. Thus the crack-arrest curves were determined with tapered DCB specimens⁶⁾ shown in Fig. 2. It has been previously confirmed⁶⁾ that the results of this DCB test are in quite good agreement with those of Double Tension test,¹¹⁾ and that this is suitable for a research tool.

If a tensile load is applied to the specimen at an appropriate temperature, a brittle crack will initiate at the notch-root where brittle weld metal was

placed, and will propagate along the plane constrained by the side-grooves. Since the spring constant decreases with crack extension, the K -value at the crack-tip is reduced with crack propagation. Thus, the brittle fracture can be arrested when the K -value at the crack-tip reaches the K_c -value of the material. Therefore, the K_c -value can be obtained as follows:

$$K_c = y \sqrt{\frac{E}{2w} \left(-\frac{dM(C)}{dC} \right)}$$

where, K_c : the critical stress intensity factor
 y : the cross-head displacement of tensile machine
 E : the Young's modulus
 w : the width of fracture surface
 C : the crack length
 $M(C)$: the spring constant as a function of crack length.

5. Low Temperature Tensile Test

In order to understand the effects of microstructure and alloying elements on brittle fracture characteristics, it is quite useful to examine the yield behaviour at low temperatures. Accordingly, tensile tests were carried out in the temperature range between -196° and 25°C . The gauge length and diameter of the specimen were 60 and 8.5 mm respectively.

III. Experimental Results

1. Microstructure

Typical examples of microstructural change with heat-treatment in the steel 273 (1% nickel steel) are shown in Photo. 1. Although the structures are typical of ferrite-pearlite, the microstructure obtained by furnace-cooling from 1200°C is much coarser than the others (Photo. 1 (a)), whereas the finest structure was achieved by the air-cooling from 900°C (Photo. 1 (c)).

The results of the lineal analysis for ferrite grains and pearlite colonies are summarized in Table 2. It can be seen that the addition of manganese or nickel greatly reduces the ferrite grain and the pearlite colony sizes.

2. Unit Crack Path

Using a brittle fracture surface of static COD specimen, the unit crack path,⁹⁾ L_c , was determined. Since it has been confirmed that the unit crack path

Fig. 1. COD test specimen

Fig. 2. Tapered DCB test specimen

Photo. 1. Typical microstructures of steels tested ($\times 100$) ($\times 4/5$) Steel 273, (a) $1200^{\circ}\text{C} \times 1\text{ hr}$ FC, (b) $900^{\circ}\text{C} \times 1\text{ hr}$ FC and (c) $900^{\circ}\text{C} \times 1\text{ hr}$ AC

Table 2. Ferrite grain size, pearlite colony size and unit crack path (linear intercept)

Steel	Heat-treatment	Ferrite grain size (μ)	Pearlite colony size (μ)	Unit crack path (μ)
270	1200°C FC	103.0	28.4	123.5
	900°C FC	21.5	11.8	27.4
	900°C AC	20.5	5.88	26.7
271 (1Mn)	1200°C FC	63.0	28.1	84.2
	900°C FC	15.5	9.75	26.0
	900°C AC	12.4	5.05	26.0
272 (1.5Mn)	1200°C FC	44.0	21.2	66.7
	900°C FC	9.3	5.83	25.3
	900°C AC	9.0	3.83	25.3
273 (1Ni)	1200°C FC	62.0	21.6	66.7
	900°C FC	18.5	9.40	30.3
	900°C AC	14.1	5.30	23.3
274 (2.5Ni)	1200°C FC	36.5	17.7	38.8
	900°C FC	18.3	7.00	21.5
	900°C AC	13.5	3.73	21.5

is independent of testing condition within cleavage fracture range,⁹⁾ this can be used as a constant for a specific specimen. The results are also shown in Table 2. It can be seen that the unit crack path varies with heat-treatment in a similar fashion to either ferrite grain or pearlite colony size.

3. Results of COD Test

The relationship between the inverse root of ferrite grain diameter, $L_f^{-1/2}$, and either $T_{\delta_{CS}=0.1}$ or $T_{\delta_{CD}=0.1}$ is shown in Fig. 3 (a) or (b), where $T_{\delta_{CS}=x}$ and $T_{\delta_{CD}=x}$ are the temperatures at which the critical COD values for static and dynamic tests are x mm. In the static test, $T_{\delta_{CS}=0.1}$ is linearly related to $L_f^{-1/2}$ for steels cooled

Fig. 3. Relationship between ferrite grain size and crack initiation temperature at $\delta_c=0.1$ mm
(a) Static COD test, (b) Dynamic COD test

from austenitizing temperatures with the same cooling rate, and reducing the ferrite grain size lowers the initiation temperature of brittle fracture. It should, however, be pointed out that the straight line showing the relationship between $T_{\delta_{CS}=0.1}$ and $L_f^{-1/2}$ for the air-cooled specimens is separated from that for the furnace-cooled specimens. Similar results were also obtained in the case of dynamic COD test (Fig. 3 (b)). In this case, the addition of manganese or nickel markedly lowers the initiation temperature of brittle fracture under a given ferrite grain size.

Figure 4 illustrates the relationships between the unit crack path, L_c , and $T_{\delta_{CS}=0.1}$, and between L_c

Fig. 4. Relationship between unit crack path and crack initiation temperature at $\delta_c=0.1$ mm
(a) Static COD test, (b) Dynamic COD test

and $T_{\delta_{CD}=0.1}$ respectively. In this case, the effect of cooling rate from austenite, which specifically dominates microstructure, cannot be eliminated as in the case of the analysis by ferrite grain size. On the other hand, however, in the latter analysis, the scattering of data was significantly large. Thus some other microstructural parameters which may control brittle fracture characteristics should be examined.

Figures 5 and 6 show the relationships between pearlite colony size, L_p , and the brittle fracture initiation temperatures for static and dynamic tests respectively. In the static test, the relationship between $L_p^{-1/2}$ and $T_{\delta_{CS}=0.4}$, $T_{\delta_{CS}=0.1}$, or $T_{\delta_{CS}=0.04}$ can be determined by a single straight line at least for steels of the same chemical composition as can be seen in Fig. 5. The addition of nickel raises the $T_{\delta_{CS}=0.4}$ temperature under a given pearlite colony size, but the effect of nickel on $T_{\delta_{CS}=0.1}$ or $T_{\delta_{CS}=0.04}$ cannot be detected. It is interesting to note that the slope of the straight line showing the relationship between $T_{\delta_{CS}=x}$ and $L_p^{-1/2}$ decreases with reducing the critical COD value. In dynamic COD test, on the other hand, the pearlite colony size dependence of $T_{\delta_{CD}=x}$ is considerably smaller than that in static test as can be seen in Fig. 6, and the addition of nickel or manganese greatly lowers $T_{\delta_{CD}=x}$ under a given pearlite colony size. That is, in the range of higher strain rates, where the amount of plastic strains prior to brittle fracture initiation is small, the effects of alloying elements such as nickel largely determine the brittle fracture characteristics.

4. Results of Tapered DCB Test

In DCB test, the relationships between $T_{K_{cn}=300}$ and $L_f^{-1/2}$, and between $T_{K_{cn}=300}$ and $L_c^{-1/2}$ are similar to those in dynamic COD tests as shown in Figs. 7 and 8, where $T_{K_{cn}=x}$ is the temperature at which the cri-

Fig. 5. Relationship between pearlite colony size and crack initiation temperature in static COD test

Fig. 6. Relationship between pearlite colony size and crack initiation temperature in dynamic COD test

Fig. 7. Relationship between ferrite grain size and crack-arrest temperature at $K_{en}=300 \text{ kg/mm}^{3/2}$

Fig. 8. Relationship between unit crack path and crack-arrest temperature at $K_{en}=300 \text{ kg/mm}^{3/2}$

Fig. 9. Relationship between pearlite colony size and crack-arrest temperature at a given toughness in tapered DCB test

tical stress intensity factor (K_c) for the propagation-arrest of brittle fracture is $\alpha \text{ kg/mm}^{3/2}$. It should be again noted that reducing either ferrite grain or unit crack path lowers $T_{K_{en}=300}$, but that the effect of

Fig. 10. Relationship between lower yield stress and ferrite grain size

cooling rate from austenite cannot be eliminated in either analysis.

In contrast, Fig. 9 demonstrates that the propagation-arrest temperatures, $T_{K_{en}=600}$, $T_{K_{en}=300}$, and $T_{K_{en}=100}$, are uniquely determined by pearlite colony size for the specimens of the same chemical composition. Here, it will be noted, further, that the effect of nickel on the propagation-arrest temperature under a given pearlite colony size becomes more prominent with reducing the K_c -value from 600 to 100 $\text{kg/mm}^{3/2}$. That is, the addition of nickel improves the propagation-arrest characteristics under a given pearlite colony size. It can, therefore, be concluded that the analysis using the mean pearlite colony size is more suitable than those employing other metallurgical factors such as ferrite grain size.

5. Results of Low Temperature Tensile Test

It has so far been well established that lower yield strength σ_{ly} , is linearly related to $L_f^{-1/2}$.¹²⁾ Thus, a similar analysis for the 0% and 2.5% nickel steels has been conducted as shown in Fig. 10. In the temperature range between ca. -100° and 25°C , the lower yield strength increases with increasing amount of nickel under a given ferrite grain size, while the addition of nickel slightly lowers the yield strength at lower temperatures. On the other hand, increasing the amount of manganese does not exhibit any significant effect on the yield strength under a given ferrite grain size.

Photograph 2 shows the secondary crack initiation

Photo. 2. Cleavage crack initiation of ferrite from pearlite crack during tensile test at -196°C . Steel 270 ($\times 500$) ($\times 4/5$)

in the vicinity of main crack path in a specimen fractured at -196°C (Steel 270). It can be seen that a crack formed within a pearlite colony propagates into the adjacent ferrite grains. Such an observation suggests that the propagation of a pearlite crack into ferrites dominates the brittle fracture process of ferritic-pearlitic steels.

IV. Discussion

1. Effects of Microstructure and Alloying Elements on Brittle Fracture Initiation Characteristics

The process of the brittle fracture in COD test can be thought as follows: The plastic zone forms initially at the tip of fatigue crack by the stress concentration as the applied bending load increases. Then the crack-tip opens and the so-called "stretched zone" is formed (in some cases, a ductile crack is produced in front of the stretched zone). If this crack opening displacement reaches a specific value for a material under a given temperature, the crack will transform into one of brittle nature, leading to a catastrophic failure.¹³⁾

Considering such macroscopic brittle fracture initiation processes in terms of microscopic processes, the tip of a fatigue crack may be regarded as blunted by the formation of the stretched zone or a ductile crack, when the crack-tip finds itself located within the plastic zone in ductile/brittle transition range. The previous investigation⁵⁾ showed that the plastic strains above ca. 25% induced pearlite colony cracks and that the critical event leading to complete fracture corresponded to the condition whether these sharp pearlite cracks cleaved the adjacent ferrite grains or not.

If this is also true for the present COD test, the stress concentration at the fatigue crack-tip due to the applied load will produce the plastic strains sufficiently large for cleaving pearlite colonies, resulting in a

Griffith flaw¹⁴⁾ with the length of L_p . If the stress distribution due to a pre-existing crack can be neglected, the K -value at the tip of a pearlite colony crack will be proportional to $L_p^{1/2}$. This might provide some physical meaning for the analysis using the inverse root of a pearlite colony size. The fact that the initiation temperature of brittle fracture cannot be explained in terms of ferrite grain size but can in terms of pearlite colony size for a given material supports this. That is, the pearlite colony size is sufficiently large as a Griffith flaw,¹⁴⁾ and formation of such large cracks as ferrite grain-size ones or of the unit crack paths cannot be the critical event leading to complete fracture. Therefore, what is important is the length of a pearlite colony crack, L_p , which forms prior to the cleavage fracture of ferrite.

Since the increase of nickel or manganese content reduces the pearlite colony size under a given heat-treatment, thus improving the low temperature toughness greatly, even though a pearlite colony is cleaved as expected from the mean pearlite colony size given, catastrophic fracture does not ensue until either the temperature is lowered sufficiently or the work-hardening raises the applied stress at the tip of the pearlite crack. Such effects can be related to the fracture stress through the plastic term of the effective surface energy for crack propagation, and will be affected by temperature, strain rate and also by alloying elements. That is, at a low strain rate, *i.e.*, in the static COD test, the $T_{\sigma_{CS}=0.4}$, at which large plastic strains are prerequisite to cleaving the ferrites adjacent to the pearlite crack, is raised by nickel addition. The effect of nickel addition on the initiation characteristics, however, decreases with reducing the critical COD-value. At a high strain rate, *i.e.*, in the dynamic COD test, on the other hand, the addition of nickel or manganese lowers the initiation temperature greatly for a given pearlite colony size, the effect of nickel being particularly large. Although the reason has not been clearly understood at present, it can be thought that the friction for slip deformation at lower temperatures is much reduced by nickel addition. In fact, the yield stress is lowered with increasing nickel content at temperatures below -135°C , though it increases at temperatures above -100°C . The fact that the occurrence of twinning at lower temperatures was greatly reduced by nickel addition as reported previously⁵⁾ might be closely related to it.

2. Effects of Microstructure and Alloying Elements on Propagation-arrest Characteristics

In the tapered DCB test carried out, since the crack-propagating plane is constrained by deep side-grooves, it was expected that the K_{IC} -values determined would be slightly lower than those obtained without side-grooves.¹⁵⁾ In addition, quantitative comparison between elastic K_{IC} -value and plastic COD-value is always difficult to achieve. The qualitative comparison, however, shows that the results of the DCB tests lie between those of the static and dynamic COD tests, and the improvement of crack-arrest properties

by nickel addition under a given pearlite colony size can also be recognized. Though much more detailed examination would obviously be needed before drawing conclusions, this suggests that the crack-arrest characteristics are essentially the same as those of the brittle fracture initiation, and implies that the strain-rate at the crack-tip during the propagation-arrest in the DCB test lies between those of the static and the dynamic COD tests during the brittle fracture initiation.

Considering the facts described above, the models for the initiation and the propagation-arrest of brittle fracture are worked up as shown in Figs. 11 and 12 schematically. During the crack-initiation, the plastic zone forms initially at the tip of the fatigue crack by increasing the applied stress (Figs. 11 (a) and (b)), and eventually the crack opens to produce the stretched zone. Then a pearlite colony within the plastic zone is cleaved (Fig. 11 (c)). Finally, this pearlite crack propagates into the adjacent grains when the work-hardening raises the applied stress sufficiently, leading to complete fracture (Fig. 11 (d)).

The process of the crack-arrest, on the other hand, can be thought as follows. If either the K -value at the crack-tip is reduced or the K_{IC} -value of the material is raised by some external causes during the crack propagation, the crack velocity will be reduced with

Fig. 11. Schematic illustration for cleavage crack initiation

Fig. 12. Schematic illustration for propagation-arrest of brittle fracture

producing a large plastic zone as can be seen in Fig. 12 (a) and (b). In this case, a pearlite colony within the plastic zone is cleaved and if this pearlite crack in turn cleaves the adjacent ferrite grains before the decelerating main crack arrives as shown in Fig. 12 (c), the brittle fracture cannot be arrested. However, if the pearlite crack does not initiate brittle fracture, the propagation of the main crack will be decelerated much further and be eventually arrested (Fig. 12 (d)). Therefore, the critical condition whether a pearlite crack in the plastic zone cleaves the adjacent ferrite grains or not corresponds to the propagation-arrest condition. Since this is exactly the reverse process of the crack-initiation, it is reasonable that the microstructural or the alloying element dependence of the crack-arrest characteristics is similar to that of the brittle fracture initiation.

V. Conclusions

(1) The static and the dynamic initiation characteristics and the propagation-arrest characteristics of brittle fracture in ferritic-pearlitic steels are improved by refining the mean pearlite colony size.

(2) A pearlite colony crack can act as a Griffith flaw, and the brittle/ductile transition properties of the ferritic-pearlitic steels of a given chemical composition are mainly determined by the mean pearlite colony size.

(3) Since the addition of nickel or manganese greatly reduces the pearlite colony size under a given heat-treatment, it improves the brittle fracture characteristics.

(4) At a given pearlite colony size, both nickel and manganese additions exhibit significant effects on brittle fracture characteristics through improving the plastic properties of ferrite.

(5) At higher strain rates the effects of alloying elements on the brittle fracture characteristics, that through modifying the properties of ferrite, predominates; at lower strain rates, on the other hand, the effect of pearlite colony size is more clearly observed while the former is almost negligible. For instance, nickel greatly improves the low temperature toughness in the dynamic initiation (dynamic COD) and the propagation-arrest (tapered DCB) tests.

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