On Delamination in Linepipe Steels

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Synopsis

Some observations are first given of the delamination cracking seen on fracture surfaces of Charpy test pieces, as follows:

1. Delamination on fracture surface of Charpy impact test piece takes place pronouncedly already around the transition temperature or where there is a marked difference between \( E \) and \( E_0 \) in the impact curve, when \( E \) is energy absorbed in a longitudinal or transverse test piece and \( E_0 \) that in a short transverse one.

2. When pronouncedly occurring, each delamination is what has groved in cleavage mode, consuming little energy in its propagation.

3. Undeveloped delaminations of lengths less than 1 mm are observed below the notch on fracture surface in a temperature region extending from NDT down to NDT minus about 50°C, which is presumed to be the stress transition temperature.

4. Delamination develops just prior to initiation of the main crack under the presence of a notch.

Consideration is then given to the conditions of initiation and growth of delamination. It is conclusively understood that the pronounced delamination observed around the transition temperature is explained if one supposes that the delamination is given a chance to develop because the stress pulse duration is increased as the ductility of the steel is increased in the transition region.

I. Introduction

Today controlled rolling is widely applied to the production of linepipe steels of high strength and toughness. As a consequence of the controlled rolling, however, a laminar structure develops parallel to the rolling plane, causing weak cohesion in the short transverse direction. It is anticipated that the laminar structure may have a significant influence on mechanical properties of the steels through a phenomenon known as delamination, which is a cracking developing perpendicular to the main crack in a stressed body containing the laminar structure.

In the present work the result of general observations will first be given of a delamination cracking seen on fracture surface of the main crack, then the conditions of initiation and growth of delamination will be considered.

II. Experimental Procedures

1. Specimens

The specimens were taken from industrial steel plates for pipe of grade API X65 prepared by controlled rolling, the metallurgical structure of which is characterized by a banding composed of ferrite and pearlite zones (Photo. 1). Chemical composition and mechanical properties of the steels used are given in Table 1 and Fig. 1.

2. Measurement and Observation

Conventional and instrumented Charpy impact tests were carried out, the load being measured through the cells buried in the pair of anvils in the latter case. The test piece was of a standard size of 10 mm × 10 mm × 55 mm with a 2 mm deep V-shaped notch. An impact machine of the maximum energy capacity either of 50 kg·m or of 30 kg·m was used depending on the toughness level of the specimen.

The fracture surfaces of the Charpy test piece were examined carefully with the naked eye and under the scanning electron microscope with special reference to the delamination cracking.

III. Experimental Results

1. General Observations

As mentioned earlier, delamination is a form of

![Photo. 1. Typical metallurgical structure of control-rolled steel characterized by banding. Plane of observation is just behind the fracture surface of transverse test piece of Steel X tested at 20°C. Delamination is observed from place to place.](Image)
Table 1. Chemical composition and mechanical properties of the specimens used

<table>
<thead>
<tr>
<th>Steel</th>
<th>Chemical composition (wt%)</th>
<th>Tensile properties*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Si</td>
</tr>
<tr>
<td>U</td>
<td>0.12</td>
<td>0.30</td>
</tr>
<tr>
<td>X</td>
<td>0.12</td>
<td>0.24</td>
</tr>
</tbody>
</table>

* In the longitudinal direction

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Figure 1. Notch-tensile properties and their orientation dependence

cracking developing perpendicular to the main crack. This is illustrated in Photos. 1 and 2. Further, in the course of experiment, it was observed that the delamination was pronounced in a temperature region of energy transition in Charpy impact curve. It appears then that the occurrence of delamination is closely associated with the change of toughness or ductility.

This view is summarized in Fig. 2 in terms of the fibrocity, the absorbed energy per unit fracture area \( \varepsilon \) and the density of delamination, where \( \varepsilon \) is the energy absorbed in a longitudinal or transverse test piece and \( A \) the fracture surface area.

In Fig. 2 a quantity, the "density of delamination" \( \varepsilon \) is introduced as a measure of the extent to which delamination develops on the fracture surface. It is defined by the total length of delamination cracks, each of which is not less than 1 mm long, i.e., as large as clearly discernible with the naked eye on the fracture surface, divided by the fracture surface area \( A \). Then it is denoted by \( \Sigma / A \).

Further, in Fig. 2, comparison of (a) and (b) with (c) will reveal that the energy transition region, i.e., where the delamination is most pronounced, coincides with a region where there is a marked difference between \( \varepsilon E/A \) and \( \varepsilon E/A \), where \( \varepsilon E \) is the energy absorbed in a short transverse test piece* shown in Fig. 2 (c).

Although the well developed delamination was not found in the temperature region of full brittle failure, undeveloped delamination, each crack being of a length less than 1 mm, was detected below the notch on the fracture surface of Steel X formed in a temperature region extending from NDT** down to NDT minus about 50°C. In this temperature region slip traces were observed on plate surfaces at the ligament of the notch,*** indicating occurrence of general yielding. The observation of the undeveloped delamination becomes possible by polishing the brittle fracture surface slightly but deep enough to obtain a microscopically flat surface to uncover the undeveloped delamination cracks buried in it.

2. Microscopic Appearance of a Delamination Cracking

To see the growth mode of a delamination crack the plane of the cracking formed in standard Charpy test piece was examined under a scanning electron microscope and an optical microscope for Steels U and X. Typical examples of the examination are given in Photos. 3 to 7. A flaky film, as seen in Photos. 3 and 4, is usually observed to cover the delamination surface. The film associated with the dimple mode of delamination growth is usually found in fragments, as seen in Photo. 4; this might be due to the lack of plastic compatibility (deformability) of the film with plastic deformation of the matrix which proceeds during formation of the delamination cracking. The film associated with the delamination growth of cleavage mode, on the other hand, has a smooth surface and

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* The "longitudinal or transverse" refers to "taken parallel to or transverse to the rolling direction," and the "short transverse test piece" is one described in Fig. 2 (c).

** A nil ductility transition point or a critical temperature below which the fracture surface looks macroscopically perfectly brittle.

*** That portion of a Charpy specimen where the notch has been placed.
Photo. 2. Macroscopic view of delamination on fracture surface of standard Charpy test piece

Fig. 2 (a). Results of Charpy test and measurement of delamination density \( \Sigma L/A \) (Steel X)

Fig. 2 (b). Results of Charpy test and measurement of delamination density \( \Sigma L/A \) (Steel U)
appears free from any heavy deformation, as seen in Photo. 3. It should be noted that when pronouncedly occurring, each delamination is what has grown in cleavage mode, consuming little energy in its propagation.

The result of electron probe microanalysis (EPMA) suggests that the flaky film is composed of manganese sulfide. An example of the analysis is illustrated in Photo. 5, where the EPMA result of the surface appearing in Photo. 3 is shown.

Photograph 6 is a cross-sectional view of the delamination, the plane of observation being just behind the fracture surface of transverse test piece of Steel X tested at $-20^\circ\text{C}$. The distribution of the voids (the cross section of delamination), as seen at bottom of Photo. 6, is found to correspond to the distribution of non-metallic inclusions, as seen at top of the photograph. The EPMA result suggests that these non-metallic inclusions are composed of manganese sulfide, as illustrated in Photo. 7.

These results of examinations suggest that the delamination nucleates at the interface of manganese sulfide inclusions and matrix, and develops into the matrix in cleavage mode or in ductile mode depending on the temperature of test. The results of the examinations are summarized in Fig. 3.

3. Observation in Relation to Delamination Growth

In what stage does delamination or microfissuring take place at the root of crack or notch in a stressed body? It might be very difficult to observe how delamination takes place in front of a running crack, but
it was possible to examine an incompletely grown delamination at the root of a stationary crack, i.e., the notch in Charpy test piece deformed by a hammer with blow energy below what was required to complete a main crack. Observation of the incompletely grown delamination was made by slightly polishing the notch prolongation after cutting in two the deformed test piece.

The result of observation is summarized in Table 2, which tells that delamination develops just prior to crack initiation under the presence of a notch. Examples of the measured delamination length \( \text{as, hammer} \)
Steel X:
Transverse test piece tested at 
-20°C
Top row:
Non-metallic inclusions in an unetched cross-section
Bottom row:
Delamination cracks in the same; these cracks were revealed as the etchant attacked their periphery preferentially.

Photo 6.
Correspondence of distribution between the cracks shown in Photo 1 and the non-metallic inclusions

Steel X: Transverse test piece tested at -20°C
Photo 7. Result of electron probe microanalysis of the non-metallic inclusion shown in Photo 6
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Table 2. Result of observation of delamination cracking in Steel X due to hammer blow of different blow energy

<table>
<thead>
<tr>
<th>Blow energy</th>
<th>Longitudinal test piece</th>
<th>Transverse test piece</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-40°C</td>
<td>0°C</td>
</tr>
<tr>
<td></td>
<td>L*  (mm)</td>
<td>M* (%)</td>
</tr>
<tr>
<td>1 kg·m**</td>
<td>2.9  - 1.0</td>
<td>0.4  - 1.2</td>
</tr>
<tr>
<td>3</td>
<td>7.5  + 6.3</td>
<td>3.7  + 5.7</td>
</tr>
<tr>
<td>5</td>
<td>3.5  + 8.9</td>
<td>6.2  + 7.8</td>
</tr>
<tr>
<td>At Fracture***</td>
<td>12.5  +</td>
<td>6.5  +</td>
</tr>
</tbody>
</table>

* L=ΣL, Total delamination length (mm)  
  M=Occurrence of main crack; + Presence of main crack  
  - Absence of main crack  

** N=Notch root contraction (%)  
At blow energy=1 kg·m, all the specimens observed showed general yielding on surfaces of notch ligament.

*** Blow energy of fracture. E=12 kg·m (-40°C), 14 kg·m (0°C and 20°C) for longitudinal test piece and 6 kg·m (-40°C) and 7 kg·m (0°C and 20°C) for transverse test piece.

Fig. 4. Relations of total delamination length to hammer blow energy

4. Instrumented Charpy Test

As mentioned in III. 1, delaminations appear pronouncedly in the temperature region of energy transition in Charpy impact curve. It has been experimentally shown for a certain steel that the transition is due to transition in the impact loading time, the maximum load being substantially unchanged in the region of energy transition.13 The instrumented Charpy impact test was carried out for the steels under consideration, the result of which is given in Fig. 5. It is confirmed from the figure that the same conclusion as stated above is valid for the present steels.

IV. Discussion

1. The Condition for Initiation of Delamination

As mentioned in III. 1, delamination is pronounced at around a temperature of energy transition in Charpy impact curve. The generally held explanation is that the delamination is caused or initiated when the laminar structure undergoes a triaxial stress pulse operating at above a temperature of stress transition. Here the condition for initiation of a delamination cracking is considered in Charpy test piece with the notch face parallel to the plate edge. Transient stress distribution in the vicinity of the notch in Charpy test piece loaded to general yielding is assumed to be as described in Fig. 6 for a hypothetical non-strain-hardening material after, for instance, A. S. Teten-
man, 2)

Stresses $\sigma_{xx}$ hence $\sigma_{yy}$ and $\sigma_{zz}$ simultaneously attain the maximum at a distance ahead of the root, because the transverse stress $\sigma_{xx}$ is greater than zero ahead of the root and since the maximum shear criterion requires that inside the plastic zone,

$$a_{yy} - a_{xx} = a_o$$ ....................... (1)

where, $a_o$ is the uniaxial yield stress, while the plane strain condition requires that

$$a_{zz} - \sqrt{a_{xx}^2 + a_{yy}^2} = 0$$ ....................... (2)

inside the plate, where $\nu$ is Poisson's ratio.

At this location of maximum $a_{yy}$ also of maximum $a_{zz}$ a delaminating crack or main crack formation is assumed to take place according to the conditions which will be considered here.

Assuming that cleavage fracture is slip induced at a critical tensile stress by Cottrell mechanism $^3$ then failure occurs when

$$\sigma_{yy} - \sqrt{a_{xx}^2 + a_{yy}^2} = 0$$ ....................... (3)

where, $\tau_1$: the friction stress

$d$: the grain size

$\mu$: the shear modulus

$\gamma_1$: the surface energy of the main crack

$\hat{\gamma}_1$: the non-dimensional parameter of the order of unity, $\hat{\gamma}_1 \approx 1$.

On the other hand, a delamination cracking is expected to take place when the following Griffith condition is satisfied,

$$(1-\nu)\sigma_o^2 \pi \frac{\pi c}{\mu} \geq \hat{\gamma}_2$$ ....................... (4)

if one assumes that inclusion-matrix cohesion is weak enough to be negligible compared with matrix cohesion surrounding the inclusion. In Eq. (4), $2\varepsilon$ is the width of the non-metallic inclusion (or its aggregation), $\gamma_2$ the surface energy of the developing delamination crack and $\hat{\gamma}_2$ the non-dimensional parameter of the order of unity, $\hat{\gamma}_2 \approx 1$, describing spatial distribution of the inclusion.

The condition that Eq. (4) be satisfied before Eq. (3) is satisfied can now be written down using relations Eqs. (1) and (2) as follows.

$$\frac{\sqrt{4a_{yy}^2} \varepsilon}{\tau_1 + \sqrt{\tau_1^2 + (4a_{yy}d)}} \leq \sqrt{\pi(1-\nu)\pi^2(2-K_p^\nu)}$$ ....................... (5)

where, $K_p = a_{yy}/a_o$, Equation (5) is satisfied if

$$\gamma_2/\gamma_1 \leq (\varepsilon/d)\left(\pi(1-\nu)^{\nu/2}(2-K_p^\nu)\right)$$ ....................... (6)

since $\left(\sqrt{4a_{yy}^2} \varepsilon/\tau_1 + \sqrt{\tau_1^2 + (4a_{yy}d)}\right) \leq \sqrt{\gamma_2/\gamma_1}(d/\varepsilon)$.

In Eq. (6), a typical value of $2\varepsilon$ and $d$ for the steels under consideration is 50 $\mu$ (Photo. 4) and 20 $\mu$ (Photo. 1), respectively, and the maximum possible value of $K_p$ is analytically estimated to be

$$K_p^{\max} = 1 + \frac{\pi}{2} \frac{a_o}{2}$$ ....................... (7)

for a non-strain-hardening material, according to the Tresca criterion, $^4$ where $\omega$ is the included angle of the notch. For Charpy V-shaped notch $K_p^{\max} = 2.18$ and for crack $K_p^{\max} = 2.57$.

Using these values Eq. (6), for the maximum value of $a_{yy}$, leads to

$$\gamma_2/\gamma_1 \approx 0.59$$ for Charpy V-shaped notch ........................ (8)

and

$$\gamma_2/\gamma_1 \approx 0.64$$ for crack ........................ (9)

Both Eqs. (8) and (9) are considered to be well satisfied in the temperature region of energy transition in Charpy impact curve for the steels under consideration, if one supposes that the values of $\pi E^\nu$, $E$ obtained from Fig. 2 give a good measure of $\gamma_2/\gamma_1$ in Eqs. (8) and (9).

2. The Condition for Growth of Delamination

The condition for the delamination cracking initiation given by the inequality (3), is, in the present case, understood to be well satisfied in the temperature region of energy transition. On the other hand, the fracture stress and accordingly the critical stress in the short transverse direction do not experience any abrupt change at around the temperature of energy transition.

Therefore it will be natural to consider that below the temperature of energy transition a delamination cracking remains undeveloped because the stress pulse duration induced in the short transverse direction in test pieces deformed in the temperature region is too short. In other words, stresses in the short transverse direction $\sigma_{zz}$ are relaxed by creating small delamination crackings, and any further development of them cannot be expected unless $\sigma_{zz}$ is further raised due to notch root contraction which needs a load pulse duration of a certain length. Then the pronounced delamination observed at around the transition temperature is explained if one supposes that the delamination has given a chance to develop because the stress pulse duration in the short transverse direction is increased as the ductility is increased in the temperature region of energy transi-
tion, as confirmed by the observation illustrated in Fig. 5 in III. 4.

At temperatures elevated further the surface energy $\gamma_2$ required to separate plate parallel to the rolling plane increases enough for initiation of delamination to be suppressed. A measure of $\gamma_1 - \gamma_2$, where $\gamma_1$ is the surface energy for the main crack formation, may be given by the difference $\gamma_1/\gamma_2 - \gamma_1/\gamma_2$.

At temperatures below NDT minus about 50°C delamination was not found. Presumably a fracture stress transition takes place at that temperature. Therefore a critical stress in the short transverse direction also decreases rapidly with temperature to such an extent that the inequality (5) cannot be satisfied.

From the above discussion it becomes clear that delamination takes place in a wide temperature region including the energy transition region, though it develops pronouncedly only in the latter. It can be expected that delamination in turn affects toughness of the specimen by relaxing the triaxial stress which caused the delamination. This problem will be treated in a subsequent paper.

V. Conclusion

As a preliminary work for discussion of the influence of delamination on the mechanical properties, the following observations and discussion were made:

(1) Delamination on fracture surface of Charpy impact test piece takes place pronouncedly at around the transition temperature or where there is a marked difference between $\gamma_1$ and $\gamma_2$ in the impact curve, where $\gamma_1$ is the energy absorbed in a longitudinal or transverse test piece and $\gamma_2$ that in a short transverse one.

(2) When pronouncedly occurring, each delamination is what has grown in cleavage mode, consuming little energy in its propagation.

(3) Undeveloped delaminations of lengths less than 1 mm were observed below the notch on fracture surface in a temperature region extending from NDT down to NDT minus about 50°C, which was presumed to be the stress transition temperature.

(4) Delamination develops just prior to initiation of the main crack under the presence of a notch.

(5) The pronounced delamination observed at around the transition temperature is explained if one supposes that the delamination has been given a chance to develop because the stress pulse duration increases as the ductility of the steel is being increased in the transition region.

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REFERENCES