The Heat-Affected Zone Toughness of Low-Carbon Microalloyed Steels

The influence of N and P on notch toughness appears to be significant

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ABSTRACT. Low-fracture toughness has been correlated with brittle zones in the HAZ of low-carbon microalloyed steels. This investigation has focused on two aspects of that problem:

1) The extent and the properties of the brittle zones as a function of heat input, refinement by subsequent weld layers and postweld heat treatment.

2) The possibility of surface crack initiation in the cap layer.

The first aspect has been examined using weld thermal simulation testing, including CCT diagrams, notch toughness measurements and microstructural examinations. The second has been investigated using shallow surface notch CTOD testing of bead-in-groove weldments, with detailed fracture surface examinations. A good qualitative relationship was established between the weld thermal simulation testing, the microstructural analysis and the CTOD tests. Two low-toughness zones were identified. Of special interest are the crack arrest properties, the influence of elements such as N, P and Nb, and the significance of local brittle zones with respect to the risk of failure of welded structures.

Introduction

The offshore activities in the North Sea have to a large extent relied on welded structures of medium-strength steel. In the past, research indicated that the hardness requirements in the heat-affected zone (HAZ) required welding with low heat inputs. At the same time, it was determined that high heat inputs should be avoided because they contributed to reduced toughness levels in the HAZ. As hardness for structural steels is largely governed by the carbon content, the reduction of this element was desirable, but its reduction lowered the strength level. Developments in steel production resulted in the introduction of thermomechanical rolling operations, which created the possibility of a large grain refinement of the microstructure that could compensate for strength losses. The rolling practice is primarily based on the inhibition of austenite grain growth by means of microalloying element additions of Nb, V and Ti. Consequently, new classes of low-carbon microalloyed steels were developed and were introduced into modern offshore structures.

Because of the critical nature of offshore activities, highlighted by tragic accidents, a thorough evaluation of the toughness behavior of weldments is required. During such studies, low-fracture toughness levels were registered in weldments of a low-carbon microalloyed steel in both as-welded (AW) and postweld heat-treated (PWHT) conditions. Toughness was evaluated by means of crack tip opening displacement (CTOD) testing. To evaluate the brittle phenomena in the HAZ in more detail, the Norwegian Petroleum Directorate initiated a research project including nine low-carbon microalloyed steels and one C-Mn steel. The C-Mn steel, used in the 1970's for offshore applications, was used as a reference steel. To understand the brittle behavior, it is important to locate which part of the HAZ reveals a low-toughness level, and also to evaluate if brittle areas can reveal brittle fracture behavior in large specimens and can initiate a final fracture behavior. In such a context, it is of interest to look at the situation near the plate surface, since from a theoretical point of view, fracturing is unlikely to occur from small surface cracks.

Background for the Tests

Single Bead Weldment

Figure 1A illustrates several zones in the HAZ of a single bead weldment. Each zone can be characterized by a certain microstructural composition, which also can clearly be seen on a macroetched specimen (Fig. 1B); however, each zone has no sharp transition, but does have a transition region. Descending from the weld interface into the base metal results in a decreasing peak temperature (T_p), implying that the different zones can be indicated with peak temperatures as follows: coarse-grained zone, 1590°C (2894°F) < T_p < 1100°C; fine-grained zone, 1100°C (2012°F) < T_p < 850°C; partially transformed zone, 850°C (1562°F) < T_p < 700°C; and tempered zone, 700°C (1292°F) < T_p.

The temperatures are only given as indications, since the actual temperatures depend on chemical composition and welding parameters. The coarse-grained zone is more or less characterized by quenched microstructures of bainite/martensite. The increase in peak temperature also resulted in an increase in austenite grain growth, followed by a subsequent coarsening of the microstructure. Consequently, there is a clear microstructural gradient in each zone; however, the microstructure is the same. The fine-grained zone is characterized by a fine
ferrite grain structure, which resulted from the normalizing heat treatment of the base metal. In the partially transformed region, the peak temperature was too low to produce a complete transformation. The pearlite has been transformed, but the transformation at the ferrite grain boundaries was only partial. Finally, the tempered region is characterized by a thermal treatment of the base material, but no change in the microstructure was observed by optical microscopy. For each point in the HAZ, or line parallel the weld interface, the thermal history is indicated schematically in Fig. 1A. The temperature cycle is characterized by the peak temperature ($T_p$) and the cooling time from 800°C to 500°C ($\Delta t_{800-500}$). The last parameter indicates how rapidly the material cools down and is dependent on the welding parameters. Increasing heat input increases the cooling time, and consequently, changes the microstructure. Another important aspect is that increasing the cooling time (for instance heat input) increases the extent of the zones (broad zones).

Multipass Weldment

The situation in a multipass weldment can be constructed from the condition shown in Fig. 2. Weld 1 in this figure can be assumed to be the single bead weld in Fig. 1. The subsequent weldment, Weld 2, will change the HAZ of Weld 1. However, it is different from the HAZ of a single bead weldment. The original microstructure is not the ferrite/pearlite microstructure of the base metal, but the bainite/martensite of the coarse-grained zone. The thermal history in such a HAZ can be characterized by two temperature cycles, as indicated in Fig. 2. Subsequent weld beads will influence the microstructures by a tempering heat treatment mechanism.

Investigated Steels

The chemical compositions are presented in Table 1. Nine steels are classified as modern low-carbon microalloyed steels, while one steel (Steel 8) is a C-Mn steel of the quality used previously for offshore structures.

Table 1—Chemical Composition of the Investigated Steels

<table>
<thead>
<tr>
<th>Chemical Composition (wt-%)</th>
<th>ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Si</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----</td>
</tr>
<tr>
<td>Steel 1</td>
<td>0.09</td>
</tr>
<tr>
<td>Steel 2</td>
<td>0.12</td>
</tr>
<tr>
<td>Steel 3</td>
<td>0.08</td>
</tr>
<tr>
<td>Steel 4</td>
<td>0.11</td>
</tr>
<tr>
<td>Steel 5</td>
<td>0.10</td>
</tr>
<tr>
<td>Steel 6</td>
<td>0.08</td>
</tr>
<tr>
<td>Steel 7</td>
<td>0.09</td>
</tr>
<tr>
<td>Steel 8</td>
<td>0.18</td>
</tr>
<tr>
<td>Steel 9</td>
<td>0.09</td>
</tr>
<tr>
<td>Steel 10</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Fig. 1—The heat-affected zone (HAZ) of a single bead weldment. A—A schematic presentation of the different zones in the HAZ of a single bead weldment; B—a macrosection of a bead in groove weldment, Steel 2.
1.3–1.6 wt-%.

All steels are microalloyed with Nb, but in different quantities, ranging from 0.017 to 0.048 wt-%. Other microalloying elements include Mo, V, Ti and Al. The levels are low for Mo, V and Ti, with an exception for Steel 2, which has a Ti content of 0.011 wt-%. The Al content varies between 0.017 and 0.036 wt-%, but that is a low level for steels. All microalloying elements are affected by the N content, which varies from 80 to 140 ppm.

Small amounts of Cu and Ni are present in the steels at a level <0.25 wt-%. An exception is made for Steel 10, which has a Ni content of 0.45 wt-%.

Steels for offshore applications require high reduction of area values in the through thickness direction. Consequently, the sulfur content is kept very low (0.001–0.005 wt-%) for all modern low-carbon microalloyed steels. In contrast, the C-Mn steel reveals a higher S content (0.019 wt-%), resulting in a quantity of elongated inclusions.

Finally, the impurity element P varies considerably for the steels, ranging from 0.005 to 0.021 wt-%. However, the reduction of P is a general trend in the production of new steels.

All steels were normalized after controlled rolling, resulting in fine-grained ferrite and pearlite in a clear banding distribution. The plate thicknesses ranged from 40 to 60 mm (1.5 to 2.4 in.).

The low-carbon microalloyed steels have similar mechanical properties: upper yield stress, 340–380 MPa (49.3–55.1 ksi); tensile strength, 480–520 MPa (69.6–75.4 ksi); elongation, 30–35%; percentage reduction of area, 70–80%; and Charpy V-notch absorbed energy at –40°C, 250–300 J (184–221 ft-lb). The C-Mn steel exhibits a similar level for mechanical properties except for a lower Charpy V-notch toughness (50 J at –20°C, or 37 ft-lb at –4°F).

Experimental Procedure

The experiments consist of the simulated weld thermal test and the surface fracture toughness tests.

The simulated weld thermal specimens are square bars 10.5 X 10.5 X 90 mm (0.4 X 0.4 X 3.5 in.), which are positioned in the weld thermal simulator, Smitweld TS1405. By means of the thermal resistance technique, the central part of the specimen was exposed to a temperature cycle with a selected peak temperature ($T_p$) and a cooling time from 800°C to 500°C (1472°F to 932°F) ($\Delta t_w$). By positioning a dilatometer on the specimen, the phase transformation was registered by recording the change in volume. After the simulation tests, the specimens were machined to Charpy V-notch specimens to determine notch toughness. Furthermore, the microstructure was investigated by preparing the specimens with grinding, polishing and etching in 2% Nital.

The surface fracture toughness specimens were extracted from single-pass groove welds with a heat input of 4 MJ/m (101.6 kJ/in.). The B X B specimens were machined from the plates and notched by means of electro-discharge machining (EDM) with $a/W = 0.05$ — Fig. 3. The notch was located so that its tip was near the weld interface, which suggested that further fracture occurred in the HAZ. As the notch was not fatigue precracked, the notch tip was blunted with a radius of $\approx 0.2$ mm, which suggests that the obtained values cannot be compared directly with standard CTOD specimens. Testing was performed at –10°C (14°F) in a displacement-controlled testing machine, at a rate of 0.01 mm/s.
Weld Thermal Simulation Results

The main tests were divided into two parts:

1) The influence of the cooling time ($\Delta t_{8/5}$) for a peak temperature of 1350°C (2462°F). As indicated in Fig. 1, the peak temperature of 1350°C is in the middle of the peak temperature range of the coarse-grained zone, and this peak temperature is used as a first characterization of the coarse-grained zone. By changing the cooling time ($\Delta t_{8/5}$) of the temperature cycle, the influence of the heat input on the coarse-grained zone can be analyzed.

2) The influence of the peak temperature ($T_p$) for a cooling time of 12 s. The HAZ consists of different microstructural zones, and a gradient exists in each zone. To investigate this situation, the peak temperature of the weld thermal simulation cycle was systematically reduced from 1350°C to 700°C (2462°F to 1292°F) for a series of specimens.

From the weld thermal specimens, the notch toughness was determined, and the microstructures analyzed. The transition curve of a simulated microstructure for Steel 1, $T_p = 1350°C$ and $\Delta t_{8/5} = 12$ s, is shown in Fig. 4. The lower shelf of the curve is positioned at $T = -20°C$ (4°F), which implies that this temperature was probably most sensitive to a change in microstructure with a coinciding change in transition temperature.

A secondary project was carried out on a few steels to investigate:

1) The influence of a postweld heat treatment. The weld thermal specimens were heat treated for 1 h at 600°C (1112°F) before testing.

2) The influence of a double weld thermal simulation cycle. By performing a second weld thermal cycle, it was intended to analyze the changes occurring in multipass welding.

Influence of the Cooling Time for a Peak Temperature of 1350°C

The cooling time ($\Delta t_{8/5}$) was varied between 4 s and 24 s, and a summary of the Charpy V-notch toughness is presented in Fig. 5. Steels 5 and 7 were not investigated since their compositions are similar to the other steels. The highest toughness is observed for Steel 10, followed by Steel 4. The other steels revealed a similar behavior, with low toughness at cooling times greater than 10 s. At lower cooling times, the toughness increases significantly. It should be noted that the C-Mn steel (Steel 8) followed this tendency, too.

Three cooling times were chosen, $\Delta t_{8/5} = 4/5$ s, 12 s and 24 s, and the microstructures investigated were as follows:

- P - pearlite;
- F - polygonal, equiaxed ferrite often located at former austenite grain boundaries;
- UB - upper bainite which is differentiated between:
  - SP - side plate structure often growing from former austenite grain boundaries with plates separated by austenite/marten­site/carbide aggregates;
  - AF - acicular intergranular ferrite plate/needle separated by high-angle boundaries;
- M - martensite.

What was observed was largely martensite and upper bainite consisting of side plate ferrite and acicular ferrite, in which the side plate ferrite structure was the dominating component. At the longest cooling time, the structures of all steels (excluding Steel 10), including the C-Mn steel, was upper bainite, as shown schematically in Fig. 6A. For the low-carbon microalloyed steels, the same microstructure was observed at the cooling time of 12 s, while the C-Mn steel displayed a large amount of martensite. However, at the shortest cooling time, deviations were observed. For instance, Steel 2 had a reduced amount of martensite compared to the other steels. As expected, the microstructure of the C-Mn steel was martensite.

With an increase in the cooling time, a considerable coarsening of the microstructure was observed. This condition is related to the increase in austenite grain size with the increase in cooling time — Fig. 6B. Also, Steel 10 showed an increase...
in austenite grain size as the cooling time increased. The microstructure of Steel 10 did not consist of upper bainite—Fig. 7. An electron microscopic evaluation is needed for an identification of the microstructure, but the transformation diagrams indicated that lower bainite could be found here.

Comparing the microstructural observations with the Charpy V-notch toughness, some interesting trends were observed:

1) A high Charpy V-notch toughness level was found for a martensite microstructure.

2) With an increasing amount of upper bainite, the notch toughness decreased, and especially for the C-Mn steel, where a rather small amount was enough to reduce the notch toughness considerably.

3) A complete upper bainite microstructure has a low notch toughness for almost all of the specimens, including the C-Mn steel. However, Steel 4 showed a rather high notch toughness with a complete upper bainite microstructure.

4) Superior toughness has been observed for Steel 10, which shows a lower bainite microstructure instead of upper bainite.

**Influence of the Peak Temperature (T_p) for a Cooling Time of 12 s**

By changing the peak temperature of the weld thermal simulation cycle, the different zones in the HAZ of a weldment were analyzed. Besides an investigation of the microstructure and its toughness, it was possible to find, to some extent, the transition peak temperatures for the zones and the toughness gradient in the zones. A summary of the Charpy V-notch toughness curves for the eight investigated steels is presented in Fig. 8. Starting at the lower peak temperatures, all microalloyed steels showed a minimum toughness in the partially transformed region. The microstructures revealed the transformation of pearlite to martensite, while transformation products were also observed at the ferrite grain boundaries. Increasing the peak temperature increased the transformation region to the extent that whole ferrite grains were transformed in the fine-grained zone. Steel 4 showed the highest values, while Steel 10 presented the lowest level. Concerning the C-Mn steel, the same toughness level was observed in the partially transformed zone as in the base metal.

Around a peak temperature of 850°C (1562°F), the partially transformed region became a fine-grained zone, characterized by a fine ferrite grain structure with a grain size finer than the normalized base metal. The Charpy V-notch toughness was raised to a high level for all the microalloyed steels, but lower than the base metal (250–300 J/184–221 ft-lb). However, it was observed that the toughness of the fine-grained zone of the C-Mn steel was higher than the base metal.

Increasing the peak temperature to higher values (>1000°C/1832°F) resulted in a transition from fine-grained to coarse-grained zone. The transition range for Steels 1, 4 and 10 and the C-Mn steel was 1000°–1100°C. A somewhat higher transition was found for Steel 2, while the highest transition (1150°–1250°C/2102°–2282°F) was observed for Steels 6, 9 and 3.

For Steels 1, 6, 9 and 3 and the C-Mn steel, the transition from high toughness in the fine-grained zone to low toughness...
in the coarse-grained zone coincides with the transition temperature of the microstructure. The microstructure is upper bainite for the microalloyed steels, while the C-Mn steel has a considerable amount of martensite. Steel 10 exhibited a special behavior, with the toughness increasing in the transition region to a very high level. Both Steels 2 and 4 show upper bainite in the coarse-grained zone; however, in a large part of the coarse-grained zone (up to 1350°C/2462°F), a high toughness level was found.

### Influence of PWHT on the Weld Thermal Specimens

The investigations were limited to Steels 1, 2, 4 and 8. The peak temperature was varied between 700° and 1350°C, and after the weld thermal simulation experiments, the specimens were heat treated for 1 h at 600°C.

The most dramatic influence of the heat treatment was observed in the partially transformed region. The Charpy V-notch toughness level was raised to the same toughness as the fine-grained zone—Fig. 9. The fine-grained zone in turn is also improved by the heat treatment. However, the low toughness part of the coarse-grained zone revealed at least the same low toughness level after the heat treatment.

Although the Charpy V-notch toughness seems not to be altered, the fracture surfaces of Steels 1, 4 and 8 revealed a large degree of intercrystalline fracture appearance after the heat treatment, compared with a transcrystalline mode of fracture before heat treatment. However, Steel 2 has a transcrystalline fracture both before and after a heat treatment.

### Influence of a Second Weld Thermal Simulation Cycle

The initial microstructure of the specimens was the coarse-grained zone ($T_p = 1350°C$ and $\Delta t_{8/5} = 12$ s). The specimens were simulated with a second cycle, with varying peak temperatures. These experiments were limited to Steels 1, 4 and 8.

In the coarse-grained zone, transition from 1000° to 1100°C (1832° to 2012°F), the notch toughness was low, as the microstructure was similar to the original microstructure of upper bainite—Fig. 10. In the fine-grained zone, the coarse-grained initial microstructure was transformed, resulting in some grain refinement of the austenite, while the austenite grain size was still too large to result in a fine ferrite grain structure. Only at the prior austenite grain boundaries was the fine ferrite grain structure observed, while upper bainite was found within the grains. A certain improvement in the Charpy V-notch toughness was observed. Steels 4 and 8 showed the largest increase, although the scatter was considerable for Steel 4. In the partially transformed zone, transformation products were observed at the prior austenite grain boundaries, but since the toughness was low initially, the same low level was observed here.

### Fracture Toughness Test Results

#### Surface Fracture Toughness

All weldments were made with the same type of electrode, using the same welding procedure and a heat input of 4
Fig. 10 — The influence of the peak temperature of the second simulated weld thermal cycle (Tp) on the Charpy V-notch toughness at −22°C. The peak temperature of the first cycle was 1350°C, while the cooling time from 800°C to 500°C for both cycles was 12 s.

M/J (101.6 kJ/in.). All steels, except for Steel 2, reveal a pop-in or a final brittle fracture—Fig. 11. A pop-in through the coarse-grained zone followed by ductile crack growth through the fine-grained zone, resulting in a final brittle fracture or further ductile crack growth, were observed for the group of steels with low CTOD values—Table 2. A final brittle fracture, with or without ductile crack growth, is shown for the group of steels with high CTOD values.

Small-Scale CTOD Testing

Small-scale CTOD specimens (10 x 10 mm/0.4 x 0.4 in., a/W = 0.3) were machined from the weld thermal specimens. The test program was limited to two simulated conditions:
1) Tp = 1350°C and At/5 = 12 s
2) Tp = 720°C and At/4 = 14 s

The first condition represented the coarse-grained HAZ, while the second simulation represented the investigation of the partially transformed region. The results are presented in Figs. 12 and 13, respectively.

Discussion

The simulated weld thermal tests and the CTOD tests identified two embrittled areas in the heat-affected zone:
1) A coarse-grained zone, consisting of a coarse microstructure of martensite or bainite.

Table 2—Schematic Presentation of the Type of Fracture in the CTOD Specimens

<table>
<thead>
<tr>
<th>Fusion Line</th>
<th>Number of specimens for each fracture type with lowest CTOD in parenthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld</td>
<td>Coarse-grained Zone</td>
</tr>
<tr>
<td>Steel</td>
<td>Steel</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>(0.47mm)</td>
</tr>
<tr>
<td>2</td>
<td>(0.7mm)</td>
</tr>
<tr>
<td>1</td>
<td>(3.3mm)</td>
</tr>
<tr>
<td>1</td>
<td>(1.76mm)</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>(5.0mm)</td>
</tr>
</tbody>
</table>

EDM notch — Ductile fracture — Brittle fracture
Final brittle fracture Φ Unloaded
2) A partially transformed zone, where only microstructures with a high-carbon content (pearlite, banding) are transformed.

All steels, except for Steel 10, exhibit low Charpy toughness values in a part of the coarse-grained zone. The part of the zone showing low toughness varies with the steel quality (Fig. 8) and the cooling rate—Fig. 5. A subsequent second weld thermal simulation cycle had only a limited improvement in the temperature range of 800°C to 1100°C—Fig. 10. Post-weld heat treatment had no beneficial effect on the low toughness in the coarse-grained zone—Fig. 9.

All steels had low Charpy toughness in the partially transformed zone (Fig. 8), but very high toughness values were obtained after PWHT—Fig. 9.

Coarse-Grained Zone

Important variables to be taken into account with steels are processing, chemistry and HAZ microstructure.

Steel Processing

All steels are delivered in the normalized condition, but there is no information regarding the detailed processing.
New methods of advanced process control, with online information regarding elements such as H and N, may play an important role in the steel quality. Segregation and microstructural banding will be influenced by the casting method and the subsequent rolling and heat treatment method (Ref. 1). Banding was observed in all steels, but no attempt has been made in order to quantify this phenomenon.

Steel Chemistry

All steels are microalloyed with Nb. Additionally, Steel 10 has a higher Ni content and some V, and Steel 2 contains a certain amount of Ti. Steel 8 is a C-Mn steel with high S content.

Nitrogen. Of special interest are the nitrogen content and the microalloying elements. The microalloying elements may play an important role in fixing free nitrogen and restricting grain growth in the coarse-grained zone. The dissolution of the common microalloying carbides in steel occurs in the range of 1000°-1100°C. An exception is found for TiN, in which dissolution starts at temperatures above 1450°C (2642°F) (Ref. 2). In Fig. 6B, the austenite grain size in the coarse-grained region is plotted as a function of the cooling rate. No restriction of grain growth was observed for Steel 2; hence, the somewhat better toughness recorded for this steel (Figs. 8 and 11) cannot be explained by reduced grain coarsening.

Recent investigations have shown that a reduction of the free nitrogen content in the coarse-grained upper bainitic microstructure will be very effective in improving the toughness (Ref. 3). Additions of trace amounts of Ti, in the range of 0.004-0.01%, are intended to inhibit the formation of free N in the heating stage of the weld thermal cycle. During cooling, it is suggested that Al may play an important role in fixing free nitrogen to form AlN (Ref. 3).

In addition, niobium carbonitrides may form at lower temperatures; hence, it is difficult first to estimate the amount of free N, and second, the proportion of the HAZ where nitrides have been dissolved during heating, leaving free N after the subsequent cooling. The total amount of N should, however, give an indication of the potential for free N. In Fig. 14, the temperature range of the coarse-grained zone with low toughness is plotted as a function of the total content of N. There is a trend towards decreasing the width of the coarse-grained zone that exhibits low toughness with a reduction in the total N content. Steels 2 and 10 have very low total N content after the steel processing, probably because of the applied BOF refining process and the suitable sealing during the casting operation so that air is not absorbed (Ref. 1). In addition, these two steels have some amounts of Ti. The importance of N control is highlighted with the strict requirements on steel for offshore structures, where both rigorous deoxidation and sulfur removal will enhance the tendency for N pickup in the steel (Ref. 4).

In Fig. 15, the minimum CTOD value obtained from the groove welds is plotted as a function of the nitrogen content. The data points are arranged in accordance with the mode of fracture (pop-in, brittle fracture, etc.), and the lowest value for each mode is plotted, with brackets indicating the number of specimens exhibiting the same mode of fracture.

Again there is a tendency for steels with the highest N content to have the lowest CTOD value, indicating that N affects both the width and the fracture toughness of the brittle part of the coarse-grained zone.

An indication of the CTOD value of the low-toughness coarse-grained zone is obtained from the weld thermal specimens—Fig. 16. The lower bound shows low CTOD values for all the steels, except for Steel 10. Steel 10 is dominated by lower bainite, while all the other low-carbon steels are dominated by upper bainite, at this specific rate of cooling (ΔT = 12 s). The C-Mn reference steel, with almost 70% martensite, forms another extreme with low CTOD values. The results show that upper bainite can be brittle, independent of the content of nitrogen.

The increased CTOD values for groove welds with decreasing nitrogen content (Fig. 15) can therefore be explained by the role played by nitrogen content.
on the width of the low toughness part of the coarse-grained zone. Hence, in CTOD testing of real weldments, a distribution of narrow low toughness zones will favor higher CTOD values—Fig. 15.

Phosphorus. The ten steels investigated are commercial steels, and their compositions are listed in Table 1. The low-carbon steels are all very clean and low in S; hence other impurity elements, such as P, may play an important role. As pointed out by McKeown, et al. (Ref. 4), P segregation to grain boundaries may be pronounced in steels with a high P to S ratio. After a PWHT of 600°C (1112°F) for 4 h, CTOD testing at the weld interface of microalloyed steels resulted in a sharp reduction in fracture toughness when the P content was higher than about 0.010% (Ref. 1).

The effect of phosphorus on the width of the low toughness region of the coarse-grained zone, the minimum CTOD values obtained from the groove weld tests, and the CTOD weld thermal simulated specimens are plotted in Figs. 17, 18 and 19, respectively.

For the steels with a P content larger than 0.01%, the minimum CTOD value is low, i.e., for Steels 1, 6 and 9 and the C-Mn steels—Fig. 18. For steels with a P content below 0.01%, an improvement is obvious, confirming the reported critical P content of about 0.01% (Ref. 1).

Both Figs. 19 and 20 independently reflect a sharp increase in fracture toughness at low P contents, while the corresponding plots with nitrogen indicated a linear relationship.

Again, the CTOD simulated weld thermal testing shows a low CTOD value for microstructures dominated by lower bainite, with a tendency for increased toughness in Steel 4—Fig. 19.

Hence, the results indicate that P acts in the same way as N; it influences the width of the low toughness, coarsely-grained zone.

PWHT of the coarse-grained zone in Steels 1, 2, 4 and 8 (only these steels were tested) did not influence the Charpy toughness or the temperature range with low toughness (Fig. 9), but the fracture mode for Steels 1, 4 and 8 changed from quasicleavage to a large amount of intercrystalline fracture after PWHT, while Steel 2 exhibited transcrysalline fracture. For Steel 1, it was found that heat treatments at 600° and 650°C both revealed low notch toughness (Ref. 5). However, the fracture surface changed from intercrystalline at 600°C to transcrysalline at 650°C. The test results suggest that P may contribute to the tendency to intercrystalline fracture, but more detailed analysis is necessary.

Niobium. All the steels are alloyed with Nb, and the content of Nb vs. the toughness was plotted in the same way as for N and P in Figs. 20, 21 and 22. Unfortunately, the steels low in P and N, Steels 2, 4 and 10, also have the lowest content of Nb, and it is difficult to point out the effect of Nb. The minimum CTOD values from the groove welds (Fig. 21) do not show the same straightforward relationship as in the case of N and P.

The effect of Nb might have been better understood if a steel with high Nb and low P and N had been included in the examination, but none of the ten commercial steels examined had such a composition.

C-Mn Reference Steel. Finally, the extensive embrittlement in Steel 8 should be noted because of the higher hardenability and higher P content. In such a steel, the problems around the brittle zones would be expected to exist in a way equivalent to Steel 1. It is, therefore, remarkable that no low-HAZ CTOD values were recorded during the comprehensive fracture toughness testing of this steel for use in offshore structures about 10 years ago (Ref. 8). A critical point in the through thickness CTOD testing is the positioning of the notch tip with respect to the brittle zones, and since brittleness in the weld metal was a problem, restrictions were put upon the positioning procedure in order not to hit the weld metal. With a somewhat curved weld interface, the result may have been that the major part of the fatigue crack front was positioned in a tough region of the HAZ. But
Fig. 18—The minimum CTOD values of the groove-welded specimens plotted as a function of the phosphorus content and related to the different fracture types.

**HAZ Microstructure**

Most of the steels exhibited the same behavior of Charpy notch toughness as related to the cooling time—Fig. 5. A sharp reduction in toughness was observed in the cooling time interval from 5 to 12 s, followed by a low notch toughness level at 24 s.

Steels 10 and 4 deviate from this trend, with a higher Charpy notch toughness. Examination by optical microscope identified a shift in microstructure with a change in cooling time—Fig. 6A. The general trend is for a structure to be dominated by martensite at the shortest cooling time, $\Delta t_{0.5} = 5$ s, and then for a gradual increase in the fraction of upper bainite with longer cooling times. Steel 10 contains a microstructure consisting largely of lower bainite at 12 s. At 24 s, the microstructure of this steel is probably still lower bainite. Steel 2 contains an upper bainitic microstructure over the whole cooling range.

The low-carbon martensite has a high toughness because autotempering can take place from a high M$_s$ temperature. The hardness gives no indication of the toughness, because this kind of martensite has a high toughness and hardness, while the bainite upper bainite has a lower toughness—Fig. 5. The upper bainite is dominated by a side plate structure with the plates separated by austenite/martensite/carbides, giving favorable conditions for initiation and propagation of cleavage fracture. Both Steels 2 and 4 exhibit a high notch toughness in a large part of the coarse-grained zone with upper bainite (Fig. 8), indicating that some additional embrittling effect is necessary in order to obtain a brittle low-carbon upper bainite structure.

**Partially Transformed Zone**

Recognizing brittleness in the partially transformed zone is not a new discovery. In a paper published in 1947, the existence of this low-toughness region was examined with notched bend specimens and heat-treated Charpy bars to simulate the thermal effect of welding (Ref. 6). Two temperatures were found to be highly deleterious—a coarse-grained structure formed at 1150°C (2102°F) and the lowest values of all, observed at 760°C (1400°F). Postheating at 450°C (842°F) and above restored a large degree of the toughness drop at 760°C. Microscopic examinations revealed that upon heating to 760°C, pearlite islands transformed to austenite with a nearly eutectoid composition. Upon cooling, these high-carbon islands were partially transformed to martensite. Postheating
served to temper and partially spheroidize the martensite.

The observations from 1947 correspond very well to the present results. Low toughness is observed in the partially transformed zone after single cycle thermal simulation (Fig. 8), and also in the temperature range which corresponds to the partially transformed zone after double simulation of the coarse-grained zone—Fig. 10.

The optical microscopic examination and work in progress on similar low-carbon microalloyed steels (Ref. 7) have identified high-carbon twinned martensite as the main embrittling factor. After single cycle transformation, the banding with high-carbon areas (pearlite) is austenitized and subsequently transformed to twinned martensite upon cooling. The martensite will reduce the toughness partly because of the residual stresses in the surrounding matrix and partly because of the preferred distribution of the martensite islands along the ferrite grain boundaries within the banding area. The work in progress (Ref. 7) has indicated that the brittleness can be avoided if the pearlite is finely dispersed.

After double simulation of the coarse-grained upper bainite, the existence of separate phases (islands) along the prior austenite grain boundaries is even visible at low magnification in the optical microscope—Fig. 23. The embrittling effect of twinned martensite in a less ductile matrix (upper bainite) is obvious.

PWHT has a remarkable effect on the toughness of the partially transformed zone—Fig. 9. The increased toughness may partly be due to a decomposition of martensite and partly to a relaxation of the residual stresses.

CTOD Results
Groove Weld Tests

Since the brittle zones can extend to the surface of a weld and the cap layer is not refined, CTOD testing with shallow surface notches was performed in order to examine whether brittle fracture could initiate from small surface defects. Fatigue precrack positioning with respect to the coarse-grained zones can be difficult, and the required fatigue precrack in the CTOD standard was substituted with an electro-discharge machined notch. Both the shallow cracks and the EDM notch result in higher fracture toughness than if measured in accordance with the CTOD standard (Ref. 5).

Most specimens were characterized with a pop-in or a final brittle fracture—Table 2. Only for Steel 2 was ductile crack growth, resulting in a maximum load recording, observed for several specimens. For all the other steels, the CTOD values (Fig. 11) represent a brittle fracture or a pop-in. The large scatter in the test results is partly caused by the

![Fig. 20 - The peak temperature range (ΔTp) of the coarse-grained zone with low Charpy V-notch toughness plotted as a function of the niobium content](image)

![Fig. 21 - The minimum CTOD values of the groove-welded specimens plotted as a function of the niobium content and related to the different fracture types](image)
Fig. 22—The CTOD results of the simulated weld thermal specimens (\(T_p = 1350\,^\circ\text{C}\) and \(\Delta t_{8/5} = 12\) s) plotted as a function of the niobium content.

Fig. 23—Double weld thermal simulation tests: the microstructure of the simulated weld thermal specimens of Steel 4 and Steel 8 with a peak temperature (\(T_p = 720\,^\circ\text{C}\)), \(\Delta t_{8/5} = 12\) s, and \(T_p = 1350\,^\circ\text{C}\) from a local brittle zone. The C-Mn steel (Steel 8) has a much lower crack initiation value, and therefore, only a limited amount of energy will be stored—Fig. 25.

The crack arrest properties of low-carbon microalloyed steels will be examined and compared with C-Mn steels in future work (Ref. 7).

Small-Scale CTOD Tests
Fatigue precracked CTOD small-scale weld thermal simulation tests, with peak temperatures corresponding to the coarse-grained region (\(T_p = 1350\,^\circ\text{C}\)), have been compared with the Charpy toughness—Fig. 26.

Again, Steels 10 and 4 represent the highest CTOD values (Fig. 26) as in the groove weld test (Fig. 11); however, for Steel 10, the fracture mode has changed from pop-in (CTOD\(_m\)) to maximum load (CTOD\(_m\)). This may be explained by the change in cooling rate. The groove weld tests had \(\Delta t_{8/5} = 24\) s, while the weld thermal simulation tests (Fig. 26) had \(\Delta t_{8/5} = 12\) s. The slower cooling rate will favor the formation of a coarse lower bainitic microstructure, while the finer lower bainite at \(\Delta t_{8/5} = 12\) s has proven to have good toughness—Fig. 5.

For Steel 2, brittle fracture was recorded, which is in agreement with the low Charpy toughness but in contrast to the groove weld results where CTOD\(_m\) values frequently were recorded—Fig. 11. This may be explained on the basis of the toughness gradient existing in the...
coarse-grained zone of a real HAZ compared with the single temperature simulation. For Steel 2, the Charpy toughness is still high at a peak temperature of 1250°C (2282°F), indicating that the high CTOD values from the groove weld testing may reflect that the size of the brittle zone is of importance; i.e., the small brittle zone in the coarse-grained HAZ at the weld interface may be of limited consequence. However, the significance of local brittle zones with respect to the risk of failure of welded structures should be further evaluated.

Conclusions

Nine modern low-carbon microalloyed steels, delivered for recent applications in offshore structures, and one C-Mn steel, used in the 1970’s for offshore purposes, have been evaluated with respect to the fracture toughness level in the heat-affected zone of weldments. The toughness was investigated by means of weld thermal simulation testing and surface fracture toughness testing. The results are as follows:

1) Weld thermal simulation testing identified two low toughness zones - the coarse-grained zone and the partially transformed zone.
2) Shallow surface notched CTOD testing revealed high CTOD values, but most specimens were characterized with a pop-in or final brittle fracture initiating from the low toughness zones.
3) The influence of elements, such as Ti, N, P, Nb and Ni is discussed, and it is suggested that N and P may be of major importance.
4) The reference C-Mn steel was at least as brittle as the low-carbon steel, and it is questioned why no low HAZ CTOD values were recorded in the comprehensive testing of this steel 10 years ago.

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References

7. Work in progress at SINTEF, Trondheim, Norway.
8. Private communication with The Welding Institute and Det Norske Veritas.