# FRACTURE BEHAVIOUR OF ULTRA-LOW CARBON BAINITIC STEELS FOR HEAVY SECTION APPLICATIONS

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A new family of ultra-low carbon bainitic (ULCB) steels for heavy plate applications has been investigated. These new materials have been developed as candidates to replace traditional heat treated high yield strength (HY) steels. The ULCB steels achieve their high strength and excellent resistance to both ductile and brittle fracture through the use of advanced alloy design and thermomechanical processing. This paper attempts to quantitatively describe how the metallurgical factors such as the steel composition, austenite conditioning and material cleanliness affect on mechanical properties, fracture appearance transition temperature and fracture toughness of the steels.

## INTRODUCTION

Traditional quenched and tempered (QT) high strength plate steels are capable of offering excellent base plate properties, however, the weldability and weldment properties have been troublesome. These weldability problems have led to high fabrication and repair costs (1). A typical example is the quenched and tempered family of HY steels which were developed and certified for commercial and defense applications in the mid-1950's (2). To overcome welding-related problems, a new approach to the design of high strength plate steels is being explored (3,4). The new steels which have been developed from these investigations are called the ultra-low carbon bainitic steels. One of the major advantages of ULCB steels over typical QT steels is that ULCB steels are capable of achieving a good combination of strength and toughness in the as-hot rolled condition, without requiring additional heat treatment. Another advantage of

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ULCB steels is their behavior during welding. Graville (5) has shown that the resistance to cold or underbead cracking is significantly improved through a reduction in carbon content. Furthermore, Haze et al. (6) have shown that the resistance to the brittle fracture of the heat-affected zone can be dramatically improved through lowering of the amount of martensite-austenite constituent, which can be accomplished by lowering the carbon content. Hence, the very low carbon contents in the ULCB steels are expected to greatly improve both the weldability and the weldment toughness of these steels (7).

## EXPERIMENTAL PROCEDURE

A series of molybdenum containing ULCB steels (24 heats) has been studied. The range of chemical composition (in wt.%) of the steels evaluated in this investigation is shown in Table 1. The steels used in this investigation were divided into three groups according to their corresponding yield strength (YS) level as follows: A) YS = 550 - 700 MPa, B) YS = 700 - 850 MPa, C) YS = 850 - 1000 MPa. Additional processing details are available elsewhere (7-9).

TABLE 1- Range of chemical composition of the steels tested, wt%.

| YS level | Mo | Ni |
|---|---|---|
| A | 1.0-1.5 | 1.5-2.0 |
| B | 1.5-2.5 | 2.0-3.5 |
| C | 2.5-3.5 | 2.5-3.5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| C | ≈ 0.020 | - | 0.03 | Ti | ≈ 0 | - | 0.020 |
| Mn | ≈ 0.50 | - | 1.0 | Nb | ≈ 0.05 | - | 0.06 |
| Cr | ≈ 0 | - | 0.70 | N | ≈ 0.006 | - | 0.009 |

P,S < 0.008

The transverse mechanical properties of the steels in the as-hot rolled condition were measured using standard procedures. The tensile properties were obtained from subsize flat specimens with a 25 mm gauge length. Impact properties were determined using the standard full- size Charpy V-notch (CVN) specimens with the notch perpendicular to the rolling plane (T-L orientation). Impact tests were done in the temperature range from -100°C to +100°C. In addition, the 50 % shear fracture appearance transition temperature (FATT) was determined from broken specimens using scanning electron microscopy. Furthermore, the fracture toughness of the steels was determined utilizing the J-integral method. Tests were carried out at room temperature using double-cantilever beam samples with a thickness of B=20 mm. The microstructural characteristics of both the prior-austenite and the final bainitic ferrite were evaluated using standard metallographic procedures involving optical microscopy (OM) as well as scanning and transmission electron microscopy (SEM and TEM). The morphology of the controlled rolled austenite grains was examined using OM and SEM, whereas the fine details of the bainitic structure were studied using SEM and TEM. The metallurgical condition of the prior-austenite grains was assessed through the measurement of its geometry by utilizing the Bioquant System-IV computer-controlled image analyzer. The non-metallic inclusions in steels were identified by OM and energy disperse spectrometry (EDS). In addition, a detailed quantitative assessment of inclusion geometry was performed by utilizing the image analyzer.

## RESULTS

The microstructural details related to the steels tested are discussed in earlier papers (9,10). A study of the inclusion chemical composition by EDS clearly showed that Al-oxides and Mn-sulfides were two common types of the non-metallic particles in each steel investigated. Besides these inclusions, small amount of Ti-nitrides and complex silicates were sometimes observed. Previous studies (4,9) have revealed that the chemical composition has a significant effect on the strength of bainitic steels in the as-hot rolled condition. This effect can be explained by the influence of the steel composition on the austenite to bainite transformation temperature. More details reviewing this effect were presented in an earlier publication (9). A summary of the effect of chemical composition (wt%) on the yield strength of ULCB steels can be represented by a linear regression equation as shown below:

$$YS,\ N/mm^2 = 25[10.2 + 1625B + 68.1(C+N) + 46.3(Ti+Nb) + 4.9Mo + 3.3Mn + 2.6Cr + 0.3Ni \quad (1)$$

It is well recognized that the toughness of low carbon steels in the transverse direction is strongly related to the geometry of non-metallic inclusions (11,12). This trend was also found in the present investigation. The factors that control the resistance of the steel to brittle fracture are somewhat more complex. It has been established (13), that resistance to brittle fracture is controlled mainly by three factors: i) the metallurgical condition of the parent austenite, ii) the cleanliness of the steel and iii) the strength level. The effect of the three factors (i-iii), indicated above, on the upper shelf energy-USE and FATT for 50% of shear fracture can be summarized by equations (2) and (3). These equations which were calculated for all 24 heats are represented by the following linear formulas:

$$USE,\ J = 377 - 0.21YS - 0.18D_\gamma - 0.083\Sigma b \quad (2)$$

$$FATT,\ ^\circ C = -191 + 0.13YS + 0.85D_\gamma + 0.008\Sigma b \quad (3)$$

where the range of variables used in the experiment are:

| | | |
|---|---|---|
| YS, MPa | = | 550 - 950 |
| $D_\gamma$, $\mu$m | = | 25 - 90 |
| $\Sigma$b, $\mu$m/mm$^{-2}$ | = | 150 - 1600 |

The results of the fracture toughness tests proved that both parameters, the J-integral $J_{1C}$ and resistance for crack propagation R=dJ/da are also sensitive to steel cleanliness as well as yield strength and austenite grain size. To describe the effect of these three factors on fracture toughness, the analysis was made in a manner similar to that used in the impact tests. The calculations of $J_{1C}$ and R as functions of YS, $D_\gamma$ and $\Sigma$b were completed for twelve different compositions of the steels tested. Results of these calculations are as follows:

$$J_{1C}\text{, kJm}^{-2} = 556 - 0.26YS - 3.2D_\gamma - 0.13\Sigma b \quad (4)$$

$$R\text{, kJm}^{-2}\text{mm}^{-1} = 896 - 0.53YS - 4.5D_\gamma - 0.17\Sigma b \quad (5)$$

After testing, both the impact and fracture toughness samples were carefully examined using the SEM. These investigations revealed several differences in the fracture behavior of ULCB steels. The fracture phenomenon was controlled mainly by microstructural factors such as cleanliness and austenite grain size as well as the strength of the steels. Results of these investigations for steels with pancaked coarse or fine austenite grains have been presented in earlier work (9) in the series of micrographs. In this work the typical stages of fracture modes related to austenite grain size are presented schematically in fig.1.

## CONCLUDING REMARKS

The strength of as the hot-rolled ULCB steels is controlled by the proper combination of alloy design and thermomechanical processing.
The cleanliness of ULCB steels strongly influences the upper shelf energy.
Because the prior-austenite grain boundaries are the only effective barriers to the growth of cleavage microcracks in ULCB steels at lower temperatures, the impact toughness is primarily controlled by austenite grain morphology.
Fracture toughness of ULCB steels at room temperature is sensitive to three factors: the steel cleanliness, austenite grain size and yield strength of the steel.
Fracture mechanisms of the as hot rolled ULCB steels depend mainly on the inclusion morphology and the prior-austenite grain size and shape distribution.

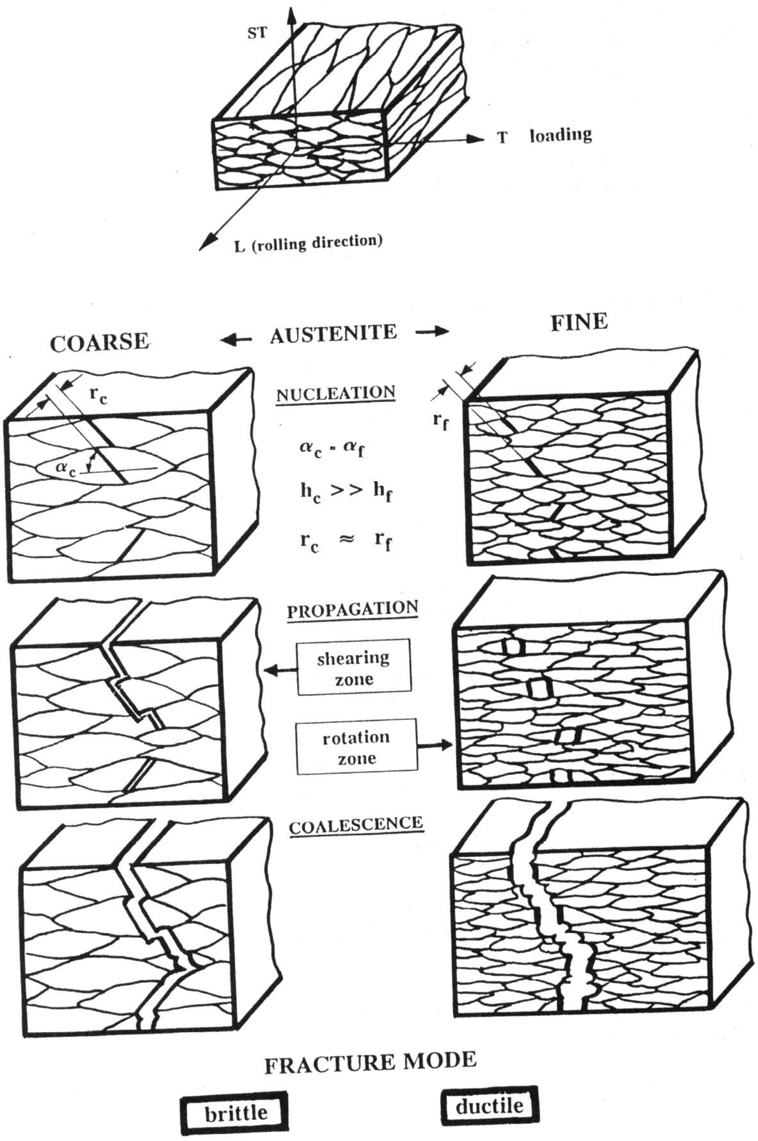


Figure 1. Fracture modes in the ULCB steels with coarse or fine austenite grains

## SYMBOLS USED

YS = yield strength, (MPa)
USE = upper shelf energy, (J)
FATT = fracture appearence transition temperature, (°C)
$J_{1C}$ = Rice'a integral, ($kJ/m^2$)
R = resistance for crack propagation
$D_\gamma$ = equivalent austenite grain diameter
$\Sigma b$ = projected inclusion length per unit area, ($\mu m/mm^2$)

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