ABSTRACT
The aim of this study was to characterize the microstructure of microalloyed linepipe steels. The steels investigated were X70 (0.04 wt% C - 0.02 wt% Ti - 0.07 wt% Nb) and X80 (0.04 wt% C - 0.025 wt% Ti - 0.09 wt% Nb) steels, where the numbers refer to their specified minimum yield strength (SMYS) in ksi. This class of steels has the advantage of high strength and good toughness combined with minimal wall thickness (15.5 mm for X70 steel). These attributes result in considerable cost savings when installation of several hundreds of kilometers of pipeline is required for oil and natural gas recovery and transport.

The present study focused on phase identification and quantification, distribution of alloying elements and inclusions and segregation effects. Both steels were primarily composed of a mixed ferrite structure, i.e., polygonal ferrite and acicular ferrite/bainite, with characteristic low angle grain boundaries and high dislocation densities. The proportion of acicular grains was higher for the X80 steel. Pockets of retained austenite, exhibiting a Kurdjumov-Sachs orientation relationship (KS-OR) with the adjoining ferrite, were found in both steels.

Five general classes of precipitates were identified in both steels: 1) Very large (2-10 μm) cuboidal TiN particles nucleated on inclusions; 2) large (0.1-1.0 μm) cuboidal TiN particles; 3) medium sized (30-50nm), irregular shaped Nb-Ti carbonitrides; 4) fine (<20nm), rounded precipitates of Nb carbonitrides with traces of Mo; 5) very fine dispersed precipitates (<5 nm in size). For X80 steels many of the large TiN precipitates were observed with Nb-rich carbonitrides precipitated epitaxially on them.

Inclusion content and morphology were analyzed in both steels. The inclusions in X70 steels were found to be primarily CaS with significant amounts of Al, O, Ti, Fe and Mn. They were essentially spherical in shape with small elliptical distortions along the rolling direction and across the width of the plate. The morphology of the inclusions in the X80 steel was very similar, however, they showed higher Mn levels.

INTRODUCTION
Microalloyed steels are low carbon steels (<0.1 wt% C in many cases), which derive their strength, toughness and weldability from a combination of low carbon content, the judicious addition of alloying elements such as Ti, Nb and Mo and a controlled roll pass schedule [1-4]. The control of precipitation behaviour during hot rolling is critical for achieving the required microstructure and properties [5-8]. A thermomechanical controlled rolling process (TMCP) with on-line accelerated cooling (OLAC) is employed for control of grain refinement and subsequent precipitation strengthening on cooling.

Although the process was developed for conventional reversing hot strip mills, at present, Steckel mills with heated coil boxes on either of a reversing finishing stand are preferred. Steckel mills provide good temperature control, resulting in conditions approaching isothermal rolling [9].

The important steps in controlled rolling of microalloyed steels are briefly described below [5,10,11,12]. After casting, the steel is reheated to temperatures around 1250°C to fully austenitize the grains and to dissolve all the microalloying additions, with the exception of some of the Ti, which is tied up in TiN [13]. TiN has a solubility product in austenite which is several orders of magnitude lower than values for TiC or Nb/C carbonitrides [14]. TiN helps prevent austenite grains from growing to abnormally large sizes by pinning the grain boundaries. During the roughing passes, large amounts of plastic deformation are provided to the slab to reduce the thickness from about 20 cm down to about 4 cm. The steel is continually deformed and recrystallized producing a fine austenite grain size. During the finishing stage of rolling at 700-900°C, austenite recrystallization is retarded, with 2 main mechanisms operating. At higher finishing temperatures, dissolved microalloying elements hinder recrystallization by a solute drag mechanism. At lower temperatures, strain induced precipitation of Nb/Ti carbonitrides at sub-grain boundaries has the effect of pinning austenite grain boundaries. Niobium is particularly effective at retarding recrystallization. The resultant structure is a highly desirable
austenite 'pancake' structure, where austenite grains are elongated along the rolling direction. Towards the end of finish rolling, ferrite grains nucleate at the prior austenite grain boundaries, as well as on slip bands within the grains, and grow across the grains away from the boundaries. Since the prior austenite grains have been pancaked, the ferrite grains do not grow much before impinging on adjacent ferrite grains. This leads to a very fine, acicular ferrite grain structure. Interphase precipitation can accompany the austenite-to-ferrite transformation, with Nb carbonitrides nucleating periodically at the γ/α phase boundary during ledge growth of ferrite. The driving force for precipitation is the large discontinuous decrease in solubility at the γ/α boundary. Particle size depends on the transformation temperature, but is typically of the order of 20 nm. Deformation may be continued after the austenite has transformed to ferrite, which leads to the development of extensive dislocation networks and strain bands. During coiling of the steel strip, at temperatures below 600°C, extremely small Nb(C,N) precipitates (<5 nm in size) nucleate heterogeneously on the dislocation networks inside the ferrite grains. These impart additional strength to the final microstructure through precipitation strengthening.

The aim of this work was to characterize and compare the microstructures of X70 and X80 pipeline steels. The microstructures were characterized using both optical and electron microscopy techniques and the corresponding microstructures were correlated with processing conditions and mechanical properties. The steels examined were commercial products manufactured by IPSCO, Inc. - the compositions and mechanical properties are shown in Tables 1 and 2, respectively. The compositions are similar, although notable differences include higher Nb and Mo levels and slightly higher Mn levels for X80 compared with X70. X80 steel also has a slightly lower C content. The higher strength and lower toughness of the X80 steel relative to the X70 steel can be attributed, in part, to the higher Nb and Mo levels, which have the effect of shifting continuous cooling transformation (CCT) curves to longer times and should increase the tendency for the formation of bainitic microstructures.

EXPERIMENTAL METHODS

The original slab thickness for both steels was 20 cm. The final gauge thicknesses of the coiled strip were 14.6 mm (X70) and 15.6 mm (X80). The rough rolling temperatures were similar for both steels; however the finish rolling process was closer to being isothermal for the X80 steel compared with the X70 steel. There was only a ≃30°C change during finishing rolling for X80 steel compared with a ≃170°C temperature change for X70 steel. The average cooling temperature was about 40°C higher for X80 steel.

Initial microscopic examination was performed using standard optical metallographic techniques. Samples were cut from three different orientations of the plate. Polished samples were etched using three different solutions (Table 3) to accentuate various features. Of the etchants used, modified LaPer's etch was particularly useful because of the different colors it imparts to constituent phases. Martensite and retained austenite show up white, ferrite is tan and bainite and carbides are etched black [15].

The sample preparation for scanning electron microscopy (SEM) was very similar to that for optical microscopy, however, the samples were etched for longer times (2-3 times longer) to enhance contrast. The SEM utilized was a Hitachi S-2700, with an ultra thin window (UTW) Ge x-ray detector. All observations were made at 20kV and a working distance of 10-15 mm.

Transmission electron microscopy (TEM) was used for higher resolution imaging and composition analysis, as well as diffraction analysis. Two types of specimens, thin foils and carbon extraction replicas, were prepared. Thin foils were prepared using a combination of electropolishing and ion milling. A 15% solution of perchloric acid in methanol cooled to −60°C was used. The potential was maintained at 40-60V with a current of 20-40 mA. After electropolishing, samples were ion milled for ≃30 minutes with an Ar ion beam produced using an accelerating voltage of 4 kV and a beam current of 0.5 mA per gun. Carbon replicas were particularly useful for examining very small precipitates, due to elimination of the masking effect of the iron matrix. Replicas provided relatively large viewing areas, which proved beneficial in analyzing precipitation distribution. All TEM samples were examined in a JEOL 2010 TEM equipped with a UTW Ge x-ray detector and operated at 200 kV.

Image analysis was performed on optical images to analyze the size, shape and distribution of inclusions in both X70 and X80 steels [16,17]. For inclusion analysis, at least 100 regions were analyzed on

| Table 1 Chemical Composition (wt%) of X70 and X80 Steels |
|---|---|---|
|   | X70 | X80 |
| C  | 0.041 | 0.033 |
| Mn | 1.76  | 1.82 |
| Ti | 0.023 | 0.024 |
| Nb | 0.067 | 0.091 |
| S  | 0.001 | 0.004 |
| Si | 0.281 | 0.274 |
| Cu | 0.193 | 0.294 |
| Mo | 0.194 | 0.256 |
| Al | 0.045 | 0.038 |
| Ca | 0.004 | 0.0027 |
| Cr | 0.058 | 0.056 |
| V  | 0.001 | 0.003 |
| N  | 0.01  | 0.01  |

| Table 2 Mechanical Properties of X70 and X80 Steels |
|---|---|
| Property | X70 | X80 |
| Yield Strength (MPa) | 545 | 568 |
| UTS (MPa) | 642 | 668.5 |
| Charpy Energy (J) | 375 | 235 |

| Table 3 Etchants Used for Optical Metallography |
|---|---|
| Etchant | Composition |
| Nital | 2% Nitric acid in ethanol |
| Picral | 4% Picric acid in ethanol |
| Modified LaPer's | a) 10% HCl in water |
| | b) Saturated solution of picric acid (4%) in 100ml ethanol |
| | c) 1g sodium metabisulphite and 1g EDTA in 100 ml water. Sample etched for 10s in a) and then for 45s in a mixture of equal parts of b) and c) |

[15] Transmission electron microscopy (TEM) was used for higher resolution imaging and composition analysis, as well as diffraction analysis. Two types of specimens, thin foils and carbon extraction replicas, were prepared. Thin foils were prepared using a combination of electropolishing and ion milling. A 15% solution of perchloric acid in methanol cooled to −60°C was used. The potential was maintained at 40-60V with a current of 20-40 mA. After electropolishing, samples were ion milled for ≃30 minutes with an Ar ion beam produced using an accelerating voltage of 4 kV and a beam current of 0.5 mA per gun. Carbon replicas were particularly useful for examining very small precipitates, due to elimination of the masking effect of the iron matrix. Replicas provided relatively large viewing areas, which proved beneficial in analyzing precipitation distribution. All TEM samples were examined in a JEOL 2010 TEM equipped with a UTW Ge x-ray detector and operated at 200 kV.

[16,17] Image analysis was performed on optical images to analyze the size, shape and distribution of inclusions in both X70 and X80 steels. For inclusion analysis, at least 100 regions were analyzed on
each side (>200 inclusions at each of the smaller areas) to give a good statistically representative count. Image analysis was done using commercially available software coupled to an optical microscope through a CCD camera. The steels were polished to a finish of 0.5 μm and examined unetched, which provided a clean, light background for the darker inclusions. Almost all inclusions were spherical or near spherical in shape, so measurement of area and aspect ratio gave a good index of the shape and size distribution of the inclusions.

RESULTS AND DISCUSSION

Overall Microstructure

Optical micrographs, from the near surface and centreline regions, for the 2 steels, are shown in Fig. 1. A mixed grain structure is apparent, consisting of primarily irregular or acicular ferrite/bainite and polygonal ferrite. The amount of polygonal ferrite is more pronounced in the X80 steel. The areas near the surface show a finer microstructure, due to the higher amounts of deformation and faster cooling rates at the surface compared with the interior. Apparent grain sizes were measured for both steels – the results are given in Table 4. The X80 steel has a finer and more uniform apparent grain size, which suggests that it contains a higher proportion of bainite or bainitic ferrite as is expected based on the alloy content. The microstructure in the X70 steel is more mixed, as evident from the large standard deviations. The additional Mo and Nb in the X80 steel have the effect of shifting the continuous cooling transformation (CCT) curves to longer times. Niobium also shifts the CCT curves to lower temperatures. Both effects retard polygonal ferrite formation and enhance the formation of bainite.

Table 4 Apparent Grain Sizes for X70 and X80 Steels

<table>
<thead>
<tr>
<th>Steel</th>
<th>Centreline Region</th>
<th>Surface Region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grain Size (μm)</td>
<td>St. Dev. (μm)</td>
</tr>
<tr>
<td>X70</td>
<td>8.8</td>
<td>4.2</td>
</tr>
<tr>
<td>X80</td>
<td>6.1</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Optical images along the centreline, for both steels, are shown in Fig. 2. Solute segregation effects are visible, particularly for X70 steel, which are artifacts of the continuous casting process. Segregation in the liquid metal during casting tends to be localized to the mid-thickness of the slab on progressive solidification from the outer surfaces, and accompanying solute rejection to the liquid core at the middle. This segregation remains through roughing and final rolling, to the cooled skelp.

Modified LaPerle's etch was effective at revealing the various constituent phases in the microstructure, particularly in identifying the martensite/retained austenite constituent (M/A). Fig. 3 shows the distribution of M/A (white areas) near the surface and the center of the plate for both X70 and X80 steels. M/A was found to be concentrated more at the centreline where the M/A islands are larger and clustered together, although finely dispersed islands were scattered throughout the thickness of the plate. This centreline effect was more pronounced in X70 steel, and correlates with the segregation observations discussed above. M/A arises due to the limited solubility of C in ferrite. When the austenite to ferrite transformation is taking place, ferrite rejects excess carbon and solutes through diffusion to the adjacent austenite grains. These small areas, which show up mainly at the triple grain boundaries, are richer in carbon and solutes and make up the M/A. The higher carbon austenite can transform to martensite on cooling or remain as retained austenite. By similar reasoning the presence of more numerous and larger areas of M/A near the center of thickness of plate can be explained. Since there is more solute segregation near the centreline and the cooling rates are lower, more time is available for solute/carbon diffusion out of the transforming grains, leading to more M/A areas.

The inclusion content in both X70 and X80 was quite low, and those present were approximately spherical in shape (Fig. 4). No stringers were observed, indicating the effectiveness of Ca treatment on shape control. Energy dispersive x-ray (EDX) analysis indicates that the inclusions in X70 steel primarily contained Ca and S with significant amounts of Al, Fe, O as well as Ti (Fig. 4b). The inclusions in X80 steel were spherical as well, but contained larger amounts of Mn in addition to the other elements. The overall Mn content is higher in X80 compared with X70 steel, but not high enough to account for the composition difference. The difference appears to be fortuitous and may just be a sampling phenomenon. The inclusions are referred to as CaS in subsequent sections, but are likely mixed oxysulphides. Mixed inclusions have been reported for other steels [18,19]. For example, in steels treated with Ca-Al deoxidizers, Al₂O₃-CaO-CaS inclusions formed in the molten steel, with CaS either distributed uniformly or preferentially precipitated on the perimeter. CaS enrichment on the perimeter was found in steel regions that were cooled relatively slowly and was believed to be due to a solubility drop during solidification.

Most of the inclusions are relatively small, very few had planar areas >10 μm². The inclusions are more numerous and slightly finer in size for X80 steel – more than 70% had planar areas <2 μm² – compared with the X70 steel, where 70% of the inclusions had planar areas <3 μm². The size distribution and frequency of inclusions do not vary appreciably across the thickness of the plate. The inclusions are slightly elongated, from rolling, along the rolling direction and across the width of the plate. The inclusions in the X80 steel are slightly rounder (the average aspect ratio is close to 1.5) when compared with the X70 steel (the average aspect ratio is closer to 2.0). This may be a consequence of the overall smaller size of X80's inclusions. The size, shape and distribution of inclusions in both X70 and X80 steels indicate the efficiency of the Ca/Si treatment in removing S from the steel. The hard CaS inclusions are difficult to deform and remain relatively spherical, compared with softer MnS inclusions during rolling. Stringers are undesirable because of their role in reducing toughness and assisting hydrogen induced cracking [20].

In addition to inclusions, other large particles (2-10 μm) were visible in the optical microscope (Fig. 5). These were copper in colour, cuboidal in shape and contained what appeared to be a second particle in the interior. The particles were present throughout the plate thickness, but were concentrated near the centreline. The origin and identity of these particles will be discussed in the subsequent section on precipitation.

Thin foils were prepared of both X70 and X80 steels. Most of the TEM micrographs shown are taken from the X70 steel, although similar microstructural features were observed for the X80 steel. A major portion of the microstructure consisted of acicular grains, confirming the optical and SEM observations. Differentiating between acicular ferrite and bainite was difficult as there were no cementite particles associated with any of the grains, either within the laths or along lath boundaries. Because of the absence of cementite, the term bainitic ferrite, instead of bainite, is probably more appropriate here in describing bainitic structures. The approach given by Collins et al [11] was utilized to differentiate between acicular ferrite and bainitic...
ferrite. Both bainitic ferrite and acicular ferrite have irregularly shaped grains with planar boundaries; however, bainitic ferrite tends to be more elongated and has a higher dislocation density – bainite laths are generally 0.5-0.7 μm in width. Examples of both bainitic ferrite and acicular ferrite are given in Figs. 6 and 7. In both cases, low angle grain boundaries are found between the laths. Selected area diffraction (SAD) patterns taken from adjacent laths in Figs. 6 and 7 indicate that the laths all have almost the same orientation (zone axis = <111> type) with only slight misorientations (~5°) across the boundaries.

Pockets of retained austenite (identified previously as white areas with modified LaPer's etch) were found to exist between clusters of ferrite grains (Fig. 8). The austenite grain (labeled as #2) in Fig. 9 shows a Kurdjumov-Sachs (KS-OR) orientation relationship with the adjoining ferrite (labeled as #1).

Precipitation

The precipitates observed in both steels were classified into 5 types, based on their size, shape, composition and processing conditions. The particles had similar structures, i.e., an fcc, NaCl - type structure, which can be attributed to the mutual solubility of Ti/Nb carbides and nitrides [21]. Much of the phase identification was done using carbon replica specimens to eliminate interference from the ferrite matrix.

Very large TiN precipitates (2-10 μm). This group of precipitates was large enough to be seen at relatively low magnifications in the optical microscope (Fig. 5). Key identifying characteristics include their copper colour and cuboidal, faceted shape. In addition, virtually all these particles had a dark, spherically shaped feature in their interior. EDX analysis in the SEM confirmed that the cuboids were TiN, with small amounts of Nb, while the spherical cores were mixed oxide/sulphide inclusions. Similar precipitation behaviour was reported in a recent paper by Saikaly et al [22] and they attributed it to TiN nucleation on inclusions during solidification in the interdendritic liquid. At 1500°C, the solubility product for TiN drops from about 3.1x10³ in liquid steel to about 2.5x10³ in austenite [14], which, given the levels of Ti and N in X70 and X80 steels, would lead to TiN precipitation. The large TiN particles were more prevalent along the centerline, where cooling rates are slower, and were observed more frequently in the X70 steel. The TiN remains undissolved during subsequent reheating at ~1250°C.

Large TiN precipitates (0.1-1.0 μm). These particles, like the ones described above, were primarily cuboidal in shape and were identified as TiN, with smaller amounts of Nb. The main difference, other than size, is the absence of an inclusion at the core. Two TiN particles are shown in Fig. 9, along with a corresponding SAD pattern. The crystal structure corresponds to the NaCl-type and is isostructural with NbN, TiC and NbC as mentioned previously. Niobium can substitute for Ti and likely does so after initial precipitation, either during cooling after casting or during reheating. These 'large' precipitates are considered separately from the previously discussed TiN particles (2-10 μm), as they come out of solution at a different stage during steel processing. The very large TiN particles precipitate during casting, nucleating on inclusions, while the large TiN particles precipitate during cooling through the austenite range and remain insoluble during subsequent reheating. Austenite grain boundaries act as heterogeneous nucleation sites for TiN, and TiN helps to restrict austenite grain growth during reheating.

In the X80 steel, many of the TiN particles served as nucleation sites for Nb-Ti carbonitrides (Fig. 10). Nb-Ti carbonitrides tended to be more irregular in shape and are discussed in the next section.

Nb-rich irregularly shaped particles (30-50 nm). This class of precipitates was mostly rounded and consisted mainly of Nb with smaller amounts of Ti. These were present throughout the ferritic grains in both X70 and X80 steels; specific examples are shown in Figs. 10 and 11. The crystal structure is also NaCl-type. The precipitates come out by a 'strain induced precipitation' mechanism and act to pin austenite grain boundaries. When the plate is deformed in the 800-1000°C range, large numbers of dislocations and strain bands are created within the microstructure. These provide heterogeneous sites for nucleation of precipitates [23]. In this temperature range, most of the Ti has already precipitated out of solution and there is strong driving force for Nb precipitation, based on solubility data for NbC and NbN [14,24]. This accounts for the high Nb content relative to Ti. The large TiN particles can also serve as nucleation sites, as shown in Fig. 10 where rounded Nb-rich carbonitride particles have grown on existing TiN particles. The growth is epitaxial, as indicated in the accompanying diffraction pattern, where a single pattern has been obtained from the 2 particles. There is spot splitting in the diffraction pattern (indicated by the arrow in Fig. 10), due to the small difference in lattice parameters for TiN and Nb-rich carbonitride.

The particles were larger and more numerous in the X80 steel compared with the X70 steel; the average size was closer to 50 nm for X80 and 20-30 nm for X70. The higher Nb levels in X80 steel, relative to X70, would result in precipitation at higher temperatures, since the solubility product is exceeded at higher temperatures, which would account for the increased nucleation and growth.

Small spherical precipitates (<20 nm). These were present throughout the grains and were quite small (<20 nm), with the majority in the 10-20 nm size range. TEM dark field images, taken from a thin foil specimen (Fig. 12) and a carbon replica specimen (Fig. 13), show the size and distribution. The strain induced precipitates are also visible in Fig. 13 and are indicated. EDX analysis indicated that they were either NbC or Nb carbonitrides. The presence of N was difficult to discern as the N peak in the EDX spectra was masked by the large C peak arising from the C support film. Molybdenum was also present in the precipitates of both steels, with a higher incidence in the X80 steel which can be attributed to its higher Mo levels. Molybdenum can partially substitute for Nb in the precipitates forming (Nb,Mo)(N,C); however, Mo levels are likely not high enough to significantly affect the amount of precipitation hardening [25,26]. MoC can form in higher Mo steels (>0.5 wt%), but was not detected in the studied steels. Precipitation occurs during the austenite to ferrite transformation and can be attributed to the approximately order of magnitude drop in solubility across the γ→α interface. The precipitates often appear as rows or sheets (Fig. 12 and 13), which are proposed to form during ledge growth of ferrite [27]. Overall, the precipitates were less numerous, by a factor of about 2, in the X80 steel compared with the X70 steel. The higher levels of Nb and Mo in X80 (compared with X70) should lower the γ→α transformation temperature and therefore decrease the particle size, which is contrary to experimental observation. It should be noted, however, that the precipitates counted included the smallest ones, which are discussed in the next section, making interpretation of the data difficult.
The diffraction pattern in Fig. 12b indicates that there is an orientation relationship between the particles and the ferrite matrix. The more intense spots in the pattern are from ferrite ([012] zone axis), while the extra spots near the centre are from the particles – the DF image in Fig. 12a was taken using one of the extra spots. The following orientation dependence was determined, assuming a NaCl-type structure for the precipitates.

[110] precipitate || [012] ferrite

Very small precipitates (<5nm). In addition to the 4 major types of precipitates already discussed, some very small (<5nm) precipitates were detected in both X70 and X80 steels (Fig. 11 and Fig. 14). The precipitates form during the later stages of processing when the strip is being cooled at temperatures <600°C. At this temperature virtually all the Ti has been depleted, and the Nb precipitates out with C and N by nucleating on dislocations (Fig. 15) and at the grain boundaries. These finely dispersed precipitates contribute to precipitation strengthening in these steels. The X80 steel was cooled at a higher temperature (about 40°C higher), which could partially account for the apparent contradictory densities (cited above) obtained for particles <20 nm in size. The higher cooling temperature may have resulted in particle coarsening.

The combination of good strength and fracture toughness (Table 2) exhibited by both the X70 and X80 steels can be attributed to the fine ferritic/bainitic structure that arises as a result of the thermomechanical processing. Grain size control is the only strengthening mechanism to provide an improvement in both strengthening and toughness. Additional strengthening is provided through precipitation hardening during cooling. The difference in mechanical properties between the X70 and X80 steels – X80 steel has a higher yield strength, but significantly lower toughness than X70 steel – can be attributed to the difference in precipitate morphology as well as the relative amount of bainitic ferrite in both steels. The coarser Nb carbonitrides in X80 steel adversely affect toughness as the higher dislocation density present in bainitic ferrite relative to acicular ferrite. The higher incidence of bainitic ferrite in X80 steel, due to the higher alloy content, does improve the strength, however. It should be emphasized that, although the fracture toughness of X80 steel is lower than its X70 counterpart, the fracture toughness of X80 steel is still remarkably high.

CONCLUSIONS
X70 and X80 microalloyed pipeline steels have been characterized in terms of constituent phases, distribution of alloying elements, inclusion composition and morphology and the various kinds of precipitates present within the microstructure. Both kinds of steels had similar microstructural constituents, however, some differences were apparent. These could be traced to differences in their chemical composition and their particular processing schedules.

The matrix was composed primarily of acicular ferrite and bainitic ferrite grains, with high dislocation densities. The X80 steel had a larger fraction of acicular grains, which can be attributed to the higher alloy content (Nb and Mo) in the X80 steel. Both X70 and X80 showed coarser microstructures near the centerline of the plate, as well as segregation effects, particularly for the X70 steel. The inclusions were composed mainly of Ca and S, with significant quantities of Al, O, Fe and Mn. The inclusions were rounded with small distortions, which were slightly more pronounced in X70 steel, along and across the rolling direction. Five types of precipitates were identified in both steels.

ACKNOWLEDGEMENTS
The authors wish to thank the Natural Sciences and Engineering Research Council (NSERC) of Canada and IPSCO, Inc. for providing financial support and for providing steel samples (IPSCO).

REFERENCES
Welded Structural Steels”, Microscopy: Materials and Techniques, Institute of Metals and Materials, Australia, pp. 49-54.


Figure 1 Optical micrographs from X70 and X80 steels taken along the rolling direction, near the centreline (a) and near the surface (b).

Figure 2 Optical micrographs from X70 (a) and X80 (b) steels taken along the rolling direction at the centreline, showing solute segregation effects.

Figure 3 Optical micrographs from X70 and X80 steels, etched with La Pera’s etchant, taken along the rolling direction, at the centreline (a) and near the surface (b).

Figure 4 Optical micrograph from X70 steel showing inclusions. Also shown is an EDX spectrum from an inclusion.
Figure 6  a) TEM bright field (BF) image from X70 steel showing bainitic ferrite grains. b) SAD pattern from boundary region between grains 1 and 2. The grains are both close to a $\langle 111 \rangle$ orientation.

Figure 7 TEM BF image from X70 steel, showing acicular ferrite. Also shown are SAD patterns taken from 2 locations. All patterns are close to a $\langle 111 \rangle$ orientation.

Figure 8 TEM BF image from X70 steel (a), showing an austenite grain (2) surrounded by ferrite (1). The SAD pattern in (b) is from grains 1 and 2.
Figure 9 TEM BF image of a replica taken from an X70 steel, showing large TiN particles. An SAD pattern from the larger particle is also shown ([100] zone axis).

Figure 10 TEM BF micrograph of an extraction replica taken from X80 steel. An SAD pattern from the two overlapping particles is also shown ([114] zone axis).

Figure 11 TEM BF image from X70 steel (replica) showing an irregularly shaped Nb-rich carbonitride and very fine carbonitrides.

Figure 12 a) TEM DF image of fine particles taken from a thin foil of X70 steel. b) SAD pattern from the centre ferrite grain in (a), showing extra spots near the central spot.

Figure 13 TEM dark DF image of precipitates taken from X70 steel.

Figure 14 TEM BF image from a thin foil sample showing very fine particles precipitated on dislocations.