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INTRODUCTION

The Association of American Railroads (AAR) Tank Car Committee recently asked the RPI (Research Progress Institute)-AAR Tank Car Safety Project to investigate the properties of micro-alloyed steels and the potential for using them as replacements for conventional tank car steels. An extensive test program was conducted by the RPI-AAR to identify candidate new steels. It was concluded the control-rolled steels of the Cb-V type showed superior weldability and improved toughness at low temperatures. Hence, specifications were developed for these micro-alloyed steels, and material was prepared and tested by members of the RPI-AAR Tank Car Committee.

In conjunction with the RPI-AAR research, the Mechanical Properties and Performance Group of the National Institute of Standards and Technology, (NIST, formerly the National Bureau of Standards) was asked by Ms. Claire Orth, Chief of the Safety Research Division of the FRA, to develop, in addition to the AAR's Tank Car Committee, a mechanical property and fracture toughness data base for a newly developed, control-rolled, micro-alloyed Cb-V steel, A 8XX grade B. A similar data base was requested for normalized AAR TC128 grade B steel which is currently used in the manufacture of all new tank cars.

EXPERIMENTAL PROCEDURE

In order to test comparable material, Mr. T.H. Dalrymple, Chief Engineer of the Union Tank Car Company (UTC) and a member of the Tank Car Safety Committee, obtained for NIST four plates of the micro-alloyed, control-rolled A 8XX grade B steel similar to that used in their research program. UTC also furnished NIST four plates of the normalized AAR TC128 grade B steel similar to that which was required for tank car construction as of January 1, 1989. The UTC purchase order to the Bethlehem Steel Company for the steel is shown in Appendix A1.

There were eight plates of steel received at NIST. Four plates were AAR TC128 grade B steel taken from heat number 803A66600, and four plates were A 8XX grade B steel taken from heat number 803A71430. A representative specimen used for the determination of chemical composition of each heat of steel was sectioned from the as-received plates. Microscopic examinations were conducted on all of the as-received plates in order to determine the as-polished and etched microstructures. These same samples were used to determine each steel's ferrite/pearlite grain size and the primary rolling direction of each plate.

Coupons representing both the ASTM LT and TL orientations (see Appendix 2 for test specimen orientation diagram) were sectioned from both steels and used for the preparation of mechanical property and fracture toughness specimens. In the ASTM LT orientation (conventionally referred to as "longitudinal" specimens), the long axis of the specimen is parallel to the rolling direction, and in the TL orientation (conventionally referred to as "transverse" specimens), the long axis of the specimen is perpendicular to the rolling direction. Because of limited plate thickness (plates were 9/16 inch thick), standard tensile test specimens, 1/4 inch in diameter with a gage length of one inch, were prepared according to ASTM designation A370-88. Duplicate tensile tests, for both the LT and TL orientations, were conducted at temperatures from -60°F to +73°F. Charpy V-notch impact (CVN) specimens were prepared from both the LT and TL orientations and tested according to ASTM designation E23-88. Duplicate CVN impact tests were conducted at temperatures from -73°F to +71°F. J-integral test specimens, 1T-(full plate thickness), were prepared according to ASTM designation E813-88 and tested at temperatures from -63°F to +73°F. Nil-ductility transition temperature test specimens were prepared according to ASTM designation E208-87. Crack-tip opening displacement (CTOD) specimens were also prepared according to ASTM designation E1290-89 and tested at temperatures from -80°F to +73°F.

<u>Steels received for mechanical property and fracture toughness tests</u>

The Report of Test and Analyses as supplied by the Bethlehem Steel Corporation's Quality Assurance Department is shown in Appendix 3. Included in the test report, along with mill particulars, are the room temperature tensile properties, and the longitudinal (L) impact properties at -50°F. The chemical composition of each steel is also shown.

For identification purposes, the control-rolled A 8XX grade B steel plates with Bethlehem heat number 803A71430 stenciled on them were labeled A, B, C, and D, and the normalized AAR TC128 grade B steel plates with Bethlehem heat number 803A66600 stenciled on them were labeled E, F, G, and H. The heat and check chemical analyses for each heat of steel, plates A and E, as determined by NIST and the Bethlehem Steel Corporation, along with the AAR chemical composition requirements for each steel, are shown in Table 1.

The chemical composition determinations, in particular the low sulfur contents and the presence of calcium, revealed that both of these steels were made using inclusion shape control practice (1). In conventionally processed steels, the sulfide inclusions are elongated in shape. However, if the final sulfur is 0.010 weight percent or less, the steel was probably desulfurized either in the hot-metal stage or by using steel-ladle metallurgy techniques. The desulfurization by Ca-Si injection usually leads to low sulfur and round inclusions. These round inclusions have a significant effect on the isotropy of the impact properties of the steel. The presence of the low sulfur and the calcium suggested that the AAR TC128 grade B steel was made using inclusion shape control practice and may have better notch toughness than the steel normally used in the manufacture of tank cars. Similar chemical composition determinations, i.e., the presence of calcium and low sulfur, were obtained for the A 8XX grade B steel. These results suggest that this steel was also made using inclusion shape control practice.

MICROSCOPIC EXAMINATIONS

As-polished microstructures of the A 8XX and AAR TC128 steels

Figure 1 shows comparative photomicrographs of typical manganese inclusions observed in a conventional steel and the complex Ca-S-Al-O non-metallic inclusions (2) observed in the steels examined in our study and normally observed in Ca-treated steels. In the conventional steel, figure 1a, the inclusions are elongated in the rolling direction, whereas in the A 8XX and AAR TC128 steels, figures 1b and 1c, respectively, the inclusions are round in shape. The rolling direction is shown by the arrow in each photomicrograph.

Etched microstructures of the A 8XX and AAR TC128 steels

Figure 2 shows the etched microstructures observed in three orthogonal directions for both the A 8XX, plate A, and AAR TC128, plate E, steels. Both microstructures are composed of ferrite plus pearlite. The dark constituent in the photomicrographs is the pearlite, and the light area the ferrite. The pearlite observed in the A 8XX steel is larger and coarser than that observed in the AAR TC128 steel. The ferrite grain size observed in the AAR TC128 steel, figure 2b, appears to be finer than that observed in the A 8XX steel, figure 2a. Microscopic examinations of plates B,C, and D, which were also A 8XX steel in the etched condition, revealed that their microstructures were similar to that observed in plate A. Similar microscopic examinations were conducted on plates F, G, and H, which were AAR TC128 steel, in the etched condition. The results revealed that their microstructures were similar to that observed in plate E.

ASTM grain size determinations

The ferrite/pearlite grain size was determined for the two steels using ASTM designation E112-88. The procedure followed is called the planimetric or Jeffries' method, and the higher the grain size number, the finer the ferrite grain size. In this method a rectangle of known area was inscribed on the photomicrograph, and a magnification was selected that gave at least 50 grains per field to be counted. Two measurements made by one observer on the A 8XX resulted in an average ferrite/pearlite ASTM grain size number of 9.5 (average grain diameter 13μm). The measurement made by another observer resulted in a grain size value 10.5 (9.4μm) for this steel. Similar grain size measurements made on the AAR TC128 steel resulted in a slightly smaller grain size number of 10 (11μm) for two observations by one observer, and a value 11 (8μm) for a second observer.

MECHANICAL PROPERTY AND FRACTURE TOUGHNESS TEST RESULTS

Tensile test results

Tables 2 and 3 show the tensile test results for the AAR TC128 steel, and tables 4 and 5 show the tensile test results for the A 8XX steel, for both the TL and LT orientations. Figure 3 shows plots of the ultimate tensile and the 0.2% offset yield strengths for these steels as tested in both orientations. The yield strengths of both steels decresed slightly from -60°F to room temperature. However, as expected, the yield strength of the control-rolled A 8XX is higher than the yield strength of the AAR TC128 grade B steel over the test temperature range. The average yield strengths (from -60°F to +73°F) of specimens taken from the A 8XX steel and tested in both the LT and TL orientations was 75.3 ksi. These yield strengths were above the minimum room temperature yield strength of 60 ksi as specified by RPI-AAR. The average yield strengths (from -60°F to +73°F) for specimens taken from the AAR TC128 grade B steel and tested in both the LT and TL orientations were also essentially the same, 61.4 and 61.5 ksi, respectively. These yield strengths were above the minimum, 50 ksi at room temperature, as stated by the AAR in section M128.05 of the Manual of Standards and Recommended Practices, Specifications for Tank Cars.

The average ultimate tensile strengths for the A 8XX grade B steel specimens taken from the LT and TL orientations, and tested from -60°F to +73°F, were 100.1 and 98.6 ksi, respectively. The specification for grade B of this experimental steel requires the tensile strength to be between 80 and 100 ksi. The average ultimate tensile strengths for the normalized AAR TC128 grade B steel specimens taken from the LT and TL orientations, and tested from -60°F to +73°F, were 86.8 and 87.5 ksi respectively. The specification for grade B of this steel requires the tensile strength to be between 81 and 101 ksi.

Average reduction in area measurements for the AAR TC128 grade B steel specimens taken from both the LT and TL orientations and tested from -60°F to +73°F were 69.4% and 71.3%, respectively. Average elongations in one inch for similar test conditions were 34.0% and 33.8% respectively. Average reduction in area measurements for the A 8XX grade B steel specimens taken from both the LT and TL orientations and tested from -60°F to +73°F were 72.3% and 71.3% respectively. Average elongations in one inch for similar test conditions were 30.0% and 31.3% respectively. The A 8XX grade B specification requires a minimum elongation in 8 inches of 15%, and 20% in 2 inches. The specification for the AAR TC128 grade B steel requires an a minimum elongation of 16% in 8 inches, and 22% for 2 inches. There is no requirement in either steel specification for a minimum in the reduction in area.

Impact test results

Tables 6 and 7 show the impact test results for the AAR TC128 grade B steel for both the ASTM TL and LT orientations, respectively. The energy absorbed and lateral expansion were plotted as a function of test temperature, and figure 4 shows these test results. When AAR TC128 grade B steel is specified for low temperature service the material must be furnished normalized to meet the CVN energy absorption requirements of 15 ft-lb minimum average of three specimens and 10 ft-lb minimum for one specimen at -50°F in the longitudinal direction of rolling, i.e., ASTM LT orientation. The average energy absorbed for specimens tested in the LT orientation at -50°F was 46 ft-lb, and the lateral expansion was 60.5 mils. For CVN specimens taken from the ASTM TL orientation and tested at -50°F, the average energy absorbed was 42 ft-lb and the lateral expansion 51 mils.

Tables 8 and 9 show the impact test results for the A 8XX steel for both the ASTM TL and LT orientations, respectively. The energy absorbed and lateral expansion were plotted as a function of test temperature, and figure 5 shows these test results. The average energy absorbed for specimens tested in the ASTM LT orientation at -50°F was 12 ft-lb, and the lateral expansion 36 mils. For CVN specimens taken from the ASTM TL orientation and tested at -50°F, the average energy absorbed was 28 ft-lb and the lateral expansion 47 mils. The impact test results show that at low test temperatures, i.e., from -70°F to about -22°F, the impact properties of the normalized and inclusion shape controlled AAR TC128 grade B steel were better than those obtained for the control-rolled and inclusion shape controlled A 8XX grade B steel.

Nil-ductility transition (NDT) temperature results

The method followed is specified in ASTM designation E 208-87. This test was conducted to determine the nil-ductility transition temperature for the AAR TC128 grade B and A 8XX steels examined in this study. The drop-weight test employs simple beam specimens specially prepared to create a material crack in the tensile surface of the specimen at an early time interval of the test. The test is conducted by subjecting each of a series of specimens of a given material to a single specified impact load at a sequence of selected temperatures to determine the maximum temperature at which a specimen fractures in a cleavage or brittle-like manner. Tables 10 and 11 show the NDT test results for steels AAR TC128 and A 8XX, respectively. The NDT temperature for the AAR TC128 grade B steel was found to be -40°F and the NDT temperature for the A 8XX steel was -10°F.

J-integral test results

The single specimen, compliance method was used to determine the J_{Ic}. The test method defined by the ASTM in designation E 813-88 covers the determination of J_{Ic} which can be used as an engineering estimate of fracture toughness near the initiation of slow stable crack growth for metallic materials. This type of fracture usually occurs in the transition and upper shelf regions of the normal "S" type Charpy impact curve. Two primary requisites for a valid J_{Ic} is that there is slow stable crack growth, i.e., no rapid cleavage fracture upon loading of the test specimen, and the test specimen be of a certain thickness.

In the test method a curve is developed when the initially fatigue cracked specimen, 1T (i.e., full plate thickness) is loaded to a predetermined load and then unloaded. Crack growth measurements are determined using compliance techniques. The specimen is then repeatedly loaded and unloaded, each time measuring the increase in stable crack growth. A plot of J, the area under the curve developed at each loading increment, versus Δa (change in crack length), is plotted and the J_{Ic}, the fracture toughness near the initiation of slow stable crack growth, is determined according to ASTM specification E 813-88. J-integral tests were conducted on both of the steels from -63°F to room temperature. The J values for the AAR TC128 and A 8XX steel specimens and their corresponding fracture toughness, K, calculated using appropriate equations, are shown in Tables 12 and 13 respectively.

In order to obtain a valid J_{Ic}, i.e., a measure of the energy per unit area needed to initiate stable crack growth, certain criteria enumerated in ASTM E813-88 must be met. In the J testing of the AAR TC128 grade B specimens, there was stable crack growth and a J_{Ic} was obtained for some specimens. In some instances, only the J_{max} was obtained. However, the specimen thickness B must be greater than or equal to $25 \cdot J_Q/\sigma_y$. This was not met for any of the specimens and therefore a valid J_{Ic} was not determined.

In general, in plane-strain plasticity, the strain rate is proportional to the stress and there are three principal stresses operating at the crack tip. These stresses are defined as σ_1, σ_2, and σ_3, but strain rate on ϵ_3 axis is equal to 0. In plane-stress plasticity theory, one of the principal stresses, $\sigma_3 = 0$ and the strain rate on the ϵ_3 axis $\neq 0$. It is generally recognized that plane-stress conditions exist in thin bodies and plane-strain conditions in thick bodies. Since the test specimens used in our study lacked sufficient thickness in order to meet plane-strain conditions, the equation applicable to plane-stress conditions was used to calculate the fracture toughness. For comparison purposes, the plane-strain fracture toughness is also shown.

Table 12 shows the experimentally obtained J values and corresponding plane-stress and plane-strain fracture toughness values calculated using the appropriate equations. The results indicate that the normalized and inclusion shape controlled AAR TC128 grade B steel at test temperatures from -63°F to +78°F was exceptionally resistant to crack initiation.

Similar 1T compact tension tests were conducted on the A 8XX steel at temperatures from -60°F to +73°F. Unlike the AAR TC128 grade B steel, unstable cleavage fracture was observed for these specimens when they were tested at -60°F, -40°F, and -20°F. At test temperatures of 0°F and +8°F there was some stable crack growth, but it was followed by unstable cleavage fracture. Only at +20°F and +73°F was there stable crack growth during the entire test. For those specimens that failed in an unstable manner, the load corresponding to the load at the initiation of rapid fracture was used to calculate J. Table 13 shows the results of these calculations. The J and corresponding plane-stress and plane-strain fracture toughness values at test temperatures from -60°F to 0°F were somewhat lower than those obtained for the AAR TC128 grade B steel.

<u>CTOD test results</u>

Due to the exceptional resistance to crack growth observed for the AAR TC128 grade B steel, crack-tip opening displacement (CTOD) tests, as designated in

ASTM E 1290-89, were conducted on the steel. In addition, CTOD tests were also conducted on the A 8XX steel. The CTOD fracture toughness test method covers the determination of the critical CTOD values at one or more of several crack extension events. These CTOD values can be used as measures of fracture toughness for metallic materials, and are appropriate for materials that exhibit a change from ductile to brittle behavior with decreasing temperature. This test method may be used to characterize the fracture toughness of materials with specimens that are too ductile or lack sufficient size to be tested for the plain-strain fracture toughness K_{Ic}, or show a propensity for <u>unstable</u> crack extension that would that would prevent the determination of a J_{Ic}.

Figures 6a and 6b show copies of the CTOD load/displacement traces obtained at the test temperature of about -80°F for representative specimens of both the A 8XX steel and AAR TC128 grade B steels respectively. In figure 6a, the load trace for the A 8XX steel is shown to abruptly drop, indicative of unstable fracture. Examination of the fracture surface, figure 7a, revealed that the mode of failure was primarily cleavage in nature. Further CTOD testing of this steel at temperatures of -60°F, -40°F, and -20°F led to similar results; i.e., unstable fracture with the mode of fracture entirely cleavage in nature. Additional tests designed to evaluate the plane-strain fracture toughness value K_{Ic} indicated that a test temperature lower than -80°F was needed in order to obtain a valid K_{Ic} according to ASTM designation E399.

In figure 6b, the load/displacement trace for the CTOD test for the AAR TC128 grade B steel tested at -82°F is shown. The load trace does not abruptly decrease as was observed for the A 8XX steel, but continues with an increasing amount of displacement until fracture occurs from overload. Additional tests were conducted at -40°F, and the results were similar to those obtained at -80°F. Examination of the fracture surface, figure 7b, for the specimen tested at -80°F, indicated that the fracture was entirely ductile in appearance with regions of dimples dispersed throughout.

Table 14 shows a comparison of the fracture toughness for the two steels using only the CTOD test results. Included in the table are the plane-stress and plane-stain fracture toughness values determined using the CTOD value obtained at the respective temperature. Noteworthy in the table is the variation in fracture toughness within test temperatures for each steel. The fracture toughness results indicate that there is less variability among the fracture toughness test results for the AAR TC128 grade B steel than among similar results for the A 8XX steel.

Tables 15 and 16 show comparisons of the fracture toughness results using CT and CTOD test results for the AAR TC128 and A 8XX steels. The results show that more consistent, i.e., less scatter within a test temperature, CT or CTOD fracture toughness results were obtained for the AAR TC128 steel than for the A 8XX steel.

<u>DISCUSSION</u>

Today there are many steels available for the consumer; each one is characterized by a particular trade name and composition. Tetelman (3) suggests that although quantitative values of fracture toughness parameters such as NDT and K_{Ic} would help in the selection of a steel for an application, these parameters are available for only a few of these steels, and the reason for this is two-fold. First, because a wide range of microstructures can be obtained in a steel of a given alloy composition just by varying the thermomechanical treatment, and secondly because the concentration of fabrication defects, for example blow holes and inclusions, is extremely dependent upon mill practice and often varies between heats of steel of the same composition or even between different areas of the billet. Tetelman has stated that since it is microstructure and defect concentration that primarily determine toughness rather than composition, per se, a large variation in toughness can be produced in a given steel simply by varying the thermomechanical treatment and fabrication practice. Our work on the two steels presented in this report corroborated his findings. We determined that the primary reason for the difference in notch toughness properties of these two steels was that the ferrite/pearlite grain size of the normalized and inclusion shape controlled AAR TC128 grade B steel was more uniform and finer than that of the control-rolled and inclusion shape controlled A 8XX steel.

In the first phase of the investigation, the chemical compositions of the as-received steel plates were determined in order to establish whether they met composition requirements. The chemical analysis results for the normalized AAR TC128 grade B steel indicated that the composition was within the allowable limits; however, the particularly low sulfur content, as compared to conventional steels, and the presence of calcium, indicated that it was not the conventional type of normalized AAR TC128 grade B steel that was used in the manufacture of tank cars as of January 1, 1989. The chemical composition of the A 8XX steel was also within the allowable limits defined by the RPI-AAR Tank Car Committee and similar to that for the steel the Committee was evaluating in its program. The sulfur content in the A 8XX steel was quite low, and the presence of calcium suggested that this steel was also made using the inclusion shape control process.

In addition to the steel being normalized (which is now required), a ladle refining procedure was used to reduce the sulfur content to where it was substantially lower than that found in conventional steels. The refining process also changed the shape of the inclusions from where they are normally elongated in the direction of primary rolling to spherical. The combination of the normalizing heat treatment and the spheroidizing of the inclusions enhanced the fracture toughness properties of AAR TC128 grade B steel. The normalizing heat treatment produced a fine, uniform ferrite/pearlite microstructure. The rounded inclusions led to enhanced impact and fracture toughness properties by increasing the resistance to crack growth.

Prior to the sectioning of the test coupons, the rolling direction was determined for each plate. Due to material anisotropy, which is primarily the result of inclusion orientation and size within the plate, it is important in the test program that specimens be taken from both the ASTM LT and TL orientations (see Appendix 2). In the ASTM LT orientation, the long axis of the specimen and the inclusions are both parallel to the rolling direction. In the ASTM TL orientation, the long axis of the specimen is perpendicular to the rolling direction and the inclusions are normally much shorter in length. Mechanical test results, in particular the impact results, clearly show a difference between the impact properties for those specimens from the LT orientation as compared to those from the TL orientation. The energy absorbed values for the LT specimens are normally greater than the energy absorbed values for the impact specimens tested from the TL orientation.

Microscopic examinations of the as polished metallographic surfaces in three orthogonal directions were conducted on both of these steels to determine the rolling direction of each steel. In conventional steels the inclusions are elongated in shape as shown in a photomicrograph, figure 1a, of a conventional steel. However, photomicrographs taken of the A 8XX and AAR TC128 steels in the as-polished condition, figures 1b and 1c respectively, revealed that the inclusions in both of these steels were round in shape. The appearance of deformed inclusions, figure 1c, with projections extending in the direction of primary deformation reinforced our views that this was the primary direction that the AAR TC128 grade B steel was rolled. This direction corresponded to the ASTM LT orientation. The determination of the rolling direction for the control-rolled A 8XX steel was more difficult. The inclusions were similar in appearance, round, to those observed for the AAR TC128 grade B steel. However, the characteristic rupturing of the inclusion's surface in the direction of primary deformation was not observed in these inclusions, see figure 1b. An extensive microscopic examination of the as-polished surface of an A 8XX specimen in the three orthogonal directions revealed the presence of minute inclusions that were elongated in one direction. Further examination of the specimen revealed that the inclusions were similar in length in all orientations examined. A consensus of observers concluded that the direction shown in figure 1b was the primary rolling direction, the ASTM LT orientation, of the A 8XX plate. The difficulty in establishing a pronounced rolling direction for the A 8XX steel clearly indicates that orientation effect is of minimal consequence for this steel.

The as-polished specimens from each steel were etched to reveal their microstructures. Figures 2a and 2b show the etched microstructures for both the A 8XX and AAR TC128 steels, respectively. The microstructure of the A 8XX steel consists of layers of ferrite, light grey constituent, with regions of pearlite, dark phase, dispersed throughout. The microstructure present in the AAR TC128 steel is somewhat different than that observed for the A 8XX steel. The ferrite is more uniform in appearance because the steel had been subjected to a heat treatment that normalizes (i.e., makes the microstructure more uniform in size) the steel.

The size of the ferrite grains, i.e., the microstructure, has a significant effect on the resultant toughness of the steel. Hence the ferrite/pearlite grain size was determined for both of these steels. Grain size measurement revealed that the normalized AAR TC1218 grade B steel has a finer grain size than the control-rolled A 8XX steel. This was not expected since the literature (1) shows that normally control-rolled steels have grain sizes of $\approx$ 4 microns or less; ASTM equivalent number $\geq$12.5. The size of the pearlite observed in the A 8XX steel appears to be larger than that observed in the AAR TC128 steel. This may be because the control-rolled A 8XX steel was finished at a higher than normal temperature.

Abrams and Slimmon (4) have stated that grain refinement is the most effective means of increasing strength as well as improving the notch toughness of the HSLA steel family of which the steel A 8XX evaluated here is a member. They have stated that a fine ferrite grain size contributes to strengthening by the well known Hall-Petch relationship. In addition to the strengthening due to the fine ferrite grain size, they have reported that for this type of steel, precipitation hardening and to some degree substructure development also have an effect. In our investigation, the yield strength was found to be greater for the A 8XX steel than for the AAR TC128 grade B steel, and this difference was attributed primarily to the precipitation hardening and substructure development rather than grain refinement.

Microscopic examinations of the grain size of the A 8XX steel showed that it is not as fine as expected in a normal controlled-rolled steel and there was essentially a duplex ferrite microstructure. This duplex ferrite microstructure, as reported by Abrams and Roe (5), causes a decrease in notch toughness when compared to a uniform, fine-grained ferrite microstructure.

Figures 8a and 8b show a comparison of the energy absorbed as a function of test temperature for both steels taken from both the LT and TL orientations. For the AAR TC128 LT specimens tested at temperatures from -70°F to +20°F, the energy absorbed was higher than that for the A 8XX steel. For those specimens taken from the TL orientation, the energy absorbed for the AAR TC128 steel was greater than that for similar specimens taken from the A 8XX steel for all test temperatures. Similar trends were also found for the lateral expansion measurements for these two steels. Figures 9a and 9b show the lateral expansion results for both of the steels after testing in the LT and TL orientations.

The NDT temperature for the AAR TC128 grade B steel was found to be -40°F, and for the A 8XX steel, -10°F. At these temperatures, specimen size, and loading rate, fracture occurs entirely by cleavage and crack propagation is brittle. It is assumed in NDT design analysis that there is a flaw in the material, or a flaw develops in the material during its operating lifetime. Certain other design criteria have been established using the applied (σ) and yield (σ_y) stresses along with the flaw size to determine when unstable cleavage fracture could occur. Normally, unstable fracture cannot occur when the $\sigma \leq 0.5\sigma_y$ if the ambient temperature is greater than NDT+30°F; if $\sigma \leq \sigma_y$ and the temperature is greater than NDT+60°F; and if σ is less than the ultimate tensile stress at a temperature greater than NDT+120°F. However, when the applied stress is greater than the yield stress, as so often occurs in derailments, and the inherent flaw is of a sufficient size, unstable cleavage fracture could occur at any temperature. Regardless of the ambient temperature, these data indicate that there is a greater tendency for unstable cleavage fracture in the A 8XX steel than in the AAR TC128 grade B steel.

Similar results, unstable cleavage fracture, were observed for the A 8XX J-integral specimens when they were tested at -60°F, -40°F, and -20°F. At test temperatures of 0°F and 8°F there was some stable crack growth, but it was followed by unstable cleavage fracture. Only at test temperatures of +20°F and +73°F was there evidence of stable crack growth. Unstable cleavage fracture was not observed in any of the AAR TC128 grade B J-integral test specimens. This steel showed stable crack growth from -63°F to +73°F. Although the A 8XX steel specimens showed unstable fracture at the indicated temperatures, fracture toughness calculations, shown in Table 13, indicated that the steel possessed relatively good fracture toughness over the range of test temperatures. At -60°F, the plane-stress K was 65 ksi•in^{½}, while at +73°F it was 330 ksi•in^{½}. A simple calculation using both the yield strength and the stress intensity shows that at -60°F a crack length of 0.42 inch is needed to initiate unstable cleavage fracture in the A 8XX steel when the applied stress is equal to the yield strength. Using the same equation for the AAR TC128 grade B steel, a crack length of 13.5 inches is needed to initiate fracture with yield strength at the level of the applied stress. The significant differences between the crack sizes needed to initiate failure in each steel indicatess the superior notch toughness of the normalized and inclusion shape controlled AAR TC128 grade B steel as compared to the control-rolled and inclusion shape controlled A 8XX grade B steel.

The CTOD results gave similar results for the fracture toughness of both of these steels. Table 14 shows a comparison of the CTOD results and their corresponding fracture toughness values. It was shown that for the A 8XX steel, all of the specimens failed in an unstable brittle manner at all the test temperatures. Corresponding fracture toughness values were essentially similar to those obtained using the 1T compact tension J-integral test specimens. Increasing test temperatures yielded increasing fracture toughness values. The CTOD results for the AAR TC128 grade B steel showed that none of the specimens failed in an unstable manner. At the test temperature -82°F, the average plane-stress J was about 2272 in-lb/in^2 and the average plane-stress K 256 ksi•in^{½}, which are representative of a very tough steel.

Tables 15 and 16 show comparisons of the fracture toughness results for both steels using both the CTOD and J-integral data. Results for the AAR TC128 grade B steel (Table 15) show the exceptional toughness obtained for this steel when tested at -63°F and -40°F. The test data for the A 8XX steel, table 16, shows that this steel has a lower fracture toughness than the AAR TC128 steel.

Conclusions

The AAR TC128 grade B steel examined in this study was not typical of the conventional normalized AAR TC128 grade B steel that is currently used in the manufacture of all new tank cars. In addition to a normalizing heat treatment, the steel had been made using inclusion shape control practice. The practice is known to enhance the notch toughness properties of the steel.

Tensile tests conducted on the A 8XX steel from -60°F to room temperature indicated that the yield strength was on the average 10 ksi higher than the AAR TC128 grade B steel.

Microscopic examinations and grain size determinations were conducted on etched specimens. The ferrite/ pearlite grain size for the A 8XX steel was found to be coarser than that of the AAR TC128 grade B steel.

Impact tests conducted on specimens taken from the ASTM LT orientation in both steels and tested at temperatures from -70°F to +20°F revealed that the A 8XX grade B steel had lower impact strength compared to the AAR TC128 grade B steel. The lower shelf energy, or the minimum energy absorbed, for the ASTM LT orientation AAR TC128 grade B test specimens was about 46 ft-lb, whereas the lower shelf energy for similarly oriented A 8XX specimens was about 10 ft-lb.

Fracture toughness tests, both CTOD and J-integral, conducted on the normalized and inclusion shape controlled AAR TC128 grade B steel from -80°F to +73°F revealed that the steel did not fail in an unstable manner, even at a test temperature of -80°F.

Fracture toughness tests conducted on the A 8XX steel showed that the toughness was much lower than that of the AAR TC128 grade B steel. At -80°F, -40°F, and -20°F, J-integral test results showed that the specimens failed in an unstable brittle manner, and the fracture appearance was cleavage. CTOD tests on the same steel showed unstable fracture over the entire test temperature range, -80°F to +20°F.

NDT determinations conducted on both of these steels indicated that the A 8XX steel (NDT -10°F) lacked notch toughness as compared to the AAR TC128 grade B steel(NDT -40°F).

The improved fracture toughness of the normalized and inclusion shape controlled AAR TC128 grade B steel as compared to the control-rolled and inclusion shape controlled A 8XX steel was probably due to the uniform ferrite/pearlite grain size of the AAR TC128 grade B steel, and that it was made using inclusion shape control practice.

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2) Wilson, A.D., "Characterizing Inclusions Shape Control in Low Sulfur C-Mn-Cb Steels," HSLA Steels-Technology and Applications, Conference Proceedings, ASM, (1984).

3) Tetelman, A. S., and McEvily, A. J.,"Fracture of Structural Materials," John Wiley & Sons Inc., pp. 493-533, 1967.

4) Abrams, H., and Slimmon, P.R., Development and Properties of Bethstar 80, a New 80 Ksi Yield Strength HSLA Plate, SAE Technical Paper Series, Paper Number 820486, February 22, 1982.

5) Abrams, H., and Roe, G. J., "Optimization of Processing, Properties, and Service Performance through Microstructural Control," ASTM STP 672, pp. 73-104, 1979.

Table 1. Chemical Composition (Wt%), the AAR Specifications, and Heat Analyses for both Steels.

	AAR TC128 grade B			A 8XX grade B		
	Specification[1]	Heat Analysis[2]	Check Analysis[3]	Specification[4]	Heat Analysis[2]	Check Analysis[3]
Carbon	0.25 max	.22	.19	0.16 max	.15	.15
Manganese	1.0-1.50	1.25	1.15	1.0-1.75	1.49	1.44
Phosphorus	0.035 max	.024	.015	0.035 max	.016	.018
Sulfur	0.040 max	.007	.009	0.010 max	.006	.007
Silicon	0.15-0.50	.213	.21	0.10-0.55	.277	.30
Nickel	0.25 max	.03	.01	NR	.03	.01
Chromium	0.25 max	.19	.21	NR	.04	.04
Molybdenum	0.08 max	.074	.07	NR	.011	.01
Copper	0.35 max	.017	.02	NR	.023	.03
Aluminum	NR[5]	.045	.059	NR	.054	.060
Niobium (Cb)	NR	NR	<.005	0.06 max[6]	.035	.039
Vanadium	0.08 max	.033	.032	0.11 max[6]	.075	.076
Nitrogen	NR	NR	.009	NR	NR	.014
Calcium	NR	NR	.005	NR	NR	.006
Titanium	NR	NR	<.005	NR	NR	<.005
C.E.[7]	0.62 max	.49	.45	0.47 max	.43	.42

1) AAR Specification for Tank Cars: Specification M-1002,M128.
2) Bethlehem Steel Corp.
3) NIST
4) Preliminary draft specification: A 8XX, Pressure vessel plates, high strength low alloy.
5) NR: Not reported
6) Niobium plus vanadium: 0.16 max
7) C.E. = Carbon Equivalent = C + Mn/6 + (Cr + Mo + V)/5 + (Cu +Ni)/15

Table 2. Tensile Test Results for AAR TC128 Grade B Steel. Specimens were Tested in the ASTM TL Orientation.

Specimen Number	Test Temp.°F	UTS (ksi)	YS(0.2%) (ksi)	RA %	EL(1") %	Flow Stress(ksi)
T1	73	83.2	60.6	70.8	32.5	71.9
T2	73	81.7	58.4	72.8	31.7	70.1
T13	40	82.9	58.6	70.0	35.5	70.8
T14	40	83.1	58.6	71.3	33.1	70.9
T11	20	85.3	58.9	70.7	32.5	72.1
T12	20	85.0	60.6	72.6	34.5	72.8
T9	0	88.1	61.1	72.9	34.9	74.6
T10	0	86.9	60.8	69.8	34.0	73.9
T7	-20	88.9	59.8	71.7	34.1	74.3
T8	-20	88.0	62.7	71.3	33.9	75.3
T5	-40	92.9	64.2	70.4	32.0	78.5
T6	-40	91.8	63.9	72.2	34.5	77.8
T3	-60	91.1	64.2	72.2	33.1	77.6
T4	-60	95.6	67.7	69.1	36.8	81.7

1) UTS: Ultimate tensile strength
2) YS: Yield strength
3) RA: Reduction in area
4) EL: Elongation in one inch
5) Flow Stress: (UTS + YS)/2

Table 3. Tensile Test Results for AAR TC128 Grade B Steel. Specimens were Tested in the ASTM LT Orientation.

Specimen Number	Test Temp. °F	UTS (ksi)	YS(0.2%) (ksi)	RA %	EL(1") %	Flow Stress(ksi)
T21	73	82.6	58.1	72.0	34.9	70.3
T22	73	82.3	56.7	69.3	34.9	69.5
T23	40	83.7	60.6	69.9	34.0	72.2
T30	40	83.8	59.1	68.5	32.9	71.4
T24	20	85.7	60.6	70.7	36.5	73.2
T31	20	85.9	61.1	69.2	34.4	73.5
T25	0	87.5	63.2	71.4	35.5	75.3
T32	0	86.4	60.6	66.3	34.6	73.5
T26	-20	88.6	62.1	71.4	34.0	75.4
T33	-20	88.4	63.2	69.5	35.2	75.8
T28	-40	89.4	65.0	69.2	33.8	77.2
T34	-40	89.0	62.1	68.3	30.0	75.6
T29	-60	90.8	62.9	67.7	32.8	76.9
T35	-60	91.0	63.7	67.3	31.6	77.3

1) UTS: Ultimate tensile strength
2) YS: Yield strength
3) RA: Reduction in area
4) EL: Elongation in one inch
5) Flow Stress: (UTS + YS)/2

Table 4. Tensile Test Results for A 8XX Grade B Steel. Specimens were Tested in the ASTM TL Orientation.

Specimen Number	Test Temp.°F	UTS (ksi)	YS(0.2%) (ksi)	RA %	EL(1") %	Flow Stress(ksi)
R1	73	94.2	71.2	71.0	33.6	82.7
R2	73	95.1	70.6	73.0	31.3	82.8
R3	40	96.1	73.7	75.7	31.8	84.9
R10	40	95.9	74.1	73.3	29.9	85.0
R4	20	96.7	72.0	67.9	32.8	84.4
R11	20	96.9	74.3	73.1	30.0	85.6
R9	0	98.6	73.0	74.3	31.5	85.8
R12	0	99.1	75.0	67.5	30.7	87.0
R6	-20	99.2	78.6	69.6	31.1	88.9
R13	-20	99.4	76.5	73.2	31.7	88.0
R7	-40	100.3	79.3	72.7	33.2	89.8
R14	-40	100.5	77.6	68.1	28.7	89.0
R8	-60	106.0	77.9	71.0	30.2	92.0
R15	-60	102.6	80.4	68.2	31.3	91.5

1) UTS: Ultimate tensile strength
2) YS: Yield strength
3) RA: Reduction in area
4) EL: Elongation in one inch
5) Flow Stress: (UTS + YS)/2

Table 5. Tensile Test Results for A 8XX Grade B Steel. Specimens were Tested in the ASTM LT Orientation.

Specimen Number	Test Temp.°F	UTS (ksi)	YS(0.2%) (ksi)	R_A %	EL(1") %	Flow Stress(ksi)
R22	73	96.3	70.6	74.8	30.2	83.4
R23	73	98.6	74.5	75.0	30.8	86.5
R24	40	97.3	71.9	74.6	30.6	84.6
R25	40	96.2	72.3	70.4	29.6	84.3
R26	20	99.7	72.9	71.1	28.9	86.3
R36	20	98.0	73.3	74.3	30.8	85.6
R28	0	99.5	75.0	72.4	29.1	87.2
R29	0	99.3	73.7	72.9	29.1	86.5
R30	-20	101.2	77.1	73.2	29.0	89.2
R31	-20	101.4	76.6	71.9	29.0	89.0
R32	-40	102.6	77.0	70.0	29.3	89.8
R33	-40	103.4	79.5	66.1	29.0	91.4
R34	-60	104.5	80.2	73.6	32.8	92.4
R35	-60	103.9	79.1	72.3	31.2	91.5

1) UTS: Ultimate tensile strength
2) YS: Yield strength
3) RA: Reduction in area
4) EL: Elongation in one inch
5) Flow Stress: (UTS + YS)/2

Table 6. Impact Test Results for AAR TC128 Grade B Steel. Specimens were Tested in the ASTM TL Orientation.

Specimen Number	Test Temperature, °F	Energy Absorbed, Ft-lb	Lateral Expansion, mils
T17	-70	40.0	54.0
T18	-70	42.0	56.0
T1	-50	47.5	47.5
T2	-50	36.0	54.5
T3	-22	52.0	66.4
T4	-22	59.0	70.5
T9	+19	73.0	70.0
T13	+19	77.0	83.0
T14	+46	106.0	89.5
T16	+46	109.0	106.0
T6	+72	107.0	106.0
T8	+72	110.0	106.5

Table 7. Impact Test Results for AAR TC128 Grade B Steel. Specimens were Tested in the ASTM LT Orientation.

Specimen Number	Test Temperature, °F	Energy Absorbed, Ft-lb	Lateral Expansion, mils
T47	-70	51.0	64.5
T51	-70	41.0	54.5
T30	-50	40.0	55.5
T31	-50	52.0	65.5
T37	-22	61.0	72.0
T38	-22	73.0	80.5
T42	+19	90.0	96.5
T44	+19	96.0	89.5
T45	+46	126.0	99.0
T46	+46	107.0	93.0
T52	+46	130.0	117.0
T39	+72	124.0	99.0
T40	+72	130.0	116.0

Table 8. Impact Test Results for A 8XX Grade B Steel. Specimens were Tested in the ASTM TL Orientation.

Specimen Number	Test Temperature, °F	Energy Absorbed, Ft-lb	Lateral Expansion, Mils
R1	-73	10.0	31.5
R2	-73	11.0	34.0
R3	-50	14.0	35.0
R4	-50	33.0	51.5
R7	-50	38.0	54.5
R5	-25	48.0	66.5
R6	-25	36.0	55.5
R8	+1	61.0	76.5
R9	+1	59.0	72.0
R10	+25	88.0	87.0
R11	+25	60.0	70.0
R12	+50	80.0	87.0
R13	+50	98.0	85.0
R14	+71	101.0	106.0
R15	+71	107.0	88.5

Table 9. Impact Test Results for A 8XX Grade B Steel. Specimens were Tested in the ASTM LT Orientation.

Specimen Number	Test Temperature, °F	Energy Absorbed, Ft-lb	Lateral Expansion, Mils
R26	-73	10.0	29.0
R27	-73	5.0	27.0
R28	-73	10.0	29.0
R29	-50	13.5	38.0
R30	-50	10.0	34.0
R31	-25	13.5	40.0
R32	-25	32.0	57.0
R33	-25	27.0	47.5
R34	+ 1	39.0	56.5
R35	+ 1	53.0	68.0
R36	+25	105.0	94.5
R37	+25	128.0	94.0
R38	+50	133.0	114.5
R39	+50	138.0	95.5
R40	+71	142.0	98.0
R41	+71	145.0	96.0

Table 10. Nil-Ductility Transition Temperature Results for AAR TC128 Grade B Steel.

Test Temperature	Break	No Break
-50° F	X	
-50° F	X	
-40° F	X	
-40° F	X	
-30° F		X
-30° F		X

NDT is -40° F

Break indicates standard test specimen fractured at that test temperature.

Table 11. Nil-Ductility Transition Temperature Results for A 8XX Grade B Steel.

Test Temperature	Break	No Break
-70° F	X	
-70° F	X	
-60° F	X	
-60° F	X	
-40° F	X	
-20° F		X
-20° F	X	
-10° F		X
-10° F	X	
-10° F	X	
0° F		X
0° F		X

NDT is -10° F

Break indicates standard test specimen fractured at that test temperature.

Table 12. Fracture Toughness Test Results for Normalized and Inclusion Shape Controlled AAR TC128 Grade B Steel. Compact Tension Specimens (1T) Were Used to Determine the J Value. LT AND TL Refer to the Specimen Orientation.

Specimen Number	Test Temp°F	J_{IC}	Plane Stress K^1	Plane Strain K^2
F2-LT	-63	2908	290	304
F1-LT	-63	2904	290	304
F3-LT	-40	2000	241	252
F9-LT	73	$(2848)^3$	287	301
F5-LT	78	1708	222	233
F15-TL	-63	$(2012)^3$	242	253
F16-TL	-63	$(1718)^3$	223	234
F17-TL	-40	2300	258	271
F25-TL	73	$(2212)^3$	253	266

1) $K=(JE)^{1/2}$: Plane stress K ($ksi\cdot in^{1/2}$) obtained using J value from CT test.

2) $K=(JE/(1-\nu))^{1/2}$: Plane strain K ($ksi\cdot in^{1/2}$) obtained using J value from CT test.

3) Maximum J value. (Unable to obtain a J_{Ic} value)

E= 29E+6 and ν =0.3

Table 13. Fracture Toughness Test Results for Control-Rolled and Inclusion Shape Controlled A 8XX Grade B Steel. Compact Tension Specimens (1T) Were Used to Determine the J Value. The Test Specimens Were Taken from the LT Orientation.

Specimen Number	Test Temp°F	J^1	Plane Stress K^2	Plane Strain K^3
B3-LT	-60	147	65	68
B1-LT	-40	165	69	72
B2-LT	-20	164	69	72
B4-LT	0	1763	226	237
B13-LT	8	1354	198	208
B5-LT	20	$(2701)^4$	279	293
B14R-LT	73	$(3762)^4$	330	346

1) The J value corresponds to the J value at unstable fracture. This was observed in specimens B1, B2, B3, B4, and B13.
2) $K=(JE)^{1/2}$: Plane stress K ($ksi \cdot in^{½}$) obtained using J value from CT test.
3) $K=(JE/(1-\nu^2))^{1/2}$: Plane strain K ($ksi \cdot in^{½}$) obtained using J value from CT test.
4) A J_{Ic} value was obtained only for specimen B5. Specimen B14R also showed stable crack growth, however a J_{Ic} was not obtained.

E= 29E+6 and ν =0.3

Table 14. Comparison of Fracture Toughness Results for Normalized AAR TC128 Grade B Steel and Control-Rolled A 8XX Steel using CTOD Test Results. Both Steels Were Made using Inclusion Shape Control Practice.

Specimen Number	Test Temp. °F	TC128 Plane Stress K^3	A 8XX Plane Stress K^3	TC128 Plane Strain K^4	A 8XX Plane Strain K^4	TC128 Plane Stress J^5	A 8XX Plane Stress J^5	TC128 Plane Strain J^6	A 8XX Plane Strain J^6	CTOD (inch) δc^7	CTOD (inch) δm^8
E8[1]	-82	251		290		2171		2894			0.0235
E9	-82	262		303		2373		3164			0.0257
A12[2]	-80		74		86		191		254	0.0017	
A9	-60		68		79		160		213	0.0014	
A11	-60		89		103		273		364	0.0025	
E10	-40	269		311		2493		3324			0.0272
E11	-40	269		311		2498		3331			0.0272
A14	-40		115		132		453		604	0.0042	
A17	-40		86		100		256		341	0.0024	
A18	-40		89		102		271		361	0.0025	
A15	-22		71		82		174		232	0.0016	
A16	-22		112		129		433		576	0.0004	
A20	-22		114		132		448		598	0.0042	
A22	0		175		202		1059		1412	0.0102	
A23	+20		194		224		1295		1727	0.0126	

1) AAR TC128 Steel - "E" specimens
2) A 8XX Steel - "A" specimens
3) $K=(1.2*E*\sigma_{flow}*\delta)^{1/2}$: Plane-stress where δ=CTOD, (ksi·in$^{1/2}$)
4) $K=(1.6*E*\sigma_{flow}*\delta)^{1/2}$: Plane-strain where δ=CTOD, (ksi·in$^{1/2}$)
5) $J=(1.2*\sigma_{flow}*\delta)$: Plane-stress where δ=CTOD, (in-lb/in^2)
6) $J=(1.6*\sigma_{flow}*\delta)$: Plane-strain where δ-CTOD, (in-lb/in^2,
7) CTOD at the onset of unstable brittle crack extension or pop-in.
8) CTOD at the first attainment of a maximum load plateau for fully plastic behavior.

Table 15. Comparison of Fracture Toughness Results using CT AND CTOD Test Results for Normalized and Inclusion Shape Controlled AAR TC128 Grade B Steel.

			CT			CTOD			
Method	Specimen Number	Test Temp. °F	J^3	Plane Stress K^4	Plane Strain K^5	Plane Stress J^6	Plane Strain J^7	Plane Stress K^8	Plane Strain K^9
CT[1]	F1	-63	2904	290	304				
CT	F2	-63	2908	290	304				
CT	F15	-63	2012	242	258				
CT	F16	-63	1718	223	238				
CT	F3	-40	2000	241	252				
CT	F17	-40	2300	258	270				
CTOD[2]	E10	-40				2493	3324	269	311
CTOD	E11	-40				2498	3331	269	311

1) CT: Compact Tension Specimen
2) CTOD: Three Point Bend Specimen
3) From J-Integral Test ($in\text{-}lb/in^2$)
4) $K=(JE)^{1/2}$ using J obtained from CT test results ($ksi\cdot in^{½}$).
5) $K=(JE/(1-\nu^2))^{1/2}$ using J obtained from CT test results ($ksi\cdot in^{½}$).
6) $J=(1.2*\sigma_{flow}*\delta)$: Plane-stress where δ=CTOD ($in\text{-}lb/in^2$).
7) $J=(1.6*\sigma_{flow}*\delta)$: Plane-strain where δ=CTOD ($in\text{-}lb/in^2$).
8) $K=(1.2*E*\sigma_{flow}*\delta)^{½}$: Plane-stress where δ=CTOD ($ksi\cdot in^{½}$).
9) $K=(1.6*E*\sigma_{flow}*\delta)^{½}$: Plane-strain where δ=CTOD ($ksi\cdot in^{½}$).

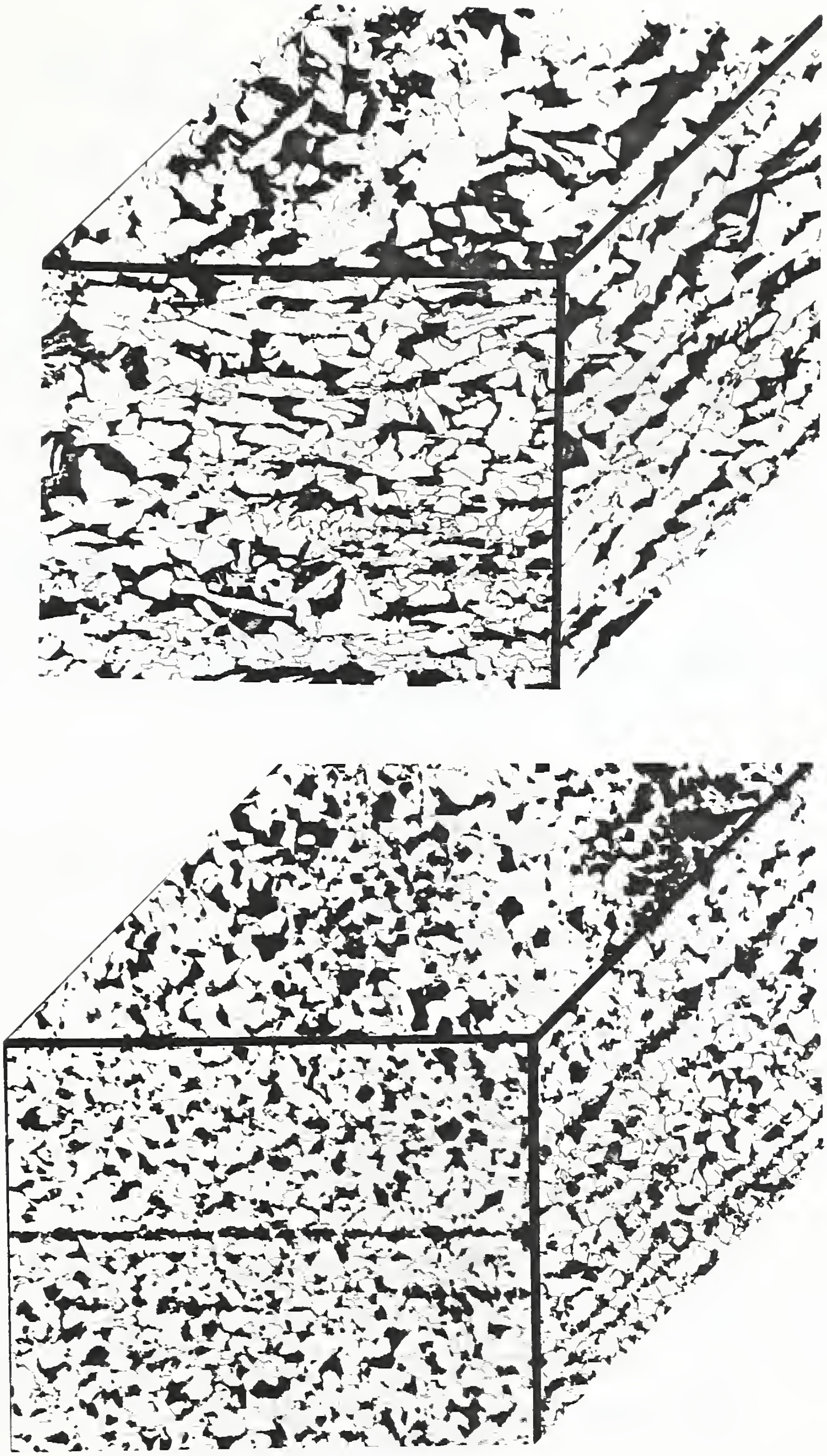
Table 16. Comparison of Fracture Toughness Using CT and CTOD Test Results for Control-Rolled and Inclusion Shape Controlled A 8XX Steel.

Test Method	Specimen Number	Test Temp. °F	CT			CTOD			
			J[3]	Plane Stress K[4]	Plane Strain K[5]	Plane Stress J[6]	Plane Strain J[7]	Plane Stress K[8]	Plane Strain K[9]
CT[1]	B3	-60	147	65	68				
CTOD[2]	A9	-60				160	213	68	79
CTOD	A11	-60				273	364	89	103
CT	B1	-40	165	69	72				
CTOD	A14	-40				453	604	115	132
CTOD	A17	-40				256	341	86	100
CTOD	A18	-40				271	361	89	102
CT	B2	-20	164	69	72				
CTOD	A20	-22				448	598	114	132
CTOD	A15	-22				124	232	71	82
CTOD	A16	-22				433	576	112	129

1) CT: Compact tension specimen
2) CTOD: Three point bend specimen
3) From J-Integral Test (in-lb/in^2)
4) $K=(JE)^{1/2}$: Plane stress K (ksi·in$^{1/2}$) obtained using J value from CT test.
5) $K=(JE/1-\nu))^{1/2}$: Plane strain K (ksi·in$^{1/2}$) obtained using J value from CT test.
6) $J=(1.2*\sigma_{flow}*\delta)$: Plane-stress where δ=CTOD (in-lb/in^2).
7) $J=(1.6*\sigma_{flow}*\delta)$: Plane-strain where δ=CTOD (in-lb/in^2).
8) $K=(1.2*E*\sigma_{flow}*\delta)^{1/2}$: Plane-stress where δ=CTOD (ksi·in$^{1/2}$).
9) $K=(1.6*E*\sigma_{flow}*\delta)^{1/2}$: Plane-strain where δ=CTOD (ksi·in$^{1/2}$).

(b) (c)

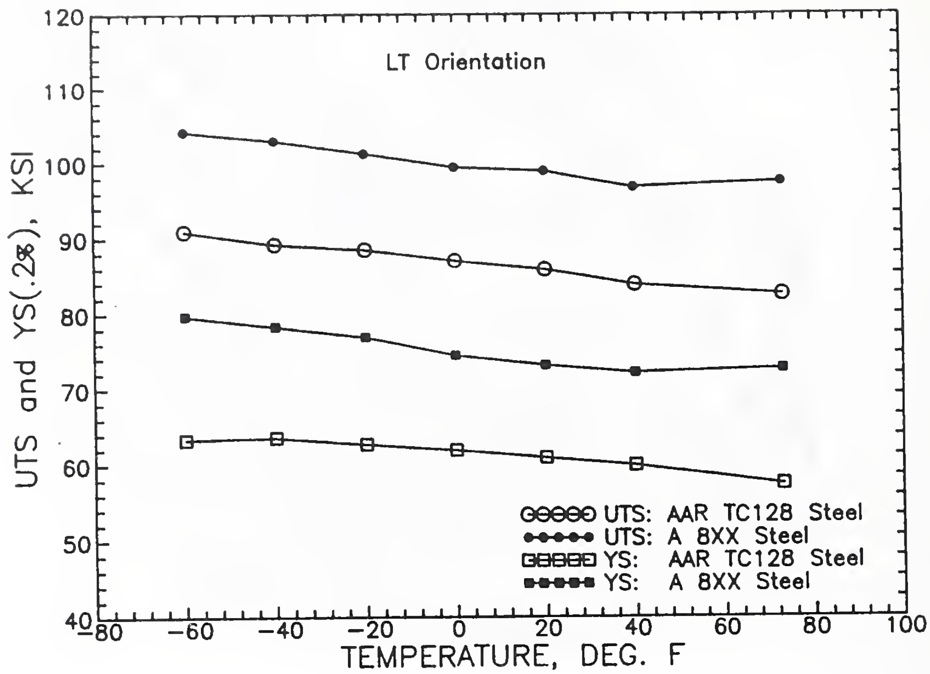
Figure 1. Photomicrographs of the inclusions observed in a conventional steel (a), the micro-alloyed, control-rolled A 8XX grade steel (b), and the AAR TC128 grade B steel (c). The arrows show the rolling direction for each steel.
As-polished. Mag. All X250.



(a)

(b)

Figure 2. Photomicrographs showing the microstructure of the A 8XX steel (a), and the AAR TC128 grade B steel (b) observed in three orthogonal directions in the etched condition.
Etch: 2% Nital. Mag. All X250



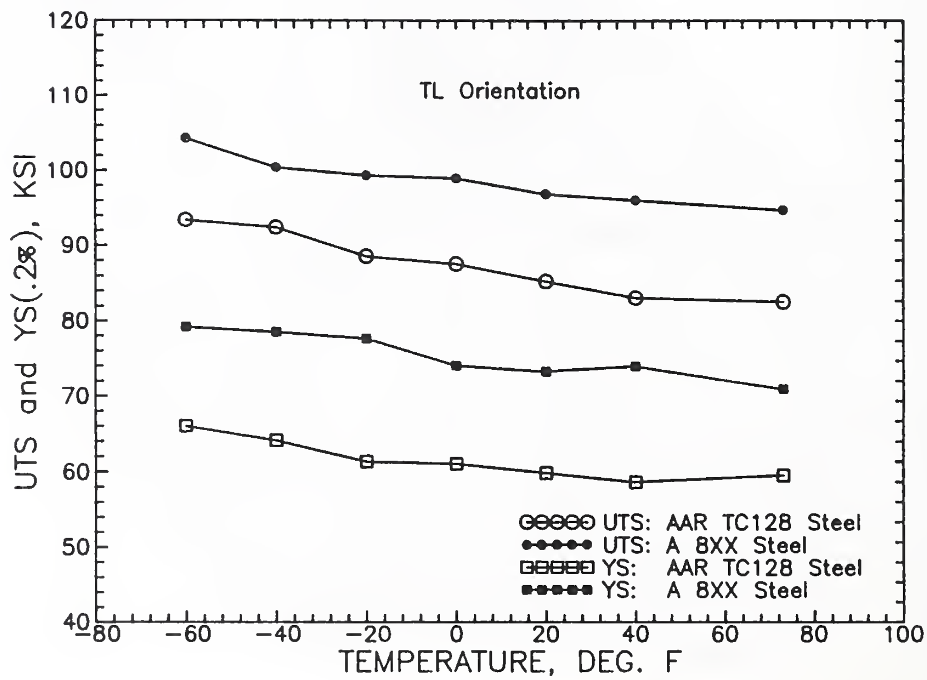


Figure 3. Ultimate and 0.2% offset yield strength for both steel versus test temperature for both the LT and TL orientations. Each point is an average of at least two values.

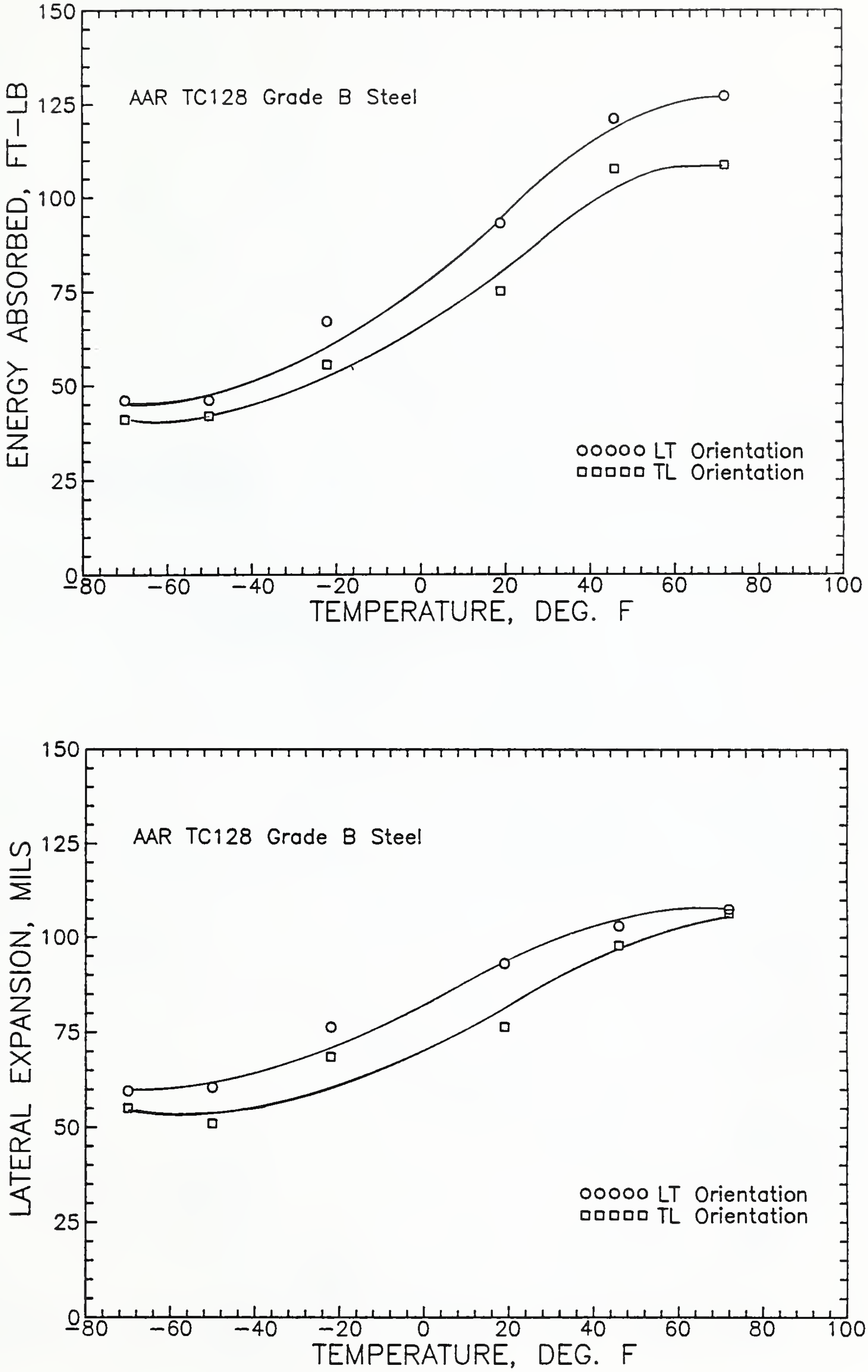
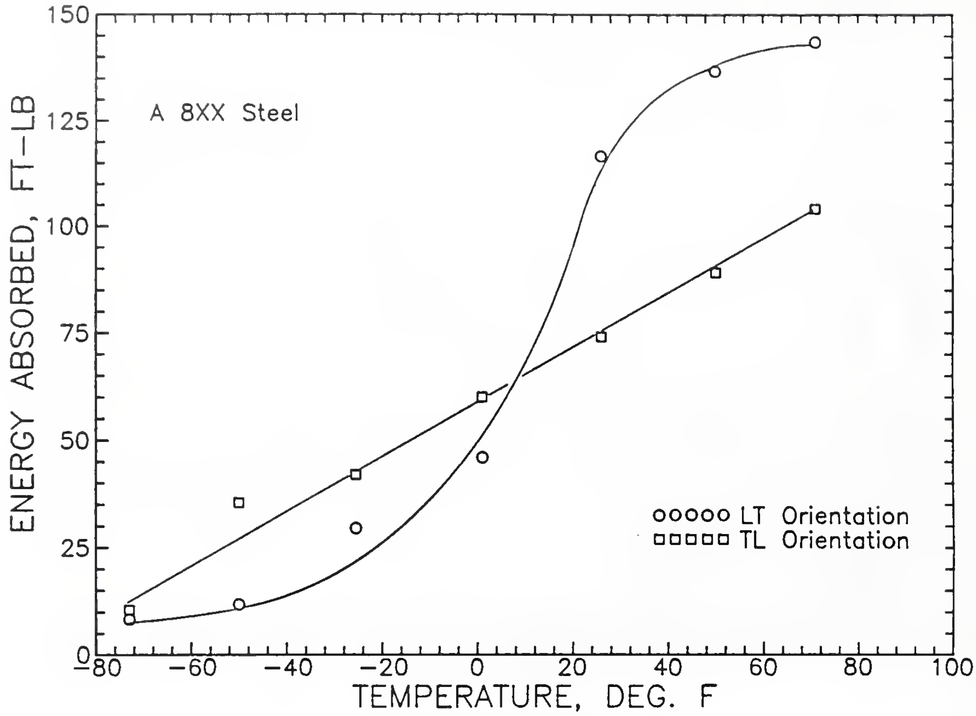


Figure 4. Energy absorbed and lateral expansion for AAR TC128 grade B steel versus test temperature for both the LT and TL orientations. Each point is an average of at least two values.



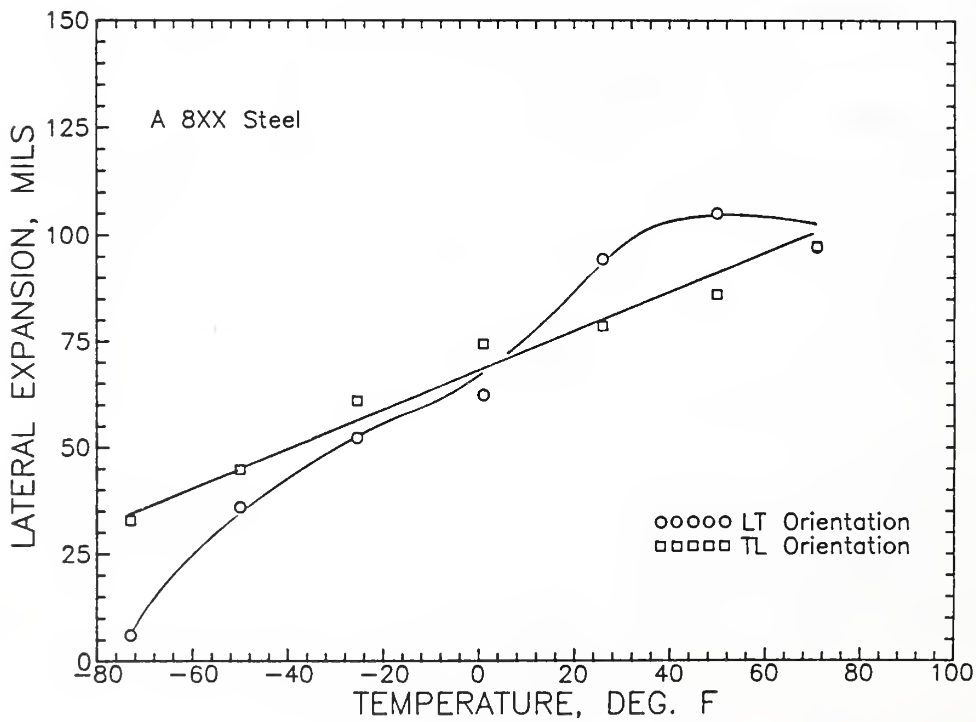
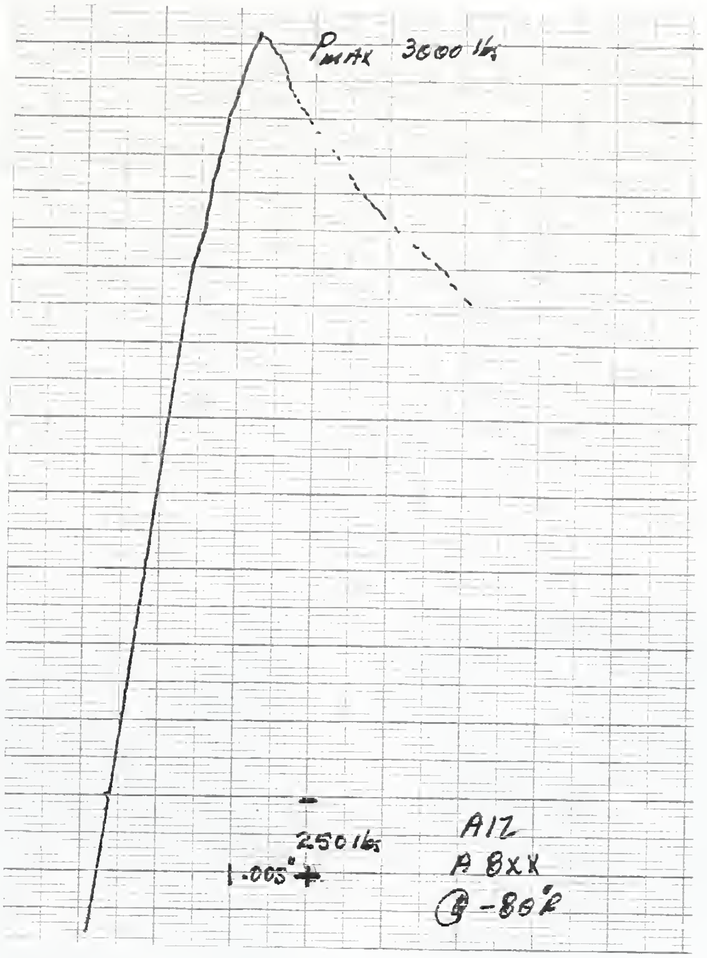
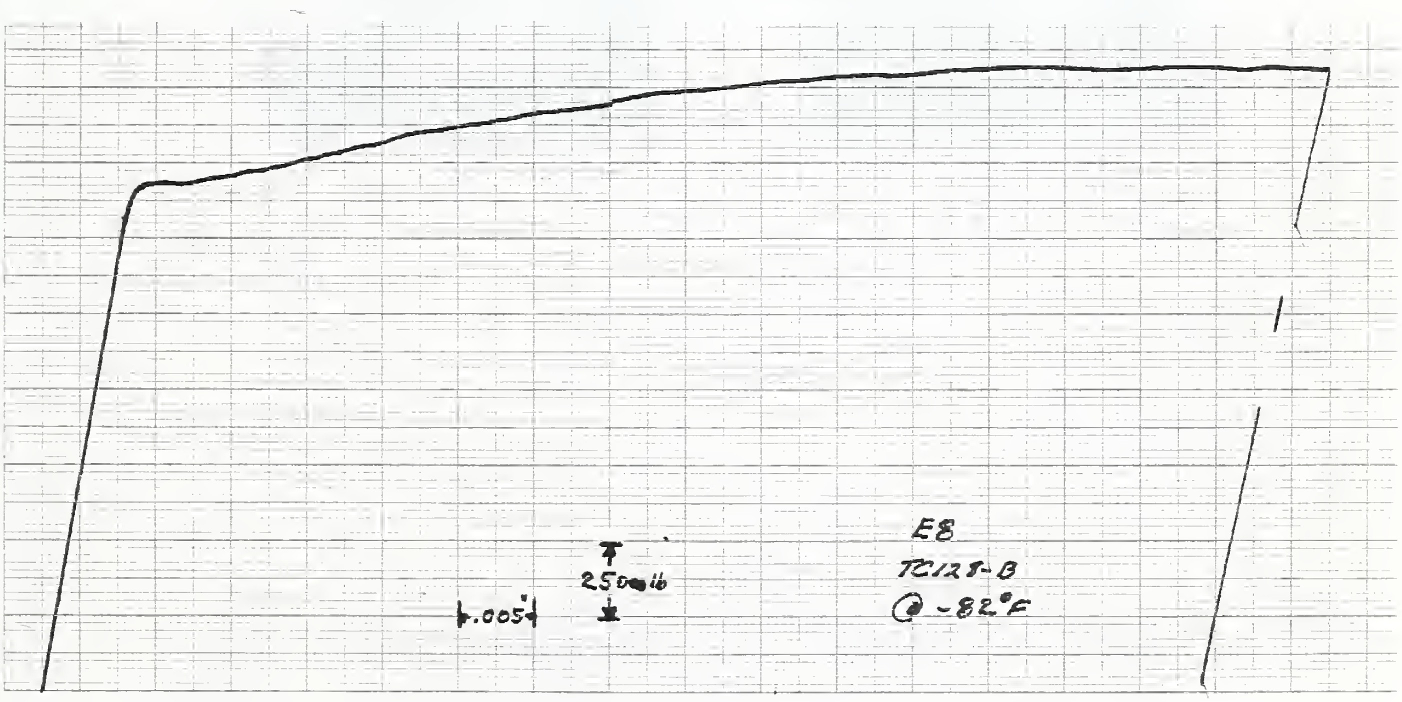


Figure 5. Energy absorbed and lateral expansion for A 8XX grade B steel versus test temperature for both the LT and TL orientations. Each point is an average of at least two values.



(a)



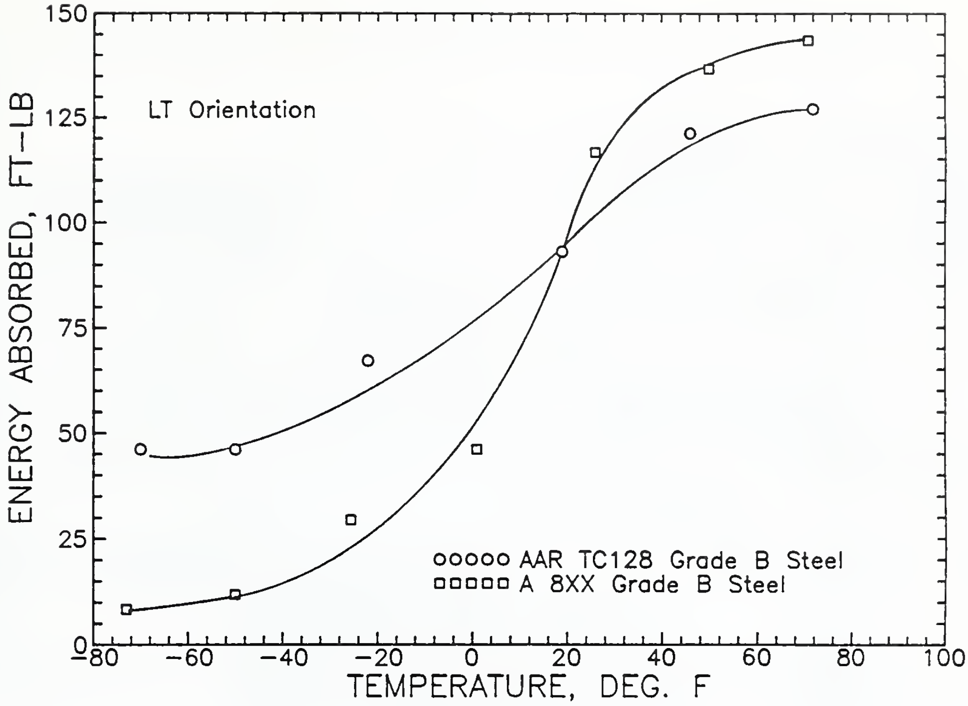
(b)

Figure 6. Load/displacement traces for the A 8XX grade B steel (a), and the AAR TC128 grade B steel (b).

(a)

(b)

Figure 7. Photomicrographs of the fracture surfaces of the two steels adjacent to the initial fatigue crack after testing at -80 F. Fractograph (a) shows the cleavage fracture that was observed on the surface of the A 8XX grade B specimen, and fractograph (b) shows the dimpled surface characteristic of ductile fracture that was observed on the surface of the AAR TC128 grade B specimen. Mag. X370



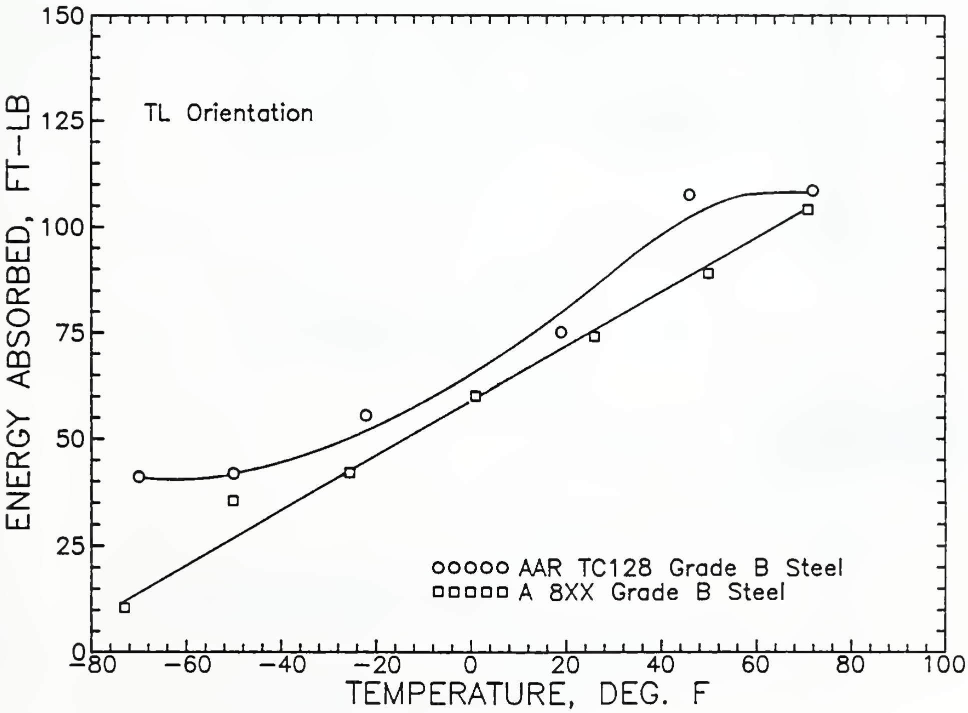
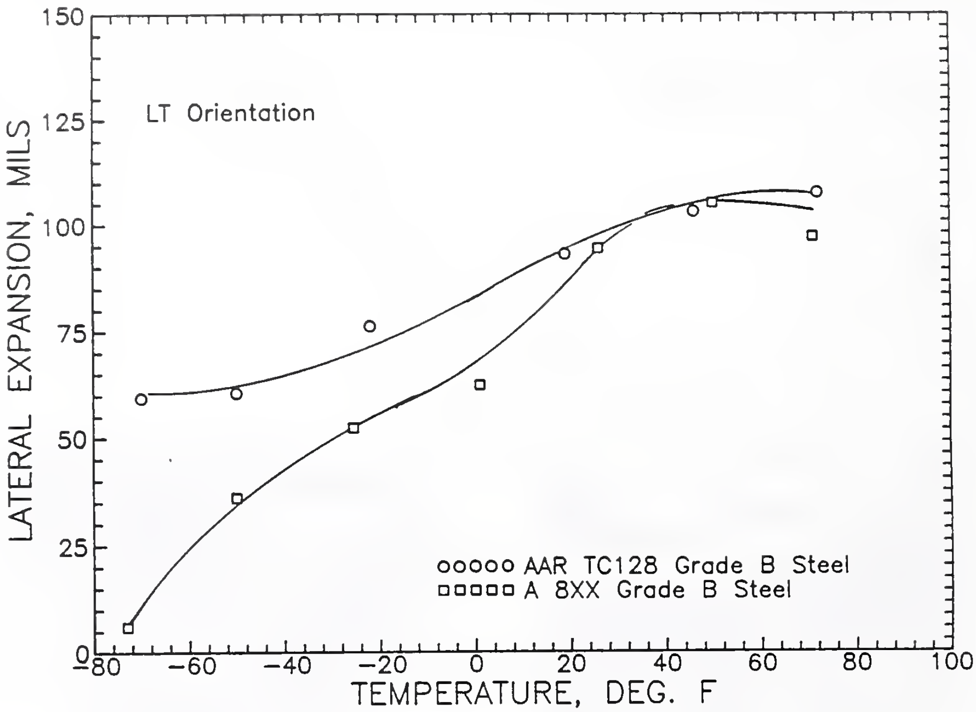


Figure 8. Energy absorbed versus test temperature and orientation for the A 8XX grade B steel and the AAR TC128 grade B steel.



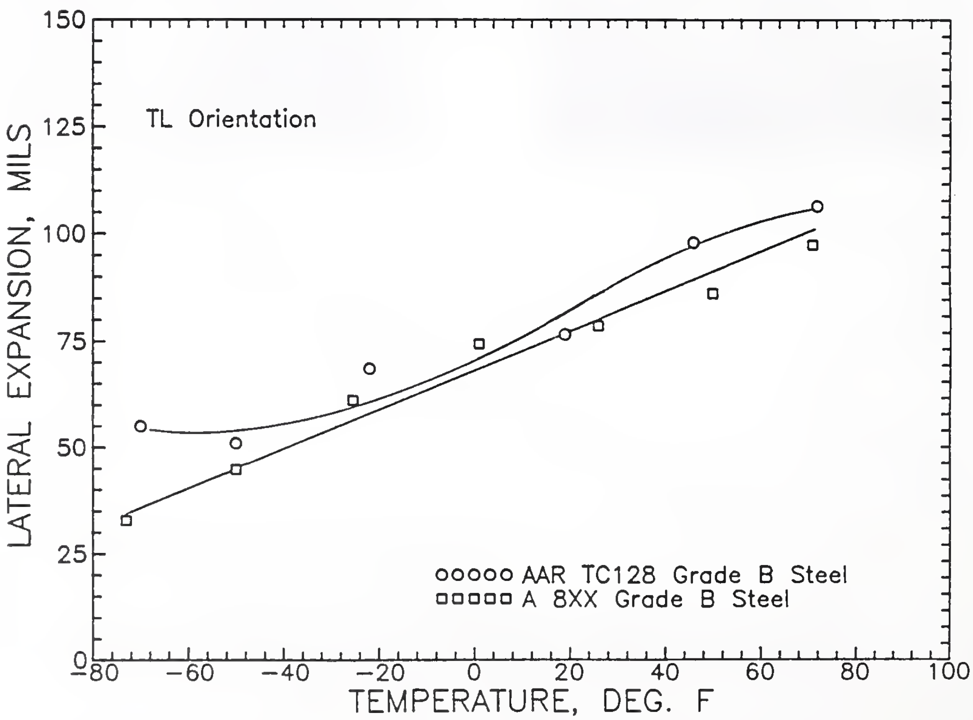


Figure 9. Lateral expansion versus test temperature and orientation for the A 8XX steel and the AAR TC128 grade B steel.

Appendix A1

151St & Railroad Avenue • East Chicago, Indiana 46312

CHICAGO (312) 374-5250
EAST CHICAGO (219) 392-1500

DITIONS ON FACE AND REVERSE SIDE

BETHLEHEM STEEL COMPANY
737 N MICHIGAN
#1050 OLYMPIA CENTER
CHICAGO, IL 60611-2615

BUYER	
01	DON OLENIK

PURCHASE ORDER DATE		
03	07	88
MONTH	DAY	YEAR

PURCHASE ORDER NO.
03-44879
MUST APPEAR ON INVOICES PACKAGES BILL OF LADING AND SHIPPING PAPERS

OFF SYSTEM

VENDOR	INSPEC.	CONTRACT	SALES/USE TAX CHARGE	
			YES	X NO

SHIPMENT TO DELIVER BY		
03	31	88
MONTH	DAY	YEAR

RECEIVING LOCATION

151ST & RAILROAD AVE
EAST CHICAGO, IN 46312
ATTN: PAUL HEIDEMAN WELDING LAB

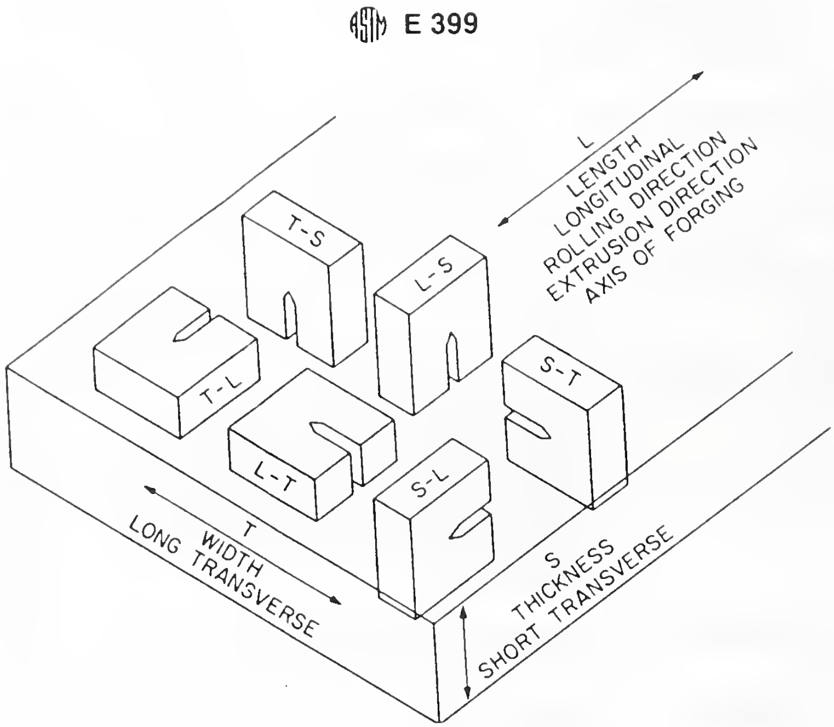
DIVISION	ACCOUNT	AREA	FUNCTION	SHOP ORDER	RPTG MARK	JOB/CAR EQUIP NO
		330	874			

TERMS	ROUTING	F.O.B.
3/4 10 N-30	TRUCK	SHIPPING POINT

#	QUANTITY REQUIRED	U/M	PART NUMBER	DESCRIPTION	SHIP QUANTITY	SHIP DATE	UNIT PRICE
				THIS ORDER IS FOR SAMPLE PLATES WHICH UTC IS PROCURING FOR THE NATIONAL BUREAU OF STANDARDS FOR TESTING IN CONJUNCTION WITH THE AAR NEW TANK STEEL PROGRAM. UTC WILL FORWARD THESE PLATES TO THE NBS AND BILL NBS FOR MATERIAL AND TRANSPORTATION COSTS. THIS IS A CHARGED ORDER.			
	33	CW	UNCODED	AAR TC-128-B NORMALIZED 4 PCS 9/16" THICK x 72" WIDE x 72" LONG 4 PCS			
	33	CW	UNCODED	GRADE B STEEL PER THE ATTACHED SPECIFICATION ASTM A8XX 9/16" THICK x 72" WIDE 4 PCS x 72" LONG			
				REF. UTC P/O 03-027003			
				REQ NO. 24293 T.H. DALRYMPLE			
				CONFIRMING ORDER TO TOM DO NOT DUPLICATE			
LD							

OVER / SHORT / DAMAGED	DESCRIBE 1	2	3	4	5	6	PARTIAL DELIVERY	ORDER COMPLETE
DATE RECEIVED								
INVOICE NO							COLLECT CHARGES	
FREIGHT COLLECT							PRO NUMBER	
PREPAID							INITIALS	
ALLOWED								

Appendix A2


E 399
L
LENGTH
LONGITUDINAL
ROLLING DIRECTION
EXTRUSION DIRECTION
AXIS OF FORGING
T-S
L-S
T-L
L-T
S-T
S-L
T
WIDTH
LONG TRANSVERSE
S
THICKNESS
SHORT TRANSVERSE

Appendix A3

48597 (Rev 8 8-86)

BETHLEHEM STEEL CORPORATION
QUALITY ASSURANCE DEPARTMENT
REPORT OF TESTS AND ANALYSES

FOR NBS TEST PLATES

BURNS HARBOR PLANT

SHIPMENT NO	DATE SHIPPED	CAR OR VEHICLE NO		
803-07461	3-24-88	GARY TFR	TRLR 27	PAGE 2

SOLD TO: UNION TANK CAR CO
151ST & RAILROAD AVE
EAST CHICAGO IN 46312

SHIP TO: UNION TANK CAR CO
151ST & RAILROAD AVE
EAST CHICAGO IN 46312

SERIAL NUMBER	PAT NO	HEAT NUMBER	NO PCS	THICKNESS INCHES	WIDTH OR DIA INCHES	LENGTH INCHES	WEIGHT POUNDS	YIELD POINT PSI	TENSILE STRENGTH PSI	ELONG IN	ELONG %
~~QUALITY STEEL MELTED & MANUFACTURED IN THE U. S. A.~~											
PLATES - AAR TC128 GR B FLANGE QUAL REV 9/1/85 --- CH-V A20SS PLT L 15 FTLB AT -50F --- NORMALIZE											
MFST - TUE THUR 7A/11A LIFT MAX 10 TON-SIZES & GRADES SEP LOAD UN-110 IN WIDE-SEP-OV 110 IN-TO 140 IN WIDE-SEP-OV 140 IN WIDE-SEP.											
CO# 3-044879 GH 021-3765A											
PLATES HEAT TREATED WITH TEST SPECIMENS ATTACHED AND YIELD STRENGTH @ .5% E.U.L.											
X 10304		803A66600	4	9/16	72	72	3308	58800	81500	8	25
				N 1650	DEG F -	29 MIN					
PLATES - AAR TRIAL SPEC GR B C.16X MN 1.00/1.65 P.035X S.010X SI.10/.55 CB.06X V.11X. CE: C + (MN/6) + (CR+MO+V/5) + (CU+NI/15)= .47 MAX PVQ. CH-V A20SS PLT L 25 FTLB AT -50F --- CONTROL ROLL											
MFST - TUE & THUR 7A/11A LIFT MAX 10 TON-SIZES & GRADES SEP LOAD UN-110 IN WIDE-SEP-OV 110 IN-TO 140 IN WIDE-SEP-OV 140 IN WIDE-SEP.											
CO# 3-044879 GH 021-3765											
X 3512		803A71430	4	9/16	72	72	3308	75600	92700	8	22
								77600	93100	8	21

Q—QUENCH TEMPERATURE T—TEMPER TEMPERATURE N—NORMALIZE TEMPERATURE

SERIAL NUMBER	PAT. NO	HEAT NUMBER	HARD	BEND	THICKNESS INCHES	TYPE	SIZE	DIR	TEST TEMP F	CHARPY IMPACT ENERGY FT. LBS. 1	2	3	SHEAR (%) 1	2	3	LAT. EXP 1	2	3
X 10304		803A66600	128		.562	V	FULL	L	-50	78	85	70						
X 3512		803A71430	CR		.562	V	FULL	L	-50	38	52	33						

CHEMICAL ANALYSIS

HEAT NUMBER	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Al	B	Cb	N	McQUAID GRAIN SIZE
803A66600	.22	1.25	.024	.007	.213	.017	.03	.19	.074	.033		.045				
803A71430	.15	1.49	.016	.006	.277	.023	.03	.04	.011	.075		.054		.035		

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Mechanical Properties and Fracture Toughness of AAR TC128 Grade B Steel and a Micro-Alloyed, Control-Rolled Steel, A 8XX Grade B, From $-80^{o}F$ to $+73^{o}F$

5. AUTHOR(S)

George E. Hicho and John H. Smith

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

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400 7th Street, SW, Washington, DC 20595

10. SUPPLEMENTARY NOTES

☐ DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

Mechanical property and fracture toughness tests were conducted on two steels from $-80^{o}F$ to $+73^{o}F$. The two steels examined were normalized and inclusion shape controlled AAR TC128 grade B steel and control-rolled and inclusion shape controlled A 8XX grade B steel. The tensile properties of the A 8XX steel were better than a A 8XX steel. However, the notch toughness, as determined by Charpy V-notch, NDT temperature, and J-integral tests, of the AAR TC 128 grade B steel was better than that of the A 8XX grade B steel. Unstable cleavage fracture was the predominate mode of failure of the A 8XX steel at low test temperatures. Metallographic investigations also showed that the ferrite/pearlite grain size of the AAR TC128 steel was more uniform and finer than that of the A 8XX steel.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

Crack tip opening displacement, fracture toughness, impact, J-integral, nil-ductility transition, steel, tensile.

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