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George E. Hicho

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Gaithersburg, MD 20899

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THE MECHANICAL, STRESS-RUPTURE, AND FRACTURE TOUGHNESS PROPERTIES OF NORMALIZED AND STRESS RELIEVED AAR TC128 GRADE B STEEL AT ELEVATED TEMPERATURES

George E. Hicho

Mechanical Properties and Performance Group
Materials Science and Engineering Laboratory
National Institute of Standards and Technology
Metallurgy Division
Gaithersburg, MD 20899

ABSTRACT

The mechanical, fracture toughness, and stress-rupture properties of a normalized and stress relieved tank car steel were found to be reduced by increased temperature and time at temperature. The effects of loading rates, 0.0127 and 0.127 cm/min, on these properties were also evaluated. Most affected was the yield strength, where at the loading rate of 0.127 cm/min, the yield strength as a function of temperature and time at temperature was greater than that obtained under similar test conditions at a loading rate of 0.0127 cm/min. The ultimate and yield strength were observed to decrease continuously from 593 °C to 677 °C for time of 60, 90, and 120 minutes. The ductility, in terms of the elongation and reduction-of-area were found to increase over these same test temperatures and times. The fracture toughness, because of the yield strength decrease as the temperature increased, decreased as the test temperature increased. Fracture toughness tests found the steel to be highly resistant to unstable fracture, and stress-rupture tests revealed that the rupture lifetime could be extended, at elevated temepratures, by reducing the maximum internal pressure of the tank car.

INTRODUCTION

As of January 1989, the Federal Railroad Administration (FRA) requires new tank cars that carry hazardous commodities be constructed of normalized AAR TC128 grade B steel and that the tank car be stress relieved after fabrication. In order to develop a database for the steel in this condition, the Mechanical Properties and Performance Group (MPPG) of the National Institute of Standards and Technology (NIST) was asked by the FRA to determine the steel's mechanical and fracture toughness properties from room temperature to the lowest temperature the steel could possibly encounter while in use in North America. This research (1, 2) detailing the steel's mechanical, fracture toughness, and crack arrest properties from room temperature to -51 °C (-60 °F) showed that the steel had acceptable tensile properties, i.e., yield, ultimate etc., but more importantly, the impact properties at low test temperatures were better than those obtained for as-rolled AAR TC128 grade B steel. The fracture toughness test results, for similar test temperatures, indicated that the normalized and stress relieved steel was more resistant to crack initiation and was better able to arrest a propagating crack than as-rolled or normalized AAR TC128 grade B steel.

Having determined the mechanical and fracture properties of the normalized and stress relieved steel from room temperature to -51 °C, the question arose as to how this steel, now in a tank car, responded once it was exposed to fire. Results obtained from previous investigations (3, 4, 5) revealed that fire temperatures at accident sites ranged from about 593 °C (1100 °F) to about 677 °C (1250 °F). These same reports indicated that once a tank car was engulfed in fire -- with the absence of a cooling environment but venting its contents via a relief valve -- it would probably explode in about 90 minutes. Over the years, as a result of research conducted by both the railroad industry and the federal government on tank cars, steps have been taken to reduce the chances of catastrophic tank car failures that were so prevalent during the 1970s (6, 7). Current research (1, 2, 8, 9) has shown that the steel now required for new tank cars, normalized and stress relieved AAR TC128 grade B steel, in the absence of a fire, is more resistant to catastrophic failure at low temperatures compared to as-rolled AAR TC128 grade B steel. The question yet unanswered was, "What are the mechanical, stress-rupture, and fracture toughness properties of the steel when subjected to a fire?" The MPPG group at NIST was requested to conduct experiments and prepare a report that detailed the mechanical, stress-rupture, and fracture toughness properties of normalized and stress relieved AAR TC128 grade B steel at temperatures and times similar to those encountered in a fire.

TEST MATERIAL

Four plates, each 1.4 cm (9/16 inch) in thickness by 183 cm (72 inch) square were made for the test program by Bethlehem Steel Corporation according to Association of American Railroads (AAR) specification M128 for grade B flange quality steel. The plates were purchased from the Bethlehem Steel Corporation, through Union Tank Car Company (UTC), with the help of Mr. Thomas Dalrymple, Chief Engineer of UTC. Appendix I shows Bethlehem Steel's test and analysis report with the chemistry and metallurgical particulars included, and that the plates were normalized after rolling. (Normalizing is a heat treatment that produces a uniform microstructure in a steel plate, which leads to improved mechanical and fracture properties).

TEST PROGRAM

Stress Relieving, As-received Microstructure, and Chemistry:

Prior to sectioning the test specimens from the plate "J", the as-rolled and normalized plate was stress relieved according to AAR specifications by the Union Tank Company. The stress relieving (recovery anneal) was done at 649 °C (1200 °F) for one hour, and photomicrographs were taken of the normalized and stress relieved plate in the unetched and etched conditions. For check purposes, the chemical composition of the as rolled plate was determined.

Microstructure and Hardness:

Uniformly sized test coupons, used to determine the affects of temperature and time on the microstructure of this steel, and hence its mechanical properties, were prepared and heated to 593, 621, 649, and 677 °C for 30, 60, 90, and 120 minutes, respectively. Photomicrographs were taken to determine the affects of temperature and time on the steel. Hardness measurements were also taken to examine the affects of time, temperature, or a combination of both on the hardness.

Hot-Tensile Program:

Standard American Society for Testing and Materials (ASTM) tensile specimens with a reduced diameter of 6.4 mm (0.250 inch) were prepared from the 1/4 thickness position in the plate according to ASTM Method A 370-90. The test specimens were taken from the ASTM L-T (long axis of specimen parallel to the rolling direction of the plate) and the ASTM T-L (long axis of the specimen perpendicular to the rolling direction of the plate) directions. The specimens were tested at 593, 621, 649, and 677 °C for 30, 60, 90, and 120 minutes, respectively, at crosshead speeds of 0.0127 cm/min (0.005 inch/min) and 0.127 cm/min (0.05 inch/min) to determine the effects of time, temperature, and strain rate. The specimens were tested in an environmental chamber with no protective atmosphere. After yielding, the crosshead speed was increased to 0.127 cm/min for those specimens that were initially loaded at 0.0127 cm/min. The crosshead speed of 0.127 cm/min was maintained throughout the test for appropriate specimens. Chart and crosshead speed, and machine compliance were used to estimate the 0.2% offset yield strength. The elongation to failure was obtained by measuring the distance between fiduciary marks, placed 2.54 cm apart, after testing.

Stress-Rupture Program:

Standard ASTM tensile specimens, identical to those described above, were tested in accordance with ASTM Method E 21-79, Elevated Temperature Tension Tests of Metallic Materials to determine the stress-rupture properties. The yield strength values obtained from the hot-tensile test results were used to set the test loads for the stress-rupture tests. Each specimen was placed in the test chamber and a minor load applied. The furnace power was activated and the specimen was allowed to reach the predetermined test temperature -- 593, 621, 649, or 677 °C. After 15 minutes at temperature (time estimated for a plate 1.4 cm in thickness to reach temperature), the load corresponding to the desired yield strength was applied to the system, and the timer activated. Specimen extension was measured by gages located outside the test chamber, and recorded as a function of time. At specimen rupture, the time was recorded. From these results -- applied stress, time to failure, and temperature, a family of curves showing stress-rupture as a function of temperature were developed.

Fracture Toughness Program:

Fracture toughness specimens were prepared and tested according to ASTM Method E 813-89, Standard Test Method for J_{IC}, a Measure of Fracture Toughness. Specimens were heated in an environmental chamber at the temperatures of 593, 621, 649, and 677 °C. Initially a specimen was heated to 677 °C for 120 minutes and tested. The test results indicated that it was virtually impossible to initiate or propagate a crack and hence, a shorter test time, 90 minutes was selected to evaluate the fracture toughness of the steel. The specimens were tested in the ASTM T-L and T-L directions. As with the hot-tensile specimens, chart speed, crosshead speed, and machine compliance were used to estimate the maximum load applied to a specimen at the onset of crack propagation. This load was used to calculate the fracture toughness.

RESULTS

Chemistry:

Table 1 shows the AAR specification to which the steel was melted, the heat check analyses as determined by the Bethlehem Steel Corporation, and the NIST check analyses. The results showed that steel was within acceptable limits and made according to the specification. Although the chromium content was 0.01 weight percent over that allowed, it was within the ASTM chemical error limits established for that element. Included in the chemical analyses results is the carbon equivalent, CE. The carbon equivalent is helpful to the metallurgist and welder in determining the susceptibility of the weld to heat affected zone cracking. The higher the CE, the higher the probability for such to occur if such practices as pre- and post-weld procedures are not stringently observed. (Other factors such as the size of the pieces welded should be considered in determining weld cracking susceptibility).

Grain Size Determinations:

ASTM Method E 112-88, Standard Test Method for Determining Grain Size, was used to determine the proeutectoid ferrite/pearlite grain size of the normalized and stress-relieved steel. The grain size was determined at the 1/4 thickness location, and at two distant locations in a coupon. The grain size for one area was 6.6 μm which corresponds to ASTM number 11.2; and 6.4 μm, ASTM number 11.3, for another area. Both grain-size numbers indicate the steel was made to fine grain practice.

Microstructural Observations:

The steel's microstructural response to temperature and time were determined. Unetched and etched specimens were examined. In the unetched condition, that is, no acid applied to the steel to reveal its microstructure, the "cleanliness" of the steel, in terms of the area percent of inclusions present, was measured optically. Figure 1 shows photomicrographs of the steel in the unetched condition and in three orthogonal directions. This shows that: 1) on the surface inclusions are "pancake" in appearance, 2) parallel to the rolling direction, inclusions are elongated, and 3) into the rolling direction, inclusions are "dots" in the photomicrograph. The elongated manganese sulfide inclusions (dark lines in the figure) reveal the primary rolling direction of the plate. Sulfides, in particular the manganese sulfide type that lie between the proeutectoid ferrite/pearlite interfaces in the steel, are paths of low resistance and promote both crack initiation and propagation. Using the ASTM metallographic standard for the determination of inclusion content of steels, the cleanliness of plate "J," as revealed by the overall inclusion content of the specimen, was found to be low compared with other steels. Normalized plate "J" was therefore classified as a "clean" steel and was found, as a result in previous work by the author (2), to have both improved impact and fracture toughness properties compared to as-rolled steel.

Figure 2 shows photomicrographs of the as-received normalized steel in the etched condition in three orthogonal directions. In the normalizing treatment, the steel is heated to 899 °C (1650 °F), held at that temperature for 30 minutes and then air cooled to room temperature. This heat treatment essentially "normalizes" the microstructure, that is the proeutectoid ferrite and pearlite (the light and dark constituents in the photomicrograph) become equiaxed in size --- an indication that grain growth has occurred, and the deformation was diminished. AAR TC128 grade B steel is normally used in the as-rolled condition. In that condition, the proeutectoid ferrite and pearlite are "pancaked" in appearance. In the rolling of the plate, both the proeutectoid ferrite and pearlite are severely deformed, and as a result the mechanical properties (9), in particular the impact strengths, are less than those measured for a normalized steel. In the same photomicrograph of the etched steel, the proeutectoid ferrite/pearlite is observed to exist in layers, that is, there is a layer of proeutectoid ferrite then a layer of pearlite repeated throughout the specimen. This layering metallurgically is called "banding," and is due primarily to chemical segregation in the ingot during metallurgical processing and <u>cannot</u> be removed by any heat treatment other than remelting the steel. The "banding" affect is more pronounced in the as-rolled steel than in the normalized steel, due to the deformation given to the steel in processing. Normalizing, an added expense, is performed <u>after the rolling</u> to reduce the deformation of the proeutectoid ferrite and pearlite by allowing grain growth of the proeutectoid ferrite and pearlite to occur. Normalizing does not relieve the deformation completely or the banding, but does metallurgically produces changes in the proeutectoid ferrite, and especially in the pearlite, that result in significant improvements in both the mechanical and impact properties of the steel.

Figure 3 shows the microstructure in two locations in the steel after stress relieving. Figures 4 through 11 show the microstructures of the normalized and stress relieved coupons after they were heat treated at 593, 621, 649, and 677 °C for 30, 60, 90, and 120 minute intervals. The photomicrographs show that there was a <u>gradual</u> increase in the size of both the pearlite and proeutectoid ferrite as the time at temperature and temperature increased. After 30 or 60 minutes and 593 °C, figures 4a and 4b, the resultant microstructures were similar to those observed for the normalized and stress-relieved material. The most significant change in microstructure occurred when the steel was treated at 677 °C for 90 and 120 minutes. At those temperatures and times, the photomicrographs (figures 11a and 11b) show that the proeutectoid ferrite grains (light constituent) have grown in size. In addition, the Fe_3C (iron carbide) - dark spheroid particles around and within the pearlite - was observed to have coarsened. Coarsening of the pearlite, which could lead to softening of the steel, was also revealed by hardness determinations.

<u>Hardness:</u>

Table 2 shows the hardness results and figure 12 is a plot of these results. The figure affirms the microstructure indications, that is, irrespective of the temperature and time -- at 593 °C to 649 °C, and for 30, 60, or 90 minutes -- the hardness did not change dramatically. Only at 677 °C, and after 60, 90, or 120 minutes at temperature, was hardness reduced. Albeit the reduction in hardness was minimal, about one Rockwell A unit, this difference will be evidenced in the mechanical property results to be presented later.

Tensile Properties:
(At room temperature to -51 °C)

For comparison purposes the ultimate tensile strength (UTS) and 0.2% offset yield strength (YS) results, determined in a previous work (2) for this same steel at temperatures ranging from 22 °C to -51 °C, are shown in figure 13. The UTS at temperatures from 22 °C to -51 °C ranged from about 620 MPa (90 ksi) to 695 MPa (101 ksi) for the L-T specimens, and 558 MPa (81 ksi) to 606 MPa (88 ksi) for the specimens tested in the T-L direction. The YS at these same temperature ranged from 427 MPa (62 ksi) to 558 MPa (72 ksi) for the L-T specimens, and 393 MPa (57 ksi) to 427 MPa (65 ksi) for the specimens tested in the T-L direction. The UTS and YS for specimens taken from the ASTM L-T direction in the test plate were greater than those for specimens taken in the ASTM T-L direction. This difference in mechanical properties could be due to either inclusion content and orientation, or the deformation given to the proeutectoid ferrite/pearlite microstructure during the rolling process. Since the steel was given a normalizing heat treatment after rolling, resulting in a uniform proeutectoid ferrite/ pearlite grain size in both L-T and T-L directions, inclusion content and orientation played the predominant roles in the steel's mechanical properties. Figure 1 shows the unetched steel three orthogonal directions, and the extent of inclusions in the steel. For tensile specimens taken in the T-L direction, that is the primary inclusions lie in planes normal to the long axis of the test specimen, less energy is needed to cause rupture of the tensile specimen. For specimens tested in the L-T direction, where the primary inclusions are aligned parallel to the long axis of the tensile specimen, more more energy, compared to the T-L specimens, is needed to cause rupture of the specimen.

Tensile Properties:
(Affects of exposure time at elevated temperature)

The UTS and YS were determined for specimens taken from the T-L and L-T directions, at temperatures of 593, 621, 649, and 677 °C for exposure times of 60, 90, and 120 minutes. Two different crosshead speeds were used to determine the affects of strain rate on the mechanical properties. Tables 3, 4, 5, and 6 show the UTS and YS, the percent elongation in 25.4 mm, and the percent reduction of area. The UTS and YS results at each temperature, at crosshead speeds of 0.0127 and 0.127 cm/min, are plotted as a function of exposure time in figures 14, 15, 16, and 17.

Figure 14, for test specimens taken from the L-T direction and strained at 0.0127 cm/min, shows that both the UTS and YS were essentially uniform over the test temperatures, regardless whether the exposure time was 60, 90, or 120 minutes. However, in the same figure, is the difference between the UTS and YS values as a function of exposure time and time at temperature. Over the test temperatures and time the difference between the UTS and YS, on the average, was about 36%.

As expected due to the change in microstructure of the steel revealed in the metallographic examinations, a difference between the room temperature (see figure 13) and the elevated temperature tensile properties was observed. The room temperature UTS and YS were 620 MPa (90 ksi) and 427 MPa (62 ksi), respectively.

Similar tensile tests were conducted on specimens taken from the same L-T direction, but pulled at a crosshead speed of 0.127 cm/minute. Figure 15 shows these test results. After 60, 90, or 120 minutes exposure at 677 °C, both the UTS and YS were essentially uniform--the UTS was 123 MPa (18 ksi) and the YS 105 MPa (15 ksi), a difference of 15% compared to 36% for specimens tested at the slower crosshead speed of 0.0127cm/min. At 593 °C the difference between the UTS and YS was 27%; at 621 °C, 23%; and at 649 °C, 17%. The affects of the increased crosshead speed, i.e., material work hardening, is shown by the decrease in the difference between the UTS and YS values, or the YS approaching the UTS value.

The differences between the room temperature and elevated temperature UTS results were consistent with those obtained at the crosshead speed of 0.0127 cm/min. However, the difference between the room and elevated temperature YS results was less, due to the increased crosshead speed of 0.127 cm/minute. The difference between the room temperature and 593 °C UTS and YS values were 61% and 59%, respectively; at 621 °C, 69% and 65%; at 649 °C, 74% and 64%; and at 677 °C, 80% and 75%. Increasing the crosshead speed to 0.127 cm/minute from 0.0127 cm/minute a did not affect the UTS results over the test temperatures, but did affect the YS results.

Figure 16 shows the UTS and YS results for specimens taken in the T-L direction, tested at 593, 621, 649, and 677 °C after exposure for 60, 90, or 120 minutes. The specimens were tested at a crosshead speed of 0.0127 cm/minute, and the figure shows that both the UTS and YS, over the test temperatures, were uniform over the range of exposure times. Differences between the UTS and YS were determined and it was found that at all test temperatures, the difference between the UTS and YS was about 36.5% similar to that found for the T-L specimens tested at the crosshead speed of 0.0127 cm/minute.

Comparison of the room temperature and elevated temperature data for these same specimens revealed that the difference between these values <u>increased</u> as the test temperature increased. At 593 °C, the difference in UTS values was 60% and 64% for the YS; at 621 °C, 69% and 70%; at 649 °C, 75% and 76%; and at 677 °C, 80% and 82%. Figure 17 shows that the UTS and YS results for T-L specimens tested at a crosshead speed of 0.127 cm/minute were essentially uniform for the test temperatures and exposure times used. The differences, on the average, between the UTS and YS were less, approximately 22%, than those measured at the higher crosshead speed. A comparison of the room temperature and elevated temperature UTS and YS results showed that the same trend observed for the UTS and YS results for the T-L specimens was found for the L-T specimens tested at the higher crosshead speed. At 593 °C the difference between the UTS and YS was 60% for the UTS and 57% for the YS; at 621 °C, 68% and 65%; at 649 °C, 75% and 71%, and at 677 °C, 80% and 76%.

Figures 18 and 19 show the affects of exposure time, temperature and crosshead speed on the UTS. Figure 18, specimens taken from the L-T direction, showed that the effect of crosshead speed, i.e., difference in UTS, was not as pronounced at the test temperatures of 593, 621, or 649 °C. Only at 677 °C was the difference evident. Similarly as shown in figure 19, for specimens taken from the T-L direction, the difference between the UTS obtained using different crosshead speeds appears to be minimal, even at 677 °C. Figures 20 and 21 show YS results for similar test conditions. For both the L-T and T-L specimens, the effects of crosshead speed are more pronounced. The overall Effect of increased crosshead speed is to increase the YS regardless of test temperature or time at temperature.

Tensile Properties:
(Effects of temperature)

Figures 22, 23, 24, and 25, plots of UTS and YS versus temperature, show that there was a continuous decrease in these values as the test temperature and time at temperature increased. Not shown in these figures, but in Tables 3, 4, 6, and 6, was that there was also a continuous increase in the percent elongation as the test temperature increased from 593 °C to 677 °C. The reduction-in-area was found to be not as sensitive to temperature as the elongation. The reduction-in-area increased, as the test temperature increased, but not to the extent the elongation increased. In figure 22, for specimens taken from the T-L direction and tested at a crosshead speed of 0.0127 cm/ minute, the UTS was 240 MPa at 593 °C and 125 MPa at 677 °C. The YS also decreased from 150 MPa at 593 °C to 76 MPa at 677 °C. The affect of increasing the crosshead speed to 0.127 cm/ minute on the UTS and YS in the T-L direction is shown in figure 23. The UTS decreased from 240 MPa at 593 °C to 126 MPa at 677 °C, and the YS decreased from 175 MPa at 593 °C to 110 MPa at 677 °C. Conversely, the elongation and reduction-in-area were found to increase as the test temperature increased. The yield-to-ultimate strength ratio (Y/T) at the higher crosshead speed was much greater (0.80) than that at the lower crosshead speed (0.60) due to the fact that yield strength is more rate sensitive than ultimate tensile strength. The Y/T ratio, however, was not affected by temperature or time at temperature. Regardless of the time or temperature, the Y/T for the specimens tested at 0.0127 cm/minute was about 0.60 and the Y/T for the specimens tested at the crosshead speed of 0.127 cm/minute was about 0.80.

Figures 24 and 25 show the UTS and YS results for specimens taken from the ASTM T-L direction and tested at crosshead speeds of 0.0127 and 0.127 cm/minute. Both the UTS and YS decrease continuously as the test temperature increased from 593 °C to 677 °C. Figure 24 shows that at a crosshead speed of 0.0127 cm/minute, the UTS decreased from 245 MPa to 125 MPa at 677 °C, and that the YS, at these same temperatures decreased from 150 MPa to 75 MPa. At the higher crosshead speed, 0.127 cm/minute and figure 25, the UTS decreased from 245 MPa to 140 MPa, and the YS decreased from 185 MPa to 110 MPa.

For both test orientations (T-L or L-T), the Y/T ratio was unaffected by test temperature or time at temperature. Regardless of these variables - time at temperature or test temperature - the Y/T ratio for specimens tested at 0.0127 cm/minute was about 0.60 and about 0.80 for specimens tested at the crosshead speed of 0.127 cm/minute.

The measured ductility was consistent with conclusions reported by Smith (10) in A paper on the elevated temperature properties of carbon steels. The ductility, as measured by the elongation and reduction-in-area, increased as the test temperature was raised above the maximum strain ageing temperature of 316 °C (600 °F). The test results indicate that with increasing temperature both the UTS and YS decrease continuously, indicating that dynamic strain ageing probably did not affect these strength properties over the test temperatures used in this investigation. These results are in agreement with Peterson (11) and Miller (12) who both found that dynamic strain ageing effects were not observed on a large number of carbon steels in hot-tensile tests conducted above 316 °C.

Stress-Rupture Properties:

The results of the stress-rupture tests were in good agreement with the results of the hot-tensile tests. Tables 7 and 8 show the results of the stress-rupture tests, which are plotted in Figure 26. The UTS values at the controlled crosshead speeds were equivalent to rupture lifetimes of approximately 10 minutes or less at the test temperatures of 593, 621, 649, and 677 °C. White et.al (13), and corroborated by Early (14), found that for a carbon steel the tensile strength values in the temperature range of 649 °C to 704 °C correspond to rupture lifetimes of 0.15 hours or less. Thus the equivalent rupture lifetimes of the elevated-temperature tensile strength values for this work are consistent with the equivalent rupture lifetimes reported for a carbon steel.

This research has confirmed that the rupture lifetime is strongly dependent on the initial applied stress level. Figure 26 is a plot of the logarithm of the applied, or initial stress level as a function of the logarithm of the time-to rupture. By extrapolation of the stress-rupture data, i.e., using the equations representing each temperature, it can be shown that rupture time could be increased by decreasing the 10-minute lifetime stress level. Table 9 shows a compilation of these results. At 593 °C, by decreasing the 10-minute lifetime stress 27%, the rupture life increased to 3 hours; an eighteen fold increase. Similarly at 677 °C, by decreasing the 10-minute-lifetime stress 43%, the rupture life increased to 3 hours. It should be noted that the 10-minute lifetime stresses at 593 °C and 677 °C were 234 MPa (34 ksi) and 124 MPa (18 ksi), respectively, and these values were significantly lower than room temperature UTS or YS values for the steel.

Included in Tables 7 and 8 is a value K. Davies, et.al (15), and later Monkman and Grant (16) found that the product of the rupture life and the minimum creep rate is a constant. This constant was also found to be independent of the applied stress and temperature. Figure 27 shows a plot of the log of the minimum creep rate, determined from the stress rupture tests, versus the log of the rupture time as function of test temperature for normalized and stress relieved AAR TC128 grade B steel. The figure verifies Davies', and Monkman's and Grant's research that the product of the rupture life and the minimum creep rate was a constant. The relationship between the minimum creep rate and applied stress was also evaluated, and figure 28 shows the relationships as a function of test temperature. Power law fits were used and the resultant curves are shown. Using figures 27 and 28 an estimate of the rupture life of the steel at a given temperature could be obtained knowing the applied stress.

The results indicate that, in an accident where a fire is involved, the stress-rupture time of this steel could be enhanced by reducing the time during which the tank car experiences the maximum internal pressure or by reducing the maximum internal pressure. The elevated-temperature rupture lifetime properties could possibly be achieved by using additional relief valves, larger flow capacity relief valves, or lower opening pressure relief valves.

Fracture Toughness Properties:

Fracture toughness tests were conducted on both the normalized, and normalized and stress relieved steel at 593, 621, 649, and 677 °C. Compact tension specimens were taken from both the ASTM T-L and L-T directions, and the results are shown in Table 10 and plotted in figure 27. In determining the fracture toughness, a small crack was grown in the specimen by fatiguing. A load was applied with the intention of propagating the initial crack. For all specimens and at each test temperature, crack growth did not occur after application of the load, indicating that the steel had sufficient energy to prevent the initial fatigue crack from propagating. The maximum load was used to calculate the J value which was then used to calculate the fracture toughness value K. (See Table 10).

Figure 27 shows that as the test temperature increased, the fracture toughness decreased. This is due to the fact that the primary mechanical property responsible for the resultant fracture toughness for the steel is the yield strength. As shown earlier in figures 24 and 25, the yield strength decreased continuously as the test temperature increased, hence the fracture toughness would be expected to follow the same trend. Test specimen orientation response (governed by inclusion orientation and rolling direction of the plate), also shown earlier in the same figures, was also followed. That is, the fracture toughness values for the L-T specimens, for both the normalized, and normalized and stress relieved conditions, were greater than the fracture toughness for the specimens taken from the T-L direction. Due to inadequate plate material, only one test specimen taken from the L-T direction was tested at 593 °C. Its fracture toughness followed the same general trend as that observed for the normalized and stress relieved material. These test results indicate that the steel even at 677 °C is highly resistant to both crack initiation and propagation.

SUMMARY

1. The chemical analysis of the as-received plate showed that the steel was within the limits stated in the specification.

2. Metallographic examination of the as-received steel in the unetched condition revealed that the steel was relatively clean, that is, it did not contain a significant number of inclusions. Inclusions normally found in this steel affect the mechanical properties.

3. Specimens were heat treated to determine the affects of temperature and time on the microstructure. Examination of the specimens in the etched condition showed that there was not a significant effect on the microstructure. The proeutectoid ferrite/pearlite did not grow to where it would affect the properties evaluated in this paper. Although the maximum temperature used in this study (677 °C) was higher than the stress relieving temperature (649 °C), no dramatic change in the microstructure was observed.

4. Hardness measurements taken on these same specimens showed that only at 677 °C was there a noticeable decrease in the hardness. This decrease appears to be due to the slight increase in the proeutectoid ferrite in the steel.

5. The hot-tensile properties were found to be anisotropic, that is they were affected by the inclusions present in the steel. Both the UTS and YS were essentially uniform with time. Representative curves of these data showed them to be essentially linear with temperature. The elevated temperature tensile properties were significantly lower than the ambient temperature mechanical properties. Increasing the crosshead speed affected the YS more than the UTS, since the YS is more rate sensitive than the UTS.

6. The stress-rupture properties were highly dependent on the applied stress level. The product of rupture life and minimum creep rate was found to be constant. Relationships were developed that could predict the rupture life at a particular temperature and an applied stress level. The stress-rupture time of this steel could be enhanced by reducing the time during which a tank car experiences the maximum internal pressure or by reducing the maximum internal pressure. The elevated-temperature rupture lifetime properties could possibly be extended by using additional relief valves, larger flow capacity relief valves, or lower opening pressure relief valves.

7. Fracture toughness tests as a function of temperature showed that at temperatures up to 650 °C, the fracture toughness was greater for the normalized and stress relieved steel than for the normalized steel. Catastrophic failure did not occur, that is the elastic strain energy present in the steel was able to prevent a pre-existing crack from propagating in a rapid manner. The fracture toughness for the specimens tested in the ASTM L-T direction was greater than that for specimens tested in the ASTM T-L direction in the plate.

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Table 1. Chemical Composition (wt%), AAR Specification, Heat and Check Analysis for Plate "J".

Element(%)	AAR[1] Specification	Heat[2] Analysis	Check[3] Analysis
Carbon	0.25 max	0.22	.21
Manganese	1.0 - 1.5	1.27	1.34
Phosphorous	0.035 max	0.015	0.017
Sulfur	0.040 max	0.012	0.012
Silicon	0.05 - 0.50	0.241	0.26
Nickel	0.25 max	0.04	0.03
Chromium	0.25 max	0.23	0.26
Molybdenum	0.08 max	0.062	0.07
Copper	0.035 max	0.034	0.04
Vanadium	0.08 max	0.034	0.036
Aluminum	NS[4]	0.065	0.070
Nitrogen	NS	NS	0.0067
CE[5]	0.62	0.50	0.51

[1] AAR Specification for Tank Cars; M-1002, M-128
[2] Bethlehem Steel Corporation
[3] National Institute of Standards & Technology
[4] Not Specified
[5] CE (%) = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15

Table 2. Hardness, Rockwell A; for Coupons that were Heat Treated at 593, 621, 649, and 677 °C for 30, 60, 90, and 120 Minutes.

Time at Temp. (min)	Temp. °C	Hard (HRA)[1]	Temp. °C	Hard (HRA)	Temp. °C	Hard (HRA)	Temp. °C	Hard (HRA)
30	593	81.8	621	81.5	649	81.6	677	81.2
60	593	81.5	621	81.7	649	81.7	677	80.2
90	593	81.5	621	81.6	649	81.6	677	80.5
120	593	81.9	621	81.7	649	82.1	677	80.6

[1] Average of four readings

Table 3. Tensile test results for specimens tested at 593, 621, 649, and 677 °C for 60, 90, and 120 minutes. Crosshead speed was 0.0127 cm/min. The specimens were taken from the ASTM T-L direction, i.e., long axis of the specimen was parallel to the rolling direction of the plate.

Specimen No.	Test Temp. (°C)	Time at Temperature (Min)	UTS (MPa)	YS (0.2%) (MPa)	Elong. 25.4 mm. (%)	RA (%)
2	677	120	119.2	77.9	ND[1]	93.7
4	677	120	121.3	77.9	ND[1]	92.6
6	677	90	123.3	77.7	ND[1]	92.8
8	677	60	123.3	82.7	ND[1]	93.0
11	649	60	153.0	95.8	78.0	88.2
13	649	90	155.7	105.4	78.1	86.4
15	649	120	156.4	102.0	76.1	77.2
17	621	60	194.3	122.0	56.9	78.8
19	621	90	195.7	126.8	57.4	79.7
21	621	120	192.2	119.9	62.8	82.4
23	593	60	236.6	150.2	58.0	74.2
25	593	90	234.9	148.8	57.4	74.3
27	593	120	237.7	153.6	40.0	75.7

[1] Not determined, gage marks obliterated during test.

Table 4. Tensile test results for specimens tested at 593, 621, 649, and 677 °C for 60, 90, and 120 minutes. Crosshead speed was 0.127 cm/min. The specimens were taken from the ASTM T-L direction, i.e., long axis of the specimen was transverse to the rolling direction of the plate.

Specimen No.	Test Temp. (°C)	Time at Temperature (Min)	UTS (MPa)	YS (0.2%) (MPa)	Elong. 25.4 mm. (%)	RA (%)
5	677	120	119.9	106.8	ND[1]	93.4
7	677	90	123.3	102.7	ND[1]	92.9
10	677	60	126.1	104.9	ND[1]	92.0
12	649	60	160.5	135.7	64.6	84.7
14	649	90	157.8	128.8	80.0	87.3
16	649	120	159.8	132.3	68.7	87.2
18	621	60	197.1	155.7	66.2	85.9
20	621	90	194.3	153.4	68.0	79.5
22	621	120	189.5	141.9	61.1	79.0
24	593	60	241.2	172.9	60.6	72.3
29	593	90	243.9	172.9	58.8	73.5
28	593	120	241.8	185.3	55.0	74.9

[1] Not determined, gage marks obliterated during test.

Table 5. Tensile test results for specimens tested at 593, 621, 649, and 677 °C for 60, 90, and 120 minutes. Crosshead speed was 0.0127 cm/min. The specimens were taken from the ASTM L-T direction, i.e., long axis of the specimen was transverse to the rolling direction of the plate.

Specimen No.	Test Temp. (°C)	Time at Temperature (Min)	UTS (MPa)	YS (0.2%) (MPa)	Elong. 25.4 mm. (%)	RA (%)
66	677	120	119.9	77.2	70.5	93.5
68	677	90	123.3	75.8	82.0	93.5
70	677	60	123.3	75.8	88.1	93.4
72	649	60	161.2	105.4	66.1	87.4
90	649	90	159.3	102.7	66.6	84.2
76	649	120	148.8	98.5	61.5	87.3
78	621	60	195.0	131.6	66.5	79.8
80	621	90	191.8	121.3	55.0	80.9
82	621	120	194.3	124.7	65.6	79.9
92	593	60	253.6	157.0	42.1	75.8
86	593	90	243.2	155.0	50.5	71.2
88	593	120	242.5	153.0	48.4	71.5

Table 6. Tensile test results for specimens tested at 593, 621, 649, and 677 °C for 60, 90, and 120 minutes. Crosshead speed was 0.127 cm/min. The specimens were taken from the ASTM L-T direction, i.e., long axis of the specimen was transverse to the rolling direction of the plate.

Specimen No.	Test Temp. (°C)	Time at Temperature (Min)	UTS (MPa)	YS (0.2%) (MPa)	Elong. 25.4 mm. (%)	RA (%)
67	677	120	122.0	104.0	80.8	92.7
69	677	90	126.1	98.5	88.8	92.1
71	677	60	126.1	101.3	88.4	91.0
73	649	60	157.1	121.9	72.8	86.2
75	649	90	154.1	121.9	60.1	85.2
77	649	120	155.7	126.8	65.4	86.3
79	621	60	195.7	147.4	60.5	78.4
81	621	90	196.4	148.1	54.8	77.6
83	621	120	195.6	150.2	61.1	78.4
91	593	60	241.2	178.5	58.3	71.0
87	593	90	245.3	178.5	45.5	69.7
89	593	120	249.4	192.6	44.3	72.7

Table 7. Stress-rupture test results for specimens that were tested at 593 °C and 621 °C at the indicated applied stresses.

Specimen No.	Test Temp. (°C)	Applied Stress (MPa)	Time to Failure (Min)	Elong. 25.4 mm. (%)	RA (%)	K[1]
32	593	170.2	170	56.2	70.6	23.0
34	593	189.5	71	55.0	72.1	22.4
40	593	213.6	27	58.4	74.8	22.8
45	593	179.1	131	56.7	70.9	21.6
46	593	199.8	49	60.6	70.8	22.3
49	593	184.0	127	56.9	68.6	20.9
54	593	186.0	84	53.0	69.8	23.3
30	621	126.1	240	74.0	78.9	23.9
33	621	126.8	219	66.6	81.5	21.9
37	621	158.5	53	67.7	83.0	25.0
38	621	144.7	85	69.4	76.4	23.0
39	621	186.0	12	56.2	76.0	18.0
47	621	144.7	113	87.2	81.7	24.9
48	621	137.8	129	66.7	78.6	24.0
53	621	128.2	236	ND[2]	79.4	22.2

[1] $K = t_f{*}(\epsilon)$ where t_f = time to failure and ϵ = minimum creep rate, mcr.
[2] Not determined.

Table 8. Stress-rupture test results for specimens that were tested at 649 °C and 677 °C at the indicated applied stresses.

Specimen No.	Test Temp. (°C)	Applied Stress (MPa)	Time to Failure (Min)	Elong. 25.4 mm. (%)	RA (%)	K[1]
36	649	105.4	115	79.5	87.4	26.9
41	649	144.7	19	65.0	83.0	22.0
42	649	117.1	75	65.1	82.9	ND[2]
50	649	130.9	33	87.2	86.6	23.7
51	649	113.7	90	81.1	86.9	24.3
35	677	84.1	78	96.7	92.0	26.0
43	677	96.5	40	71.9	92.3	24.3
44	677	110.2	22	93.6	92.6	24.2
52	677	89.6	75	96.6	93.8	24.9

1 $K = t_f * (\dot{\epsilon})$ where t_f = time to failure and $\dot{\epsilon}$ = minimum creep rate, mcr.
2 Not determined.

Table 9. Effects of decreasing the 10-minute lifetime stress on the rupture life.

		Increase in Rupture Life					
Temperature	10-Minute Lifetime Stress (MPa)	One Hour	Stress	Two Hours	Stress	Three Hours	Stress
593 °C	234.3	-17%	194.5	-23%	180.4	-27%	171.0
621 °C	190.0	-19%	153.9	-26%	140.6	-30%	133.0
649 °C	157.2	-23%	121.0	-33%	105.3	-38%	97.5
677 °C	123.8	-27%	90.4	-37%	78.0	-43%	70.6

Table 10. Fracture toughness results for specimens tested at 593, 621, 649, and 677 °C. Specimens were held at the respective temperature 90 minutes prior to testing.

Specimen No.	Test Temp. °C	Cond.[1]	Orient.	Fracture Toughness J^2	J^3	K^4	K^5
CT-19	593	A+SR	TL	809	140	153	168
CT-22	593	A+SR	TL	1021	176	175	193
CT-35	593	N	LT	1237	213	193	212
CT-46	593	A+SR	LT	1713	296	227	250
CT-43	593	A+SR	LT	1429	267	207	228
CT-12	593	A+SR	TL	632	109	138	152
CT-20	621	A+SR	TL	647	112	139	153
CT-23	621	A+SR	TL	649	112	140	154
CT-8	621	A+SR	TL	1055	182	178	196
CT-47	621	A+SR	TL	1351	233	201	221
CT-31	621	N	LT	1144	197	185	204
CT-21	649	A+SR	TL	367	63	105	116
CT-24	649	A+SR	TL	506	87	123	135
CT-44	649	A+SR	LT	995	172	173	190
CT-48	649	A+SR	LT	970	168	171	188
CT-32	649	A+SR	LT	1004	173	174	191
CT-33	649	A+SR	LT	964	166	170	187
CT-18	677	A+SR	TL	429	74	113	124
CT-45	677	A+SR	LT	686	118	143	157
CT-34	677	N	LT	745	129	150	165
CT-36	677	N	LT	727	126	148	163

1 A+SR: Normalized plus stress relieved
N: Normalized
2 $(Ft.- lbs)/in^2$
3 KJ/m^2
4 $Ksi*in^{1/2}$ $K = (JE)^{1/2}$ where $E = 29E6$
5 $MPa*M^{1/2}$

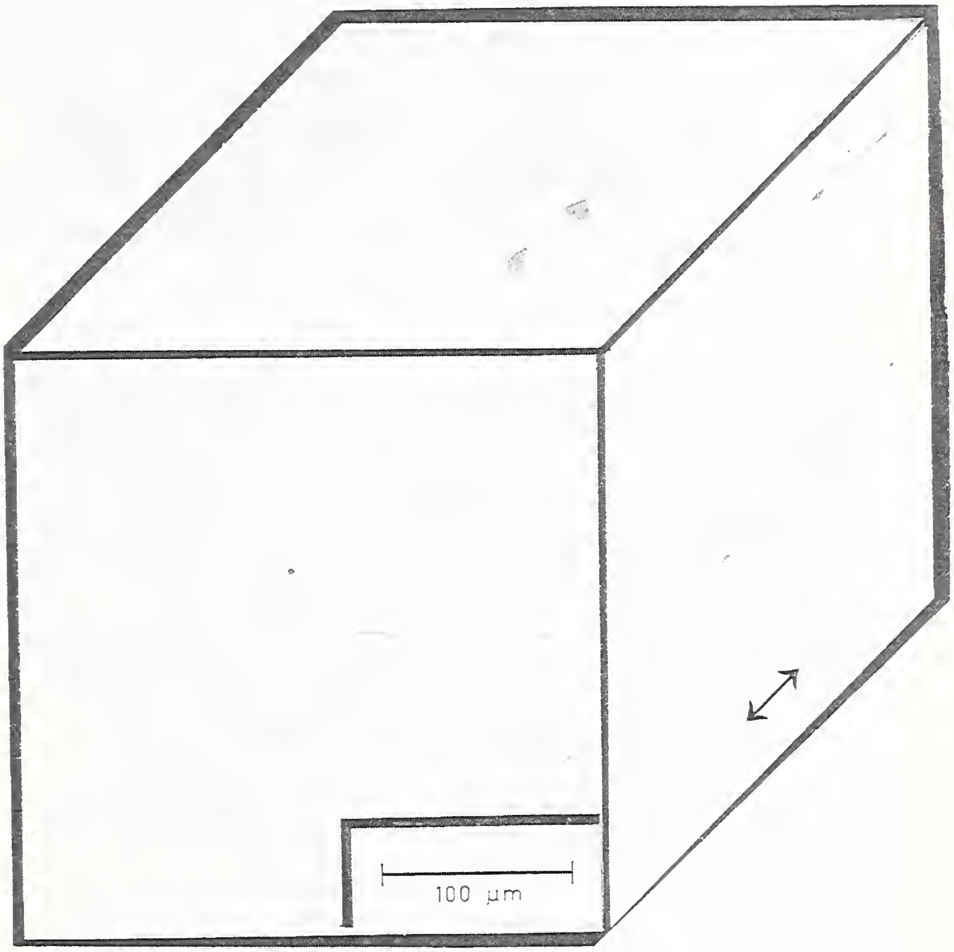
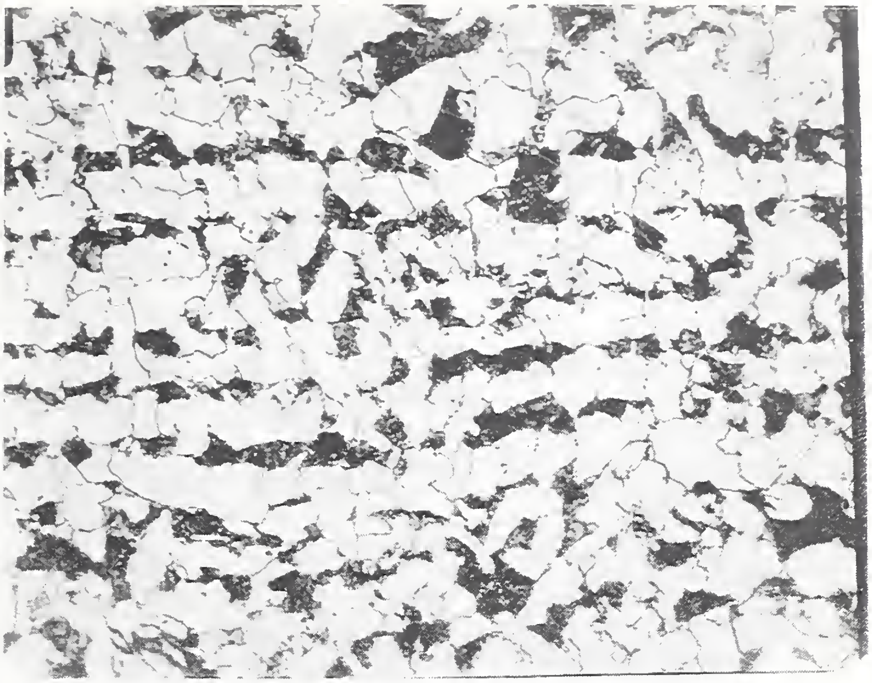


Figure 1. Photomicrographs of the as-received normalized AAR TC128 grade B steel in three orthogonal direction and in the unetched condition. Plate rolling direction shown by arrow in the photomicrograph.

Figure 2. Photomicrographs of the as-received normalized AAR TC128 grade B steel in three orthogonal directions in the etched condition. Etch: 1% Nital



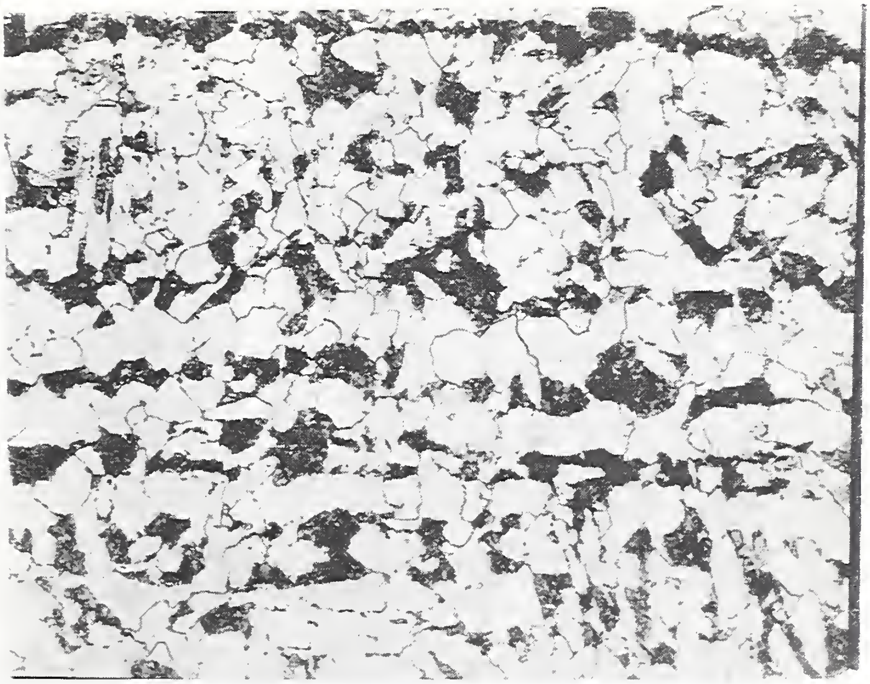
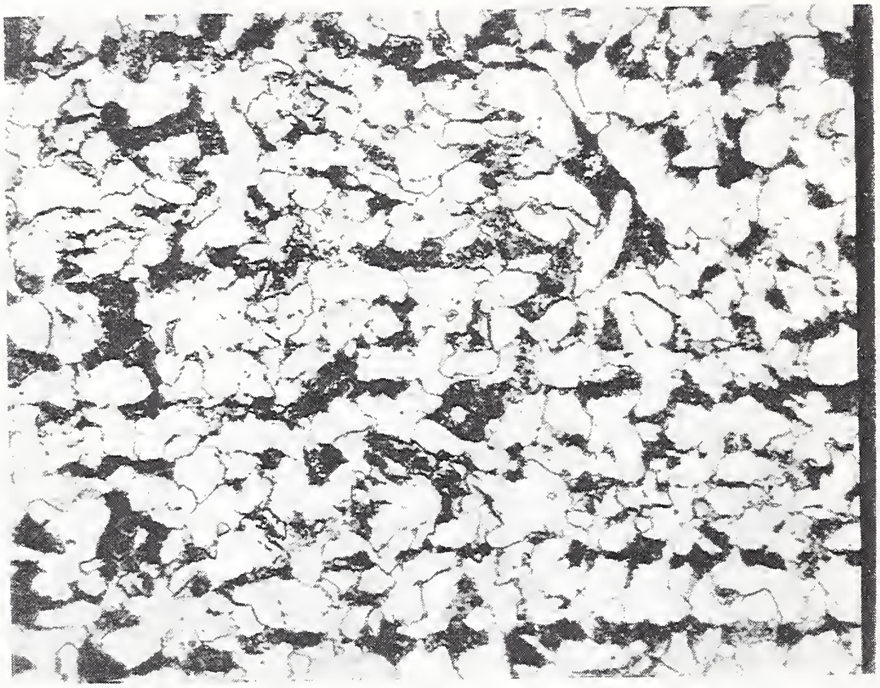
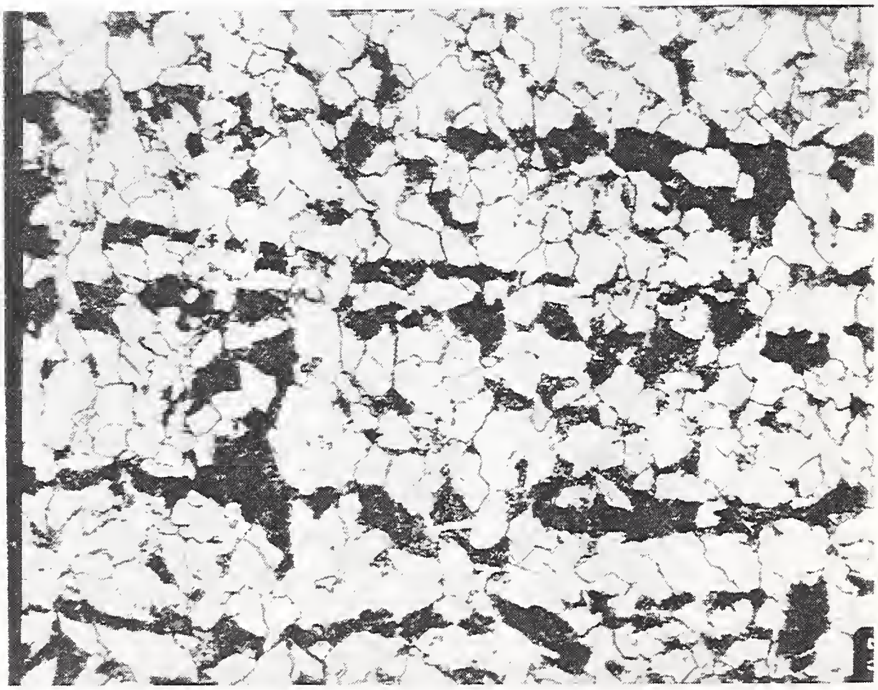


Figure 3. Photomicrographs of the as-received normalized and stress relieved AAR TC128 grade B taken at two different locations.
Etch: 1% Nital Mag. X500.



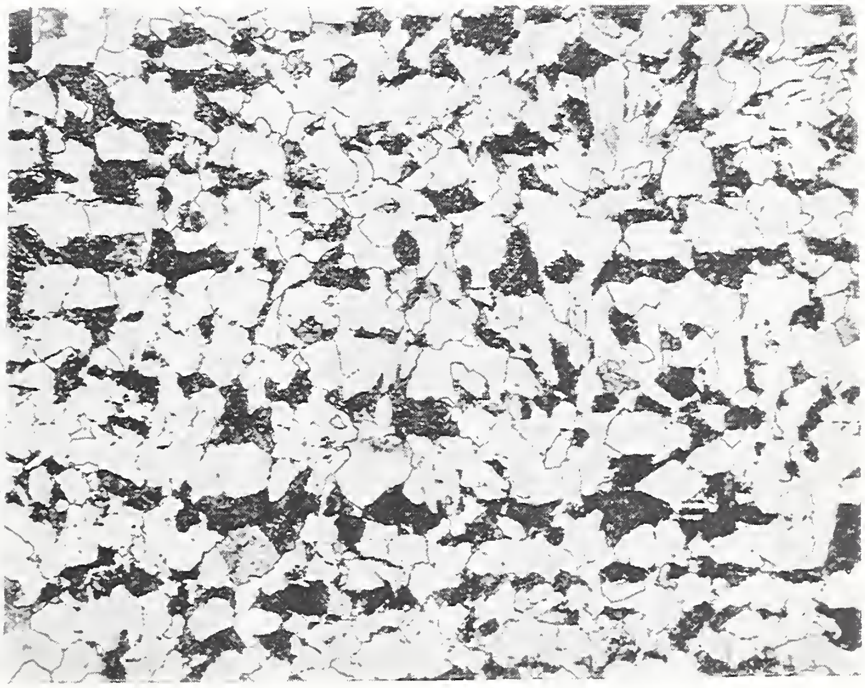
(a)



(b)

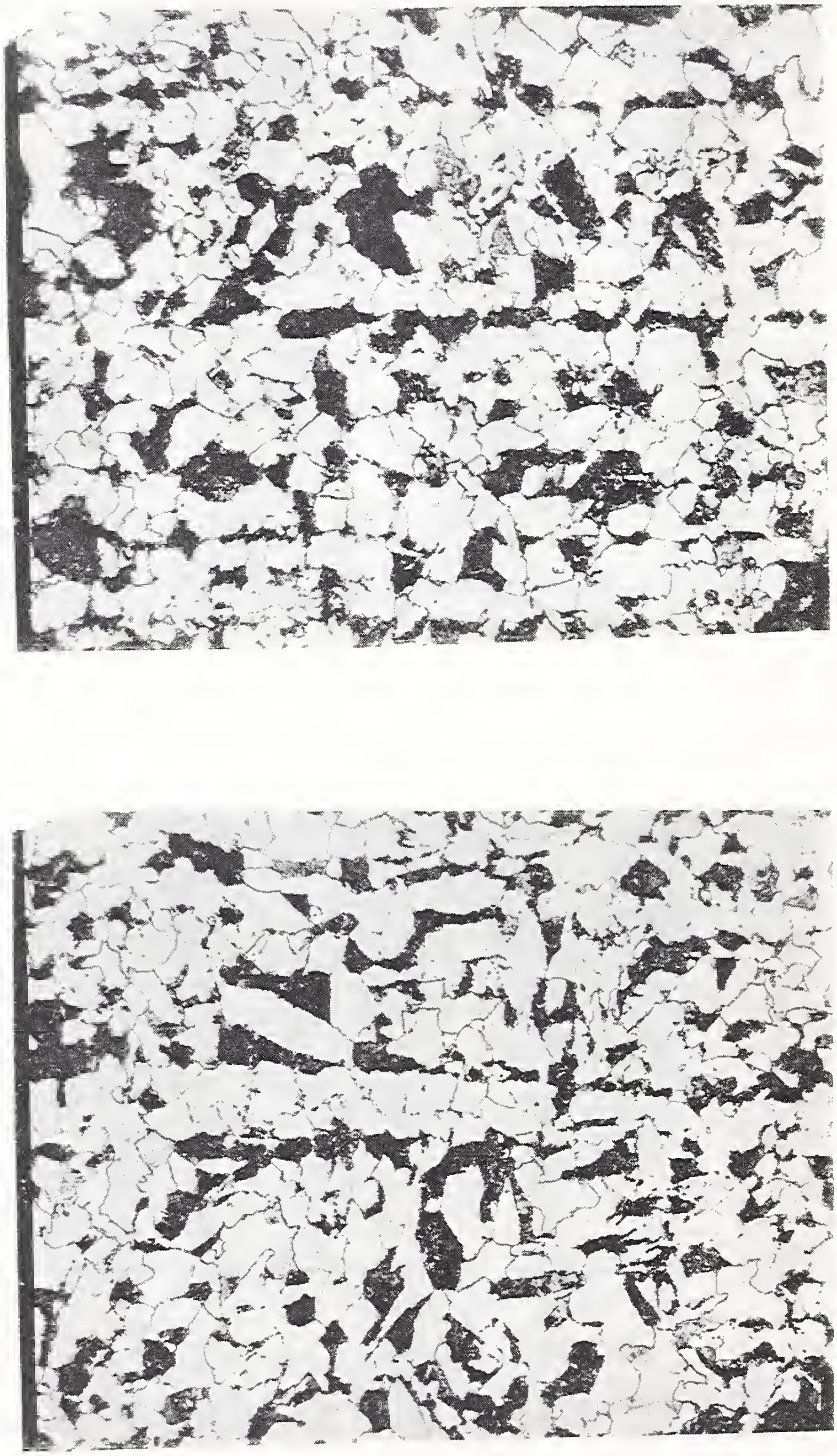
Figure 4. Photomicrographs of as-received normalized and stress relieved AAR TC128 grade B steel after 30 (a) and 60 (b) minutes at 593 C. Etch: 1% Nital Mag. X500.

(a)



(b)

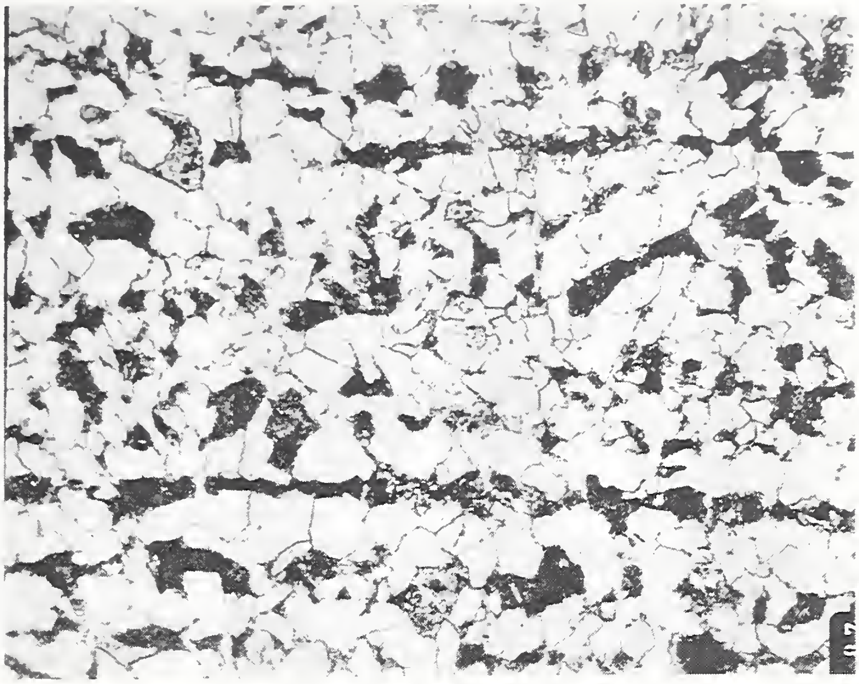
Figure 5. Photomicrographs of as-received normalized and stress relieved AAR TC128 grade B steel after 90 (a) and 120 (b) minutes at 593 C. Etch: 1% Nital Mag. X500.



(a)

(b)

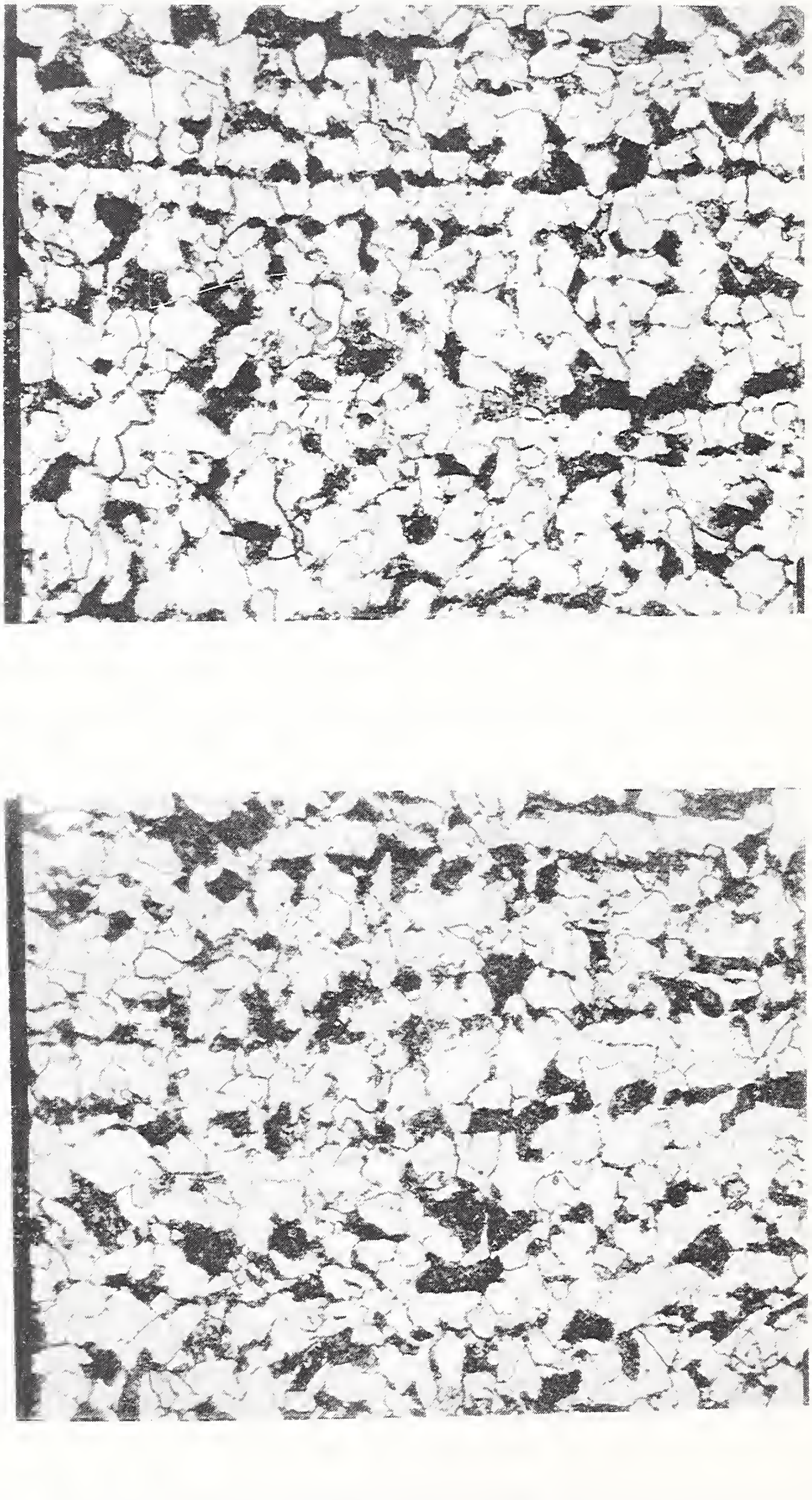
Figure 6. Photomicrographs of as-received normalized and stress relieved AAR TC128 grade B steel after 30 (a) and 60 (b) minutes at 621 C. Etch: 1% Nital Mag. X500.



(a)

(b)

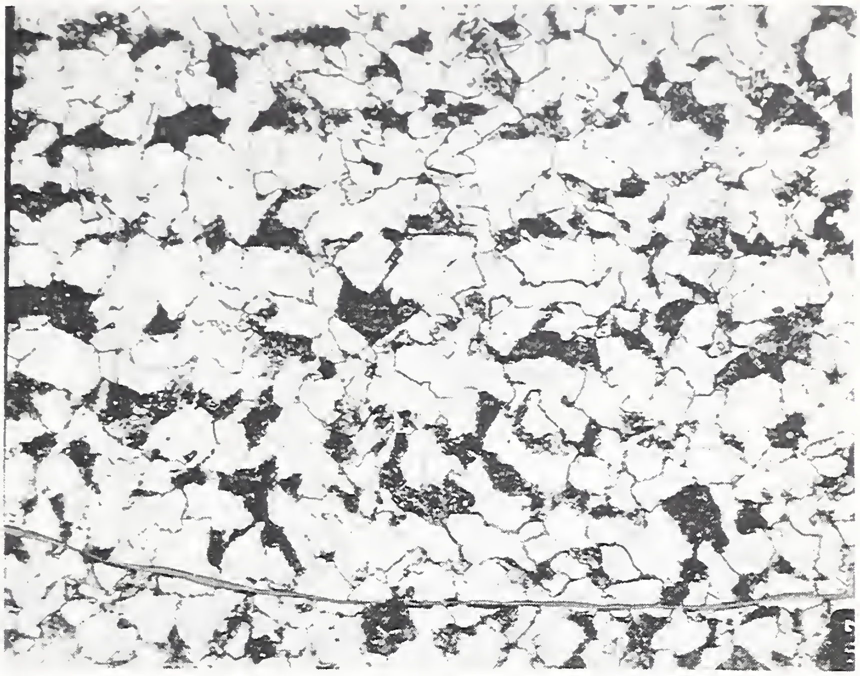
Figure 7. Photomicrographs of as-received normalized and stress relieved AAR TC128 grade B steel after 90 (a) and 120 (b) minutes at 621 C. Etch: 1% Nital Mag. X500.



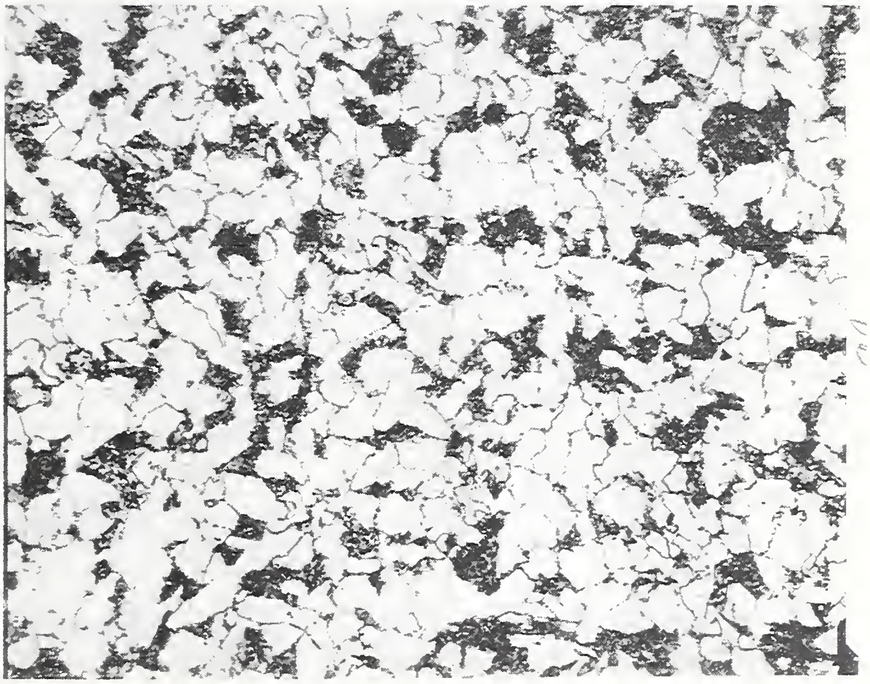
(a)

(b)

Figure 8. Photomicrographs of as-received normalized and stress relieved AAR TC128 grade B steel after 30 (a) and 60 (b) minutes at 649 C. Etch: 1% Nital Mag. X500.



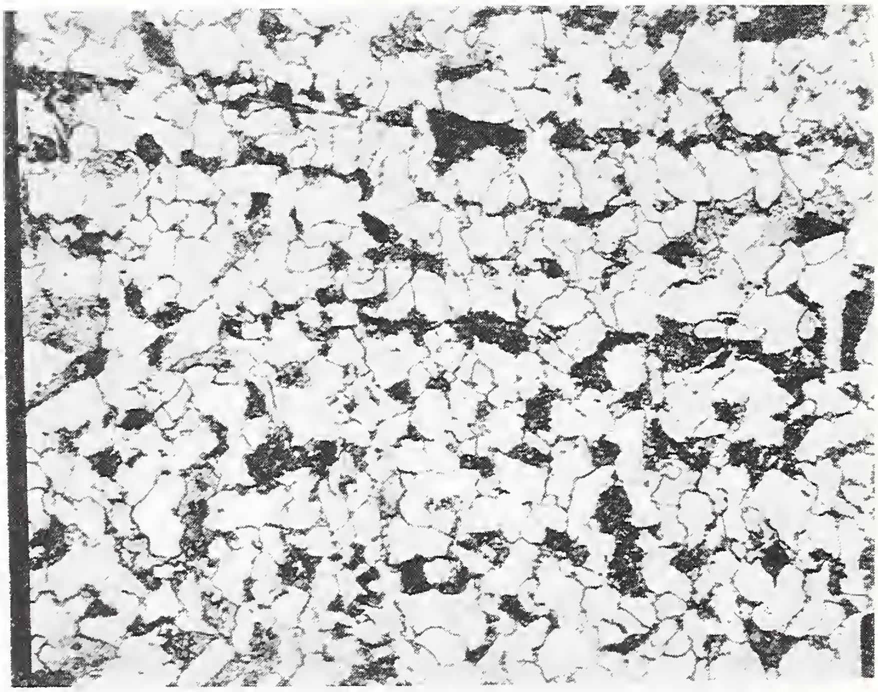
(a)



(b)

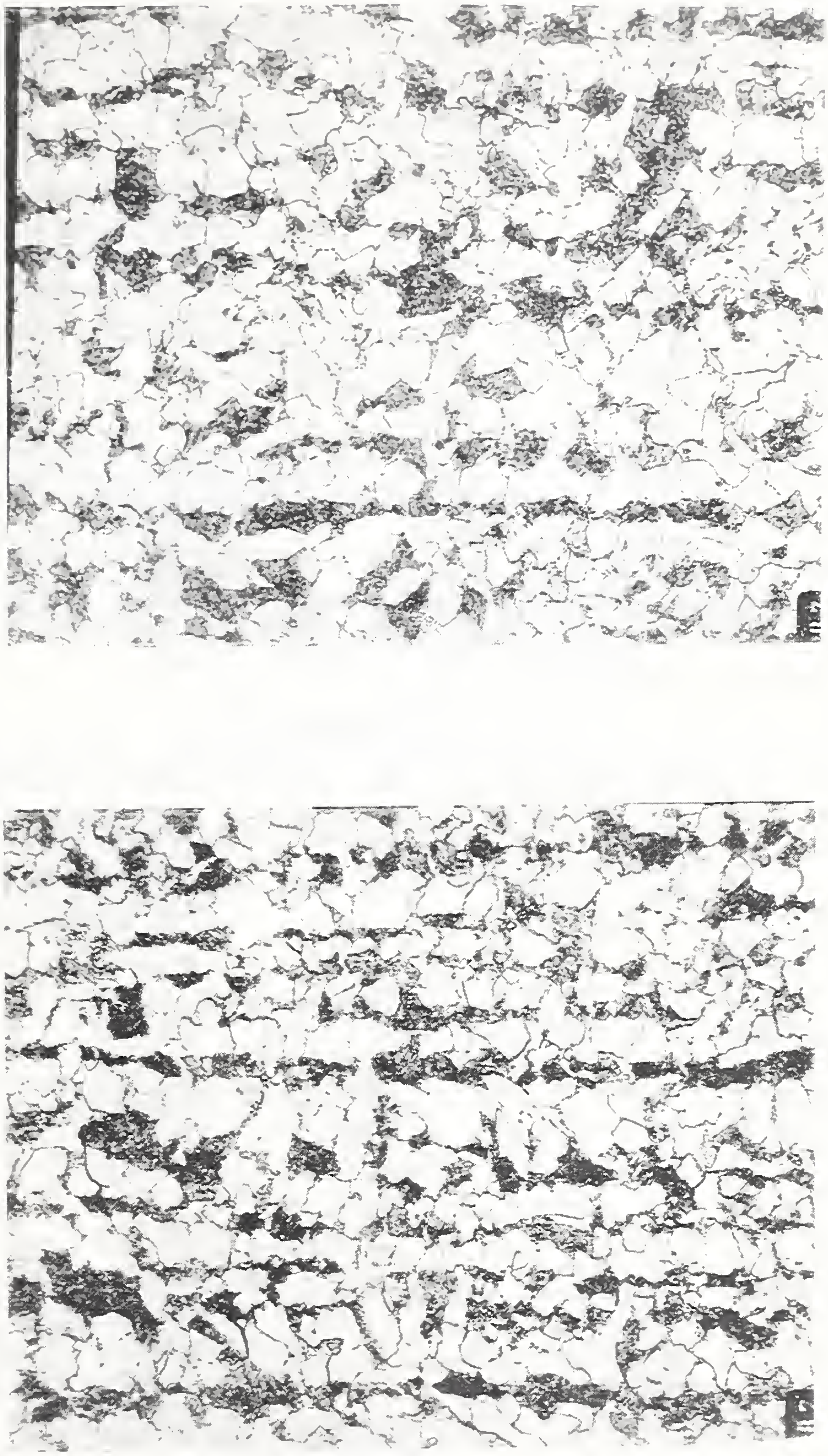
Figure 9. Photomicrographs of as-received normalized and stress relieved AAR TC128 grade B steel after 90 (a) and 120 (b) minutes at 649 C. Etch: 1% Nital Mag. X500.

(a)



(b)

Figure 10. Photomicrographs of as-received normalized and stress relieved AAR TC128 grade B steel after 30 (a) and 60 (b) minutes at 677 C. Etch: 1% Nital Mag. X500.



(a)

(b)

Figure 11. Photomicrographs of as-received normalized and stress relieved AAR TC128 grade B steel after 90 (a) and 120 (b) minutes at 677 C. Etch: 1% Nital Mag. X500.

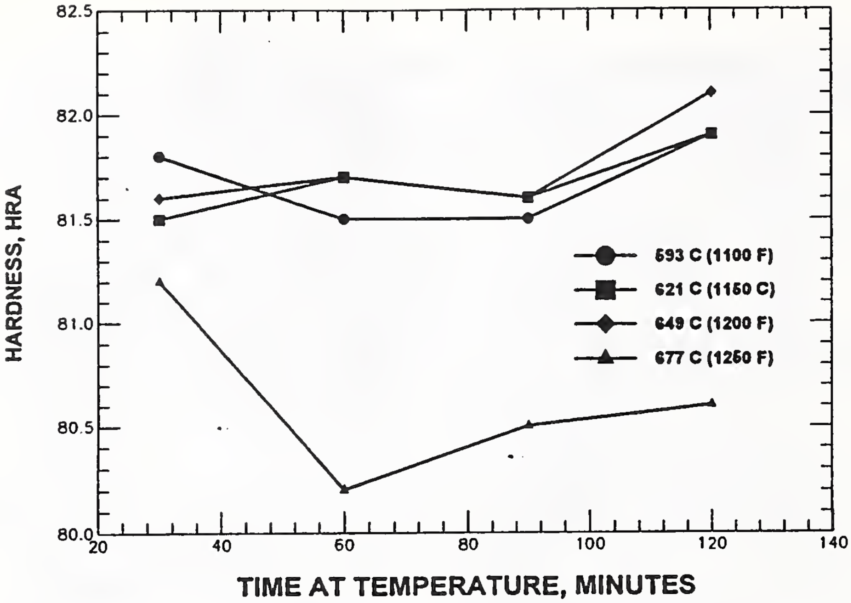


Figure 12. Average hardness (Rockwell A) versus time at 593 C, 621 C, 649 C, and 677 C for normalized and stress relieved AAR TC128 grade B steel specimens.

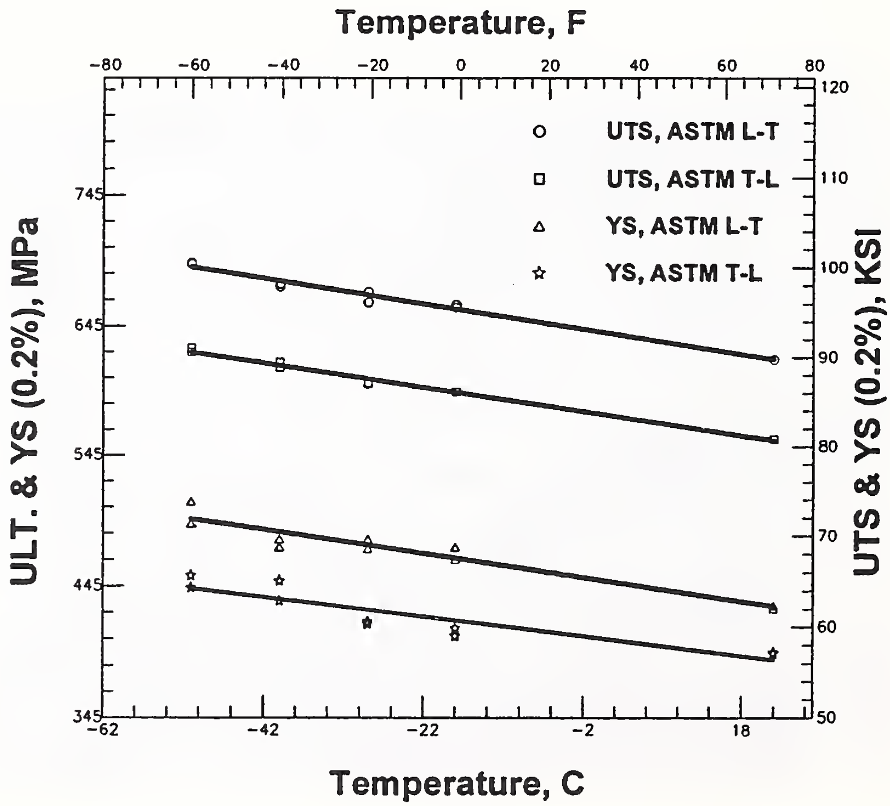


Figure 13. UTS and YS results for normalized and stress relieved AAR TC128 grade B tensile specimens tested at room temperature to -51 C.

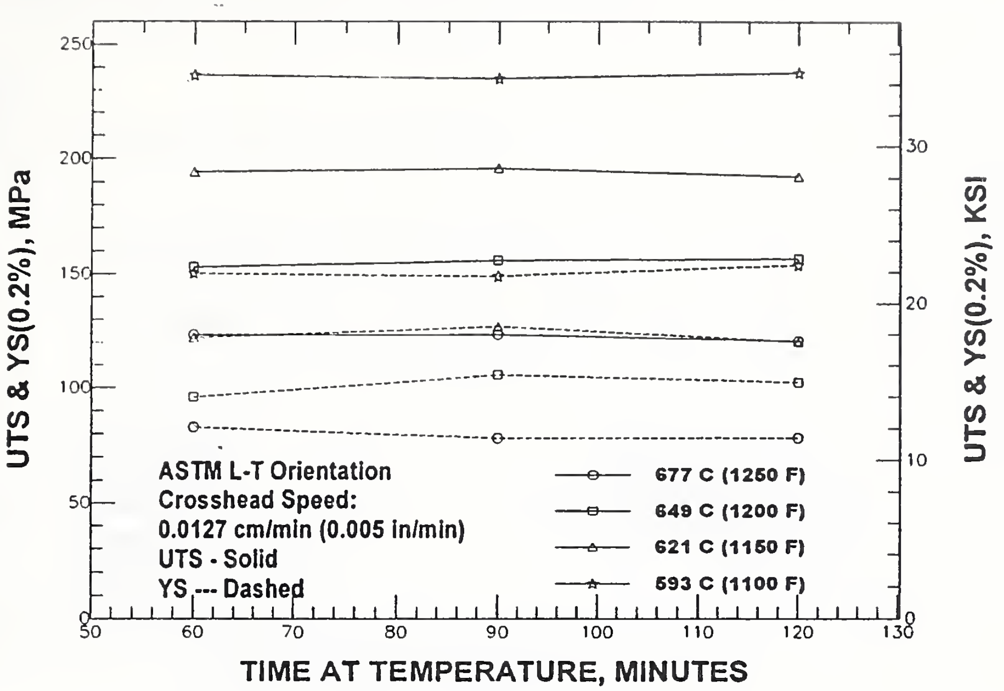


Figure 14. UTS and YS results for specimens tested at a crosshead speed of 0.0127 cm/minute and taken from the ASTM L-T direction in the plate.

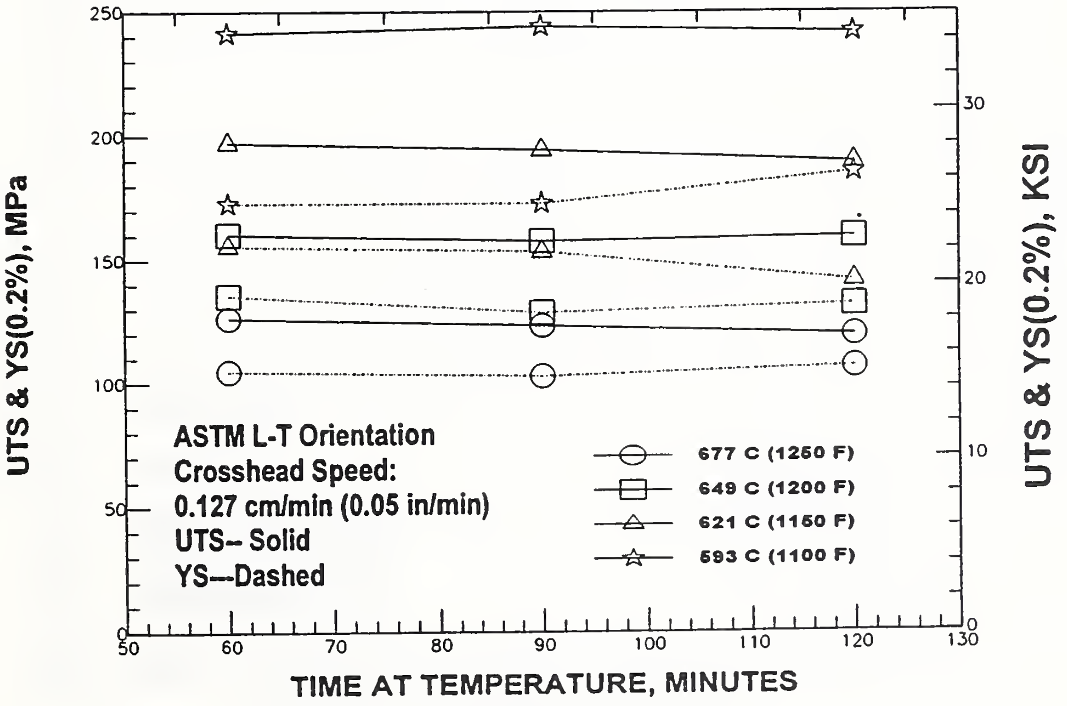


Figure 15. UTS and YS results for specimens tested at a crosshead speed of 0.127 cm/minute and taken from the ASTM L-T direction in the plate.

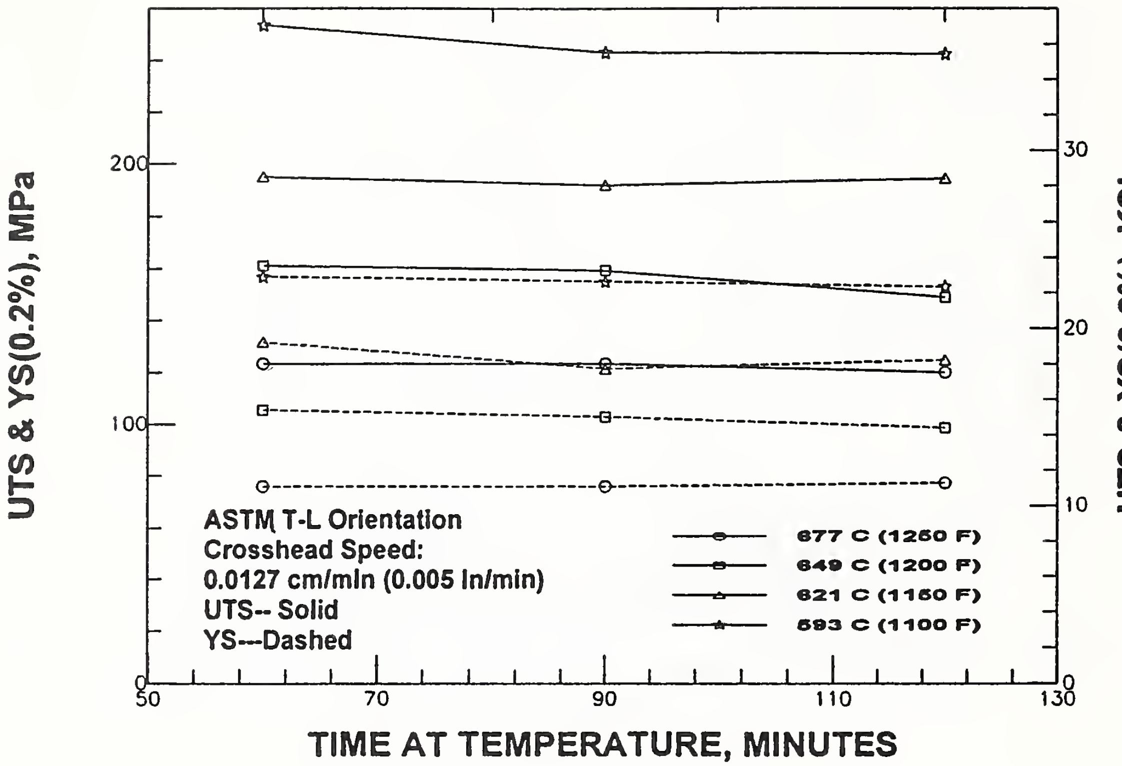


Figure 16. UTS and YS results for specimens tested at a crosshead speed of 0.0127 cm/minute and taken from the ASTM T-L direction in the plate.

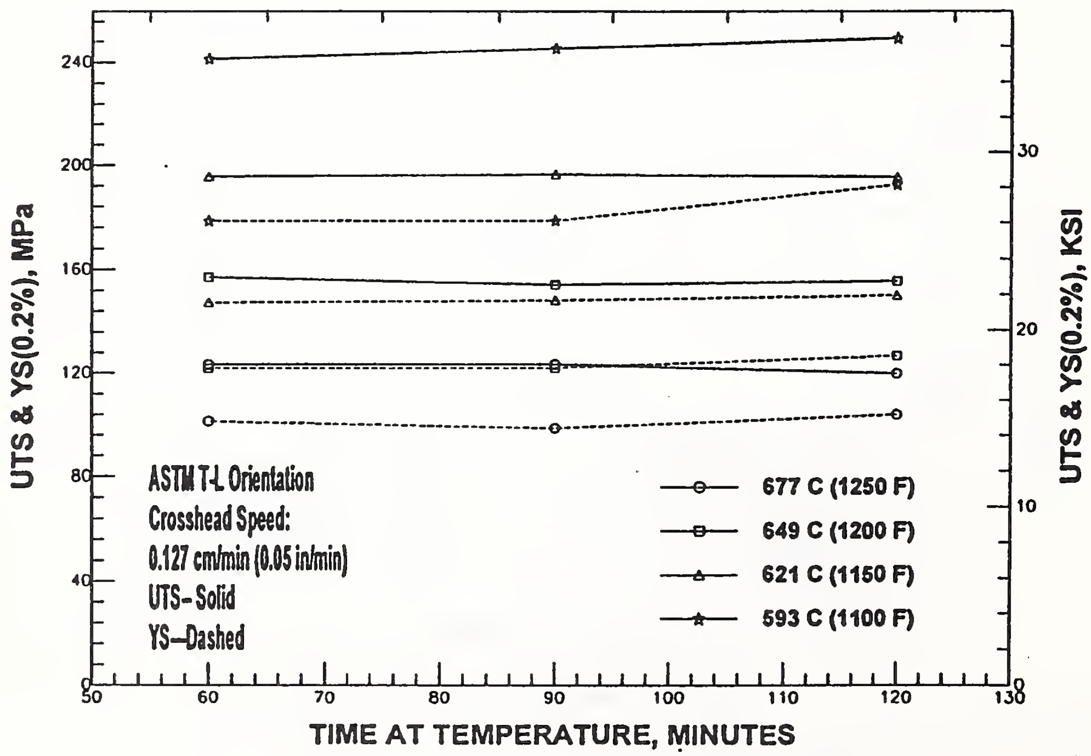


Figure 17. UTS and YS results for specimens tested at a crosshead speed of 0.127 cm/minute and taken from the ASTM T-L direction in the plate.

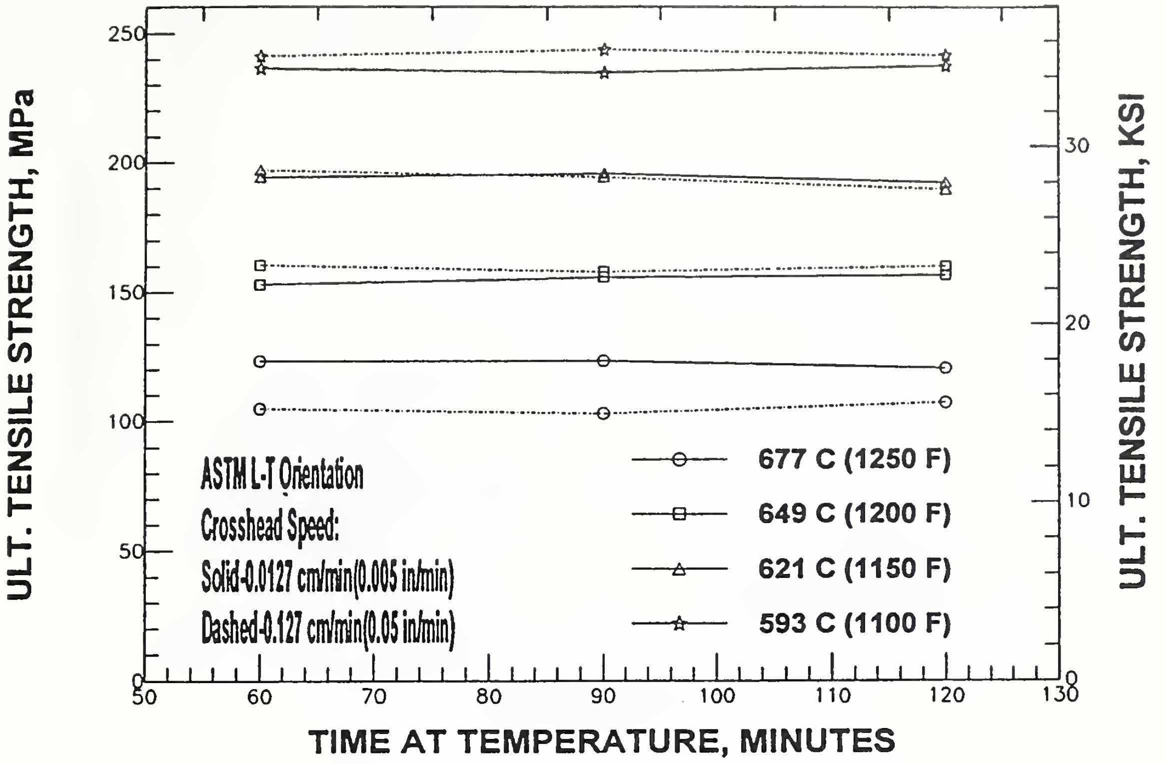


Figure 18. Affects of crosshead speed, temperature, and time on the UTS. Specimens were taken from the ASTM L-T direction in the plate.

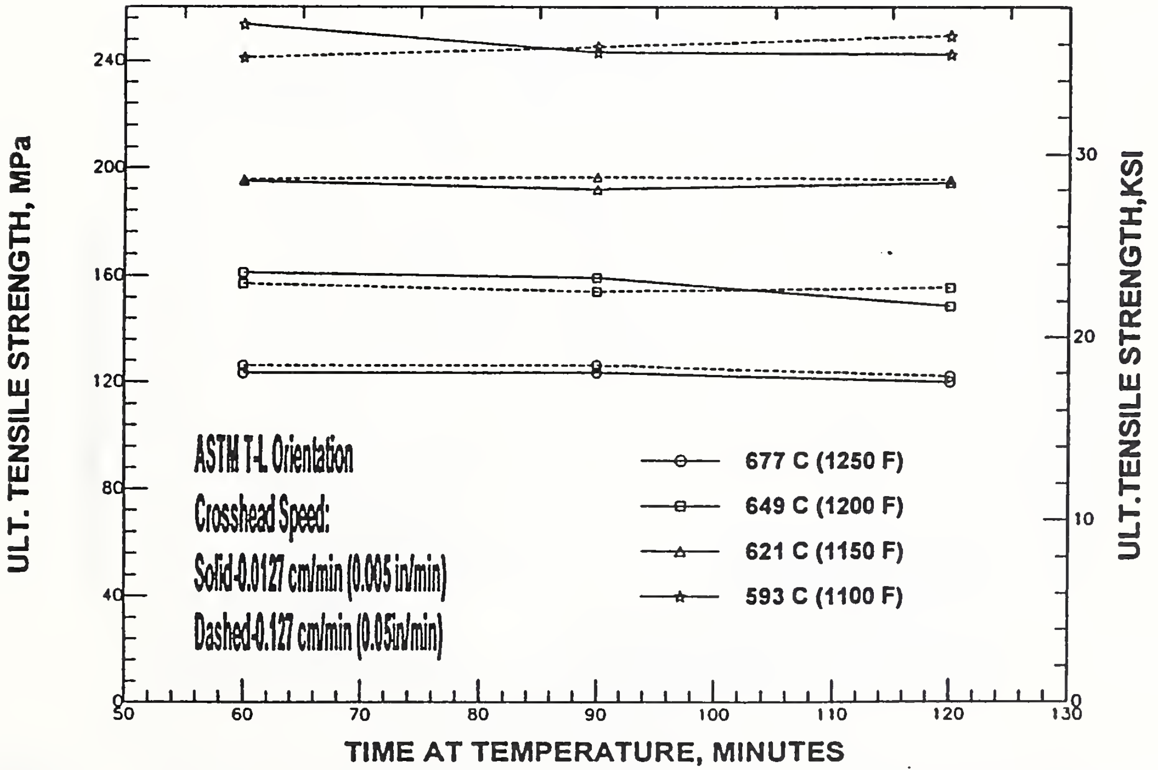


Figure 19. Affects of crosshead speed, temperature, and time on the UTS. Specimens were taken from the ASTM T-L direction in the plate.

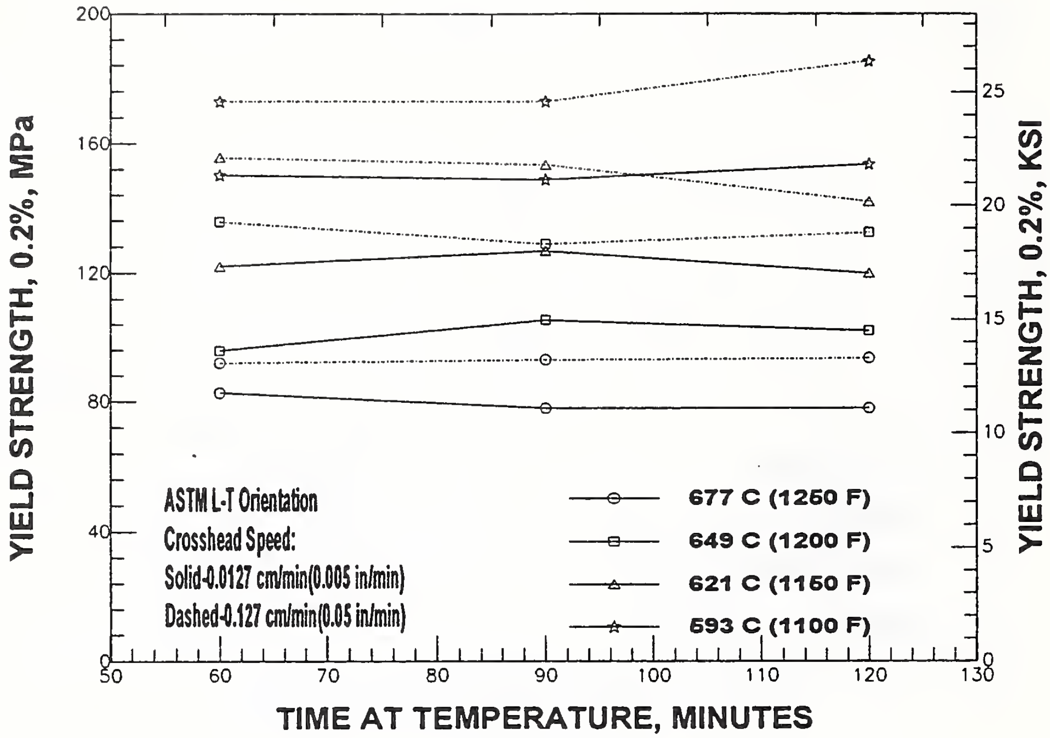


Figure 20. Affects of crosshead speed, temperature, and time on the YS. Specimens were taken from the ASTM L-T direction in the plate.

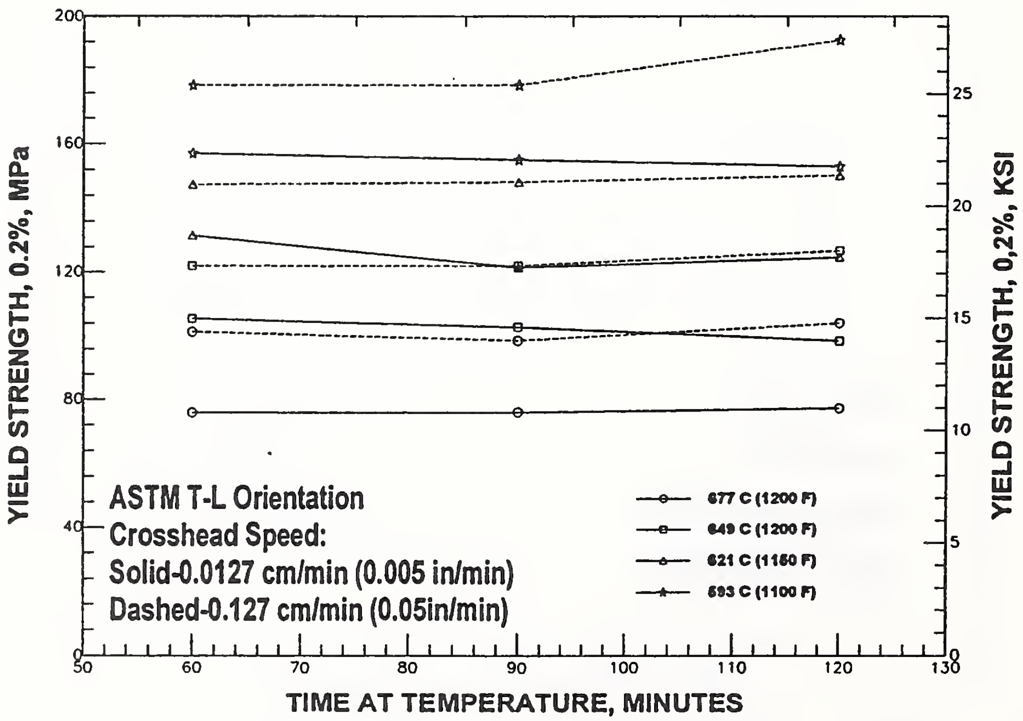


Figure 21. Effects of crosshead speed, temperature, and time on the YS. Specimens were taken from the ASTM T-L direction in the plate.

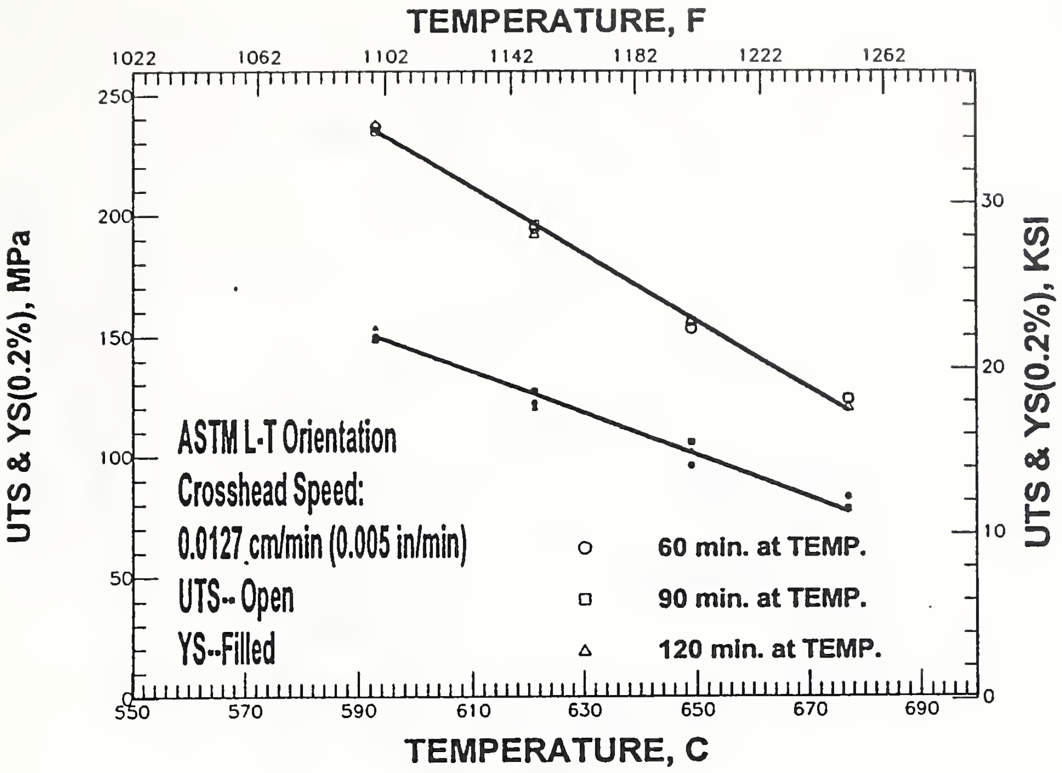


Figure 22. UTS and YS as a function of temperature. Specimens were taken from the ASTM L-T direction in the plate and tested at a crosshead speed of 0.0127 cm/minute.

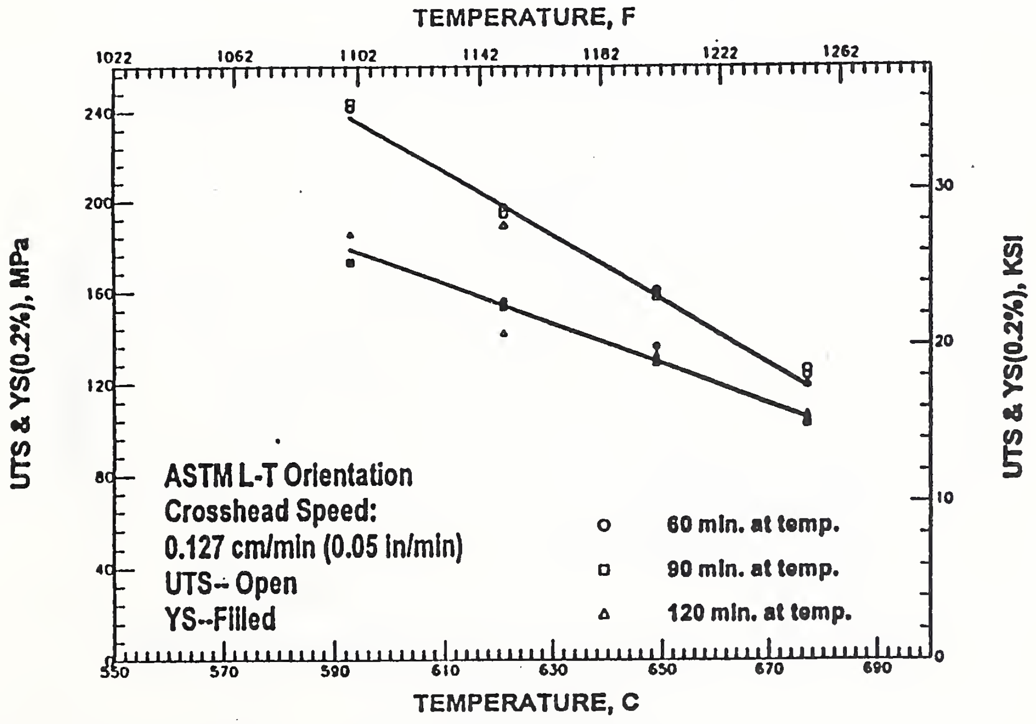


Figure 23. UTS and YS as a function of temperature. Specimens were taken from the ASTM L-T direction in the plate and tested at a crosshead speed of 0.127 cm/minute.

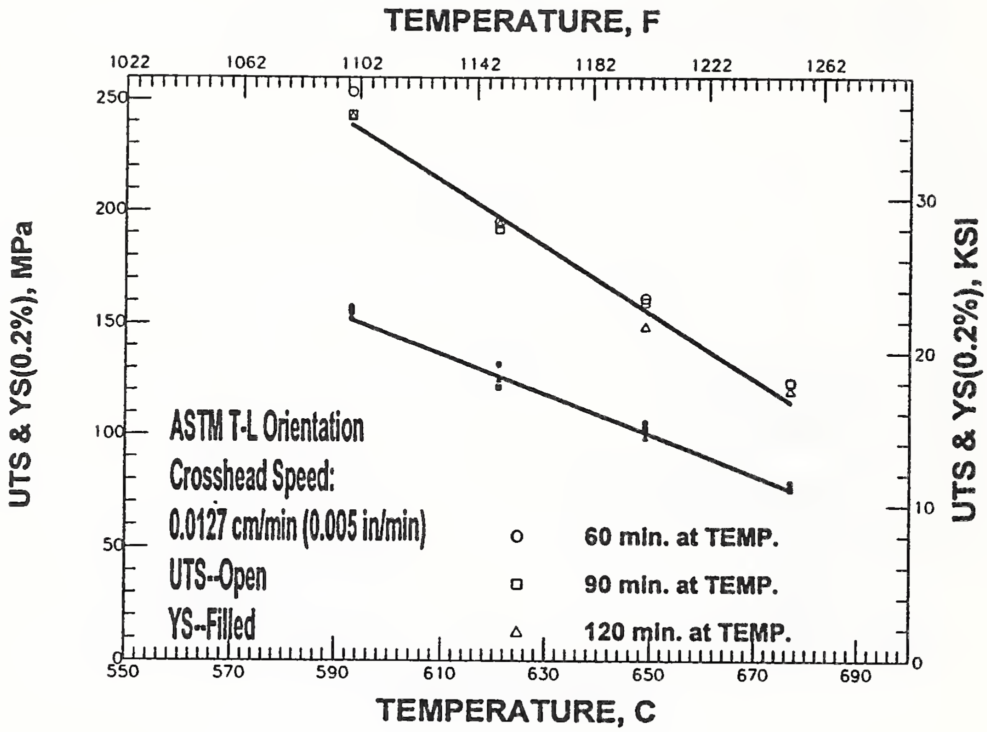


Figure 24. UTS and YS as a function of temperature. Specimens were taken from the ASTM T-L direction in the plate and tested at a crosshead speed of 0.0127 cm/minute.

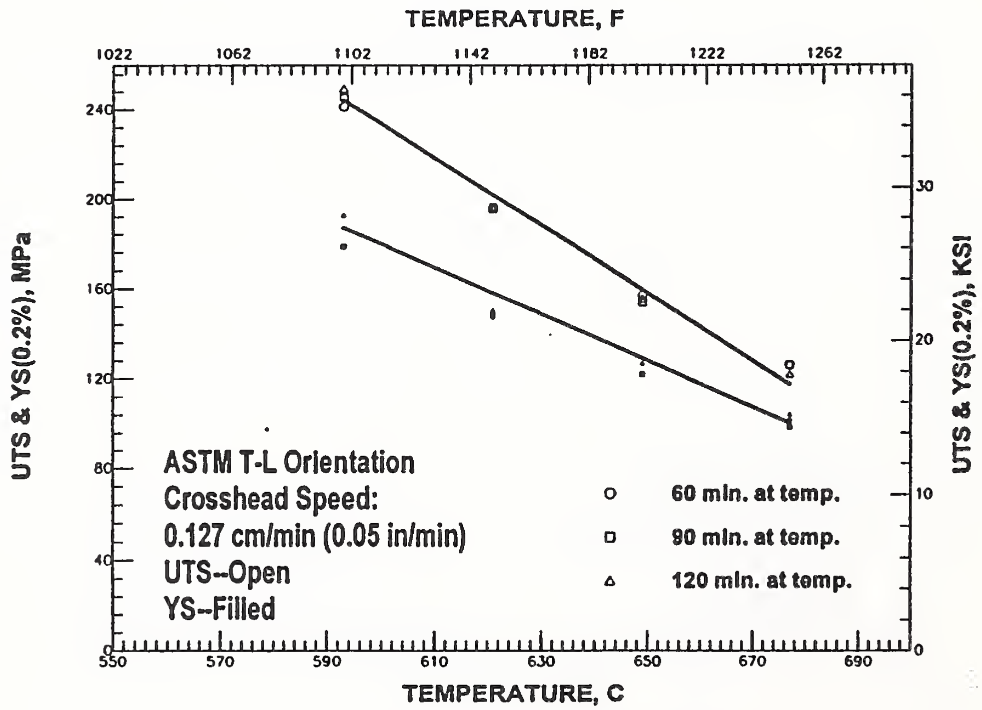


Figure 25. UTS and YS as a function of temperature. Specimens were taken from the ASTM T-L direction in the plate and tested at a crosshead speed of 0.127 cm/minute.

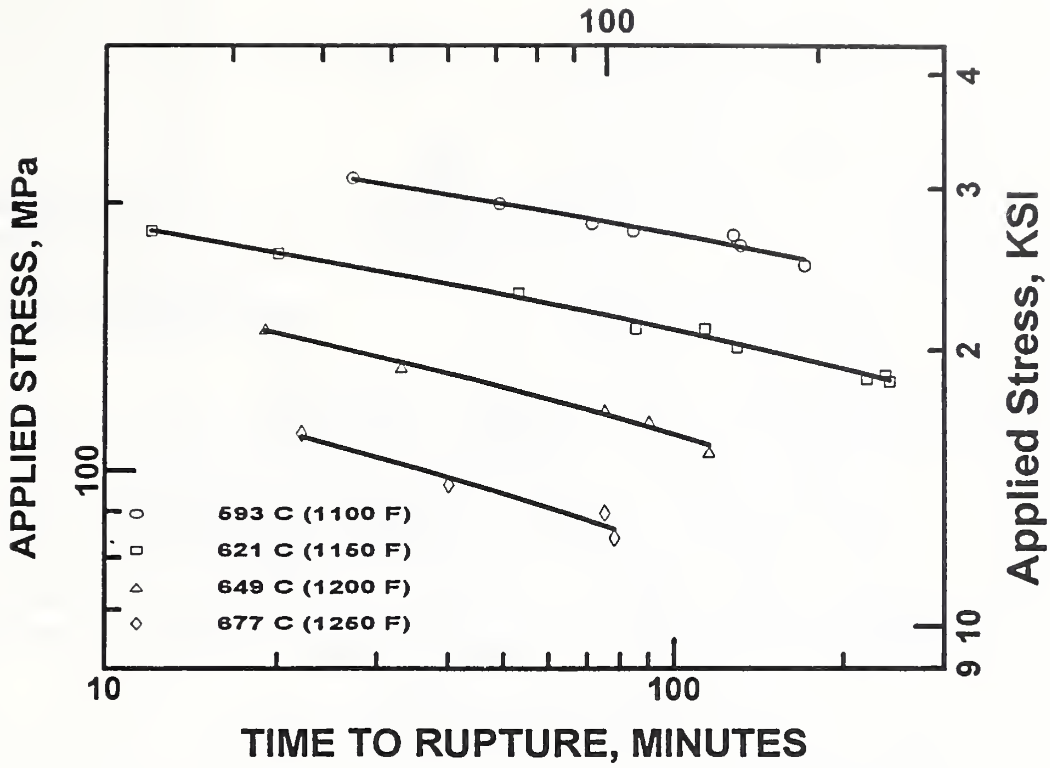


Figure 26. Applied stress versus time to rupture as a function of temperature.

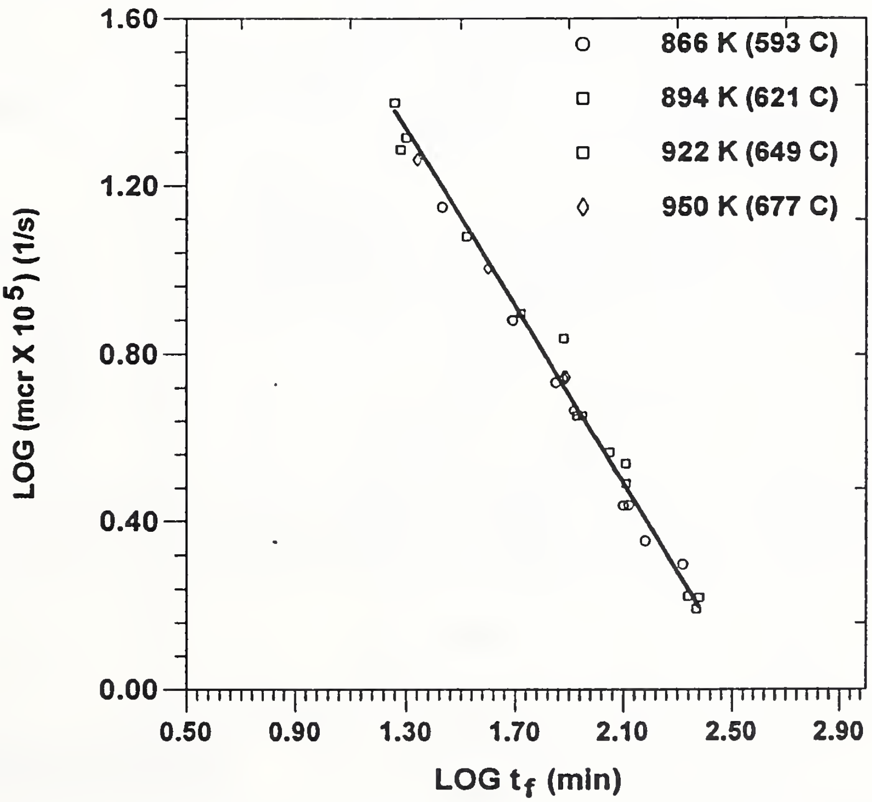


Figure 27. Log of the minimum creep rate versus the log of the time to failure.

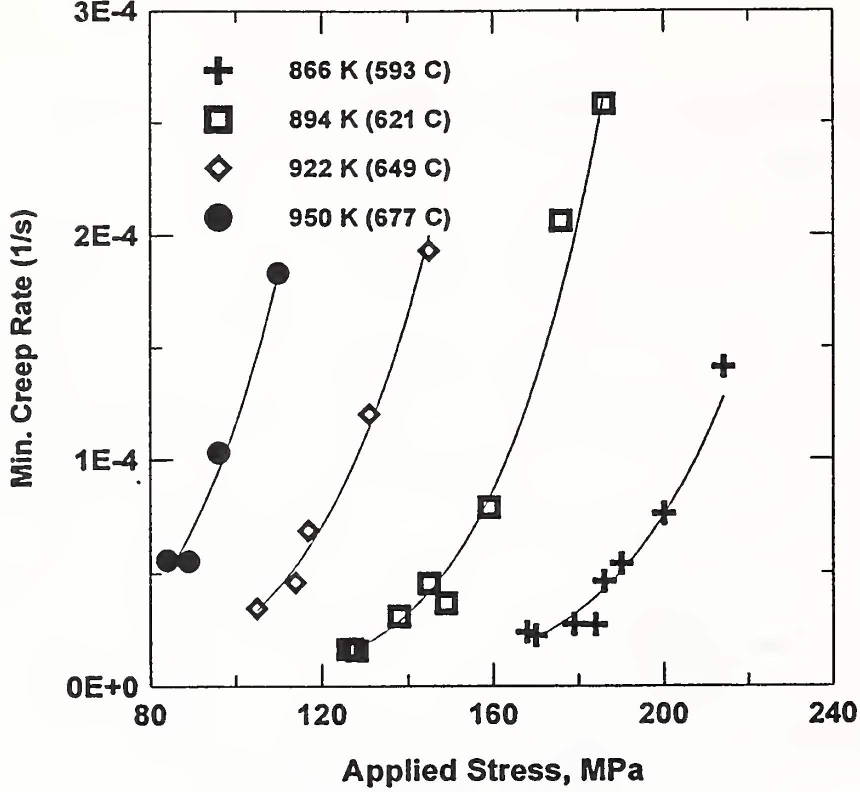


Figure 28. Minimum creep rate versus the applied stress as a function of temperature.

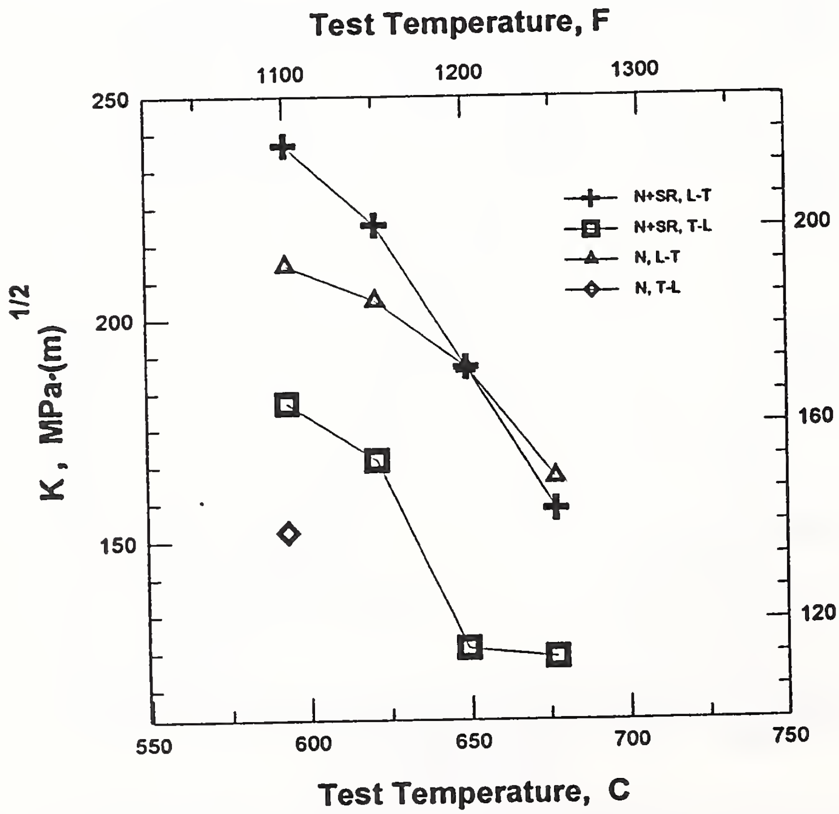


Figure 29. Fracture toughness versus test temperature. Both the ASTM T-L and L-T directions are shown in the figure.

Appendix I

QUALITY ASSURANCE DEPARTMENT

BURNS HARBOR PLANT

REPORT OF TESTS AND ANALYSES

SHIPMENT NO.	DATE SHIPPED	CAR OR VEHICLE NO.		
803-09465	5- 9-89	GARY TFR	TRLR 4007	PAGE

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

QUALITY STEEL MELTED & MANUFACTURED IN THE U. S. A.

PLATES - AAR TC128 GR B FLANGE QUAL REV 9/1/85 — PLT NORMALIZE

MFST - TRIAL. ORDER LIFT MAX 10 TON-SIZES & GRADES SSP UNLDG OH-PLATE HOOK

CO# 3-47132 GH 021-8706

PLATES HEAT TREATED WITH TEST SPECIMENS ATTACHED AND YIELD STRENGTH @ .5% E.U.:

SERIAL NUMBER	PAT. NO.	HEAT NUMBER	SIZE AND QUANTITY: NO. PCS.	THICKNESS INCHES	WIDTH OR DIA. INCHES	LENGTH INCHES	WEIGHT POUNDS	YIELD POINT PSI	TENSILE STRENGTH PSI	ELONG. IN	%
B 10492		803C67159	4	9/16	72	72	3308	58400	83600	8	18

N 1650 DEG F. — 29 MIN

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

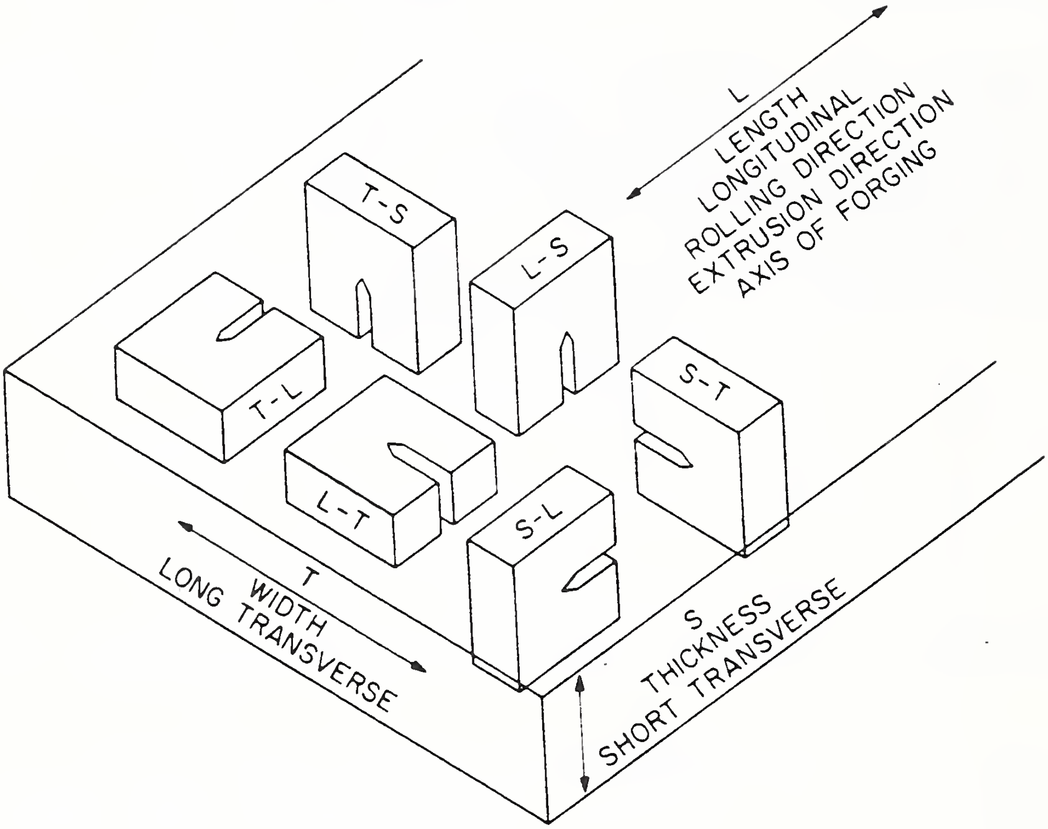
SERIAL NUMBER	PAT. NO.	HEAT NUMBER	HARD	BEND	CHARPY IMPACT: THICKNESS INCHES	TYPE	SIZE	DIR.	TEST TEMP. °F	ENERGY FT. LBS. 1	2	3	SHEAR (%) 1	2	3	LAT. EXP. MI 1	2

HEAT NUMBER	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Al	B	Cb	N
803C67159	.22	1.27	.015	.012	.241	.034	.04	.23	.062	.034		.065			

I CERTIFY THAT THE ABOVE RESULTS ARE A TRUE AND CORRECT COPY OF RECORDS PREPARED AND MAINTAINED BY BETHLEHEM IN COMPLIANCE WITH THE REQUIREMENTS OF THE SPECIFICATION CITED ABOVE.

SUPT. QUALITY ASSURANCE A. J. BARSOPHY PER PJH

E 399



Crack Plane Orientation Code for Rectangular Sections