NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 355

Notch Toughness Variability in Bridge Steel Plates

Transportation Research Board
National Research Council

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Report 355

Notch Toughness Variability in Bridge Steel Plates

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Subject Areas

Bridges, Other Structures, and Hydraulics and Hydrology
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff
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Board

This report contains the findings of a study that was performed to establish the variability of Charpy V-notch (CVN) impact toughness within plates of A572 Grade 50 and A588 steels. The study included plate thickness up to 4 inches meeting AASHTO Zone 3 fracture notch toughness requirements. Both existing literature and the results of research conducted for this study were examined in an attempt to define the variability in CVN values. The report provides a comprehensive description of the research, including a discussion of the statistical analysis methods used, along with recommended revisions to the AASHTO *Guide Specifications for Fracture Critical Non-Redundant Steel Bridge Members*. The proposed revisions are intended to provide a reasonable certainty of safe and effective performance of steel plate with respect to toughness. The contents of this report will be of immediate interest and use to bridge engineers, materials engineers, steel bridge fabricators, specification writing bodies, researchers, and others concerned with the design and fabrication of steel bridge elements.

It is unlikely that all portions of a steel bridge plate will have the same CVN value reported by the mill supplying the steel. This is due to several factors, including natural variation in the material and differences in the processing of various plates. It is important, however, that the bridge community have a specification that ensures, with reasonable certainty, that the toughness at any location in a plate is sufficient for an acceptable level of performance. The specification must consider, along with other factors, the spatial variations in toughness for normalized plates versus plates supplied in the as-rolled condition.

The AASHTO *Guide Specifications for Fracture Critical Non-Redundant Steel Bridge Members*, published in 1978, cover the toughness requirements for bridge steel for fracture-critical members. Based on the failure investigation of a fracture-critical member, the specification later was tightened through a requirement for increased sampling and testing at a lower temperature. Subsequently, additional research was performed in an AISI-sponsored study, and as a result, the requirements for materials to be used in regions with service temperatures in Zones 1 and 2 were restored to their original form. However, the research that supported that change did not include material processed for fracture-critical-member applications in Zone 3.

NCHRP Project 12-31, "Notch Toughness Variability in Bridge Steel Plates," was initiated with the objective of developing needed improvements in bridge steel plate CVN impact-toughness testing and acceptance criteria for applications in regions with service temperatures in Zone 3. The researchers evaluated existing literature and data, and performed analytical studies and laboratory testing to develop new data. This report documents the work performed under Project 12-31 and discusses the testing procedure used and the statistical analyses performed in the preparation of the proposed specifications.

The specification calls for testing both ends of as-rolled plate, versus one end for normalized plate, because of the greater variability in toughness in as-rolled plate. Additionally, an increase in minimum allowable test values, as a percentage of required average toughness, is proposed for both plate types. The changes are recommended for all temperature zones. The specification recommended in this report should provide a mechanism for better assurance of the suitability of steel bridge plate with respect to toughness. The AASHTO Highway Subcommittee on Bridges and Structures is expected to act on the proposed specification at its annual meeting in 1994.

The proposed specification is based on the premise that average toughness of steel plate, computed from CVN test results, is a sufficient predictor of fracture performance. Additional research to correlate CVN values to the fracture behavior of full-thickness plate also is recommended in the report.

NOTCH TOUGHNESS VARIABILITY IN BRIDGE STEEL PLATES

SUMMARY

Forty-four plates from four domestic suppliers were tested to determine the variability of the notch (Charpy V-notch) toughness within the plates. Three thicknesses of plates (1-, 2-, and 4-in.) and two American Society for Testing and Materials (ASTM) specifications of material (A572 and A588) were included in the program. The material was purchased for use in fracture-critical applications in the lowest temperature zone—Zone 3.

The analysis of over 7,500 Charpy V-notch (CVN) test results indicated that a specification for fracture toughness of fracture-critical bridge steels must explicitly account for the variability of the plate. Two types of variability were found in the tested plates. Some as-rolled plates showed significant variation in average toughness from one end to the other along the rolling direction of the plates. Other plates had relatively uniform average toughness with large scatter at each location. Normalized plates had almost uniform toughness. A statistically based specification was developed and tested against the results of this study. The specification was designed to minimize the risk of the owner accepting a defective plate. The specification requires testing both ends of plates supplied in the as-rolled condition to account for end-to-end variations. Normalized plates are to be tested at only one end because of their uniformity. A statistically based specification procedure was initially developed that accounted for the variability of the plate by increasing the required specification average test values in proportion to the standard deviation of the test. This initial procedure worked well with the plates tested in this study.

Additional data from various producers from tests on steel bridge plates were provided during the review of the final report. Many of the plates from this producer data set had extremely high toughness at one end and good toughness at the other. The standard deviation of the toughness from the two ends was quite large. The large standard deviation would have caused rejection of the plate even though the toughness of the plates was acceptable. A revised format for the specification was developed to ensure that high-toughness plates such as these would not be rejected. The specification changes consist of increasing the toughness of the acceptable lowest single-test value of the tests at each end of the plate. The average of each set of three specimens must meet the present specification values. The test temperatures of the original guide specification were found to be adequate. Tests on full-size beam tests in an FHWA-sponsored study at Lehigh University have shown that plates meeting the average toughness values of the specification and tested at the original specification temperature provide adequate crack tolerance in welded bridge members.

Many of the 98 plates included in the industry data provided in the review comments were not Zone 3 material. These as-rolled plates exhibited considerable end-to-end variation in toughness. Consequently, the proposed specifications changes are recommended for all temperature zones. As-rolled plates are more likely to be supplied for Zones 1 and 2 than for Zone 3. These plates must be sampled at both ends to ensure that the plate has the desired toughness level.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

1.1 RESEARCH PROBLEM STATEMENT

The purpose of the research performed was to determine the variability of the notch toughness of bridge steels for fracture-critical members for applications in regions with service temperatures in Zone 3. The material, welding, inspection, and fatigue design requirements are more stringent for fracture-critical members (FCM) than for nonfracture-critical members. A guide specification entitled *Guide Specification for Fracture Critical Non-Redundant Steel Bridge Members* (*1*) was adopted by American Association of State Highway and Transportation Officials (AASHTO) in September 1978. The guide specification covers the toughness requirements for the material and the welding procedures, process controls, and inspection requirements. The AASHTO *Standard Specifications for Highway Bridges* contains the fatigue allowable stress requirements for FCM.

The reduced allowable fatigue stress ranges and more stringent welding and inspection requirements applied to fracture-critical members were implemented to provide a lower probability of fatigue crack initiation in these critical members. Lowering the design stress range increases the fatigue life in proportion to the cube of the reduction in stress range. For example, a Category C detail has an allowable stress for over 2 million cycles of 10 ksi for a redundant load path structure and 9 ksi for a nonredundant, fracture-critical, load-path member. This 10 percent reduction in stress range produces a 37 percent increase in the expected mean fatigue life. The welding and inspection requirements reduce the probability of a flaw in the weld that could initiate a fatigue fracture.

The toughness requirements of the steel were increased to provide a larger stable fatigue crack size. The largest stable fatigue crack—the largest crack the material can tolerate before rapid or brittle crack extension will occur—is directly proportional to the notch toughness of the material. The "P" sampling requirements of AASHTO T-243 (ASTM A673) are required for FCM. The "P" sampling requires that three samples from each plate be tested. Non-FCM are sampled using an "H," heat lot, frequency.

In 1981, the toughness requirements for FCM were changed. The testing temperature was reduced by 20°F and three specimens from each end of the plate were required to be tested. These changes in the specification were in response to a fracture of an FCM in a tied arch. The investigation of the fracture revealed that the toughness of the plate did not match the values reported by the manufacturer. Furthermore, specimens taken from various locations on the fractured plate indicated that the toughness in the plate varied. The increased sampling reduces the possibility of a plate with systematic end-to-end toughness differences in an FCM. The lower testing temperature increases the average toughness the plate will have at the expected minimum service temperature.

Based on the results of an AISI-sponsored study, the requirements for Zone 1 and 2 material were changed back to the original guide specification requirement in 1986. The study included material ordered to a notch toughness specification but not exclusively FCM bridge material. The steel tested was not processed in a manner similar to FCM material for Zone 3 applications. The data from the AISI study, supplied to the University of Texas at Austin (UT) for analysis, were analyzed in a manner similar to the results of this investigation (*2*).

The purpose of the present research study was to determine the requirements for Zone 3 material for FCM. A statistically valid experiment was developed that allowed the significance of the variables listed below upon the variability of CVN values to be determined. The following primary variables are included:

1. Grade of steel
2. Thickness of plate
3. Length of plate
4. Producer of the plate
5. Processing of the plate.

In addition to these primary variables, the influence of the following secondary variables was evaluated:

1. Quarter-thickness level
2. Mid-thickness versus quarter-thickness toughness for the 4-in. plates
3. Mill test reported toughness versus UT measured toughness.

1.2 RESEARCH OBJECTIVES AND APPROACH

A product specification is a method of determining that the product has the desired properties required in its application. The notch toughness of a steel plate measured using a CVN specimen is not a constant value. Three adjacent specimens fabricated and tested under identical conditions will not produce identical toughness values. The present specification recognizes this inherent variability by using the average of the three specimens to determine the conformance of the plate. In addition, the present specification has two additional provisions: (1) A retest is required if the energy value for more than one of the three test specimens is below the minimum average requirements, or if the energy value for one of the three specimens is less than two-thirds of the specified minimum average require-

Table 1.1. Minimum test results meeting specifications

	Test Result 1	Test Result 2	Test Result 3
	ft-lbs.	ft-lbs.	ft-lbs.
Spec. 1	16.8	16.8	25.1
Spec. 2	29.3	25.1	25.1
Spec. 3	29.3	33.4	25.1
Average	25.1	25.1	25.1
Standard Deviation	7.2	8.3	0

Table 1.2. Probability of CVN values

Plate	Value that 75% of Population will Exceed with a Probability of 75%
1	14.6
2	12.8
3	25.1

ments. (2) The energy of each of the retest specimens must equal or exceed the specified minimum energy requirement. These two minimum specimen toughness requirements limit the acceptable variability of a low-toughness plate. A plate that just meets the average toughness of requirement of 25 ft-lbs and also meets the minimum individual specimen requirement may have the test results shown in Table 1.1.

All the test results satisfy all the provisions of the AASHTO FCM specifications. Each specimen has the same average toughness. The values exceed 16.7 ft-lbs, two-thirds of 25 ft-lbs, and only one or no specimen has a value less than 25 ft-lbs. The results are the minimum sets of toughness values that are possible and still meet all the specification requirements.

If these test results came from three different plates, the data indicate that the variability of these minimum toughness plates is different. The standard deviation of tests indicates that Plate 3 has no variability and Plate 2 has the largest variability. If the CVN values are normally distributed, one can estimate the probability of the occurrence of a lower CVN value in the plate (*1*). Because only three test results are available, the true value of the average and the standard deviation of the CVN values is not known. A probability for the estimate must be selected. The estimated CVN value that 75 percent of values will exceed with a probability of 75 percent for the plates is given in Table 1.2.

The larger variability of Plate 2, as estimated by the standard deviation of the results, causes the estimated value to be lower. The present specification does not provide a constant probability of occurrence of a particular value of CVN.

The analysis of the test results performed above assumes that the plate is homogeneous with respect to toughness. A nonhomogeneous plate is one in which the toughness is different, the mean or standard deviation is different, at various locations within the plate. As it is impossible to test all locations within the plate and still have material to fabricate the bridge member, estimates of the plate toughness based on samples outside the final dimensions of the plate are relied on. The interim specification addresses variation in toughness with respect to location by requiring tests at both ends of the plate.

The interim specification does not combine the results at both ends to refine the estimates of the average toughness of the plate and its standard deviation. The six tests provide a more accurate estimate of the true values of the statistics. If the three sets of test results discussed above are combined to represent the values from each end of a plate, the estimates of the 75 percent CVN values shown in Table 1.3 can be calculated.

Combining the results of the two sets of three tests reduces the standard deviation and increases the accuracy of the estimates of the mean and standard deviation. The 75 percent exceedence value is increased because of the more reliable estimates of the statistics and the decreased standard deviation. The current interim specification does not use the information from the tests at each end of the plate to provide a more accurate estimate of the plate toughness.

As indicated in this example, the suitability of a plate for use in a fracture-critical member must be based not only on the average mean toughness but also on the scatter in the results as measured by the standard deviation of the results. The behavior of the plates in this study will be compared using both the mean and standard deviation. Statements concerning the probability of a particular toughness level can be made using these statistics. Obviously, in a fracture-critical member we would like to have a low probability of a material with low toughness. Once the probability is determined, the combination of the mean and standard deviation (or a lower limit value) of the mill test results can be specified.

The research plan and analysis scheme used in the research was directed toward developing a statistically based specification that accounts for the variability of the test results at a location, as well as the variability from location to location within the plate. The goal is to have a specification that provides a reasonable assurance—a high probability—that the plate has toughness that meets or exceeds the required toughness to provide a reliable structure.

1.3 SCOPE OF THE INVESTIGATION

The research examined the variation of Charpy V-notch (CVN) toughness of 1-, 2-, and 4-in. plates of A588 and A572 Grade 50 plate. The plate was purchased from four different steel companies. Forty-four plates were tested. Sixteen 1-in., sixteen 2-in., and twelve 4-in. plates were tested. Half the plates were of each type of steel. Mill 2 did not supply 4-in. plate. The term "mill" will be used in place of manufacturer in the remainder of the report because each manufacturer may have more than one mill that could have supplied the plate. The plate

Table 1.3. Probability of CVN values: Two ends tested

Test Combinations	Standard Deviation	Value that 75% of the Population Will Exceed with a 75% Probability
1 & 1	6.5	18.0
1 & 2	7.0	17.5
1 & 3	4.6	20.1
2 & 2	7.4	17.1
2 & 3	5.2	19.4
3 & 3	0	25.1

was ordered to meet the original guide specification toughness requirements for Zone 3. The mills were asked to test both ends of the plate but were required to meet the requirements at only one end of the plate. All the plates meet the requirements at both ends of the plate. (Appendix B, not published herein, contains the results of the mill tests of each plate supplied.)

Each plate was sampled at the nine locations shown in Figure 1.1. Six specimens, three from each quarter-thickness level, were fabricated from locations A, B, C, D, E, F, G, H, and J. An additional 24 specimens, 12 from each quarter-thickness level, were fabricated from locations C, E, and G. These additional specimens were used to develop the toughness versus temperature transition curves. Three specimens at each location were tested at the test temperature required in the original guide specification. The remaining three specimens were tested 20°F below the specification temperature. The 4-in.-thick plates were also sampled at the mid-thickness using the same sampling plan except that only 20 additional specimens were fabricated for the transition curves. One full-size longitudinal tension test was performed on each plate. The tensile specimen was taken from location K in Figure 1.1. Over 7,500 specimens were fabricated and tested in the research.

The details of the fabrication and testing of the CVN specimens are given in Appendix A. All testing and specimen fabrication was performed in conformance with the applicable AASHTO and ASTM specifications. Quality control checks were made on each set of specimens fabricated.

1.4 STATISTICAL ANALYSIS TECHNIQUES

Standard statistical analysis techniques were used to evaluate the data generated in this study. The sections below are intended to give the reader some background concerning the techniques and terms employed in the study. Statistical analysis of the data is required because the quantity being measured—the toughness of the plates—is not constant. The results of multiple replicate tests at a location are not equal. The results at different locations within the plate are also not the same. To determine whether the results from location to location within the plate are to be expected because of the variability of the toughness or whether the results represent a significant effect of location, the statistical method of analysis called analysis of variance (ANOVA) was employed.

An estimate of the mean and dispersion (standard deviation) of the toughness in the plate can be estimated from the data generated in this study. The precise value of these statistics is unknown. The reliability of these estimates of the toughness depends on the number of samples used to calculate the quantities. If every part of the plate were tested we would know the true values of the statistic. Because a finite number of tests was performed, judgments about the data cannot be made in complete confidence. There is always some risk involved because the true value of the statistics is not known. A significance level is employed in the judgments made in this study. The significance level indicates the risk of making a false judgment about the data.

The sampling procedure used allowed the within-plate variation to be measured at the nine locations. The six samples at each location were used to determine the variation at the location. The variation within the plate was determined by using the statistical method ANOVA. This analysis technique determines whether the average toughness measured at each of the nine locations would be expected if the plate were homogeneous. A homogeneous plate may exhibit variability at each location, that is, the individual CVN values at a location may not be the same. A homogeneous plate, however, should produce an average toughness at each location that would be expected based on the variability of the plate. Because of the homogeneous variability of the CVN values, the average would not be expected to be the same at each location. A nonhomogeneous plate would be one in which the measured toughness is not consistent with the scatter in the results at the other locations.

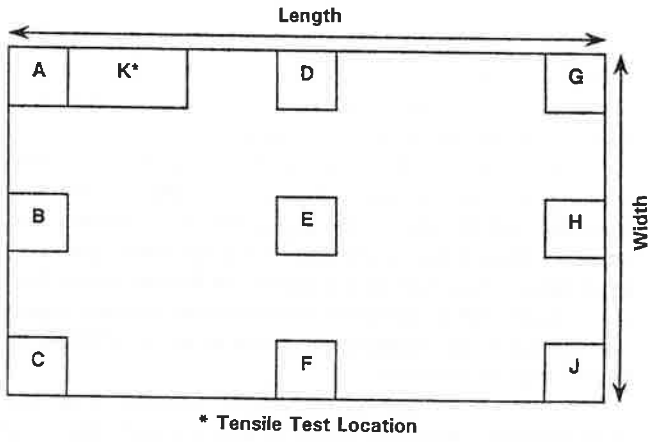


Figure 1.1. Labels of the nine test locations in each plate.

ANOVA is a statistical method for detecting differences between multiple groups of data, called *populations.* It is used to determine if certain variables have an effect on the means of the populations. When one variable is studied, the technique is called *single-variable* or *one-way* ANOVA. In this study, it is desirable to analyze the effect location may have on the fracture toughness of the plate. The independent variable is location, and the populations are the CVN values at the nine different locations sampled by UT. This method was also used to determine if the sides or ends of the plates produced significantly different values.

ANOVA studies the variation of values within each population and compares that with the variation between the averages of the populations. For example, within each location there may be very little scatter; however, between locations there may be large differences in the toughness. If this is so, location has a significant effect on the CVN values; the toughness depends on where the CVN tests are performed. The variation within locations is called the *error* and the variation between locations is the *regression.*

The first step in an ANOVA assumes a null hypothesis to be true. The null hypothesis states that the variable being studied has no effect on the population means. ANOVA determines the risk of incorrectly rejecting the null hypothesis for the alternative hypothesis, that location is a significant variable. The risk is called the significance level.

The significance level varies from 0 to 1.0 because it is a risk or probability. Higher significance levels indicate that the variable has little effect, whereas small significance levels lead to the conclusion that the null hypothesis should be rejected with little probability of a false conclusion. In other words, the variable is significant. For this study, a significance level of 0.05 or lower was associated with location having a significant effect on the toughness of a given plate.

The significance level only indicates the probability of falsely rejecting the null hypothesis. It does not indicate how much effect the variable has on the population. This becomes very important when trying to compare two plates with significance levels close to zero. Location is significant for both plates; however, it is difficult to determine on which plate it is more significant. Therefore, an intermediate calculation in the ANOVA, the F-ratio, is often observed.

The F-ratio is the ratio of the sample estimates of the variances (standard deviation squared) between populations and within populations. The higher the F-ratio, the greater the variability between locations than within, and thus the more significant location is. The F-ratio is inversely related to the significance level. The significance level is calculated from the F-ratio using the sample sizes and number of populations, called the degrees of freedom (DOF). The significance level can be compared for different tests, regardless of their DOFs. However, the F-ratio cannot be used to compare tests with different DOFs.

In this study, three different ANOVA tests were performed on each plate, one using the CVN values at the specification temperature, a second using the values from 20°F below the specification temperature, and a third using combined temperatures. The DOFs are identical for the first two tests, but the combined temperature analysis uses twice as large a sample size. Therefore, it is valid to compare F-ratios at the individual temperatures but not to compare those with the F-ratios from the combined temperature analyses.

1.5 ORGANIZATION OF THE REPORT

Chapter 2 summarizes the CVN test results of this investigation and provides an analysis of the ANOVA tests. Chapter 3 discusses the development and evaluation of the recommended specifications for Zone 3 material for fracture-critical members. The specific recommendations for changes to the AASHTO specification are presented in Chapter 4 along with suggestions for future research. Appendix A, published herein, summarizes the procedures used during specimen fabrication and testing. Analyses of the tensile and chemistry tests on the plate material are also contained in Appendix A. Appendix B, which presents a summary of the CVN test data for all plates tested, is not published in this report. However, qualified researchers may obtain a loan copy by writing to the Transportation Research Board Business Office, 2101 Constitution Ave., N.W., Washington, D.C. 20418.

CHAPTER 2

FINDINGS

A summary of the Charpy V-notch (CVN) test results is presented in this chapter. Procedures employed during specimen fabrication and testing are summarized in Appendix A, along with the results and analysis of the tensile and chemistry tests on the plate material. (Appendix B presents a summary of the CVN test data for all plates tested.) The analysis of the results is presented in this chapter. The average toughness and variation of toughness within the plates is presented first. The toughness of the plate at the specification test temperature relative to the upper shelf energy and a toughness of 15 ft-lbs is analyzed to characterize the plates with respect to the CVN toughness transition curve. The variation within the plates is estimated from the standard deviation of the specimens from the nine locations in the plate tested at the specification temperature and at 20°F lower. The influences of mill, grade of steel, processing, thickness, and length on the plate variability are also presented.

The results of the analysis of variance (ANOVA) to determine the variation from location to location in the plates are presented. This analysis was performed to determine if the location within the plate is a significant variable. This analysis determines whether the variability within the plate is homogeneous.

The analysis of the variance between the tests performed at the University of Texas at Austin (UT) with respect to the mill tests is also presented. In addition, the data from additional testing performed by the mills to confirm their original tests are also analyzed. The data are presented from a round-robin experiment with the mills.

2.1 OVERALL PLATE BEHAVIOR

Table 2.1 summarizes the results of the 27 specimens (3 specimens each at nine locations) tested at the test temperature corresponding to the original fracture-critical members (FCM) specifications. The plates in the table are listed in descending order of the toughness calculated as the average toughness of the plates minus two standard deviations. This statistic is shown in the last column of the table. The processing used by the mills for each plate is listed under the column labeled process. Plates shown with "N" were normalized after rolling. Plates supplied as-rolled are labeled with "AR" in this column. The second to the last column, labeled Q% ≤ 1.8, will be discussed in Chapter 4. Some mills supplied pairs of plates cut from the same plate rather than a plate from a separate slab or heat of steel. The paired plate is listed in the column labeled adjacent plate.

The average toughness of the plate minus two standard deviations provides an estimate of the toughness that will be exceeded with a probability of approximately 97.5 percent. This is an approximate calculation as this would be true only if the actual average and standard deviation of the toughness values were known and the toughness were normally distributed. The values range from 79.1 ft-lbs for Plate 6 to –9.8 for Plate 32 at the bottom of the table. The negative values listed for this statistic are obviously not possible. Values less than 2 ft-lbs indicate the plates have a 97.5 percent probability of producing values on the lower shelf of the CVN transition curve. This ranking of the plates provides a simple way to evaluate the probability of the plate having a toughness less than an acceptable value. Ranking the plates by average toughness alone would not account for the variability of the results. For example, Plates 1 and 17 have about the same average toughness, 27.1 and 23.8 ft-lbs, respectively. The standard deviations of the plates are 2.8 and 9.9 ft-lbs. The large difference in standard deviations indicates that the variability of Plate 17 is much larger than Plate 1. A histogram showing the distribution of the individual test results of these two plates is shown in Figure 2.1. Even though the mean toughness of the plates is similar, the probability of lower toughness values is higher in Plate 17 than in Plate 1. The lowest test value shown in Table 2.1 for Plate 17 is 7.7 ft-lbs. The lowest test value for Plate 1 is 20 ft-lbs. Plate 1 had the smallest variability of all the plates tested.

The difference in the variability of these two plates can also be illustrated by comparing the percentage of the 27 specimens with toughness values less than or equal to 15 and 25 ft-lbs. This statistic is listed in the third and fourth columns from the right in Table 2.1. Plate 1 had no values less than or equal to 15 ft-lbs and 18.5 percent less than or equal to 25 ft-lbs. Plate 17 had 22.2 percent and 55.6 percent of its results at these limits.

2.2 TRANSITION TEMPERATURE EVALUATION

The relationship of the tests performed at the specification test temperature relative to the overall transition curve of the plate were analyzed as shown in Figure 2.2. The CVN curve is shown with a flat upper shelf energy level at high temperature and a steep portion where the toughness increases rapidly with temperature, called the transition zone. The ratio of the energy level at the specification test temperature to 15 ft-lbs was calculated to provide an index of the specification energy level relative to the transition level. Fifteen ft-lbs was selected because it is commonly used as an energy level to define the transition temperature of structural steels. The ratio of the upper shelf energy level to the energy at the specification test temperature was also calculated to indicate the relative position of the test temperature in the transition region. These ratios were calculated using the average from the three locations in each plate where the transition curve was developed. Both the middle- and

Table 2.1. Summary of test results

Thickness (inch)	Mill	Process	Grade	Plate No.	Adjacent Plate	Test Temp. °F	Average (ft-lbs)	Std. Dev.	Min. (ft-lbs)	Max. (ft-lbs)	%≤15	%≤25	Q%≤1.8	Avg.-2S ft-lbs.
1	3	AR	588	6	7	10	135.7	28.3	92.2	203.5	0	0	0	79.1
2	3	N	588	29		10	94.2	10.6	71.7	118.9	0	0	0	73.0
1	4	N	572	11	12	10	83.8	9.8	65.8	104.5	0	0	0	64.2
4	1	N	572	35		10	96.5	16.7	66.3	152.3	0	0	0	63.1
1	4	N	572	12	11	10	89.4	14.7	59.8	137.3	0	0	0	60.0
4	1	N	572	37		10	77.7	9.5	63.4	98.0	0	0	0	58.7
2	4	N	588	24		10	75.2	8.8	60.9	94.9	0	0	0	57.5
2	3	N	588	21		10	72.7	8.2	56.9	85.9	0	0	0	56.4
2	4	N	588	23		10	99.6	21.8	61.9	164.9	0	0	0	55.9
2	4	N	572	27		10	81.2	12.9	59.0	112.4	0	0	0	55.4
2	3	N	572	28		10	77.1	11.4	60.1	113.8	0	0	0	55.3
2	4	N	572	20		10	78.1	12.7	47.5	104.2	0	0	0	52.8
1	3	AR	588	7	6	10	134.8	41.1	74.5	252.2	0	0	0	52.6
1	3	AR	572	8	4	10	92.6	20.4	50.8	126.8	0	0	0	51.8
1	4	N	588	15	16	10	62.8	6.4	52.8	80.5	0	0	0	50.0
1	4	N	588	16	15	10	63.6	7.0	53.5	83.0	0	0	0	49.7
4	1	N	588	34	33	10	74.3	12.6	54.6	109.9	0	0	0	49.2
4	3	N	588	36	39	10	69.2	10.4	49.8	91.8	0	0	0	48.4
4	4	N	572	42	41	10	57.9	6.6	48.1	76.0	0	0	0	44.8
4	4	N	572	41	42	10	61.1	9.3	45.3	75.9	0	0	0	42.5
4	4	N	588	43	40	10	55.7	6.7	48.1	77.6	0	0	0	42.4
4	3	N	572	44	38	10	52.4	5.0	40.9	63.4	0	0	0	42.3
1	2	AR	572	10		10	67.3	14.2	29.9	85.0	0	0	0	38.8
2	3	N	572	30		10	51.3	6.3	36.7	63.6	0	0	0	38.7
4	3	N	572	38	44	10	59.0	11.3	36.3	74.5	0	0	0	36.5
4	4	N	588	40	43	10	48.2	6.3	35.8	61.9	0	0	0	35.5
4	3	N	588	39	36	10	76.3	21.7	47.0	157.2	0	0	0	32.8
4	1	N	588	33	34	10	67.0	19.3	12.6	94.1	3.70	7.4	0	28.3
1	2	AR	572	13		10	73.2	22.8	21.3	104.2	0	3.7	8	27.6
1	1	AR	588	5		-5	67.6	21.0	35.0	106.0	0	0	8	25.7
1	2	AR	588	9		-5	67.1	21.6	19.8	99.0	0	3.7	17	23.9
1	1	AR	588	1		10	27.1	2.8	20.0	33.5	0	18.5	0	21.4
1	1	AR	572	2	3	-5	58.4	19.9	28.3	99.9	0	0	14	18.5
1	1	AR	572	3	2	-5	57.1	19.5	12.7	96.0	3.7	7.4	28	18.0
2	2	AR	572	19		10	32.0	9.8	12.0	62.0	3.7	14.8	36	12.4
1	2	AR	588	14		-5	57.5	23.2	11.1	98.1	7.4	11.1	42	11.1
2	1	AR	572	31		10	41.0	15.6	8.6	70.4	7.4	14.8	44	9.9
2	2	AR	588	18		10	41.0	15.7	6.1	58.8	14.8	18.5	58	9.6
2	2	AR	572	17		10	23.8	9.9	7.7	51.3	22.2	55.6	83	4.1
2	1	AR	588	25		10	33.2	16.0	10.6	63.0	7.4	40.7	83	1.1
1	3	AR	572	4	8	10	103.4	51.3	10.5	231.9	3.7	11.1	44	0.8
2	2	AR	588	22		10	35.3	18.5	7.6	66.2	14.8	33.3	92	-1.7
2	1	AR	572	26		10	37.7	22.1	4.3	75.8	22.2	33.3	81	-6.5
2	1	AR	588	32		10	46.6	28.2	11.8	105.1	14.8	25.9	72	-9.8

quarter-thickness specimens of the 4-in. plates were included. Figure 2.3 shows the histogram of the specification temperature energy divided by 15 for all the plates. The average ratio was 4.35, which indicates that most of the plates' transition temperatures were above the specification test temperature. Nine locations sampled had averages less than or equal to 15 ft-lbs. Figure 2.4 shows the histogram for the upper shelf energy divided by the specification test temperature energy. The average was 1.91. Three locations had a ratio of 1.1 or less. More than 30 locations had values above 2, indicating that in general the specification temperature was below the upper shelf temperature. The results indicate that the specification test temperature is in the toughness transition region of the CVN curve for most of the plates.

2.3 PROCESSING

The processing of the plates had the most significant effect on the ranking of the plates. The processing of the plates is listed in the third column of Table 2.1. AR denotes as-rolled plate and N denotes normalized plate. The normalized plates generally produced the highest average toughness values and smallest standard deviations. The high average toughness and small standard deviation of these normalized plates resulted in their ranking in the top two-thirds of the table. Exceptions do exist. Plate 1, a 1-in. as-rolled plate, had the smallest standard deviation and Plate 6, also a 1-in. as-rolled plate, had the highest average toughness.

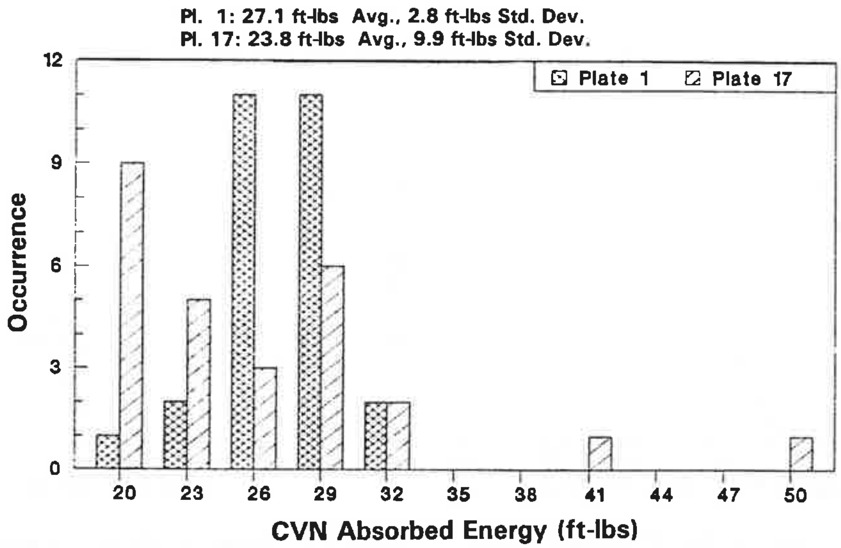


Figure 2.1. Two plates with averages close to the AASHTO acceptance criterion.

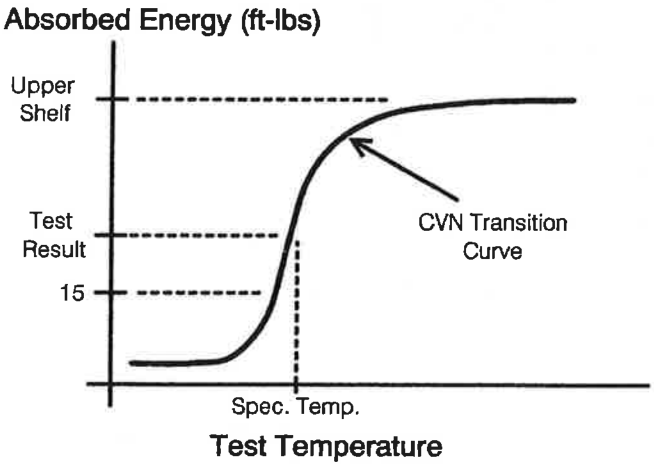


Figure 2.2. Transition temperature evaluation.

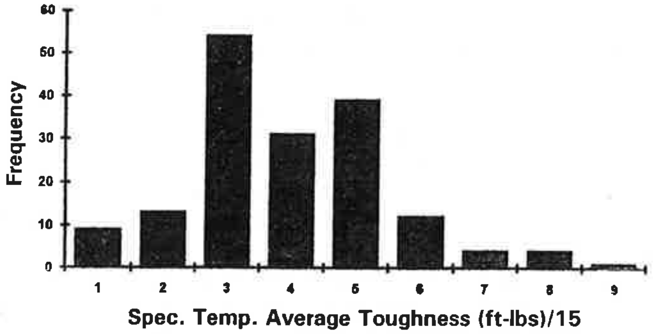


Figure 2.3. Location average toughness divided by 15.

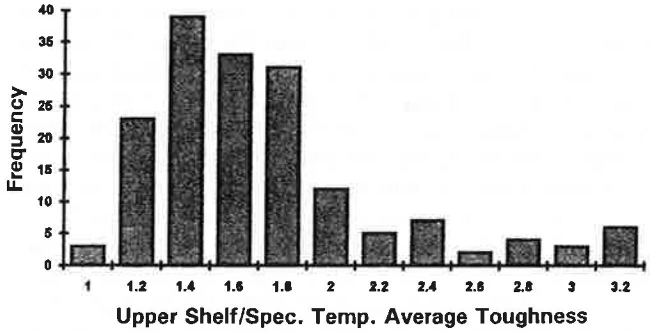


Figure 2.4. Upper shelf energy divided by specification temperature average toughness.

The influence of processing on the estimated 97.5 percent probability toughness level is shown in Figure 2.5. The cumulative frequency of the average toughness minus two standard deviations for the two processes is shown. The cumulative frequency is the result of numerically integrating the histogram of the statistic. The influence of processing on the statistic can be evaluated by selecting a particular toughness level and reading the corresponding percentage on the vertical axis. Using 25 ft-lbs as the toughness value, 75 percent of the as-rolled plates had a lower value while none (0 percent) of the normalized plates had a value equal to or less than 25 ft-lbs. The normalized curve is also steeper, indicating that the variation of this statistic is less for the normalized plates.

2.4 PLATE THICKNESS EFFECTS

The first column in Table 2.1 lists the plate thickness. The plates at the top of the list are mainly 1- and 2-in. normalized plates. At the bottom of the list are as-rolled 1- and 2-in. plates.

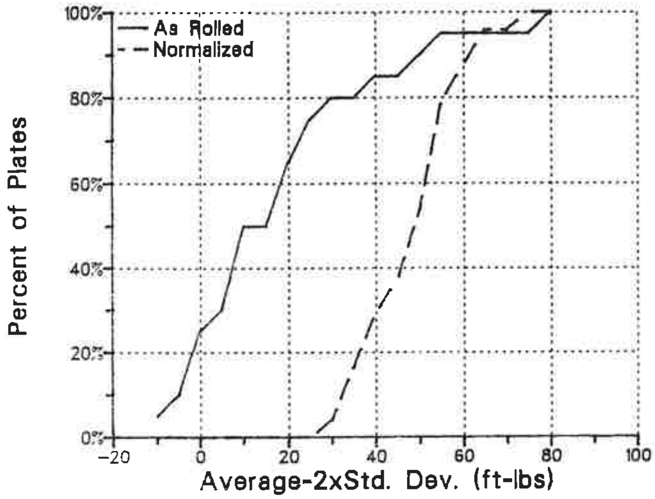


Figure 2.5. Cumulative frequency of Avg.-2S as-rolled and normalized plate.

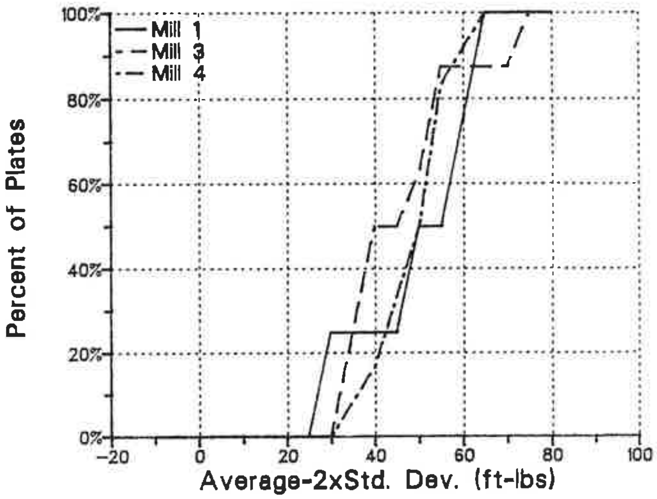


Figure 2.6. Cumulative frequency of average-2x standard deviation of normalized plates for each mill.

The normalized 4-in. plate is grouped in the center of the table. Mills 1 and 2 supplied as-rolled 1- and 2-in. plates. These plates are grouped at the bottom of the list. Mill 3 supplied as-rolled 1-in. plate and normalized 2-in. plate. The Mill 3 as-rolled 1-in. plate is mainly near the top of the table with the exception of Plate 4. The normalized 2-in. plate from Mill 3 is comparable to the normalized 2-in. plate from Mill 4. Mill 4 1-in. normalized plate provided comparable results with the normalized 2-in. plate they provided. All the 4-in. plates are normalized and are grouped at the middle of the table. The analysis of the results indicates that the processing of the plates was more important than the thickness of the plates. Normalized plates produce higher toughness with less variability. The 4-in. normalized plates have rankings lower than the normalized 1- and 2-in. plates. Exceptions to the general trends do exist. For example, the highest-ranked plate is an as-rolled 1-in. plate from Mill 3. This plate had the highest average toughness of all the plates tested.

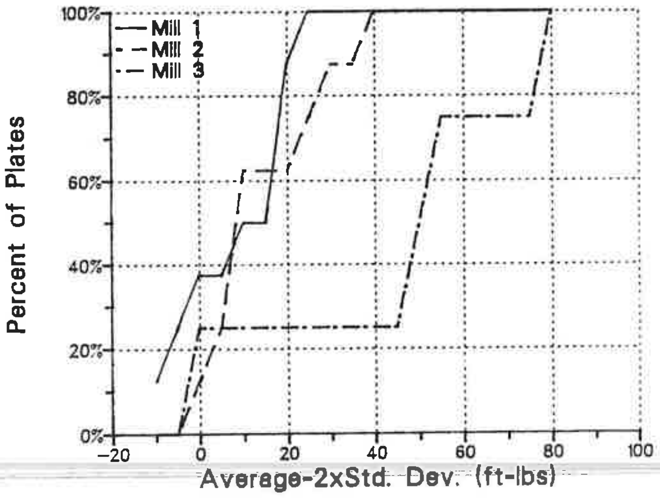


Figure 2.7. Cumulative frequency of average-2x standard deviation of as-rolled plate by mill.

2.5 GRADE OF STEEL

The grade of steel, ASTM A572 Grade 50 and A588 or AASHTO M223 Grade 50 and M222, had no significant effect on the results. No trends in average toughness and plate variability were found with respect to grade of steel. Examination of Table 2.1 shows that an equal number of A588 and A572 plates are at the top and bottom of the table. An ANOVA was performed on each thickness to further examine the effect of grade of steel. No significant effects were found.

2.6 MILL

The influence of the mill producing the plate was analyzed for each method of processing the plates. Figure 2.6 shows the results for the normalized plates from Mills 1, 3, and 4. Mill 4 provided all normalized plates while Mill 1 provided only normalized 4-in. plates. Mill 3 provided normalized 2- and 4-in. plates. Mill 2 provided all as-rolled plate. No significant difference is indicated in the results of the normalized plate from these three mills.

Figure 2.7 shows the cumulative frequency diagram for the as-rolled plate supplied by Mills 1, 2, and 3. Mill 3 1-in. plate shows more variation than the 1- and 2-in. as-rolled plates from Mills 1 and 2. However, the overall toughness of the Mill 3 plates was superior. Twenty-five percent (one of four) of the Mill 3 plates had a value less than or equal to 25 ft-lbs. One hundred percent of the Mill 1 plates and 75 percent of the Mill 2 plates had values less than or equal to 25 ft-lbs.

The influence of the supplier mill on plate performance is not significant for normalized plate. Plates supplied in the as-rolled condition indicate a significant difference between the mills.

Table 2.2. ANOVA of location

Mill	Process	Steel	Plate	Thick in.	Length ft.	Combined Temps		Spec. Temp		Spec. Temp - 20		Signif. ≤ 0.5%	Eval.
						F Ratio	Sign. Level	F Ratio	Sign. Level	F Ratio	Sign. Level		
1	AR	A572	13	1	20	.56	81%	.53	82%	.69	70%	0	
4	N	A588	24	2	20	.93	50%	.66	57%	3.54	1%	1	
3	AR	A588	7	1	20	.98	46%	.68	71%	.32	.95%	0	
3	N	A588	21	2	20	1.00	45%	.66	72%	.76	64%	0	
3	AR	A572	4	1	20	1.09	39%	1.08	42%	1.42	26%	0	
2	AR	A588	9	1	20	1.10	38%	1.30	30%	.75	65%	0	
3	AR	A572	8	1	20	1.32	26%	1.04	44%	.80	61%	0	
4	N	A588	15	1	20	1.46	20%	1.34	29%	.46	87%	0	
3	N	A572	28	2	40	1.49	19%	1.44	25%	.82	60%	0	
3	N	A588	29	2	40	1.56	16%	4.39	0%	.78	62%	1	
4	N	A572	42	4	10	1.71	12%	.97	49%	1.37	27%	0	
4	N	A588	40	4	10	1.90	8%	1.75	16%	1.57	20%	0	
4	N	A572	41	4	10	1.98	7%	1.04	45%	2.02	10%	0	
4	N	A572	20	2	40	1.98	7%	.82	59%	2.72	4%	1	
1	N	A588	33	4	10	2.08	6%	1.31	30%	1.21	35%	0	
3	N	A572	44	4	10	2.08	6%	1.57	20%	3.54	1%	1	
1	AR	A572	25	2	40	2.18	5%	3.62	1%	.55	81%	2	
3	AR	A588	6	1	20	2.20	4%	.82	59%	1.40	26%	1	N.S.
1	N	A588	34	4	10	2.33	3%	.94	51%	2.57	5%	2	N.S.
4	N	A588	16	1	20	2.48	3%	.69	70%	2.85	3%	2	N.S.
2	AR	A572	17	2	20	2.53	2%	1.69	17%	1.81	14%	1	
1	AR	A588	31	2	20	2.54	2%	1.94	12%	2.05	10%	1	
2	AR	A588	18	2	28	2.65	2%	.87	56%	3.00	3%	2	
2	AR	A572	10	1	20	2.74	1%	2.44	6%	2.36	6%	1	
1	AR	A588	1	1	20	2.96	1%	3.08	2%	3.58	1%	3	N.S.
1	N	A572	37	4	10	3.05	1%	1.34	29%	2.17	J8%	1	N.S.
4	N	A588	23	2	40	3.27	1%	2.27	7%	2.32	7%	1	N.S.
2	AR	A588	22	2	20	3.80	0%	1.26	32%	2.92	3%	2	
2	AR	A572	19	2	28	4.12	0%	3.48	1%	2.11	9%	2	
4	N	A588	43	4	10	4.42	0%	1.32	30%	2.75	4%	2	N.S.
4	N	A572	27	2	20	4.93	0%	2.46	5%	2.22	8%	1	N.S.
4	N	A572	11	1	20	5.02	0%	5.79	0%	2.29	7%	2	N.S.
1	N	A572	35	4	10	5.74	0%	1.91	12%	5.07	0%	2	N.S.
3	N	A572	30	2	20	6.69	0%	3.71	1%	3.05	2%	3	N.S.
2	AR	A588	14	1	20	6.78	0%	3.16	2%	4.31	0%	3	
3	N	A588	36	4	10	7.12	0%	3.38	2%	4.04	1%	3	N.S.
1	AR	A572	3	1	20	7.73	0%	4.14	1%	2.80	3%	3	
3	N	A572	38	4	10	9.49	0%	5.20	0%	5.80	0%	3	
1	AR	A588	5	1	20	9.73	0%	4.52	0%	6.13	0%	3	
1	AR	A572	2	1	20	10.92	0%	4.58	0%	5.00	0%	3	
3	N	A588	39	4	10	12.78	0%	7.20	0%	10.65	0%	3	
1	AR	A572	32	2	20	18.15	0%	10.37	0%	11.46	0%	3	
1	AR	A588	26	2	40	30.33	0%	11.93	0%	23.69	0%	3	

This difference is probably due to the interaction of the rolling practices and chemistry variation from mill to mill. Normalizing the plates after rolling eliminates these differences.

2.7 ANALYSIS OF VARIANCE OF LOCATION

The data were analyzed using ANOVA to determine the influence of location on the CVN results. This analysis was performed to determine if the location within the plate was a significant variable on the toughness. Plates that have a significant variation in toughness because of location are not homogeneous. A sample taken at one location may not provide a reliable estimate of the toughness at other locations within the same plate. Table 2.2 lists the results of the one-way ANOVA performed on each plate with location as the variable. The plates are listed in ascending order of F ratio (descending order of significance) from the analysis of the combined temperature analysis. Three different ANOVA tests were performed on each plate. One used the CVN values at the specification temperature. The second used the CVN values tested at the specification temperature minus 20°F. The third analysis used the combined data from the two test temperatures. Three replicate specimens at each of the nine locations within the plate were tested at the two temperatures. The degrees of freedom are identical for the individual temperature analysis. The combined temperature data have twice the sample size. The calculated significance from the analysis depends upon the sample size. Therefore, the larger combined data sample size makes the analysis more sensitive.

The effect of temperature on fracture toughness was eliminated when combining the two temperature test results normalized the data. Each CVN specimen value was divided by the average of the plate at the corresponding temperature. The normalized values were used in the ANOVA of the combined temperature results.

Plates at the top of Table 2.2 have a low F-ratio and a large significance level. The high significance levels indicate the risk of incorrectly assuming that location has no effect upon average toughness. For example, Plate 13 at the top of the table has a significance level of 80.8 percent. The significance level of 80.8 percent represents the probability of incorrectly rejecting the null hypothesis—that location within the plate has no effect upon the results—for the alternative hypothesis: that location is a significant variable. Plate 26 at the bottom of the table has the highest F-ratio and a significance of 0.00 percent. The probability is nil that location has no effect on the test results of Plate 26.

The second to the last column summarizes the ANOVA of the plates for the tests at the two temperatures and the combined temperature data. The number of data sets that produced a significance level equal to or less than 5 percent is totaled. Plates at the top of the table, the ones with the highest significance for the combined temperature data, are seen to produce significance levels greater than 5 percent at all temperatures. The plates at the bottom of the list had significance levels less than 5 percent for all the data sets. The ANOVA results from the combined data set will be used in the remainder of the report. The combined data set results are the most sensitive because of the larger sample size; they produced results reasonably consistent with the analysis of the individual temperature data.

The letters N.S. in the last column of the table indicate that the plates are judged to not have an important variation among the locations even though the ANOVA indicates a low significance level. The plates noted as N.S. had small coefficients of variation (the standard deviation divided by the average). Although statistically significant, the very small variation of the plates is not of practical concern. Very small differences in the average toughness of the plates from location to location will produce a low significance because of the small variability of these plates.

Figures 2.8 and 2.9 show the average and scatter at the nine locations for the combined temperatures for Plates 30 and 27, respectively. The very small scatter in the test results is shown by the height of the vertical lines. These plates were judged not to have significant practical variation from location to location. Figures 2.10 and 2.11 show the data from Plates 26 and 32, respectively. The larger scatter in the test results at a location relative to Plates 30 and 27 is very evident. Plate 26 shows a significant trend of increasing toughness from the end of the plate with locations A, B, and C to the end with G, H, and J. The results differ by a factor of almost 7. Plate 32 exhibited a significant side-to-side variation in toughness. The side of the plate with locations C, F, and J had significantly lower toughness than the side with locations A, D, and G. The variability of Plates 26 and 32 was characterized as being systematic. The variation was not due to random variation from location to location.

The influence of processing on the results of the ANOVA of location for the combined temperature data is shown in Figure 2.12. The cumulative frequency of the significance level of the

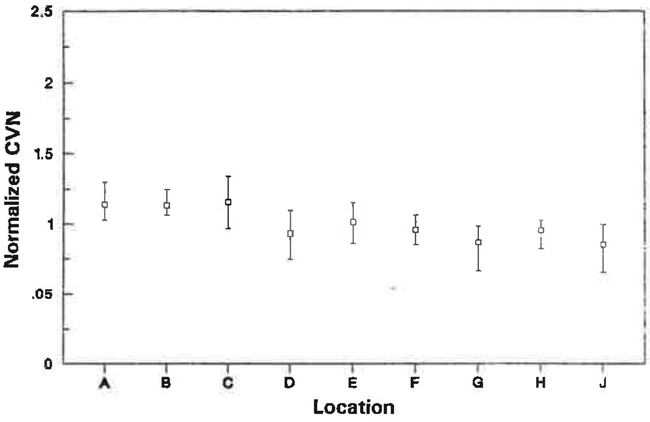


Figure 2.8. Plate 30 location ranges and averages: combined temperatures.

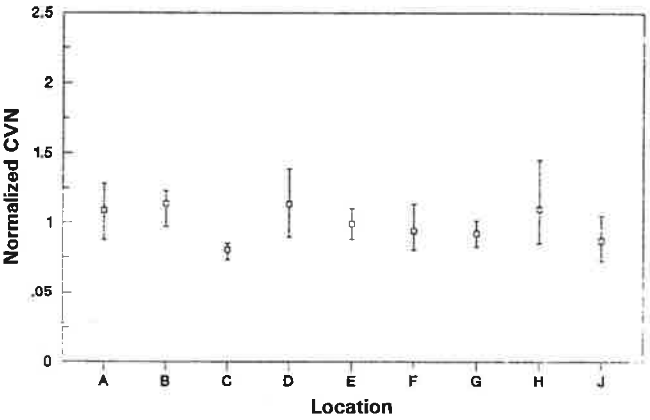


Figure 2.9. Plate 27 location ranges and averages: combined temperatures.

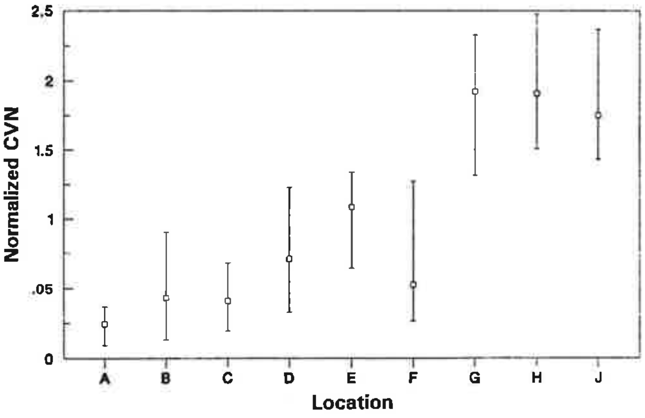


Figure 2.10. Plate 26 location ranges and averages: combined temperatures.

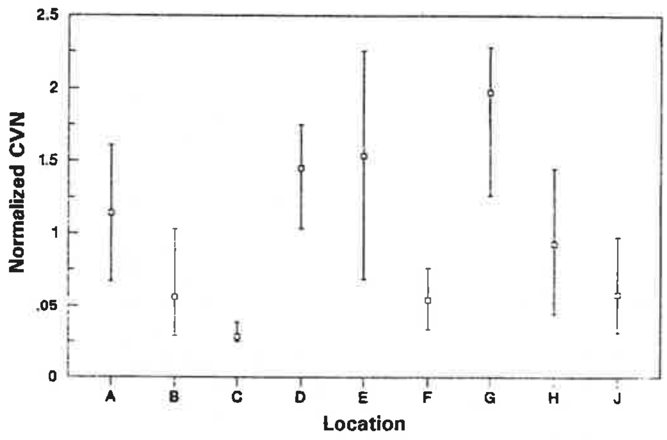


Figure 2.11. Plate 32 location ranges and averages: combined temperatures.

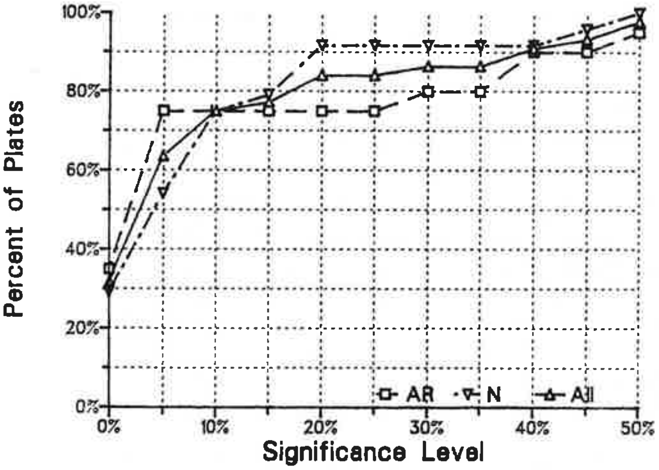


Figure 2.12. Cumulative frequency of significance level of location for as-rolled and normalized plate.

20 as-rolled (AR) plates and the 24 normalized (N) plates is shown along with the results for all the plates taken together. At the 5 percent level of significance, 55 percent of the normalized plates and 75 percent of the as-rolled plates have location as a significant variable. However, 11 of the 13 normalized plates with significance levels less than 5 percent were judged to have no significant practical variation from location to location. Therefore, from a practical standpoint only 2 of the 24 normalized plates (8 percent) showed location to be a significant variable.

Figure 2.13 shows the cumulative frequency of the significance of location for the plates grouped according to thickness. At the 5 percent level, all thicknesses produced similar percentages of plates with significant effect of location upon the results.

Figure 2.14 shows the data grouped according to the producing mill. Mill 3 had the least percentage of plates in which location was significant at the 5 percent level. Mill 4, which normalized all plates, had the next lowest. Seventy-five percent of Mill 2 and 92 percent of Mill 1 plates showed location to be significant at the 5 percent level. Mill 1 provided as-rolled steel for the 1- and 2-in.-thick plates. Mill 2, which did not provide 4-in. plates, provided only as-rolled plates. The larger percentage of plates with location as a significant variable for Mills 1 and 2 was due to the larger percentage of as-rolled plates supplied.

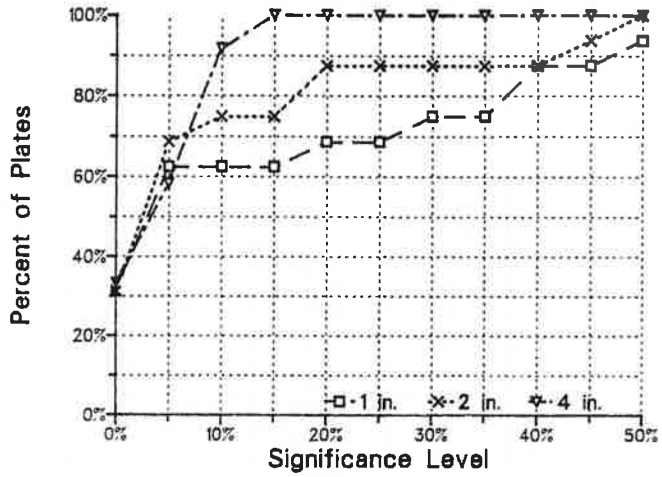


Figure 2.13. Cumulative frequency of significance level of location by plate thickness.

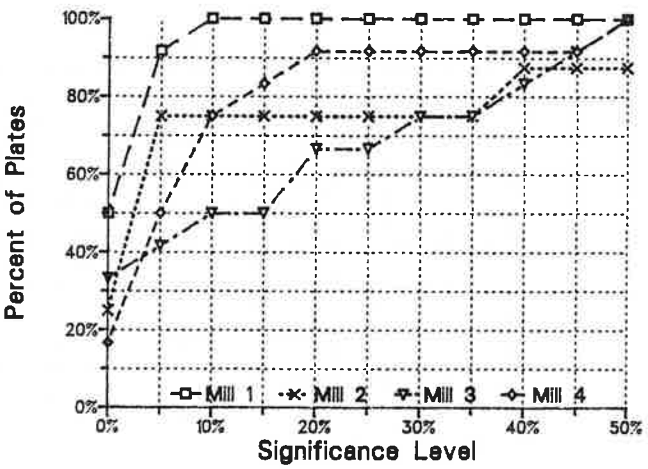


Figure 2.14. Cumulative frequency of significance level of location by mills.

2.8 SYSTEMATIC VARIATION OF 2-INCH PLATES

Systematic variation of the fracture toughness within a plate was observed in the 2-in. plates supplied. Systematic variation is defined as variation of the CVN values along either the length or the width of the plate. Additional analyses of variance were performed on each of the 2-in. plates to quantify the systematic variation.

Table 2.3. Analysis of variance on end; combined temperatures

Mill	Steel	Plate	Length (ft)	Processing	F Ratio	Signif. Level
1	A572	26	40	FGP, Control Rolled	101.01	0.0000
3	A572	30	20	FGP, Normalized	24.92	0.0000
2	A572	19	28		14.41	0.0000
2	A572	17	20		10.07	0.0002
4	A572	20	40	FGP, Normalized	7.16	0.0018
4	A588	23	40	FGP, Normalized	6.99	0.0021
2	A588	22	20		6.97	0.0021
1	A588	25	40	Control Rolled	5.26	0.0084
1	A588	32	20	Control Rolled	4.62	0.0143
2	A588	18	28		3.49	0.0381
4	A572	27	20	FGP, Normalized	0.60	0.5505
3	A588	21	20	FGP, Normalized	0.51	0.6057
3	A588	29	40	FGP, Normalized	0.40	0.6698
3	A572	28	40	FGP, Normalized	0.30	0.7408
1	A572	31	20	FGP, Control Rolled	0.19	0.8318
4	A588	24	20	FGP, Normalized	0.12	0.8870

Table 2.4. Analysis of variance on side; combined temperatures

Mill	Steel	Plate	Length (ft)	Processing	F Ratio	Signif. Level
1	A588	32	20	Control Rolled	25.17	0.0000
4	A572	27	20	FGP, Normalized	10.55	0.0001
1	A572	31	20	FGP, Control Rolled	7.57	0.0013
3	A588	29	40	FGP, Normalized	4.03	0.0238
2	A588	18	28		3.99	0.0246
4	A588	23	40	FGP, Normalized	3.394	0.0413
3	A572	28	40	FGP, Normalized	2.47	0.0948
4	A588	24	20	FGP, Normalized	2.39	0.1020
1	A588	25	40	Control Rolled	1.48	0.2373
2	A572	19	28		1.23	0.3023
3	A572	30	20	FGP, Normalized	0.64	0.5317
1	A572	26	40	FGP, Control Rolled	0.57	0.5672
2	A572	17	20		0.36	0.6986
2	A588	22	20		0.28	0.7578
3	A588	21	20	FGP, Normalized	0.20	0.8159
4	A572	20	40	FGP, Normalized	0.12	0.8917

2.9 ANOVA

The ANOVA was performed as described above, except the populations being considered were no longer individual locations but groups of locations corresponding to the ends or sides of each plate. Thus for each analysis, three populations were compared (side, center, and side or end, center, and end), with each population comprising three locations. The analysis used the normalized CVN values for each plate, allowing the two test temperatures to be combined. This improves the sensitivity of the analysis, as described previously.

Tables 2.3 and 2.4 present the results for the analyses considering systematic variation from end to end and side to side, respectively. The tables are ordered by decreasing F-ratios; plates demonstrating a high degree of systematic variation along the plate length or width are at the top of the tables.

With one exception, the six plates indicating that systematic variation along the length was not significant were normalized plates. Ten plates had significant variation from end to end. The first five plates in Table 2.3, corresponding to the highest F-ratios, are all A572 steel, followed by five plates of A588 steel. Length is a secondary factor; for two plates of the same mill (and processing) and type of steel, the longer plate generally exhibits a higher F-ratio. For Mills 1, 2, and 3, the type of steel is of greater importance than the length. For Mill 4, the reverse is true.

These trends were not observable in the ANOVA tests of systematic variation from side to side. The results of the analysis are given in Table 2.4. Only six plates had a statistically significant variation across the width at the 5 percent level of significance. The variation across the width of these plates was much less than the variation along the length that some of the plates exhibited.

The two plates with the highest significance from end to end and the two plates with the highest significance from side to side constituted the four plates with the highest significance with individual locations as the variable. This is expected.

Figures 2.8 and 2.10 plot the location ranges and averages for the two plates with the highest F-ratios from the end-to-end analyses, using the combined temperature data. Plate 26 (Figure 2.10) demonstrates a severe change in toughness from one end of the plate to the other. It has an F-ratio greater than 100. Plate 30 (Figure 2.8) is also significant statistically; the end with locations A, B, and C is relatively tougher than the other end. However, the differences from one end to the other are minimal and not of practical importance, especially compared to Plate 26. Plate 30 was normalized, whereas Plate 26 was as-rolled.

Figures 2.9 and 2.11 plot the two plates with the largest F-ratios from the side-to-side analyses, using the combined temperature data. Plate 32 (Figure 2.11) clearly demonstrates a variation in toughness from side to side. Plate 27 (Figure 2.9) also demonstrates the similar, statistically significant systematic variation. While the variation within Plates 32 and 27 is statistically significant, the relative magnitudes of the variation from one side to the other indicate that the variation within Plate 32 is more important than that within Plate 27. Plate 32 was as-rolled and Plate 27 was normalized. The low standard deviations of normalized plates allow very small variations of toughness between locations to conclude location as statistically significant.

Overall, Mill 3 has less systematic variation than the other mills. Mill 1 has the greatest systematic variation: all four Mill 1 2-in. plates have F-ratios greater than 5 for one of the two cases analyzed. Mill 1 Plates 26 and 32 exhibited very severe systematic variation along their length and their width, respectively. All four Mill 1 plates were control-rolled and not normalized.

2.10 EVALUATION OF MILL 1 PLATES SYSTEMATIC VARIATION

An investigation of the Mill 1 plates was made to determine possible causes of the systematic variation of toughness. First, additional chemical samples were analyzed by the independent laboratory under contract with the University of Texas at Austin (UT) to determine if a difference in chemical composition corresponds with the variation. Two samples were tested from Plates 25, 26, and 32: one sample each from the end or side exhibiting high toughness and the end or side exhibiting low toughness. No significant differences in composition were observed. Mill 1 also performed an extensive chemical analysis on Plate 32, which exhibited the most severe systematic variation along the width of all the plates. The mill results are presented in Table 2.5 as percent weights. The compositions of five UT locations and the two mill test locations were determined. The first two columns identify the location. The carbon content varied from 0.11 to 0.13 percent, with increasing percentages corresponding with lower toughness. No other trends in chemistry were observed.

Mill 1 performed microstructural analyses of Plates 25, 26, 31, and 32 to determine the ferrite grain sizes, percentage of coarse grain ferrite, the percentage of pearlite, and the cleanliness throughout the plates. Three or more locations were examined per plate. The samples were obtained from UT within the 12″ × 18″ area of a given UT test location. Additionally, the engineering logs from the rolling mill were examined to evaluate the rolling processes.

Table 2.6 shows the results of the microstructural analysis. All four plates exhibited a ferrite/pearlite aggregate microstructure (the volume fraction of bainite was found to be zero for all the plates). Below is a brief discussion of each Mill 1 plate and the corresponding conclusions for the causes of systematic variability.

The UT location averages of Plate 26 varied from 10 to 23 ft-lbs at one end to 62 to 63 ft-lbs at the other end at the specification temperature. Figure 2.10 shows this variation using normalized data from both test temperatures. Table 2.6 shows that the ferrite grain size varied considerably along the length, with a fine grain size at the end exhibiting the higher toughness and a significantly coarser grain size at the other end. (Higher American Society for Testing and Materials (ASTM) numbers and smaller linear intercept distances indicate finer grain sizes.) Figure 2.15 shows the general microstructure of two UT samples from different ends of the plate at 200 times magnification. The difference in grain sizes probably is a result of a temperature gradient during processing along the length of the plate. Larger grain sizes are associated with higher temperatures. The mill believes the temperature gradient occurred while the slab was being reheated before rolling and that it persisted throughout the controlled-rolling process. The mill judged the plate to be relatively dirty and observed many coarse oxides.

Plate 31 ranked third most significant in the ANOVA with end as the variable, using the combined temperature data. Although the toughness at either end is very similar, the center of the plate exhibits a higher toughness. The location averages ranged from 24 to 50 ft-lbs at the ends while the range at the center was 41 to 56 ft-lbs at the specification temperature. The ferrite grain sizes showed a trend that would predict the opposite variation in the plate, a lower toughness in the center resulting from a larger grain size than at the ends of the plate. However, the mill assessed the grain size as coarser than desired, especially with the patches of coarse grain ferrite present, for consistently meeting the Zone 3 AASHTO requirements. (Mill 1 acknowledges linear intercept distances of 7 to 8 μm as desirable.) The plate was judged to be cleaner than Plate 26, with the observed inclusions consisting mainly of elongated manganese sulfides.

ANOVA along the length of Plate 25 concluded that systematic variation exists from end to end. One end exhibits location averages between 17 and 22 ft-lbs, whereas the center of the plate has averages of 30 to 55 ft-lbs at the specification temperature. The other end has averages of 27 to 46 ft-lbs. The mill declares that the "scatter between locations is normal." The plate has a standard deviation of 16 ft-lbs. However, the mill acknowledges that the overall toughness is inadequate for consistently meeting Zone 3 requirements; the plate average CVN is 33 ft-lbs at the specification temperature. This is attributed to the larger-than-desired grain sizes and the substantial amount of

Table 2.5. Additional Mill 1 chemical analysis of Plate 32

	Loc	Avg.[a]	C	Mn	P	S	Si	Ni	Cr	Cu	V	Nb	Al
UT	A	56.0	.12	1.20	.015	.017	.37	.32	.58	.27	.016	.039	.054
UT	C	12.2	.13	1.25	.016	.020	.38	.33	.60	.29	.017	.041	.058
UT	E	87.3	.11	1.19	.014	.015	.37	.31	.59	.27	.016	.037	.057
UT	G	84.1	.12	1.22	.015	.018	.38	.32	.60	.28	.016	.039	.058
UT	J	25.6	.12	1.19	.014	.017	.37	.32	.59	.28	.016	.036	.058
MILL	C	72	.11	1.20	.014	.016	.37	.31	.59	.27	.016	.035	.059
MILL	J	48	.12	1.26	.016	.017	.39	.33	.61	.29	.017	.042	.059

[a] Location average at the specification temperature, ft-lbs.

Table 2.6. Microstructure analysis of the Mill 1 plates

	Plate	Loc	Ferrite Grain Size		Percent Coarse Grain Ferrite (volume)	Percent Pearlite (volume)
			Linear Intercept [a]	ASTM Number		
UT	26	A	10.6	9.8	-	28.0
UT	26	C	11.4	9.6	-	24.0
UT	26	E	9.1	10.3	-	28.0
UT	26	J	7.7	10.7	-	27.3
MILL	26	C	6.9	11.1	-	29.1
MILL	26	J	7.2	10.9	-	26.7
UT	31	A	9.5	10.1	2.9	26.9
UT	31	E	11.1	9.7	2.5	25.8
UT	31	J	10.0	10.0	3.5	25.0
UT	25	A	10.5	9.8	6.3	20.3
UT	25	E	9.3	10.2	6.8	21.1
UT	25	J	10.3	9.9	5.3	18.1
MILL	25	J	9.7	10.1	10.9	19.2
UT	32	A	10.5	9.8	1.6	18.7
UT	32	C	8.5	10.5	6.8	27.8
UT	32	E	9.5	10.1	Trace	16.0
UT	32	G	9.3	10.2	2.4	20.8
UT	32	J	9.9	10.0	1.6	18.9
MILL	32	C	8.4	10.5	9.3	17.8
MILL	32	C	8.4	10.5	8.1	16.1
MILL	32	J	8.2	10.6	8.0	20.6

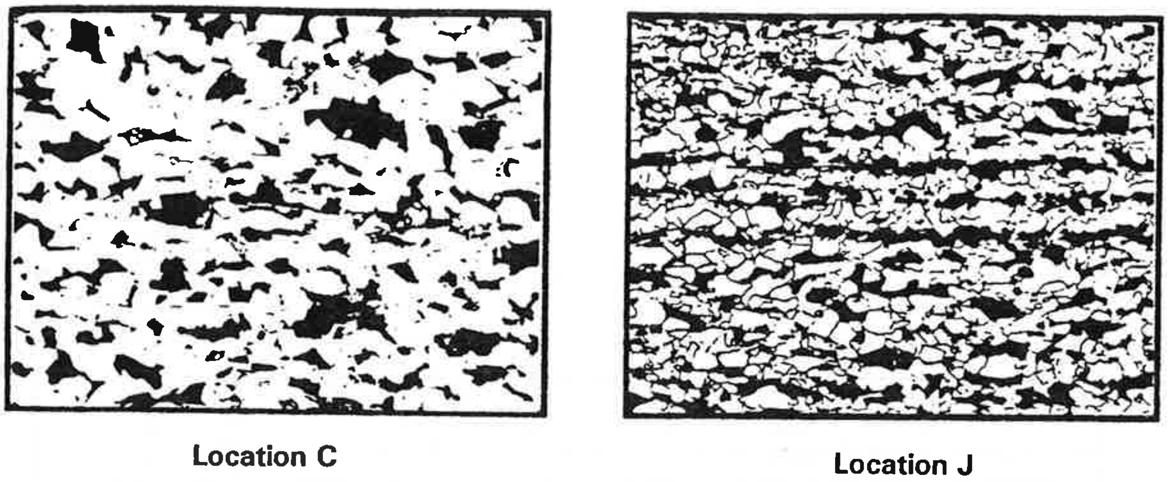
[a] Measured in micro-meters.

coarse grain ferrite present. The plate was evaluated as having good cleanliness, with most of the inclusions being elongated manganese sulfides, similar to Plate 31.

Plate 32 had the greatest systematic variation from one side of the plate to the other (See Figure 2.11). Plate 32 was produced from the same heat as Plate 25; therefore, the comments regarding cleanliness of Plate 25 apply to Plate 32 also. The toughness variation within this plate is attributed to the varying percentages of pearlite and coarse grain ferrite. In the locations exhibiting low toughness, these percentages are much higher than the locations with average or high toughness. The differences in microstructure are attributed to temperature gradients and possible chemical segregation.

2.11 CONCLUSIONS OF SYSTEMATIC VARIABILITY STUDY

It would be expected that more plates demonstrated systematic variation along their length than their width. Differences in


Location C

Location J

Figure 2.15. Grain sizes of Plate 26.

temperature during the rolling process presumably account for the systematic variation in toughness. Two factors can cause greater temperature gradients along the length than the width. First, the plates are 4 to 8 times longer than they are wide. Second, the temperature is difficult to maintain consistently from end to end because the plate length increases as the plate is rolled and the plate moves through the reheating furnace and rolls along its length in continuous processing mills. It appears that "control-rolled" processing may not maintain consistent temperatures within the plate. This situation may be caused by previous temperature gradients from the reheating furnace. Normalized plates are expected to have less systematic variation as the heat-treating process produces a more homogeneous microstructure and therefore more consistent mechanical properties throughout the plate. It is possible that (a) the normalized plates exhibiting systematic variation were improperly normalized or (b) such large variations within the plate existed before normalizing that a uniform fracture toughness (or uniformly varying toughness) throughout the plate was not achieved.

Thirteen of the sixteen 2-in. plates exhibited statistically significant systematic variation of the fracture toughness along either the length or the width. Sufficient consideration of such variation must be made when developing recommendations for specification requirements, the subject of the next chapter.

2.12 ANALYSIS OF QUARTER- AND MID-THICKNESS VARIATIONS OF 4-INCH PLATES

Table 2.7 lists the average plate toughness of the 4-in. plates in descending order of average toughness for the quarter- and mid-thickness levels of the plate. The plates are listed in descending order of average toughness at the specification level. Figure 2.16 is a plot of the average toughness at the two levels. The dashed line indicates equal values for both levels. The number of plates above and below the line are about equal for both test temperatures. The results do not indicate a significant difference between the toughness in the two levels in the plates. The two data farthest to the right of the dashed line are both from Plate 35, which was the highest toughness plate.

An ANOVA was performed on these plates to determine the significance level of the CVN results at the quarter- and mid-thickness of the plates. Table 2.8 summarizes the results of this analysis. The significance levels calculated are generally large, indicating that location within the thickness of the plate is not a significant factor. Plates 35 and 34 show significance at the 5 percent level for the specification temperature. In both of these plates, the quarter-thickness toughness was greater than the mid-thickness toughness. Four plates had significance values less than 5 percent at 20°F below the specification temperature. Two of these plates, Plates 38 and 41, had higher toughness at the mid-thickness level than at the quarter-thickness level.

The normalized 4-in. plate tested in this study did not show a significant difference in toughness between the quarter-thickness and the mid-thickness level in the plate. The standard quarter-thickness test location provides a reasonable indication of the plates' overall toughness. Thick nonnormalized plates may not behave in a similar manner.

2.13 ANALYSIS OF MILL AND UT TEST RESULTS

Each plate or set of plates supplied was tested by the mill at each end. One mill, Mill 3, tested at additional locations at the end of the plate. The results of this mill test were compared to the test results at UT for the specification temperature. In addition to the original mill tests, Mills 1 and 2 participated in a retest of samples of their plates. The mills were provided with steel plate samples adjacent to the areas tested by UT.

Table 2.9 lists the results of the statistical analysis performed on the UT and mill data. The results are grouped by mills and listed in ascending order of the absolute value of the Student's *t*-statistic calculated using the means and standard deviation of the two sets of test results. Values of *t* less than approximately 2 indicate that the average toughness calculated from the mill and UT tests agree at the 5 percent level of significance. Data sets, which at this significance level are judged to be equal, are indicated by a "yes" in the column labeled "Equal Means." The corresponding analysis for the retests is shown in the last columns.

Table 2.7. Plate rankings by average CVN at specification temperature

Mill	Loc.	Steel Spec.	Plate No.	Spec. Temp. CVN Avg. (ft-lbs)	Rank @ Spec. Temp. -20° F	Spec. - 20° F CVN Avg. (ft-lbs)
1	¼	A572	35	96.5	1	81.1
1	½	A572	35	83.3	5	64.3
3	½	A588	39	82.9	2	71.4
1	½	A572	37	78.7	4	66.0
1	¼	A572	37	77.7	6	60.7
3	¼	A588	39	76.3	3	67.4
1	¼	A588	34	74.3	8	60.2
1	½	A588	33	71.9	12	54.6
3	¼	A588	36	69.2	9	58.1
1	¼	A588	33	66.9	7	60.4
4	½	A572	41	65.5	13	54.3
1	½	A588	34	65.3	11	55.3
3	½	A588	36	64.7	10	56.0
3	½	A572	38	64.1	14	54.2
4	½	A572	42	61.5	16	48.0
4	¼	A572	41	61.1	15	49.6
3	¼	A572	38	59.0	19	47.1
4	¼	A572	42	57.9	18	47.1
4	½	A588	43	57.2	17	48.0
4	¼	A588	43	55.7	20	44.5
3	¼	A572	44	52.3	21	44.0
3	½	A572	44	49.5	22	42.9
4	¼	A588	40	48.2	23	42.0
4	½	A588	40	45.5	24	36.5

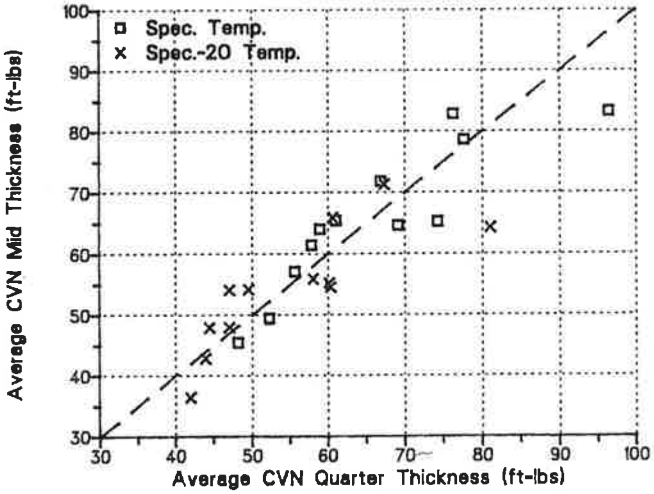


Figure 2.16. Average toughness of quarter- and mid-thickness levels of 4-in. plate.

Figure 2.17 shows the average of the original mill tests and UT tests plotted against one another. The dashed line corresponds to equal values. The majority of the mill test averages are above the line, indicating higher averages for the mill tests. Figure 2.18 shows the difference between the mill tests and the pooled standard deviation of both sets of data multiplied by the correction for the degrees of freedom used in the *t*-statistic. The dashed lines correspond to the approximate 5 percent significance levels. The data indicate that at the 5 percent level of significance half of the test data from Mills 1, 3, and 4 were within the expected range. Only one of the averages from Mill 2 was within this range. The agreement between the mill and UT tests for most of the plates was judged to be good. Plates with high toughness tended to show the greatest disagreement. However, the toughness of both the mill and UT for these plates exceeded the required average toughness by at least a factor of 2.

Similar graphs for the retest data are shown in Figures 2.19 and 2.20. The position of the original data is shown by a box and the retest data by the "X" symbol. In general, the retests by the two mills showed better agreement with the UT tests than the original values reported by the mills.

The retest of material from Plate 26 by Mill 1 produced values within the expected range. The disagreement between the original mill data and the UT data of Plate 26 was traced to a sam-

Table 2.8. Analysis of variance results for plate depth significance

Mill	Plate No.	Spec. Temp.		Spec. Temp. - 20° F	
		F-Ratio	Sign. Level	F-Ratio	Sign. Level
1	37	0.127	0.7264	3.897	0.0537
4	43	0.506	0.4878	1.934	0.1703
1	33	1.331	0.2538	2.146	0.1489
3	39	1.395	0.2429	0.559	0.4660
4	40	1.981	0.1652	9.212	0.0037
3	36	2.214	0.1428	0.346	0.5650
3	38	2.480	0.1214	4.267	0.0439
4	41	2.939	0.0924	6.702	0.0125
4	42	3.005	0.0889	0.288	0.5995
3	44	3.118	0.0833	0.336	0.5706
1	35	4.324	0.0425	10.427	0.0022
1	34	7.278	0.0094	2.453	0.1234

pling error by the mill. The data from the UT tests of this plate were presented in Figure 2.10. This plate had a significant variation in toughness from one end of the plate to the other that was the result of improper reheating of the plate before the final rolling. The sampling error occurred in the specimens reported by the mill to be adjacent to UT test location C. The average of the original mill tests at this location was 89 ft-lbs. The average of the UT tests at location C was 18.2 ft-lbs. The retests by the mill of material adjacent to location C produced an average toughness of 21.5 ft-lbs. The retests agreed with the results of the UT tests. The chemical analysis of the original mill tests indicated that the material was of similar chemistry to the plate supplied by UT. However, the grain size at the low-toughness end of the plate was large and much larger than the grain size found in the specimens reported by the mill to be from this end of the plate. The conclusion of the investigation was that the specimens reported by the mill at the low-toughness end of Plate 26 came from material probably from the same heat as the plate supplied to UT but was not from the end of the plate supplied to UT.

The results of Mill 3 retests did not provide a conclusive cause for the difference between the mill and UT results. The retest of Plate 17 produced values with the expected mean. However, the retests of Plates 19, 18, and 22 still produced significantly different values. The mean of the retests of these three plates was significantly less than the mean of the original mill tests. The retests of Plates 18 and 22, the 2-in. A588 plates, had tremendous scatter. The range for Plate 18 was from 21 to 112 ft-lbs. The range for Plate 22 was from 11 to 130 ft-lbs. The standard deviations of both the UT and mill retests are also large. The disagreement between the Mill 3 retests and UT appears to result from the large variability within the Mill 3 plates, and from testing and specimen preparation variances between UT and the mill.

2.14 ROUND-ROBIN EXPERIMENT

A round-robin experiment between the mills and UT was performed to determine the reason for the disagreement between the mill and UT CVN values. In general, the mill values were consistently higher than the UT values. Two possible causes for this difference were investigated. The first was notching of the specimens and the second was testing procedures. Specimen blanks machined to the cross-sectional dimensions of the specimens were obtained from the supplier of the National Institute of Standards and Technology (NIST) calibration specimens. These are high-strength 4340 steel. The cost of the specimens was paid by American Iron and Steel Institute (AISI). The NIST specimens are used to check the calibration of the Charpy test machine as required in *ASTM E23.* They are normally supplied completely machined with notches in two energy levels. The low-energy blanks were used in the round-robin experiment. The dimensions of the blanks were checked against the ASTM dimensional requirements. Seven of the 215 blanks did not meet the 90° ±10 minute angle between adjacent sides. These blanks were not used in the round-robin experiment.

Fifteen replicate specimens were used. A large number of replicates were used to increase the sensitivity of the experiment. Thirty specimen blanks were sent to each mill to be notched along with 15 specimens notched by UT. The mills tested the 15 specimens notched by UT and 15 of the specimens they notched. The remaining 15 specimens notched by the mill were sent to UT for testing. The test temperature of the specimens was 40°F. This temperature was selected based on initial testing at UT to determine the relationship between test temperature and energy. The results of these tests are shown in Figure 2.21. The specimens showed no significant decrease in toughness for temperatures below 40°F. A higher toughness would have been desirable so that the toughness of the specimens would be in the range of the toughness of the plates tested. To have a comparable toughness level, a testing temperature of 150°F would be required. A survey of the mills indicated that tests at such a high temperature would be out of the range of the temperature baths they normally use. To ensure that the same equipment and procedures were used for the round-robin tests as were used in the tests of the plate material, a test temperature of 40°F was selected.

Table 2.9. Analysis of UT and mill test results

Mill	Thick in.	Plate No.	Steel	Process	Univ. of Texas			Mill			Org. Mill and UT		Retests			Retests Mill and UT	
					Avg. ft-lbs.	St. Dev. ft -lbs.	Num. Tests	Avg. ft-lbs.	St. Dev. ft-lbs.	Num. Tests	Students	Equal Means	Avg. ft-lbs.	St. Dev. ft-lbs.	Num. Tests	Students	Equal Means
1	4	37	A572	N	77.7	9.5	27	78.3	13.2	6	.14	YES					
1	4	33 & 34	A588	N	70.6	16.5	54	65.0	23.7	6	-.76	YES					
1	2	25	A588	AR	33.2	16.0	27	39.2	8.9	6	.89	YES					
1	2	32	A588	AR	46.6	28.2	27	59.7	23.7	6	1.05	YES					
1	2	31	A572	AR	41.0	15.6	27	51.2	17.6	6	1.41	YES					
1	1	5	A588	AR	67.6	21.0	27	86.2	12.7	6	2.10	NO					
1	1	2 & 3	A572	AR	57.8	19.6	54	79.0	17.1	6	2.55	NO					
1	1	1	A588	AR	27.1	2.8	27	32.3	3.1	6	4.01	NO					
1	2	26	A572	AR	37.7	22.1	27	76.5	16.3	6	4.06	NO	49.9	30.3	12	1.44	YES
1	4	35	A572	N	96.5	16.7	27	138.3	24.7	6	5.15	NO					
2	1	13	A572	AR	73.2	22.8	27	72.8	20.3	6	-.04	YES					
2	2	17	A572	AR	23.7	9.8	27	32.2	4.8	6	2.09	NO	27.4	8.4	30	1.53	YES
2	1	9	A588	AR	67.1	21.6	27	89.2	5.0	6	2.58	NO					
2	1	14	A588	AR	57.4	23.2	27	84.5	22.4	6	2.60	NO					
2	2	19	A572	AR	32.0	9.8	27	44.3	9.1	6	2.82	NO	23.8	7.6	18	-3.01	NO
2	1	10	A572	AR	67.3	14.2	27	86.3	8.4	6	3.18	NO					
2	2	18	A588	AR	41.0	15.7	27	75.8	14.3	6	4.99	NO	69.4	22.7	51	5.88	NO
2	2	22	A588	AR	35.3	18.5	27	78.5	22.3	6	5.01	NO	55.9	28.7	84	3.55	NO
3	2	28	A572	N	77.1	11.4	27	82.2	14.2	12	1.19	YES					
3	2	21	A588	N	72.7	8.2	27	77.8	16.7	12	1.36	YES					
3	1	4 & 8	A572	AR	98.0	39.1	54	116.0	32.9	21	1.87	YES					
3	2	29	A588	N	94.1	10.6	27	86.8	12.9	12	-1.88	YES					
3	4	36 & 39	A588	N	72.7	17.1	54	96.6	24.6	21	4.84	NO					
3	1	6 & 7	A588	AR	135.3	35.0	54	186.7	35.4	21	5.70	NO					
3	2	30	A572	N	51.3	6.3	27	70.2	1.9	12	6.83	NO					
3	4	38 & 44	A572	N	55.7	9.3	54	73.1	10.5	21	7.06	NO					
4	2	27	A572	N	81.2	12.9	27	81.0	13.5	5	-.03	YES					
4	1	15 & 16	A588	N	63.2	6.7	54	66.3	7.2	6	1.08	YES					
4	1	11 & 12	A572	N	86.6	12.7	54	93.0	14.6	6	1.16	YES					
4	2	23	A588	N	99.6	21.8	27	110.7	12.9	6	1.20	YES					
4	4	41 & 42	A572	N	59.5	8.1	54	67.7	7.4	6	2.35	NO					
4	2	24	A588	N	75.2	8.8	27	85.3	8.9	6	2.55	NO					
4	2	20	A572	N	78.1	12.7	17	101.2	19.5	6	3.70	NO					
4	4	40 & 43	A588	N	51.9	7.5	54	70.7	5.6	6	5.97	NO					

A summary of the measurements of the 15 specimens sent to UT that were notched by the mills is shown in Table 2.10. The data for the UT-notched specimens are also listed. The three notch dimensions checked were the included angle of the notch, the ligament below the notch, and the radius of the notch. The measurements were made using an optical comparator with a micrometer stage. The dimensions were checked on both sides of the specimens. The hard material of the specimens presented difficulties in the notching operation. The specimens notched at UT were notched using the same setup as the test specimens from the plates except that the broach speed was reduced.

All the UT specimens failed by 0.001 in. to meet the ligament requirement. This failure was due to the additional pressure applied to the broach and fixture by the hard material. Even though this dimensional error was discovered before the specimens were shipped to the mill, no adjustment to the equipment was made, so a fair comparison could be made with the mills' notches. Mills 1, 2, and 4 reported difficulties notching the specimens with their normal equipment. Mill 3, which ground its notches, had no difficulties meeting all the dimensional requirements. Mill 1 notches were very rough and variable. Mill 4 notches had an average ligament value within the specifications; however, all the specimens had ligaments either too large or too small to meet the specifications. Mill 2 had the best notches machined using a single-tooth flycutter.

Because of the hardness of the steel, no definitive conclusion can be reached regarding the ability of all the parties to produce specimens meeting the specifications. Only Mill 3 procedures

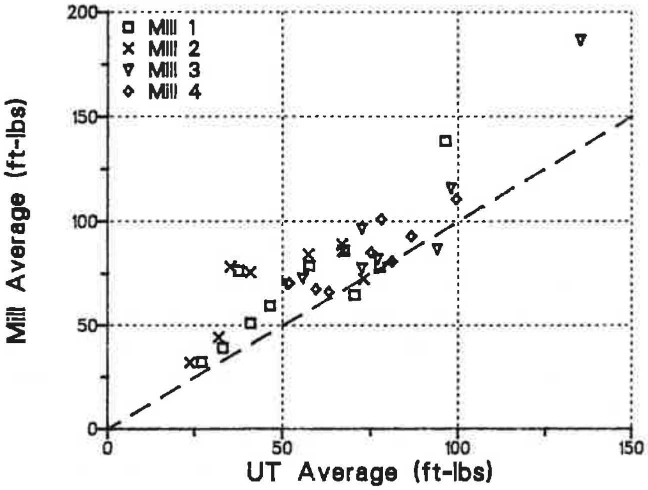


Figure 2.17. Mill and UT average toughness.

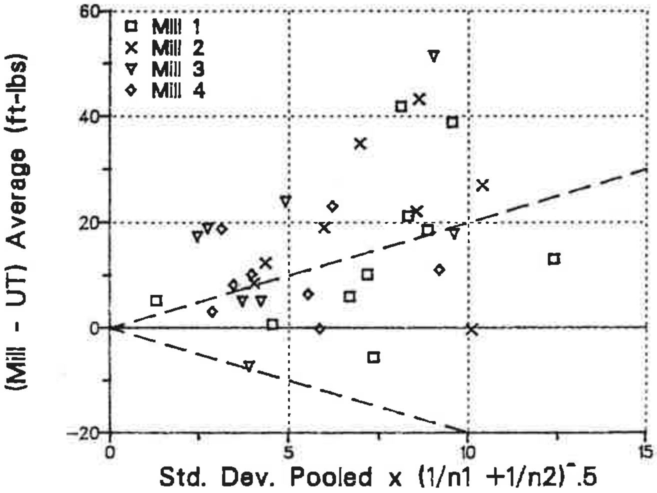


Figure 2.18. Difference in average toughness compared with expected.

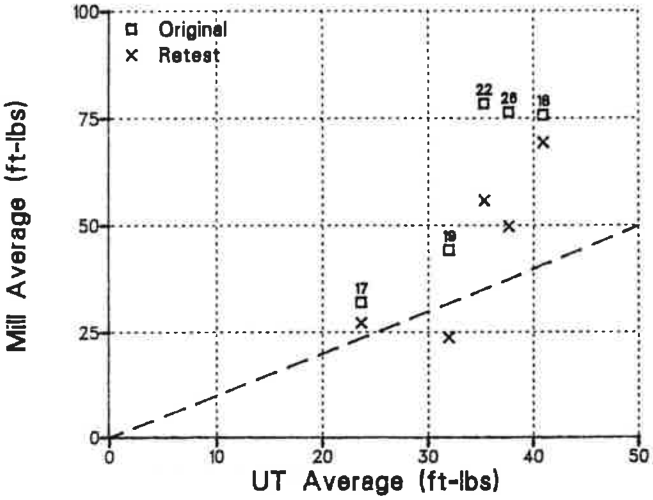


Figure 2.19. Mill retest and UT averages.

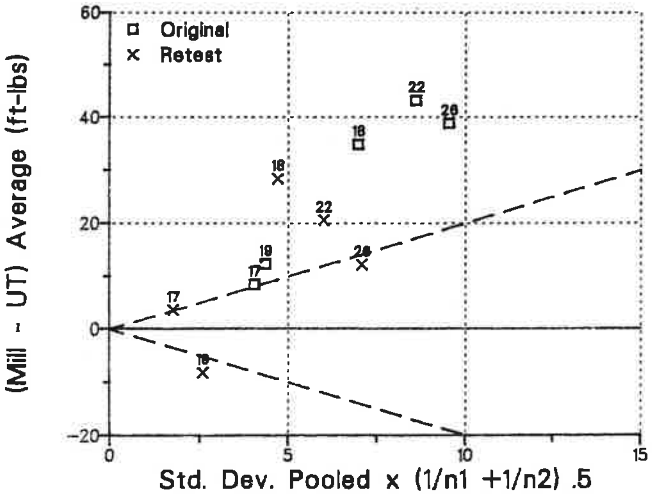


Figure 2.20. Difference in retest average toughness compared with expected.

produced notches meeting all the specification dimensions. All UT specimens met the angle and root radius requirements. Mill 1 had the greatest variability in notch dimensions.

The influence of testing procedures and equipment on the results can be determined by first comparing the tests by the mills of the specimens notched by UT. These data are summarized in Table 2.11. All the mills' average toughness exceeds the average from the test performed at UT. At the 5 percent level, only the results from Mill 1 agree with the UT values. The standard deviations of the results from Mills 2 and 3 agree with UT. The large standard deviations of Mills 1 and 4 indicate that their procedures result in greater variability.

Table 2.12 summarizes the results of the specimens notched by each mill and tested at that mill and by UT. Once again the mills consistently produced higher toughness values. None of the mill average values agree with the UT averages at the 5 percent level of significance. The standard deviations of the results from Mills 2, 3, and 4 agree with the UT values. Mill 2 standard deviation is less than that of UT.

The test results indicate the mills' testing equipment and procedures produce higher average toughness values. This difference occurred with the specimens notched by UT and by the mills. Mill 1 test procedure produced the greatest variability. Table 2.13 summarizes the difference in average toughness between the mills and UT for the round-robin tests and also the average of the difference of the average toughness between the mills and UT for the test plates. The retests done by the mills were included in the test plate statistics where applicable. The last column in the table is the percentage of the plates from each mill in which the mill average agreed with the UT average at the 5 percent significance level. The results of Mills 1, 3, and 4 appear consistent between the round-robin tests and the tests

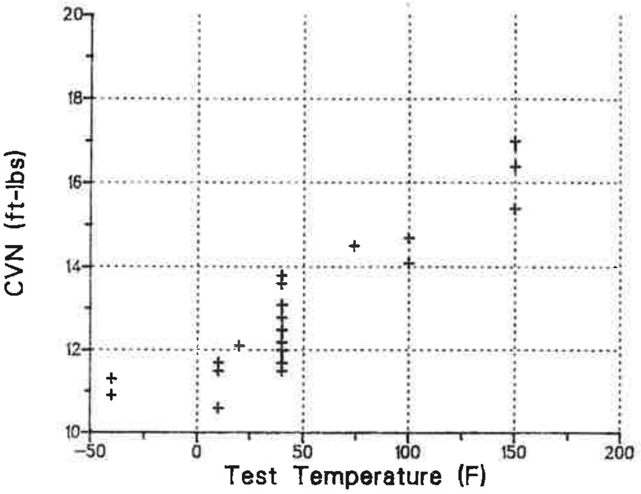


Figure 2.21. Toughness transition behavior of round-robin specimens (UT notch).

performed upon the plates. At least 50 percent of the plates from these mills agreed with the UT plates. The percent difference in average toughness of the plates is comparable to the difference found in the round-robin tests. Mill 2 round-robin results are consistently high and their plate difference is more than twice the round-robin percent difference. It appears that the procedures used by Mill 2 in the round-robin were different than those used for testing the plates.

The higher values obtained by the mills cannot be explained by the results of the round-robin tests. Both the mills and UT have calibrated their machines using the NIST specimens in accordance with ASTM E23. This calibration ensures that the test machine and its measuring system are accurate. It appears that the difference must be caused by the procedures employed by each facility. The authors know of no variation in test procedure other than testing at a lower temperature that produces a lower toughness value. The temperature-measuring equipment employed by UT was calibrated at least once a month using a standardized thermometer. Temperature inaccuracy is not likely the cause of the lower test values from the UT tests. Many

Table 2.10. Notch measurements of round-robin specimens

	Method of Notching	Avg. degrees	Angle Std. Dev. degrees	Min. degrees	Max. degrees	Percent Fail	Avg. in.	Ligament Std. Dev. in.	Min. in.	Max. in.	Percent Fail	Radius Percent Fail
Mill 1	Flycut	45.61	.67	46.78	43.45	13%	.3172	.0020	.3209	.3142	73%	33%
Mill 2	Flycut	45.52	.36	46.09	44.24	7%	.3152	.0002	.3154	.3149	0%	20%
Mill 3	Ground	45.03	.32	45.15	44.15	0%	.3146	.0002	.3149	.3142	0%	0%
Mill 4	Flycut	45.43	.43	45.43	44.23	0%	.3149	.0026	.3173	.3108	100%	20%
UT	Broach	45.38	.48	45.55	44.25	0%	.3167	.0003	.3171	.3162	100%	0%
Spec.		45.00		46.00	44.0		.3150		.3140	.3160		.011-0.09 in.
		Accuracy: ± .25 degrees						Accuracy: ± .0002 in.				

Table 2.11. Tests of UT-notched CVN specimens

Test Location	Average ft-lbs	Std. Dev. ft-lbs	Mill-UT / UT	Equal Mean	Mill/UT Std. Dev.	Equal Std. Dev.
Mill 1	12.9	.99	4%	Yes	1.80	No
Mill 2	14.2	.56	15%	No	1.02	Yes
Mill 3	13.7	.59	11%	No	1.07	Yes
Mill 4	14.3	.96	16%	No	1.75	No
UT	12.3	.55				

Table 2.12. Tests of mill-notched specimens

Notch	Average ft-lbs	Std. Dev. ft-lbs	Average ft-lbs	Std. Dev. ft-lbs	(Mill-UT)/UT	Equal Mean	Mill/UT Std. Dev.	Equal Std. Dev.
Mill 1	13.7	1.53	11.8	.97	17%	No	1.58	No
Mill 2	13.1	.52	11.2	.62	17%	No	.84	Yes
Mill 3	14.1	.64	12.1	.64	16%	No	1.00	Yes
Mill 4	14.1	.70	13.0	.67	8%	No	1.04	Yes

Table 2.13. Percent difference between mill and UT average results

	UT Notch %	Mill Notch %	Test Plates %	Plates Equal %
Mill 1	4	17	29	60
Mill 2	15	17	49	25
Mill 3	11	16	20	50
Mill 4	16	8	15	50

variations in the test procedures can produce a higher test value. The following is a list of these variations.

1. Testing at too high a temperature caused by (a) taking an inaccurate temperature of the bath, (b) not leaving the specimen in the bath long enough to reach the proper temperature, (c) not inserting the centering tongs back into the bath after testing to ensure the tongs are at the same temperature as the bath, or (d) allowing the specimen to warm by taking too long to test the specimen after removal from the bath.
2. Not centering the specimen or placing it away from the anvil.
3. Rounding the test values improperly. All the mills rounded their values to whole ft-lbs.

We believe one or all of the above variations from correct testing procedures may be responsible for the higher values of the mills, not only in the original tests of the plates but also in the round-robin tests. In the UT tests, if any of the items listed in 1 and 2 in the list above occurred, the test was not performed and the specimen was placed back into the bath for testing later.

2.15 SUMMARY OF RESULTS

All the plates tested showed variation in the CVN both at a particular location and from location to location. Normalized plates produced the smallest variability. No significant influence of the type of steel was found in the results. Plate length was not found to be a significant cause of variability. Two-inch as-rolled plates produced the most variability. Two of the 2-in. as-rolled plates from Mill 1 had significant systematic differences in toughness. The mid- and quarter-thickness locations of the 4-in. plates produced similar toughness values. The measured toughness of the mills was generally higher than the values obtained by UT. The difference was not significant for all plates. In general, the mill results provided a reasonable estimate of the plates' toughness.

CHAPTER 3

DEVELOPMENT OF RECOMMENDED SPECIFICATIONS

3.1 PRESENT SPECIFICATION

The original *Guide Specification for Fracture Critical Non-Redundant Steel Bridge Members* was based on ensuring at typical bridge-loading rates that the material would have a toughness level that ensures a nonplane strain fracture. A material with this level of toughness will undergo through thickness yielding before fracture. An increase in toughness with thicker welded plates is specified to account for the greater through thickness constraint offered by these plates. Toughness levels are increased for higher strength material to provide a consistent level of inelastic behavior. A temperature difference in the testing temperature relative to the expected lowest service temperature is used to account for the difference in material fracture behavior with strain or loading rate.

The dynamic Charpy V-notch (CVN) tests are performed at a higher temperature than the service temperature because of the slower loading rate of the bridge in relation to the impact loading rate of the CVN test. The temperature difference is a function of the yield strength of the material. Higher strength steels show less of a temperature difference with loading rate. The guide specification uses a temperature difference of 70°F for all steels, a yield strength less than 65 ksi. Steels with mill tests reporting yield strengths above 65 ksi are tested at a temperature 15°F lower for each increment of 10 ksi above 65 ksi.

Figure 3.1 depicts the basis of the approach taken in the guide specification for setting test temperatures and energy levels. The left-hand curve depicts the CVN behavior of the material at an intermediate loading rate (time to maximum load on the order of 1 second). This loading rate is typical of the loading rates of main members from traffic loading. The toughness of the material at this intermediate service loading rate should exceed 15 ft-lbs at the service temperature. The specification test temperature of the dynamic toughness, measured in the CVN tests performed by the supplier, is above the service temperature to account for the difference in the dynamic loading rate of the standard CVN test (approximately 1 millisecond) and the service loading rate. The variability of the CVN results is shown by the histogram of results at the specification test temperature. To ensure that the toughness is above 15 ft-lbs, the required specification values must be set at a greater level.

Barsom has shown that 15 ft-lbs is sufficient toughness to provide the desired behavior (*3*). The average toughness specified in the guide specification is higher than 15 ft-lbs, to provide greater reliability for fracture-critical steels. A study at Lehigh University investigated the adequacy of the specifications in full-size beam specimens with a variety of welded details (*4*). The beams were subjected to their full design fatigue life to generate typical fatigue cracks. The specimens were then cooled to a low temperature to produce a brittle fracture. Often no fatigue crack was produced after the application of the design fatigue cycles, or the fatigue crack was of insufficient size to trigger an unstable extension. These beams were then cycled further to develop larger fatigue cracks and then were fracture tested.

Figure 3.2 shows the results of the beam tests performed at Lehigh. The vertical axis of the graph is the length of the fatigue crack on the surface of the specimen when it was tested. This fatigue crack length is the maximum visible size crack the beam could tolerate at full service load at the test temperature. The horizontal axis is the beam test temperature minus the temperature at which the average toughness of the flange plate was 15 ft-lbs. This temperature difference was used because all the plates

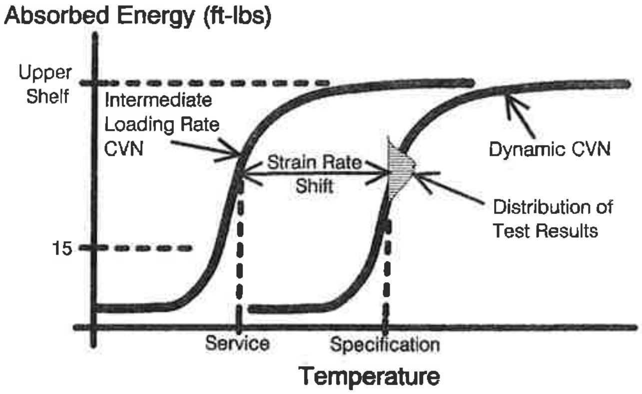


Figure 3.1. Specification approach to CVN toughness.

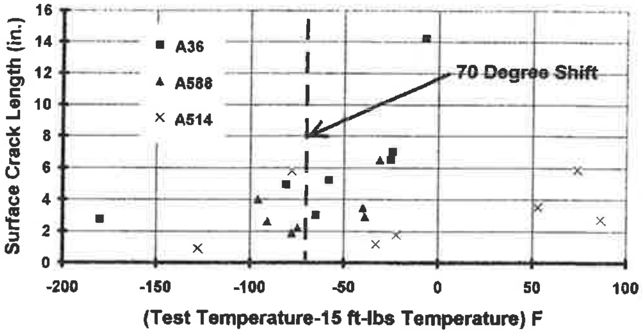


Figure 3.2. Lehigh study beam test results.

Table 3.1. AASHTO Guide Specification requirements

ASTM Designation	Zone 1 Service Temp. 0° F	Zone 2 Service Temp. -30° F	Zone 3 Service Temp. -60° F
A36, A572 GR 50, A588 4-in. Mech. Fast. & up to 2-in. Welded	25 @ 70° F	25 @ 40° F	25 @ 10° F
A588 Over 2-in. Welded	30 @ 70° F	30 @ 40° F	30 @ 10° F
A514 4-in. Mech. Fast. & up to 2-1/2-in. Welded	35 @ 0° F	35 @ 0° F	35 @ -30° F
A514 Over 2-1/2-in. Welded	45 @ 0° F	45 @0° F	Not Permitted

exceeded the specification requirements. The vertical dashed line in the figure is plotted at a temperature difference of 70 dgF, which corresponds to the shift used in the specifications for material with a yield strength less than or equal to 65 ksi. The A36 and A588 beams had surface crack lengths from 2 to 5 in. long at 70°F temperature difference. At higher temperatures the crack size was greater and at lower temperatures it was less. An average toughness of 15 ft-lbs appears to provide adequate size cracks for inspection before unstable propagation. It should be noted that these size cracks were generated after the full design cycles of load had been applied.

The A514 test beams show a smaller surface crack size at the 70°F difference temperature. This is consistent with the specifications, because a smaller temperature shift of 30°F as well as higher required toughness is specified with this higher-strength steel.

The interim guide specifications employed a 20°F lower test temperature. This 20°F lower test temperature corresponds to a –50°F difference in Figure 3.2. The difference in crack size at –70°F and –50°F is not significant. The original test temperatures of the guide specification are sufficient to provide an easily detectable fatigue crack before unstable crack propagation.

On the basis of analysis of the Lehigh test data and the work by Barsom, the researchers conclude that the temperature shift employed in the guide specification and a 15 ft-lb average toughness are adequate to ensure a large stable fatigue crack size before unstable or brittle fracture. The recommended design specification developed later in this chapter will be based on these criteria.

3.2 COMPARISON OF UT AND RETEST RESULTS TO GUIDE SPECIFICATION

The original guide specification requirements are summarized in Table 3.1 (*1*). The test result average must meet or exceed the values listed. A retest is required if more than one of the specimens has a value below the required average or if a single specimen has a value less than two-thirds of the required average. All the specimens in the retest must exceed the required average.

The results of the three specimens tested at the nine locations at the specification temperature and the retests performed by the mills are compared with the specification requirements in this section. The mill tests showed that all the plates met the specification requirements at both ends of the plates. Thirteen of the 44 plates tested in this research had one or more locations that failed to meet the specification requirements. A location was considered as failing to meet the specification if the average of the three specimens did not meet the requirements or if the results would have required a retest. The plates not meeting the requirements are listed in Table 3.2. A blank in the table for a location indicates that the location met the specification requirements. All the plates from Mill 4 that were normalized met the requirements at all locations. Only one of the plates from Mill 3 at one location did not meet the requirements. The last column in the table lists the results of a simulation using the recommended specification that will be discussed later.

The results of the retests performed by Mills 1 and 2, evaluated with respect to the specification, are shown in Table 3.3. Only plates that did not satisfy the specification at some location were retested. The plates and locations for retesting were selected by the mills with advice from UT. Mill 2 did the most retests. As many as nine sets of three specimens were retested by Mill 2 from a particular location within a plate. The retests agree reasonably well with the UT results. Plate 18 was the only plate retested by a mill that did not produce test results below the specification requirements.

The results of the tests performed by UT and the retests by the mills indicate that the guide specification requirements even in plates tested at both ends do not ensure that a plate will have the desired toughness at every location. The results presented in Chapter 2 indicate that the probability of a location having a toughness less than 15 ft-lbs is quite high for some of the plates tested. A statistically based specification that includes the variability of the test results is developed in the next section.

3.3 SELECTION OF A PERCENT DEFECTIVE QUALITY ASSURANCE PLAN

The original AASHTO *Guide Specification* is deemed inadequate for the following reasons.

1. Twelve of the 44 plates had one or more specimens with an absorbed energy value at the specification temperature below the desired quality level of 15 ft-lbs. This is an unusually high risk to the consumer, given the consequences of accepting defective material.
2. There are no provisions to account for the different variations of the fracture toughness (standard deviations) among different plates.

Table 3.2. Locations not meeting AASHTO Guide Specification—Quarter thickness—UT test location

Mill	Plate	Thickness	A	B	C	D	E	F	G	H	J	Simulation %Q < 1.8
1	1	1	1, 2									.0
1	2	1								3		14.0
1	26	2	1,2,3	1,3	1,2,3			2,3				80.6
1	31	2		3						1,2,3		44.4
1	25	2	2						1,2,3	1,2	1,2,3	83.3
1	32	2			1,2,3			1,2,3			2,3	72.2
1	33	4	3	3								36.1
2	14	1		3						3		42.0
2	17	2	1,2,3		1,2,3	3			1,2	1,2,3	1,2,3	83.3
2	19	2								1,2,3		36.1
2	18	2					1,2,3		3		3	58.3
2	22	2		1,2,3	1,2,3	3			3			91.7
3	4	1						3				44.0

Failure Criteria:
1 - Location average < Required average
2 - Two or more specimens < Required average
3 - One or more specimens < 2/3 of required average

Table 3.3. Evaluation of retests with Guide Specification requirements

Mill	Plate	Thickness	Location	Retest Replicate Set						
				1	2	3	4	5	6	7
1	26	2	C	1,3	1,2,3	n.t.	n.t.	n.t.	n.t.	n.t.
1	26	2	J			n.t.	n.t.	n.t.	n.t.	n.t.
2	17	2	C			1,2,3	n.t.	n.t.	n.t.	n.t.
2	17	2	G	3				1,2	1,2	1
2	19	2	C	1,2		1,2	n.t.	n.t.	n.t.	n.t.
2	19	2	G	1,3	1,2	1,3	n.t.	n.t.	n.t.	n.t.
2	18	2	C	9 sets tested – All meet specification						
2	18	2	G	9 sets tested – All meet specification						
2	22	2	A		3					
2	22	2	C			3		2,3	3	
2	22	2	F							
1	22	2	G	2,3	3					

n.t. = No tests
Failure Criteria:
1 - Location average < required average
2 - Two or more specimens < required average
3 - One or more specimens < 2/3 of required average

3. Systematic variability of the fracture toughness along the length and/or width of a plate is not accounted for by a random sampling plan.

4. Examination of a fractured plate in an in-service fracture-critical member revealed that the toughness was sufficiently substandard that the material should not have been qualified for service.

5. There is an absence of a clear statistical understanding of the relationship between the acceptance criteria and the desired quality level (15 ft-lbs).

Therefore, an alternative quality assurance plan is proposed. The recommended plan is intended to ensure an acceptable level of performance in nonredundant fracture-critical bridge plate. To ensure acceptable performance, two distinct approaches are possible for any specification: a method specification that controls the manufacturing processes or an end-result specification that monitors the actual fracture toughness (*4*). The AASHTO *Guide Specification* is an end-result specification.

End-result specifications assess the fracture toughness directly while method specifications attempt indirectly to ensure adequate fracture toughness by monitoring the influencing production parameters. The end-result specification requires monitoring of the product—usually by performing acceptance tests—allowing the producer complete freedom in achieving adequate fracture toughness by whatever methods are technically and economically feasible. An end-result specification also provides a more direct and quantitative evaluation of the plate quality. For these reasons, an end-result specification is recommended.

The necessary components of an end-result specification are the type and method of quality testing to be used, the number of tests to be performed (the sample size), the frequency of the testing (the lot size), the procedures followed for obtaining the test specimens (the sampling plan), any required processing of the test data, the limits imposed on the test data (acceptance criteria), and the actions to be taken if the acceptance criteria are not met (retest provisions) (*6*).

The type and method of testing must produce both accurate and precise results without unreasonable difficulty or economic costs. The precision of any test method is proportional to the square root of the number of tests performed. Because the number of tests required directly influences the economic cost, it is possible that a less precise and less expensive test method with a greater sample size is favored over a more precise but more costly test method; the increased number of tests offsets the lower precision.

The AASHTO *Guide Specification* requires Charpy V-notch specimens to be manufactured and tested in accordance with ASTM A370, A673, and E23 specifications (*7, 8, 9*). This is accepted as a sufficiently accurate and precise test method given its economic costs (*10*). Therefore, other test methods of determining fracture toughness were not evaluated.

The test temperature of the CVN specimens is a variable of the test method. Barsom and the Lehigh University data have shown that a fracture toughness of 15 ft-lbs is sufficient. Because of the transition curves of steel, lowering the test temperature would be conservative. However, the degree of safety depends on the shape of the transition curve, which may be different for each plate. The transition curves and transition temperatures developed from the UT data vary from plate to plate; therefore, a consistent factor of safety cannot be ensured by decreasing the test temperature. Also, the increase in the tolerable crack size was found not to be significant in the Lehigh tests for a 20°F reduction in test temperature. For these reasons, it is recommended that the test temperature not be used as a variable to provide a factor of safety in the specification. The test temperature should remain at the temperature used in the original AASHTO *Guide Specification.*

The lot size is chosen to segregate any differences in the variables influencing the fracture toughness. Chapter 2 demonstrated that the fracture toughness varied significantly from plate to plate, in both overall toughness (plate average) and variability (plate standard deviation). Therefore, each plate should be defined as a separate lot. The AASHTO *Guide Specification* uses a "P" sampling frequency for fracture-critical plates, where the "P" refers to each plate. The "P" sampling frequency is consistent with the results of this study and is recommended in the proposed specification.

The remaining variables to be defined are the sample size, sampling procedure, computational requirements of the test data, the acceptance criteria, and retest provisions. The type of quality assurance plan will determine the relationship between the sample size and the acceptance criteria and the necessary computational procedures. The sampling plan must be designed to meet the underlying assumptions of the statistics used to develop the quality assurance plan.

Typically, quality assurance plans are based on the average (central tendency), the standard deviation (dispersion), or combinations thereof, of the characteristic(s) being controlled, in this case the CVN absorbed energy values. The AASHTO *Guide Specification* directly controls only the central tendency of the fracture toughness within a plate. The average of three specimens is compared with an acceptance criterion. The guide specification indirectly takes into account the standard deviation by imposing an acceptance criterion that is greater than the desired quality level (15 ft-lbs) and by the secondary retest criteria (2 or more values greater than required average and all values greater than two-thirds the required average). However, an underlying assumption of the guide specification is that the standard deviation does not vary significantly from plate to plate, that it is essentially constant.

The analysis of the data in Chapter 2 shows that the standard deviations of the plates do vary significantly. Figure 3.3 is a histogram of the CVN values from two plates that have a plate average toughness of approximately the guide specification acceptance criterion, 25 ft-lbs. The figure clearly shows the difference in dispersion of the two plates. Plate 17 is less desirable than Plate 1, as it has a greater number of low-toughness CVN absorbed energy values. However, the guide specification cannot differentiate between the two plates. It is clear that both the overall toughness and dispersion of the plate in question must directly influence the plate acceptance criteria. The acceptance criteria of a plate must be a function of its average and standard deviation.

The central tendency and dispersion may be either previously known or unknown. Known averages, μ, and standard deviations, σ, are called *population values,* while unknown averages, $\bar{x}$, and deviations, s, are calculated from the test data and are called *sample estimates.* Because the true average toughness and standard deviation of each plate is not known, the quality assurance plan must use sample estimates of these values.

3.3.1 Description of a Percent Defective Plan

The following discussions are based largely on the work by Weed (*11*). Percent defective specifications are also documented in AASHTO R9-86, "Acceptance Sampling Plans for Highway Construction" (*12*). A variable percent defective quality assurance plan (or its complement, percent within limits) determines the necessary acceptance criterion for a given sample size to ensure with a known probability that a given percentage

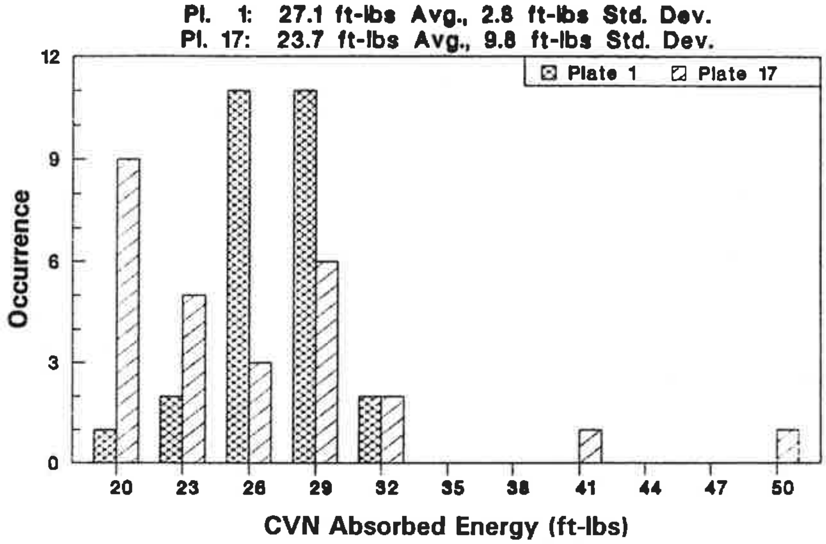


Figure 3.3. Two plates with averages close to the AASHTO acceptance criterion.

of the parent population (the percent defective) does not exceed a lower or an upper limit or a combination of the two. Acceptance is based on both the average and standard deviation. These values may be sample estimates if the statistics are based on a symmetrical beta distribution (*13*). Weed reports that similar plans have been implemented in Military Standard 414, the governing specification for procurement of all materials by the U.S. government, and ACI 214, the code describing the statistical evaluation of the compressive strength of concrete cylinders.

The percent defective plan recommended in this study offers three significant advantages over other quality assurance plans (*5, 11*); a quantitative evaluation of the plate quality is possible rather than a simple accept/reject decision, an inherent incentive for manufacturers to produce a more homogeneous (lower standard deviation) plate with a higher toughness, and a prior knowledge of the risks to both the producer and consumer. The first advantage is useful to the producer, providing evaluation and feedback of the production methods. A higher toughness plate with less variation resulting in a safer, more reliable bridge design is desirable to the bridge engineer. Prior knowledge of the risks is valuable to all interested parties.

3.3.2 Theory

The population of fracture toughness within a plate is assumed to be normally distributed with an average μ and a standard deviation σ. A lower limit L is defined, corresponding with a fracture toughness that is known to affect the desired overall performance. For any given plate and its distribution of fracture toughness, there is an unknown percentage of the distribution falling below the lower limit L, called the true percent defective. Figure 3.4 illustrates the true percent defective of a normal distribution. The smaller the standard deviation σ and the greater the difference between the population average μ and the lower limit L, the smaller the true percent defective will be.

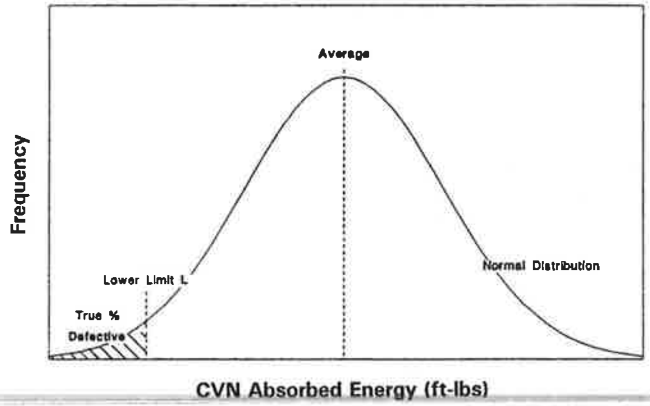


Figure 3.4. Distribution of the parent population.

Engineering judgment determines an acceptable percent defective, recognizing that the material is inherently variable and that a small percentage of defective material, called the acceptable quality level (AQL), is acceptable. It is desired to use material with a true percent defective less than the AQL. However, the true percent defective of a plate is unknown and must be estimated. The percent defective quality assurance plan estimates the percent defective by applying statistical probability concepts to the sample average and standard deviation of a random sample of size n.

Similar to the parent population, the sample has a distribution defined by its sample average $\bar{x}$ and sample standard deviation s. The sample distribution also has a percentage of defective material falling below the lower limit L. The sample percent defective is an estimate of the true (population) percent defective and is called the estimated percent defective. Figure 3.5 illus-

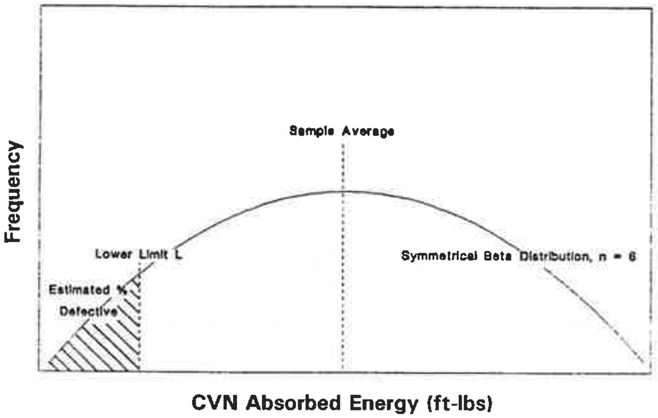


Figure 3.5. Distribution of the sample population.

trates the estimated percent defective of a sample distribution. Unfortunately, the estimated percent defective cannot be compared directly with the acceptable percent defective (AQL) because of the additional variability of the sample distribution from sampling and testing.

The estimated percent defective may be greater or less than the true percent defective, even though the sample was taken from the parent population. This may be further explained by an example. If a population has a true percent defective of 10 percent, it is possible for a random sample to contain a higher amount of the defective material, possibly 15 percent, or a lower amount of defective material, possibly 5 percent. However, it is highly unlikely that the estimated percent defective could be as high as 60 percent. Therefore an allowable estimated percent defective, sometimes denoted by *M*, must be determined based on some defined risks.

Given a distribution defined by its average and standard deviation, it is a relatively easy computation to determine the percent defective that falls below a lower quality limit *L*, if the distribution is normal. However, since it is necessary to use estimates of both the average and standard deviation, a symmetrical beta distribution is required to describe the random sample (*13*). Fortunately, the method for determining a sample estimated percent defective is simplified by the use of tables presented in Appendix C of *AASHTO R9-86*. The sample estimated percent defective is compared to the allowable estimated percent defective, which is based on the sample size *n* and the AQL. The allowable estimated percent defective is the acceptance criterion.

The sample estimated percent defective is determined by first computing the sample quality index *Q* from Equation 3.1. Using the tables in Appendix C of *AASHTO R9-86*, the estimated percent defective corresponding to the sample quality index is determined for the given sample size *n*. This estimated percent defective is compared to the allowable estimated percent defective. The estimated percent defective must be less than or equal to the allowable estimated percent defective.

$$Q = \frac{(\bar{x} - L)}{s} \tag{3.1}$$

It is also possible to describe the acceptance criterion in terms of the required or critical quality index, sometimes called the acceptance constant and symbolized with a *k*, because there is a corresponding quality index for any percent defective, given a sample size *n*. The sampled quality index must be greater than or equal to the critical quality index. These requirements are shown in Equation 3.2. Thus, higher sample quality indices are more desirable. The producer can achieve this by raising the average toughness of the product, reducing the variation of the fracture toughness (standard deviation), or a combination of both. The inherent motivation to produce a tougher, more homogeneous plate is considered advantageous to the bridge engineer and to the general public.

$$\begin{gathered} \textit{Percent Defective}_{\text{estimated}} \leq \textit{Percent Defective}_{\text{allowable}} \\ Q_{\text{sampled}} \geq Q_{\text{critical}} \end{gathered} \tag{3.2}$$

A specification may use either a critical quality index or an allowable estimated percent defective; they are identical acceptance criteria. However, if only the allowable estimated percent defective is specified, the manufacturer must use the tables in Appendix C of *AASHTO R9-86* to determine the estimated percent defective from the sample quality index. If a critical quality index is used, the tables are not necessary. For this reason, it is recommended that the critical quality index be specified.

3.4 DEVELOPMENT OF THE SPECIFICATION

Using a percent defective plan, a critical quality index and the corresponding allowable estimated percent defective are uniquely defined by specifying any two of the following variables: the sample size *n*, the allowable quality level (AQL) and the associated producer's risk (α), or the rejectable quality level (RQL) and the associated consumer's risk (β). This section defines these variables and the recommended acceptance criterion. The relationship between the true percent defective of a plate and the probability of accepting that plate using the recommended critical quality index is described.

3.4.1 Assumptions of Normality and Random Sampling

Before the specification is developed, it is necessary to ensure that the assumptions of the percent defective plan are met. It assumes that the population of the characteristic being evaluated (CVN absorbed energy) is normally distributed and that a random sampling procedure is followed for obtaining the test samples.

There are various methods of checking the assumption of normality for any distribution (graphical means including plotting the cumulative frequency curve on probability paper, a chi-square goodness of fit test, and comparisons of the skewness and kurtosis parameters). For simplicity, a graphical approach is used in this study. The data from the 2-in. plates were used because they contained data from all four mills and equal numbers of as-rolled and normalized plates.

It was desired to combine the populations of CVN values from the 2 test temperatures and the 16 different 2-in. plates.

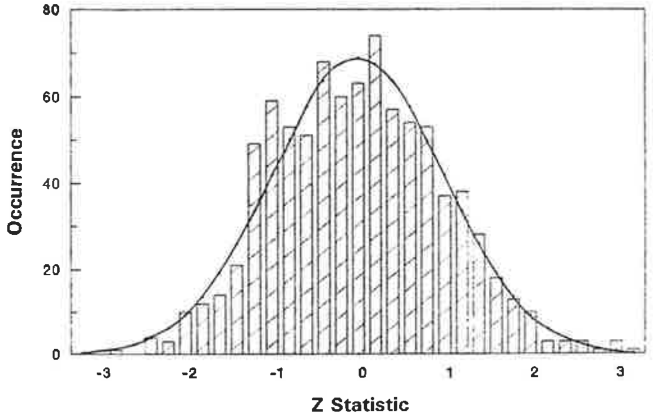


Figure 3.6. Demonstration of normality.

The effects of test temperature and plate average toughness and standard deviation were eliminated by computing the *z*-statistic for each individual CVN value, using Equation 3.3, where the individual CVN value is normalized by both its plate average toughness and standard deviation.

$$z_{\text{statistic}} = \frac{x - \bar{x}_{pl}}{s_{pl}} \tag{3.3}$$

Using the 16 two-in. plates and both test temperatures, 864 *z*-statistics were computed. These are plotted in a histogram and compared with a standard normal distribution in Figure 3.6. The distribution of fracture toughness is represented by the vertical bars. The curve depicts the standard normal distribution, a normal distribution with an average of 0 and a standard deviation of 1. The agreement between the theoretical normal curve and the test data is sufficient to satisfy the requirements of normality.

Random sampling is satisfied if there is an equal probability of obtaining a test sample from any location within the lot being sampled. For a rolled steel plate it is impossible to ensure theoretical random sampling because the plate is no longer completely functional if a sample has been removed from its center. The only area available for sampling is the cropped material outside the plate's finished dimensions. Several locations within the cropped material can be sampled; however, the cost of testing increases with each additional location sampled. In addition, the total cost of testing depends more on the number of locations than on the number of samples; testing 10 specimens from each of two locations may be cheaper than and as effective as testing 5 specimens from each of four different locations. The sampling plan defines the number of locations to be sampled and where they are located.

The analysis of variability in Chapter 2 concluded that location is significant for the as-rolled plates, and, in general, not significant for the normalized plates. For normalized plates, random sampling can be satisfied by sampling a single location because the samples from that location are representative of the entire plate. To simplify the specification and respond to a survey of the project panel, the sampling of normalized plates has been made identical to that of as-rolled plates in the recommended specification. The variation in toughness from location to location within the as-rolled plates requires that multiple locations be sampled. Because of the prohibitive cost of sampling several locations, two locations are recommended for sampling.

Sampled locations must be taken from the cropped material to maintain the plate's integrity. The sampled locations should be adjacent to the finished dimensions of the plate in accordance with ASTM A673. Two locations are required; one location from each end must be sampled. Requiring both ends of the plates to be sampled will ensure that any variation in the fracture toughness along the plate length is represented in the test sample. The smaller variation across the width, which was found to be significant in six plates in the analysis in Chapter 2, is not accounted for in the recommended sampling plan. The variation across the width of the plates was much less than the variation along the length. It is possible to require sampling of locations from diagonally opposite corners of the as-rolled plates; however, it was judged unnecessary.

Table 3.4. Recommended values of lower limit (L)

Guide Specification Required Average ft-lbs	Lower Limit L ft-lbs
25	15
30	18
35	21
45	27

3.4.2 The Lower Limit L

The lower limit L is used in the calculation of a sample quality index. It defines the CVN absorbed energy associated with a difference in the performance of the plate. Material with absorbed energy values below the lower limit is described as defective. As discussed previously, a 15 ft-lbs lower limit (at +10°F) of the fracture toughness corresponds with nonplane strain behavior and an adequate stable crack size. Fifteen ft-lbs is the recommended lower limit for material required to have an average toughness of 25 ft-lbs in the guide specification. The value of L for thicker or higher-strength material can be calculated by multiplying the guide specification values by 15/25 (0.6). The recommended values of L are given in Table 3.4.

3.4.3 The Acceptable and Rejectable Quality Levels

The acceptable and rejectable quality levels are the values of percent defective below the lower limit L associated with material of acceptably good performance and unacceptably poor performance, respectively. The acceptance criteria should result in a high probability of acceptance for material with a percent defective below the AQL and a low probability of acceptance for material with a percent defective above the RQL.

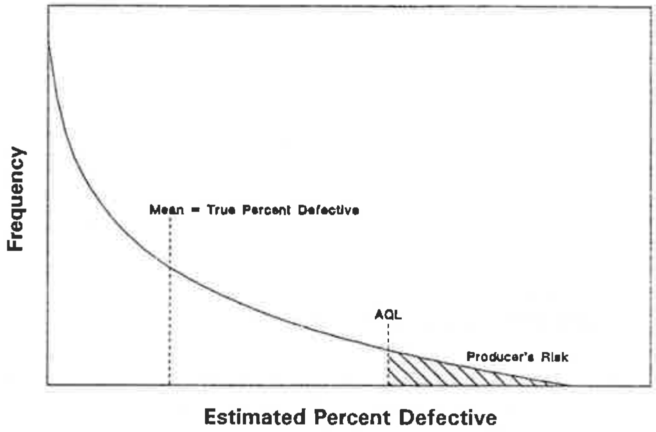


Figure 3.7. Distribution of the sample estimated percent defective.

The AQL and RQL are normally established at 2 percent and 20 percent defective, respectively. By specifying an AQL greater than 0 percent, it is recognized that the material is truly variable and that a small percentage of material below the lower limit L is acceptable. (If an AQL of 0 percent defective were desired, only material with no variability could be accepted.)

3.4.4 Consumer's and Producer's Risks

The consumer's risk (beta error) is the probability of accepting a rejectable plate as defined by the RQL. It is the risk that the consumer will receive a poor quality plate. The producer's risk (alpha error) is the probability of rejecting an acceptable plate as defined by the AQL. It is the risk that the producer will have to scrap a good plate. For a given sample size, increasing one risk will cause a decrease of the other; they are inversely related. Increasing the sample size simultaneously decreases both risks. The risks need to be reasonably low without requiring too large and costly a sample size.

Specifying the producer's risk and AQL for a given sample size yields the allowable estimated percent defective and its associated critical quality index. Figure 3.7 shows the distribution of the estimated percent defective values, corresponding to an infinite number of acceptance tests of a given sample size (*14*). The producer's risk is equal to the area under the distribution's upper tail.

The figure also shows the average of the distribution, which corresponds exactly with the true percent defective. Although any single estimated percent defective is unlikely to match the true percent defective, on the average the acceptance tests will predict the true percent defective. This ensures a fair and accurate evaluation of the plates in the long run.

The consumer's risk is determined from a statistical analysis based on the noncentral t distribution. The beta error is best depicted by an operating characteristic curve, described below. The specification recommendations were developed with the goal of achieving a consumer's risk of 10 percent or less based on an RQL of 20 percent defective.

3.4.5 Sample Size

The sample size must meet a balance between adequate precision and feasible economic cost. Increasing the sample size is the only way of simultaneously decreasing the alpha and beta errors. Therefore, the sample size should be as large as possible without being too costly. The AASHTO guide specification requires three CVN tests and the interim specification requires six samples. A range of three to ten specimens per plate is considered economically feasible. An even sample size will allow an equal number of specimens at each of the two locations required for the as-rolled plates. A total sample size of six, three at each end of the plate, was found to provide an adequate balance of the errors.

3.4.6 The Critical Quality Index

The critical quality index is determined by using the previously discussed concepts of statistical probability for a given sample size, AQL, and alpha error. The statistical analysis was aided by the use of a computer program developed by Barros (*14*). The program is quite capable, offering several statistical analysis options related to the development of percent-defective specifications. It computes the allowable estimated percent defective and critical quality index for any specified sample size and combination of AQL and producer's risk. The program also produces the corresponding operating characteristic curve describing the consumer's risk.

The following observations were made while developing the recommended specification. Increasing the sample size produces lower risks, increases the cost of testing, and results in a higher critical quality index. The higher critical quality index is associated with the increased precision of a larger sample size. If the sample size is maintained and the producer's risk increased corresponding with a decreased consumer's risk, the critical quality index increases.

Using the AQL of 2 percent defective and the goals of a sample size of less than 10 with a consumer's risk of approximately 0.10, combinations were iteratively tested until the desired specification results were achieved. This resulted in an economical sample size of $n = 6$ and producer's and consumer's risks of 30 percent and 10 percent, respectively. The critical quality index was found to be 1.80 with an associated allowable estimated percent defective of 1.01 percent. Two locations, at opposite ends of the plate, are required for testing with three specimens from each location.

3.4.7 Operating Characteristic Curves

The operating characteristic (O.C.) curve is the best description of the theoretical performance of the recommended sample size and critical quality index. Any combination of sample size and critical quality index defines a unique O.C. curve. It is independent of the lower limit L. The true percent defective is plotted on the horizontal axis against the probability of acceptance on the vertical axis. The curve shows the relationship between any possible percent defective and the probability of

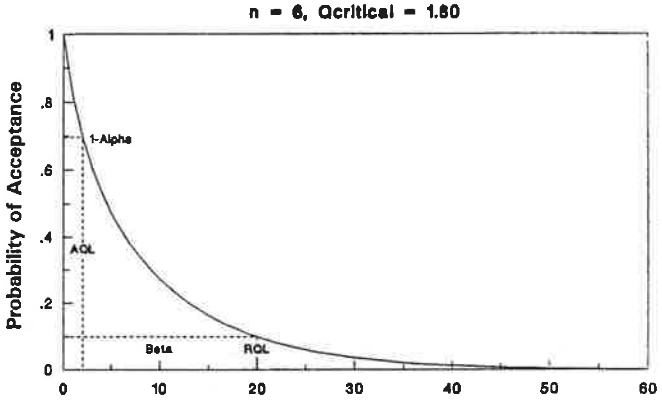


Figure 3.8. Operating characteristic curve.

acceptance. Figure 3.8 shows the O.C. curve for the recommended specification. The AQL and RQL are identified on the horizontal axis. Since the alpha error is the probability of rejection, its complement, 1-alpha, and the beta error are shown on the vertical axis. The O.C. curve was determined using Barros's program.

The ideal O.C. curve is a vertical line at the AQL, with a 0 percent probability of accepting plates with percent defective greater than the AQL and a 100 percent probability of accepting plates with percent defective less than the AQL. (In this situation, the RQL is equal to the AQL.) However, the ideal curve is achievable only by sampling the entire population. The variability associated with a random sample and estimating the percent defective of the parent population using a sample of size *n* requires some risks of accepting rejectable plates, rejecting acceptable plates, and varying probabilities of acceptance in an intermediate zone of nominal quality between the AQL and RQL.

The influence of the sample size and the alpha and beta errors on the O.C. curve is easily described. The steepness of the curve is a function of the sample size: the larger the number of samples, the steeper the curve. Increasing the producer's risk shifts the curve to the left, resulting in a decreased consumer's risk.

3.5 EVALUATION OF RECOMMENDED SPECIFICATION REQUIREMENTS

The acceptance criterion of a critical quality index of 1.80 was applied to the 44 plates of this study. The CVN data from the nine University of Texas (UT) test locations, the original mill tests, and the retests by the mills were used in simulations to evaluate the recommended specification. All data used in the evaluation were from tests at the specification test temperature. Equation 3.4 gives the recommended acceptance criterion. The recommended lower limit L of 15 ft-lbs for 1- and 2-in. plate and 18 ft-lbs for the 4-in. plate was used in the simulation. The purpose of this simulation study was to determine the ability of the specification to screen the plates and to compare the theoretical operating characteristics of the specification with actual test data.

$$\frac{(\bar{x} - L)}{s} \geq 1.80 \qquad (3.4)$$

3.5.1 UT Data Simulation

Three samples from each end of the plate are required in the recommended specification. Since the University of Texas CVN

Table 3.5. Application of the recommended acceptance criteria to the UT test data

Plate No.	Mill	Thickness in.	UT Tests					Q Mill Tests	Probability of Acceptance Mill Retests
			Average ft-lbs	Std. Dev.	Min.	Percent Defect.	Probability of Acceptance		
13	2	1	73.2	22.8	21.3	0	.92	2.84	
5	1	1	67.6	21.0	35.9	0	.92	5.61	
2	1	1	58.4	19.9	28.3	0	.86	3.74	
9	2	1	67.1	21.6	19.8	0	.83	14.73	
19	2	2	32.0	9.8	12.0	3.7	.74	3.22	.19
3	1	1	57.1	19.5	12.7	3.7	.72	3.74	
14	2	1	57.4	23.2	11.1	7.4	.58	3.11	
31	1	2	41.0	15.6	8.6	7.4	.56	2.05	
4	3	1	103.4	51.3	10.5	3.7	.56	3.07	
18	2	2	41.0	15.7	6.1	14.8	.42	4.26	0,1.00
32	1	2	46.6	28.2	11.8	14.8	.28	1.88	
26	1	2	37.7	22.1	4.3	22.2	.19	3.78	
17	2	2	23.7	9.8	7.7	22.2	.17	3.61	.53
25	1	2	33.2	16.0	10.6	7.4	.17	2.73	
22	2	2	35.3	18.5	7.6	14.8	.08	2.85	.47

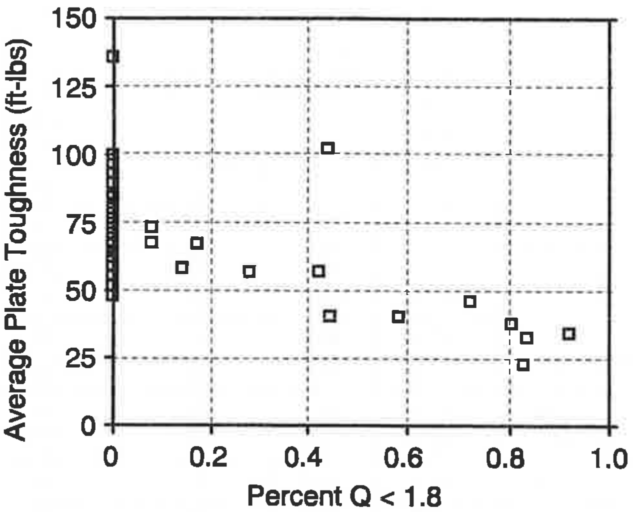


Figure 3.9. Probability of rejection versus average plate toughness.

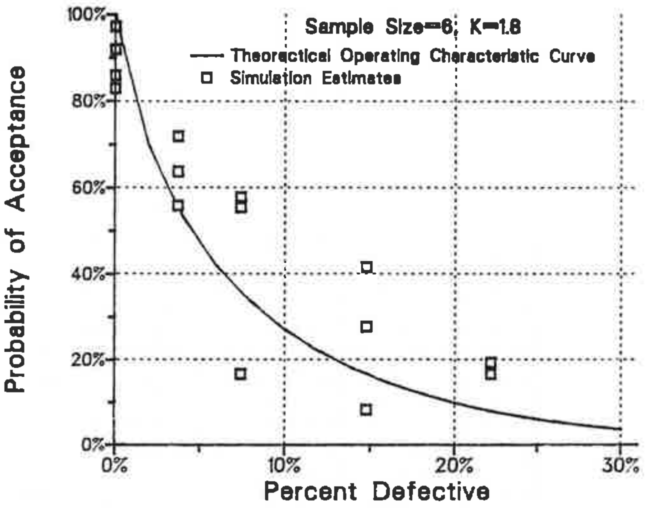


Figure 3.10. Comparison of simulation results with operating characteristic curve.

tests provide data for three specimens at nine different locations per plate, 36 combinations of any two UT test locations were evaluated as possible test samples from each of the plates. This simulates checking the plate 36 times with respect to the specification. The quality index was determined for each of the 36 combinations using Equation 3.1. The fraction of the 36 combinations that met or exceeded the acceptance criterion is listed as the plate's probability of acceptance in Table 3.5. Only the plates which produced a probability of acceptance less than 1 are shown in Table 3.5. The percentage of failures (1 – the probability of acceptance) is listed in the last column of Table 2.1 for all plates. The 15 plates listed in Table 3.5 are the only plates that might be rejected using the UT data and the recommended specification provisions. The percent defective values listed in the table are the percentage of the 27 specimens tested by UT with a value less than L. Because all the plates listed in Table 3.5 are 2-in. or less, the value of L is 15 ft-lbs.

The plates in Table 3.5 are listed in descending order of probability of acceptance. Plates at the top of the list have the highest probability of meeting the specification. The average toughness, standard deviation, and minimum value of the 27 UT tests are listed for comparison. Plates with a low probability of acceptance have either a low average toughness coupled with a standard deviation of about 20 ft-lbs or a high average toughness with a large standard deviation. The influence of the average toughness upon the probability of rejection of all 44 plots is shown in Figure 3.9. A trend of increasing probability of rejection with lower average toughness is evident in the figure. The trend of the data indicates that an average toughness of 25 ft-lbs will result in a probability of 1 for the rejection of a plate. Plate 1 with an average of 27.1 and an extremely small standard deviation of 2.8 ft-lbs is the only exception to the trend. Note also in Table 3.5 that plates with no test values less than 15 ft-lbs (Plates 13, 5, 2, and 9) have a probability of acceptance less than 1. This indicates a slight penalty to the supplier that an adequate plate based on this simulation might be rejected by the proposed specification. The greatest risk to the supplier is 17 percent for these four plates.

Figure 3.10 shows the theoretical operating curve for the recommended specification along with the results of the simulation using the UT results from Table 3.5. The agreement between the theory and the simulation was judged to be reasonable. Simulation points above the theoretical curve indicate that the specification is unconservative. A larger sample in the simulation would be expected to improve the agreement. Rolling practices that produce a plate with a probability of acceptance less than 80 percent would probably not be employed by a mill because of the slim 20 percent chance that the plate would meet the specification.

3.5.2 Mill Data Simulation

The Q values for the six results reported by the mills are listed in Table 3.5 for the plates that had a probability of acceptance less than 1 based on the UT tests. The calculated Q values exceed 1.8. Therefore, all the plates would be accepted based on these original mill tests. Plate 32 had the lowest Q value whereas Plate 9 had the largest. The large Q value for Plate 9 was due to an extremely small standard deviation of 5 ft-lbs.

The Q values greater than 1.8 in Table 3.5 are not unexpected. The mill tests produced consistently higher values than UT tests. Tests at Mills 1 and 2, particularly Mill 2, produced the largest number of values outside the expected range. All the plates except one listed in Table 3.5 are from these two mills.

The retest results were used to perform an additional set of simulations. The probability of acceptance based on these additional simulations is listed in the last column of Table 3.5. The retests of Plate 26 by Mill 1 produced a probability of acceptance of 0. All four sets of test data did not meet the recommended requirement. The original mill data which produced a Q value of 3.78 had a sampling error.

The retests done by Mill 2 indicated a probability of rejection for all the plates. The retests of Plate 18 were done at the mill test laboratory and the research laboratory of Mill 2. An analysis

Table 3.6. Summary of review comments data

Mill	Thickness in.	Steel	End 1		End 2		Both Ends		Guide Spec. Avg. ft-lb	Minimum Value ft-lb
			Average ft-lb	Standard Deviation ft-lb	Average ft-lb	Standard Deviation ft-lb	Average ft-lb	Standard Deviation ft-lb		
A	2.75	A36	152.7	93.0	89.3	25.7	121.0	70.2	25	60
A	0.375	A36	117.3	21.8	33.0	2.0	75.2	48.2	25	31
A	0.375	A36	142.7	21.2	29.0	3.6	85.8	63.7	25	25
A	0.375	A36	46.7	4.0	163.3	10.5	105.0	64.3	25	42
A	0.5	A36	44.3	28.0	130.7	61.2	87.5	63.6	25	20
A	0.6875	A36	100.0	13.0	40.0	9.6	70.0	34.4	25	33
A	1.375	A36	48.0	18.7	67.3	33.3	57.7	26.4	25	30
A	1.5	A36	29.3	14.0	98.3	107.3	63.8	78.2	25	17
A	2.5	A36	65.0	29.1	57.0	27.7	61.0	25.8	25	25
A	0.3125	A572	29.7	0.6	91.7	3.5	60.7	34.0	25	29
A	0.75	A572	186.0	18.5	72.0	10.8	129.0	63.9	25	60
A	0.75	A572	33.3	7.8	47.7	17.0	40.5	14.2	25	27
A	1	A572	36.7	14.2	122.3	24.2	79.5	50.2	25	24
A	1.125	A572	46.3	7.6	60.0	37.4	53.2	25.3	25	35
A	2	A572	56.7	7.6	25.7	5.1	41.2	17.9	25	20
A	2.125	A572	120.0	35.0	65.0	36.1	92.5	43.8	30	25
A	2.25	A572	89.7	13.7	34.7	2.1	62.2	31.4	30	33
A	2	A572	115.0	8.7	45.0	6.2	80.0	38.9	25	38
A	2.5	A572	166.7	15.3	40.0	5.0	103.3	70.1	30	35
A	0.5	A588	88.7	19.8	220.0	74.5	154.3	86.9	25	71
A	0.5	A588	160.3	79.9	62.7	13.5	111.5	74.1	25	49
A	0.5	A588	169.7	121.8	129.3	102.4	149.5	103.0	25	29
A	0.5625	A588	35.3	17.1	119.3	17.9	77.3	48.6	25	24
A	0.625	A588	198.0	72.7	61.3	49.1	129.7	93.2	25	33
A	0.625	A588	142.7	36.7	67.0	32.9	104.8	51.9	25	48
A	0.625	A588	156.7	22.0	58.0	33.4	107.3	59.7	25	30
A	0.625	A588	180.3	103.3	108.7	45.4	144.5	81.5	25	61
A	0.75	A588	62.7	21.1	227.0	8.9	144.8	91.2	25	45
A	1	A588	106.0	76.4	74.7	55.3	90.3	62.1	25	18
A	1.125	A588	63.3	9.0	207.7	56.0	135.5	86.8	25	54
A	1.125	A588	79.0	2.6	26.0	1.0	52.5	29.1	25	25
A	1.25	A588	28.3	3.5	100.7	10.1	64.5	40.2	25	25
A	1.375	A588	113.0	25.2	50.7	34.2	81.8	43.4	25	21
A	1.375	A588	42.0	18.4	103.3	14.4	72.7	36.7	25	21
A	1.5	A588	35.3	16.2	49.3	14.0	42.3	15.6	25	25
A	1.5	A588	28.7	2.1	62.3	30.6	45.5	26.7	25	27
A	1.5	A588	48.7	13.1	133.3	4.2	91.0	47.2	25	35
A	2.5	A588	172.3	21.6	61.7	32.1	117.0	65.4	30	37
A	2.5	A588	116.7	12.7	49.3	1.2	83.0	37.8	30	48
A	2.75	A588	69.3	5.9	248.0	27.7	158.7	99.5	30	65

Table 3.6. Summary of review comments data (continued)

Mill	Thickness in.	Steel	End 1		End 2		Both Ends		Guide Spec. Avg. ft-lb	Minimum Value ft-lb
			Average ft-lb	Standard Deviation ft-lb	Average ft-lb	Standard Deviation ft-lb	Average ft-lb	Standard Deviation ft-lb		
B	1.5	A572	36.0	9.5	34.7	15.2	35.3	11.4	25	21
B	2.75	A572	31.3	2.1	66.3	5.7	48.8	19.5	30	29
B	0.5	A572	238.7	25.8	86.3	1.5	162.5	85.0	25	85
B	0.5	A572	75.3	13.6	219.0	36.8	147.2	82.5	25	61
B	1	A572	51.7	6.5	26.7	4.2	39.2	14.5	25	22
B	0.5	A572	126.7	9.9	43.3	29.2	85.0	49.6	25	26
B	0.5	A572	104.7	8.1	44.0	12.2	74.3	34.5	25	30
B	0.5	A572	36.0	9.2	93.3	11.4	64.7	32.7	25	26
B	2.75	A572	42.0	4.0	24.7	8.1	33.3	11.1	30	20
B	2.75	A572	30.0	0.0	65.7	2.1	47.8	19.6	30	30
B	2.75	A572	23.3	4.2	42.0	2.0	32.7	10.6	30	20
B	1.3125	A572	67.7	25.1	18.7	1.2	43.2	31.2	25	18
B	1.3125	A572	111.3	16.0	27.0	1.7	69.2	47.3	25	25
B	1.3125	A572	132.7	14.7	34.7	2.1	83.7	54.5	25	33
B	1.3125	A572	139.7	5.9	42.3	18.9	91.0	54.8	25	26
B	1	A572	66.0	38.9	148.7	22.1	107.3	53.4	25	36
B	1	A572	66.0	38.9	50.3	25.5	58.2	30.7	25	25
B	2.75	A572	48.0	25.6	71.3	19.1	59.7	23.9	30	24
B	2.75	A572	31.7	4.5	33.7	13.5	32.7	9.1	30	20
B	2.75	A572	64.7	17.2	30.7	5.5	47.7	21.9	25	25
B	2	A572	34.7	18.6	60.0	4.4	47.3	18.4	25	22
B	1.625	A572	89.0	19.9	41.7	8.3	65.3	29.3	25	35
B	2	A572	52.7	27.0	32.3	8.4	42.5	21.0	25	27
B	1.5	A572	27.7	7.1	93.7	12.7	60.7	37.3	25	20
B	2	A572	124.0	6.9	25.7	14.2	74.8	54.8	25	17
B	2	A572	49.0	13.9	50.0	27.1	49.5	19.2	25	24
B	0.625	A572	25.3	2.1	91.3	14.7	58.3	37.4	25	23
B	2.5	A572	125.7	40.2	62.0	11.8	93.8	43.8	30	52
B	2	A572	93.3	52.8	68.3	19.6	80.8	38.2	25	36
B	2	A572	48.0	6.1	126.7	8.4	87.3	43.6	25	41
B	0.625	A588	20.0	1.7	3.53	3.1	27.7	8.7	25	19
B	0.5	A588	261.7	1.5	85.7	8.7	173.7	96.6	25	76
B	0.4375	A588	43.3	11.5	113.3	12.1	78.3	39.8	25	30
B	1	A588	260.0	1.0	64.0	3.5	162.0	107.4	25	60
B	0.4375	A588	20.7	5.5	86.0	4.0	53.3	36.0	25	17
B	0.4375	A588	45.0	20.1	118.0	4.0	81.5	42.0	25	26
B	0.5625	A588	242.7	9.3	80.7	6.7	161.7	89.0	25	75
B	1.75	A588	40.0	19.1	43.7	14.5	41.8	15.3	25	20
B	1.25	A588	59.3	21.2	53.7	32.6	56.5	24.8	25	27
B	2	A588	112.0	43.2	52.3	5.9	82.2	42.8	25	48
B	1.25	A588	132.7	9.7	59.0	32.0	95.8	45.5	25	23
B	1.25	A588	130.7	11.4	59.0	32.0	94.8	44.7	25	23
B	3	A588	60.7	40.2	65.7	11.4	63.2	26.5	30	36

Table 3.6. Summary of review comments data (continued)

Mill	Thickness in.	Steel	End 1		End 2		Both Ends		Guide Spec. Avg. ft-lb	Minimum Value ft-lb
			Average ft-lb	Standard Deviation ft-lb	Average ft-lb	Standard Deviation ft-lb	Average ft-lb	Standard Deviation ft-lb		
B	0.5625	A588	101.3	16.8	39.3	13.3	70.3	36.6	25	28
B	0.5625	A588	170.0	15.9	67.0	21.0	118.5	58.8	25	49
B	0.5625	A588	80.7	20.0	41.3	10.3	61.0	25.8	25	30
B	0.5625	A588	46.3	24.8	71.0	28.5	58.7	27.5	25	32
B	0.5625	A588	55.3	12.2	136.7	11.4	96.0	45.8	25	42
B	0.5625	A588	29.3	4.2	128.7	1.2	79.0	54.5	25	26
B	0.5625	A588	30.0	3.5	44.7	17.6	37.3	13.9	25	25
B	0.5625	A588	33.3	5.8	43.7	19.1	38.5	13.9	25	28
C	0.625	A572	156.3	11.7	6.13	25.7	108.8	55.0	25	46
C	1.375	A572	48.0	5.3	124.3	24.2	86.2	44.7	25	44
C	0.75	A6	121.7	45.1	72.3	61.4	97.0	55.2	25	32
C	0.5	A36	100.7	37.3	54.0	37.0	77.3	41.9	25	26
C	0.875	A36	74.3	46.0	51.7	6.7	63.0	31.9	25	38
C	2.75	A572	192.3	28.9	64.0	39.5	128.2	76.8	30	24

of the data indicated a significant difference between the tests performed at the two locations. The two probabilities listed in Table 3.5 for Plate 18 are for each set of test data taken separately. All the simulations using the research laboratory data failed to meet the recommended specification requirement. All the mill test laboratory simulations met the specification. The remainder of the retest data from other Mill 2 plates produced results in reasonable agreement with the simulations using the UT. Since the mill retests did not encompass all nine locations but only selected locations, the difference between the retests and UT simulations is expected. The original mill tests by Mill 2 appear to be in error and to have positive bias.

3.6 ANALYSIS OF INDUSTRY DATA

In the review comments of the draft final report, the reseachers received data from 98 plates that did not satisfy the requirements presented in the previous section. The data came from three steel mills. A36, A572 Gr. 50, and A588 steel data were included. Plates for fracture-critical and nonfracture-critical components were included in the database. The plates were tested at each end. A summary of the tests results reported on these plates is given in Table 3.6.

None of the plates satisfied the requirements of the previous section. Four of the plates did not meet the original guide specification at one end. The average toughness of many of these plates was above 100 ft-lbs. Consequently, it appeared that the proposed specification based on the average toughness and standard deviation of the results of both ends of the plate was unduly conservative. Most of the plates had very large standard deviations and significant differences between the toughness of the two ends. The large difference in toughness between the two ends produced the large standard deviation. Figure 3.11 shows a histogram of the tests from these plates. The energy value of each result divided by the average of all the results for the plate is plotted on the abscissa. The histogram has two distinct peaks, at approximately 0.5 and 1.5. This indicates that the values from each end of the plate are not from the same population. The quality index procedure assumes that the six test results are from the same population. Many of the plates with high toughness would pass the quality index criteria if the values at the high end of the plate were halved. A specification that rejects plates with high toughness but would accept them with lower toughness is undesirable.

Various methods of formulating a specification that did not reject desirable plates but also provided an operating curve similar to the quality index procedure were investigated. A simple specification formulation was found to produce almost identical results. Increasing the lower bound value of the specification from 0.67 to 0.8 times the required average produced almost the same results as the quality-index-based criteria and did not reject the plates with high toughness in the industry database. The required average used in the proposed specification is the same as the average in the original guide specification.

Table 3.7 lists the plates in the industry database that would not satisfy the proposed specification. Also listed in the table are the results of applying the original guide specification criteria to the data from both ends of the plates. Sixteen plates of the 98 would be rejected using the proposed specification. Only four would be rejected by the original guide specification criteria.

The data from the plates tested as part of this research were also analyzed to determine the relationship of the proposed specification with the specification formulated using a quality index, *Q*, of 1.8 Table 3.8 lists the plates that fail to meet the proposed specification at one or more locations. The number of locations that fail to meet the guide and the proposed specification are listed. The last three columns list the probability of the plates being rejected based on the test results from the nine locations

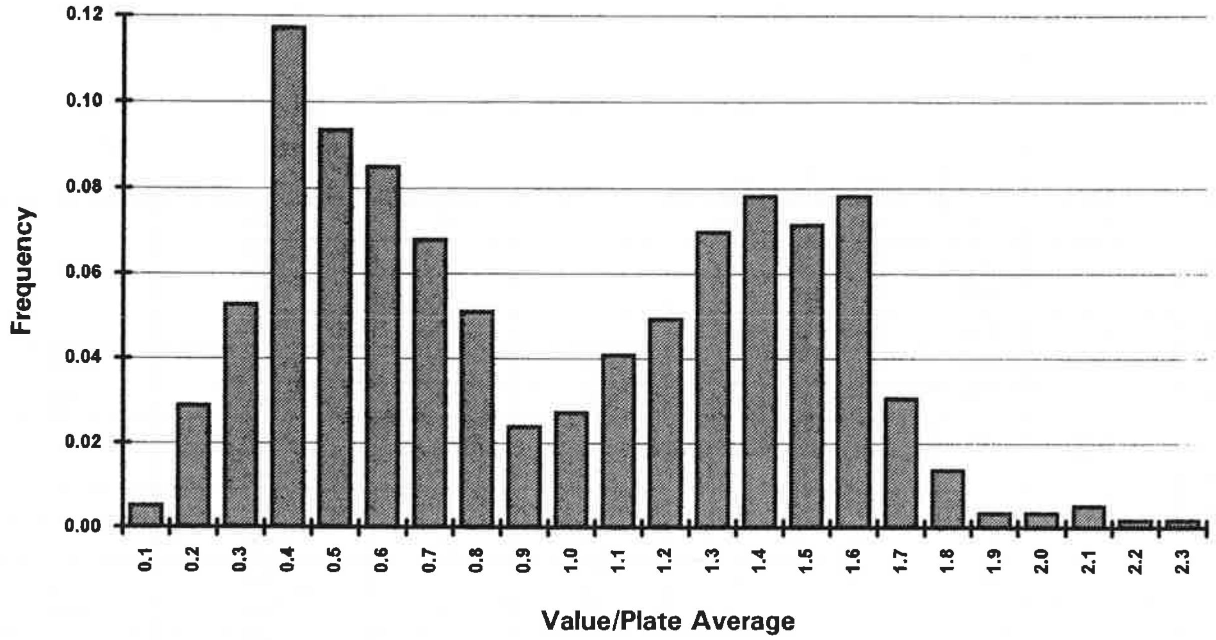


Figure 3.11. Histogram of normalized review comments data.

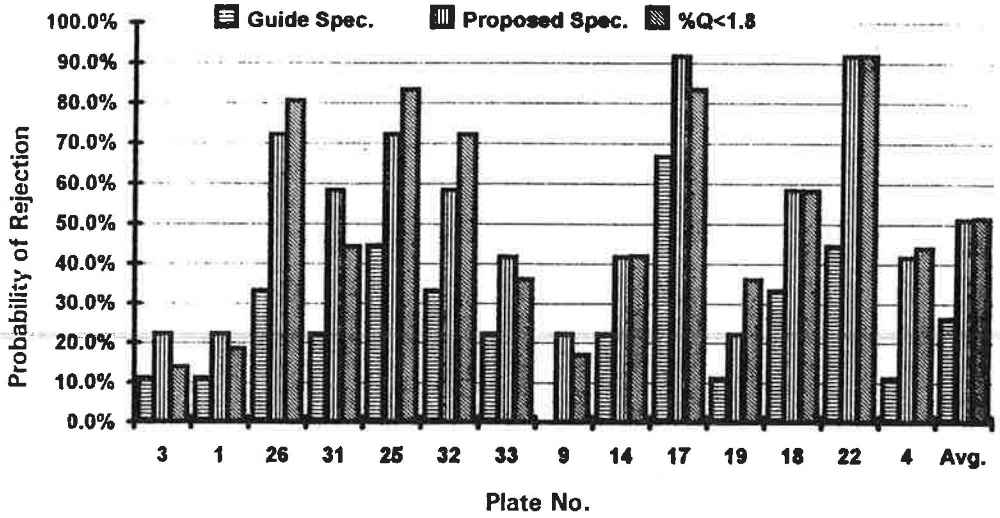


Figure 3.12. Probability of rejecting a plate for proposed guides and quality index specifications.

sampled. The proposed specification produces results almost identical to the quality index method. The probability of rejection using the proposed specification is on the average twice that of the guide specification. The increase in the probability of rejection relative to the guide specification occurs because of testing at both ends as well as the increase in the lower limit from 0.67 to 0.8. Figure 3.12 shows the probability of rejection for these plates using the three specification formulations. The agreement between the proposed and the more complex quality assurance method is remarkable.

Based on the analysis of the data from the 98 plates tested by the mills and the 44 plates tested as part of this study, a lower limit to the test values in the specification equal to 0.8 times the required average provides a workable and fair specification requirement. The user's risk is almost the same as provided by a quality index of 1.8. The data supplied by the mills reinforces the need to test both ends of the plates. The large differences in toughness between the two ends of the plates rule out specifications that require testing at only one end.

Table 3.7. Review comments plates not meeting proposed specification

Mill	Thickness	Steel	Both Ends		Guide Spec. Avg.	Minimum Value	Specification (.8x Spec. Avg.)	Present Guide Specification
			Average	Standard Deviation				
	in.		ft-lb	ft-lb	ft-lb	ft-lb		
A	0.5	A36	87.5	63.6	25	20	FAIL	
A	1.5	A36	63.8	78.2	25	17	FAIL	
A	2	A572	41.2	17.9	25	20	FAIL	
A	1	A588	90.3	62.1	25	18	FAIL	
B	2.75	A572	33.3	11.1	30	20	FAIL	FAIL
B	2.75	A572	32.7	10.6	30	20	FAIL	FAIL
B	1.3125	A572	43.2	31.2	25	18	FAIL	
B	2.75	A572	59.7	23.9	30	24	FAIL	
B	2.75	A572	32.7	9.1	30	20	FAIL	
B	1.5	A572	60.7	37.3	25	20	FAIL	
B	2	A572	74.8	54.8	25	17	FAIL	
B	0.625	A588	27.7	8.7	25	19	FAIL	FAIL
B	0.4375	A588	53.3	36.0	25	17	FAIL	FAIL
B	1.75	A588	41.8	15.3	25	20	FAIL	
B	2.25	A588	49.3	27.0	30	23	FAIL	
C	2.75	A572	128.2	76.8	30	24	FAIL	

Table 3.8. Analysis of test plates versus proposed specification

Plate No.	Mill	Thickness in.	Steel	Plate Average ft-lb	Standard Deviation ft-lb	Guide Spec. Avg. ft-lb	Minimum Value ft-lb	Number of Locations Not Meeting		Probability of Not Meeting Specifications		
								Guide	Proposed	Guide	Proposed	Simulation %Q < 1.8
3	1	1	A572	57.1	19.5	25	12.7	1	1	11.1%	22.2%	14.0%
1	1	1	A588	27.1	2.8	25	20	1	1	11.1%	22.2%	18.5%
26	1	2	A572	37.7	22.1	25	4.3	3	4	33.3%	72.2%	80.6%
31	1	2	A572	41.0	15.6	25	8.6	2	3	22.2%	58.3%	44.4%
25	1	2	A588	33.2	16.0	25	10.6	4	4	44.4%	72.2%	83.3%
32	1	2	A588	46.6	28.2	25	11.8	3	3	33.3%	58.3%	72.2%
33	1	4	A588	66.9	19.3	30	12.6	2	2	22.2%	41.7%	36.1%
9	2	1	A588	67.1	21.6	25	19.8	0	1	0.0%	22.2%	17.0%
14	2	1	A588	57.4	23.2	25	11.1	2	2	22.2%	41.7%	42.0%
17	2	2	A572	23.7	9.8	25	7.7	6	6	66.7%	91.7%	83.3%
19	2	2	A572	32.0	9.8	25	12	1	1	11.1%	22.2%	36.1%
18	2	2	A588	41.0	15.7	25	6.1	3	3	33.3%	58.3%	58.3%
22	2	2	A588	35.3	18.5	25	7.6	4	6	44.4%	91.7%	91.7%
4	3	1	A572	103.4	51.3	25	10.5	1	2	11.1%	41.7%	44.0%
							Average =	2.36	2.79	26.2%	51.2%	51.5%

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

4.1 SUMMARY

The tests of the 44 plates included in the research showed that the Charpy V-notch (CVN) test values varied at a particular location and at the nine locations sampled. Plates that were normalized after rolling had the smallest variability. The variation in the plate toughness was found to be essentially the same for the two temperatures tested. The top-quarter and lower-quarter thickness locations had the same toughness. The toughness of the mid-thickness and quarter-thickness of the 4-in. plates, which were all normalized, was the same.

Sixteen of the plates had significant variation in toughness along their length. All the 98 plates in the industry database, supplied as part of the review comments, exhibited significant end-to-end toughness variation. The variation along the length of the plates was significant only in the as-rolled plates, not in the normalized plates.

The CVN tests performed at the mills compared reasonably well with the test performed in the research. One plate was sampled incorrectly by Mill 2. The large variability of Mill 3 plates caused a wide scatter in the test results by the mill. The plates from Mill 3 that had the largest scatter have a high probability of rejection by the proposed specification.

The round-robin testing of the NIST steel specimens indicated that the notching procedure used by Mill 1 did not produce consistent notch geometry. Only the ground notches of Mill 3 met all the specification requirements. The notch and any testing differences between the mills and University of Texas (UT) produced a maximum average difference of 2 ft-lbs.

The CVN values at a particular location and at the test locations within the plates varied. Only one plate that had a low average toughness of 27.1 ft-lbs exhibited uniform toughness throughout the plate. The ratio between the largest test value and the smallest test value of some of the plates exceeded 10. This variation must be considered in the construction of the specification and acknowledged in the interpretation of check tests performed upon material. It is highly unlikely that a sample taken from a plate will match the value reported in the mill test report. The specification must ensure with reasonable certainty that the testing and sampling performed by the mill will ensure that the toughness anywhere in the plate is adequate for performance. The toughness level considered adequate is not the same as the specification requirement. The specification requirement must be higher to account for the variability in the material.

4.2 PROPOSED SPECIFICATION

The goal of the specification is to provide a risk of less than 10 percent that a rejectible plate is accepted with a 30 percent risk that an acceptable plate is rejected. These risks are associated with an allowable estimated percent defective of 1.01 percent. If three CVN specimens are taken from 200 locations from a plate meeting this specification and the results of each location are paired with one other, there is a 10 percent probability that one of the pairs may have an average toughness less than the required lower limit of acceptability. On the other hand, there is a 30 percent risk that this plate may be rejected as a result of the tests performed by the producer.

The lower limit of acceptable toughness selected for the specification was 0.6 of the guide specification average. For example, for Grade 50 plates used in welded construction less than or equal to 2½ in. in thickness, the lower limit is 15 ft-lbs. This level of toughness provides more than adequate toughness to ensure that the stable fatigue crack length will exceed 2 in. in length. Thicker plates or plates with higher strength have a higher value of average toughness required and a correspondingly higher lower limit to provide an equally stable crack size.

All the 98 plates in the industry database and many of the as-rolled plates in this study exhibited significant end-to-end variations in toughness. Testing at both ends of a plate must be done to assess the toughness of these plates. The plates in the industry database were for Zones 1, 2, and 3. As-rolled plates are most likely to be supplied for Zones 1 and 2. Controlled rolling is the most economical method of meeting the toughness requirements at the higher test temperatures of Zones 1 and 2. Consequently, it is recommended that testing at both ends of the plates be reinstated into the AASHTO specification for all temperature zones for as-rolled plates. Normalized plates need only be tested at one end.

The specific recommendations for changes to the AASHTO specification are these:

- Plates for fracture-critical members that are not normalized are to be tested at both ends of the rolled plate. The testing shall consist of three CVN specimens from each end, tested at the original guide specification temperature. Plates normalized after rolling are to be tested at one end only.
- The minimum value of the CVN tests must exceed the 0.8 average value required. The average of the three test results from each sample must exceed the required average.
- Most of the footnotes should be removed from tables and placed in the specification text.

The required averages and test temperatures recommended are the same as the original AASHTO guide specification. The recommended changes to the *Guide Specifications for Fracture Critical Non-Redundant Steel Bridge Members* are given below.

Delete paragraph 7.1 and replace it with the following paragraphs 7.1, 7.2, 7.3, and 7.4. In addition, replace the existing

Table 4.1. Recommended changes to Table 7.1 of the AASHTO *Guide Specifications for Fracture Critical Non-Redundant Steel Bridge Members* (see Reference *1*)

AASHTO M270 (ASTM A709) Grade	Connection Method	Thickness inches	Minimum Average Energy ft-lbs	Minimum Test Value Energy ft-lbs	Test Temperature - F		
					Zone 1	Zone 2	Zone 3
36F	Welded or Mechanically Fastened	to 4 in. inclusive	25	20	70°	40°	10°
50F/50WF	Mechanically Fastened	to 4 in. inclusive	25	20	70°(a)	40°(a)	10°(a)
50F/50WF	Welded	to 2 in. inclusive	25	20	70°(a)	40°(a)	10°(a)
50F/50WF	Welded	over 2 to 4 in. inclusive	30	24	70°(a)	40°(a)	10°(a)
70WF	Mechanically Fastened	to 4 in. inclusive	30	24	50°(b)	20°(b)	-10°(b)
70WF	Welded	to 2-1/2 in. inclusive	30	24	50°(b)	20°(b)	-10°(b)
70WF	Welded	over 2-1/2 to 4 in. inclusive	35	28	50°(b)	20°(b)	-10°(b)
100F/100WF	Mechanically Fastened	to 4 in. inclusive	35	28	0°	0°	-30°
100F/100WF	Welded	to 2-1/2 in. inclusive	35	28	0°	0°	-30°
100F/100WF	Welded	over 2-1/2 to 4 in. inclusive	45	36	0°	0°	Not Permitted

(a) If the yield point of the material exceeds 65 ksi, the testing temperature for the minimum average required shall be reduced by 15° F for each increment of 10 ksi above 65 ksi. The yield point is the value given on the certified "Mill Test Report."

(b) If the yield point of the material exceeds 85 ksi, the testing temperature for the minimum average required shall be reduced by 15° F for each increment of 10 ksi above 85 ksi. The yield strength is the value given on the certified "Mill Test Report."

Table 7.1 with the recommended changes as shown here in Table 4.1.

7.1 The CVN-impact testing shall be "P" plate frequency in accordance with AASHTO Specification T-243 (A673/673M). Plates supplied in the as-rolled condition shall be sampled at each end of the plate-as-rolled. Plate normalized after rolling shall be sampled at one end of the plate-as-heat-treated.

7.2 The average value of the three test specimens at each sample location shall be equal to or exceed the average listed in Table 7.1. All test values shall be equal to or exceed the minimum value listed in Table 7.1.

7.3 The Charpy test pieces shall be coded with respect to heat/plate number and that code shall be recorded on the mill-test report of the steel supplier with the test results.

7.4 If requested by the engineer, the broken pieces from each test location (three specimens, six halves) shall be packaged and forwarded to the quality assurance organization of the state.

4.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The following topics are suggested for future research.

1. The influence of CVN variation at a location upon the full-thickness toughness of the plates needs to be determined. The present literature on this subject contains conflicting data. The CVN specimen samples an extremely small volume of material. All the plates tested exhibited variation in CVN values at a location in the plate. Since these specimens were machined and tested identically, the differences in the energy values must be due to differences in the toughness of the material in the ligament ahead of the notch. Would a full-thickness specimen behave in accordance with the average CVN toughness or the lowest value? The results of this research would help in the interpretation of the significance of the scatter in CVN results. The proposed specification is based on average toughness. If a weak link at a location, as determined from the CVN specimen, dominates the fracture performance, the specification philosophy needs to be changed. In addition, the present test location of one-quarter thickness is used to obtain an average measure of the toughness through the thickness of a plate. This is the proper location if the full-thickness plate results show the behavior matches the average toughness of the plate. An experimental program comparing the full-thickness fracture behavior of various plates with their CVN results is needed.

2. A quality certification program needs to be developed for steel producers. The present study has shown that the state of the art of controlled rolling of plates as practiced by the four mills that participated in the research can produce considerable end-to-end differences in toughness. Normalized plates show very little variation. A process is needed to qualify producers to ensure that their rolling procedures do not produce results that are not considered in the present specification. For example, sampling only the ends of a plate produced by a mill that produces plates with the lowest toughness in the center of the plate would not be desirable. New producers are entering the domestic market. A means of qualifying these new producers or mills which change their rolling practices needs to be developed.

3. The applicability of heat-lot (H sampling in A673) testing for nonfracture-critical applications needs to be determined. Does the present sampling of the thickest plate in the heat for toughness ensure that the thinner plates rolled from the heat are adequate when different rolling practices are used for each thickness? A statistical study of the relationship of the heat-lot toughness to the plate toughness is needed.

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APPENDIX A

TEST PLATES AND EXPERIMENTAL PROCEDURES

A.1 TEST PLATES

The 44 plates included in this study came from four different mills. A description of each plate and the plate number assigned to the plate is given in Table A.1. The plates were 1-, 2-, and 4-in. thick and 60-in. wide except for plate 17, which was 84-in. wide. Each mill supplied two A572 Grade 50 plates and two A588 plates. The length of each plate is shown in the table. Table A.1 gives the steel type for each plate and the processing reported on the mill certificate by the manufacturer. The plates noted in Table A.1 as being from a contiguous plate for a given steel type were cut by the manufacturer from one larger plate. The plates noted as being from the same heat were rolled from the same heat for the indicated steel type and manufacturer.

All plate was ordered to meet the toughness requirements of the AASHTO *Guide Specifications for Fracture Critical Non-Redundant Steel Bridge Members* subjected to Zone 3 temperatures. Only one end of the plate was required to be tested for conformance to the specification requirements; however, each manufacturer was asked to test the other end of the plate for information only. The mill test reports showed that all plates

Table A.1. Description of test plates

Plate Number	Mill	Thickness in.	Steel	Size		Processing	Notes
				Width	Length		
1	1	1	A588	60	240	CR	Same heat as Pl. 5
2	1	1	A572	60	240	FGP, CR	Contiguous to Pl. 3
3	1	1	A572	60	240	FGP, CR	Contiguous to Pl. 2
4	3	1	A572	60	240	FGP	Contiguous to Pl. 8
5	1	1	A588	60	240	CR	Same heat as Pl. 1
6	3	1	A588	60	240	FGP	Contiguous to Pl. 7
7	3	1	A588	60	240	FGP	Contiguous to Pl. 6
8	3	1	A572	60	240	FGP	Contiguous to Pl. 4
9	2	1	A588	60	240		Same heat as Pl. 14
10	2	1	A572	60	240		Same heat as Pl. 13
11	4	1	A572	60	240	FGP, N	Contiguous to Pl. 12
12	4	1	A572	60	240	FGP, N	Contiguous to Pl. 11
13	2	1	A572	60	240		Same heat as Pl. 10
14	2	1	A588	60	240		Same heat as Pl. 9
15	4	1	A588	60	240	FGP, N	Contiguous to Pl. 16
16	4	1	A588	60	240	FGP, N	Contiguous to Pl. 15
17	2	2	A572	84	240		
18	2	2	A588	60	336		
19	2	2	A572	60	336		
20	4	2	A572	60	480	FGP, N	Same heat as Pl. 27
21	3	2	A588	60	240	FGP, N	Same heat as Pl. 29
22	2	2	A588	60	240		
23	4	2	A588	60	480	FGP, N	Same heat as Pl. 24
24	4	2	A588	60	240	FGP, N	Same heat as Pl. 23
25	1	2	A588	60	480	CR	Same heat as Pl. 32
26	1	2	A572	60	480	FGP, CR	
27	4	2	A572	60	240	FGP, N	Same heat as Pl. 20
28	3	2	A572	60	480	FGP, N	Same heat as Pl. 30
29	3	2	A588	60	480	FGP, N	Same heat as Pl. 21
30	3	2	A572	60	240	FGP, N	Same heat as Pl. 28
31	1	2	A572	60	240	FGP, CR	
32	1	2	A588	60	240	CR	Same heat as Pl. 25
33	1	4	A588	60	120	N	Contiguous to Pl. 34
34	1	4	A588	60	120	N	Contiguous to Pl. 33
35	1	4	A572	60	120	FGP, N	
36	3	4	A588	60	120	FGP, N	Contiguous to Pl. 39
37	1	4	A572	60	120	FGP, N	
38	3	4	A572	60	120	FGP, N	Contiguous to Pl. 44
39	3	4	A588	60	120	FGP, N	Contiguous to Pl. 36
40	4	4	A588	60	120	FGP, N	Contiguous to Pl. 43
41	4	4	A572	60	120	FGP, N	Contiguous to Pl. 41
42	4	4	A572	60	120	FGP, N	Contiguous to Pl. 42
43	4	4	A588	60	120	FGP, N	Contiguous to Pl. 40
44	3	4	A572	60	120	FGP, N	Contiguous to Pl. 38

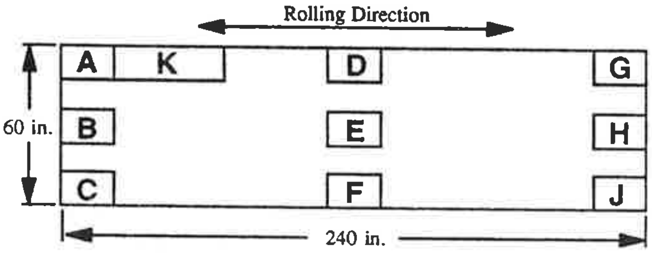


Figure A.1. Test locations.

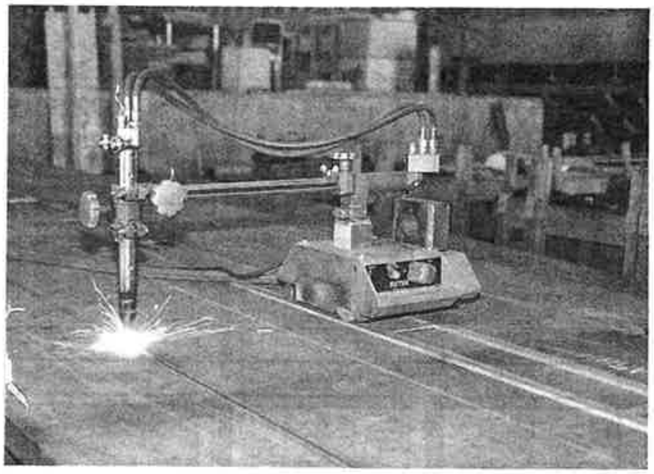


Figure A.2. Oxyacetylene track torch.

met the required toughness at both ends of the plate. The required test average for the 1- and 2-in. plates is 25 ft-lbs and 30 ft-lbs for the 4-in. plates at the temperature required in the specification of 10°F. If the yield strength determined by the mill exceeded 65 ksi, the test temperature was lowered to -5°F in conformance with the guide specification. The manufacturers also tested the tensile strength of each plate and performed a chemical analysis. With the exception of manufacturer 4, all the broken CVN specimens tested by the manufacturers were shipped to the university for examination.

A.2 SAMPLING PLAN

This study sampled the nine locations shown in Figure A.1. Locations A-J (12″ × 18″) were the impact specimen locations and location K (12″ × 36″) was the tensile specimen location. At each of the nine impact test locations, three specimens were tested at the specification temperature and three specimens were tested at 20°F below the specification temperature. If the mill reported a value higher than 65 ksi for the yield strength, the plate had a specification temperature of –5°F; otherwise, the specification temperature was 10°F. At locations C, E, and G, a full transition curve was developed using an additional 24 specimens. The transition curve was developed by testing sets of three specimens at selected temperatures. The test matrix for all the specimens in a plate is shown in Table A.2.

The sampling plan allowed the variation of the plate to be determined in a systematic fashion. For example, it can be ascertained if a particular location, side, or end of the plate was consistently different from other locations. Testing each location at two temperatures allowed the influence of temperature, i.e., transition behavior, upon the variability to be determined.

A.3 SPECIMEN FABRICATION

The first step in producing the test specimens was flame cutting pieces of the plate from the nine impact test locations and the tensile test location. Figure A.2 shows the oxyacetylene track torch used for cutting. Each piece was labeled with a code using permanent paint pens. The code identified the manufacturer, the steel type, the plate thickness, the size of the plate, and the location of the piece within the supplied plate. The pieces were stored on pallets for later saw cutting.

To simplify the cutting, the size of the pieces retained for cutting the CVN and tension specimens was larger than required. Since the thicker plates required a larger piece to ensure that the CVN specimens were one plate thickness from a burned edge, the size required for the 4-in. plates was used for all plate thicknesses.

Using a horizontal cut-off saw, each piece for impact testing was roughly saw-cut into a blank block 2.165-in. (± 0.100-in.)

Table A.2. Test matrix

Location	Specification Temperature	Specification Temperature - 20°F	Transition Specimens	Mid-Thickness 4-Inch Plate		
				Specification Temperature	Specification Temperature - 20°F	Transition Specification
A	3	3		3	3	
B	3	3		3	3	
C	3	3	24	3	3	20
D	3	3		3	3	
E	3	3	24	3	3	20
F	3	3		3	3	
G	3	3	24	3	3	20
H	3	3		3	3	
J	3	3		3	3	
TOTAL	27	27	72	27	27	60

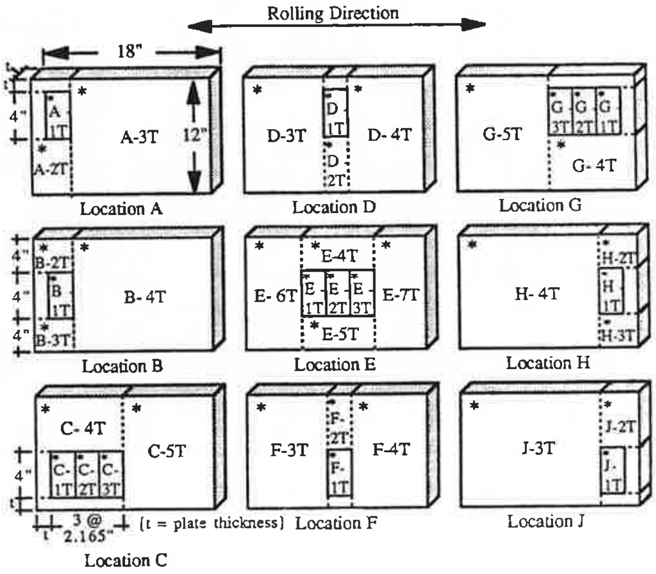


Figure A.3. Blank block locations.

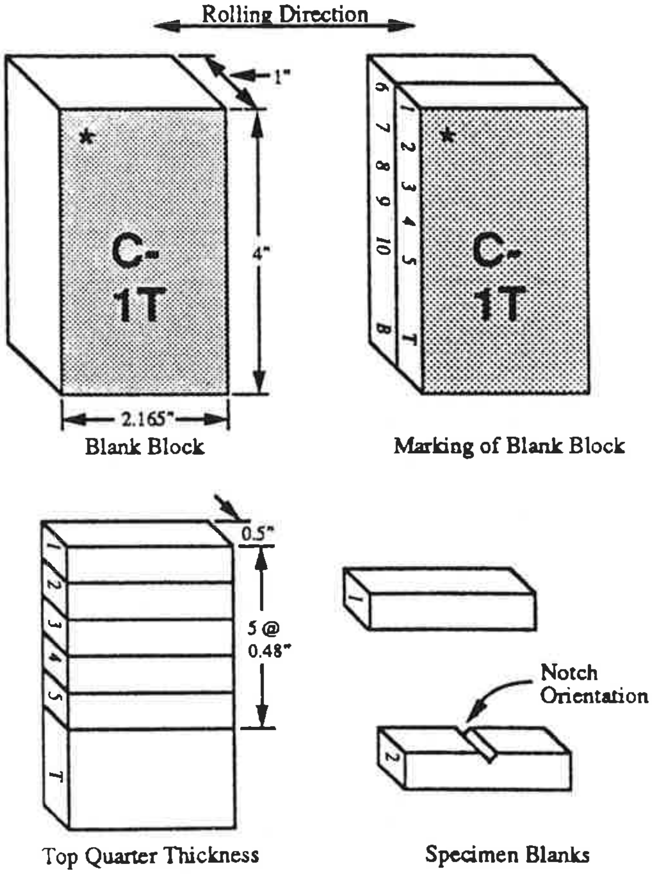


Figure A.4. Sawing out specimen blanks.

wide and 4-in. long. Figure A.3 shows the locations of the blank blocks within the flame-cut impact test pieces. The width of these blocks was the nominal length for the Charpy specimen. The size of the block ensured that the CVN specimens would be oriented in longitudinal direction. Since a full transition curve was developed at locations C, E, and G, three blank blocks were needed from these locations. At the other locations only one blank block was required to produce the number of specimens necessary for testing. The plate number was marked with a die stamp on each of the blocks. The location within the plate as well as a "T" for the top of the plate and a "B" for the bottom of the plate was marked on the block, using permanent paint pens. An asterisk was marked in the upper left-hand corner of each blank block as well as on any other piece that was produced during the sawing process to denote the rolling direction of the piece. Thus, the rolling direction of each piece was known. All the remaining material was permanently marked by die stamping and stored for possible future use.

The next step in the fabrication process produced specimen blanks. Figure A.4 outlines this process for location C. First, each specimen blank was marked with a die stamp before being cut out of the blank block. As specified in ASTM A673, the center longitudinal axis of the CVN specimen was located midway between the surface and the center of the plate thickness. This is called the quarter thickness. Two quarter thicknesses were available from the plate, the top quarter thickness and the bottom quarter thickness. Both were sampled in this research project. The end of the specimen on the right side of the blank block (opposite the asterisk) was marked with the plate number and location within the plate. The left end of the specimen (closest to the asterisk) was marked with its number within the blank block. Locations C, E, and G were marked 1-5, 11-15, and 21-25 for the top quarter thickness of each blank block. The bottom quarter thicknesses were marked 6-10, 16-20, and 26-30, respectively. All other locations were marked 1-3 for the top quarter thickness and 4-6 for the bottom quarter thickness.

The mid-thickness specimens from the 4-in. plates were cut from the same specimen blanks as the quarter-thickness specimens. The numbering of these specimens was continued from the number of the quarter-thickness specimen. The numbering system used provided a unique number for each specimen that identified its location within the plate and notch orientation.

Another horizontal cut-off saw was used for sawing the specimen blanks. Sawing jigs were made to increase accuracy and decrease production time. First, the blank block was sliced in two so that the quarter thicknesses produced were each $\frac{1}{2}$-in. thick. Then the individual specimen blank was cut. The cross-section dimension of the specimen blank was 0.5-in. × 0.48-in. This size allowed each specimen to be cleaned up during the milling and grinding process without having too much excess material that would increase the production time in the machine shop. The remaining material from each quarter thickness was marked and saved for possible future use.

The specimen blanks were machined to the specifications of ASTM A370 and E23. First, the specimen blanks were milled on two adjacent sides to the specified finish of 63 micro in. or less. Figure A.5 shows the mill equipped with eight custom-made vises that hold the blanks and produce one 90° angle (± 10 minutes). The other two sides of the specimen were then finished on a surface grinder to ensure conformance to the dimensional tolerances of 10 mm (± 0.025 mm) square.

The major problem encountered during the milling and grinding process was producing the 90° angles between adjacent sides

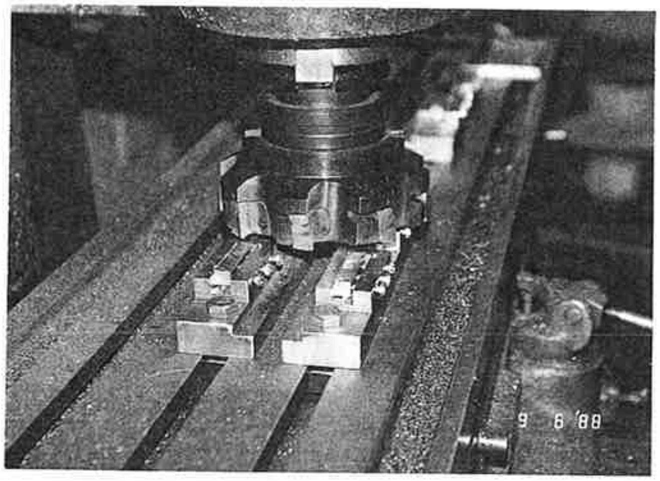


Figure A.5. Specimen milling vises.

of the specimen. In early attempts all four sides of the specimen were milled and ground. However, repetitive machining on each side created a much greater chance that the angle would not be square. The main problem was removing the burrs produced during sawing, milling, and grinding so that the specimen would sit correctly in the milling vise or on the surface grinder. After much experimentation, the process of milling two sides and grinding two sides was determined to give the best results. Also, the method of hand filing each specimen to remove the burrs was replaced with a belt sander. This method reduced the filing time as well as produced a more accurate specimen.

Next, 10 percent of the specimens were randomly checked for 90° angles and proper cross-section dimension and length. A digital micrometer was used to check the cross-section dimension and length to within 0.001 mm. The 90° angles were checked using surface block, gage blocks, and a dial gage.

The notch was then cut with a mini-broach to minimize cold working of the notch root. Figure A.4 shows the notch orientation. The notch was made on the left side of the Charpy specimen number. This produced a notch that was always transverse to the rolling direction of the plate since the specimens were marked as described above. A random check using a 100-power optical comparator, shown in Figure A.6, ensured conformance with the proper notch configuration. The dimension to the bottom of the notch was 8 mm (± 0.025 mm), the radius of the notch was 0.25 mm (± 0.025 mm), and the angle of the notch was 45° (± 1 deg).

A.4 TESTING APPARATUS AND PROCEDURE

The specimens were tested using a Tinius-Olsen 264 ft-lb capacity impact testing machine shown in Figure A.7. The machine was calibrated three times during the research project using two sets of Watertown Arsenal/NIST calibration specimens. The calibrations were performed before the testing of the plates was started, after approximately half the plates were tested, and at the end of all the testing. The results of the calibration are shown in Table A.3 below. The average of the five specimens must be within the specified maximum and minimum. These tolerances and the larger of ±5 percent and ±1 ft-lb added to the specified nominal values. The machine and our testing techniques produced average values within the specified range for the three calibrations. Before and after testing each plate a windage test was performed on the machine. The machine produced the required value of 0.0 ft-lb each test.

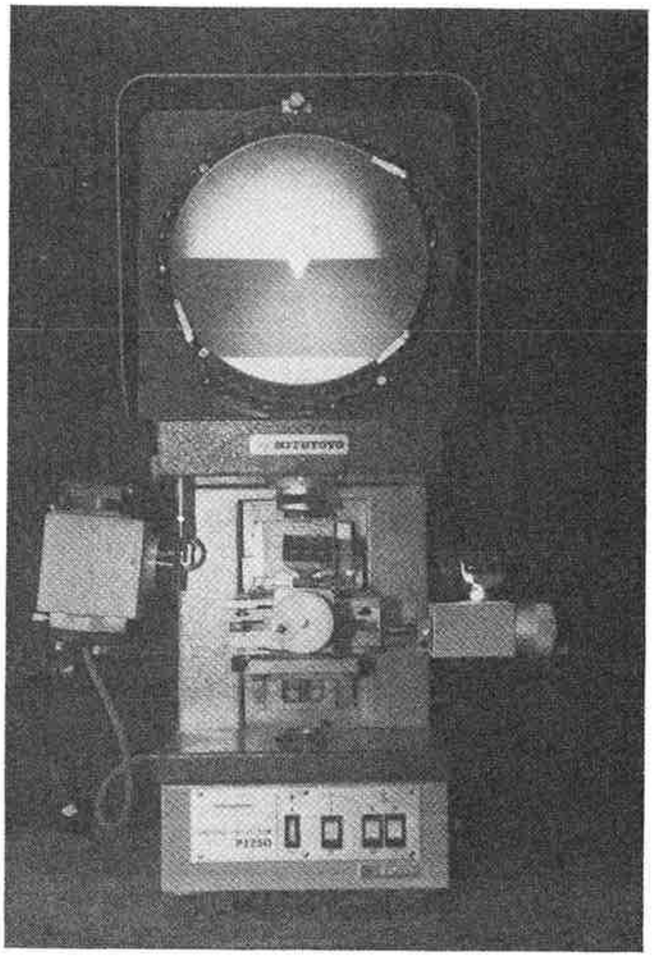


Figure A.6. Optical comparator.

The testing was conducted in accordance with ASTM E23. As shown in Figure A.8. the specimens were cooled in a temperature bath of methanol. The bath and specimens were held at the test temperature, with a tolerance of –3°F and +0°F, for 5 minutes before testing the specimens. The digital thermometer used for testing was checked against a certified calibrated thermometer. For testing, the specimens were randomly selected from each quarter thickness, two from one side of the plate and one from the other side. All specimens were broken within 5 sec after being removed from the bath. The broken specimens were saved so that the fracture surface could be examined if necessary.

The energy value for each specimen was recorded directly onto a computer spreadsheet at the time it was tested. Also measured and recorded onto the spreadsheet were the lateral expansion and the percent shear for each specimen. Figure A.9 shows the lateral expansion gage. Average values were calculated for each temperature within a location for all the recorded

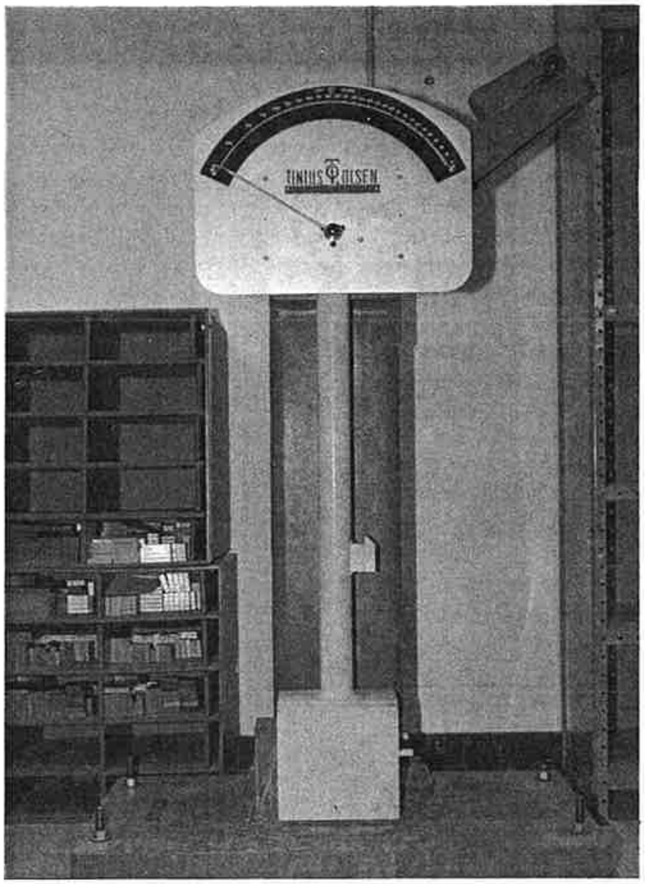


Figure A.7. Tinius-Olsen impact-testing machine.

data. Data from each Charpy test were plotted immediately after testing so that the next test temperature could be chosen to define the transition curve more accurately. In addition to the three transition curves, a fourth figure was generated by the spreadsheet that displays the average CVN energy value for each location and for the overall plate at the specification temperature, and at 20°F below the specification temperature. Appendix B contains the individual CVN data, average value of the three replicate specimens, and the four graphs for each plate. However, the data, graphs, and mill test summary for Plate 26 is included at the end of this Appendix. This data set is typical of the information contained in Appendix B for all the plates.

A.5 TENSILE TESTS

All tensile tests performed by the mills were in the direction transverse to the rolling direction, in conformance with the specifications. The tensile tests performed in this study were in the longitudinal direction. Tensile tests performed by UT were conducted in accordance with ASTM A370 using the plate-type specimen. The plate-type specimen is 1.5 in. wide with a thickness equal to the plate thickness and an 8-in. gage length. Mills 1 and 3 used a plate-type specimen for their 1-inch plate. Mills 2 and 4 used the round tension test specimen for their 1-in. plates and all mills used this smaller specimen for their 2- and 4-in. plates. The round specimen has a 0.5-in. diameter and a gage length of 2 in. The static yield was not reported by the manufacturers. The static yield for this study was determined by locking the hydraulic loading system for 3 minutes and then recording the load. This was done three times and the results were averaged. The chemical analysis reported as part of this study was performed by an independent laboratory. Appendix B includes all the data supplied by the producers for each plate.

Table A.4 summarizes the results of the tensile tests performed by each mill and the UT tests. The average of the results of the multiple tests run by Mill 3 is listed in the table. The tensile tests performed as part of this study were probably run at a slower strain rate than those done by the mills. The slower rate of loading produced the lower dynamic yield of the UT tests relative to the mill tests. Figure A.10 shows the dynamic yield strength reported by the mills divided by the value from the UT tests grouped by mills. The dynamic yield strength reported by the mills is between 0.98 and 1.16 times the value measured in the UT tests. The average value is about 1.07. No significant difference among the mills is evident except for the results of Mill 3, which have the least variation. Figure A.11 shows the dynamic yield strengths reported by the mills divided by the required yield strength of 50 ksi. The 1-in. plate supplied by the mills had the highest strength. The yield strength decreased with the thicker material. The 4-in. A572 plate supplied by Mill 3 is the major exception to this trend. This material had a high alloy and carbon content relative to the other A572 plate in the study.

Figure A.12 shows the dynamic yield strength measured in the UT tests divided by the required value of 50 ksi. The trends with respect to thickness discussed above are also evident in this figure. Eleven of the tests produced values less than 50 ksi. The plates with mill test values less than approximately 5 percent above the required value of 50 ksi failed to meet the 50 ksi requirement in the UT tests. The failure of these plates to meet the specification requirements in the UT tests was attributed to the faster strain rate employed by the mills.

The static yield strength of the plates was measured for reference purposes. Figure A.13 shows the dynamic divided by the static yield strength from the UT tests. The 1- and 2-in. plates had dynamic yield strengths 5 percent greater than the static values. The 4-in. plate test results show greater scatter and a larger difference in the yield strengths. This difference is due to difficulties encountered in the testing of these large specimens. The testing machine was not capable of maintaining the crosshead deformation during the static yield strength measurements of the 4-in. plates. Consequently, elastic unloading of the specimens occurred, reducing the measured static yield strength. The static yield strengths measured on the 4-in. plates are not considered to be valid and are presented only for completeness.

A.6 CHEMISTRY TESTS

There were no large discrepancies between the chemical analysis reported by the mills and the independent laboratory employed by UT to perform the chemical analysis. The mill test results for each plate are in Appendix B. The chemical analysis was performed on half a broken Charpy specimen. The Charpy specimen used was selected because it had a toughness value close to the average toughness of the plate. The chemistry of

Table A.3

Watertown/NIST Calibration Specimen Results					
High Energy Specimens			Low Energy Specimens		
Test Date	Spec. Number	Absorbed Energy ft-lbs	Test Date	Spec. Number	Absorbed Energy ft-lbs
4/21/88	EE7-0464	74.6	4/21/88	DD8-0796	12.7
	EE7-0344	73.3		DD8-0410	13.6
	EE7-0701	72.8		DD8-0056	12.5
	EE7-0517	76.1		DD8-0282	12.9
	EE7-0985	74.6		DD8-0175	12.7
	Average	74.3		Average	12.9
Specified	Nominal	74.7	Specified	Nominal	13.3
Specified	Maximum	78.4	Specified	Maximum	14.3
Specified	Minimum	71.0	Specified	Minimum	12.3
2/20/89	MM5-0959	66.3	2/20/89	LL3-0825	11.9
	MM5-0067	69.7		LL3-0116	11.4
	MM5-0631	70.8		LL3-0478	10.9
	MM5-0064	71.2		LL3-0511	11.4
	MM5-0236	74.3		LL3-0286	12.2
	Average	70.5		Average	11.6
Specified	Nominal	72.7	Specified	Nominal	11.8
Specified	Maximum	76.3	Specified	Maximum	12.8
Specified	Minimum	69.1	Specified	Minimum	10.8
5/31/90	MM5-0475	76.2	5/31/90	LL3-0430	11.4
	MM5-0585	74.0		LL3-0500	11.6
	MM5-0913	77.1		LL3-0547	11.4
	MM5-4084	75.8		LL3-0662	11.7
	MM5-4086	71.0		LL3-0922	11.7
	Average	74.8		Average	11.6
Specified	Nominal	72.7	Specified	Nominal	11.8
Specified	Maximum	76.3	Specified	Maximum	12.8
Specified	Minimum	69.1	Specified	Minimum	10.8

the steel was checked for more elements than required in the material specification to give a complete chemical breakdown of each steel.

Table A.5 lists the results of the analysis performed upon the A588 plate. Mill 1 supplied Grade B plate. All the other mills supplied Grade A plate. Because of the overlap in the chemistry requirements, most of the plates met both Grade A and Grade B requirements. All plates met the chemistry requirements of the specifications. The heat listed in the table is an index with respect to each mill. Plates with the same heat letter were produced from the same heat by that mill. All the A588 plates from Mill 4 were from the same heat.

Table A.6 shows the results of the A572 plate chemical analysis. Mill 1 was the only supplier of plates containing significant amounts of niobium. Mill 3 supplied plates with considerable amounts of nickel, chromium, and copper. In particular, the 4-in. plate supplied by Mill 3, which had the highest strength of the plates supplied by Mill 3 and also the highest strength of 4-in. plate supplied by all the mills, had an unusual chemistry. This material had a carbon content at the limit of the specification with a copper and nickel content that met the requirements for A588. The chromium content is less than allowed for A588. All the plates met the requirements of the specification. Due to the overlap in the specification with respect to the four types of A572, many of the plates met the requirements for more than one type.

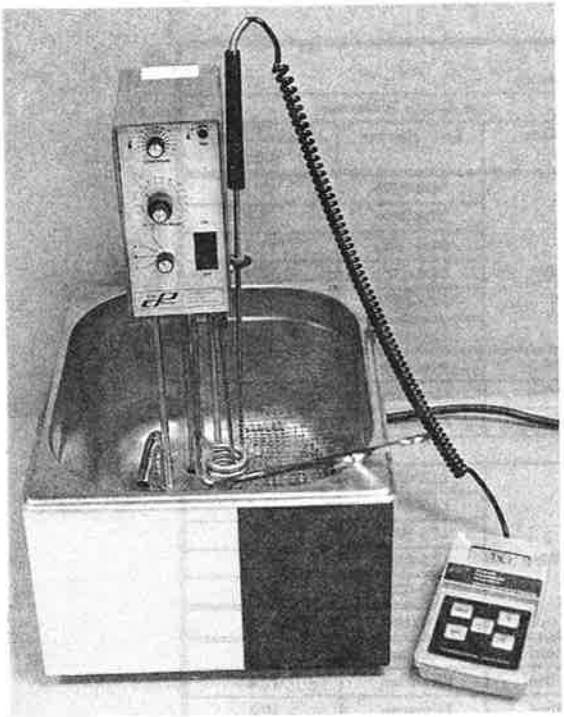


Figure A.8. Temperature bath.

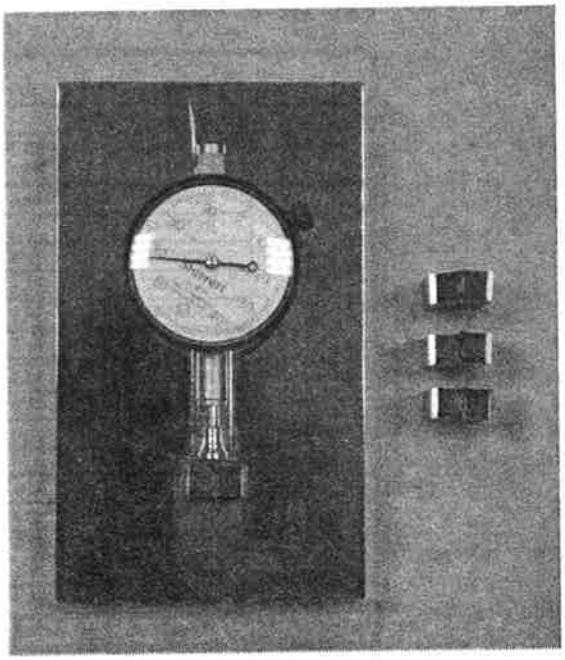


Figure A.9. Lateral expansion gage.

Table A.4. Mill 1

TENSION TESTS								
Mill	Plate Thick. in.	Plate No.	Test Location	Dyn. Yield Strength ksi	Static Yield ksi	Tensile Strength ksi	Percent Elong.	Gage Length in.
1	1	1	Mill	64.8	NR	84.3	22	8
			UT	61.7	58.2	82.9	25	8
	1	2	Mill	68.5	NR	88.2	20	8
			UT	67.2	64.4	89.3	25	8
	1	3	Mill	68.5	NR	88.2	20	8
			UT	67.8	64.9	89.9	25	8
	1	5	Mill	66.3	NR	88.7	23	8
			UT	63.0	60.4	82.5	26	8
	2	25	Mill	59.5	NR	81.3	26	2
			UT	53.9	51.9	73.8	32	8
	2	26	Mill	59.2	NR	83.1	25	2
			UT	60.1	57.7	87.2	27	8
	2	31	Mill	62.1	NR	85.4	25	2
			UT	54.5	51.6	83.2	30	8
	2	32	Mill	61.9	NR	87.0	24	2
			UT	57.5	53.5	77.5	31	8
	4	33	Mill	54.2	NR	78.5	26	2
			UT	46.8	42.0	74.5	37	8
	4	34	Mill	54.2	NR	78.5	26	2
			UT	48.2	44.4	76.2	37	8
	4	35	Mill	54.1	NR	80.6	23	2
			UT	48.2	44.5	74.0	39	8
	4	37	Mill	52.8	NR	78.1	30	2
			UT	48.7	43.1	75.9	37	8

Table A.4. Mill 2

Tension Tests								
Mill	Plate Thick. in.	Plate No.	Test Location	Dyn. Yield Strength ksi	Static Yield ksi	Tensile Strength ksi	Percent Elong.	Gage Length in.
2	1	9	Mill	66.3	NR	91.0	25	2
			UT	58.4	55.9	83.0	26	8
	1	10	Mill	62.8	NR	83.7	25	2
			UT	58.4	55.6	81.8	26	8
	1	13	Mill	62.6	NR	86.1	28	2
			UT	60.9	58.1	83.8	25	8
	1	14	Mill	66.6	NR	91.4	26	2
			UT	59.7	57.4	83.7	22	8
	2	17	Mill	59.0	NR	85.1	23	2
			UT	59.6	56.1	87.8	26	8
	2	18	Mill	57.9	NR	87.5	28	2
			UT	49.5	48.1	NR	32	8
	2	19	Mill	53.0	NR	79.8	25	2
			UT	50.9	46.6	81.4	28	8
	2	22	Mill	57.3	NR	86.0	28	2
			UT	52.7	50.3	79.3	30	8

Table A.4. Mill 3

Tension Tests								
Mill	Plate Thick. in.	Plate No.	Test Location	Dyn. Yield Strength ksi	Static Yield ksi	Tensile Strength ksi	Percent Elong.	Gage Length in.
3	1	4	Mill	55.6	NR	75.3	25	8
			UT	52.5	49.9	76.6	27	8
	1	6	Mill	57.2	NR	79.7	22	8
			UT	56.0	53.6	63.2	27	8
	1	7	Mill	57.5	NR	78.3	23	8
			UT	56.6	53.4	82.6	29	8
	1	8	Mill	55.8	NR	75.6	24	8
			UT	52.6	50.5	83.8	28	8
	2	21	Mill	52.5	NR	85.6	24	2
			UT	48.8	46.0	71.9	32	8
	2	28	Mill	59.0	NR	85.6	24	2
			UT	53.1	50.4	78.8	31	8
	2	29	Mill	54.2	NR	78.0	25	2
			UT	50.9	47.5	72.6	32	8
	2	30	Mill	58.4	NR	83.7	24	2
			UT	53.7	51.1	78.4	37	8
	2	36	Mill	52.1	NR	80.3	28	2
			UT	48.0	42.9	74.3	38	8
	4	38	Mill	63.0	NR	91.7	23	2
			UT	60.0	57.0	86.5	32	8
	4	39	Mill	51.6	NR	79.2	27	2
			UT	48.2	45.2	NR	36	8
	4	44	Mill	63.8	NR	92.4	22	2
			UT	59.1	56.1	82.5	32	8

Table A.4. Mill 4

Tension Tests								
Mill	Plate Thick. in.	Plate No.	Test Location	Dyn. Yield Strength ksi	Static Yield ksi	Tensile Strength ksi	Percent Elong.	Gage Length in.
4	1	11	Mill	58.5	NR	80.0	35	2
			UT	55.5	53.3	79.0	29	8
	1	12	Mill	58.5	NR	80.0	35	2
			UT	55.1	52.6	79.1	30	8
	1	15	Mill	59.5	NR	85.5	30	2
			UT	59.9	56.2	85.3	28	8
	1	16	Mill	59.5	NR	85.5	30	2
			UT	57.0	53.9	81.1	28	8
	2	20	Mill	51.0	NR	77.5	30	2
			UT	49.4	47.2	74.8	32	8
	2	23	Mill	54.0	NR	81.5	31	2
			UT	52.1	49.9	78.2	32	8
	2	24	Mill	57.0	NR	83.0	30	2
			UT	55.1	53.1	79.4	32	8
	2	27	Mill	54.0	NR	79.0	30	2
			UT	47.1	44.6	70.7	34	8
	4	40	Mill	54.0	NR	81.0	30	2
			UT	51.2	48.8	78.1	34	8
	4	41	Mill	54.5	NR	80.0	30	2
			UT	50.5	47.9	78.1	36	8
	4	42	Mill	54.5	NR	80.0	30	2
			UT	48.1	43.1	76.5	35	8
	4	43	Mill	54.0	NR	81.0	30	2
			UT	50.0	48.8	78.1	34	8

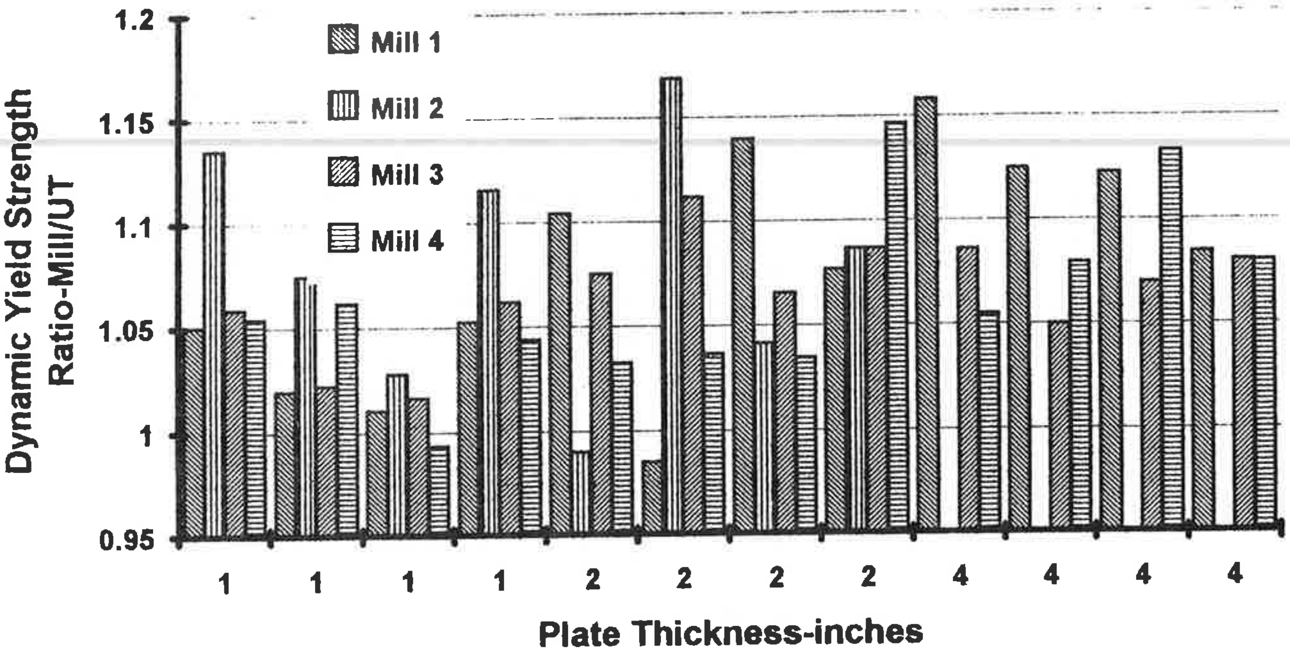


Figure A.10. Ratio of mill to UT dynamic yield strengths.

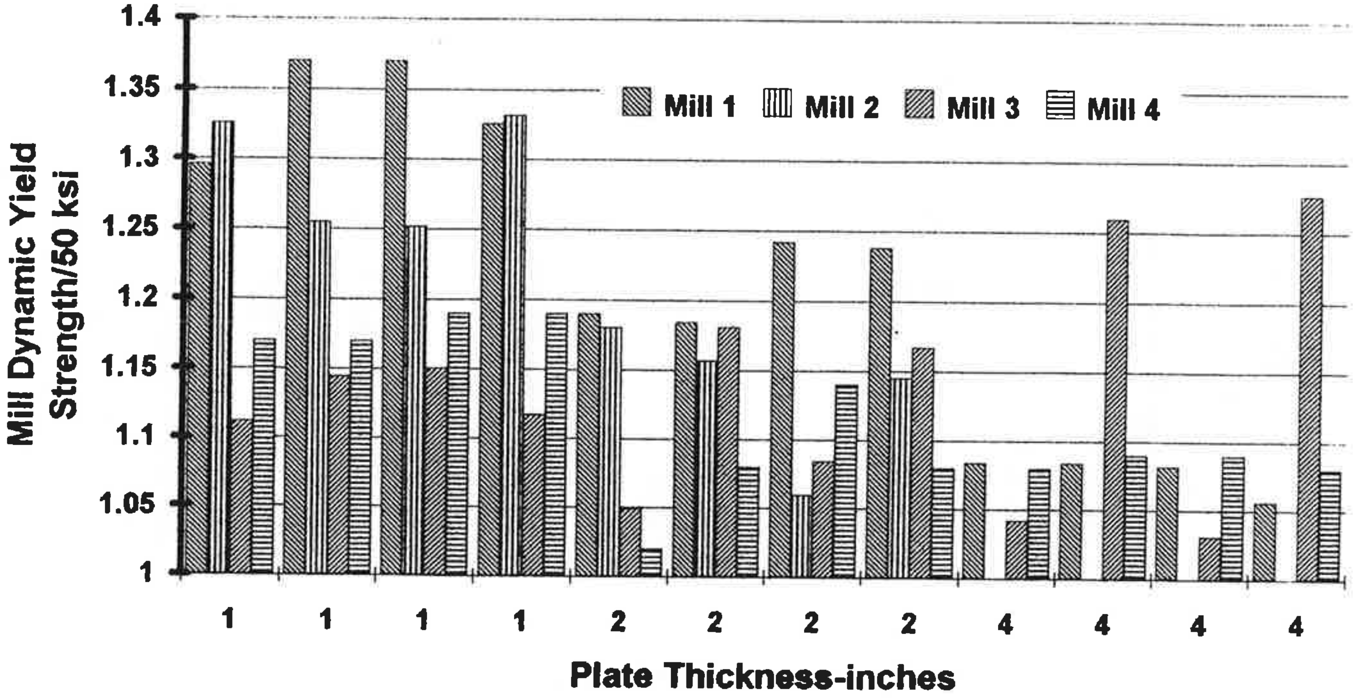


Figure A.11. Mill dynamic yield strength.

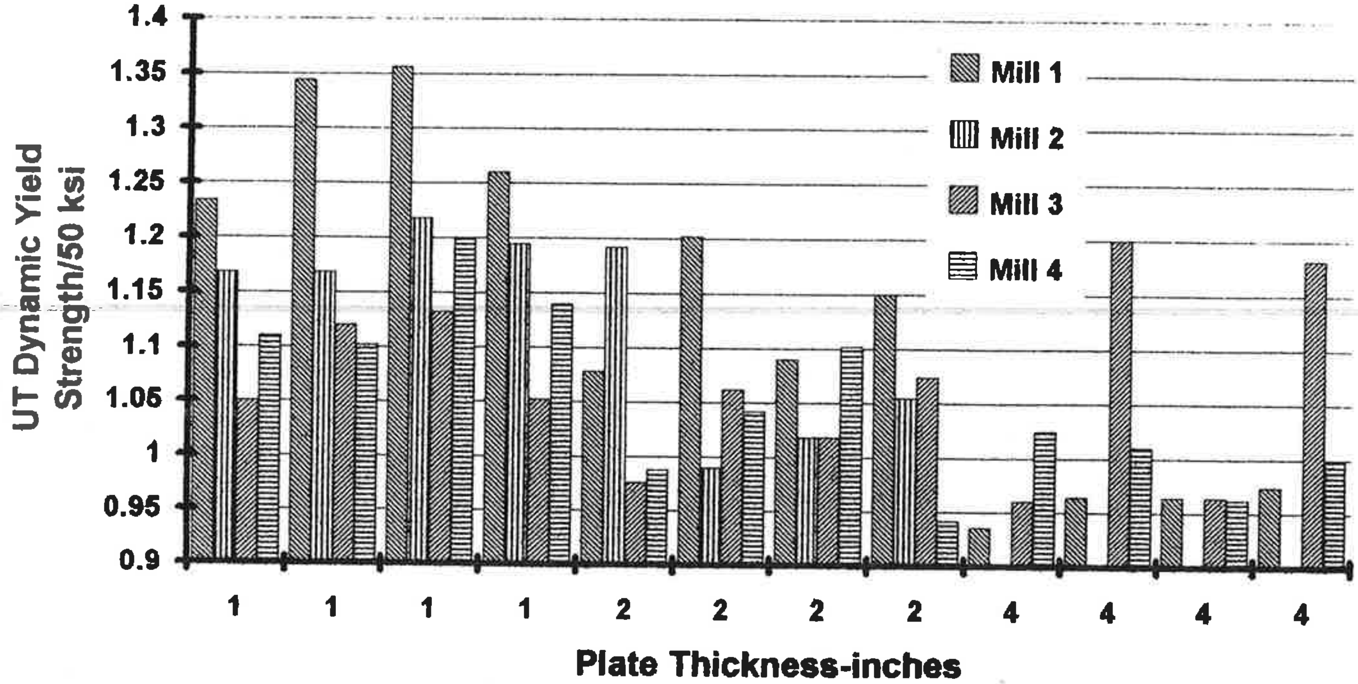


Figure A.12. Dynamic yield strength of UT tests divided by 50 ksi.

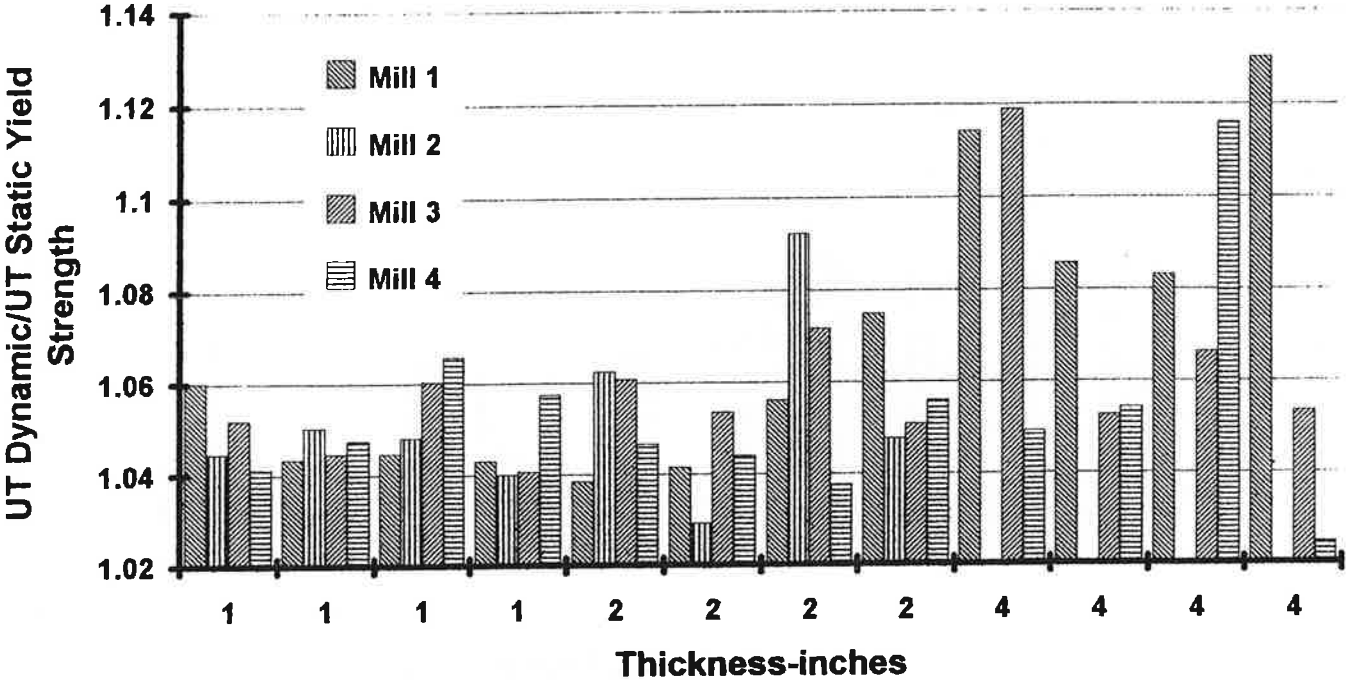


Figure A.13. Dynamic-to-static yield strength ratio.

Table A.5. Chemistry of A588 plates

Mill	Thickness in.	Plate No.	Heat	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	Zi	Nb	Ti	Al	B	N	Grade
1	1	1	A	.11	1.14	.013	.023	.36	.29	.59	<0.01	.27	.015	a	.033	a	.056	b	.0070	B
	1	5	A	.12	1.11	.012	.017	.34	.28	.57	<0.01	.27	.014	a	.030	a	.054	b	.0075	B
	2	25	A	.10	1.10	.012	.022	.35	.28	.57	.01	.26	.014	a	.030	a	.059	b	.0065	B
	2	32	A	.13	1.19	.016	.025	.37	.30	.59	.01	.28	.016	a	.038	a	.065	b	.0085	B
	4	33	B	.16	1.21	.017	.038	.41	.29	.56	.01	.28	.069	a	.008	.005	.053	b	.0090	A,B
	4	34	B	.16	1.24	.014	.020	.34	.29	.52	.01	.27	.060	a	a	a	.037	b	.0089	A,B
2	1	9	A	.14	.93	.010	.008	.39	.21	.55	<0.01	.31	.046	a	a	a	.050	b	.0084	A,B
	1	14	A	.14	.91	.009	.008	.37	.21	.53	<0.01	.30	.043	a	a	a	.038	b	.0076	A,B
	2	18	B	.16	.93	.008	.014	.40	.20	.52	<0.01	.30	.043	a	a	a	.060	b	.0059	A,B
	2	22	C	.14	1.09	.012	.020	.45	.22	.57	.01	.35	.050	a	a	a	.046	b	.0053	A,B
3	1	6	A	.13	1.05	.015	.007	.37	.21	.52	.05	.28	.066	a	a	a	.051	.0009	.0087	A,B
	1	7	A	.13	1.05	.014	.006	.36	.20	.51	.05	.28	.065	a	a	a	.021	.0007	.0086	A,B
	2	21	B	.14	.91	.012	.022	.34	.11	.52	.04	.28	.058	a	a	a	.015	b	.0100	A,B
	2	29	B	.14	.92	.011	.019	.36	.11	.53	.04	.27	.058	a	a	a	.016	b	.0090	A,B
	4	36	C	.16	1.02	.014	.022	.35	.12	.47	.04	.26	.063	a	a	a	.037	.0005	.0140	A,B
	4	39	C	.15	.98	.012	.018	.34	.12	.46	.04	.25	.060	a	a	a	.089	b	.0120	A,B
4	1	15	A	.16	1.09	.008	.010	.43	.21	.57	.02	.27	.050	a	a	a	.026	b	.0075	A,B
	1	16	A	.16	1.12	.009	.012	.43	.21	.58	.02	.28	.052	a	a	a	.031	b	.0076	A,B
	2	23	A	.16	1.10	.009	.014	.45	.22	.57	.02	.28	.052	a	a	a	.027	b	.0080	A,B
	2	24	A	.16	1.12	.010	.017	.46	.22	.58	.02	.28	.053	a	a	a	.029	b	.0081	A,B
	4	40	A	.16	1.13	.009	.016	.43	.21	.53	.02	.29	.052	a	a	a	.024	b	.0080	A,B
	4	43	A	.16	1.12	.009	.014	.43	.21	.53	.02	.29	.051	a	a	a	.022	b	.0081	A,B
	Max. All Plates			.16	1.24	.017	.038	.46	.30	.59	.05	.35	.069	N/A	.038	.005	.089	.0009	.0140	
	Min. All Plates			.10	.91	.008	.006	.34	.11	.46	.01	.25	.014	N/A	.008	.005	.015	.0005	.0053	
Specification	- A588 Grade A Max.:			.12	1.25	.040	.050	.65	.40	.65		.40	.100							
	A588 Grade A Min.:				.80			.30		.40		.25	.020							
	A588 Grade B Max.:			.20	1.35	.040	.050	.50	.50	.70		.40	.100							
	A588 Grade B Min.:				.75			.15		.40		.25	.010							
a <.005	b <.0005																			

Table A.6. Chemistry of A572 plates

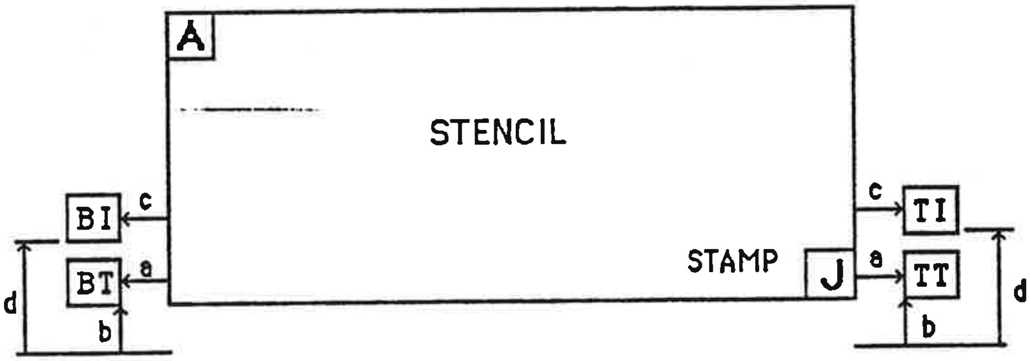
Mill	Thickness in.	Plate No.	Heat	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	Zi	Nb	Ti	Al	B	N	Nb+V	U/N	Type
1	1	2	A	.21	1.18	.010	.013	.22	.01	.20	.06	.02	.045	a	.032	a	.056	b	.0083	.077	5.1	1,2,3,4
	1	3	A	.21	1.19	.010	.014	.22	.01	.20	.06	.02	.045	a	.034	a	.056	b	.0087	.079	5.2	1,2,3,4
	2	26	B	.19	1.25	.015	.016	.23	.02	.22	.06	.02	.052	a	.036	a	.052	b	.0070	.088	7.4	1,2,3,4
	2	31	C	.19	1.29	.021	.022	.25	.01	.22	.06	.02	.052	a	.037	a	.035	b	.0071	.089	7.3	1,2,3,4
	4	35	D	.19	1.23	.017	.023	.24	<.01	.20	.05	.01	.046	a	.035	a	.064	b	.0085	.081	7.1	1,2,3,4
	5	37	D	.20	1.22	.013	.017	.23	.02	.18	.05	.02	.048	a	.035	a	.051	b	.0068	.083	7.1	1,2,3,4
2	1	10	A	.15	1.24	.010	.011	.28	.03	.03	<.01	.02	.060	a	a	a	.041	b	.0083		7.2	2,4
	1	13	A	.15	1.24	.010	.012	.28	.03	.03	<.01	.02	.059	a	a	a	0.10	.0005	.0082		7.2	2,4
	2	17	B	.19	1.20	.008	.010	.23	.03	.02	<.01	.01	.096	a	a	a	.031	b	.0090		10.7	2,4
	2	19	C	.20	1.09	.012	.011	.20	<.01	.02	<.01	.01	.081	a	a	a	.008	b	.0065		12.5	2,4
3	1	4	A	.13	1.16	.012	.006	.18	.13	.19	.04	.23	.028	a	a	a	.006	.0005	.0076		3.7	2
	1	8	A	.12	1.17	1.12	.007	.19	.13	.19	.04	.23	.029	a	a	a	.009	b	.0075		3.9	2
	2	28	B	.23	1.16	.010	.015	.19	.10	.14	.03	.09	.048	a	a	a	.015	b	.0080		6.0	2,4
	2	30	B	.23	1.18	.010	.020	.19	.10	.14	.03	.09	.048	a	a	a	.016	b	.0081		5.9	2,4
	4	38	C	.23	1.27	.018	.018	.24	.17	.23	.05	.26	.069	a	a	a	.009	.0008	.0120		5.8	2,4
	4	44	C	.23	1.31	.020	.010	.26	.17	.24	.05	.26	.072	a	.006	a	.011	.0007	.0120	.070	6.0	2,4
4	1	11	A	.20	1.18	.015	.011	.18	.02	.06	.01	.04	.054	a	a	a	.011	b	.0075		7.2	2,4
	1	12	A	.21	1.20	.015	.010	.18	.02	.06	.01	.04	.053	a	a	a	.013	b	.0075		7.1	2,4
	2	20	B	.20	1.12	.008	.012	.17	.06	.12	.01	.07	.061	a	a	a	.019	b	.0085		7.2	2,4
	2	27	B	.19	1.07	.007	.014	.17	.06	.11	.01	.07	.057	a	a	a	.030	b	.0087		6.6	2,4
	4	41	C	.20	1.34	.012	.014	.23	.06	.10	.01	.08	.087	a	a	a	.021	b	.0093		9.4	2,4
	4	42	C	.20	1.31	.014	.013	.27	.06	.10	.02	.08	.086	a	.005	.006	.022	b	.0099	.091	8.7	2,4
Max. All Plates				.23	1.34	.021	.023	.28	.17	.24	.06	.26	.096	N/A	.037	.006	.064	.0008	.0120	.091	12.5	
Min. All Plates				.12	1.07	.007	.006	.17	.01	.02	.01	.01	.028	N/A	.005	.006	.006	.0005	.0065	.077	3.7	
Specification Maximums				.23	1.35	.040	.050	.40														
Type 1 (Nb)														.005	-.050							
Type 2 (V)												.010	-.150									
Type 3 (V+Nb)														.050	max.							
Type 4 (N+V)																			.02	-.15		
a <.005 b <.0005																			.015	max	>4	

TYPICAL DATA FOR PLATE CONTAINED IN APPENDIX B

MILL DATA SHEET

Plate No: 26
Manf: 1

Serial Number: W169738
Heat Number: 802Z34680
Yield Point (psi): 59200
Tensile Strength (psi): 83100
Elongation (%): 25 {Gage Length (in): 2}
Steel Type: A572-85 Gr. 50
Thickness (in): 2
Length (in): 480 Width (in): 60
Notes: Control Rolled
Fine Grain Practice



Bottom
Ba : 0"
Bb : 1.5"
Bc : 0"
Bd : 9.5"
Spec. Code : V34

Top
Ta : 0"
Tb : 1.5"
Tc : 0"
Td : 9.5"
Spec. Code : V33

CHARPY IMPACT MILL TESTS (foot-lbs)

	Test	Test #1			Test #2			Test #3			CVN
	Temp	CVN	Lt.Ex.	%Sh.	CVN	Lt.Ex.	%Sh.	CVN	Lt.Ex.	%Sh.	Avg
Top	+10°F	54	51	50	79	73	70	59	55	40	64
Bot	+10°F	87	77	70	94	76	85	86	72	70	89

Chemical Analysis

C	Mn	P	S	Si	Cu	Ni	Cr	V	Al	Cb
.18	1.25	.014	.013	.233	NA	NA	NA	.055	.053	NA

MILL VERIFICATION CVN RESULTS

Plate No: 26

Manf: 1

Location	Replicate	CVN Absorbed Energy (ft-lbs)			
		Test #1	Test #2	Test #3	CVN Avg.
C	1	32	29	5	22.0
C	2	35	14	14	21.0
J	1	79	81	85	81.7
J	2	57	82	85	74.7

Plate: 26
Date: June 12, 1989
Spec. Temp: + 10 F

Windage: 0
Personnel: DAG

	Location	A		
Spec. No.	Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
2	10	4.3	3	0
3	10	10.9	10	0
5	10	13.8	11	5
1	-10	10.2	8	5
4	-10	8.3	7	0
6	-10	2.8	3	0

Average

Location	A		
Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
10	9.7	8.0	2
-10	7.1	6.0	2

	Location	B		
Spec. No.	Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
1	10	25.7	21	10
3	10	9.6	10	0
4	10	34.1	29	20
2	-10	4.1	4	0
5	-10	10.2	10	5
6	-10	8.6	8	0

Location	B		
Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
10	23.1	20.0	10
-10	7.6	7.3	2

	Location	C		
Spec. No.	Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
2	10	7.5	6	0
15	10	21.2	16	10
27	10	25.8	22	15
10	-10	10.0	8	5
18	-10	15.2	16	10
24	-10	6.1	4	0
7	80	47.7	38	35
13	80	43.4	37	40
25	80	40.1	36	40
1	40	43.2	35	40
19	40	30.1	27	20
28	40	16.4	14	0
9	25	15.8	14	5
12	25	9.4	9	0
26	25	25.2	21	20
4	-30	7.1	5	0
16	-30	4.6	5	0
23	-30	4.2	1	0
5	-50	6.2	9	0
14	-50	6.1	9	5
29	-50	3.4	5	0
8	60	43.2	41	40
20	60	41.1	35	30
22	60	30.3	25	20
6	100	54.9	47	50
17	100	64.6	55	60
21	100	51.4	50	50
3	-70	3.2	1	0
11	-70	4.2	6	0
30	-70	4.2	6	0

Location	C		
Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
10	18.2	14.7	8
-10	10.4	9.3	5
80.2	43.7	37.0	38
40	29.9	25.3	20
25	16.8	14.7	8
-30	5.3	3.7	0
-50	5.2	7.7	2
60	38.2	33.7	30
100	57.0	50.7	53
-70	3.9	4.3	0

Plate: 26

Location D

Spec. No.	Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
1	10	24.2	25	20
2	10	35.3	31	25
6	10	25.9	24	15
3	-10	37.4	32	30
4	-10	10.1	9	0
5	-10	13.6	12	5

Average

Location D

Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
10	28.5	26.7	20
-10	20.4	17.7	12

Location E

Spec. No.	Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
6	10	45.3	39	30
18	10	41.0	48	45
24	10	50.4	44	40
5	-10	19.6	19	10
14	-10	40.1	34	30
26	-10	28.4	26	20
3	80	81.2	82	90
16	80	57.3	53	70
29	80	78.8	66	85
8	40	62.7	55	50
11	40	21.9	32	10
23	40	57.8	52	40
1	25	50.8	55	45
19	25	56.8	49	40
25	25	50.6	46	45
7	-30	21.3	23	15
13	-30	11.2	11	0
30	-30	5.7	5	0
9	-50	6.7	5	0
12	-50	4.8	4	0
21	-50	3.8	2	0
4	60	61.7	57	55
17	60	57.3	50	50
28	60	64.6	52	45
2	100	104.3	82	90
20	100	92.7	74	80
27	100	95.3	74	80
10	-70	3.7	4	0
15	-70	3.3	4	0
22	-70	8.6	7	0

Location E

Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
10	45.6	43.7	38
-10	29.4	26.3	20
80.2	72.4	67.0	82
40	47.5	46.3	33
25	52.7	50.0	43
-30	12.7	13.0	5
-50	5.1	3.7	0
60	61.2	53.0	50
100	97.4	76.7	83
-70	5.2	5.0	0

Location F

Spec. No.	Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
3	10	15.1	12	0
5	10	47.9	44	40
6	10	14.0	13	5
1	-10	8.2	7	0
2	-10	17.4	15	5
4	-10	8.1	7	0

Location F

Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
10	25.7	23.0	15
-10	11.2	9.7	2

Plate: 26

	Location	G		
Spec. No.	Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
3	10	71.5	59	50
20	10	49.6	49	40
22	10	68.1	57	50
8	-10	66.3	56	55
11	-10	61.4	53	50
29	-10	70.9	59	65
5	80	126.4	87	95
14	80	131.2	91	95
30	80	89.7	75	90
10	40	86.5	71	65
17	40	67.2	67	60
24	40	99.5	77	80
6	25	67.1	52	50
15	25	90.4	73	65
23	25	77.3	62	60
2	-30	57.1	50	50
18	-30	34.4	21	15
26	-30	33.2	28	20
4	-50	43.3	38	35
19	-50	9.5	9	0
25	-50	50.8	43	40
9	60	78.2	65	70
12	60	130.8	91	85
21	60	131.9	92	90
7	100	114.8	93	95
13	100	115.2	86	85
28	100	114.3	87	85
1	-70	49.7	45	40
16	-70	9.0	7	0
27	-70	4.3	3	0

Average

Location	G		
Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
10	63.1	55.0	47
-10	66.2	56.0	57
80.2	115.8	84.3	93
40	84.4	71.7	68
25	78.3	62.3	58
-30	41.6	33.0	28
-50	34.5	30.0	25
60	113.6	82.7	82
100	114.8	88.7	88
-70	21.0	18.3	13

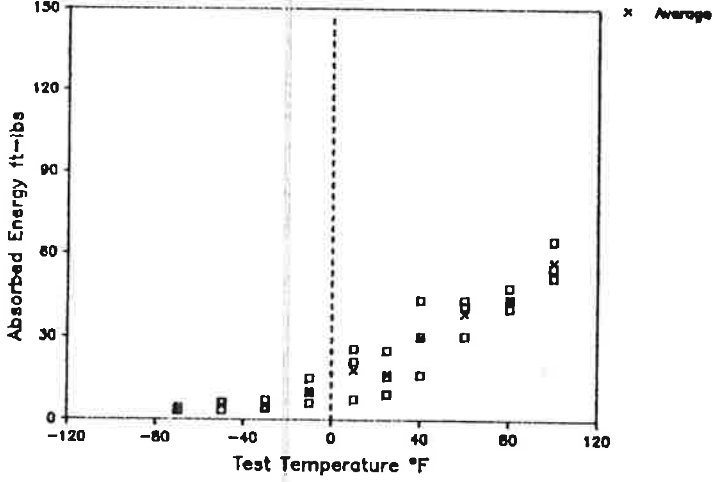
	Location	H		
Spec. No.	Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
2	10	64.8	54	45
4	10	57.0	47	40
6	10	67.9	58	50
1	-10	64.8	54	50
3	-10	75.4	64	60
5	-10	55.9	47	50

Location	H		
Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
10	63.2	53.0	45
-10	65.4	55.0	53

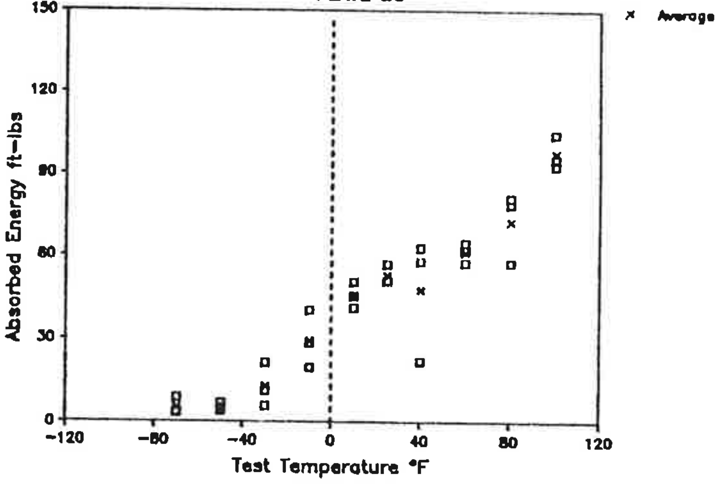
	Location	J		
Spec. No.	Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
1	10	75.8	63	60
4	10	54.4	43	40
5	10	56.3	49	55
2	-10	53.5	47	45
3	-10	72.1	61	60
6	-10	43.6	38	40

Location	J		
Test Temp-°F	Energy ft-lbs	Lat Exp mils	% Shear
10	62.2	51.7	52
-10	56.4	48.7	48

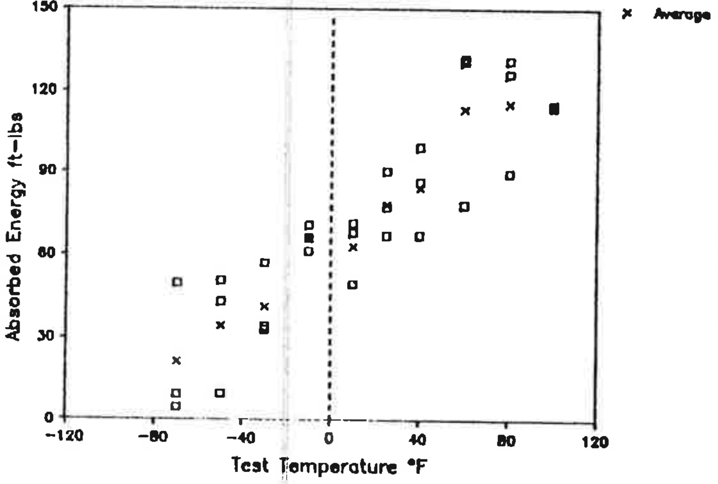
LOCATION C
PLATE 26



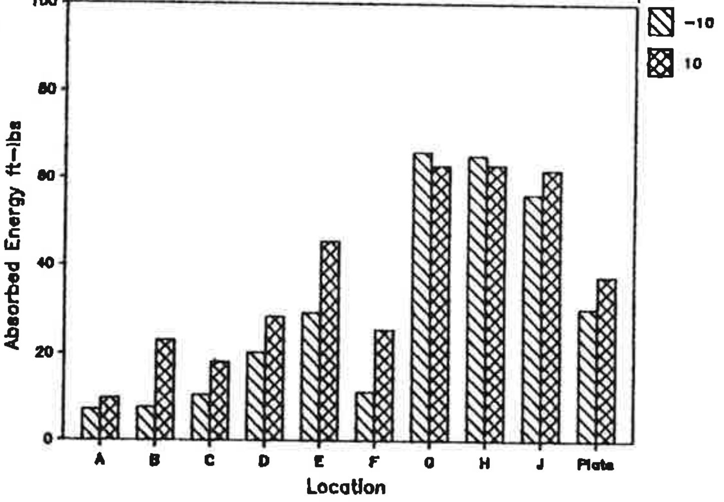
LOCATION E
PLATE 26



LOCATION G
PLATE 26



Avg. CVN at Spec. & Spec.−20 Test Temps.



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