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Statistical Analysis of Structural Plate Mechanical Properties

by

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American Iron and Steel Institute

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The University of Texas at Austin

American Iron and Steel Institute

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FINAL REPORT

Prepared for

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This work was sponsored by the American Iron and Steel Institute (AISI) and was performed for the AISI Technical Committee on Plates.

FORWARD

This work was sponsored by the American Iron and Steel Institute (AISI) and was performed for the AISI Technical Committee on Plates. In 1974, AISI published a report dealing with variations found in hot-rolled steel plate. Entitled "The Variation of Product Analysis and Tensile Properties: Carbon Steel Plates and Wide Flange Shapes", that report described the probability that tensile properties may differ among test locations within a plate other than the reported test location. In 1979 and again in 1989, AISI also published informational reports entitled "The Variations in Charpy V-Notch Impact Test Properties in Steel Plates".

In 1998, the AISI Technical Committee on Plates and Shapes included in their Workplans an item to update the aforementioned studies to reflect current mill practice. By the end of 1999, an acceptable proposal and format was developed with the University of Texas at Austin under the direction of Dr. Karl Frank, Department of Civil Engineering. Data was eventually collected from participating members of the AISI Committee and forwarded anonymously for inclusion in this study.

The following report describes the extensive analysis of the current data that includes both tensile and Charpy V-Notch data. Due to constraints, complete chemical data that could compare differences in product analyses within plates and from plate to plate could not be accomplished by the participating mills. An excellent treatment of the results is detailed within this report. The overall values described in these results have changed greatly from the previous studies. This is mainly due to the effects of better quality and the fact that higher strength steels have become the focus of production now compared to thirty years ago when much of the data dealt with lower strength steels. It is important to note that while this is true, the variations encountered in the treatment of the data have remained largely comparable. One interesting observation on tensile properties is that as a function of required minimum strength, yield strength has a smaller standard deviation compared to the earlier data. Another is the nearly three-fold increase in absorbed energy values reflecting the improved quality of the more current steels.

On behalf of the Committee, I would like to thank Dr. Karl Frank and his staff for a thorough and detailed report. I would also like to personally thank those members of the Plate Committee who provided extensive data at great expense of time and money to their companies and for their continued dedication to the completion of this Workplan.

Kenneth E. Orie

Chairman, AISI Technical Committee on Plates

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CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION

The purpose of this research is to survey the mechanical properties of A572 and A588 plates produced in North America. The study focuses on three aspects: chemical properties, tensile properties, and toughness properties. Results from this study can be of benefit to specification-writing bodies and other users interested in the variability of mechanical properties of A572 and A588 plates. The results can also help update present databases on plate properties that do not include modern production techniques and new mills and producers.

1.2 SCOPE OF RESEARCH

The test results were supplied by a total of six mills from five producers in North America. Steel plates of both A572 and A588 grade from a total of 1,326 heats were analyzed. Overall statistical summaries were computed for carbon equivalent (CE), yield strength, tensile strength, yield to tensile ratio, and yield point to yield strength ratio.

The statistical relationship between carbon equivalent and (i) yield strength; (ii) tensile strength; and (iii) yield to tensile ratio was also studied.

A statistical analysis of the Charpy V-Notch toughness test results was conducted based on sixty-nine A588 and A572 steel plates from four of the six mills who participated in the survey. The study was conducted for three test temperatures (0°F, 40°F, and 70°F), four thickness groups (T1 to T4, defined later), and two steel grades (A572 and A588). Additionally, a detailed study was conducted in order to compare the variability within a plate with the variability between plates.

The effect of the selection of a reference location (from among the 7 possible sampled locations) with respect to absorbed energy was studied. This was done separately for low- and high-toughness plates. This effect of reference location was studied by computing the percentage of samples that had absorbed energy values greater than a specified level below the absorbed energy associated with the reference location. Finally, absorbed energy and lateral expansion were studied jointly in order to estimate the statistical correlation between these two parameters as obtained from results of the Charpy V-Notch tests.

CHAPTER 2
DATA DESCRIPTION AND PREPARATION

2.1 DESCRIPTION OF DATA

Five North American steel producers participated in this study and provided data on steel properties from six mills. The test results from these producers were supplied to the University of Texas at Austin in the form of EXCEL spreadsheet files. The duration for collecting the data from all the producers was a six-month period from January to June 2002.

It should be noted that a mill number was assigned for each mill that participated and was used for reference instead of a producer name throughout this study. The number assigned to a mill was done according to the order that the test results were received from the mills.

Mills 1, 3, 4, and 5 submitted data corresponding to the requested standard spreadsheet format. However, Mills 2 and 6 only submitted mill test data for the plates tested.

2.1.1 THE 4-MILL GROUP

The data files from Mills 1, 3, 4, and 5 (we will refer to these mills as the "4-mill group") contained the following information for each plate:

1. Name of Producer
2. Mill
3. ASTM Specification
4. Type of Specification
5. Heat No.
6. Casting Method
7. Plate Thickness
8. Discrete Length or Coil
9. As-Rolled Plate Width
10. As-Rolled Plate Length

11. Method of Production
12. Chemistry (Heat Analysis) including the following elements:

    Carbon, Manganese, Phosphorus, Sulfur, Columbium, Vanadium, Nitrogen, Silicon, Copper, Aluminum, Titanium, Boron, Lead, Tin, Nickel, Chromium, and Molybdenum

13. Transverse Tensile Test Results from each test, including data on:

    Specimen Type and Size

    Yield Point

    Yield Strength (based on ASTM A370 Section 13.2)

    Tensile Strength

    Elongation

14. Longitudinal Charpy V-Notch Impact Test Results of three specimens from each test location and test temperature of 0°F, 40°F, and 70°F, including data on:

    Absorbed Energy

    Lateral Expansion.

Each as-rolled plate was sampled in the seven locations shown in Figure 2.1. Nine CVN and one tensile test coupon were obtained from each location providing a total of 7 tensile and 63 CVN specimens per plate.

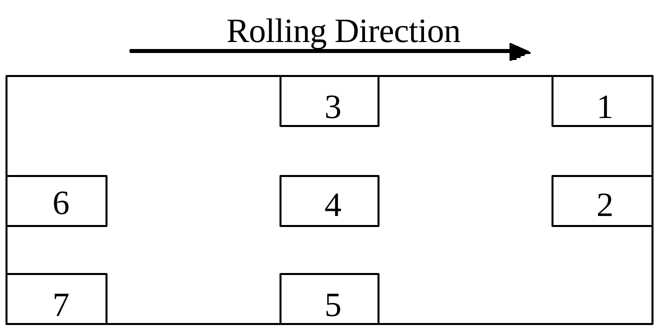


Figure 2.1: Locations of Specimens Studied in Plates.

2.1.2 THE 2-MILL GROUP

Due to the fact that the data from Mills 2 and 6 (we will refer to these mills as the "2-mill group") were in the form of mill test reports that were not compatible with the data from the other mills (i.e., the 4-mill group) and also did not include CVN test results, the statistical analyses of the 4-mill group and the 2-mill group were conducted separately. Most plates from the 2-mill group included only one test location per plate, while all plates from the 4-mill group included seven test locations per plate. In other words, the survey data provided by the 4-mill group could be used in a study of variability within a plate as well as between plates, but the mill test data provided by the 2-mill group could be used only in a study of the variability between plates.

Mills 2 and 6 (the 2-mill group) submitted acceptable data from 1280 heats while the Mills 1, 3, 4, and 5 (the 4-mill group) submitted data from 46 heats only. This large discrepancy in the number of data in the two groups would bias the results towards Mills 2 and 6, further justifying the need for separate statistical analyses of the two groups.

2.2 DATA PREPARATION

Before the statistical analysis process could be conducted, all the data had to be prepared and carefully organized to facilitate the analysis. The data preparation process began with the rearranging and organizing of the data from all the mills into groups. The initial sorting criteria were producer and ASTM specification. The next criterion was plate thickness, t, where the plates were grouped according to the following thickness ranges defined:

Group T1 *t* 0.75 in.

Group T2 0.75 in. < *t* 1.5 in.

Group T3 1.5 in. < *t* 2.5 in.

Group T4 2.5 in. < *t* 4.0 in.

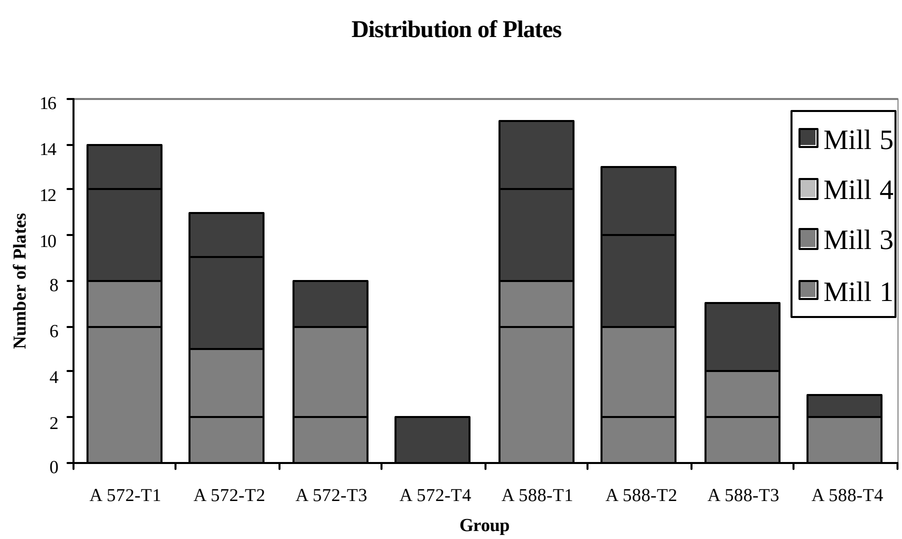
The description of the organized data from the 4-mill group (Mills 1, 3, 4, and 5) is summarized in Table 2.1.

Table 2.1: Data Description for the 4-Mill Group (Mills 1, 3, 4, and 5).

Mill		1		3		4			5	
Casting Method		Ingot and Strand Cast		Strand Cast		Strand Cast			Ingot and Strand Cast	
Method of Production		BOF		N/A		BOF			BOF(5), EAF(13)	
No. of Heats		10		10		10			15	
No. of Plates		20		19		16			18	
ASTM Specification		A572	A588	A572	A588	A572		A588	A572	A588
		Type 2	Grade B	Type 2	Grade A	Type 2	Type 3	Grade B	Type 2	Grade A/B
No. of Plates(Heats) in Each Group	T1	6(3)	6(3)	2(1)	2(1)	4(2)	0	4(2)	2(2)	3(2)
	T2	2(1)	2(1)	3(2)	4(2)	0	4(3)	4(3)	2(2)	3(2)
	T3	2(1)	2(1)	4(2)	2(1)	0	0	0	2(2)	3(2)
	T4	0	0	0	2(1)	0	0	0	2(2)	1(1)
No. of Data for Tensile Test		140		133		112			126	
No. of Data for CVN Test	0 F	420		399		336			378	
	40 F	420		399		336			378	
	70 F	420		399		336			378	

The distribution of plates among the four mills is presented graphically in Figure 2.2.

Figure 2.2: Distribution of Plates for the 4-Mill Group (Mills 1, 3, 4 and 5).



It can be observed from Figure 2.2 that the number of plates decreases with increasing plate thickness. Group T4 had the lowest number of plates – only five out of the total of 73 plates including both A572 and A588 grades; while Group T1 contained the majority of the studied plates with a total of 29 plates.

A few minor inconsistencies were found in the submitted data and are summarized as follows:

1. Mills 1, 3, and 5 did not report a Yield Point in the tensile test data. As such, these plants were not included in analyses requiring yield point data.
2. In Mill 3, there were four pairs of slabs (or four heats) that had exactly the same CVN test results. These were obviously errors in the data that necessitated their removal.

The description of the organized data from the 2-mill group (Mills 2 and 6) is summarized in Table 2.2.

Table 2.2: Data Descriptions for the 2-Mill Group (Mills 2 and 6).

Mill		2		6	
Casting Method		N/A		Strand Cast	
Method of Production		N/A		N/A	
No. of Heats		105		1175	
No. of Plates		232		3063	
ASTM Specification		A572 Type 2	A588 Grade A/B	A572 Type 2	A588 Grade A/B
No. of Plates(Heat) in Each Group	T1	207(91)	17(10)	1133(430)	84(50)
	T2	8(4)	0	804(255)	101(58)
	T3	0	0	402(160)	171(51)
	T4	0	0	327(148)	41(23)
No. of Data for Tensile Test		334		2233	

The distribution of plates between the two mills is presented graphically in Figure 2.3.

Figure 2.3: Distribution of Plates for the 2-Mill Group (Mills 2 and 6).

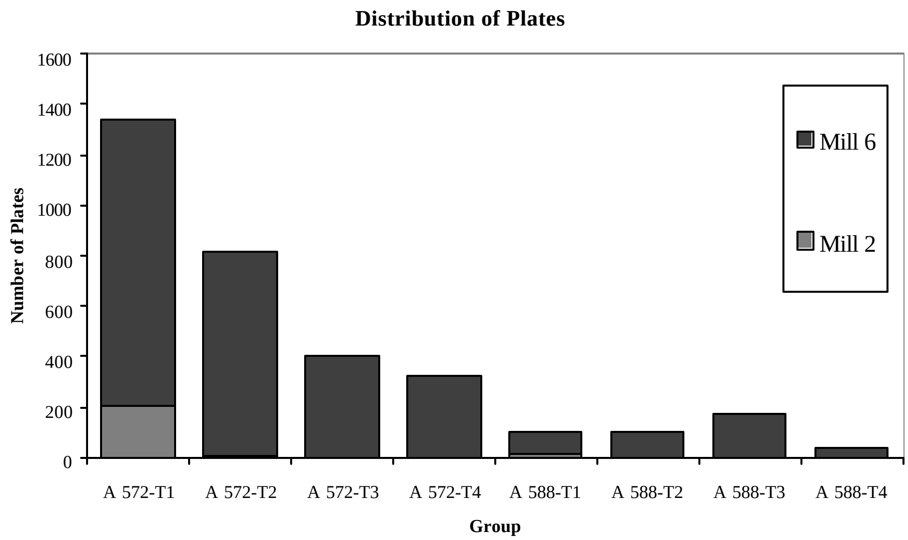


Figure 2.3 reveals that the number of plates from Mill 6 clearly dominates the overall number of plates for the 2-mill group. The group A572-T1 had the largest number of plates, greater than 1300 in number, from a total of 3295 plates in the 2-mill group. The majority of the data from Mill 2 was from the T1-thickness group; only eight plates from Mill 2 were thicker than 0.75 in. (the upper bound for plate thickness in Group T1).

It should be noted that for Mill 2, the number of tensile test data equals 334 due to the fact that out of the total of 232 plates, 151 plates had one test location, 60 plates had two locations, and 21 plates had three locations per plate. Unlike Mill 2, all the plates from Mill 6 had only one test location per plate but tensile test data from 830 plates, of a total of 3063 plates, were missing resulting in a number of tensile test data equal to 2233 for Mill 6.

2.3 PROPERTIES TO BE STUDIED

In the statistical analyses, data on the following six properties were studied:

1. Carbon Equivalent
2. Yield Strength
3. Tensile Strength
4. Yield to Tensile Ratio
5. Yield Strength to Yield Point Ratio
6. Charpy V-Notch toughness

2.3.1 CARBON EQUIVALENT

The carbon equivalent of a steel is a chemical property that indicates its weldability or the ease with which the steel can be welded using a conventional method. The higher the carbon equivalent of a steel, the more difficult it is to weld and the higher the chance of producing microstructures, for instance, martensite which is susceptible to brittle fracture (ASTM A6/A6M).

The carbon equivalent (CE) of a steel (given in percent weight) may be computed with the help of the following equation:

$$CE = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15} \tag{2.1}$$

where C, Mn, Cr, Mo, V, Ni and Cu are the percent weights of Carbon, Manganese, Chromium, Molybdenum, Vanadium, Nickel, and Copper, respectively, in the steel (ASTM A709/A709M). The carbon equivalent is a property of the heat; hence, all plates in the same heat have the same carbon equivalent. Current ASTM standards for grades A572 and A588 steel do not specify requirements for the carbon equivalent value.

2.3.2 YIELD STRENGTH

The yield strength is defined by ASTM A370 as "the stress at which a material exhibits a specified limiting deviation from the proportionality of stress and strain". The yield strength values used in this study are based on the use of a 0.2% offset. Current ASTM Specifications of A572 and A588 grade 50 steel specify a minimum yield point of

50 ksi. (Note that yield point is not the same as yield strength and is defined later.) The variation in yield strength generally stems from differences in the chemical composition of steel, the material thickness, the rate of straining in the inelastic range, the difference between mills, the differences in the same mill over time (Galambos and Ravindra, 1978).

2.3.3 TENSILE STRENGTH

Based on ASTM A370, the tensile strength is determined by dividing the maximum load the specimen sustains during a tension test by the original cross-sectional area of the specimen.

2.3.4 YIELD TO TENSILE RATIO

The yield to tensile ratio is the ratio of the yield strength to the tensile strength. This ratio indicates the ductility of the steel. It is difficult to achieve ductile behavior if the yield to tensile ratio is high, approaching unity. ASTM standards for grades A572 and A588 steel do not specify requirements for the yield to tensile ratio.

2.3.5 YIELD STRENGTH TO YIELD POINT RATIO

The yield point or upper yield point is defined by ASTM A370 as "the first stress in a material, less than the maximum obtainable stress, at which an increase in strain occurs without an increase in stress." The yield strength to yield point ratio is an indication of the difference between the yield strength and the yield point. The A572 and A588 specifications specify a minimum yield point. Alpsten (1972) suggested that mill testing procedures should be based on the yield strength instead of the yield point value when defining the yield stress level. This recommendation was based on the fact that the yield point is more sensitive than yield strength to the strain rate. This sensitivity causes the lack of correlation with the static yield stress level in structures. To attempt to understand the significance of the difference between yield strength and yield point, we study the yield strength to yield point ratio.

2.3.6 CHARPY V-NOTCH TOUGHNESS

A material's fracture toughness is indicated by its resistance to unstable crack propagation in the presence of notch and can thus be indirectly measured by the Charpy V-Notch Impact test. Two parameters, absorbed energy and lateral expansion, may be measured in a test. The CVN test is one of many tests used to evaluate the toughness of a material and is widely used in the steel industry as well as in many specifications, e.g., in AASHTO specifications.

In order to prevent brittle fracture, it is necessary to specify minimum requirements of notch toughness for a steel plate subjected to welding (Rolfe, 1977). The ASTM standards for A572 and A588 grade steel do not specify requirements for CVN toughness. However, the ASTM A709 specification for steel intended for use in bridges does specify minimum absorbed energy requirements.

CHAPTER 3
ANALYSIS OF DATA

The various analysis steps undertaken with the data obtained from the plates as described in Chapter 2 are described next.

For both the 2- and 4-mill groups, the data on carbon equivalent, yield strength, tensile strength, yield to tensile ratio and yield strength to yield point ratio were analyzed to determine the mean values and coefficient of variation (the coefficient of variation or c.o.v. refers to the ratio of the standard deviation to the mean) for each thickness group and specification (grade of steel). These results are presented. For the 4-mill group because the number of plates is considerably smaller than for the 2-mill group, the raw data in the individual plates are also presented.

For the results from the CVN impact tests obtained from the 4-mill group, the three values of absorbed energy at each test temperature were averaged before a statistical analysis was conducted. This average value is referred to as the three-test average in the following. Numerical statistical summaries and graphical representations were developed for each thickness group, specification and test temperature. The data were analyzed for each mill separately and then combined in order to determine the overall statistics.

Again, the statistical analysis of data from the 2-mill group (Mills 2 and 6) only includes carbon equivalent, yield strength, tensile strength, and yield to tensile ratio because of the incompatibility of the data format with the data from the 4-mill group and because of the lack of CVN impact test data as previously mentioned.

3.1 CARBON EQUIVALENT (CE)

In discussing the data and statistical analysis on carbon equivalent values, it should be noted that in some mills, not all the slabs in the same heat reported the same carbon equivalent value. The raw data for the 4-mill group are for all the slabs are first shown; then, statistical studies for both mill groups are presented based on heats.

3.1.1 ORGANIZED DATA FROM THE 4-MILL GROUP

Tables 3.1 to 3.4 present the organized data on carbon equivalent value for all the slabs from mills 1, 3, 4, and 5, respectively. In each table, the carbon equivalent is presented for each steel grade and each thickness group. The mean, low, and high values observed in each thickness group are also shown in the last three columns of each table.

Table 3.1: Raw Data on Carbon Equivalent Values from Mill 1.

Grade	Thickness Group	Carbon Equivalent (%) from Mill 1			
		Carbon Equivalent	Mean	Low	High
A 572	T1	0.365	0.398	0.365	0.438
		0.365			
		0.391			
		0.391			
		0.438			
		0.438			
	T2	0.391	0.391	0.391	0.391
		0.391			
	T3	0.385	0.385	0.385	0.385
		0.385			
A 588	T1	0.435	0.449	0.421	0.491
		0.435			
		0.491			
		0.491			
		0.421			
		0.421			
	T2	0.457	0.457	0.457	0.457
		0.457			
	T3	0.499	0.499	0.499	0.499
		0.499			

Table 3.2: Raw Data on Carbon Equivalent Values from Mill 3.

Grade	Thickness Group	Carbon Equivalent (%) from Mill 3			
		Carbon Equivalent	Mean	Low	High
A 572	T1	0.368	0.368	0.368	0.368
		0.368			
	T2	0.393	0.391	0.389	0.393
		0.389			
		0.389			
	T3	0.396	0.404	0.396	0.412
		0.396			
		0.412			
		0.412			
A 588	T1	0.422	0.422	0.422	0.422
		0.422			
	T2	0.416	0.415	0.413	0.416
		0.416			
		0.413			
		0.413			
	T3	0.462	0.462	0.462	0.462
		0.462			
	T4	0.485	0.485	0.485	0.485
		0.485			

Table 3.3: Raw Data on Carbon Equivalent Values from Mill 4.

Grade	Thickness Group	Carbon Equivalent (%) from Mill 4			
		Carbon Equivalent	Mean	Low	High
A 572	T1	0.413	0.415	0.408	0.421
		0.419			
		0.408			
		0.421			
	T2	0.449	0.440	0.433	0.449
		0.443			
		0.437			
		0.433			
A 588	T1	0.428	0.439	0.428	0.450
		0.440			
		0.439			
		0.450			
	T2	0.489	0.481	0.478	0.489
		0.478			
		0.479			
		0.479			

Table 3.4: Raw Data on Carbon Equivalent Values from Mill 5.

Grade	Thickness Group	Carbon Equivalent (%) from Mill 5			
		Carbon Equivalent	Mean	Low	High
A 572	T1	0.414	0.408	0.402	0.414
		0.402			
	T2	0.382	0.405	0.382	0.428
		0.428			
	T3	0.435	0.446	0.435	0.457
		0.457			
	T4	0.446	0.440	0.433	0.446
		0.433			
A 588	T1	0.437	0.437	0.435	0.437
		0.437			
		0.435			
	T2	0.480	0.469	0.447	0.480
		0.480			
		0.447			
	T3	0.440	0.451	0.440	0.457
		0.457			
		0.457			
	T4	0.510	0.510	0.510	0.510

3.1.2 STATISTICAL ANALYSIS RESULTS FROM ALL MILLS

Tables 3.5 and 3.6 summarize the statistical analysis results for the 4-mill group (mills 1, 3, 4, and 5) and the 2-mill group (mills 2 and 6), respectively. Each table includes the mean and coefficient of variation values of the carbon equivalent for each thickness group from the individual mills as well as the overall statistics (i.e., including all the mills in the corresponding mill group).

Table 3.5: Statistical Analysis of Carbon Equivalent for the 4-Mill Group.

Group	Carbon Equivalent (CE) %														
	Mill 1			Mill 3			Mill 4			Mill 5			Overall		
	No. of Heats	Mean	COV, %	No. of Heats	Mean	COV, %	No. of Heats	Mean	COV, %	No. of Heats	Mean	COV, %	No. of Heats	Mean	COV, %
A572-T1	3	0.40	4.60	1	0.37	-	2	0.42	1.82	2	0.41	2.16	8	0.40	6.29
A572-T2	1	0.39	-	2	0.39	0.72	3	0.44	1.82	2	0.41	7.92	8	0.41	6.67
A572-T3	1	0.38	-	2	0.40	2.67	0	-	-	2	0.45	3.55	5	0.42	7.28
A572-T4	0	-	-	0	-	-	0	-	-	2	0.44	2.17	2	0.44	2.17
A588-T1	3	0.45	8.26	1	0.42	-	2	0.44	1.64	2	0.44	0.27	8	0.44	5.10
A588-T2	1	0.46	-	2	0.42	0.62	3	0.48	1.22	2	0.47	4.13	8	0.46	6.50
A588-T3	1	0.50	-	1	0.46	-	0	-	-	2	0.45	2.10	4	0.46	5.33
A588-T4	0	-	-	1	0.49	-	0	-	-	1	0.51	-	2	0.50	3.54
A572 All Groups	5	0.39	3.60	5	0.39	1.80	5	0.43	1.82	8	0.42	4.48	23	0.41	6.39
A588 All Groups	5	0.46	6.24	5	0.44	0.37	5	0.46	1.39	7	0.46	2.50	22	0.46	5.57
All Data	10	0.43	5.30	10	0.42	1.23	10	0.45	1.60	15	0.44	3.62	45	0.43	5.97

Table 3.6: Statistical Analysis of Carbon Equivalent for the 2-Mill Group.

Group	Carbon Equivalent (CE) %					
	Mill 2			Mill 6		
	No. of Heats	Mean	COV, %	No. of Heats	Mean	COV, %
A572-T1	91	0.32	18.3	430	0.35	11.9
A572-T2	4	0.35	26.4	255	0.34	10.9
A572-T3	-	-	-	160	0.40	5.07
A572-T4	-	-	-	148	0.40	4.49
A588-T1	10	0.42	18.9	50	0.44	2.94
A588-T2	-	-	-	58	0.44	2.75
A588-T3	-	-	-	51	0.47	2.62
A588-T4	-	-	-	23	0.48	2.21
A572 All Groups	95	0.32	18.8	993	0.36	9.58
A588 All Groups	10	0.42	18.9	182	0.46	2.70
All Data	105	0.33	18.9	1175	0.38	8.56

From Table 3.5, it may be observed that, for any one mill in the 4-mill group, the average carbon equivalent ranged from 0.37% to 0.51%. The overall variability in carbon equivalent values measured was small; for an individual mill in the 4-mill group, the largest coefficient of variation for any heat and thickness group was 8.26% (for the A588-T1 group). Also, when the mean from all mills was considered for any thickness group, the largest coefficient of variation was 6.67% (for the A572-T2 group).

Similarly, from Table 3.6, it may be observed that Mill 2 had relatively higher variability of the carbon equivalent than Mill 6 with coefficient of variation values ranging from 18.3% to 26.4% for Mill 2. The average carbon equivalent for the 2-mill group ranged from 0.32% to 0.48%.

Tables 3.5 and 3.6 also show that the carbon equivalent generally increases with increasing plate thickness for both steel grades. This trend may be attributed to the mill practice of adjusting the carbon content in thicker plates in order to maintain a desired strength through the entire thickness. The specified alloy content of A588 leads to the higher carbon equivalent values relative to A572 plates of the same thickness as was seen in the data. The similar ranges of carbon equivalent values obtained for both mill groups reveal that the studied plates from all the mills possess about the same degree of weldability.

3.1.3 CORRELATION STUDIES INVOLVING CARBON EQUIVALENT

The statistical correlation between carbon equivalent and average yield strength, between carbon equivalent and average tensile strength, and between carbon equivalent and average yield to tensile ratio was studied and the results from that study are summarized in Figures 3.1 to 3.3 for the 4-mill group (Mills 1, 3, 4, and 5). In each figure, for each steel grade separately, data for the two parameters being studied are shown along with a regression line as well as an estimate of the correlation coefficient. The number of data used corresponds to the number of slabs tested.

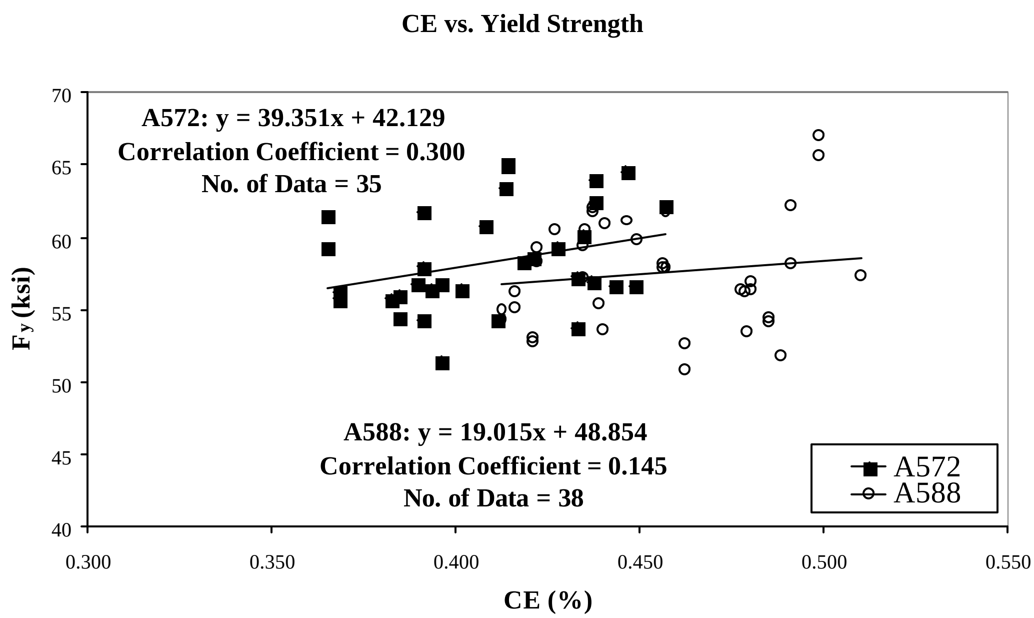


Figure 3.1: CE versus Yield Strength for the 4-Mill Group.

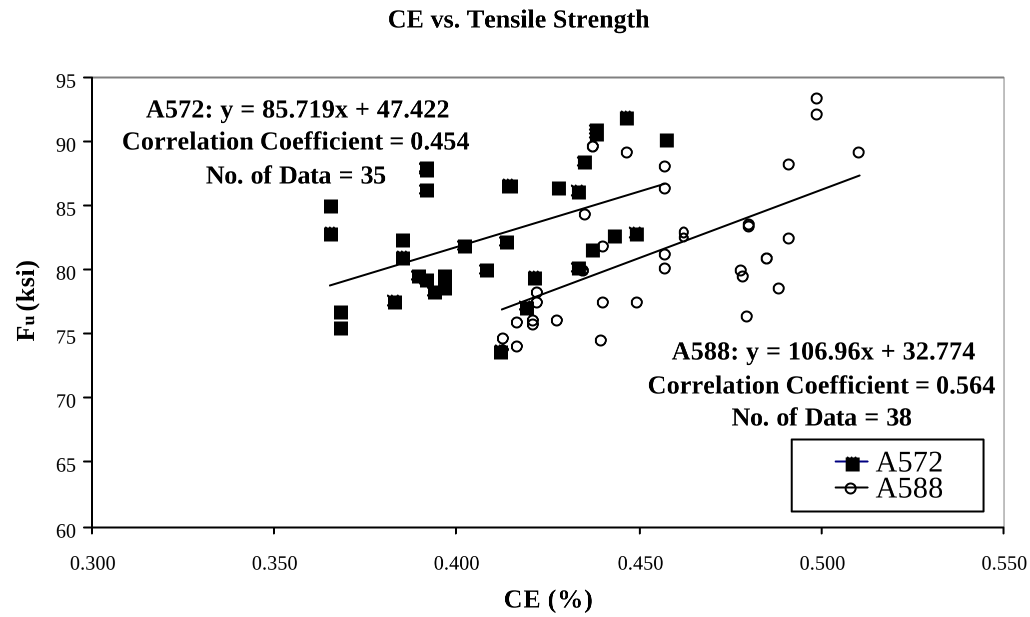


Figure 3.2: CE versus Tensile Strength for the 4-Mill Group.

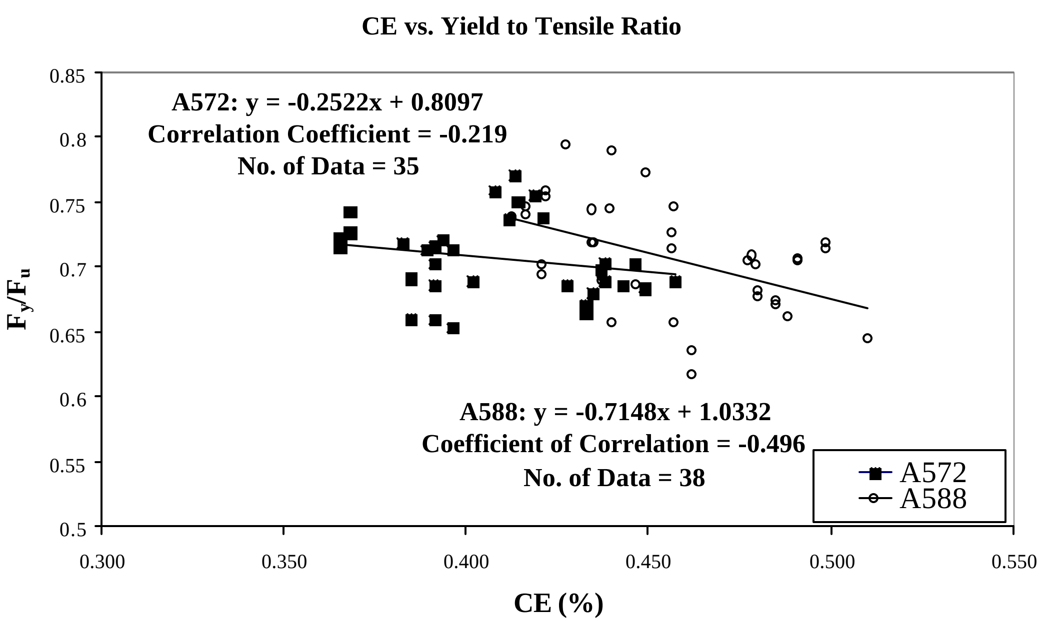


Figure 3.3: CE versus Yield to Tensile Ratio for the 4-Mill Group.

Similarly for the 2-mill group (Mills 2 and 6), the statistical correlation between carbon equivalent and the same strength parameters from tensile test data was studied and similar plots to those presented for the 4-mill group are shown in Figures 3.4 to 3.6 for the 2-mill group.

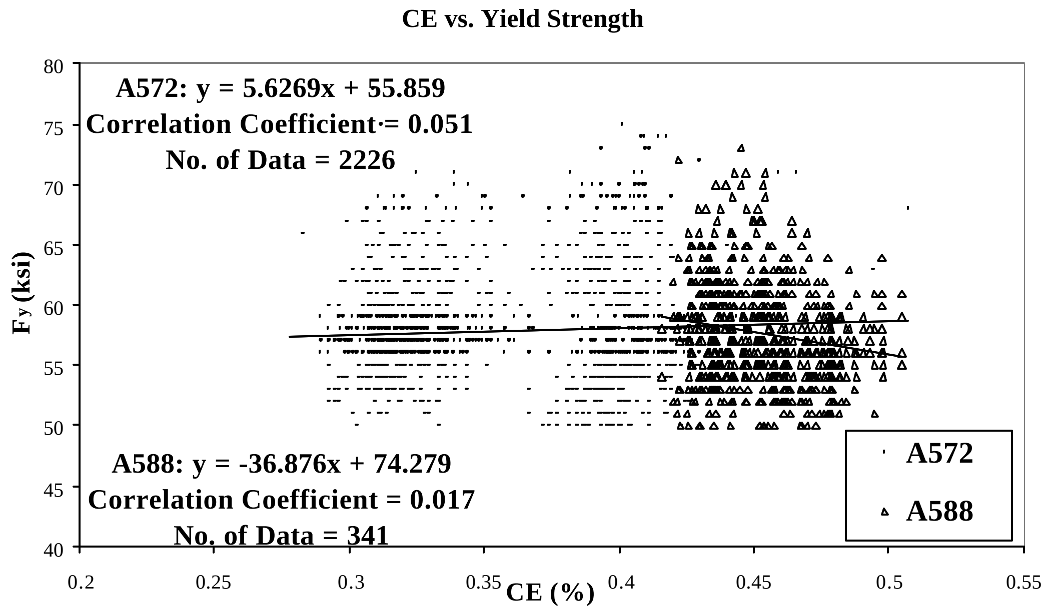


Figure 3.4: CE versus Yield Strength for the 2-Mill Group.

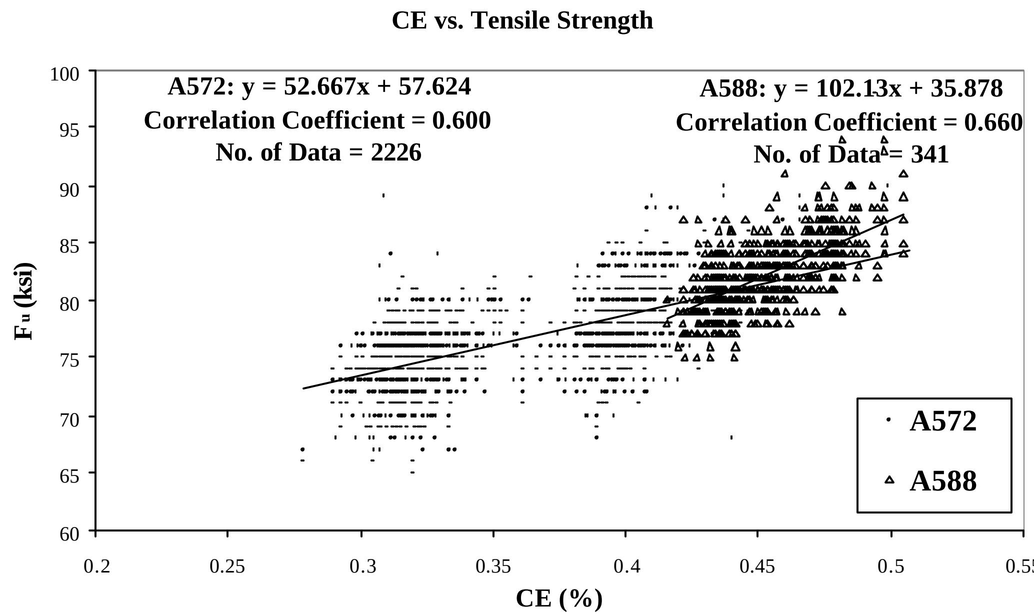


Figure 3.5: CE versus Tensile Strength for the 2-Mill Group.

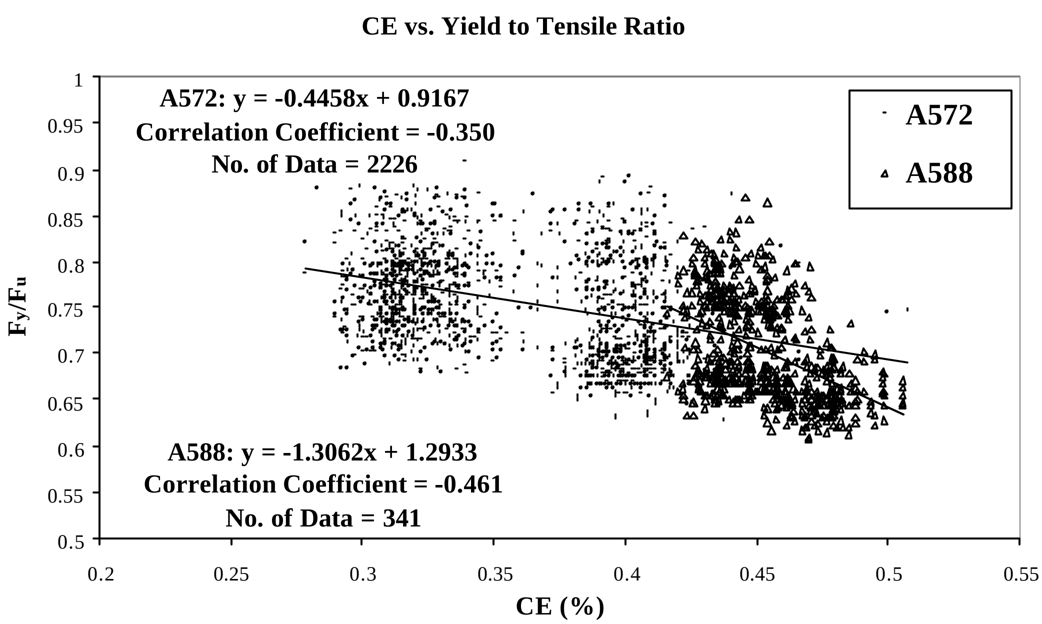


Figure 3.6: CE versus Yield to Tensile Ratio for the 2-Mill Group.

It may be observed from Figures 3.2 and 3.5 that the carbon equivalent shows fairly strong positive relation with the tensile strength, with correlation coefficients as high as 0.60 and 0.66 for the A572 and A588 steel grades, respectively, based on results for the 2-mill group, with slightly weaker correlation for the 4-mill group. The tensile strength increases with the increasing carbon equivalent in both grades of steel.

However, no significant statistical correlation was observed between the carbon equivalent and the yield strength as may be confirmed from a study of Figures 3.1 and 3.4.

A mild negative correlation was observed between the carbon equivalent and the yield to tensile ratio with correlation coefficients of -0.35 and -0.46 for the A572 and A588 steel grades, respectively, based on results for the 2-mill group as seen in Figure 3.6. Figure 3.3 shows similar mild negative correlation for the 4-mill group as well. The negative correlation coefficient values suggest an inverse relationship between the carbon equivalent and the yield to tensile ratio.

3.2 YIELD STRENGTH (F_Y)

3.2.1 ORGANIZED DATA FROM THE 4-MILL GROUP

Tables 3.7 to 3.10 present the organized data on yield strength for all the slabs from mills 1, 3, 4, and 5 respectively. In each table, the yield strength at seven locations on each plate sampled is presented for each steel grade and each thickness group. The mean, low, and high values observed for each sampled plate are also shown in the last three columns of each table.

Table 3.7: Raw Data on Yield Strength from Mill 1.

Grade	Thickness Group	Yield Strength (ksi) from Mill 1									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	58.3	57.0	60.1	60.0	61.2	58.2	59.9	59.2	57.0	61.2
		62.8	60.5	63.5	61.5	61.5	59.9	60.0	61.4	59.9	63.5
		54.1	55.3	54.2	54.1	54.0	53.9	54.6	54.3	53.9	55.3
		65.4	60.5	62.9	62.8	61.4	57.5	61.4	61.7	57.5	65.4
		61.8	63.0	61.4	61.1	61.6	64.6	63.1	62.4	61.1	64.6
		62.9	67.9	62.6	62.6	63.3	63.6	64.8	64.0	62.6	67.9
	T2	57.6	58.4	56.9	57.1	56.1	61.7	57.8	57.9	56.1	61.7
		70.4	56.9	60.2	61.5	61.9	60.4	60.7	61.7	56.9	70.4
	T3	54.4	52.5	55.9	53.0	53.2	56.5	54.8	54.3	52.5	56.5
		58.4	57.6	58.8	56.8	52.5	53.0	54.5	55.9	52.5	58.8
A 588	T1	57.9	58.4	59.6	58.0	57.3	57.5	67.3	59.4	57.3	67.3
		54.9	60.6	56.4	56.8	56.5	57.2	58.5	57.3	54.9	60.6
		63.8	65.0	62.7	62.6	63.2	59.7	58.0	62.1	58.0	65.0
		57.5	58.0	57.3	59.2	57.8	58.5	58.8	58.2	57.3	59.2
		53.2	52.6	52.4	52.8	53.2	54.3	52.8	53.0	52.4	54.3
		53.1	52.0	52.6	51.3	53.9	53.3	53.2	52.8	51.3	53.9
	T2	64.2	61.3	59.2	60.0	58.1	59.4	60.2	60.3	58.1	64.2
		53.9	54.7	55.2	55.2	55.4	51.0	54.9	54.3	51.0	55.4
	T3	66.5	68.6	62.4	65.7	62.2	65.5	68.3	65.6	62.2	68.6
		68.0	66.7	66.4	65.2	63.9	73.4	64.9	66.9	63.9	73.4

Table 3.8: Raw Data on Yield Strength from Mill 3.

Grade	Thickness Group	Yield Strength (ksi) from Mill 3									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	56.0	55.0	56.0	55.0	56.0	58.0	57.0	56.1	55.0	58.0
		58.0	54.0	55.0	55.0	56.0	55.0	57.0	55.7	54.0	58.0
	T2	57.0	55.0	56.0	58.0	56.0	57.0	56.0	56.4	55.0	58.0
		58.0	57.0	56.0	55.0	56.0	58.0	57.0	56.7	55.0	58.0
		58.0	57.0	56.0	55.0	56.0	58.0	57.0	56.7	55.0	58.0
	T3	56.0	54.0	54.0	47.0	49.0	51.0	49.0	51.4	47.0	56.0
		58.0	57.0	56.0	55.0	56.0	58.0	57.0	56.7	55.0	58.0
		55.0	54.0	55.0	53.0	54.0	54.0	55.0	54.3	53.0	55.0
		55.0	54.0	55.0	53.0	54.0	54.0	55.0	54.3	53.0	55.0
A 588	T1	58.0	58.0	58.0	58.0	58.0	59.0	59.0	58.3	58.0	59.0
		60.0	60.0	58.0	59.0	59.0	59.0	60.0	59.3	58.0	60.0
	T2	56.0	56.0	51.0	56.0	56.0	56.0	55.0	55.1	51.0	56.0
		57.0	56.0	55.0	55.0	56.0	57.0	57.0	56.1	55.0	57.0
		56.0	56.0	55.0	54.0	54.0	55.0	55.0	55.0	54.0	56.0
		55.0	54.0	55.0	53.0	54.0	54.0	55.0	54.3	53.0	55.0
	T3	54.0	51.0	50.0	52.0	52.0	54.0	55.0	52.6	50.0	55.0
		52.0	50.0	51.0	51.0	51.0	50.0	51.0	50.9	50.0	52.0
	T4	53.0	54.0	55.0	53.0	55.0	54.0	55.0	54.1	53.0	55.0
		54.0	55.0	54.0	54.0	55.0	54.0	55.0	54.4	54.0	55.0

Table 3.9: Raw Data on Yield Strength from Mill 4.

Grade	Thickness Group	Yield Strength (ksi) from Mill 4									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	67.1	67.5	58.5	58.4	59.3	67.2	65.8	63.4	58.4	67.5
		58.6	59.4	57.4	57.2	57.2	61.1	56.8	58.2	56.8	61.1
		67.3	64.9	57.0	56.1	57.2	60.0	62.7	60.7	56.1	67.3
		57.8	60.6	55.5	54.9	55.3	63.5	62.9	58.6	54.9	63.5
	T2	57.2	56.1	55.1	58.3	55.1	57.7	56.9	56.6	55.1	58.3
		57.7	55.8	54.7	55.6	55.9	58.8	57.7	56.6	54.7	58.8
		56.3	54.9	53.2	58.2	58.4	58.9	58.4	56.9	53.2	58.9
		53.9	53.1	51.1	54.3	55.6	55.3	52.8	53.7	51.1	55.6
A 588	T1	66.5	69.5	58.9	53.2	53.2	59.5	62.2	60.4	53.2	69.5
		61.9	65.0	58.1	56.4	60.0	63.9	61.4	61.0	56.4	65.0
		57.1	56.0	50.6	54.1	56.4	54.2	59.6	55.4	50.6	59.6
		62.5	60.7	54.4	54.6	59.1	60.5	66.4	59.7	54.4	66.4
	T2	52.3	50.9	52.4	51.3	52.6	50.4	52.7	51.8	50.4	52.7
		54.8	56.1	57.6	57.1	56.3	57.0	55.3	56.3	54.8	57.6
		51.8	52.4	57.1	53.3	51.1	53.6	54.8	53.4	51.1	57.1
		55.8	54.4	54.8	58.6	53.4	59.3	56.7	56.1	53.4	59.3

Table 3.10: Raw Data on Yield

Grade	Thickness Group	Yield Strength (ksi) from Mill 5									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	63.9	63.7	65.7	64.9	64.7	65.4	66.7	65.0	63.7	66.7
		55.6	55.4	55.9	56.3	57.1	56.4	58.1	56.4	55.4	58.1
	T2	55.3	55.4	55.7	55.9	56.1	56.1	55.3	55.7	55.3	56.1
		58.6	58.9	59.9	59.4	60.4	57.4	60.4	59.3	57.4	60.4
	T3	59.9	59.6	60.0	60.4	60.2	60.1	60.6	60.1	59.6	60.6
		62.3	59.9	61.5	63.0	62.3	64.0	61.8	62.1	59.9	64.0
	T4	64.2	63.6	65.6	65.3	64.3	66.0	62.8	64.5	62.8	66.0
		56.2	56.7	57.8	57.0	58.2	56.9	58.1	57.3	56.2	58.2
A 588	T1	61.5	64.9	61.2	60.9	62.7	60.2	62.4	62.0	60.2	64.9
		59.1	60.3	63.6	62.9	62.9	61.3	62.1	61.7	59.1	63.6
		61.0	58.8	61.1	62.1	61.6	59.8	58.5	60.4	58.5	62.1
	T2	56.6	56.8	57.0	57.1	56.5	57.0	57.2	56.9	56.5	57.2
		55.5	58.1	56.4	56.1	57.8	55.0	55.7	56.4	55.0	58.1
		59.0	61.7	63.4	61.4	61.1	62.4	59.0	61.1	59.0	63.4
	T3	57.6	58.3	59.1	58.0	57.2	56.9	58.0	57.9	56.9	59.1
		56.3	58.2	57.6	57.9	57.2	58.2	59.3	57.8	56.3	59.3

Strength from Mill 5.

3.2.2 STATISTICAL ANALYSIS RESULTS FROM ALL MILLS

Tables 3.11 and 3.12 summarize the statistical analysis results for the 4-mill group (mills 1, 3, 4, and 5) and the 2-mill group (mills 2 and 6), respectively. Each table includes the mean and coefficient of variation values of the yield strength for each thickness group from the individual mills as well as overall statistics (i.e., including all the mills in the corresponding mill group).

Table 3.11: Statistical Analysis of Yield Strength for the 4-Mill Group.

Group	Yield Strength, F_y (ksi)														
	Mill 1			Mill 3			Mill 4			Mill 5			Overall		
	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %
A572-T1	42	60.5	5.74	14	55.9	2.16	28	60.3	6.72	14	60.7	7.52	98	59.8	6.52
A572-T2	14	59.8	6.10	21	56.6	1.81	28	56.0	3.64	14	57.5	3.52	77	57.1	4.52
A572-T3	14	55.1	4.00	28	54.2	4.74	0	-	-	14	61.1	2.24	56	56.2	6.51
A572-T4	0	-	-	0	-	-	0	-	-	14	60.9	6.38	14	60.9	6.38
A588-T1	42	57.1	6.76	14	58.8	1.36	28	59.1	7.81	21	61.4	2.61	105	58.7	6.48
A588-T2	14	57.3	6.20	28	55.1	2.35	28	54.4	4.54	21	58.1	4.23	91	55.9	5.01
A588-T3	14	66.3	4.28	14	51.7	3.07	0	-	-	21	57.9	1.41	49	58.5	10.0
A588-T4	0	-	-	14	54.3	1.34	0	-	-	7	57.3	1.32	21	55.3	2.96
A572 All Groups	70	59.3	5.56	63	55.4	3.43	56	58.1	5.52	56	60.1	5.39	245	58.2	5.98
A588 All Groups	70	59.0	6.13	70	55.0	2.16	56	56.8	6.53	70	59.0	2.86	266	57.5	6.72
All Data	140	59.1	5.85	133	55.2	2.84	112	57.4	6.03	126	59.4	4.20	511	57.8	6.37

Table 3.12: Statistical Analysis of Yield Strength for the 2-Mill Group.

Group	Yield Strength, F_y (ksi)					
	Mill 2			Mill 6		
	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %
A572-T1	282	58.6	6.08	857	61.0	7.78
A572-T2	8	60.5	3.78	626	56.5	5.88
A572-T3	-	-	-	271	54.3	5.37
A572-T4	-	-	-	260	54.5	5.83
A588-T1	44	63.6	5.59	59	62.1	6.37
A588-T2	-	-	-	73	55.0	4.71
A588-T3	-	-	-	71	54.1	4.41
A588-T4	-	-	-	16	54.7	3.52
A572 All Groups	290	58.7	6.03	2014	57.9	6.79
A588 All Groups	44	63.6	5.59	219	56.6	5.17
All Data	334	59.3	5.97	2233	57.7	6.66

From Table 3.11, it may be observed that, for the 4-mill group, the average yield strength ranged from 51.7 to 66.3 ksi. With respect to variability in yield strength values, the largest coefficients of variation values obtained for any single mill and for the 4-mill group were 7.81% and 10.0%, respectively. Considering all of the data, the coefficient of variation was 6.37%.

Similarly, from Table 3.12, it may be observed that both mills showed small variability in yield strength recorded with coefficient of variation values ranging from 3.52% to 7.78%. The average yield strength recorded for the two mills ranged from 54.1 to 63.6 ksi. Considering all of the data, the coefficient of variation was 6.66%.

Another important observation that may be made from Tables 3.11 and 3.12 is that the yield strength values obtained from the surveyed tests (with the 4-mill group) and the mill tests (with the 2-mill group) are quite similar. These values generally exceeded the minimum requirement of 50 ksi for both steel grades – only one plate (an A572-T3 plate from Mill 3 that can be examined in Table 3.8) from all of the data gathered showed three locations of the seven where this minimum value was not attained.

3.2.3 DISTRIBUTION OF SAMPLED YIELD STRENGTH VALUES

The percent of sampled test locations on the plates studied that had yield strength values greater than or equal to a specific strength level was studied. The specific yield strength levels considered are 50 and 55 ksi. The 50 ksi level was selected since it is the specification requirement value; the 55 ksi level was selected since it represents a value 10% above the specification requirement. The statistical analysis results are shown in Table 3.13. It should be noted that since most plates from Mills 2 and 6 had only one test location per plate, this analysis included only the data from the 4-mill group (Mills 1, 3, 4, and 5).

It may be observed from Table 3.13 that all groups except A572-T3 had 100% percent of sampled yield strength values greater than or equal to the required yield strength. In other words, in almost every case, all seven locations from each plate had yield strength equal to or greater than 50 ksi. However, it was found that for the A572 and A588 grades, the percentage of the sample (considering all thickness groups) that had yield strength values greater than 55 ksi decreased to 84.0% and 73.3%, respectively.

Table 3.13: Percent of All Test Locations that had Yield Strength Greater than or Equal to a Specific Strength Level (4-Mill Group).

Percent Greater than or Equal to Specific Yield Strength (%)					
Group	Number of Test Locations	50 ksi		55 ksi	
		Mean	COV, %	Mean	COV, %
A572-T1	98	100	0	91.8	24.9
A572-T2	77	100	0	89.6	24.8
A572-T3	56	94.6	16.0	60.7	57.3
A572-T4	14	100	0	100	0
A588-T1	105	100	0	79.0	44.2
A588-T2	91	100	0	69.2	50.4
A588-T3	49	100	0	73.5	61.9
A588-T4	21	100	0	61.9	53.3
A572 All Groups	245	98.7	7.4	84.0	33.4
A588 All Groups	266	100	0	73.3	48.8

3.3 TENSILE STRENGTH (F_U)

3.3.1 ORGANIZED DATA FROM THE 4-MILL GROUP

Tables 3.14 to 3.17 present the organized data on tensile strength for all the slabs from mills 1, 3, 4, and 5, respectively. In each table, the tensile strength at seven locations on each plate is presented for each steel grade and each thickness group. The mean, low, and high values observed for each sampled plate are also shown in the last three columns of each table.

Table 3.14: Raw Data on Tensile Strength from Mill 1.

Grade	Thickness Group	Tensile Strength (ksi) from Mill 1									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	82.2	80.3	84.7	83.8	85.9	80.5	82.5	82.8	80.3	85.9
		86.1	82.9	87.6	85.9	85.9	82.6	83.8	85.0	82.6	87.6
		79.9	77.9	79.8	79.2	79.4	79.2	78.8	79.2	77.9	79.9
		90.8	87.1	88.1	87.9	87.2	86.2	87.7	87.9	86.2	90.8
		89.5	92.4	89.8	92.0	89.2	92.3	88.5	90.5	88.5	92.4
		89.8	95.7	89.6	90.7	89.1	92.0	89.7	90.9	89.1	95.7
	T2	86.9	90.1	86.6	88.0	87.5	87.5	88.7	87.9	86.6	90.1
		88.4	86.4	84.8	85.7	85.4	86.9	85.6	86.2	84.8	88.4
	T3	82.4	82.9	81.9	81.8	82.1	82.3	82.9	82.3	81.8	82.9
		80.4	81.0	81.3	80.3	80.8	81.8	81.3	81.0	80.3	81.8
A 588	T1	80.7	80.0	80.4	80.1	77.9	79.7	80.4	79.9	77.9	80.7
		78.3	80.0	80.0	80.2	80.1	80.0	80.1	79.8	78.3	80.2
		88.4	89.8	88.3	87.7	88.1	87.9	87.2	88.2	87.2	89.8
		83.8	82.8	82.1	82.5	81.8	82.5	80.8	82.3	80.8	83.8
		75.7	75.9	75.0	75.7	75.5	76.5	75.3	75.7	75.0	76.5
		76.1	75.6	76.1	75.7	76.2	76.4	76.2	76.0	75.6	76.4
	T2	81.2	79.8	79.8	80.6	80.8	81.7	83.0	81.0	79.8	83.0
		81.4	82.1	83.1	83.1	83.9	82.4	83.4	82.8	81.4	83.9
	T3	93.6	93.6	89.9	91.2	90.2	92.9	92.7	92.0	89.9	93.6
		94.2	91.8	93.4	92.8	92.9	94.4	93.4	93.3	91.8	94.4

Table 3.15: Raw Data on Tensile Strength from Mill 3.

Grade	Thickness Group	Tensile Strength (ksi) from Mill 3									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	75.0	76.0	77.0	75.0	74.0	77.0	75.0	75.6	74.0	77.0
		80.0	75.0	78.0	79.0	75.0	76.0	74.0	76.7	74.0	80.0
	T2	78.0	76.0	78.0	78.0	79.0	80.0	79.0	78.3	76.0	80.0
		80.0	79.0	79.0	79.0	79.0	81.0	80.0	79.6	79.0	81.0
		80.0	79.0	79.0	79.0	79.0	81.0	80.0	79.6	79.0	81.0
	T3	80.0	80.0	78.0	77.0	78.0	79.0	79.0	78.7	77.0	80.0
		80.0	79.0	79.0	79.0	79.0	81.0	80.0	79.6	79.0	81.0
		74.0	74.0	74.0	73.0	74.0	73.0	74.0	73.7	73.0	74.0
		74.0	74.0	74.0	73.0	74.0	73.0	74.0	73.7	73.0	74.0
A 588	T1	77.0	76.0	77.0	77.0	77.0	77.0	81.0	77.4	76.0	81.0
		78.0	78.0	78.0	78.0	78.0	79.0	78.0	78.1	78.0	79.0
	T2	75.0	75.0	69.0	75.0	75.0	75.0	74.0	74.0	69.0	75.0
		76.0	75.0	75.0	77.0	75.0	77.0	76.0	75.9	75.0	77.0
		75.0	76.0	74.0	74.0	74.0	74.0	75.0	74.6	74.0	76.0
		74.0	74.0	74.0	73.0	74.0	73.0	74.0	73.7	73.0	74.0
	T3	84.0	82.0	80.0	82.0	83.0	84.0	85.0	82.9	80.0	85.0
		84.0	83.0	83.0	80.0	82.0	82.0	83.0	82.4	80.0	84.0
	T4	80.0	81.0	81.0	80.0	81.0	81.0	81.0	80.7	80.0	81.0
		81.0	80.0	81.0	81.0	82.0	80.0	81.0	80.9	80.0	82.0

Table 3.16: Raw Data on Tensile Strength from Mill 4.

Grade	Thickness Group	Tensile Strength (ksi) from Mill 4									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	84.4	85.1	79.0	79.5	79.2	84.4	83.8	82.2	79.0	85.1
		71.4	78.4	77.7	78.3	77.6	78.5	78.5	77.2	71.4	78.5
		84.3	83.3	78.1	77.9	78.1	78.7	79.5	80.0	77.9	84.3
		78.4	79.9	78.5	78.4	78.4	81.4	81.4	79.5	78.4	81.4
	T2	82.1	83.2	82.5	83.7	82.2	83.1	83.4	82.9	82.1	83.7
		82.3	83.0	81.8	83.1	82.3	83.7	82.2	82.6	81.8	83.7
		81.0	81.4	81.4	81.4	81.2	82.0	82.6	81.6	81.0	82.6
		80.9	80.9	79.3	79.2	79.6	80.0	80.9	80.1	79.2	80.9
A 588	T1	77.2	81.2	73.5	73.5	73.7	75.7	77.2	76.0	73.5	81.2
		76.9	79.2	75.4	76.5	77.3	78.3	77.6	77.3	75.4	79.2
		74.0	73.3	72.9	75.5	75.4	74.4	75.5	74.4	72.9	75.5
		78.7	78.0	75.0	75.3	76.8	77.7	80.3	77.4	75.0	80.3
	T2	78.4	78.0	78.0	77.5	80.4	77.9	78.7	78.4	77.5	80.4
		80.1	80.7	79.4	79.7	79.7	80.4	79.4	79.9	79.4	80.7
		76.1	76.7	75.4	76.7	75.7	76.7	77.1	76.3	75.4	77.1
		78.8	79.6	79.2	79.4	79.0	79.8	79.6	79.3	78.8	79.8

Table 3.17: Raw Data on Tensile Strength from Mill 5.

Grade	Thickness Group	Tensile Strength (ksi) from Mill 5									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	86.3	85.9	86.3	87.0	87.1	86.0	87.9	86.6	85.9	87.9
		81.3	82.0	83.1	80.5	81.3	81.8	82.9	81.8	80.5	83.1
	T2	77.5	78.6	78.0	77.9	77.8	76.9	76.1	77.5	76.1	78.6
		84.1	85.1	87.4	87.2	88.9	85.5	86.7	86.4	84.1	88.9
	T3	89.4	89.4	86.9	87.5	86.9	89.3	89.3	88.4	86.9	89.4
		88.6	90.0	91.2	92.6	89.5	88.7	90.3	90.1	88.6	92.6
	T4	89.9	92.5	94.9	92.3	91.1	90.9	91.8	91.9	89.9	94.9
		85.0	85.6	86.4	86.2	87.1	86.5	86.3	86.2	85.0	87.1
A 588	T1	89.0	90.9	90.6	90.1	89.7	88.9	87.8	89.6	87.8	90.9
		87.8	86.8	90.2	90.1	90.4	91.1	90.3	89.5	86.8	91.1
		82.8	82.6	84.7	86.3	85.9	83.8	83.7	84.3	82.6	86.3
	T2	81.1	81.7	84.1	84.2	83.8	85.0	84.6	83.5	81.1	85.0
		85.3	84.4	81.9	82.8	82.4	83.1	83.0	83.3	81.9	85.3
		88.4	87.7	89.9	90.0	89.5	90.7	87.6	89.1	87.6	90.7
	T3	81.9	83.0	82.4	82.0	82.1	79.8	80.6	81.7	79.8	83.0
		80.2	81.0	82.3	80.0	79.9	83.4	81.0	81.1	79.9	83.4
		80.6	79.6	81.2	78.6	79.8	80.8	80.0	80.1	78.6	81.2
	T4	88.7	88.8	89.4	89.4	89.4	88.2	89.3	89.0	88.2	89.4

3.3.2 STATISTICAL ANALYSIS RESULTS FROM ALL MILLS

Tables 3.18 and 3.19 summarize the statistical analysis results for the 4-mill group (mills 1, 3, 4, and 5) and the 2-mill group (mills 2 and 6), respectively. Each table includes the mean and coefficient of variation values of the tensile strength for each thickness group from the individual mills as well as overall statistics (i.e., including all the mills in the corresponding mill group).

Table 3.18: Statistical Analysis of Tensile Strength for the 4-Mill Group.

Group	Tensile Strength, F_u (ksi)														
	Mill 1			Mill 3			Mill 4			Mill 5			Overall		
	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %
A572-T1	42	86.1	5.30	14	76.1	2.41	28	79.7	3.67	14	84.2	3.10	98	82.6	6.23
A572-T2	14	87.0	1.67	21	79.1	1.40	28	81.8	1.55	14	82.0	5.81	77	82.1	4.24
A572-T3	14	81.7	1.03	28	76.4	3.76	0	-	-	14	89.3	1.75	56	80.9	7.09
A572-T4	0	-	-	0	-	-	0	-	-	14	89.0	3.60	14	89.0	3.60
A588-T1	42	80.3	5.38	14	77.8	1.53	28	76.3	2.83	21	87.8	3.27	105	80.4	6.44
A588-T2	14	81.9	1.63	28	74.5	1.98	28	78.5	1.93	21	85.3	3.56	91	79.4	5.68
A588-T3	14	92.6	1.49	14	82.6	1.75	0	-	-	21	81.0	1.54	49	84.8	6.18
A588-T4	0	-	-	14	80.8	0.72	0	-	-	7	89.0	0.53	21	83.5	4.81
A572 All Groups	70	85.4	4.23	63	77.3	2.84	56	80.8	2.79	56	86.1	3.77	245	82.4	5.76
A588 All Groups	70	83.1	4.16	70	78.1	1.64	56	77.4	2.41	70	85.1	2.81	266	81.1	6.02
All Data	140	84.2	4.20	133	77.7	2.28	112	79.1	2.61	126	85.6	3.28	511	81.7	5.90

Table 3.19: Statistical Analysis of Tensile Strength for the 2-Mill Group.

Group	Tensile Strength, F_u (ksi)					
	Mill 2			Mill 6		
	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %
A572-T1	282	72.1	7.07	857	75.8	5.65
A572-T2	8	79.7	8.97	626	75.9	3.94
A572-T3	-	-	-	271	78.7	4.56
A572-T4	-	-	-	260	77.9	3.87
A588-T1	44	83.5	10.2	59	81.2	3.03
A588-T2	-	-	-	73	81.4	2.81
A588-T3	-	-	-	71	83.8	2.89
A588-T4	-	-	-	16	83.8	1.77
A572 All Groups	290	72.3	7.15	2014	76.5	4.80
A588 All Groups	44	83.5	10.2	219	82.3	2.84
All Data	334	73.8	7.77	2233	77.1	4.62

From Table 3.18, it may be observed that, for the 4-mill group, the average tensile strength ranged from 74.5 to 92.6 ksi. With respect to variability in tensile strength values, the largest coefficients of variation values obtained for any single mill and for the 4-mill group were 5.81% and 7.09%, respectively. Considering all of the data, the coefficient of variation was 5.90%.

Similarly, from Table 3.19, it may be observed that both mills showed small variability in tensile strength with coefficient of variation values ranging from 1.77% to 10.2%. The average tensile strength recorded for the two mills ranged from 72.1 to 83.8 ksi.

Another important observation that may be made from Tables 3.17 and 3.18 is that the tensile strength values obtained from the surveyed tests (with the 4-mill group) and the mill tests (with the 2-mill group) are quite similar. These values exceed the minimum requirements of 65 ksi for both steel grades.

3.3.3 DISTRIBUTION OF SAMPLED TENSILE STRENGTH VALUES

The percent of sampled test locations on the plates studied that had tensile strength values greater than or equal to a specific strength level was studied. The specific strength levels considered are 65 and 70 ksi. The 65 ksi level was selected since it is the specification requirement value; the 70 ksi level was selected as it is 5 ksi (approximately 8%) above the specification requirement. The statistical analysis results are shown in Table 3.20. Again, it should be noted that since most plates from Mills 2 and 6 had only one test location per plate, this analysis included only the data from the 4-mill group (Mills 1, 3, 4, and 5).

It may be observed from Table 3.20 that all groups had 100% percent of sampled tensile strength values greater than or equal to the required tensile strength. In other words, in all cases, all seven locations from each plate had tensile strength equal to or greater than 65 ksi. This is also true for the 70 ksi level with only exception: the A588-T2 plates had 98.9% of the samples with tensile strengths greater than 70 ksi. The results suggest that most plates had adequate tensile strength with low variability.

Table 3.20: Percent of All Test Locations that has Tensile Strength Greater than or Equal to Specific Strength Level (4-Mill Group).

Percent Greater than or Equal to Specific Tensile Strength (%)					
Group	Number of Test Locations	65 ksi		70 ksi	
		Mean	COV, %	Mean	COV, %
A572-T1	98	100	0	100	0
A572-T2	77	100	0	100	0
A572-T3	56	100	0	100	0
A572-T4	14	100	0	100	0
A588-T1	105	100	0	100	0
A588-T2	91	100	0	98.9	4.0
A588-T3	49	100	0	100	0
A588-T4	21	100	0	100	0
A572 All Groups	245	100	0	100	0
A588 All Groups	266	100	0	99.6	2.3

3.4 YIELD TO TENSILE RATIO

3.4.1 ORGANIZED DATA FROM THE 4-MILL GROUP

Tables 3.21 to 3.24 present the organized data on yield to tensile ratio for all the slabs from mills 1, 3, 4, and 5 respectively. In each table, the yield to tensile ratio at seven locations on each plate is presented for each steel grade and each thickness group. The mean, low, and high values observed for each sampled plate are also shown in the last three columns of each table.

Table 3.21: Raw Data on Yield to Tensile Ratio from Mill 1.

Grade	Thickness Group	Yield to Tensile Ratio from Mill 1									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	0.71	0.71	0.71	0.72	0.71	0.72	0.73	0.72	0.71	0.73
		0.73	0.73	0.72	0.72	0.72	0.73	0.72	0.72	0.72	0.73
		0.68	0.71	0.68	0.68	0.68	0.68	0.69	0.69	0.68	0.71
		0.72	0.69	0.71	0.71	0.70	0.67	0.70	0.70	0.67	0.72
		0.69	0.68	0.68	0.66	0.69	0.70	0.71	0.69	0.66	0.71
		0.70	0.71	0.70	0.69	0.71	0.69	0.72	0.70	0.69	0.72
	T2	0.66	0.65	0.66	0.65	0.64	0.71	0.65	0.66	0.64	0.71
		0.80	0.66	0.71	0.72	0.72	0.70	0.71	0.72	0.66	0.80
	T3	0.66	0.63	0.68	0.65	0.65	0.69	0.66	0.66	0.63	0.69
		0.73	0.71	0.72	0.71	0.65	0.65	0.67	0.69	0.65	0.73
A 588	T1	0.72	0.73	0.74	0.72	0.74	0.72	0.84	0.74	0.72	0.84
		0.70	0.76	0.71	0.71	0.71	0.72	0.73	0.72	0.70	0.76
		0.72	0.72	0.71	0.71	0.72	0.68	0.67	0.70	0.67	0.72
		0.69	0.70	0.70	0.72	0.71	0.71	0.73	0.71	0.69	0.73
		0.70	0.69	0.70	0.70	0.70	0.71	0.70	0.70	0.69	0.71
		0.70	0.69	0.69	0.68	0.71	0.70	0.70	0.69	0.68	0.71
	T2	0.79	0.77	0.74	0.74	0.72	0.73	0.73	0.75	0.72	0.79
		0.66	0.67	0.66	0.66	0.66	0.62	0.66	0.66	0.62	0.67
	T3	0.71	0.73	0.69	0.72	0.69	0.71	0.74	0.71	0.69	0.74
		0.72	0.73	0.71	0.70	0.69	0.78	0.69	0.72	0.69	0.78

Table 3.22: Raw Data on Yield to Tensile Ratio from Mill 3.

Grade	Thickness Group	Yield to Tensile Ratio from Mill 3									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	0.75	0.72	0.73	0.73	0.76	0.75	0.76	0.74	0.72	0.76
		0.73	0.72	0.71	0.70	0.75	0.72	0.77	0.73	0.70	0.77
	T2	0.73	0.72	0.72	0.74	0.71	0.71	0.71	0.72	0.71	0.74
		0.73	0.72	0.71	0.70	0.71	0.72	0.71	0.71	0.70	0.73
		0.73	0.72	0.71	0.70	0.71	0.72	0.71	0.71	0.70	0.73
	T3	0.70	0.68	0.69	0.61	0.63	0.65	0.62	0.65	0.61	0.70
		0.73	0.72	0.71	0.70	0.71	0.72	0.71	0.71	0.70	0.73
		0.74	0.73	0.74	0.73	0.73	0.74	0.74	0.74	0.73	0.74
		0.74	0.73	0.74	0.73	0.73	0.74	0.74	0.74	0.73	0.74
A 588	T1	0.75	0.76	0.75	0.75	0.75	0.77	0.73	0.75	0.73	0.77
		0.77	0.77	0.74	0.76	0.76	0.75	0.77	0.76	0.74	0.77
	T2	0.75	0.75	0.74	0.75	0.75	0.75	0.74	0.75	0.74	0.75
		0.75	0.75	0.73	0.71	0.75	0.74	0.75	0.74	0.71	0.75
		0.75	0.74	0.74	0.73	0.73	0.74	0.73	0.74	0.73	0.75
		0.74	0.73	0.74	0.73	0.73	0.74	0.74	0.74	0.73	0.74
	T3	0.64	0.62	0.63	0.63	0.63	0.64	0.65	0.63	0.62	0.65
		0.62	0.60	0.61	0.64	0.62	0.61	0.61	0.62	0.60	0.64
	T4	0.66	0.67	0.68	0.66	0.68	0.67	0.68	0.67	0.66	0.68
		0.67	0.69	0.67	0.67	0.67	0.68	0.68	0.67	0.67	0.69

Table 3.23: Raw Data on Yield to Tensile Ratio from Mill 4.

Grade	Thickness Group	Yield to Tensile Ratio from Mill 4									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	0.80	0.79	0.74	0.73	0.75	0.80	0.79	0.77	0.73	0.80
		0.82	0.76	0.74	0.73	0.74	0.78	0.72	0.76	0.72	0.82
		0.80	0.78	0.73	0.72	0.73	0.76	0.79	0.76	0.72	0.80
		0.74	0.76	0.71	0.70	0.71	0.78	0.77	0.74	0.70	0.78
	T2	0.70	0.67	0.67	0.70	0.67	0.69	0.68	0.68	0.67	0.70
		0.70	0.67	0.67	0.67	0.68	0.70	0.70	0.68	0.67	0.70
		0.70	0.67	0.65	0.71	0.72	0.72	0.71	0.70	0.65	0.72
		0.67	0.66	0.64	0.69	0.70	0.69	0.65	0.67	0.64	0.70
A 588	T1	0.86	0.86	0.80	0.72	0.72	0.79	0.81	0.79	0.72	0.86
		0.80	0.82	0.77	0.74	0.78	0.82	0.79	0.79	0.74	0.82
		0.77	0.76	0.69	0.72	0.75	0.73	0.79	0.74	0.69	0.79
		0.79	0.78	0.73	0.73	0.77	0.78	0.83	0.77	0.73	0.83
	T2	0.67	0.65	0.67	0.66	0.65	0.65	0.67	0.66	0.65	0.67
		0.68	0.70	0.73	0.72	0.71	0.71	0.70	0.70	0.68	0.73
		0.68	0.68	0.76	0.69	0.68	0.70	0.71	0.70	0.68	0.76
		0.71	0.68	0.69	0.74	0.68	0.74	0.71	0.71	0.68	0.74

Table 3.24: Raw Data on Yield to Tensile Ratio from Mill 5.

Grade	Thickness Group	Yield to Tensile Ratio from Mill 5									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	0.74	0.74	0.76	0.75	0.74	0.76	0.76	0.75	0.74	0.76
		0.68	0.68	0.67	0.70	0.70	0.69	0.70	0.69	0.67	0.70
	T2	0.71	0.70	0.71	0.72	0.72	0.73	0.73	0.72	0.70	0.73
		0.70	0.69	0.69	0.68	0.68	0.67	0.70	0.69	0.67	0.70
	T3	0.67	0.67	0.69	0.69	0.69	0.67	0.68	0.68	0.67	0.69
		0.70	0.67	0.67	0.68	0.70	0.72	0.68	0.69	0.67	0.72
	T4	0.71	0.69	0.69	0.71	0.71	0.73	0.68	0.70	0.68	0.73
		0.66	0.66	0.67	0.66	0.67	0.66	0.67	0.66	0.66	0.67
A 588	T1	0.69	0.71	0.68	0.68	0.70	0.68	0.71	0.69	0.68	0.71
		0.67	0.69	0.71	0.70	0.70	0.67	0.69	0.69	0.67	0.71
		0.74	0.71	0.72	0.72	0.72	0.71	0.70	0.72	0.70	0.74
	T2	0.70	0.70	0.68	0.68	0.67	0.67	0.68	0.68	0.67	0.70
		0.65	0.69	0.69	0.68	0.70	0.66	0.67	0.68	0.65	0.70
		0.67	0.70	0.71	0.68	0.68	0.69	0.67	0.69	0.67	0.71
	T3	0.70	0.70	0.72	0.71	0.70	0.71	0.72	0.71	0.70	0.72
		0.70	0.72	0.70	0.72	0.72	0.70	0.73	0.71	0.70	0.73
		0.72	0.74	0.73	0.73	0.73	0.70	0.72	0.73	0.70	0.74
	T4	0.65	0.64	0.65	0.64	0.65	0.63	0.65	0.64	0.63	0.65

3.4.2 STATISTICAL ANALYSIS RESULTS FROM ALL MILLS

Tables 3.25 and 3.26 summarize the statistical analysis results for the 4-mill group (mills 1, 3, 4, and 5) and the 2-mill group (mills 2 and 6), respectively. Each table includes the mean and coefficient of variation values of the yield to tensile ratio for each thickness group from the individual mills as well as overall statistics (i.e., including all the mills in the corresponding mill group).

Table 3.25: Statistical Analysis of Yield to Tensile Ratio for 4-Mill Group.

Group	Yield to Tensile Ratio (F_y/F_u)														
	Mill 1			Mill 3			Mill 4			Mill 5			Overall		
	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %
A572-T1	42	0.70	2.48	14	0.73	2.92	28	0.76	4.07	14	0.72	4.64	98	0.73	4.89
A572-T2	14	0.69	6.29	21	0.72	1.53	28	0.68	2.04	14	0.70	2.67	77	0.70	3.90
A572-T3	14	0.68	4.59	28	0.71	5.53	0	-	-	14	0.68	2.28	56	0.69	5.14
A572-T4	0	-	-	0	-	-	0	-	-	14	0.68	3.28	14	0.68	3.28
A588-T1	42	0.71	3.74	14	0.76	1.52	28	0.79	5.44	21	0.70	2.59	105	0.73	5.76
A588-T2	14	0.70	7.23	28	0.74	1.26	28	0.68	3.75	21	0.68	2.07	91	0.71	4.94
A588-T3	14	0.72	3.34	14	0.63	2.16	0	-	-	21	0.70	11.49	49	0.68	9.55
A588-T4	0	-	-	14	0.67	1.15	0	-	-	7	0.64	0.92	21	0.66	2.30
A572 All Groups	70	0.69	3.94	63	0.72	4.01	56	0.72	3.33	56	0.70	3.37	245	0.71	4.59
A588 All Groups	70	0.71	4.57	70	0.71	1.48	56	0.74	4.80	70	0.69	6.65	266	0.71	6.18
All Data	140	0.70	4.27	133	0.71	2.97	112	0.73	4.14	126	0.69	5.42	511	0.71	5.48

Table 3.26: Statistical Analysis of Yield to Tensile Ratio for Two-Mill Group.

Group	Yield to Tensile Ratio (F_y/F_u)					
	Mill 2			Mill 6		
	No. of Tests	Mean	COV, %	No. of Tests	Mean	COV, %
A572-T1	282	0.81	4.11	857	0.80	4.47
A572-T2	8	0.76	6.02	626	0.74	4.38
A572-T3	-	-	-	271	0.69	3.39
A572-T4	-	-	-	260	0.70	3.63
A588-T1	44	0.77	6.42	59	0.76	4.78
A588-T2	-	-	-	73	0.68	3.49
A588-T3	-	-	-	71	0.64	2.83
A588-T4	-	-	-	16	0.65	2.51
A572 All Groups	290	0.81	4.17	2014	0.76	4.26
A588 All Groups	44	0.77	6.42	219	0.69	3.77
All Data	334	0.81	4.49	2233	0.75	4.22

It can be observed from Table 3.25 that, for the 4-mill group, the average yield to tensile ratio ranged from 0.63 to 0.79. With respect to variability in yield to tensile ratios, the largest coefficients of variation values obtained for any single mill and for the 4-mill group were 11.49% and 9.55%, respectively. Considering all of the data, the coefficient of variation was 5.48%.

Similarly, from Table 3.26, it may be observed that both mills showed small variability in yield to tensile ratio with coefficient of variation values ranging from 2.51% to 6.42%. The average yield to tensile ratio for the two mills ranged from 0.64 to 0.81.

An important observation that may be made from Tables 3.25 and 3.26 is that the yield to tensile ratio from all six mills was found to be lower than the maximum permissible ratio of 0.85, which while not necessarily a requirement for plate specifications under study, is a common requirement for other product forms of the same steel covered by A992. In both steel grades, the average yield to tensile ratio for all mills was seen to decrease with an increase in plate thickness, except for a few cases where this trend was not observed.

3.5 YIELD STRENGTH TO YIELD POINT RATIO

3.5.1 ORGANIZED DATA FROM MILL 4

Since mill 4 was the only mill that reported data on yield point, table 3.27 presents the organized data on yield strength to yield point ratio for mill 4. In the table, the yield strength to yield point at seven locations on each plate is presented for each steel grade and each thickness group. The mean, low, and high values observed for each sampled plate is also shown in the last three columns.

Table 3.27: Raw Data on Yield Strength to Yield Point Ratio from Mill 4.

Grade	Thickness Group	Yield Strength to Yield Point (ksi) from Mill 4									
		LOCATION							Mean	Low	High
		1	2	3	4	5	6	7			
A 572	T1	0.98	0.99	0.98	0.97	1.00	0.96	0.98	0.98	0.96	1.00
		1.00	1.00	1.00	1.00	1.00	1.07	0.97	1.01	0.97	1.07
		0.97	1.04	1.00	1.00	1.09	1.01	0.99	1.01	0.97	1.09
		0.98	1.00	0.99	1.00	0.99	1.03	0.98	0.99	0.98	1.03
	T2	1.02	1.00	1.03	1.01	0.99	1.01	1.03	1.01	0.99	1.03
		1.00	1.01	1.01	1.00	1.01	1.03	1.00	1.01	1.00	1.03
		1.07	1.00	1.02	1.22	1.08	1.11	1.16	1.09	1.00	1.22
		0.98	1.00	1.01	0.97	1.02	0.96	1.02	1.00	0.96	1.02
A 588	T1	1.07	1.01	1.07	0.98	0.97	0.99	0.97	1.01	0.97	1.07
		0.97	0.99	1.03	0.96	1.00	1.01	0.97	0.99	0.96	1.03
		0.98	1.00	0.98	1.01	1.04	0.99	0.99	1.00	0.98	1.04
		1.00	0.99	0.98	0.99	0.98	0.97	0.98	0.98	0.97	1.00
	T2	1.02	1.02	1.05	1.00	1.00	1.00	1.04	1.02	1.00	1.05
		1.00	1.00	1.02	0.99	1.00	0.99	1.00	1.00	0.99	1.02
		0.98	0.97	-	1.03	1.01	0.98	0.99	1.00	0.97	1.03
		1.00	1.00	1.02	1.11	1.02	1.13	1.00	1.04	1.00	1.13

3.5.2 STATISTICAL ANALYSIS RESULTS FOR MILL 4

The statistical analysis results for mill 4 are summarized in table 3.28. Since no other mill provided data on yield point, overall statistics for all mills for the yield strength to yield point ratio could not be determined as was done for other parameters discussed. Table 3.28 shows that the average yield strength to yield point ratio of a572-t1, a572-t2, a588-t1 and a588-t2 groups was close to unity; the ratio (averaged for each thickness group) is seen to range from 0.99 to 1.01. In other words, the yield point level is very close to the yield strength with an average discrepancy of only about 1%. Moreover, the variability of this ratio for mill 4 is also relatively small with coefficient of variation values ranging from 1.70% to 3.48%. Considering all of the data, the coefficient of variation was 2.45%.

Table 3.28: Statistical Analysis of Yield Strength to Yield Point Ratio for Mill 4.

Group	Yield Strength to Yield Point Ratio (F_y/Y_p)		
	Mill 4		
	No. of Tests	Mean	COV, %
A572-T1	28	0.99	2.80
A572-T2	28	1.01	1.20
A572-T3	0	-	-
A572-T4	0	-	-
A588-T1	28	1.00	3.48
A588-T2	28	1.01	1.70
A588-T3	0	-	-
A588-T4	0	-	-
A572 All Groups	56	1.00	2.14
A588 All Groups	56	1.00	2.73
All Data	112	1.00	2.45

3.6 CHARPY V-NOTCH TOUGHNESS (CVN)

Charpy V-notch test data were only available for the mills in the 4-mill group. Figure 3.7 shows the distribution of plates among the four mills (Mills 1, 3, 4, and 5) for which CVN test data were available. It should be noted that this distribution is different from the one in Figure 2.2 due to the deletion of erroneous CVN test data as discussed in Section 2.2.

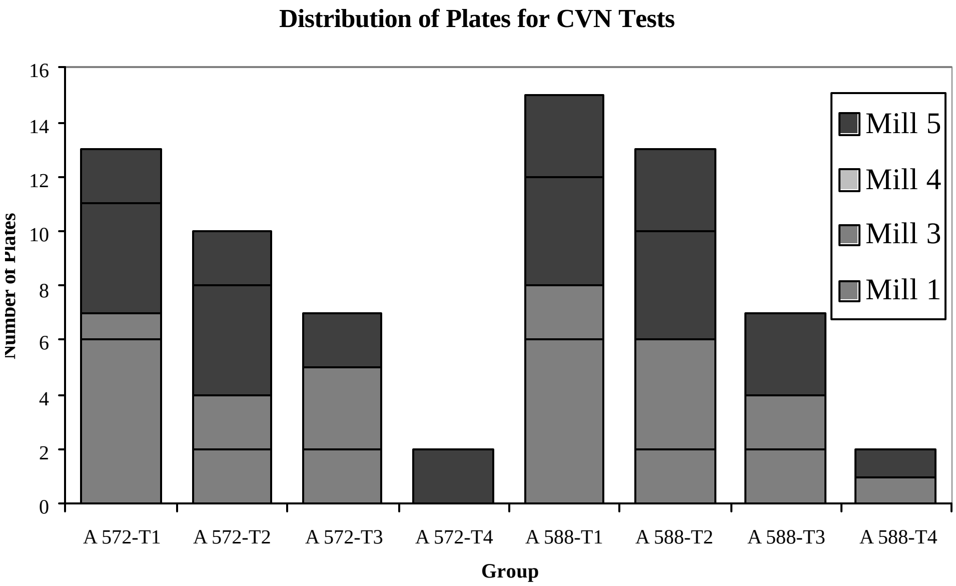


Figure 3.7: Distribution of Plates for CVN Tests (Mills 1, 3, 4, and 5).

3.6.1 ORGANIZED DATA FROM THE 4-MILL GROUP

Tables 3.29 to 3.32 present the three-test averages of absorbed energy from Mills 1, 3, 4, and 5, respectively. In each table, the three-test average of absorbed energy values at seven locations is presented for each steel grade and each thickness group. The mean, low, and high values for each sampled plate are also shown in the last three columns of each table.

Table 3.29: Three-Test Average of Absorbed Energy (ft-lbs) from Mill 1.

Grade	Thickness Group	Test Temperature	Three-Test Average of Absorbed Energy (ft-lbs) from Mill 1									
			LOCATION							Mean	Low	High
			1	2	3	4	5	6	7			
A 572	T1	0 F	48.3	58.3	21.7	21.0	17.0	41.7	67.0	39.3	17.0	67.0
			39.7	49.0	31.7	17.0	12.7	31.3	37.3	31.2	12.7	49.0
			46.7	91.7	32.3	69.3	70.7	93.3	87.3	70.2	32.3	93.3
			91.0	41.7	78.7	17.3	38.7	27.0	22.0	45.2	17.3	91.0
			40.7	9.3	30.0	5.7	11.3	6.7	10.7	16.3	5.7	40.7
			18.0	4.7	36.7	7.7	10.0	12.7	13.0	14.7	4.7	36.7
		40 F	77.3	85.0	39.7	33.7	38.3	88.0	62.0	60.6	33.7	88.0
			62.3	80.7	40.7	31.0	29.7	52.7	57.7	50.7	29.7	80.7
			116.7	108.7	85.3	85.7	100.0	118.3	108.7	103.3	85.3	118.3
			143.7	79.7	123.7	81.7	103.3	89.0	97.3	102.6	79.7	143.7
			55.0	12.7	50.7	17.3	39.0	11.3	34.7	31.5	11.3	55.0
			27.3	10.0	36.7	19.7	41.7	30.7	45.0	30.1	10.0	45.0
		70 F	96.3	116.0	83.3	65.0	60.7	96.3	88.0	86.5	60.7	116.0
			76.3	77.7	50.0	45.0	51.7	88.3	105.0	70.6	45.0	105.0
			142.7	120.7	121.3	128.3	116.3	157.7	119.7	129.5	116.3	157.7
			137.7	100.7	127.7	83.0	130.0	107.7	124.3	115.9	83.0	137.7
			43.3	23.3	46.7	27.0	52.3	20.7	56.3	38.5	20.7	56.3
			51.0	21.3	50.7	43.7	70.7	38.7	64.3	48.6	21.3	70.7
	T2	0 F	42.7	5.7	30.3	22.0	10.3	20.7	24.3	22.3	5.7	42.7
			14.3	22.7	76.3	31.3	55.3	33.3	30.3	37.7	14.3	76.3
		40 F	46.7	46.7	33.0	49.0	55.7	40.3	60.7	47.4	33.0	60.7
			38.3	46.0	65.3	109.7	106.7	58.3	82.7	72.4	38.3	109.7
		70 F	65.7	65.7	43.3	68.7	64.7	49.0	45.7	57.5	43.3	68.7
			71.3	89.3	123.3	129.0	116.0	117.3	96.7	106.1	71.3	129.0
	T3	0 F	3.3	3.0	3.7	12.0	11.3	9.0	21.3	9.1	3.0	21.3
			18.3	17.0	15.0	15.3	14.7	15.3	18.0	16.2	14.7	18.3
		40 F	6.0	5.7	6.7	19.3	18.3	22.0	24.7	14.7	5.7	24.7
			32.7	27.0	25.7	22.7	19.7	19.0	22.7	24.2	19.0	32.7
		70 F	7.7	13.3	17.0	23.7	28.7	32.3	66.3	27.0	7.7	66.3
			31.0	28.7	28.7	31.3	23.3	38.0	25.3	29.5	23.3	38.0
A 588	T1	0 F	125.3	57.0	191.0	66.0	186.7	114.0	209.0	135.6	57.0	209.0
			197.3	78.3	212.0	65.3	187.3	144.7	207.0	156.0	65.3	212.0
			79.0	17.7	39.0	32.0	66.7	19.0	27.7	40.1	17.7	79.0
			55.3	17.3	83.0	20.0	29.3	19.0	31.3	36.5	17.3	83.0
			94.7	68.3	101.0	90.3	104.0	56.0	103.3	88.2	56.0	104.0
			79.0	55.3	54.0	95.0	98.0	91.7	102.7	82.2	54.0	102.7
		40 F	196.0	111.3	214.0	151.3	204.3	140.0	207.0	174.9	111.3	214.0
			210.7	99.3	213.3	123.0	188.0	196.0	207.7	176.9	99.3	213.3
			79.3	40.3	70.0	62.0	70.7	67.0	103.0	70.3	40.3	103.0
			95.7	45.7	84.3	50.7	63.3	43.0	94.3	68.1	43.0	95.7
			237.7	130.0	160.7	129.7	195.3	161.0	218.3	176.1	129.7	237.7
			212.3	68.3	129.0	71.7	194.7	89.3	164.0	132.8	68.3	212.3
		70 F	224.3	164.3	218.7	188.3	186.7	158.7	206.7	192.5	158.7	224.3
			181.0	120.3	202.0	134.0	233.3	171.3	225.0	181.0	120.3	233.3
			76.7	50.0	111.3	113.0	101.3	94.3	93.3	91.4	50.0	113.0
			97.7	90.0	102.3	90.7	97.3	83.7	115.7	96.8	83.7	115.7
			255.3	217.7	257.3	176.7	261.3	163.3	269.7	228.8	163.3	269.7
			206.7	192.7	151.3	170.7	231.7	135.0	249.0	191.0	135.0	249.0
	T2	0 F	42.7	75.0	56.3	78.0	21.3	77.0	49.0	57.0	21.3	78.0
			64.7	111.3	52.3	10.3	26.3	77.3	71.3	59.1	10.3	111.3
		40 F	161.3	183.3	93.0	189.3	115.3	73.0	205.0	145.8	73.0	205.0
			113.0	188.3	115.3	64.7	97.0	104.0	104.0	112.3	64.7	188.3
		70 F	174.7	207.7	164.3	156.0	158.7	166.0	127.3	165.0	127.3	207.7
			168.0	91.0	175.3	138.7	147.7	168.3	165.0	150.6	91.0	175.3
	T3	0 F	13.7	13.3	10.7	15.3	12.3	14.3	17.3	13.9	10.7	17.3
			10.3	22.7	11.7	7.0	17.0	12.0	13.7	13.5	7.0	22.7
		40 F	24.7	21.3	16.7	18.3	32.3	22.3	20.3	22.3	16.7	32.3
			25.7	27.0	18.0	15.3	13.3	12.0	22.7	19.1	12.0	27.0
		70 F	33.3	52.7	35.7	45.7	46.7	24.7	30.0	38.4	24.7	52.7
			22.3	17.7	39.0	54.0	35.3	18.7	34.0	31.6	17.7	54.0

Table 3.30: Three-Test Average of Absorbed Energy (ft-lbs) from Mill 3.

Grade	Thickness Group	Test Temperature	Three-Test Average of Absorbed Energy (ft-lbs) from Mill 3									
			LOCATION							Mean	Low	High
			1	2	3	4	5	6	7			
A 572	T1	0 F	58.3	65.0	90.3	80.3	70.7	67.3	65.0	71.0	58.3	90.3
		40 F	86.7	92.7	83.7	98.0	75.7	67.7	96.0	85.8	67.7	98.0
		70 F	109.7	107.3	110.0	114.0	116.7	110.7	109.7	111.1	107.3	116.7
	T2	0 F	76.7	75.0	70.3	51.0	51.3	85.3	89.3	71.3	51.0	89.3
			58.7	65.0	90.3	80.3	70.7	67.3	65.0	71.0	58.7	90.3
		40 F	95.0	87.0	92.3	99.7	88.3	129.7	122.0	102.0	87.0	129.7
			86.7	92.7	83.7	98.0	75.7	67.7	96.0	85.8	67.7	98.0
		70 F	106.3	97.0	101.0	101.7	89.0	119.3	104.7	102.7	89.0	119.3
			109.7	107.3	110.0	114.0	116.7	110.7	109.7	111.1	107.3	116.7
	T3	0 F	105.7	64.7	92.3	73.0	91.0	19.7	82.3	75.5	19.7	105.7
			31.3	33.7	109.0	62.0	118.7	96.0	102.3	79.0	31.3	118.7
			142.0	136.0	160.0	150.0	167.3	154.3	157.3	152.4	136.0	167.3
		40 F	109.3	35.3	146.7	87.0	120.0	64.3	132.0	99.2	35.3	146.7
			43.7	37.7	140.7	72.7	144.0	99.0	164.7	100.3	37.7	164.7
			152.3	158.7	193.3	194.7	190.7	188.0	179.0	179.5	152.3	194.7
		70 F	166.0	123.3	120.3	83.0	160.7	121.3	131.0	129.4	83.0	166.0
			64.3	54.0	164.3	89.0	173.7	115.3	165.3	118.0	54.0	173.7
			184.0	177.7	180.7	187.3	189.3	178.7	182.7	182.9	177.7	189.3
A 588	T1	0 F	254.3	241.3	150.3	127.7	138.3	217.7	178.0	186.8	127.7	254.3
			228.7	154.7	146.3	122.0	124.0	156.0	150.7	154.6	122.0	228.7
		40 F	262.0	249.7	185.3	207.7	223.7	267.0	207.3	229.0	185.3	267.0
			261.7	237.7	211.0	186.3	220.0	145.7	161.3	203.4	145.7	261.7
		70 F	256.0	266.3	240.3	256.3	245.3	232.3	233.7	247.2	232.3	266.3
			254.0	247.7	201.3	196.7	226.3	219.0	226.0	224.4	196.7	254.0
	T2	0 F	158.3	202.3	138.0	173.0	194.7	134.3	141.3	163.1	134.3	202.3
			135.0	134.7	190.7	216.0	132.3	136.7	127.7	153.3	127.7	216.0
			240.3	230.7	271.0	261.3	266.7	271.7	267.3	258.4	230.7	271.7
			142.0	136.0	160.0	150.0	167.3	154.3	157.3	152.4	136.0	167.3
		40 F	214.7	230.3	254.3	246.3	215.0	241.7	201.3	229.1	201.3	254.3
			139.7	137.7	242.0	204.3	231.3	212.3	195.7	194.7	137.7	242.0
			262.0	259.3	272.3	269.3	270.7	268.0	263.7	266.5	259.3	272.3
			152.3	158.7	193.3	194.7	190.7	188.0	179.0	179.5	152.3	194.7
		70 F	216.7	233.3	223.0	213.3	212.3	240.7	252.7	227.4	212.3	252.7
			177.3	155.3	241.0	238.3	227.0	246.0	233.7	217.0	155.3	246.0
			262.3	252.0	257.3	255.0	253.7	254.7	254.0	255.6	252.0	262.3
			184.0	177.7	180.7	187.3	189.3	178.7	182.7	182.9	177.7	189.3
	T3	0 F	72.3	78.0	102.7	43.0	83.3	10.3	59.3	64.1	10.3	102.7
			89.0	42.3	110.0	24.7	107.7	61.3	88.7	74.8	24.7	110.0
		40 F	83.0	67.3	109.0	35.0	103.7	101.7	85.7	83.6	35.0	109.0
			116.7	33.7	122.7	45.3	137.0	100.0	107.3	94.7	33.7	137.0
		70 F	145.0	127.7	129.7	166.0	132.0	108.7	122.0	133.0	108.7	166.0
			165.0	130.7	140.0	135.3	136.0	61.0	155.3	131.9	61.0	165.0
	T4	0 F	64.7	71.0	98.3	43.0	69.0	23.3	59.3	61.2	23.3	98.3
		40 F	130.7	67.3	109.0	35.0	103.7	101.7	85.7	90.4	35.0	130.7
		70 F	145.0	127.7	129.7	166.0	132.0	108.7	122.0	133.0	108.7	166.0

Table 3.31: Three-Test Average of Absorbed Energy (ft-lbs) from Mill 4.

Grade	Thickness Group	Test Temperature	Three-Test Average of Absorbed Energy (ft-lbs) from Mill 4									
			LOCATION							Mean	Low	High
			1	2	3	4	5	6	7			
A 572	T1	0 F	107.3	105.0	147.0	128.0	174.3	125.3	129.3	130.9	105.0	174.3
			125.3	151.0	120.3	131.7	90.7	136.0	139.3	127.8	90.7	151.0
			126.7	125.7	129.0	135.0	129.3	131.0	137.0	130.5	125.7	137.0
			158.0	154.3	133.3	122.0	175.0	150.0	166.7	151.3	122.0	175.0
		40 F	117.0	121.7	152.7	117.3	160.7	119.7	122.7	130.2	117.0	160.7
			140.7	142.0	139.0	130.3	148.7	142.7	126.0	138.5	126.0	148.7
			122.3	134.3	158.0	147.3	147.7	134.0	137.3	140.1	122.3	158.0
			172.3	148.7	155.3	147.7	183.7	154.0	169.0	161.5	147.7	183.7
		70 F	107.0	124.0	169.3	144.7	177.0	134.3	145.7	143.1	107.0	177.0
			143.7	121.0	149.7	153.7	140.3	139.0	136.7	140.6	121.0	153.7
			119.7	127.3	169.0	156.7	159.7	133.0	133.3	142.7	119.7	169.0
			175.7	153.7	182.3	179.7	210.0	149.3	166.3	173.9	149.3	210.0
	T2	0 F	60.0	49.0	32.7	29.0	42.0	40.3	46.0	42.7	29.0	60.0
			78.7	56.3	69.3	49.3	53.7	73.0	80.7	65.9	49.3	80.7
			53.0	41.0	50.3	59.0	38.0	77.0	59.7	54.0	38.0	77.0
			127.7	123.0	112.7	124.0	123.3	131.7	116.3	122.7	112.7	131.7
		40 F	92.7	71.0	67.7	72.0	61.3	67.7	91.0	74.8	61.3	92.7
			111.0	106.0	100.3	87.0	104.0	117.3	109.7	105.0	87.0	117.3
			99.0	93.3	96.7	98.3	88.7	105.7	103.7	97.9	88.7	105.7
			160.0	148.7	147.7	142.3	159.7	159.0	159.7	153.9	142.3	160.0
		70 F	100.0	104.7	80.0	85.7	89.0	93.0	102.3	93.5	80.0	104.7
			123.0	110.7	114.3	109.3	104.7	120.3	125.0	115.3	104.7	125.0
			99.7	106.0	101.7	105.3	102.3	134.7	122.3	110.3	99.7	134.7
			174.3	172.7	159.0	179.0	164.7	161.3	147.7	165.5	147.7	179.0
A 588	T1	0 F	99.0	99.0	121.7	123.3	120.0	142.7	144.7	121.5	99.0	144.7
			94.7	102.7	152.3	128.3	106.0	132.7	153.7	124.3	94.7	153.7
			161.7	104.7	161.0	115.3	155.7	160.0	143.7	143.1	104.7	161.7
			146.0	141.0	195.3	155.7	141.3	144.0	145.0	152.6	141.0	195.3
		40 F	94.3	135.7	164.0	162.7	132.3	113.3	163.3	138.0	94.3	164.0
			101.0	115.7	179.0	171.0	120.7	150.7	168.3	143.8	101.0	179.0
			180.3	129.0	175.0	146.3	172.7	187.7	180.7	167.4	129.0	187.7
			153.3	147.7	202.0	215.7	208.0	141.7	143.0	173.0	141.7	215.7
		70 F	92.0	122.7	144.7	134.7	159.7	158.3	114.7	132.4	92.0	159.7
			100.7	136.0	169.0	171.3	124.3	163.7	136.7	143.1	100.7	171.3
			159.0	158.3	197.0	166.7	161.0	172.7	171.3	169.4	158.3	197.0
			153.3	152.7	204.3	216.0	214.0	138.3	150.3	175.6	138.3	216.0
	T2	0 F	187.0	243.0	245.3	303.3	70.0	292.7	243.0	226.3	70.0	303.3
			172.0	121.0	203.3	192.3	172.3	130.0	186.3	168.2	121.0	203.3
			287.3	275.7	273.7	292.3	282.0	298.0	280.7	284.2	273.7	298.0
			199.0	184.0	100.0	108.3	135.0	198.7	168.3	156.2	100.0	199.0
		40 F	115.7	299.0	294.7	290.0	219.7	285.3	287.7	256.0	115.7	299.0
			247.0	230.7	231.3	255.7	231.7	247.0	236.0	239.9	230.7	255.7
			289.7	290.0	286.3	286.3	294.7	297.7	288.7	290.5	286.3	297.7
			229.0	218.0	221.0	161.7	220.7	232.7	243.7	218.1	161.7	243.7
		70 F	253.7	316.3	318.7	312.0	237.0	313.7	304.0	293.6	237.0	318.7
			207.7	214.0	206.7	246.3	214.0	215.0	207.0	215.8	206.7	246.3
			275.0	280.0	278.7	278.3	278.7	282.7	277.3	278.7	275.0	282.7
			232.0	233.0	238.3	233.0	226.7	264.7	227.3	236.4	226.7	264.7

Table 3.32: Three-Test Average of Absorbed Energy (ft-lbs) from Mill 5.

Grade	Thickness Group	Test Temperature	Three-Test Average of Absorbed Energy (ft-lbs) from Mill 5									
			LOCATION							Mean	Low	High
			1	2	3	4	5	6	7			
A 572	T1	0 F	42.3	53.3	42.3	73.3	55.7	87.0	61.3	59.3	42.3	87.0
			27.3	33.0	21.3	19.7	23.3	13.3	15.0	21.9	13.3	33.0
		40 F	69.7	51.3	72.7	90.7	77.0	111.3	76.0	78.4	51.3	111.3
			32.0	31.3	23.7	29.3	34.3	42.0	46.0	34.1	23.7	46.0
		70 F	96.3	91.3	94.7	101.7	100.0	118.7	73.0	96.5	73.0	118.7
			83.7	90.7	83.3	75.0	78.0	84.7	79.7	82.1	75.0	90.7
	T2	0 F	111.0	103.3	108.0	113.3	108.3	148.0	118.3	115.8	103.3	148.0
			26.7	30.7	23.0	21.7	31.7	24.3	21.7	25.7	21.7	31.7
		40 F	139.0	141.3	132.7	148.0	138.3	138.7	121.3	137.0	121.3	148.0
			55.0	86.7	59.3	47.0	77.3	74.3	52.0	64.5	47.0	86.7
		70 F	149.7	167.7	170.0	149.3	186.7	210.0	192.7	175.1	149.3	210.0
			118.0	125.7	86.7	107.0	127.7	118.3	98.7	111.7	86.7	127.7
	T3	0 F	66.3	85.3	90.0	68.3	34.3	43.7	84.0	67.4	34.3	90.0
			10.7	6.7	13.3	20.7	20.7	16.0	21.3	15.6	6.7	21.3
		40 F	67.3	97.3	80.7	78.0	107.3	70.7	64.0	80.8	64.0	107.3
			21.3	19.7	21.7	22.3	18.3	19.7	18.3	20.2	18.3	22.3
		70 F	103.3	102.7	110.3	115.0	144.0	112.7	109.7	114.0	102.7	144.0
			19.0	28.3	24.3	40.7	30.0	12.3	28.3	26.1	12.3	40.7
	T4	0 F	11.0	11.0	8.3	8.3	8.7	8.3	9.7	9.3	8.3	11.0
			18.3	14.3	20.0	11.3	18.3	14.7	29.7	18.1	11.3	29.7
		40 F	14.3	10.7	12.3	12.7	12.7	22.0	15.3	14.3	10.7	22.0
			30.0	29.3	40.3	27.0	26.3	42.7	34.0	32.8	26.3	42.7
		70 F	14.3	16.0	16.0	17.3	17.3	21.3	18.3	17.2	14.3	21.3
			55.7	42.3	41.7	37.7	75.7	37.7	56.7	49.6	37.7	75.7
A 588	T1	0 F	69.7	39.3	33.0	26.3	54.7	49.3	82.0	50.6	26.3	82.0
			33.0	10.7	28.7	26.3	19.7	25.0	23.7	23.9	10.7	33.0
			136.7	109.3	137.7	110.7	84.7	79.0	41.7	100.0	41.7	137.7
		40 F	84.7	99.7	74.3	39.7	82.7	83.7	129.7	84.9	39.7	129.7
			74.7	23.0	90.7	72.3	66.0	36.7	28.7	56.0	23.0	90.7
			259.3	155.7	100.0	107.7	118.7	140.7	151.3	147.6	100.0	259.3
		70 F	120.3	110.0	86.0	69.3	107.7	90.3	162.3	106.6	69.3	162.3
			128.7	89.3	95.0	123.3	89.7	57.7	82.3	95.1	57.7	128.7
			229.3	186.0	153.3	160.3	154.7	192.0	196.0	181.7	153.3	229.3
	T2	0 F	106.7	60.3	92.7	72.3	98.3	94.7	75.3	85.8	60.3	106.7
			123.0	41.7	85.3	94.0	126.3	86.3	95.0	93.1	41.7	126.3
			61.0	75.0	72.3	107.7	79.7	52.3	50.7	71.2	50.7	107.7
		40 F	152.3	161.7	90.7	116.7	119.0	119.7	113.0	124.7	90.7	161.7
			111.0	121.7	140.0	136.0	165.0	146.0	147.7	138.2	111.0	165.0
			97.3	82.7	100.7	103.3	123.3	117.7	104.0	104.1	82.7	123.3
		70 F	161.3	166.0	123.0	137.0	148.0	143.0	127.3	143.7	123.0	166.0
			149.3	143.7	166.7	166.3	187.7	159.7	145.3	159.8	143.7	187.7
			106.7	110.3	137.7	145.7	133.3	142.7	142.3	131.2	106.7	145.7
	T3	0 F	81.7	35.0	22.0	26.3	13.7	21.3	32.7	33.2	13.7	81.7
			67.7	66.0	102.7	91.3	111.0	62.3	84.3	83.6	62.3	111.0
			130.7	124.3	116.3	142.7	116.3	105.3	129.7	123.6	105.3	142.7
		40 F	55.7	65.7	53.3	59.7	31.3	38.0	62.7	52.3	31.3	65.7
			123.0	85.7	120.0	119.7	114.3	129.0	103.3	113.6	85.7	129.0
			149.3	145.0	140.0	151.3	155.3	154.3	153.0	149.8	140.0	155.3
		70 F	109.0	89.0	36.3	31.3	36.0	82.0	76.0	65.7	31.3	109.0
			112.0	109.7	125.7	124.3	136.0	115.3	113.0	119.4	109.7	136.0
			159.0	154.0	135.0	135.0	142.3	162.0	165.0	150.3	135.0	165.0
	T4	0 F	29.7	19.3	21.0	22.3	27.0	28.7	22.7	24.4	19.3	29.7
		40 F	51.0	39.0	43.7	47.0	55.7	57.0	56.3	50.0	39.0	57.0
		70 F	86.0	91.0	92.3	105.3	82.3	95.3	75.0	89.6	75.0	105.3

3.6.2 STATISTICAL ANALYSIS RESULTS FROM All MILLS

Tables 3.33 to 3.36 summarize the statistical analysis results for Mills 1, 3, 4, and 5, respectively. Each table includes the minimum, maximum, mean, and coefficient of variation values of the absorbed energy for each steel grade, each thickness group, and for three test temperatures. In addition, due to the fact that the coefficients of variation on absorbed energy are significantly large (e.g., 72.5% for A572-T1 at 0°F), it is important to determine whether this large variability stems from the variability in the specimens within a plate or from the variability between plates.

A one-way analysis of variance (ANOVA) was performed in order to determine the variability of absorbed energy within a plate and the variability between plates. The formulas used in the analysis are presented as follows:

$$SST = \left(\sum_{j=1}^{k} \sum_{i=1}^{m} E_{i,j}^2 \right) - \frac{\left(\sum_{j=1}^{k} \sum_{i=1}^{m} E_{i,j} \right)^2}{k \cdot m} \tag{3.1}$$

$$SSA = \frac{\sum_{j=1}^{k} \left(\sum_{i=1}^{m} E_{i,j} \right)^2}{k} - \frac{\left(\sum_{j=1}^{k} \sum_{i=1}^{m} E_{i,j} \right)^2}{k \cdot m} \tag{3.2}$$

$$SSW = SST - SSA \tag{3.3}$$

$$F = \frac{MSA}{MSW}; \quad \text{where} \quad MSA = \frac{SSA}{k-1}, \; MSW = \frac{SSW}{k(m-1)} \tag{3.4}$$

where,

$E_{i,j}$ = Absorbed Energy at location i of slab j,

m = Number of locations on a single slab (m = 7, here),

i = Index for location on a slab; possible values are 1 to m,

k = Number of slabs (in each thickness group),

SST = Total sum of squares,

SSA = Sum of squares between plates,

SSW = Sum of squares within a plate,

MSA = Variance between plates,

MSW = Variance within a plate,

F = F-ratio.

The F-ratio is used to compare the variability between plates to the variability within a plate. If this ratio is greater than one, it indicates that variability between plates is larger than the variability within a plate. However, since the F-ratio cannot be used to compare tests with different degrees of freedom (Frank et al., 1992), a p value (determined from the F-ratio and the number of degrees of freedom) is used instead in order to compare the variability for the eight groups of steel plates (corresponding to the two grades of steel and four thickness groups). This p value also helps make direct conclusions regarding whether or not the variability within a plate (based on the seven locations there) is significant at a specified level of significance. The level of significance used in this study is 5%. For instance, if the p value is less than 5% or 0.05, it means that the variability among the seven locations within a plate is not significant or that the large variability mainly stems from variability between plates.

Table 3.33: Statistical Analysis of Absorbed Energy for Mill 1.

Group	No. of Test Locations	Absorbed Energy (ft-lbs) 0 F				MSA	MSW	F-Ratio	p-value
		Min	Max	Mean	COV, %	(ft^2-lbs^2)	(ft^2-lbs^2)		
A572-T1	42	4.7	93.3	36.2	72.5	2980.1	369.3	8.07	0.000
A572-T2	14	5.7	76.3	30.0	61.5	828.0	299.6	2.76	0.123
A572-T3	14	3.0	21.3	12.7	46.7	178.6	23.1	7.74	0.012
A588-T1	42	17.3	212.0	89.8	65.1	16584.9	1582.4	10.5	0.000
A588-T2	14	10.3	111.3	58.1	46.5	14.7	787.2	0.019	0.890
A588-T3	14	7.0	22.7	13.7	27.4	0.5	15.1	0.034	0.887
Group	No. of Test Locations	40 F				MSA	MSW	F-Ratio	p-value
		Min	Max	Mean	COV, %	(ft^2-lbs^2)	(ft^2-lbs^2)		
A572-T1	42	10.0	143.7	63.1	55.6	7594.5	349.6	21.7	0.000
A572-T2	14	33.0	109.7	59.9	40.0	2187.5	439.9	4.97	0.045
A572-T3	14	5.7	32.7	19.4	41.9	317.5	45.3	7.01	0.021
A588-T1	42	40.3	237.7	133.2	46.2	19132.5	1650.7	11.6	0.000
A588-T2	14	64.7	205.0	129.0	36.2	3911.1	2041.4	1.92	0.191
A588-T3	14	12.0	32.3	20.7	27.1	34.6	31.3	1.10	0.315
Group	No. of Test Locations	70 F				MSA	MSW	F-Ratio	p-value
		Min	Max	Mean	COV, %	(ft^2-lbs^2)	(ft^2-lbs^2)		
A572-T1	42	20.7	157.7	81.6	46.0	9183.2	326.7	28.1	0.000
A572-T2	14	43.3	129.0	81.8	36.5	8273.3	278.9	29.7	0.000
A572-T3	14	7.7	66.3	28.2	48.2	21.5	198.7	0.11	0.746
A588-T1	42	50.0	269.7	163.6	37.1	22137.1	1119.4	19.8	0.000
A588-T2	14	91.0	207.7	157.8	17.0	723.8	716.2	1.01	0.335
A588-T3	14	17.7	54.0	35.0	33.7	162.3	136.7	1.19	0.297

Table 3.34: Statistical Analysis of Absorbed Energy for Mill 3.

Group	No. of Test Locations	Absorbed Energy (ft-lbs) 0 F Min	Max	Mean	COV, %	MSA (ft^2-lbs^2)	MSW (ft^2-lbs^2)	F-Ratio	p-value
A572-T1	7	58.3	90.3	71.0	15.3	-	117.8	-	-
A572-T2	14	51.0	90.3	71.2	17.8	0.2	172.9	0.001	0.970
A572-T3	21	19.7	167.3	102.3	43.6	13204.5	740.9	17.8	0.000
A588-T1	14	122.0	254.3	170.7	26.7	3626.8	1942.6	1.87	0.197
A588-T2	28	127.7	271.7	181.8	27.9	18423.5	593.7	31.0	0.000
A588-T3	14	10.3	110.0	69.5	44.3	398.2	994.9	0.40	0.539
A588-T4	7	23.3	98.3	61.2	38.4	-	552.7	-	-
Group	No. of Test Locations	40 F Min	Max	Mean	COV, %	MSA (ft^2-lbs^2)	MSW (ft^2-lbs^2)	F-Ratio	p-value
A572-T1	7	67.7	98.0	85.8	12.9	-	122.8	-	-
A572-T2	14	67.7	129.7	93.9	17.2	922.9	205.2	4.50	0.055
A572-T3	21	35.3	194.7	126.4	42.0	14837.8	1482.0	10.0	0.001
A588-T1	14	145.7	267.0	216.2	17.4	2288.6	1343.0	1.70	0.217
A588-T2	28	137.7	272.3	217.5	19.0	10487.1	602.9	17.4	0.000
A588-T3	14	33.7	137.0	89.1	36.6	427.2	1117.4	0.38	0.549
A588-T4	7	35.0	130.7	90.4	34.7	-	982.3	-	-
Group	No. of Test Locations	70 F Min	Max	Mean	COV, %	MSA (ft^2-lbs^2)	MSW (ft^2-lbs^2)	F-Ratio	p-value
A572-T1	7	107.3	116.7	111.1	2.8	-	9.8	-	-
A572-T2	14	89.0	119.3	106.9	7.5	248.6	48.1	5.17	0.042
A572-T3	21	54.0	189.3	143.4	29.9	8408.1	1115.5	7.54	0.004
A588-T1	14	196.7	266.3	235.8	8.8	1813.4	311.3	5.82	0.033
A588-T2	28	155.3	262.3	220.7	14.6	6308.9	384.0	16.4	0.000
A588-T3	14	61.0	166.0	132.5	19.6	4.2	729.5	0.01	0.922
A588-T4	7	108.7	166.0	133.0	13.7	-	331.1	-	-

Table 3.35: Statistical Analysis of Absorbed Energy for Mill 4.

Group	No. of Test Locations	Absorbed Energy (ft-lbs)				MSA	MSW	F-Ratio	p-value
		0 F							
		Min	Max	Mean	COV, %	(ft^2-lbs^2)	(ft^2-lbs^2)		
A572-T1	28	90.7	175.0	135.1	14.4	830.4	322.8	2.57	0.077
A572-T2	28	29.0	131.7	71.3	46.3	8830.7	119.9	73.7	0.000
A588-T1	28	94.7	195.3	135.4	17.8	1569.8	460.3	3.41	0.033
A588-T2	28	70.0	303.3	208.7	32.8	24302.1	2250.8	10.8	0.000
Group	No. of Test Locations	40 F				MSA	MSW	F-Ratio	p-value
		Min	Max	Mean	COV, %	(ft^2-lbs^2)	(ft^2-lbs^2)		
A572-T1	28	117.0	183.7	142.6	12.1	1245.9	179.7	6.93	0.001
A572-T2	28	61.3	160.0	107.9	28.3	7742.5	82.4	94.0	0.000
A588-T1	28	94.3	215.7	155.5	20.0	2087.8	825.8	2.53	0.081
A588-T2	28	115.7	299.0	251.1	17.4	6508.0	1344.2	4.84	0.009
Group	No. of Test Locations	70 F				MSA	MSW	F-Ratio	p-value
		Min	Max	Mean	COV, %	(ft^2-lbs^2)	(ft^2-lbs^2)		
A572-T1	28	107.0	210.0	150.1	15.3	6729.6	369.2	18.2	0.000
A572-T2	28	80.0	179.0	121.2	24.0	1770.6	107.6	16.5	0.000
A588-T1	28	92.0	216.0	155.1	19.5	2997.5	658.9	4.55	0.011
A588-T2	28	206.7	318.7	256.1	14.4	9163.5	375.6	24.4	0.000

Table 3.36: Statistical Analysis of Absorbed Energy for ill 5.

Group	No. of Test Locations	Absorbed Energy (ft-lbs) 0 F Min	Max	Mean	COV, %	MSA (ft^2-lbs^2)	MSW (ft^2-lbs^2)	F-Ratio	p-value
A572-T1	14	13.3	87.0	40.6	56.3	4915.6	156.2	31.48	0.000
A572-T2	14	21.7	148.0	70.7	67.8	28410.0	120.6	235.56	0.000
A572-T3	14	6.7	90.0	41.5	74.2	9394.8	246.7	38.08	0.000
A572-T4	14	8.3	29.7	13.7	44.6	268.7	18.2	14.76	0.002
A588-T1	21	10.7	137.7	58.1	67.3	10430.5	541.2	19.27	0.000
A588-T2	21	41.7	126.3	83.4	27.4	866.2	483.9	1.79	0.195
A588-T3	21	13.7	142.7	80.2	52.1	14358.1	340.5	42.17	0.000
A588-T4	7	19.3	29.7	24.4	16.5	-	16.2	-	-
Group	No. of Test Locations	40 F Min	Max	Mean	COV, %	MSA (ft^2-lbs^2)	MSW (ft^2-lbs^2)	F-Ratio	p-value
A572-T1	14	23.7	111.3	56.2	47.6	6864.3	202.7	33.9	0.000
A572-T2	14	47.0	148.0	100.8	39.1	18409.0	145.4	127	0.000
A572-T3	14	18.3	107.3	50.5	66.0	12841.1	130.6	98.3	0.000
A572-T4	14	10.7	42.7	23.5	46.1	1201.0	27.8	43.2	0.000
A588-T1	21	23.0	259.3	96.2	55.3	15356.4	1434.6	10.7	0.001
A588-T2	21	82.7	165.0	122.3	18.8	2058.0	361.6	5.69	0.012
A588-T3	21	31.3	155.3	105.2	40.6	16977.5	137.2	124	0.000
A588-T4	7	39.0	57.0	50.0	14.0	-	48.7	-	-
Group	No. of Test Locations	70 F Min	Max	Mean	COV, %	MSA (ft^2-lbs^2)	MSW (ft^2-lbs^2)	F-Ratio	p-value
A572-T1	14	73.0	118.7	89.3	13.9	723.8	105.8	6.84	0.023
A572-T2	14	86.7	210.0	143.4	26.3	14081.1	367.1	38.4	0.000
A572-T3	14	12.3	144.0	70.0	67.0	26986.8	138.1	195	0.000
A572-T4	14	14.3	75.7	33.4	57.9	3669.8	99.7	36.8	0.000
A588-T1	21	57.7	229.3	127.8	36.9	15465.7	751.5	20.6	0.000
A588-T2	21	106.7	187.7	144.9	13.3	1436.6	253.5	5.67	0.012
A588-T3	21	31.3	165.0	111.8	36.3	12849.5	402.0	32.0	0.000
A588-T4	7	75.0	105.3	89.6	10.9	-	94.8	-	-

Table 3.33 shows that, for Mill 1, there were three groups (A572-T2, A588-T2, and A588-T3) at 0°F and 70°F where the *p* value was greater than 0.05. Test locations impact the variability in absorbed energy in these three groups. In other words, the large variability mainly stems from the variability within a plate. In contrast, there were only two thickness groups at 40°F (A588-T2 and A588-T3) that suggest larger within-plate variability arising from test location differences.

By interpreting results for other mills in a manner similar to that discussed for Mill 1, it is found, as seen from Table 3.34, that Mill 3 had three thickness groups (A572-T2, A588-T1, and A588-T3) that showed significant within-plate variability for 0°F and 40°F. At 70 °F, there was only one thickness group (A588-T3) that suggests significant within-plate variability.

It can be observed from Table 3.35 that Mill 4 had relatively low *p* values with only one thickness group displaying the significance of within-plate variability at 0°F and 40°F. The between-plate variability dominated the overall variability for every thickness group at 70°F.

Finally, for Mill 5, Table 3.36 shows that the between-plate variability dominated the overall variability in almost every group studied at all test temperatures. With only one exception (A588-T2, 0°F), no *p* value exceeded 0.05, which indicates that within-plate variability was not significant for Mill 5.

Although the four mills studied do not show similar variability trends, an overall analysis summarized in Table 3.37 that combines the data from all the mills (in the 4-mill group) clearly shows that the variability between plates dominates the overall variability for both grades of steel and for all thickness groups at the three test temperatures. In summary, it is seen that for every thickness group, within-plate variability arising from samples at different test locations was not significant with respect to the overall variability. The variability in absorbed energy mainly stems from the variability between plates.

Table 3.37: Statistical Analysis of absorbed Energy for the 4-Mill Group.

Group	No. of Test Locations	Absorbed Energy (ft-lbs) 0 F				MSA	MSW	F-Ratio	p-value
		Min	Max	Mean	COV, %	(ft^2-lbs^2)	(ft^2-lbs^2)		
A572-T1	91	4.7	175.0	70.0	71.4	16776.6	302.8	55.4	0.000
A572-T2	70	5.7	148.0	62.9	55.7	8299.8	166.6	49.8	0.000
A572-T3	49	3.0	167.3	59.3	86.4	18285.4	394.6	46.3	0.000
A572-T4	14	8.3	29.7	13.7	44.6	268.7	18.2	14.8	0.002
A588-T1	105	10.7	254.3	106.4	54.9	18148.2	1123.0	16.2	0.000
A588-T2	91	10.3	303.3	148.3	52.8	38849.0	1108.0	35.1	0.000
A588-T3	49	7.0	142.7	58.1	73.3	11464.3	434.5	26.4	0.000
A588-T4	14	19.3	98.3	42.8	58.6	4754.6	284.5	16.7	0.002
A572 All Groups	224	3.0	175.0	61.9	74.6	13704.0	262.5	52.2	0.000
A588 All Groups	259	7.0	303.3	108.6	66.2	31210.3	942.1	33.1	0.000
Group	No. of Test Locations	40 F				MSA	MSW	F-Ratio	p-value
		Min	Max	Mean	COV, %	(ft^2-lbs^2)	(ft^2-lbs^2)		
A572-T1	91	10.0	183.7	88.3	52.4	14344.6	257.3	55.8	0.000
A572-T2	70	33.0	160.0	94.1	35.9	7449.8	191.0	39.0	0.000
A572-T3	49	5.7	194.7	74.1	82.3	24976.2	685.4	36.4	0.000
A572-T4	14	10.7	42.7	23.5	46.1	1201.0	27.8	43.2	0.000
A588-T1	105	23.0	267.0	142.8	42.6	18883.6	1346.5	14.0	0.000
A588-T2	91	64.7	299.0	192.3	35.1	27697.1	996.6	27.8	0.000
A588-T3	49	12.0	155.3	76.5	63.7	16257.9	387.0	42.0	0.000
A588-T4	14	35.0	130.7	70.2	43.1	5734.1	515.5	11.1	0.005
A572 All Groups	224	5.7	194.7	82.9	58.0	14667.5	315.9	46.4	0.000
A588 All Groups	259	12.0	299.0	143.7	51.9	33660.0	997.1	33.8	0.000
Group	No. of Test Locations	70 F				MSA	MSW	F-Ratio	p-value
		Min	Max	Mean	COV, %	(ft^2-lbs^2)	(ft^2-lbs^2)		
A572-T1	91	20.7	210.0	106.1	39.4	11281.5	281.4	40.1	0.000
A572-T2	70	43.3	210.0	114.9	30.1	7942.6	181.8	43.7	0.000
A572-T3	49	7.7	189.3	89.6	69.7	27123.0	574.3	47.2	0.000
A572-T4	14	14.3	75.7	33.4	57.9	3669.8	99.7	36.8	0.000
A588-T1	98	50.0	269.7	162.5	35.4	18168.3	815.3	22.3	0.000
A588-T2	91	91.0	318.7	204.4	26.7	19765.2	402.4	49.1	0.000
A588-T3	49	17.7	166.0	95.8	52.1	16974.8	419.8	40.4	0.000
A588-T4	14	75.0	166.0	111.3	23.8	6586.7	213.0	30.9	0.000
A572 All Groups	224	7.7	210.0	100.7	47.8	14823.3	303.0	48.9	0.000
A588 All Groups	259	17.7	318.7	162.4	40.9	28198.0	562.8	50.1	0.000

It can also be observed from Table 3.37 that most plates had relatively high absorbed energy values with average values (considering all thickness groups) of 61.9, 82.9, and 100.7 ft-lbs, respectively at 0, 40 and 70°F for the A572 steel; and 108.6, 143.7 and 162.4 ft-lbs, respectively, at 0, 40 and 70°F for the A588 steel. Clearly, the A588 steel plates showed higher absorbed energy values than the A572 steel plates did. The trend of a decrease in absorbed energy being accompanied by a decrease in test temperature is what one might expect because the material has lower resistance to brittle fracture at lower temperatures. Another observation from the test results is that, in most of the cases studied, the absorbed energy tends to decrease with an increase in plate thickness. In other words, the thicker the steel plate, the lower the fracture toughness measured (through the absorbed energy value).

Frequency distributions of the absorbed energy for each steel grade and thickness group are presented in Figures 3.8 to 3.15. Both histograms and cumulative distributions are shown for the three test temperatures. Finally, frequency distributions of the absorbed energy for the A572 and A588 steel grades are presented in Figures 3.16 and 3.17, respectively, where plates of all thickness groups are included.

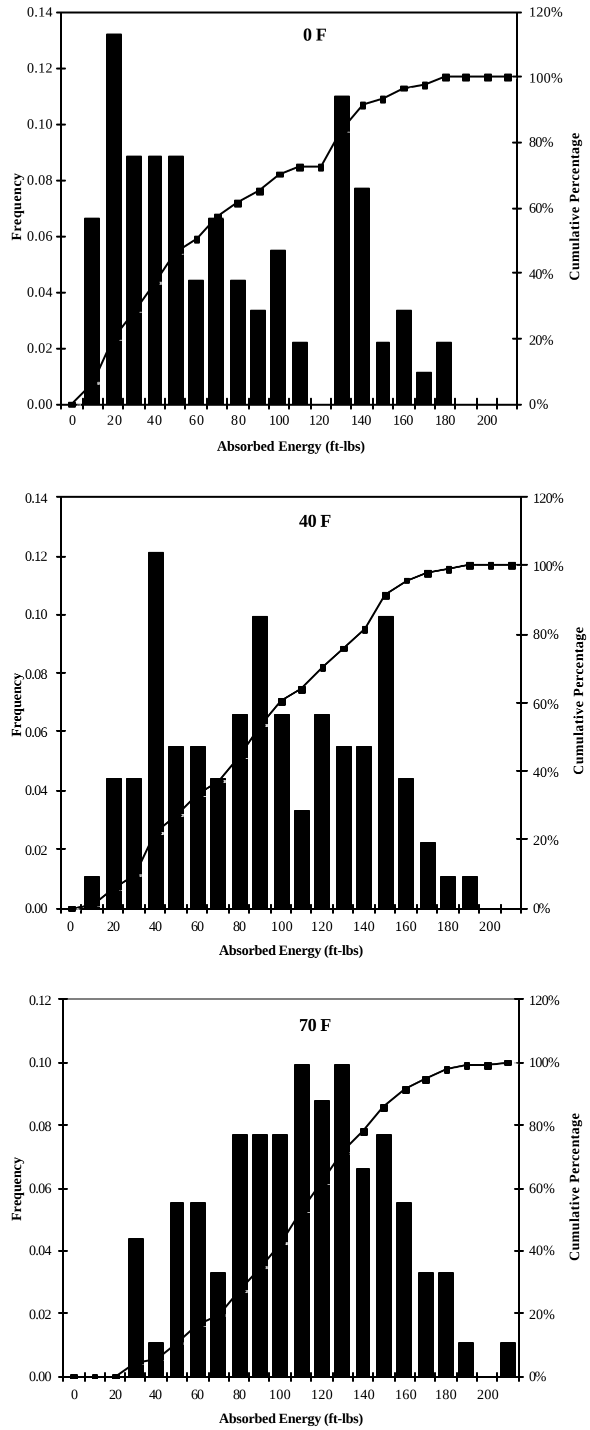


Figure 3.8: Absorbed Energy Frequency Distribution for the A572-T1 Group.

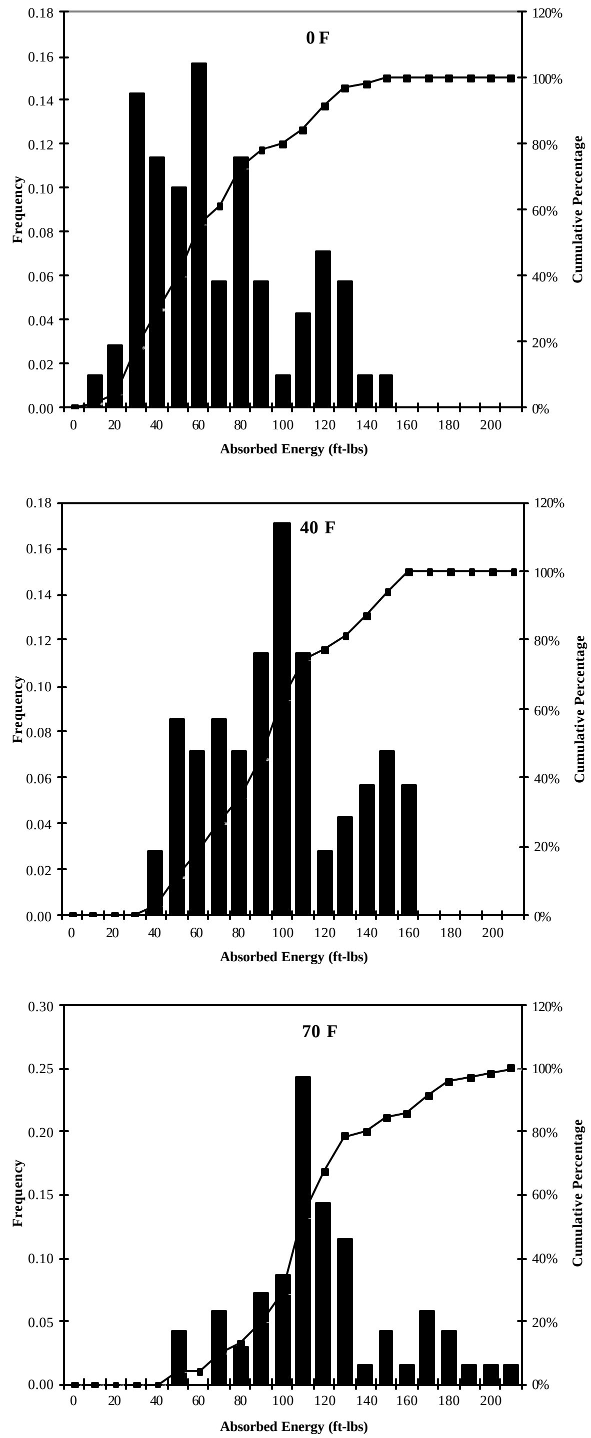


Figure 3.9: Absorbed Energy Frequency Distribution for the A572-T2 Group.

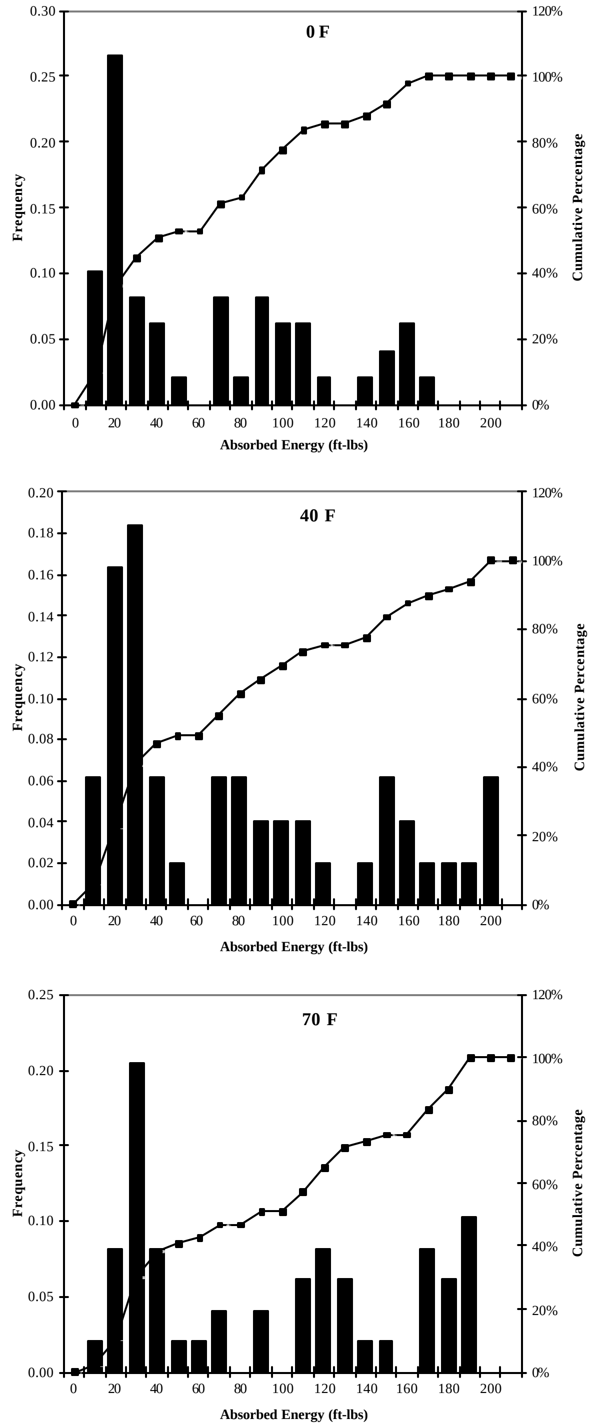


Figure 3.10: Absorbed Energy Frequency Distribution for the A572-T3 Group.

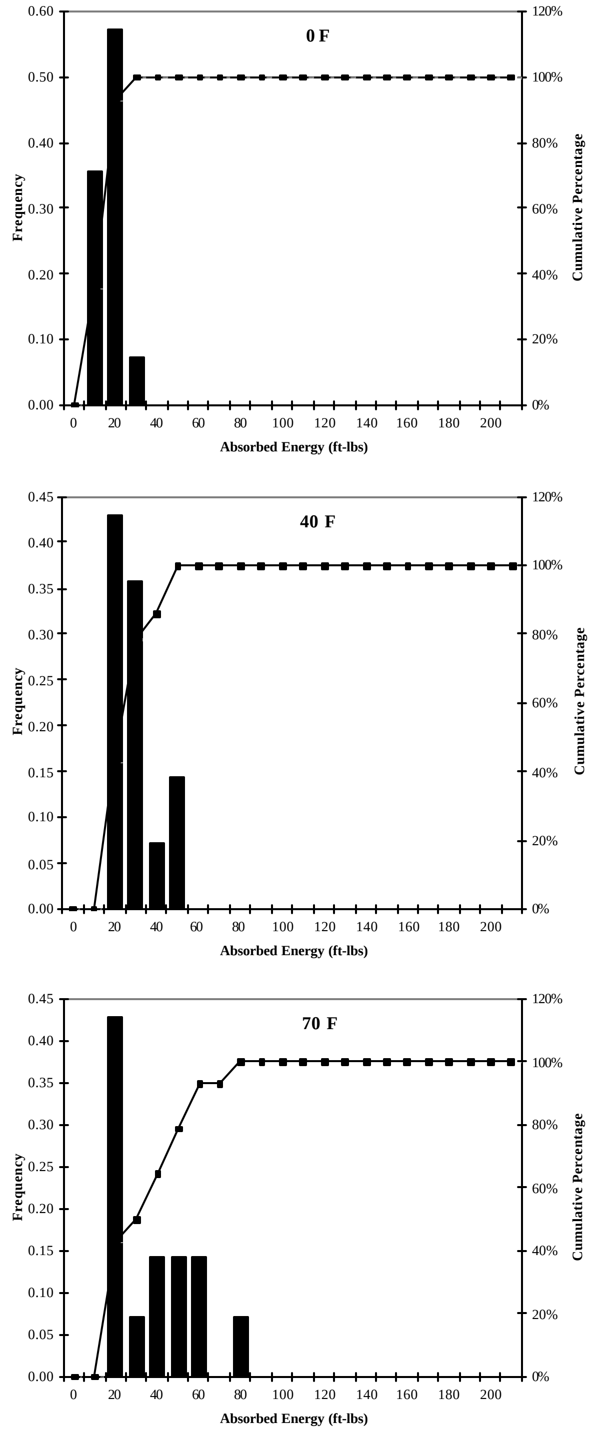


Figure 3.11: Absorbed Energy Frequency Distribution for the A572-T4 Group.

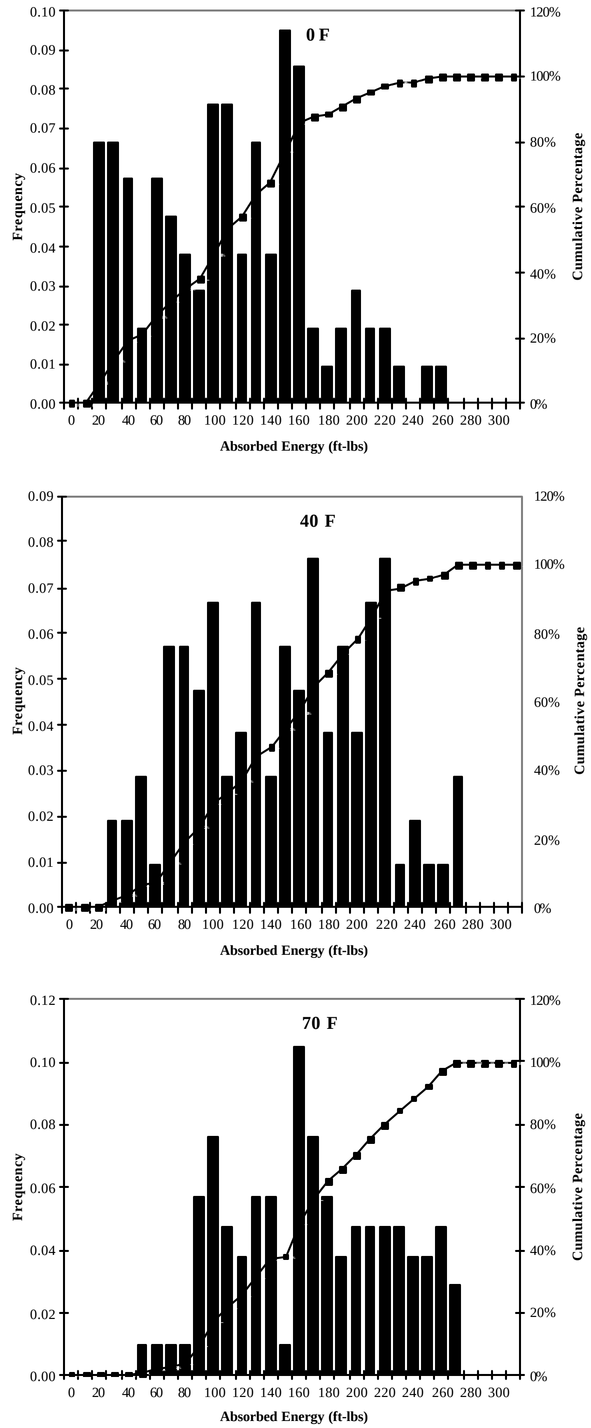


Figure 3.12: Absorbed Energy Frequency Distribution for the A588-T1 Group.

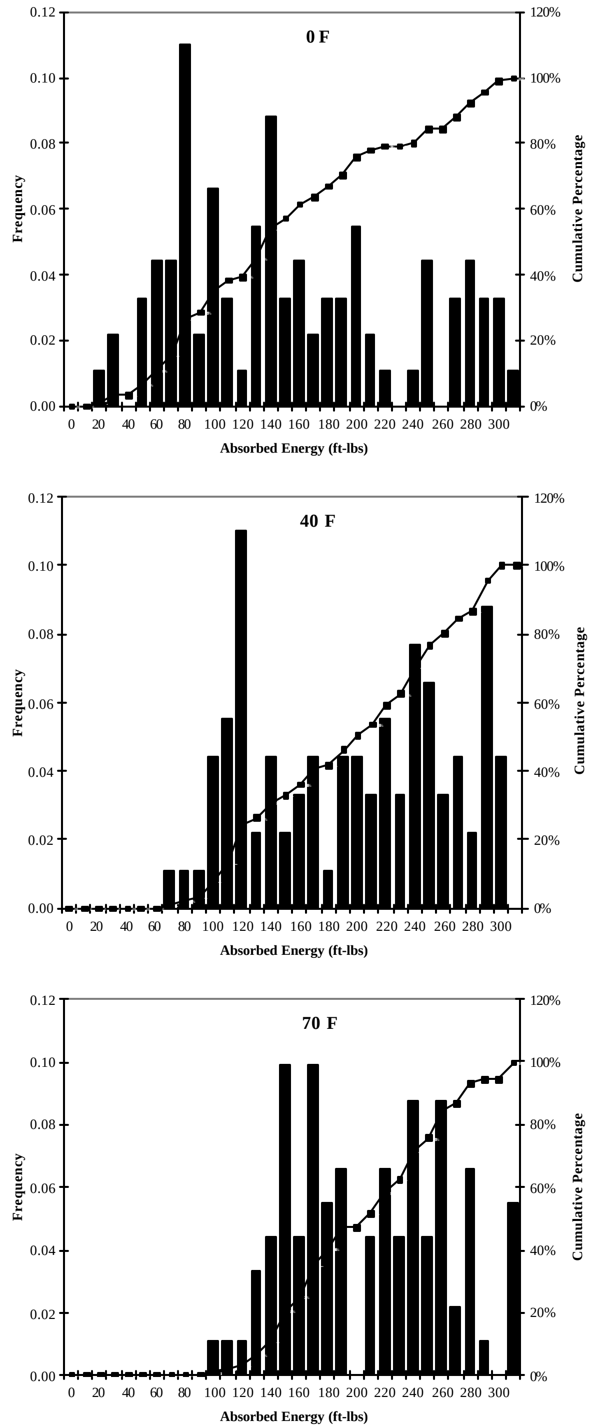


Figure 3.13: Absorbed Energy Frequency Distribution for the A588-T2 Group.

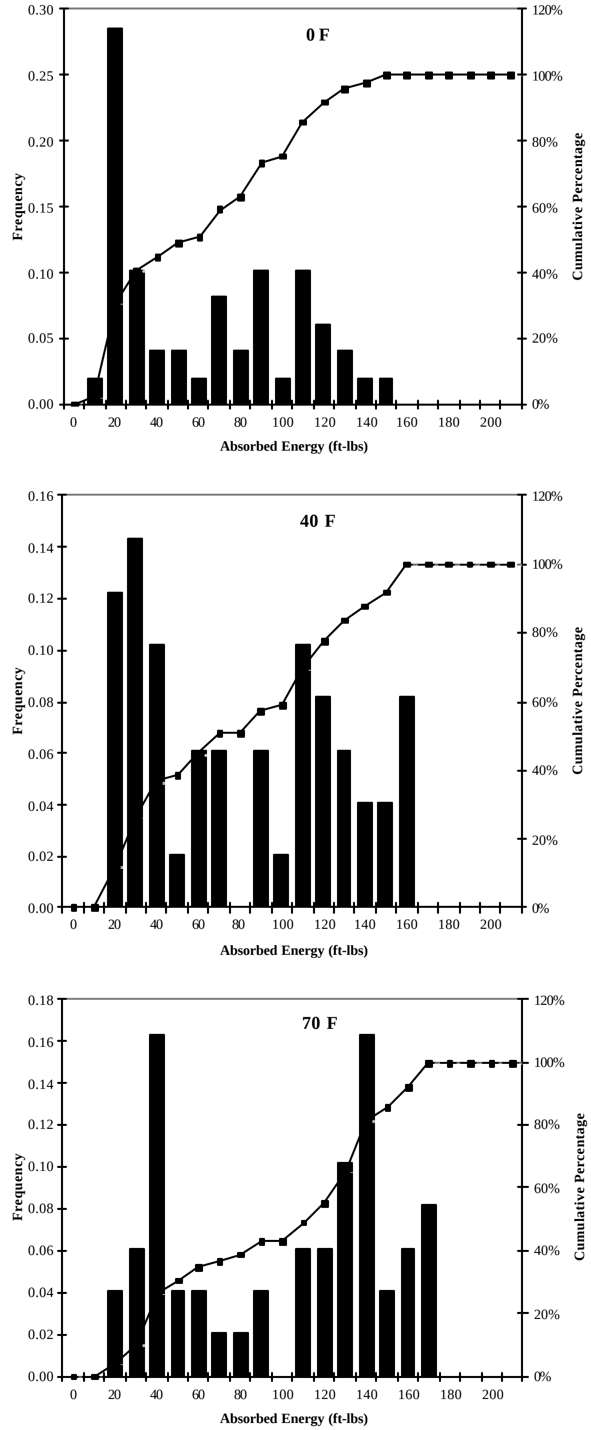


Figure 3.14: Absorbed Energy Frequency Distribution for the A588-T3 Group.

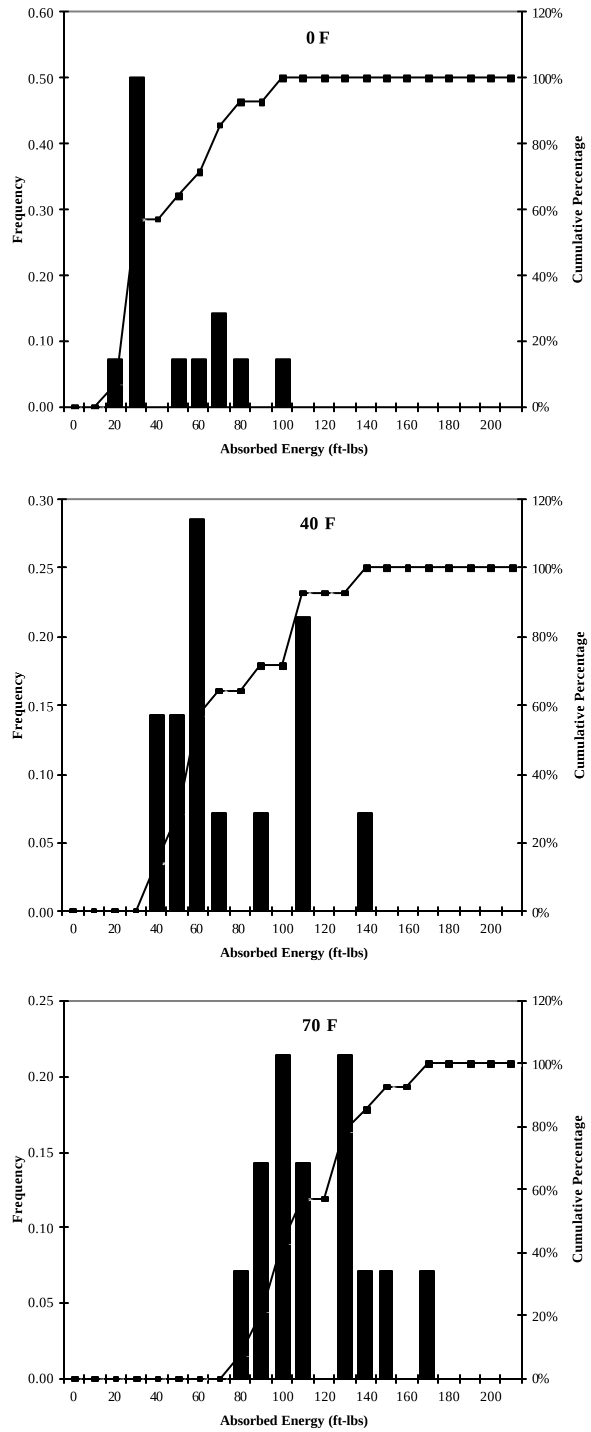


Figure 3.15: Absorbed Energy Frequency Distribution for the A588-T4 Group.

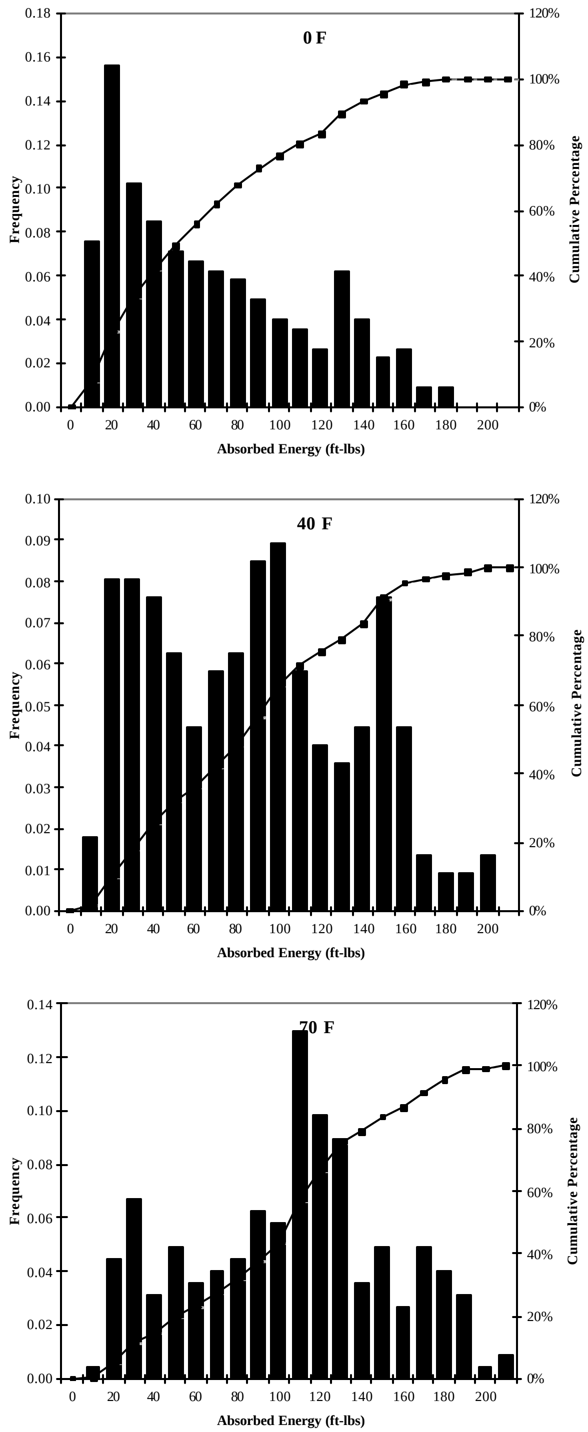


Figure 3.16: Absorbed Energy Frequency Distribution for all A572 Steel Plates.

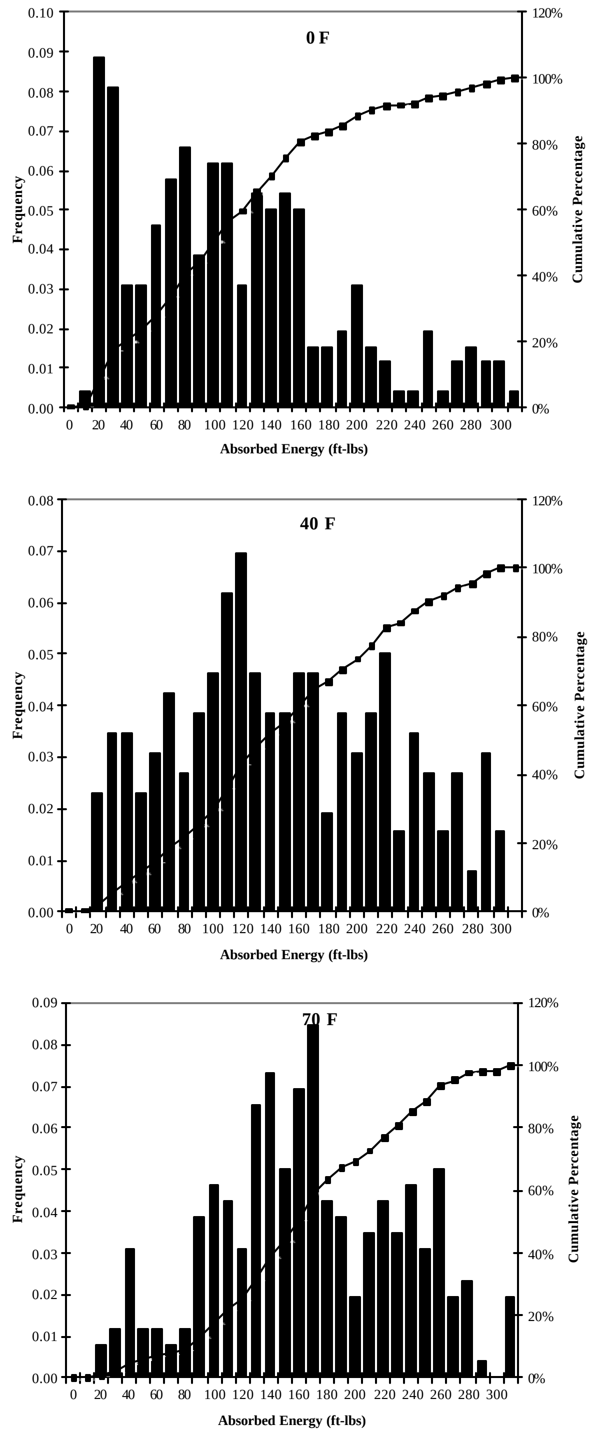


Figure 3.17: Absorbed Energy Frequency Distribution for all A588 Steel Plates.

3.6.3 REFERENCE LOCATION EFFECT IN CHARPY V-NOTCH TESTS

With Charpy V-notch test results, it is customary to calculate the probability that a three-test average absorbed energy value for any location tested will exceed the absorbed energy associated with a reference location less some specified value, a (AISI, 1979). In this study, the seven locations in a plate are each considered as the reference location and for different values of a equal to 5, 10, and 15 ft-lbs, results are presented for the percentage of samples that had absorbed energy greater than that the absorbed energy at the reference location, E_{ref}, reduced by a.

Results of the analyses are summarized in Tables 3.38 to 3.49. Tables 3.38 to 3.40 are for Mill 1 with a = 5, 10, and 15 ft-lbs, respectively. Tables 3.41 to 3.43 are for Mill 3 with a = 5, 10, and 15 ft-lbs, respectively. Tables 3.44 to 3.46 are for Mill 4 with a = 5, 10, and 15 ft-lbs, respectively. Tables 3.47 to 3.49 are for Mill 5 with a = 5, 10, and 15 ft-lbs, respectively.

In each table, for a given plate, the percent of locations with three-test average absorbed energy greater than $E_{ref}–a$ is presented for each of seven possible choices of reference location. For each mill in the 4-mill group, results are presented for each grade of steel, for each thickness group, and for each test temperature. Average percentages for each plate are also presented, as are the minimum mean and maximum mean values for each thickness group and test temperature.

By way of illustration, the first six rows of Table 3.38 present Mill 1 results for group A572-T1 at a test temperature of 0°F. On average, the percentage of plates in this group that had absorbed energy greater than $E_{ref}–5$ ranged from 61.2 % to 73.5%. This means that if an A572-T1 steel plate were to be ordered from Mill 1 and a location, x, was selected at random to conduct CVN impact tests at 0°F and yielded an absorbed energy average value, $E_{ref,x}$, from three tests, the probability that any other location on the plate might have yield an averaged absorbed energy (from three tests) greater than $E_{ref,x}–5$ (ft-lbs) would vary between 61.2% and 73.5%. For higher values of a, these probabilities would increase.

Table 3.38: Effect of Reference Location for Mill 1, a = 5.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 5 For Mill 1									
			LOCATION							Mean	Min Mean	Max Mean
			1	2	3	4	5	6	7			
A 572	T1	0 F	42.9	28.6	100.0	100.0	100.0	57.1	14.3	63.3	61.2	73.5
			42.9	14.3	71.4	100.0	100.0	71.4	42.9	63.3		
			85.7	42.9	100.0	71.4	71.4	28.6	42.9	63.3		
			14.3	57.1	28.6	100.0	57.1	71.4	100.0	61.2		
			14.3	100.0	28.6	100.0	85.7	100.0	85.7	73.5		
			28.6	100.0	14.3	100.0	85.7	71.4	71.4	67.3		
		40 F	42.9	28.6	85.7	100.0	100.0	28.6	57.1	63.3	59.2	65.3
			42.9	14.3	71.4	100.0	100.0	57.1	42.9	61.2		
			28.6	57.1	100.0	100.0	71.4	28.6	57.1	63.3		
			14.3	100.0	28.6	100.0	42.9	71.4	57.1	59.2		
			28.6	100.0	28.6	85.7	57.1	100.0	57.1	65.3		
			71.4	100.0	42.9	85.7	28.6	71.4	28.6	61.2		
		70 F	42.9	14.3	71.4	100.0	100.0	42.9	71.4	63.3	59.2	67.3
			57.1	57.1	85.7	100.0	85.7	28.6	14.3	61.2		
			28.6	100.0	85.7	42.9	100.0	14.3	100.0	67.3		
			14.3	85.7	57.1	100.0	42.9	71.4	57.1	61.2		
			57.1	100.0	57.1	85.7	28.6	100.0	28.6	65.3		
			57.1	100.0	57.1	71.4	14.3	85.7	28.6	59.2		
	T2	0 F	14.3	100.0	28.6	71.4	100.0	71.4	71.4	65.3	63.3	65.3
			100.0	85.7	14.3	71.4	28.6	71.4	71.4	63.3		
		40 F	71.4	71.4	100.0	71.4	28.6	85.7	14.3	63.3	59.2	63.3
			100.0	85.7	57.1	28.6	28.6	71.4	42.9	59.2		
		70 F	57.1	57.1	100.0	57.1	57.1	85.7	100.0	73.5	59.2	73.5
			100.0	85.7	28.6	14.3	57.1	57.1	71.4	59.2		
	T3	0 F	100.0	100.0	100.0	57.1	57.1	57.1	14.3	69.4	69.4	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
		40 F	100.0	100.0	100.0	57.1	57.1	57.1	28.6	71.4	71.4	79.6
			14.3	71.4	71.4	100.0	100.0	100.0	100.0	79.6		
		70 F	100.0	85.7	85.7	57.1	42.9	42.9	14.3	61.2	61.2	75.5
			71.4	85.7	85.7	71.4	100.0	14.3	100.0	75.5		
A 588	T1	0 F	57.1	100.0	42.9	85.7	42.9	71.4	14.3	59.2	57.1	65.3
			42.9	85.7	14.3	100.0	57.1	71.4	28.6	57.1		
			14.3	100.0	42.9	71.4	28.6	100.0	71.4	61.2		
			28.6	100.0	14.3	100.0	57.1	100.0	57.1	65.3		
			71.4	85.7	42.9	71.4	42.9	100.0	42.9	65.3		
			71.4	100.0	100.0	57.1	42.9	57.1	28.6	65.3		
		40 F	57.1	100.0	14.3	71.4	42.9	85.7	42.9	59.2	59.2	63.3
			42.9	100.0	28.6	85.7	71.4	57.1	42.9	61.2		
			28.6	100.0	71.4	85.7	71.4	71.4	14.3	63.3		
			28.6	100.0	42.9	71.4	57.1	100.0	28.6	61.2		
			14.3	100.0	71.4	100.0	42.9	71.4	28.6	61.2		
			14.3	100.0	57.1	100.0	28.6	71.4	42.9	59.2		
		70 F	14.3	85.7	28.6	71.4	71.4	100.0	42.9	59.2	57.1	63.3
			57.1	100.0	42.9	85.7	14.3	71.4	28.6	57.1		
			85.7	100.0	28.6	28.6	42.9	71.4	71.4	61.2		
			57.1	85.7	42.9	85.7	57.1	100.0	14.3	63.3		
			57.1	71.4	57.1	85.7	42.9	100.0	14.3	61.2		
			42.9	57.1	85.7	71.4	28.6	100.0	14.3	57.1		
	T2	0 F	85.7	42.9	57.1	42.9	100.0	42.9	71.4	63.3	57.1	63.3
			57.1	14.3	71.4	100.0	85.7	28.6	42.9	57.1		
		40 F	57.1	42.9	85.7	28.6	71.4	100.0	14.3	57.1	57.1	61.2
			42.9	14.3	42.9	100.0	85.7	71.4	71.4	61.2		
		70 F	28.6	14.3	57.1	85.7	85.7	57.1	100.0	61.2	61.2	63.3
			57.1	100.0	14.3	85.7	71.4	57.1	57.1	63.3		
	T3	0 F	100.0	100.0	100.0	100.0	100.0	100.0	71.4	95.9	75.5	95.9
			100.0	14.3	100.0	100.0	42.9	85.7	85.7	75.5		
		40 F	71.4	100.0	100.0	100.0	14.3	85.7	100.0	81.6	75.5	81.6
			42.9	42.9	85.7	100.0	100.0	100.0	57.1	75.5		
		70 F	85.7	14.3	71.4	42.9	42.9	100.0	85.7	63.3	63.3	67.3
			100.0	100.0	42.9	14.3	57.1	100.0	57.1	67.3		

Table 3.39: Effect of Reference Location for Mill 1, a = 10.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 10 For Mill 1									
			LOCATION							Mean	Min Mean	Max Mean
			1	2	3	4	5	6	7			
A 572	T1	0 F	57.1	28.6	100.0	100.0	100.0	57.1	28.6	67.3	65.3	83.7
			71.4	28.6	71.4	100.0	100.0	71.4	71.4	73.5		
			85.7	42.9	100.0	71.4	71.4	42.9	42.9	65.3		
			14.3	57.1	28.6	100.0	57.1	100.0	100.0	65.3		
			14.3	100.0	28.6	100.0	100.0	100.0	100.0	77.6		
			71.4	100.0	14.3	100.0	100.0	100.0	100.0	83.7		
		40 F	42.9	42.9	100.0	100.0	100.0	28.6	57.1	67.3	67.3	75.5
			57.1	14.3	85.7	100.0	100.0	57.1	57.1	67.3		
			57.1	71.4	100.0	100.0	71.4	57.1	71.4	75.5		
			14.3	100.0	28.6	100.0	57.1	100.0	71.4	67.3		
			28.6	100.0	28.6	100.0	57.1	100.0	57.1	67.3		
			85.7	100.0	71.4	100.0	42.9	71.4	42.9	73.5		
		70 F	57.1	14.3	71.4	100.0	100.0	57.1	71.4	67.3	65.3	75.5
			57.1	57.1	100.0	100.0	100.0	28.6	14.3	65.3		
			28.6	100.0	100.0	85.7	100.0	14.3	100.0	75.5		
			28.6	85.7	57.1	100.0	57.1	85.7	57.1	67.3		
			57.1	100.0	57.1	100.0	57.1	100.0	42.9	73.5		
			71.4	100.0	71.4	85.7	28.6	85.7	28.6	67.3		
	T2	0 F	14.3	100.0	71.4	71.4	100.0	71.4	71.4	71.4	69.4	71.4
			100.0	100.0	14.3	85.7	28.6	71.4	85.7	69.4		
		40 F	85.7	85.7	100.0	85.7	71.4	100.0	28.6	79.6	63.3	79.6
			100.0	100.0	71.4	28.6	28.6	71.4	42.9	63.3		
		70 F	57.1	57.1	100.0	57.1	57.1	100.0	100.0	75.5	67.3	75.5
			100.0	85.7	57.1	28.6	57.1	57.1	85.7	67.3		
	T3	0 F	100.0	100.0	100.0	100.0	100.0	100.0	28.6	89.8	89.8	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
		40 F	100.0	100.0	100.0	57.1	57.1	57.1	57.1	75.5	75.5	91.8
			42.9	100.0	100.0	100.0	100.0	100.0	100.0	91.8		
		70 F	100.0	100.0	100.0	71.4	57.1	57.1	14.3	71.4	71.4	95.9
			100.0	100.0	100.0	100.0	100.0	71.4	100.0	95.9		
A 588	T1	0 F	57.1	100.0	42.9	100.0	42.9	71.4	14.3	61.2	61.2	71.4
			42.9	85.7	28.6	100.0	57.1	71.4	42.9	61.2		
			14.3	100.0	57.1	71.4	28.6	100.0	85.7	65.3		
			28.6	100.0	14.3	100.0	71.4	100.0	57.1	67.3		
			71.4	85.7	57.1	71.4	57.1	100.0	57.1	71.4		
			71.4	100.0	100.0	57.1	57.1	57.1	42.9	69.4		
		40 F	57.1	100.0	42.9	71.4	57.1	85.7	42.9	65.3	59.2	73.5
			42.9	100.0	42.9	85.7	71.4	71.4	42.9	65.3		
			57.1	100.0	85.7	85.7	85.7	85.7	14.3	73.5		
			28.6	100.0	42.9	100.0	57.1	100.0	28.6	65.3		
			14.3	100.0	71.4	100.0	42.9	71.4	28.6	61.2		
			14.3	100.0	57.1	100.0	28.6	71.4	42.9	59.2		
		70 F	28.6	100.0	28.6	71.4	71.4	100.0	42.9	63.3	57.1	77.6
			71.4	100.0	42.9	85.7	28.6	71.4	28.6	61.2		
			85.7	100.0	28.6	28.6	71.4	71.4	71.4	65.3		
			85.7	100.0	57.1	100.0	85.7	100.0	14.3	77.6		
			57.1	71.4	57.1	85.7	57.1	100.0	28.6	65.3		
			42.9	57.1	85.7	71.4	28.6	100.0	14.3	57.1		
	T2	0 F	85.7	42.9	71.4	42.9	100.0	42.9	85.7	67.3	61.2	67.3
			57.1	14.3	71.4	100.0	85.7	42.9	57.1	61.2		
		40 F	57.1	42.9	85.7	42.9	71.4	100.0	14.3	59.2	59.2	69.4
			71.4	14.3	42.9	100.0	85.7	85.7	85.7	69.4		
		70 F	42.9	14.3	85.7	85.7	85.7	71.4	100.0	69.4	69.4	69.4
			57.1	100.0	42.9	85.7	85.7	57.1	57.1	69.4		
	T3	0 F	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	89.8	100.0
			100.0	42.9	100.0	100.0	85.7	100.0	100.0	89.8		
		40 F	100.0	100.0	100.0	100.0	28.6	100.0	100.0	89.8	85.7	89.8
			57.1	57.1	100.0	100.0	100.0	100.0	85.7	85.7		
		70 F	100.0	42.9	85.7	42.9	42.9	100.0	100.0	73.5	69.4	73.5
			100.0	100.0	57.1	14.3	57.1	100.0	57.1	69.4		

Table 3.40: Effect of Reference Location for Mill 1, *a* = 15.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 15 For Mill 1									
			LOCATION							Mean	Min Mean	Max Mean
			1	2	3	4	5	6	7			
A 572	T1	0 F	57.1	42.9	100.0	100.0	100.0	57.1	28.6	69.4	67.3	87.8
			71.4	42.9	85.7	100.0	100.0	85.7	71.4	79.6		
			100.0	42.9	100.0	71.4	71.4	42.9	42.9	67.3		
			28.6	71.4	28.6	100.0	71.4	100.0	100.0	71.4		
			28.6	100.0	28.6	100.0	100.0	100.0	100.0	79.6		
			100.0	100.0	14.3	100.0	100.0	100.0	100.0	87.8		
		40 F	42.9	42.9	100.0	100.0	100.0	42.9	57.1	69.4	69.4	81.6
			57.1	14.3	100.0	100.0	100.0	71.4	57.1	71.4		
			57.1	71.4	100.0	100.0	100.0	57.1	71.4	79.6		
			14.3	100.0	28.6	100.0	71.4	100.0	71.4	69.4		
			28.6	100.0	42.9	100.0	57.1	100.0	57.1	69.4		
			85.7	100.0	71.4	100.0	71.4	85.7	57.1	81.6		
		70 F	71.4	14.3	71.4	100.0	100.0	71.4	71.4	71.4	69.4	79.6
			57.1	57.1	100.0	100.0	100.0	57.1	14.3	69.4		
			42.9	100.0	100.0	100.0	100.0	14.3	100.0	79.6		
			57.1	85.7	57.1	100.0	57.1	85.7	57.1	71.4		
			57.1	100.0	57.1	100.0	57.1	100.0	57.1	75.5		
			85.7	100.0	85.7	85.7	28.6	85.7	57.1	75.5		
	T2	0 F	28.6	100.0	71.4	85.7	100.0	85.7	85.7	79.6	71.4	79.6
			100.0	100.0	14.3	85.7	28.6	85.7	85.7	71.4		
		40 F	100.0	100.0	100.0	85.7	71.4	100.0	71.4	89.8	65.3	89.8
			100.0	100.0	71.4	28.6	28.6	85.7	42.9	65.3		
		70 F	57.1	57.1	100.0	57.1	57.1	100.0	100.0	75.5	71.4	75.5
			100.0	85.7	57.1	57.1	57.1	57.1	85.7	71.4		
	T3	0 F	100.0	100.0	100.0	100.0	100.0	100.0	57.1	93.9	93.9	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
		40 F	100.0	100.0	100.0	100.0	100.0	57.1	57.1	87.8	87.8	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
		70 F	100.0	100.0	100.0	85.7	71.4	57.1	14.3	75.5	75.5	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
A 588	T1	0 F	71.4	100.0	42.9	100.0	42.9	71.4	14.3	63.3	63.3	79.6
			57.1	100.0	42.9	100.0	57.1	71.4	42.9	67.3		
			28.6	100.0	71.4	100.0	28.6	100.0	100.0	75.5		
			28.6	100.0	14.3	100.0	100.0	100.0	100.0	77.6		
			71.4	100.0	71.4	71.4	71.4	100.0	71.4	79.6		
			71.4	100.0	100.0	57.1	57.1	71.4	57.1	73.5		
		40 F	57.1	100.0	42.9	85.7	57.1	85.7	57.1	69.4	59.2	75.5
			57.1	100.0	42.9	85.7	71.4	71.4	57.1	69.4		
			71.4	100.0	85.7	85.7	85.7	85.7	14.3	75.5		
			42.9	100.0	42.9	100.0	71.4	100.0	42.9	71.4		
			14.3	100.0	71.4	100.0	42.9	71.4	28.6	61.2		
			14.3	100.0	57.1	100.0	28.6	71.4	42.9	59.2		
		70 F	28.6	100.0	42.9	71.4	71.4	100.0	42.9	65.3	59.2	87.8
			71.4	100.0	42.9	100.0	28.6	71.4	28.6	63.3		
			85.7	100.0	42.9	42.9	71.4	71.4	71.4	69.4		
			100.0	100.0	85.7	100.0	100.0	100.0	28.6	87.8		
			57.1	71.4	57.1	100.0	57.1	100.0	57.1	71.4		
			57.1	57.1	85.7	71.4	28.6	100.0	14.3	59.2		
	T2	0 F	85.7	42.9	85.7	42.9	100.0	42.9	85.7	69.4	65.3	69.4
			71.4	14.3	71.4	100.0	85.7	57.1	57.1	65.3		
		40 F	57.1	42.9	85.7	42.9	71.4	100.0	14.3	59.2	59.2	73.5
			71.4	14.3	71.4	100.0	85.7	85.7	85.7	73.5		
		70 F	57.1	14.3	85.7	85.7	85.7	85.7	100.0	73.5	71.4	73.5
			57.1	100.0	57.1	85.7	85.7	57.1	57.1	71.4		
	T3	0 F	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.0	100.0
			100.0	85.7	100.0	100.0	100.0	100.0	100.0	98.0		
		40 F	100.0	100.0	100.0	100.0	85.7	100.0	100.0	98.0	98.0	98.0
			100.0	85.7	100.0	100.0	100.0	100.0	100.0	98.0		
		70 F	100.0	42.9	100.0	71.4	71.4	100.0	100.0	83.7	73.5	83.7
			100.0	100.0	57.1	14.3	71.4	100.0	71.4	73.5		

Table 3.41: Effect of Reference Location for Mill 3, a = 5.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 5 For Mill 3									
			LOCATION							Mean	Min Mean	Max Mean
			1	2	3	4	5	6	7			
A 572	T1	0 F	100.0	85.7	14.3	28.6	57.1	85.7	85.7	65.3	65.3	65.3
		40 F	71.4	42.9	71.4	28.6	85.7	100.0	42.9	63.3	63.3	63.3
		70 F	100.0	100.0	100.0	85.7	28.6	100.0	100.0	87.8	87.8	87.8
	T2	0 F	57.1	71.4	71.4	100.0	100.0	28.6	28.6	65.3	65.3	65.3
			100.0	85.7	14.3	28.6	57.1	85.7	85.7	65.3		
		40 F	71.4	100.0	85.7	57.1	100.0	14.3	28.6	65.3	63.3	65.3
			71.4	42.9	71.4	28.6	85.7	100.0	42.9	63.3		
		70 F	57.1	85.7	85.7	85.7	100.0	14.3	71.4	71.4	71.4	87.8
			100.0	100.0	100.0	85.7	28.6	100.0	100.0	87.8		
	T3	0 F	14.3	85.7	42.9	71.4	42.9	100.0	57.1	59.2	59.2	63.3
			100.0	100.0	28.6	71.4	14.3	57.1	42.9	59.2		
			85.7	100.0	42.9	71.4	14.3	71.4	57.1	63.3		
		40 F	57.1	100.0	14.3	71.4	42.9	85.7	28.6	57.1	57.1	65.3
			85.7	100.0	42.9	71.4	42.9	57.1	14.3	59.2		
			100.0	85.7	42.9	42.9	57.1	57.1	71.4	65.3		
		70 F	14.3	85.7	85.7	100.0	28.6	85.7	42.9	63.3	59.2	77.6
			85.7	100.0	42.9	71.4	14.3	57.1	42.9	59.2		
			71.4	100.0	100.0	57.1	28.6	100.0	85.7	77.6		
A 588	T1	0 F	14.3	28.6	71.4	100.0	85.7	42.9	57.1	57.1	57.1	65.3
			14.3	57.1	71.4	100.0	100.0	42.9	71.4	65.3		
		40 F	28.6	42.9	100.0	85.7	57.1	14.3	85.7	59.2	57.1	59.2
			14.3	28.6	57.1	71.4	42.9	100.0	85.7	57.1		
		70 F	42.9	14.3	71.4	42.9	57.1	100.0	100.0	61.2	61.2	61.2
			14.3	28.6	100.0	100.0	57.1	71.4	57.1	61.2		
	T2	0 F	57.1	14.3	100.0	42.9	28.6	100.0	85.7	61.2	61.2	71.4
			85.7	85.7	28.6	14.3	100.0	85.7	100.0	71.4		
			85.7	100.0	57.1	71.4	57.1	42.9	57.1	67.3		
			85.7	100.0	42.9	71.4	14.3	71.4	57.1	63.3		
		40 F	85.7	57.1	14.3	42.9	85.7	42.9	100.0	61.2	59.2	77.6
			100.0	100.0	14.3	57.1	28.6	42.9	71.4	59.2		
			100.0	100.0	57.1	57.1	57.1	71.4	100.0	77.6		
			100.0	85.7	42.9	42.9	57.1	57.1	71.4	65.3		
		70 F	100.0	42.9	57.1	100.0	100.0	28.6	14.3	63.3	61.2	85.7
			85.7	100.0	42.9	57.1	71.4	14.3	57.1	61.2		
			14.3	100.0	85.7	100.0	100.0	100.0	100.0	85.7		
			71.4	100.0	100.0	57.1	28.6	100.0	85.7	77.6		
	T3	0 F	57.1	42.9	14.3	85.7	28.6	100.0	71.4	57.1	57.1	61.2
			57.1	85.7	28.6	100.0	28.6	71.4	57.1	61.2		
		40 F	71.4	85.7	14.3	100.0	42.9	42.9	71.4	61.2	57.1	61.2
			42.9	100.0	28.6	85.7	14.3	71.4	57.1	57.1		
		70 F	28.6	71.4	71.4	14.3	71.4	100.0	85.7	63.3	63.3	65.3
			14.3	85.7	71.4	85.7	71.4	100.0	28.6	65.3		
	T4	0 F	57.1	42.9	14.3	85.7	57.1	100.0	71.4	61.2	61.2	61.2
		40 F	14.3	85.7	28.6	100.0	57.1	57.1	71.4	59.2	59.2	59.2
		70 F	28.6	71.4	71.4	14.3	71.4	100.0	85.7	63.3	63.3	63.3

Table 3.42: Effect of Reference Location for Mill 3, a = 10.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 10 For Mill 3, LOCATION 1	2	3	4	5	6	7	Mean	Min Mean	Max Mean
A 572	T1	0 F	100.0	100.0	14.3	42.9	85.7	100.0	100.0	77.6	77.6	77.6
		40 F	71.4	71.4	85.7	42.9	100.0	100.0	57.1	75.5	75.5	75.5
		70 F	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	T2	0 F	71.4	71.4	71.4	100.0	100.0	42.9	28.6	69.4	69.4	77.6
			100.0	100.0	14.3	42.9	85.7	100.0	100.0	77.6		
		40 F	100.0	100.0	100.0	71.4	100.0	28.6	28.6	75.5	75.5	75.5
			71.4	71.4	85.7	42.9	100.0	100.0	57.1	75.5		
		70 F	85.7	100.0	85.7	85.7	100.0	14.3	85.7	79.6	79.6	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
	T3	0 F	14.3	85.7	42.9	85.7	57.1	100.0	71.4	65.3	65.3	73.5
			100.0	100.0	42.9	71.4	28.6	57.1	57.1	65.3		
			100.0	100.0	57.1	85.7	28.6	71.4	71.4	73.5		
		40 F	57.1	100.0	14.3	71.4	42.9	85.7	28.6	57.1	57.1	73.5
			100.0	100.0	42.9	71.4	42.9	57.1	14.3	61.2		
			100.0	100.0	57.1	57.1	57.1	71.4	71.4	73.5		
		70 F	28.6	85.7	85.7	100.0	28.6	85.7	71.4	69.4	63.3	95.9
			85.7	100.0	42.9	71.4	42.9	57.1	42.9	63.3		
			100.0	100.0	100.0	100.0	71.4	100.0	100.0	95.9		
A 588	T1	0 F	14.3	28.6	71.4	100.0	85.7	42.9	57.1	57.1	57.1	71.4
			14.3	71.4	71.4	100.0	100.0	71.4	71.4	71.4		
		40 F	28.6	42.9	100.0	85.7	57.1	28.6	85.7	61.2	59.2	61.2
			14.3	28.6	57.1	71.4	57.1	100.0	85.7	59.2		
		70 F	42.9	14.3	100.0	42.9	71.4	100.0	100.0	67.3	67.3	67.3
			28.6	28.6	100.0	100.0	71.4	71.4	71.4	67.3		
	T2	0 F	57.1	28.6	100.0	42.9	28.6	100.0	100.0	65.3	65.3	77.6
			100.0	100.0	28.6	14.3	100.0	100.0	100.0	77.6		
			100.0	100.0	71.4	71.4	71.4	57.1	71.4	77.6		
			100.0	100.0	57.1	85.7	28.6	71.4	71.4	73.5		
		40 F	85.7	57.1	28.6	42.9	85.7	42.9	100.0	63.3	63.3	91.8
			100.0	100.0	14.3	71.4	28.6	57.1	71.4	63.3		
			100.0	100.0	71.4	85.7	85.7	100.0	100.0	91.8		
			100.0	100.0	57.1	57.1	57.1	71.4	71.4	73.5		
		70 F	100.0	42.9	85.7	100.0	100.0	42.9	14.3	69.4	69.4	98.0
			85.7	100.0	57.1	57.1	71.4	42.9	71.4	69.4		
			85.7	100.0	100.0	100.0	100.0	100.0	100.0	98.0		
			100.0	100.0	100.0	100.0	71.4	100.0	100.0	95.9		
	T3	0 F	57.1	57.1	14.3	85.7	42.9	100.0	71.4	61.2	61.2	61.2
			57.1	85.7	28.6	100.0	28.6	71.4	57.1	61.2		
		40 F	71.4	85.7	42.9	100.0	42.9	42.9	71.4	65.3	63.3	65.3
			57.1	100.0	42.9	85.7	14.3	71.4	71.4	63.3		
		70 F	28.6	85.7	85.7	14.3	71.4	100.0	85.7	67.3	67.3	71.4
			28.6	85.7	85.7	85.7	85.7	100.0	28.6	71.4		
	T4	0 F	71.4	57.1	14.3	85.7	71.4	100.0	71.4	67.3	67.3	67.3
		40 F	14.3	85.7	57.1	100.0	57.1	57.1	71.4	63.3	63.3	63.3
		70 F	28.6	85.7	85.7	14.3	71.4	100.0	85.7	67.3	67.3	67.3

Table 3.43: Effect of Reference Location for Mill 3, a = 15.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 15 For Mill 3									
			LOCATION							Mean	Min Mean	Max Mean
			1	2	3	4	5	6	7			
A 572	T1	0 F	100.0	100.0	28.6	57.1	100.0	100.0	100.0	83.7	83.7	83.7
		40 F	85.7	71.4	85.7	71.4	100.0	100.0	71.4	83.7	83.7	83.7
		70 F	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	T2	0 F	71.4	71.4	71.4	100.0	100.0	57.1	57.1	75.5	75.5	83.7
			100.0	100.0	28.6	57.1	100.0	100.0	100.0	83.7		
		40 F	100.0	100.0	100.0	100.0	100.0	28.6	28.6	79.6	79.6	83.7
			85.7	71.4	85.7	71.4	100.0	100.0	71.4	83.7		
		70 F	85.7	100.0	100.0	100.0	100.0	42.9	85.7	87.8	87.8	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
	T3	0 F	42.9	85.7	57.1	85.7	57.1	100.0	71.4	71.4	67.3	83.7
			100.0	100.0	57.1	71.4	28.6	57.1	57.1	67.3		
			100.0	100.0	71.4	100.0	57.1	85.7	71.4	83.7		
		40 F	57.1	100.0	28.6	71.4	57.1	85.7	42.9	63.3	61.2	77.6
			100.0	100.0	42.9	71.4	42.9	57.1	14.3	61.2		
			100.0	100.0	71.4	57.1	71.4	71.4	71.4	77.6		
		70 F	28.6	85.7	85.7	100.0	28.6	85.7	85.7	71.4	65.3	100.0
			100.0	100.0	42.9	71.4	42.9	57.1	42.9	65.3		
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
A 588	T1	0 F	28.6	28.6	85.7	100.0	100.0	42.9	57.1	63.3	63.3	71.4
			14.3	71.4	71.4	100.0	100.0	71.4	71.4	71.4		
		40 F	42.9	42.9	100.0	85.7	57.1	28.6	85.7	63.3	59.2	63.3
			14.3	28.6	57.1	71.4	57.1	100.0	85.7	59.2		
		70 F	57.1	42.9	100.0	57.1	100.0	100.0	100.0	79.6	67.3	79.6
			28.6	28.6	100.0	100.0	71.4	71.4	71.4	67.3		
	T2	0 F	57.1	28.6	100.0	57.1	28.6	100.0	100.0	67.3	67.3	83.7
			100.0	100.0	28.6	14.3	100.0	100.0	100.0	77.6		
			100.0	100.0	71.4	71.4	71.4	71.4	71.4	79.6		
			100.0	100.0	71.4	100.0	57.1	85.7	71.4	83.7		
		40 F	100.0	57.1	42.9	42.9	100.0	57.1	100.0	71.4	65.3	100.0
			100.0	100.0	28.6	71.4	28.6	57.1	71.4	65.3		
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
			100.0	100.0	71.4	57.1	71.4	71.4	71.4	77.6		
		70 F	100.0	57.1	100.0	100.0	100.0	42.9	28.6	75.5	75.5	100.0
			85.7	100.0	71.4	71.4	71.4	57.1	71.4	75.5		
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
	T3	0 F	71.4	57.1	14.3	85.7	57.1	100.0	71.4	65.3	61.2	65.3
			57.1	85.7	28.6	100.0	28.6	71.4	57.1	61.2		
		40 F	71.4	85.7	42.9	100.0	42.9	42.9	71.4	65.3	65.3	67.3
			57.1	100.0	42.9	100.0	28.6	71.4	71.4	67.3		
		70 F	42.9	85.7	85.7	14.3	85.7	100.0	100.0	73.5	71.4	73.5
			28.6	85.7	85.7	85.7	85.7	100.0	28.6	71.4		
	T4	0 F	71.4	71.4	14.3	85.7	71.4	100.0	71.4	69.4	69.4	69.4
		40 F	14.3	85.7	57.1	100.0	57.1	57.1	71.4	63.3	63.3	63.3
		70 F	42.9	85.7	85.7	14.3	85.7	100.0	100.0	73.5	73.5	73.5

Table 3.44: Effect of Reference Location for Mill 4, a = 5.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 5 For Mill 4									
			LOCATION							Mean	Min Mean	Max Mean
			1	2	3	4	5	6	7			
A 572	T1	0 F	100.0	100.0	28.6	71.4	14.3	71.4	71.4	65.3	61.2	79.6
			71.4	14.3	85.7	57.1	100.0	57.1	42.9	61.2		
			100.0	100.0	100.0	42.9	100.0	85.7	28.6	79.6		
			57.1	71.4	85.7	100.0	14.3	71.4	28.6	61.2		
		40 F	100.0	100.0	28.6	100.0	14.3	100.0	71.4	73.5	63.3	73.5
			71.4	71.4	71.4	100.0	14.3	71.4	100.0	71.4		
			100.0	85.7	14.3	42.9	42.9	85.7	85.7	65.3		
			42.9	100.0	71.4	100.0	14.3	71.4	42.9	63.3		
		70 F	100.0	85.7	28.6	57.1	14.3	71.4	57.1	59.2	59.2	69.4
			71.4	100.0	28.6	28.6	85.7	85.7	85.7	69.4		
			100.0	85.7	14.3	42.9	42.9	71.4	71.4	61.2		
			57.1	100.0	42.9	57.1	14.3	100.0	71.4	63.3		
	T2	0 F	14.3	42.9	100.0	100.0	71.4	71.4	57.1	65.3	63.3	73.5
			28.6	85.7	57.1	100.0	100.0	57.1	28.6	65.3		
			71.4	100.0	71.4	42.9	100.0	14.3	42.9	63.3		
			71.4	71.4	100.0	71.4	71.4	28.6	100.0	73.5		
		40 F	28.6	85.7	85.7	85.7	100.0	85.7	28.6	71.4	65.3	71.4
			42.9	71.4	85.7	100.0	85.7	14.3	57.1	65.3		
			71.4	100.0	85.7	71.4	100.0	28.6	42.9	71.4		
			57.1	85.7	85.7	100.0	57.1	57.1	57.1	71.4		
		70 F	42.9	42.9	100.0	85.7	85.7	71.4	42.9	67.3	65.3	73.5
			42.9	85.7	71.4	100.0	100.0	42.9	42.9	69.4		
			100.0	85.7	100.0	85.7	100.0	14.3	28.6	73.5		
			42.9	42.9	85.7	28.6	71.4	85.7	100.0	65.3		
A 588	T1	0 F	100.0	100.0	71.4	71.4	71.4	28.6	28.6	67.3	63.3	75.5
			100.0	85.7	28.6	57.1	85.7	57.1	28.6	63.3		
			42.9	100.0	42.9	85.7	57.1	57.1	71.4	65.3		
			85.7	100.0	14.3	28.6	100.0	100.0	100.0	75.5		
		40 F	100.0	71.4	42.9	42.9	71.4	85.7	42.9	65.3	59.2	65.3
			100.0	85.7	14.3	42.9	71.4	57.1	42.9	59.2		
			42.9	100.0	71.4	85.7	71.4	14.3	42.9	61.2		
			57.1	85.7	42.9	14.3	28.6	100.0	100.0	61.2		
		70 F	100.0	71.4	42.9	57.1	28.6	28.6	85.7	59.2	59.2	67.3
			100.0	71.4	28.6	28.6	85.7	42.9	71.4	61.2		
			100.0	100.0	14.3	57.1	100.0	42.9	57.1	67.3		
			85.7	85.7	42.9	28.6	28.6	100.0	85.7	65.3		
	T2	0 F	85.7	71.4	71.4	14.3	100.0	28.6	71.4	63.3	59.2	63.3
			71.4	100.0	14.3	28.6	71.4	85.7	42.9	59.2		
			42.9	100.0	100.0	28.6	71.4	14.3	71.4	61.2		
			28.6	42.9	100.0	85.7	71.4	28.6	57.1	59.2		
		40 F	100.0	28.6	42.9	71.4	85.7	71.4	71.4	67.3	65.3	81.6
			42.9	100.0	100.0	14.3	100.0	42.9	85.7	69.4		
			100.0	100.0	100.0	100.0	42.9	28.6	100.0	81.6		
			42.9	85.7	85.7	100.0	85.7	42.9	14.3	65.3		
		70 F	85.7	57.1	28.6	57.1	100.0	57.1	71.4	65.3	65.3	93.9
			100.0	57.1	100.0	14.3	57.1	57.1	100.0	69.4		
			100.0	85.7	100.0	100.0	100.0	71.4	100.0	93.9		
			85.7	71.4	28.6	71.4	100.0	14.3	100.0	67.3		

Table 3.45: Effect of Reference Location for Mill 4, *a* = 10.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 10 For Mill 4									
			LOCATION							Mean	Min Mean	Max Mean
			1	2	3	4	5	6	7			
A 572	T1	0 F	100.0	100.0	28.6	71.4	14.3	71.4	71.4	65.3	65.3	95.9
			85.7	14.3	85.7	71.4	100.0	57.1	57.1	67.3		
			100.0	100.0	100.0	100.0	100.0	100.0	71.4	95.9		
			71.4	71.4	85.7	100.0	28.6	71.4	42.9	67.3		
		40 F	100.0	100.0	28.6	100.0	28.6	100.0	100.0	79.6	65.3	81.6
			71.4	71.4	85.7	100.0	71.4	71.4	100.0	81.6		
			100.0	85.7	14.3	42.9	42.9	85.7	85.7	65.3		
			42.9	100.0	100.0	100.0	14.3	100.0	42.9	71.4		
		70 F	100.0	85.7	28.6	57.1	28.6	71.4	57.1	61.2	61.2	75.5
			85.7	100.0	57.1	28.6	85.7	85.7	85.7	75.5		
			100.0	100.0	28.6	42.9	42.9	85.7	85.7	69.4		
			71.4	100.0	57.1	57.1	14.3	100.0	71.4	67.3		
	T2	0 F	14.3	71.4	100.0	100.0	85.7	85.7	71.4	75.5	73.5	85.7
			57.1	100.0	57.1	100.0	100.0	57.1	42.9	73.5		
			71.4	100.0	85.7	71.4	100.0	14.3	71.4	73.5		
			71.4	85.7	100.0	85.7	85.7	71.4	100.0	85.7		
		40 F	28.6	100.0	100.0	85.7	100.0	100.0	28.6	77.6	75.5	89.8
			71.4	85.7	85.7	100.0	85.7	42.9	85.7	79.6		
			85.7	100.0	100.0	100.0	100.0	71.4	71.4	89.8		
			57.1	100.0	100.0	100.0	57.1	57.1	57.1	75.5		
		70 F	57.1	42.9	100.0	100.0	100.0	85.7	57.1	77.6	73.5	81.6
			57.1	100.0	100.0	100.0	100.0	71.4	42.9	81.6		
			100.0	100.0	100.0	100.0	100.0	14.3	28.6	77.6		
			57.1	57.1	85.7	42.9	85.7	85.7	100.0	73.5		
A 588	T1	0 F	100.0	100.0	71.4	71.4	71.4	28.6	28.6	67.3	65.3	79.6
			100.0	100.0	28.6	57.1	85.7	57.1	28.6	65.3		
			57.1	100.0	57.1	85.7	57.1	57.1	71.4	69.4		
			100.0	100.0	14.3	42.9	100.0	100.0	100.0	79.6		
		40 F	100.0	71.4	42.9	42.9	71.4	85.7	42.9	65.3	63.3	73.5
			100.0	85.7	28.6	42.9	85.7	57.1	42.9	63.3		
			71.4	100.0	71.4	85.7	71.4	42.9	71.4	73.5		
			71.4	100.0	42.9	28.6	42.9	100.0	100.0	69.4		
		70 F	100.0	85.7	42.9	57.1	28.6	28.6	85.7	61.2	61.2	75.5
			100.0	71.4	42.9	42.9	85.7	42.9	71.4	65.3		
			100.0	100.0	14.3	100.0	100.0	57.1	57.1	75.5		
			85.7	85.7	42.9	28.6	42.9	100.0	85.7	67.3		
	T2	0 F	85.7	71.4	71.4	14.3	100.0	28.6	71.4	63.3	61.2	77.6
			71.4	100.0	14.3	42.9	71.4	100.0	42.9	63.3		
			71.4	100.0	100.0	42.9	100.0	28.6	100.0	77.6		
			28.6	42.9	100.0	100.0	71.4	28.6	57.1	61.2		
		40 F	100.0	42.9	71.4	71.4	85.7	71.4	71.4	73.5	69.4	95.9
			42.9	100.0	100.0	42.9	100.0	42.9	100.0	75.5		
			100.0	100.0	100.0	100.0	100.0	71.4	100.0	95.9		
			71.4	85.7	85.7	100.0	85.7	42.9	14.3	69.4		
		70 F	85.7	57.1	57.1	71.4	100.0	71.4	71.4	73.5	73.5	100.0
			100.0	100.0	100.0	14.3	100.0	100.0	100.0	87.8		
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
			100.0	100.0	71.4	100.0	100.0	14.3	100.0	83.7		

Table 3.46: Effect of Reference Location for Mill 4, a = 15.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 15 For Mill 4									
			LOCATION							Mean	Min Mean	Max Mean
			1	2	3	4	5	6	7			
A 572	T1	0 F	100.0	100.0	28.6	71.4	14.3	71.4	71.4	65.3	65.3	100.0
			85.7	28.6	85.7	85.7	100.0	71.4	71.4	75.5		
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
			71.4	71.4	100.0	100.0	28.6	71.4	57.1	71.4		
		40 F	100.0	100.0	28.6	100.0	28.6	100.0	100.0	79.6	77.6	91.8
			100.0	85.7	100.0	100.0	71.4	85.7	100.0	91.8		
			100.0	100.0	42.9	85.7	85.7	100.0	85.7	85.7		
			42.9	100.0	100.0	100.0	42.9	100.0	57.1	77.6		
		70 F	100.0	85.7	28.6	71.4	28.6	85.7	71.4	67.3	67.3	85.7
			85.7	100.0	85.7	71.4	85.7	85.7	85.7	85.7		
			100.0	100.0	42.9	42.9	42.9	100.0	100.0	75.5		
			71.4	100.0	57.1	71.4	14.3	100.0	85.7	71.4		
	T2	0 F	42.9	71.4	100.0	100.0	100.0	100.0	85.7	85.7	77.6	93.9
			57.1	100.0	71.4	100.0	100.0	57.1	57.1	77.6		
			85.7	100.0	100.0	71.4	100.0	14.3	71.4	77.6		
			85.7	100.0	100.0	100.0	100.0	71.4	100.0	93.9		
		40 F	28.6	100.0	100.0	100.0	100.0	100.0	28.6	79.6	79.6	95.9
			85.7	85.7	100.0	100.0	85.7	71.4	85.7	87.8		
			100.0	100.0	100.0	100.0	100.0	85.7	85.7	95.9		
			85.7	100.0	100.0	100.0	85.7	85.7	85.7	91.8		
		70 F	85.7	57.1	100.0	100.0	100.0	100.0	71.4	87.8	79.6	91.8
			85.7	100.0	100.0	100.0	100.0	85.7	71.4	91.8		
			100.0	100.0	100.0	100.0	100.0	28.6	28.6	79.6		
			71.4	85.7	100.0	57.1	85.7	100.0	100.0	85.7		
A 588	T1	0 F	100.0	100.0	71.4	71.4	71.4	28.6	28.6	67.3	67.3	87.8
			100.0	100.0	28.6	57.1	100.0	57.1	28.6	67.3		
			57.1	100.0	57.1	100.0	71.4	57.1	71.4	73.5		
			100.0	100.0	14.3	100.0	100.0	100.0	100.0	87.8		
		40 F	100.0	71.4	42.9	42.9	71.4	85.7	42.9	65.3	65.3	75.5
			100.0	100.0	42.9	42.9	85.7	57.1	42.9	67.3		
			71.4	100.0	71.4	85.7	71.4	57.1	71.4	75.5		
			100.0	100.0	42.9	42.9	42.9	100.0	100.0	75.5		
		70 F	100.0	85.7	57.1	71.4	28.6	42.9	85.7	67.3	67.3	87.8
			100.0	85.7	42.9	42.9	85.7	42.9	85.7	69.4		
			100.0	100.0	14.3	100.0	100.0	100.0	100.0	87.8		
			85.7	100.0	42.9	42.9	42.9	100.0	100.0	73.5		
	T2	0 F	85.7	71.4	71.4	28.6	100.0	28.6	71.4	65.3	63.3	87.8
			71.4	100.0	28.6	42.9	71.4	100.0	71.4	69.4		
			100.0	100.0	100.0	71.4	100.0	42.9	100.0	87.8		
			28.6	42.9	100.0	100.0	71.4	42.9	57.1	63.3		
		40 F	100.0	71.4	71.4	71.4	85.7	71.4	71.4	77.6	77.6	100.0
			57.1	100.0	100.0	42.9	100.0	57.1	100.0	79.6		
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
			85.7	85.7	85.7	100.0	85.7	85.7	42.9	81.6		
		70 F	85.7	71.4	71.4	71.4	100.0	71.4	71.4	77.6	77.6	100.0
			100.0	100.0	100.0	14.3	100.0	100.0	100.0	87.8		
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
			100.0	100.0	100.0	100.0	100.0	14.3	100.0	87.8		

Table 3.47: Effect of Reference Location for Mill 5, a = 5.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 5 For Mill 5									
			LOCATION							Mean	Min Mean	Max Mean
			1	2	3	4	5	6	7			
A 572	T1	0 F	100.0	71.4	100.0	28.6	71.4	14.3	42.9	61.2	61.2	69.4
			42.9	14.3	71.4	85.7	71.4	100.0	100.0	69.4		
		40 F	85.7	100.0	85.7	28.6	71.4	14.3	71.4	65.3	65.3	69.4
			85.7	85.7	100.0	85.7	71.4	28.6	28.6	69.4		
		70 F	71.4	85.7	85.7	42.9	57.1	14.3	100.0	65.3	65.3	73.5
			71.4	14.3	71.4	100.0	100.0	57.1	100.0	73.5		
	T2	0 F	85.7	100.0	100.0	57.1	85.7	14.3	28.6	67.3	67.3	77.6
			71.4	42.9	100.0	100.0	28.6	100.0	100.0	77.6		
		40 F	71.4	71.4	85.7	14.3	71.4	71.4	100.0	69.4	63.3	69.4
			85.7	14.3	71.4	100.0	42.9	42.9	85.7	63.3		
		70 F	100.0	71.4	71.4	100.0	42.9	14.3	28.6	61.2	61.2	61.2
			57.1	28.6	100.0	71.4	28.6	57.1	85.7	61.2		
	T3	0 F	71.4	42.9	28.6	71.4	100.0	85.7	42.9	63.3	63.3	73.5
			100.0	100.0	85.7	57.1	57.1	71.4	42.9	73.5		
		40 F	100.0	28.6	57.1	57.1	14.3	85.7	100.0	63.3	63.3	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
		70 F	100.0	100.0	71.4	57.1	14.3	71.4	71.4	69.4	67.3	69.4
			85.7	71.4	71.4	14.3	57.1	100.0	71.4	67.3		
	T4	0 F	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	77.6	100.0
			85.7	100.0	57.1	100.0	85.7	100.0	14.3	77.6		
		40 F	100.0	100.0	100.0	100.0	100.0	14.3	100.0	87.8	75.5	87.8
			100.0	100.0	28.6	100.0	100.0	28.6	71.4	75.5		
		70 F	100.0	100.0	100.0	100.0	100.0	57.1	100.0	93.9	71.4	93.9
			42.9	100.0	100.0	100.0	14.3	100.0	42.9	71.4		
A 588	T1	0 F	28.6	71.4	85.7	100.0	42.9	57.1	14.3	57.1	57.1	71.4
			28.6	100.0	57.1	71.4	85.7	71.4	85.7	71.4		
			28.6	57.1	28.6	57.1	71.4	85.7	100.0	61.2		
		40 F	71.4	28.6	85.7	100.0	71.4	71.4	14.3	63.3	59.2	63.3
			42.9	100.0	14.3	42.9	57.1	71.4	85.7	59.2		
			14.3	42.9	100.0	85.7	71.4	57.1	42.9	59.2		
		70 F	28.6	57.1	85.7	100.0	57.1	85.7	14.3	61.2	59.2	61.2
			14.3	71.4	42.9	28.6	71.4	100.0	85.7	59.2		
			14.3	57.1	100.0	71.4	100.0	42.9	42.9	61.2		
	T2	0 F	14.3	100.0	57.1	85.7	42.9	57.1	85.7	63.3	63.3	63.3
			28.6	100.0	85.7	57.1	28.6	85.7	57.1	63.3		
			71.4	57.1	57.1	14.3	42.9	100.0	100.0	63.3		
		40 F	28.6	14.3	100.0	85.7	71.4	71.4	85.7	65.3	61.2	65.3
			100.0	85.7	71.4	71.4	14.3	42.9	42.9	61.2		
			85.7	100.0	85.7	71.4	14.3	28.6	71.4	65.3		
		70 F	28.6	28.6	100.0	71.4	42.9	57.1	100.0	61.2	61.2	69.4
			85.7	100.0	42.9	42.9	14.3	57.1	100.0	63.3		
			100.0	100.0	71.4	42.9	71.4	42.9	57.1	69.4		
	T3	0 F	14.3	42.9	85.7	71.4	100.0	85.7	42.9	63.3	61.2	63.3
			85.7	100.0	28.6	42.9	14.3	100.0	57.1	61.2		
			42.9	57.1	85.7	14.3	85.7	100.0	42.9	61.2		
		40 F	71.4	28.6	71.4	57.1	100.0	85.7	42.9	65.3	63.3	75.5
			57.1	100.0	57.1	57.1	71.4	14.3	85.7	63.3		
			85.7	85.7	100.0	71.4	57.1	57.1	71.4	75.5		
		70 F	14.3	28.6	85.7	100.0	100.0	42.9	57.1	61.2	61.2	69.4
			100.0	100.0	42.9	42.9	14.3	85.7	100.0	69.4		
			42.9	57.1	100.0	100.0	71.4	42.9	28.6	63.3		
	T4	0 F	57.1	85.7	85.7	85.7	57.1	57.1	85.7	73.5	73.5	73.5
		40 F	71.4	85.7	71.4	71.4	71.4	71.4	71.4	73.5	73.5	73.5
		70 F	42.9	28.6	28.6	14.3	42.9	14.3	57.1	32.7	32.7	32.7

Table 3.48: Effect of Reference Location for Mill 5, a = 10.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 10 For Mill 5									
			LOCATION							Mean	Min Mean	Max Mean
			1	2	3	4	5	6	7			
A 572	T1	0 F	100.0	71.4	100.0	28.6	71.4	14.3	71.4	65.3	65.3	85.7
			71.4	42.9	100.0	100.0	85.7	100.0	100.0	85.7		
		40 F	85.7	100.0	85.7	28.6	85.7	14.3	85.7	69.4	69.4	79.6
			100.0	100.0	100.0	100.0	85.7	42.9	28.6	79.6		
		70 F	85.7	85.7	85.7	71.4	85.7	14.3	100.0	75.5	75.5	93.9
			100.0	57.1	100.0	100.0	100.0	100.0	100.0	93.9		
	T2	0 F	100.0	100.0	100.0	85.7	100.0	14.3	57.1	79.6	79.6	95.9
			100.0	100.0	100.0	100.0	71.4	100.0	100.0	95.9		
		40 F	85.7	85.7	85.7	71.4	85.7	85.7	100.0	85.7	71.4	85.7
			100.0	28.6	85.7	100.0	42.9	42.9	100.0	71.4		
		70 F	100.0	71.4	71.4	100.0	42.9	14.3	42.9	63.3	63.3	71.4
			57.1	57.1	100.0	85.7	57.1	57.1	85.7	71.4		
	T3	0 F	71.4	42.9	42.9	71.4	100.0	100.0	42.9	67.3	67.3	87.8
			100.0	100.0	100.0	71.4	71.4	100.0	71.4	87.8		
		40 F	100.0	28.6	57.1	71.4	14.3	100.0	100.0	67.3	67.3	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
		70 F	100.0	100.0	100.0	71.4	14.3	85.7	100.0	81.6	77.6	81.6
			100.0	85.7	85.7	14.3	71.4	100.0	85.7	77.6		
	T4	0 F	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	89.8	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	28.6	89.8		
		40 F	100.0	100.0	100.0	100.0	100.0	85.7	100.0	98.0	83.7	98.0
			100.0	100.0	42.9	100.0	100.0	42.9	100.0	83.7		
		70 F	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	71.4	100.0
			42.9	100.0	100.0	100.0	14.3	100.0	42.9	71.4		
A 588	T1	0 F	28.6	85.7	100.0	100.0	57.1	57.1	14.3	63.3	63.3	87.8
			71.4	100.0	85.7	85.7	100.0	85.7	85.7	87.8		
			28.6	57.1	28.6	57.1	85.7	85.7	100.0	63.3		
		40 F	71.4	28.6	85.7	100.0	85.7	85.7	14.3	67.3	61.2	67.3
			57.1	100.0	14.3	57.1	57.1	85.7	100.0	67.3		
			14.3	42.9	100.0	100.0	71.4	57.1	42.9	61.2		
		70 F	28.6	57.1	85.7	100.0	57.1	85.7	14.3	61.2	61.2	69.4
			28.6	85.7	71.4	28.6	85.7	100.0	85.7	69.4		
			14.3	57.1	100.0	100.0	100.0	57.1	42.9	67.3		
	T2	0 F	28.6	100.0	57.1	85.7	57.1	57.1	85.7	67.3	67.3	71.4
			28.6	100.0	85.7	85.7	28.6	85.7	85.7	71.4		
			85.7	57.1	57.1	14.3	57.1	100.0	100.0	67.3		
		40 F	28.6	28.6	100.0	85.7	85.7	85.7	85.7	71.4	65.3	71.4
			100.0	85.7	71.4	71.4	14.3	57.1	57.1	65.3		
			85.7	100.0	85.7	85.7	28.6	28.6	85.7	71.4		
		70 F	28.6	28.6	100.0	85.7	57.1	71.4	100.0	67.3	67.3	77.6
			100.0	100.0	57.1	57.1	14.3	57.1	100.0	69.4		
			100.0	100.0	71.4	57.1	71.4	71.4	71.4	77.6		
	T3	0 F	14.3	57.1	100.0	85.7	100.0	100.0	57.1	73.5	67.3	73.5
			100.0	100.0	28.6	57.1	28.6	100.0	57.1	67.3		
			57.1	85.7	85.7	14.3	85.7	100.0	57.1	69.4		
		40 F	71.4	42.9	71.4	71.4	100.0	100.0	71.4	75.5	75.5	89.8
			71.4	100.0	71.4	71.4	71.4	57.1	85.7	75.5		
			100.0	100.0	100.0	85.7	71.4	85.7	85.7	89.8		
		70 F	14.3	42.9	100.0	100.0	100.0	57.1	57.1	67.3	67.3	73.5
			100.0	100.0	42.9	57.1	14.3	100.0	100.0	73.5		
			57.1	57.1	100.0	100.0	100.0	57.1	42.9	73.5		
	T4	0 F	85.7	100.0	100.0	100.0	85.7	85.7	100.0	93.9	93.9	93.9
		40 F	71.4	100.0	85.7	85.7	71.4	71.4	71.4	79.6	79.6	79.6
		70 F	42.9	42.9	28.6	14.3	57.1	28.6	57.1	38.8	38.8	38.8

Table 3.49: Effect of Reference Location for Mill 5, a = 15.

Grade	Thickness Group	Test Temperature	Percent Greater Than Eref - 15 For Mill 5 — LOCATION 1	2	3	4	5	6	7	Mean	Min Mean	Max Mean
A 572	T1	0 F	100.0	100.0	100.0	42.9	100.0	28.6	71.4	77.6	77.6	95.9
			100.0	71.4	100.0	100.0	100.0	100.0	100.0	95.9		
		40 F	85.7	100.0	85.7	57.1	85.7	14.3	85.7	73.5	73.5	93.9
			100.0	100.0	100.0	100.0	100.0	85.7	71.4	93.9		
		70 F	85.7	85.7	85.7	85.7	85.7	14.3	100.0	77.6	77.6	98.0
			100.0	85.7	100.0	100.0	100.0	100.0	100.0	98.0		
	T2	0 F	100.0	100.0	100.0	100.0	100.0	14.3	85.7	85.7	85.7	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
		40 F	85.7	85.7	100.0	71.4	85.7	85.7	100.0	87.8	75.5	87.8
			100.0	42.9	100.0	100.0	42.9	42.9	100.0	75.5		
		70 F	100.0	71.4	71.4	100.0	42.9	14.3	42.9	63.3	63.3	77.6
			71.4	57.1	100.0	85.7	57.1	71.4	100.0	77.6		
	T3	0 F	71.4	42.9	42.9	71.4	100.0	100.0	42.9	67.3	67.3	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
		40 F	100.0	28.6	85.7	100.0	28.6	100.0	100.0	77.6	77.6	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
		70 F	100.0	100.0	100.0	100.0	14.3	100.0	100.0	87.8	87.8	87.8
			100.0	85.7	100.0	57.1	85.7	100.0	85.7	87.8		
	T4	0 F	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	93.9	100.0
			100.0	100.0	100.0	100.0	100.0	100.0	57.1	93.9		
		40 F	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	95.9	100.0
			100.0	100.0	100.0	100.0	100.0	71.4	100.0	95.9		
		70 F	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	77.6	100.0
			71.4	100.0	100.0	100.0	14.3	100.0	57.1	77.6		
A 588	T1	0 F	28.6	100.0	100.0	100.0	57.1	71.4	28.6	69.4	63.3	93.9
			85.7	100.0	85.7	85.7	100.0	100.0	100.0	93.9		
			28.6	57.1	28.6	57.1	85.7	85.7	100.0	63.3		
		40 F	85.7	28.6	85.7	100.0	85.7	85.7	14.3	69.4	65.3	69.4
			57.1	100.0	14.3	57.1	57.1	100.0	100.0	69.4		
			14.3	42.9	100.0	100.0	85.7	57.1	57.1	65.3		
		70 F	57.1	57.1	85.7	100.0	57.1	85.7	14.3	65.3	65.3	71.4
			28.6	85.7	85.7	28.6	85.7	100.0	85.7	71.4		
			14.3	57.1	100.0	100.0	100.0	57.1	57.1	69.4		
	T2	0 F	57.1	100.0	57.1	100.0	57.1	57.1	85.7	73.5	71.4	73.5
			28.6	100.0	85.7	85.7	28.6	85.7	85.7	71.4		
			100.0	71.4	71.4	14.3	57.1	100.0	100.0	73.5		
		40 F	28.6	28.6	100.0	85.7	85.7	85.7	85.7	71.4	71.4	77.6
			100.0	100.0	71.4	85.7	14.3	71.4	71.4	73.5		
			100.0	100.0	85.7	85.7	28.6	57.1	85.7	77.6		
		70 F	42.9	28.6	100.0	100.0	71.4	71.4	100.0	73.5	73.5	79.6
			100.0	100.0	57.1	57.1	14.3	85.7	100.0	73.5		
			100.0	100.0	71.4	71.4	71.4	71.4	71.4	79.6		
	T3	0 F	14.3	85.7	100.0	100.0	100.0	100.0	85.7	83.7	69.4	85.7
			100.0	100.0	42.9	57.1	28.6	100.0	57.1	69.4		
			85.7	85.7	100.0	42.9	100.0	100.0	85.7	85.7		
		40 F	71.4	71.4	71.4	71.4	100.0	100.0	71.4	79.6	79.6	98.0
			71.4	100.0	71.4	71.4	85.7	71.4	85.7	79.6		
			100.0	100.0	100.0	100.0	85.7	100.0	100.0	98.0		
		70 F	14.3	57.1	100.0	100.0	100.0	57.1	57.1	69.4	69.4	89.8
			100.0	100.0	85.7	100.0	42.9	100.0	100.0	89.8		
			57.1	71.4	100.0	100.0	100.0	57.1	57.1	77.6		
	T4	0 F	85.7	100.0	100.0	100.0	100.0	85.7	100.0	95.9	95.9	95.9
		40 F	85.7	100.0	100.0	85.7	71.4	71.4	71.4	83.7	83.7	83.7
		70 F	57.1	42.9	42.9	14.3	57.1	42.9	57.1	44.9	44.9	44.9

3.6.3.1 REFERENCE LOCATION EFFECT AS A FUNCTION OF TOUGHNESS

Results from the study of the effect of selecting a reference location in the use of Charpy V-notch test results for individual mills in the 4-mill group were presented in Tables 3.38 to 3.49.

The results from the four mills were combined and then grouped by (i) steel grade; (ii) thickness range; and (iii) toughness in order to determine overall statistical summaries based on the CVN test data and to examine the role of reference location selection. For each steel grade and thickness group, plates were divided into "Lower Toughness" and "Higher Toughness" groups depending on whether or not the absorbed energy value was below 50 ft-lbs. The lower toughness plates, thus, had absorbed energy below 50 ft-lbs in at least one location while the higher toughness plates had absorbed energy equal to or greater than 50 ft-lbs in all seven locations. The purpose of this separate analysis was to concentrate on the results from the group of plates that might be critical in actual use, namely, the lower toughness plates. The higher toughness plates were considered to be non-critical since their very high toughness (or absorbed energy) values greatly exceeded any requirements that might be made of them. It was thought to be interesting to see if similar conclusions related to reference location may be made for lower toughness plates as for the higher toughness plates.

Figure 3.18 presents the distribution of plates by toughness. It should be noted that the number of plates shown corresponds to plates at three test temperatures; hence, the number of plates is three times the actual number of plates presented in Figure 3.7. It may be observed from Figure 3.18 that a larger fraction of the plates were in the higher toughness category, especially for the A588 steel where, for example, the group A588-T2 had only two plates of "lower toughness." Our study, again, is focused on the determining if different conclusions about the CVN test results are reached for the lower toughness plates than for the higher toughness plates.

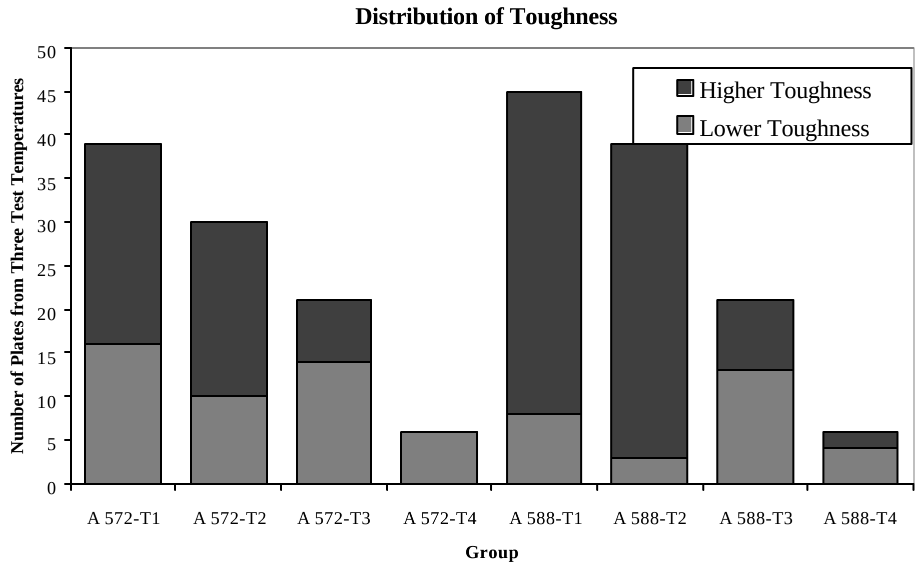


Figure 3.18: Distribution of Plates by Toughness.

The range of mean values for the percentage of plates that had absorbed energy greater than $E_{ref}–\alpha$ is presented in Figures 3.19 and 3.20 for A572 and A588 steels, respectively. The figures show the range of mean values for two cases: lower toughness plates and higher toughness plates, for three values of α (5, 10, and 15 ft-lbs), and for three test temperatures: 0°F, 40°F and 70°F. Also, indicated on the figures is the number of mean values in the two toughness groups.

By way of illustration, Figure 3.19 for the 0°F test temperature suggests that from the 22 lower toughness plates gathered from all four mills, it was found that the probability that the three-test-averaged absorbed energy might exceed E_{ref}–5 (ft-lbs) varies from 59.2% to 100%. For E_{ref}–10 (ft-lbs), this probability range varies from 65.3% to 100%, and for E_{ref}–15 (ft-lbs), this probability range varies from 67.3% to 100%. In contrast, for the higher toughness plates, the probability range for E_{ref}–5 (ft-lbs) varies from 61.2% to 79.6%; for E_{ref}–10 (ft-lbs), it varies from 65.3% to 95.9%; and for E_{ref}–15 (ft-lbs), it varies from 65.3% to 100%.

Studying all the results, it is seen that the range of probabilities that a three-test-averaged absorbed energy might exceed $E_{ref}–\alpha$ (for α equal to 5, 10, or 15 ft-lbs) seems to vary from 55% to 100% for higher toughness plates and 57% to 100% for lower toughness plates. Hence, in general, no significant difference was noted in the results from lower toughness plates and higher toughness plates.

With reference to Figures 3.19 and 3.20, in the vertical lines displaying the data, only when the bottom (or top) circles for the lower toughness plates are significantly lower than the corresponding bottom (or top) horizontal dashes for the higher toughness plates, might there be any concern related to the lower toughness plates. Studying Figures 3.19 and 3.20, again, it might be concluded that, for the cases studied, there are no major differences between the lower and higher toughness plates based on the CVN test data, except perhaps for A588 steel at 70°F but this might be due to insufficient data for the lower toughness plates (only four mean values were available there).

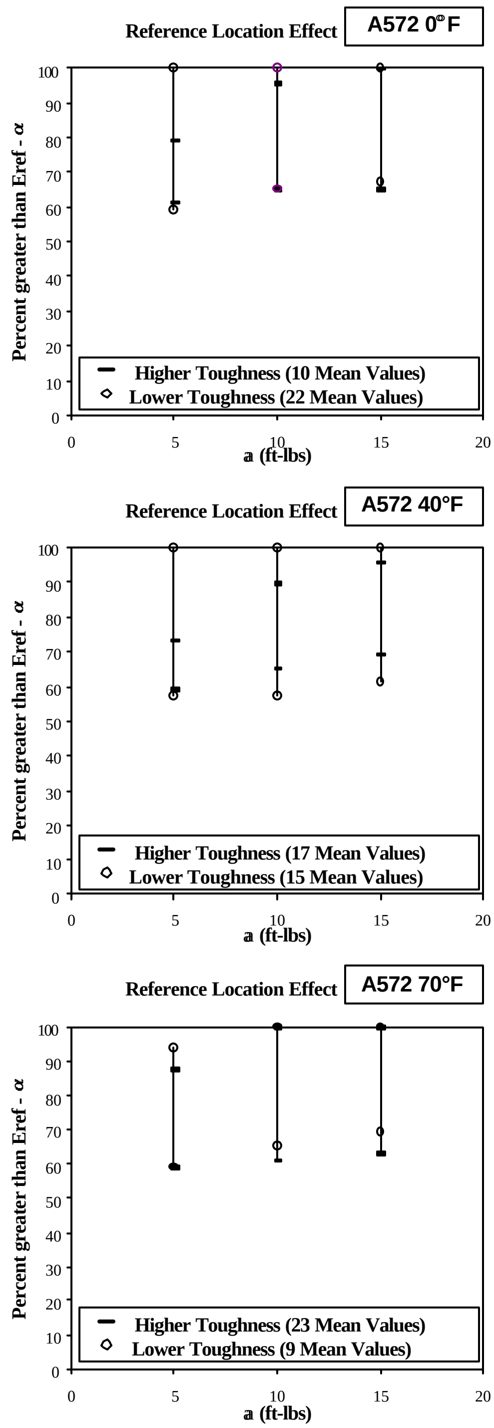


Figure 3.19: Reference Location Effect for A572 Steel as a Function of Toughness (Data from the 4-Mill Group).

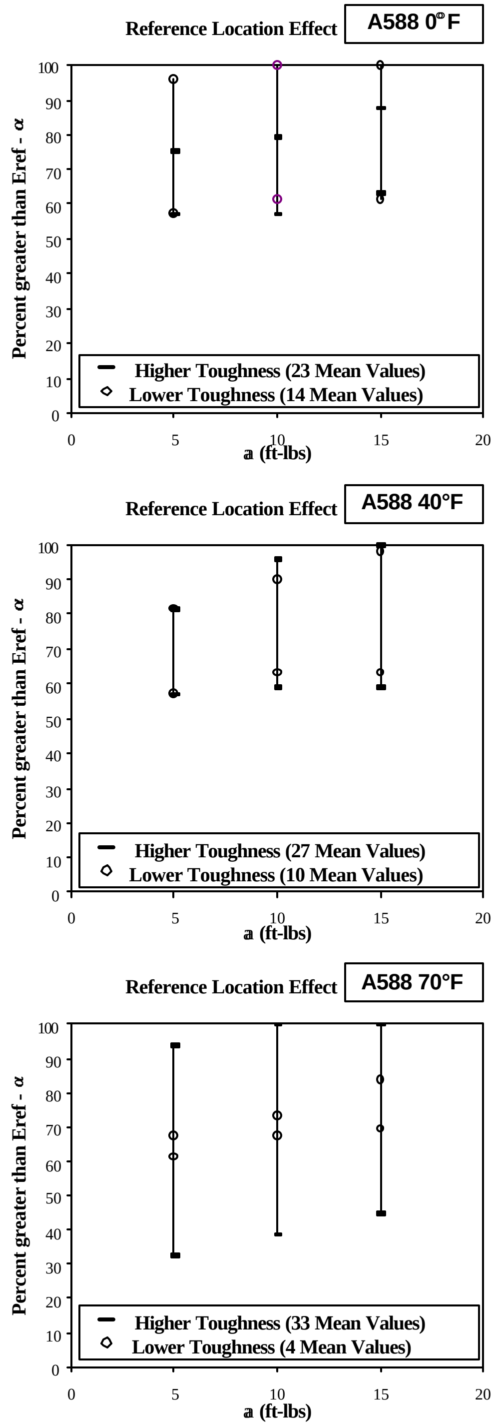


Figure 3.20: Reference Location Effect for A588 Steel as a Function of Toughness (Data from the 4-Mill Group).

3.6.4 CORRELATION BETWEEN ABSORBED ENERGY AND LATERAL EXPANSION

Statistical correlation between absorbed energy and lateral expansion obtained from CVN tests was studied and is described graphically in Figures 3.21, 3.22, and 3.23 for the test temperatures of 0°F, 40°F, and 70°F, respectively. In each figure, the data from all mills in the 4-mill group are shown along with two least-squares regression lines, one using the data where absorbed energy was below 100 ft-lbs, and the other where the absorbed energy was above 150 ft-lbs. The correlation coefficient between absorbed energy and lateral expansion is also indicated for the two portions separately. It should be noted that the number of data in each plot is not the same due to the missing lateral expansion data from some tests.

From Figures 3.21 to 3.23, it may be observed that absorbed energy shows strong positive correlation with lateral expansion for absorbed energy levels below 100 ft-lbs, with correlation coefficients varying from 0.935 at 70°F to 0.959 at 0°F. The regression lines are, expectedly, good fits to the data in this range.

In contrast, no significant correlation was found between absorbed energy and lateral expansion for absorbed energy levels greater than 150 ft-lbs at all test temperatures. The lateral expansion appears to stop increasing when it reaches approximately 100 mils in the CVN tests even as absorbed energy levels increase.

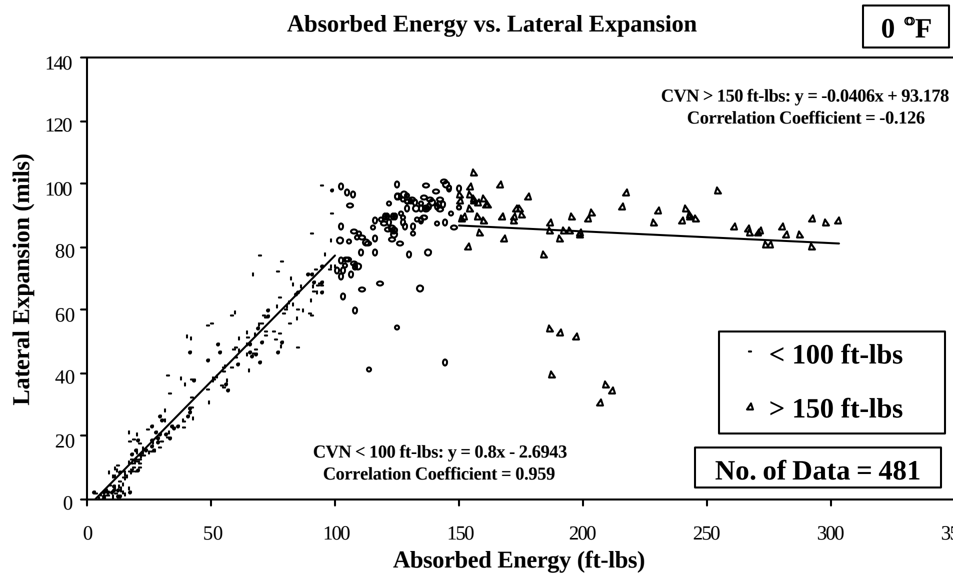


Figure 3.21: Absorbed Energy versus Lateral Expansion Plot at 0°F based on Test Data from the 4-Mill Group.

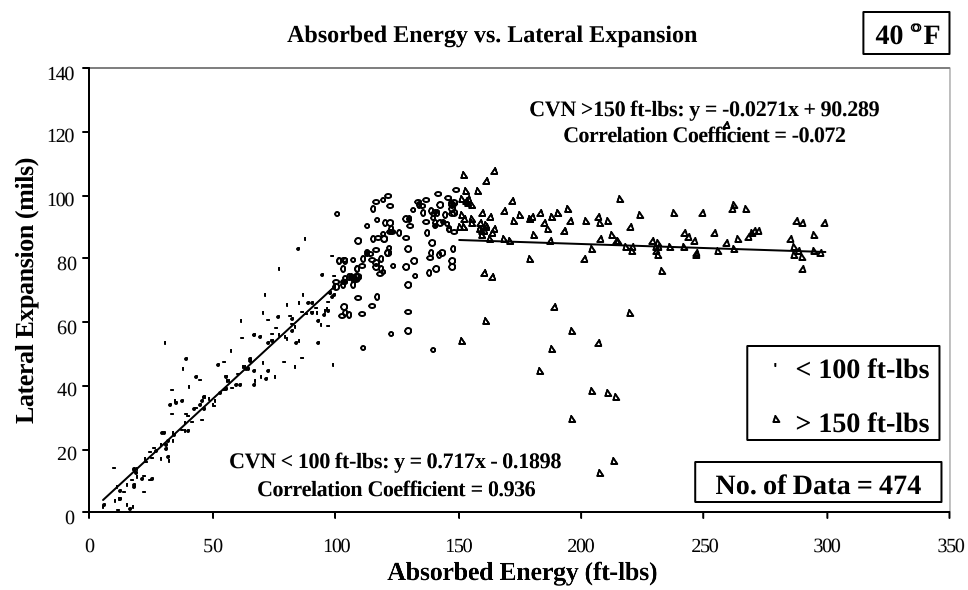


Figure 3.22: Absorbed Energy versus Lateral Expansion Plot at 40°F based on Test Data from the 4-Mill Group.

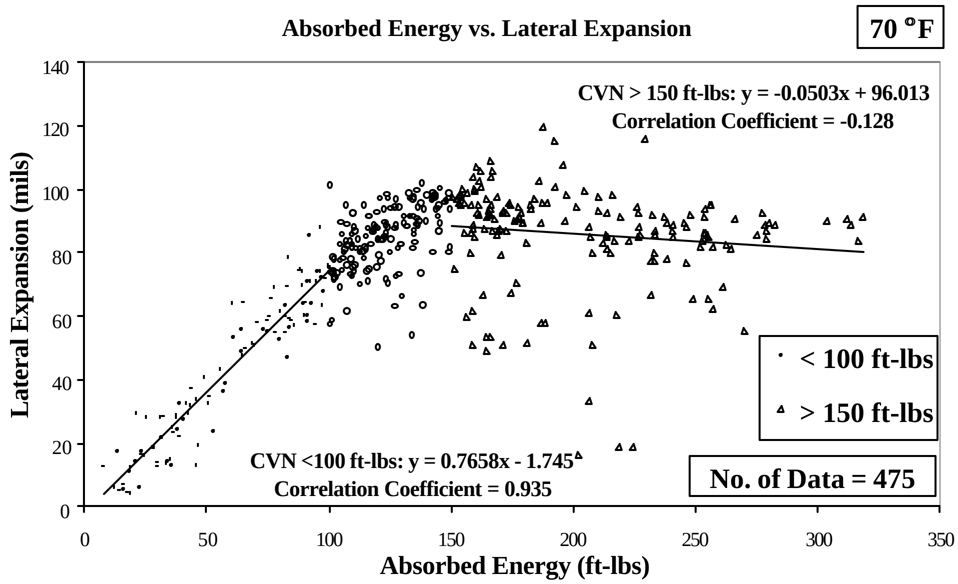


Figure 3.23: Absorbed Energy versus Lateral Expansion Plot at 70° F based on Test Data from the 4-Mill Group.

3.7 COMPARISON OF THE PRESENT STUDY WITH PREVIOUS STUDIES

In Section 3.7.1, results from the statistical analysis of tensile properties of the plates are compared with those from a 1974 study conducted by the American Iron and Steel Institute (AISI, 1974). In Section 3.7.2, results from the statistical analysis of Charpy V-Notch toughness properties are compared with those from a 1989 study (AISI, 1989).

3.7.1 TENSILE PROPERTIES

Results from the statistical analysis of tensile properties from the four-mill group are summarized in order to compare with the results from the 1974 study (SU/20 Survey of the Variation of Tension Test Values within an As-Rolled Carbon Steel Plate). The comparison includes the frequency distributions of tensile properties, the differences in tensile properties from a reference location, and the variation of tensile properties as a function of reference test values.

It should be noted that the 1974 study did not specifically mention any ASTM grade of steel. For the sake of reference, the 1974 survey data showed that the majority of the plates tested had carbon content between 0.16 and 0.25% comparable to maximum allowable values ranging from 0.19 to 0.26% for A572 and A588 grade steels per specifications.

The SU/20 survey's objective was to quantify the variations in tensile properties within an as-rolled plate. There were seven test locations per plate. Nine steel producers provided the test data for 369 carbon steel plates. The analysis results of yield strength from the present study are compared with those of yield point from the 1974 study since the values of the two parameters (yield point and yield strength) are almost identical as discussed previously in Section 3.5.2 (the average yield strength to yield point ratio ranges from 0.99 to 1.01 for Mill 4).

3.7.1.1 TENSILE STRENGTH

For the sake of comparison of the data in the two studies, Table 3.50 summarizes the frequency distributions of tensile strength at the reference location. The reference location used in the present study is location 1 (see Figure 2.1), which corresponds to the location that was used in the 1974 study.

Table 3.50: Frequency Distributions of Tensile Strength at the Reference Location.

Range (ksi)	Frequency (%)		
	1974 Study	Present Study	
	Carbon Steel	A572	A588
$20 \leq F_u < 30$	-	-	-
$30 \leq F_u < 40$	-	-	-
$40 \leq F_u < 50$	2.3	-	-
$50 \leq F_u < 60$	18.8	-	-
$60 \leq F_u < 70$	56.5	-	-
$70 \leq F_u < 80$	16.8	22.8	42.1
$80 \leq F_u < 90$	5.6	74.3	52.6
$F_u \geq 90$	-	2.9	5.3
No. of Tests	357	35	38

It may be observed from Table 3.50 that in general both A572 and A588 steel plates of the present study have higher tensile strength than the carbon steel plates of the 1974 study. Most of the plates in the present study have tensile strength values in the 80 to 90 ksi range while most in the 1974 study had tensile strength values in the 60 to 70 ksi range. There was, however, a much larger number of tests available in the 1974 study.

Table 3.51 summarizes the differences in tensile strength at other locations from the value at the reference location. The presented statistics include the mean value and the standard deviation of these differences.

Table 3.51: Differences in Tensile Strength at other Locations from the Value at the Reference Location.

Statistics	Differences from Reference Test (ksi)		
	1974 Study	Present Study	
	Carbon Steel	A572	A588
Mean	0.115	-0.002	-0.047
Standard Deviation	1.89	2.37	1.60
No. of Tests	2125	210	228

It may be observed from Table 3.51 that in the present study, the mean values of the differences from the value at the reference location are smaller than that from the 1974 study. However, the standard deviations of this difference are fairly similar in both studies. Note that the standard deviations normalized with respect to the required values of tensile strength for A572 and A588 steel plates are 3.65% and 2.29%, respectively, which are smaller than the 4% value based on the 1974 study and reported in ASTM A6, Appendix X2.

Table 3.52 summarizes the variation of tensile strength for various reference test strength ranges. In each range of tensile strength, the reference test average, the mean value, and the standard deviation of the differences from the reference location are presented.

Table 3.52: Variation of Tensile Strength for Various Reference Test Strength Ranges.

Study	Range (ksi)	$F_u \leq 60$	$60 \leq F_u < 70$	$70 \leq F_u < 80$	$80 \leq F_u < 90$	$F_u \geq 90$
1974-Carbon Steel	No. of Tests	487	1174	368	120	-
	Reference Test Average (ksi)	55.7	64.6	74.4	83.9	-
	Average Difference (ksi)	0.399	0.100	-0.023	-0.038	-
	Standard Deviation (ksi)	1.55	1.80	1.83	2.45	-
Present-A572	No. of Tests	-	-	48	156	6
	Reference Test Average (ksi)	-	-	76.0	84.1	90.8
	Average Difference (ksi)	-	-	0.946	-0.162	-3.43
	Standard Deviation (ksi)	-	-	2.47	2.22	0.692
Present-A588	No. of Tests	-	-	96	120	12
	Reference Test Average (ksi)	-	-	76.6	83.5	93.9
	Average Difference (ksi)	-	-	-0.053	0.099	-1.47
	Standard Deviation (ksi)	-	-	1.48	1.66	1.25

It may be observed from Table 3.52 that for the 1974 study, the mean values of the differences from the reference location decrease with increasing tensile strength. In the present study, the A588 steel plates do not show this trend. However, the mean values of the differences from the reference location from both studies are fairly small, ranging from –3.43 to 0.946 ksi. The variation of the differences from the reference location is also small in both studies with the standard deviations ranging from 0.692 to 2.47 ksi.

Similar to the 1974 study, probability plots for the difference relative to the reference location in tensile strength are constructed and shown in Figures 3.24 and 3.25 for both A572 and A588 steel plates, respectively, in the present study. For example, suppose the reference location of an A588 grade plate had a tensile strength of 80 ksi, use the 77.5-85 ksi line of Fig. 3.25 to see that there is a 90% probability that any other location of the plate would have a tensile strength greater than 78 ksi (i.e., 80 ksi minus 2 ksi). Reading off horizontally at 90%, the 77.5-85 ksi line shows a difference of -2 ksi from the reference value.

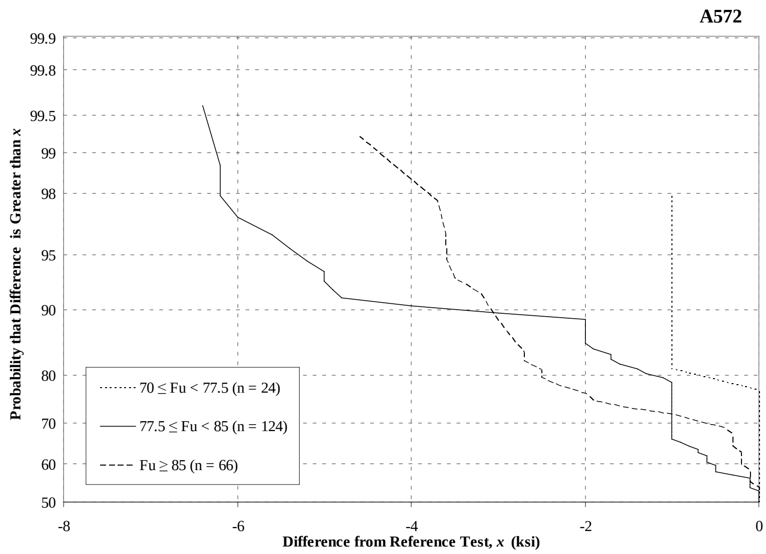


Figure 3.24: Probability Plot of Tensile Strength Difference Relative to Reference Location for A572.

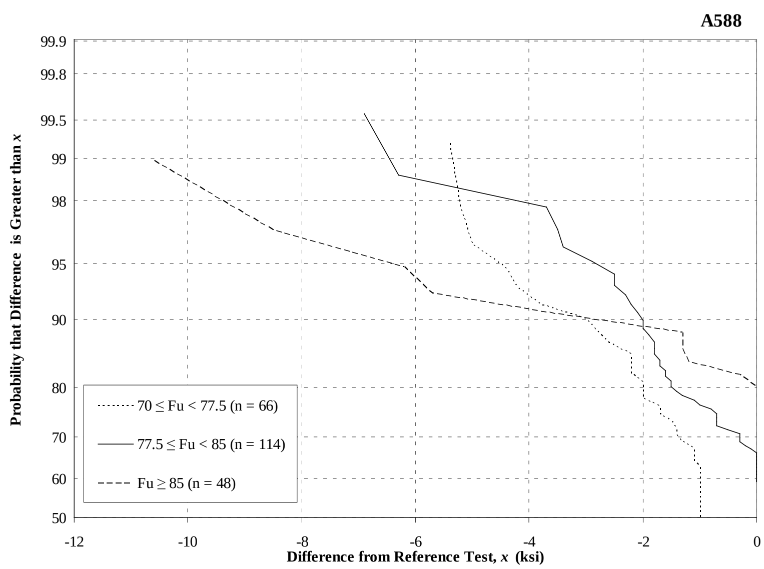


Figure 3.25: Probability Plot of Tensile Strength Difference Relative to Reference Location for A588.

3.7.1.2 YIELD STRENGTH

A comparison of the yield strength from the present study with the yield point from the 1974 study is conducted in a similar manner to that used for the tensile strength. Table 3.53 summarizes the frequency distributions of yield strength at the reference location. Again, the reference location used in the present study is location 1 (see Figure 2.1), which corresponds to the location that was used in the 1974 study.

Table 3.53: Frequency Distributions of Yield Strength at the Reference Location.

Range (ksi)	Frequency (%)		
	1974 Study	Present Study	
	Carbon Steel	A572	A588
$20 \leq F_y < 30$	2.0	-	-
$30 \leq F_y < 40$	51.8	-	-
$40 \leq F_y < 50$	39.4	-	-
$50 \leq F_y < 60$	5.1	71.4	76.3
$60 \leq F_y < 70$	1.7	25.7	23.7
$70 \leq F_y < 80$	-	2.9	-
No. of Tests	357	35	38

It may be observed from Table 3.53 that in general both the A572 and A588 steel plates of the present study have higher yield strength values than the carbon steel plates of the 1974 study. Most of the plates in the present study have yield strength values in the 50 to 60 ksi range while most of those in the 1974 study had yield strength values in the 30 to 40 ksi range. There was, however, a much larger number of tests available in the 1974 study.

Table 3.54 summarizes the differences in yield strength at other locations from the value at the reference location. The presented statistics include the mean value and the standard deviation of these differences.

Table 3.54: Differences in Yield Strength at Other Locations from the Value at the Reference Location.

Statistics	Differences from Reference Test (ksi)		
	1974 Study	Present Study	
	Carbon Steel	A572	A588
Mean	-0.117	-1.08	-0.271
Standard Deviation	2.23	3.05	2.70
No. of Tests	2125	210	228

It may be observed from Table 3.54 that in the present study, the mean values of the differences from the value at the reference location are greater than that from the 1974 study. However, the standard deviations of this difference are fairly similar in both studies. Note that the standard deviations normalized with respect to the required values of yield strength for A572 and A588 steel plates are 6.10% and 5.46%, respectively, which are smaller than the 8% value based on the 1974 study and reported in ASTM A6, Appendix X2.

Table 3.55 summarizes the variation of yield strength for various reference test strength ranges. In each range of yield strength, the reference test average, the mean value, and the standard deviation of the differences from the reference location are presented.

Table 3.55: Variation of Yield Strength for Various Reference Test Strength Ranges.

Study	Range (ksi)	$F_y \leq 40$	$40 \leq F_y < 50$	$F_y \geq 50$
1974-Carbon Steel	No. of Tests	1170	831	150
	Reference Test Average (ksi)	36.0	44.2	55.8
	Average Difference (ksi)	0.107	-0.196	-0.360
	Standard Deviation (ksi)	2.02	2.18	2.17
Present-A572	No. of Tests	-	-	210
	Reference Test Average (ksi)	-	-	59.1
	Average Difference (ksi)	-	-	-1.08
	Standard Deviation (ksi)	-	-	3.05
Present-A588	No. of Tests	-	-	228
	Reference Test Average (ksi)	-	-	57.7
	Average Difference (ksi)	-	-	-0.271
	Standard Deviation (ksi)	-	-	2.70

It may be observed from Table 3.55 that the mean values of the differences from the reference location in both studies are fairly small, ranging from –1.08 to 0.107 ksi. The variation in the differences from the reference location is also small in both studies with the standard deviations ranging from 2.02 to 3.05 ksi.

Similar to the 1974 study, probability plots for the difference relative to the reference location in yield strength are constructed and shown in Figures 3.26 and 3.27 for both A572 and A588 steel plates, respectively, in the present study. For example, suppose the reference location of an A588 grade plate had a yield strength of 60 ksi, use the 57.5-65 ksi line of Fig. 3.27 to see that there is a 90% probability that any other location of the plate would have a yield strength greater than 57.7 ksi (i.e., 60 ksi minus 2.3 ksi). Reading off horizontally at 90%, the 57.5-65 ksi line shows a difference of -2.3 ksi from the reference value.

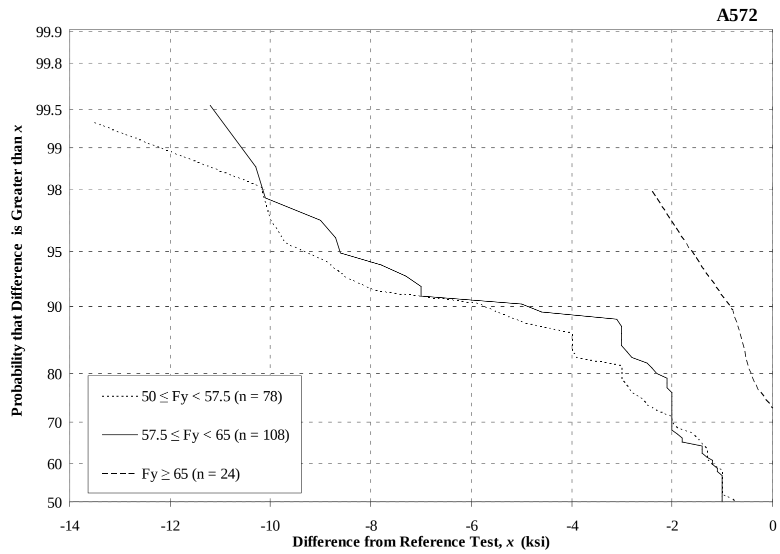


Figure 3.26: Probability Plot of Yield Strength Difference Relative to Reference Location for A572.

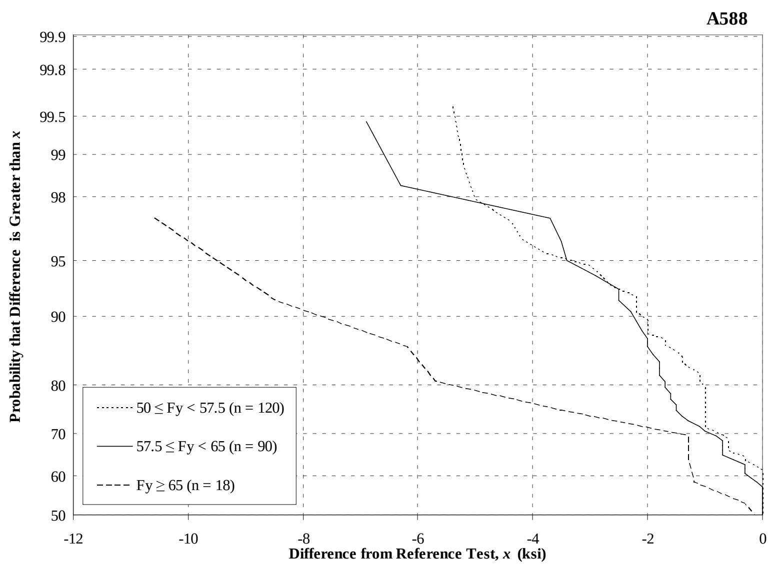


Figure 3.27: Probability Plot of Yield Strength Difference Relative to Reference Location for A588.

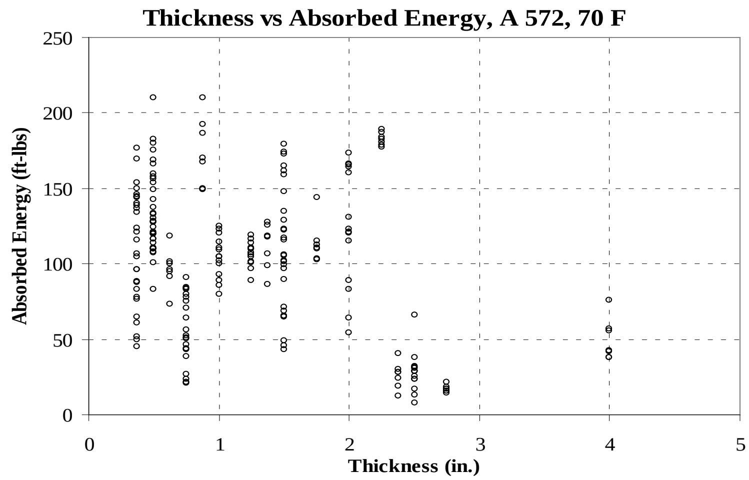
3.7.2 CHARPY V-NOTCH TOUGHNESS

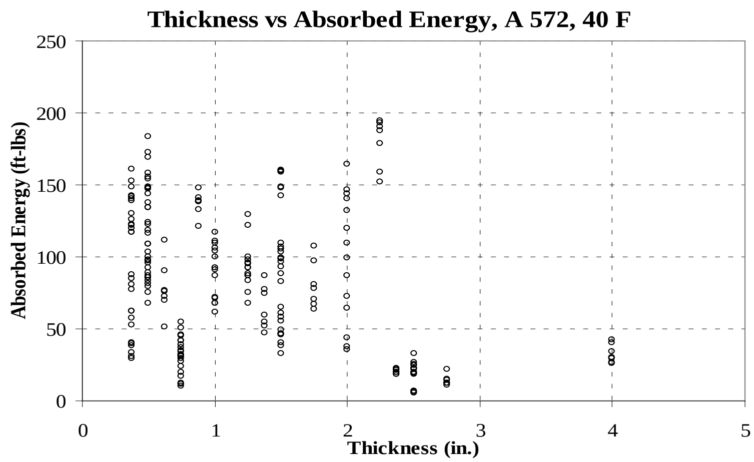
The statistical analysis results are summarized in order to compare with the results from the 1989 study conducted by the American Iron and Steel Institute (AISI, 1989). The comparison includes the thickness versus absorbed energy plots, the three-test average of absorbed energy, the three-test average of lateral expansion, the differences in three-test average of absorbed energy from reference location, and the correlation between absorbed energy and lateral expansion.

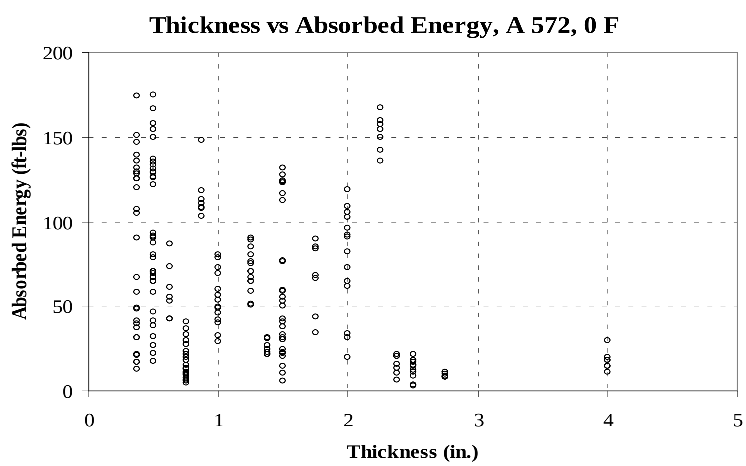
The 1989 study's objective was to quantify the variability of impact test properties between test locations. Forty-seven A572 Grade 50 and forty-seven A588 steel plates with the thickness up to four inches from four steel producers were tested in the year 1983. There were nine test locations per plate. This study also combined the 1989 statistical analysis results with those from the ear1ier 1979 study (AISI, 1979).

3.7.2.1 THICKNESS VERSUS ABSORBED ENERGY PLOTS

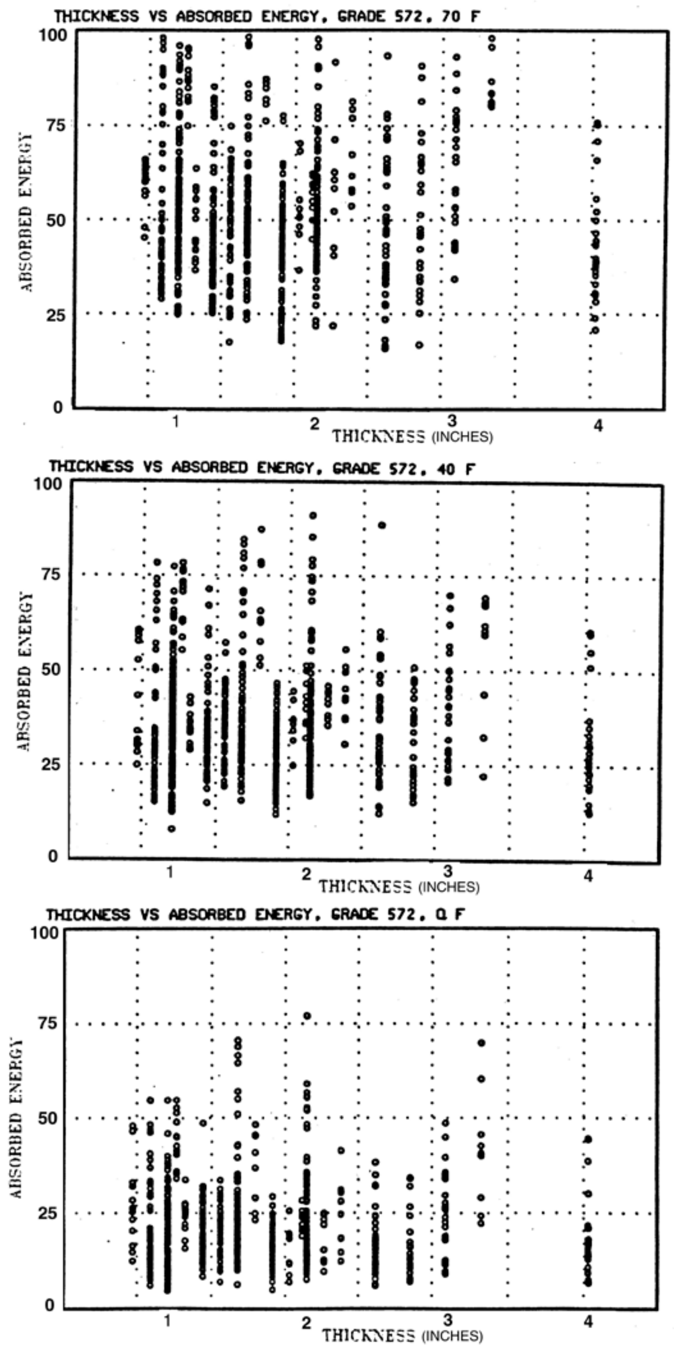
For the sake of comparison of the data in the two studies, Figure 3.28 shows the distribution of absorbed energy by plate thickness for A572 steel plates in both studies. Part (a) includes results from the present study and Part (b) includes results from the 1989 study. Similarly, Figure 3.29 shows the distribution of absorbed energy by plate thickness for A588 steel plates in both studies.





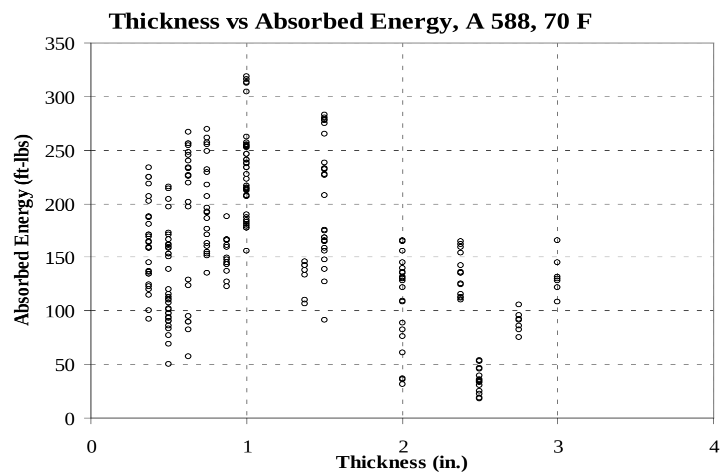


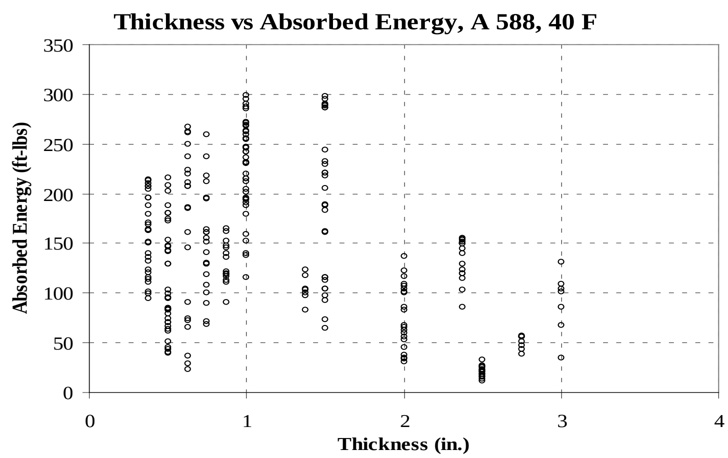
(a) Results from the Present Study.

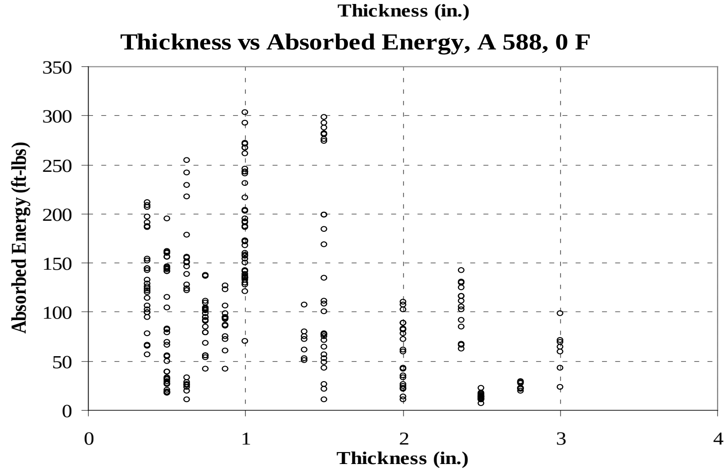


(b) Results from the 1989 Study.

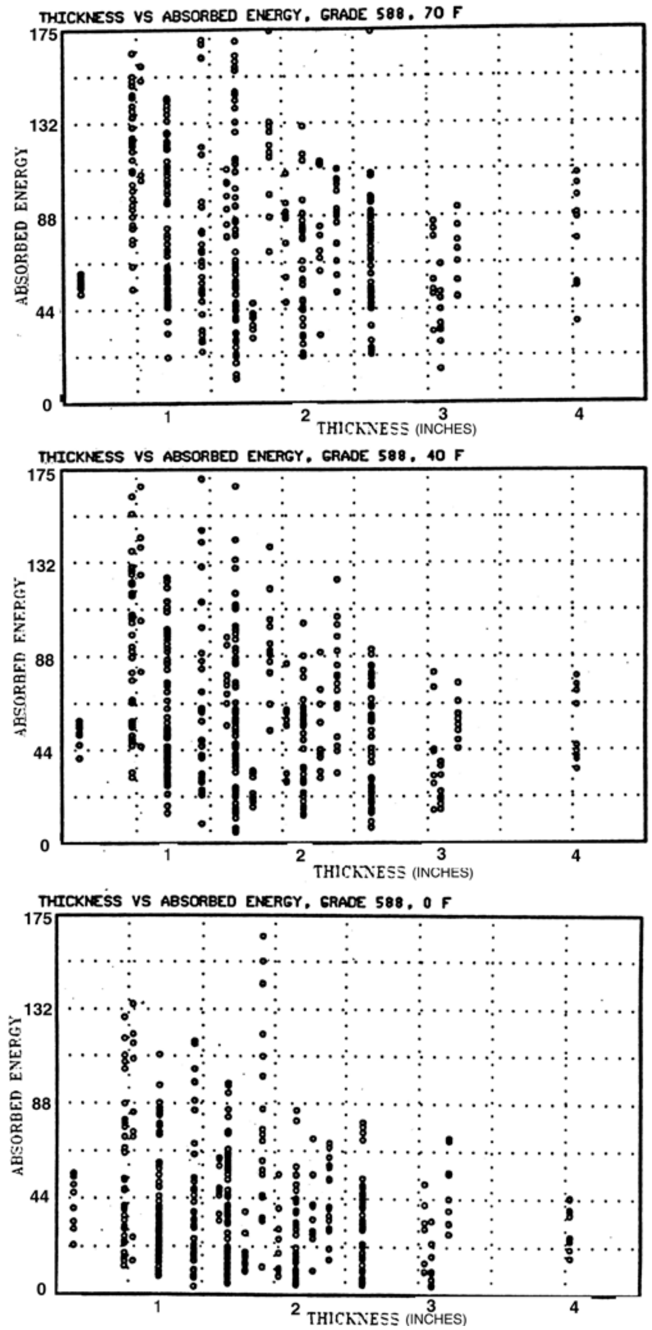
Figure 3.28: Thickness Versus Absorbed Energy Plot for A572.







(a) Results from the Present Study.



(b) Results from the 1989 Study.

Figure 3.29: Thickness Versus Absorbed Energy Plot for A588.

3.7.2.2 THREE-TEST AVERAGE OF ABSORBED ENERGY

Table 3.56 summarizes the three-test average of absorbed energy including all thickness groups. Part (a) includes results from the present study and Part (b) includes results from the 1989 study.

Table 3.56: Three-Test Average of Absorbed Energy for All Thickness Groups.

ASTM Specification	Test Temperature	Three-Test Average of Absorbed Energy (ft-lbs)					No. of Tests
		Mean	SD	COV (%)	Min	Max	
A 572	0 F	61.9	46.2	74.6	3.0	175.0	224
	40 F	82.9	48.1	58.0	5.7	194.7	224
	70 F	100.7	48.2	47.8	7.7	210.0	224
A 588	0 F	108.6	71.9	66.2	7.0	303.3	259
	40 F	143.7	74.5	51.9	12.0	299.0	259
	70 F	162.4	66.5	40.9	17.7	318.7	259

(a) Results from the Present Study.

ASTM Specification	Test Temperature	Three-Test Average of Absorbed Energy (ft-lbs)					No. of Tests
		Mean	SD	COV (%)	Min	Max	
A 572	0 F	21.2	11.2	52.8	4.7	77.0	785
	40 F	36.4	15.0	41.2	8.0	91.0	785
	70 F	53.5	19.4	36.3	16.0	124.7	785
A 588	0 F	40.6	28.5	70.2	3.7	165.0	417
	40 F	62.9	39.5	62.8	5.3	290.0	417
	70 F	85.2	45.2	53.1	11.3	256.0	417

(b) Results from the 1989 Study.

It may be observed from Table 3.56 that the absorbed energy values from the present study are approximately two to three times greater than those from the 1989 study at all test temperatures and for both steel grades. This is a significant increase in absorbed energy. In addition, the variability in absorbed energy is seen to have increased slightly in A572 steel plates and decreased slightly in A588 steel plates as is evident from the ratio of the standard deviation to the mean values (coefficient of variation, COV).

3.7.2.3 THREE-TEST AVERAGE OF LATERAL EXPANSION

Table 3.57 summarizes the three-test average of lateral expansion for all thickness groups. Part (a) includes results from the present study and Part (b) includes results from the 1989 study.

Table 3.57: Three-Test Average of Lateral Expansion for All Thickness Groups.

ASTM Specification	Test Temperature	Three-Test Average of Lateral Expansion (mils)					No. of Tests
		Mean	SD	COV (%)	Min	Max	
A 572	0 F	44.3	31.7	71.4	0.0	99.7	224
	40 F	55.2	28.7	52.0	1.7	101.7	224
	70 F	67.6	26.7	39.4	5.0	101.0	224
A 588	0 F	60.4	30.7	50.8	0.0	103.7	258
	40 F	69.8	26.4	37.8	0.0	122.3	251
	70 F	76.6	24.5	32.0	0.0	119.7	253

(a) Results from the Present Study.

ASTM Specification	Test Temperature	Three-Test Average of Lateral Expansion (mils)					No. of Tests
		Mean	SD	COV (%)	Min	Max	
A 572	0 F	19.0	10.7	56.3	1.7	61.0	785
	40 F	32.3	12.9	39.9	9.0	71.3	785
	70 F	45.8	14.7	32.1	13.0	92.7	785
A 588	0 F	32.3	20.5	63.5	0.5	95.0	417
	40 F	46.6	22.0	47.2	4.3	95.3	417
	70 F	58.4	19.8	33.9	6.0	95.0	417

(b) Results from the 1989 Study.

Similar to the absorbed energy, it may be observed from Table 3.57 that the lateral expansion from the present study is generally larger than those from the 1989 study at all test temperatures and for both steel grades. The variability in lateral expansion is seen to have increased slightly in A572 steel plates and decreased slightly in A588 steel plates.

3.7.2.4 DIFFERENCES IN THREE-TEST AVERAGE OF ABSORBED ENERGY FROM REFERENCE LOCATION

Table 3.58 summarizes the differences in three-test average of absorbed energy from reference location including all thickness groups. Part (a) includes results from the present study and Part (b) includes results from the 1989 study.

Table 3.58: Differences in Three-Test Average of Absorbed Energy from Reference Location Including All Thickness Groups.

ASTM Specification	Test Temperature	Difference in Absorbed Energy from Reference Test(ft-lbs)				No. of Tests
		Mean	SD	Min	Max	
A 572	0 F	-0.17	24.8	-86.0	87.3	192
	40 F	1.13	25.9	-74.0	121.0	192
	70 F	2.79	25.6	-83.0	109.3	192
A 588	0 F	-9.97	40.9	-132.0	116.3	222
	40 F	-7.27	54.0	-159.3	183.3	222
	70 F	-2.30	34.1	-104.0	70.7	222

(a) Results from the Present Study.

ASTM Specification	Test Temperature	Difference in Absorbed Energy from Reference Test(ft-lbs)				No. of Tests
		Mean	SD	Min	Max	
A 572	0 F	0.43	9.00	-31.3	26.7	686
	40 F	-1.82	12.4	-56.7	41.3	686
	70 F	-0.75	17.7	-72.7	101.6	686
A 588	0 F	4.24	30.4	-153.3	119.7	370
	40 F	10.4	46.8	-136.9	230.7	370
	70 F	8.77	59.9	-206.7	224.6	370

(b) Results from the 1989 Study.

It should be noted that the reference location used in the present study is location 1 (see Figure 2.1), which corresponds to the location that was used in the 1989 study. It may be observed from Table 3.58 that the results from both studies are fairly similar with minor differences in variability.

Similar to the 1989 study, probability plots for the difference relative to the reference location in absorbed energy are constructed and shown in Figures 3.30 and 3.35 for both A572 and A588 steel plates at three test temperatures (0, 40 and 70°F), respectively, in the present study. For example, suppose the reference location of an A588 grade plate had a three-test average absorbed energy value of 150 ft-lbs at 0°F, use the 100-200 ft-lbs line of Fig. 3.31 to see that there is a 90% probability that any other location of the plate would have a three-test average absorbed energy value greater than 85 ft-lbs (i.e., 150 ft-lbs minus 65 ft-lbs). Reading off horizontally at 90%, the 100-200 ft-lbs line shows a difference of -65 ft-lbs from the reference value.

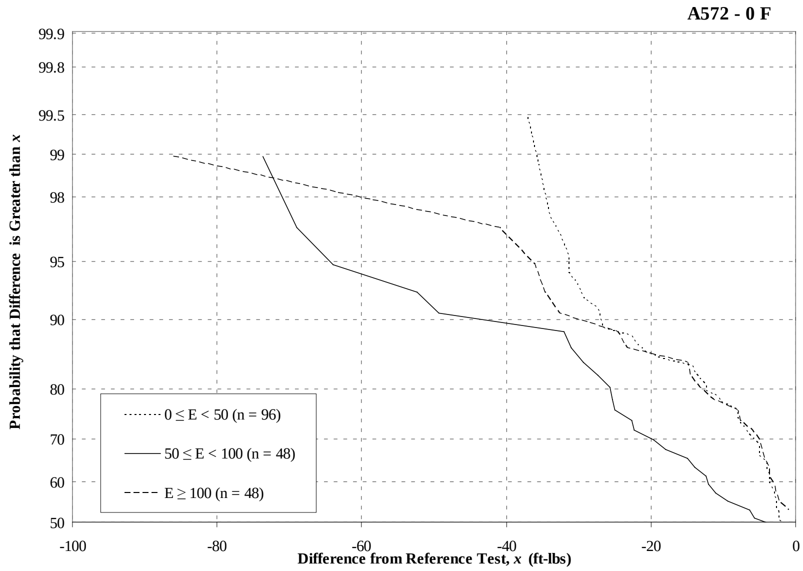


Figure 3.30: Probability Plot of Absorbed Energy Difference Relative to Reference Location for A572 at 0°F.

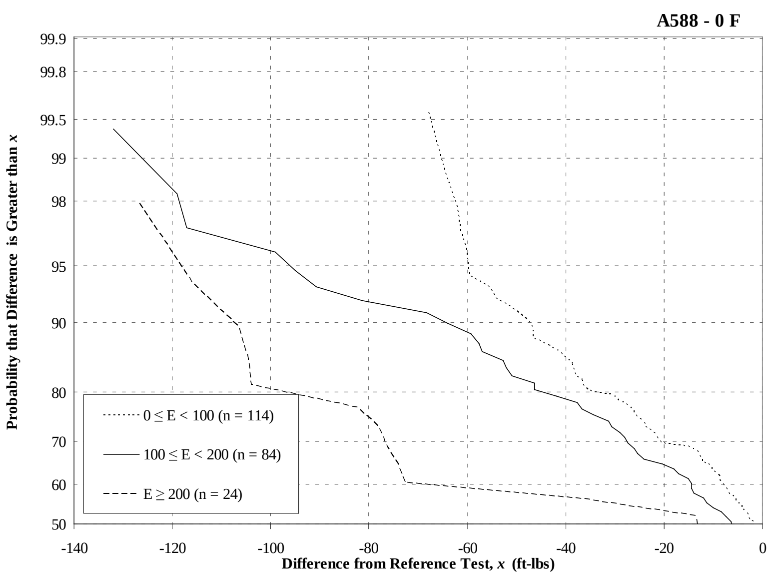


Figure 3.31: Probability Plot of Absorbed Energy Difference Relative to Reference Location for A588 at 0°F.

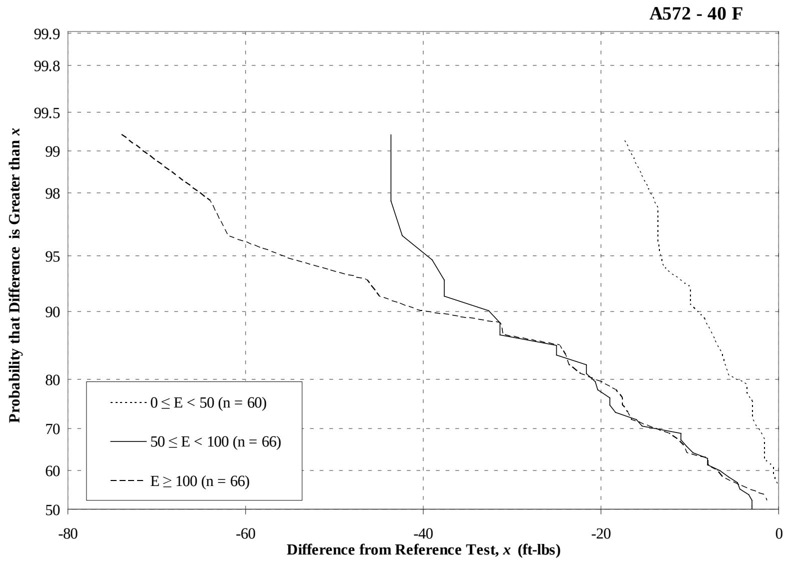


Figure 3.32: Probability Plot of Absorbed Energy Difference Relative to Reference Location for A572 at 40°F.

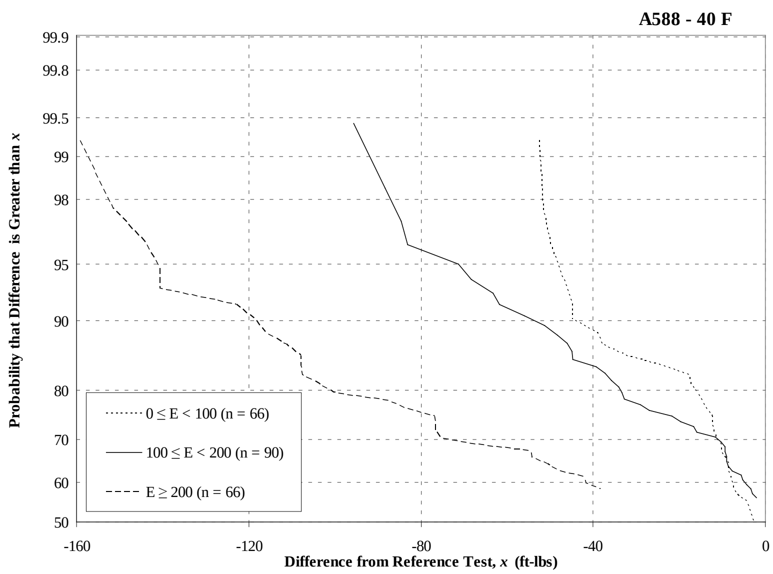


Figure 3.33: Probability Plot of Absorbed Energy Difference Relative to Reference Location for A588 at 40°F.

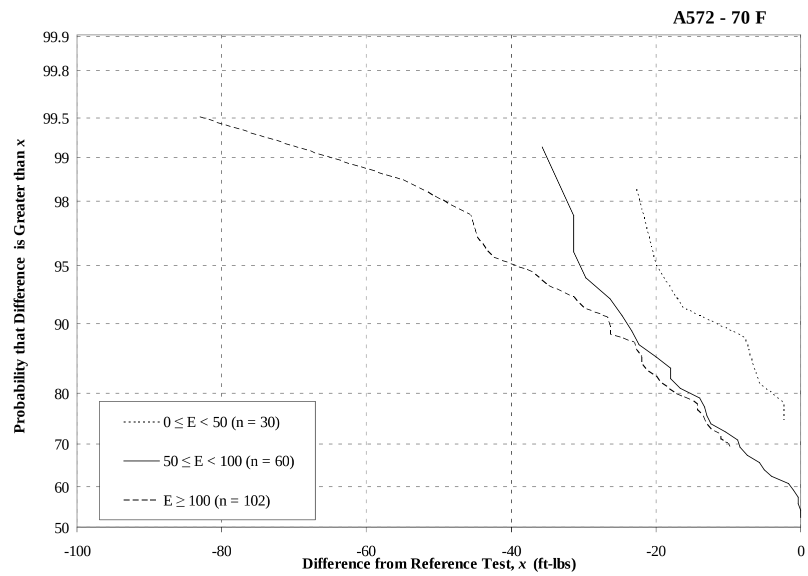


Figure 3.34: Probability Plot of Absorbed Energy Difference Relative to Reference Location for A572 at 70°F.

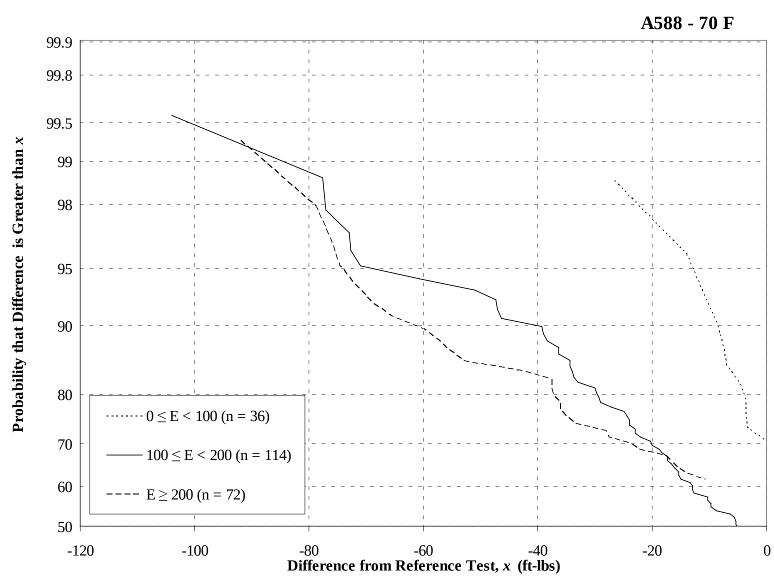
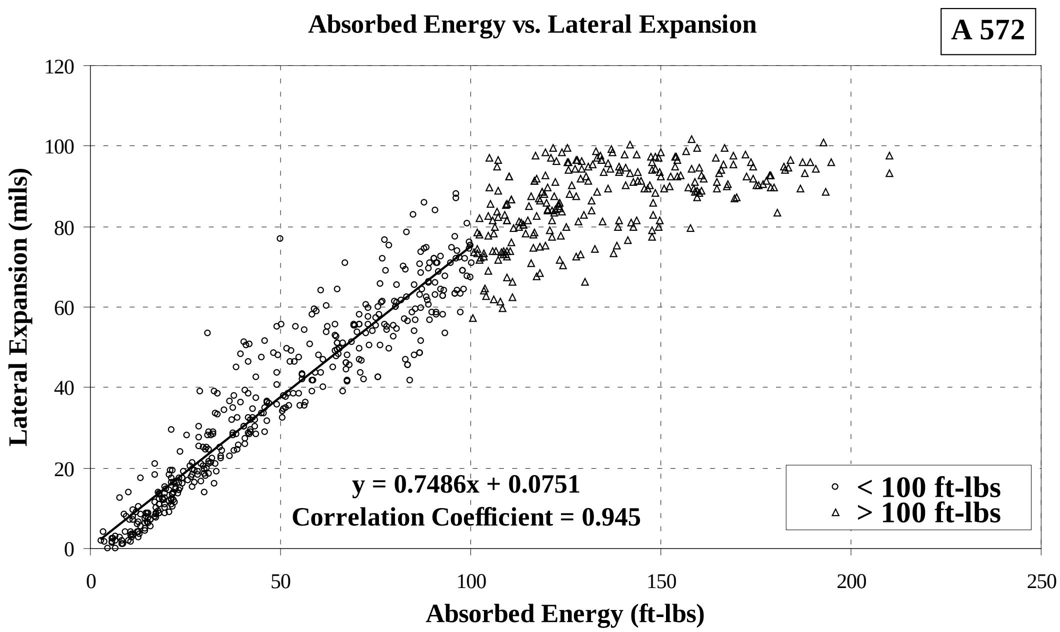


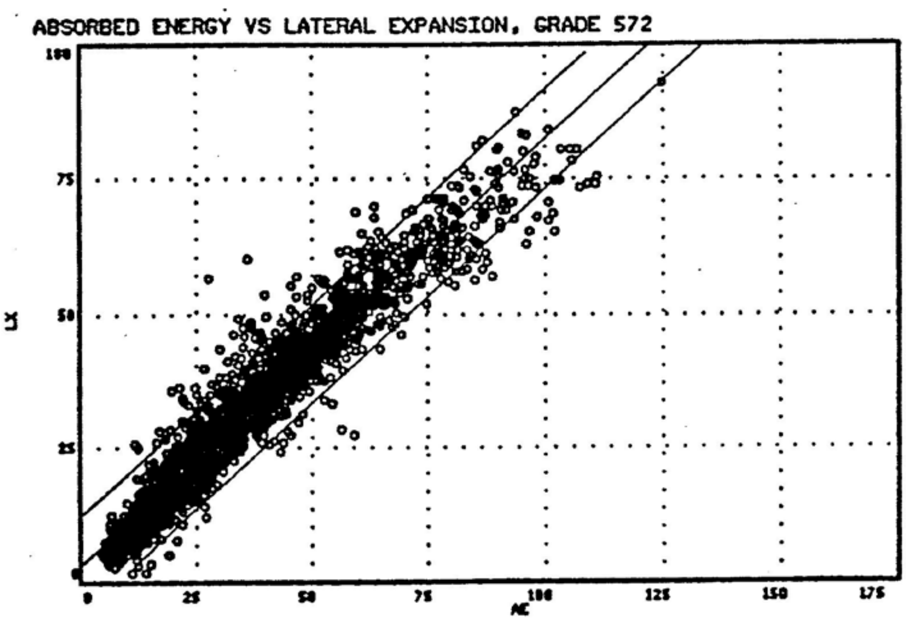
Figure 3.35: Probability Plot of Absorbed Energy Difference Relative to Reference Location for A588 at 70°F.

3.7.2.5 CORRELATION BETWEEN ABSORBED ENERGY AND LATERAL EXPANSION.

Figures 3.36 and 3.37 present the absorbed energy versus lateral expansion plots for A572 and A588 steel plates respectively. Each plot contains data from all thickness groups and includes all test temperatures. Part (a) includes results from the present study and Part (b) includes results from the 1989 study.

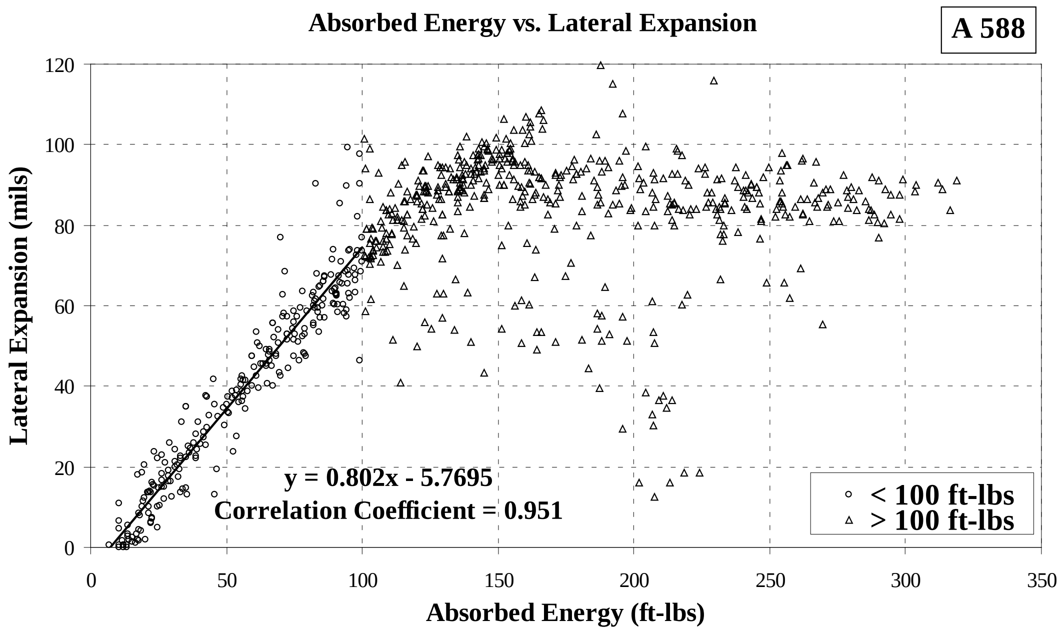


(a) Results from the Present Study.

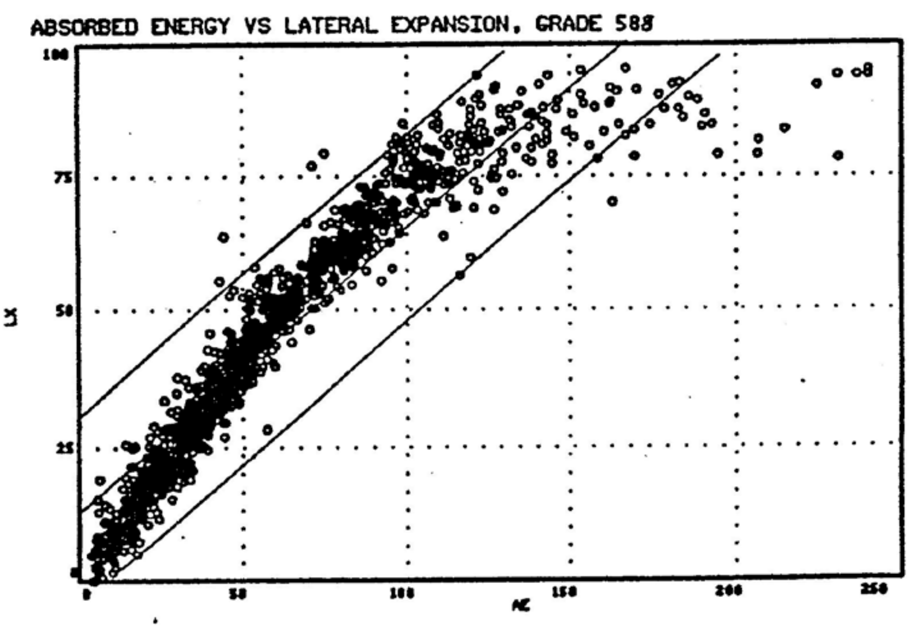


(b) Results from the 1989 Study.

Figure 3.36: Absorbed Energy versus Lateral Expansion Plot for A572, (all thickness groups and test temperatures).



(a) Results from the Present Study.



(b) Results from the 1989 Study.

Figure 3.37: Absorbed Energy versus Lateral Expansion Plot for A588, (all thickness groups and test temperatures).

It may be observed from Figures 3.36 and 3.37 that the steel plates in the present study have more upper shelf data for lateral expansion than in the 1989 study, especially for the A588 steel plates. The plots of absorbed energy and lateral expansion from both studies are quite similar with a very strong correlation between absorbed energy and lateral expansion as can be seen from the correlation coefficients of 0.945 and 0.951 respectively for A572 and A588 steel plates based on the present study. It should be noted that this strong correlation exists only in the range from 0 to 100 ft-lbs absorbed energy.

CHAPTER 4
CONCLUSIONS

4.1 SUMMARY OF RESULTS

From the statistical analysis of data related to carbon equivalent (CE) values, it can be concluded that the studied plates had mean CE values ranging from 0.32% to 0.51% with low variability. Considering all the data from the 4-mill group, the coefficient of variation on CE was about 6% for both grades of steel.

The correlation studies involving CE showed strong statistical correlation with tensile strength, with correlation coefficients of 0.60 and 0.66 for A572 and A588 steel plates, respectively, based on results from the 2-mill group. However, no significant correlation could be found between carbon equivalent and yield strength. A mild negative correlation was seen to exist between carbon equivalent and the yield to tensile ratio with correlation coefficients of -0.35 and -0.46 for A572 and A588 steel plates, respectively, based on results from the 2-mill group.

Several conclusions may be drawn from the statistical analysis of tensile test data. First, the average yield strength of the studied plates ranged from 51.7 to 66.3 ksi with small variability as may be seen from coefficients of variation values of less than 7% based on the data from the 4-mill group. The study related to the percentage of test locations that had yield strength greater than or equal to specific yield strength revealed that for 72 out of the 73 plates studied, all seven locations met the requirement of minimum yield strength (50 ksi); the percentage of test locations that had yield strength greater than or equal to 55 ksi was, on average, 84.0% for A572 steel plates, and 73.3% for A588 steel plates, based on results from the 4-mill group.

The studied plates also showed high tensile strength with an average varying from 74.5 to 92.6 ksi for the 4-mill group and 72.1 to 83.8 ksi for the 2-mill group. The variability is also small with coefficients of variation values of 5.90% for the 4-mill group, when all the data are considered. A study related to the percentage of test locations that had tensile strength greater than or equal to specific yield strength revealed that for all plates studied, all seven locations met the requirement of minimum tensile strength of 65 ksi and also met a higher level of 70 ksi, with only one exception, that for A588-T2 plates, where 98.9 percent of tests showed tensile strengths greater than or equal to 70 ksi.

The average yield to tensile ratio of all studied plates ranged from 0.63 to 0.81 with small variability based on coefficient of variation values of 4.22% for the 2-mill group and 5.48% for the 4-mill group. It may be seen that the yield to tensile ratio is lower than the maximum permissible ratio required in A992 steel which is 0.85. For both steel grades, results from all mills showed that the average yield to tensile ratio generally decreased with an increase in plate thickness, except for a few cases where this trend was not observed.

In studying the yield strength to yield point ratio, the data from Mill 4 indicated that the yield point level is very close to the yield strength with an average discrepancy of only about 1%. The overall variability in this ratio, considering all the data, was 2.45%.

Overall, the mill test data obtained from Mills 2 and 6 (the 2-mill group) gave similar analysis results to those obtained from Mills 1, 3, 4 and 5 (the 4-mill group) which were surveyed data according to a specified format. The 2-mill group included a considerably larger number of data than the 4-mill group but did not include Charpy V-notch impact test data.

The analysis of Charpy V-Notch impact test data led to several conclusions. The studied plates generally had high absorbed energy values, with averages of 61.9, 82.9, and 100.7 ft-lbs at 0°F, 40°F, and 70°F, respectively, for A572 steel plates, and 108.6, 143.7 and 162.4 ft-lbs at 0°F, 40°F, and 70°F, respectively, for A588 steel plates. In most of the cases studied, the absorbed energy tended to decrease with an increase in plate thickness.

Variability in absorbed energy levels for the plates was seen to be large with a coefficient of variation as high as 74.6% for A572 steel plates at 0°F. The variability in absorbed energy values was studied in detail and was found to be dominated by variability between plates. In other words, the test location variability or variability within a plate was not a significant part of the total variability.

With regard to the effect of choice of a reference location with corresponding absorbed energy, E_{ref}, the percentage of samples with three-test average absorbed energy greater than $E_{ref}-\alpha$ was studied for each of seven possible choices of reference location and by changing the value of α.

No significant differences between the analysis results from lower toughness plates and higher toughness plates were found. The range of probabilities that a three-test-averaged absorbed energy might exceed $E_{ref}-\alpha$ (for α equal to 5, 10, or 15 ft-lbs) generally varied from 55% to 100% for higher toughness plates and 57% to 100% for lower toughness plates for A572 steel. Somewhat lower percentages were possible for A588 steel plates.

The study of statistical correlation between absorbed energy values and lateral expansion suggests that, for both grades of steel and at all test temperatures, a strong positive statistical correlation exists between these two variables for absorbed energy levels below 100 ft-lbs. However, no significant correlation could be found for absorbed energy levels above 150 ft-lbs. Lateral expansion appears to stop increasing when it reaches approximately 100 mils in the CVN tests even as absorbed energy levels increase.

The comparison of the tensile properties of the present study and the 1974 study reveals that A572 and A588 steel plates of the present study have higher tensile strength and yield strength than those of the carbon steel plates of the 1974 study. The variation of the tensile properties within a plate from both studies is fairly small with the standard deviations ranging from 1.60 to 3.05 ksi.

The comparison of the Charpy V-Notch toughness properties of the present study and the 1989 study reveals that the absorbed energy and lateral expansion values from the present study are generally larger than those from the 1989 study at all test temperatures and for both steel grades. In addition, the variability in absorbed energy and lateral expansion is seen to have decreased slightly in A572 steel plates and increased slightly in A588 steel plates as is evident from the ratio of the standard deviation to the mean values.

The differences in three-test average of absorbed energy from reference location are quite similar in both studies. The statistical relationship between absorbed energy and lateral expansion from both studies is quite similar with a very strong correlation between absorbed energy and lateral expansion as can be seen from the correlation coefficients of 0.945 and 0.951 respectively for A572 and A588 steel plates based on the present study.

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