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Statistical Analysis of Structural Plate Mechanical Properties

by

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Sponsored by
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.

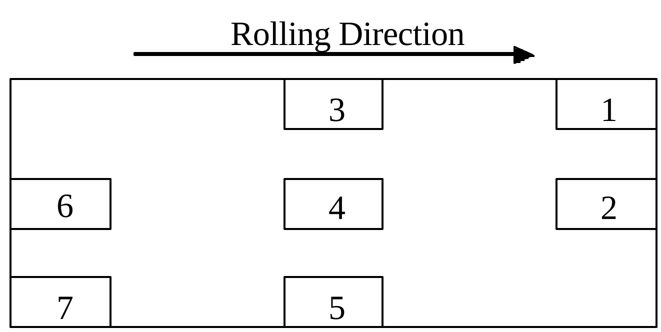


Figure 2.1: Locations of Specimens Studied in Plates.

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.

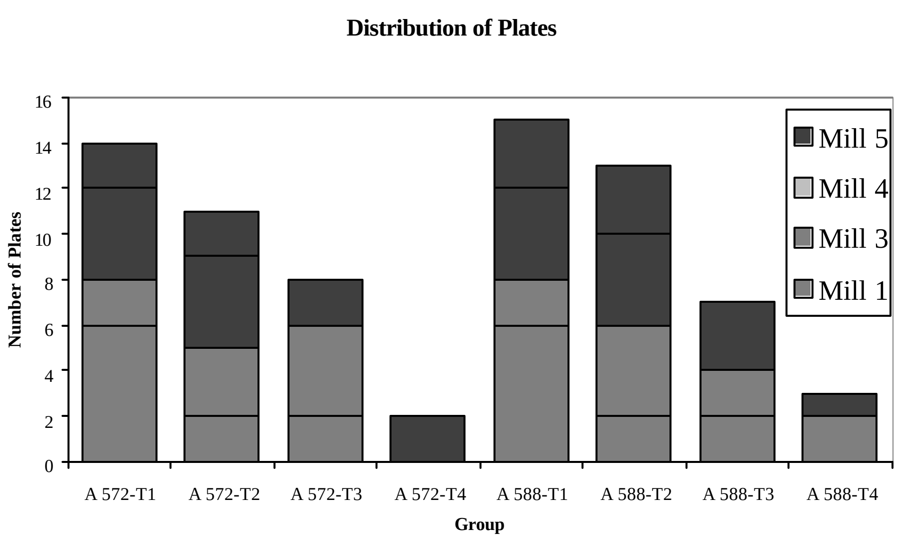
The description of the organized data from the 4-mill group (Mills 1, 3, 4, and 5) is summarized in Table 2.1.

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).

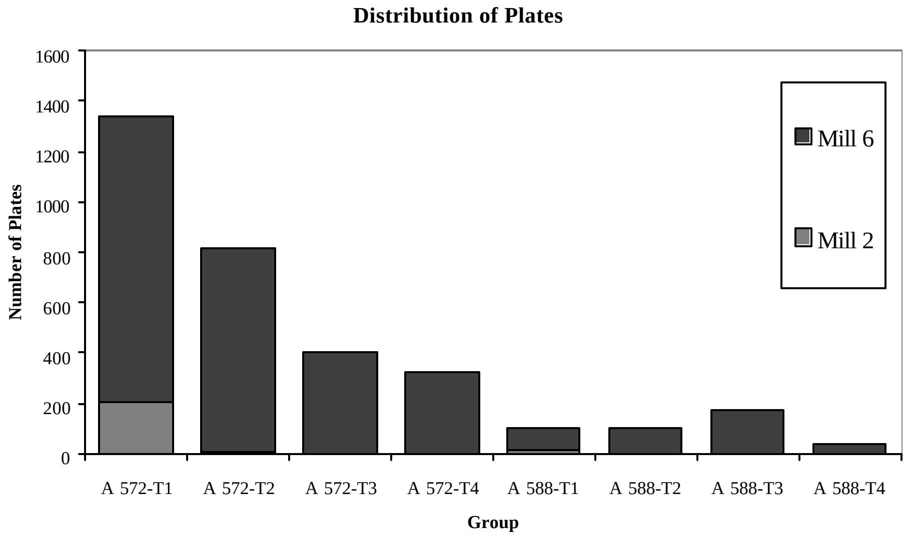


Figure 2.3 reveals that the number of plates from Mill 6 clearly dominates the overall number of plates for the 2-mill group. The group A572-T1 had the largest number of plates, greater than 1300 in number, from a total of 3295 plates in the 2-mill group. The majority of the data from Mill 2 was from 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:

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

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.

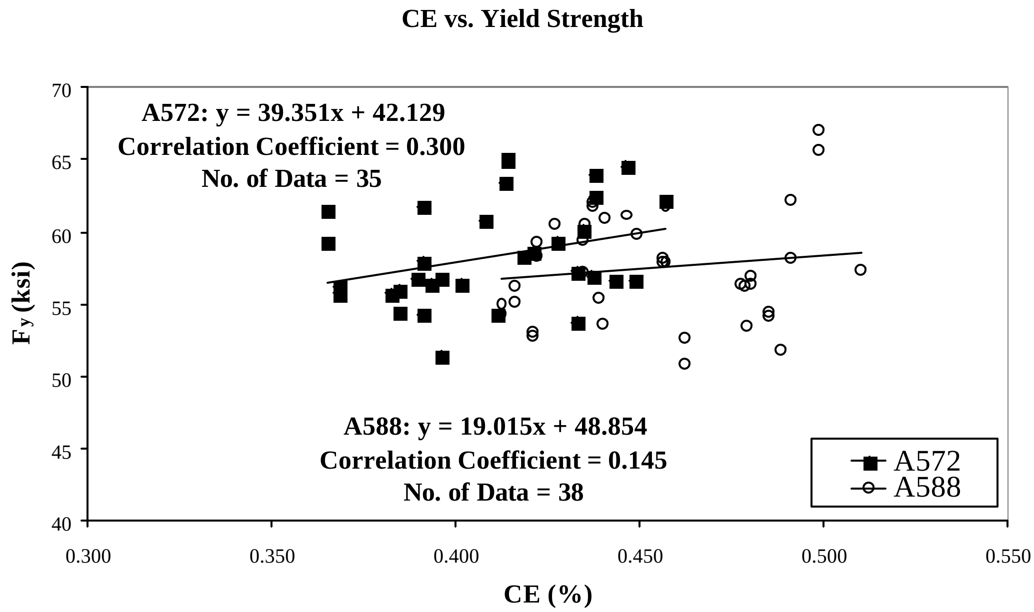


Figure 3.1: CE versus Yield Strength for the 4-Mill Group.

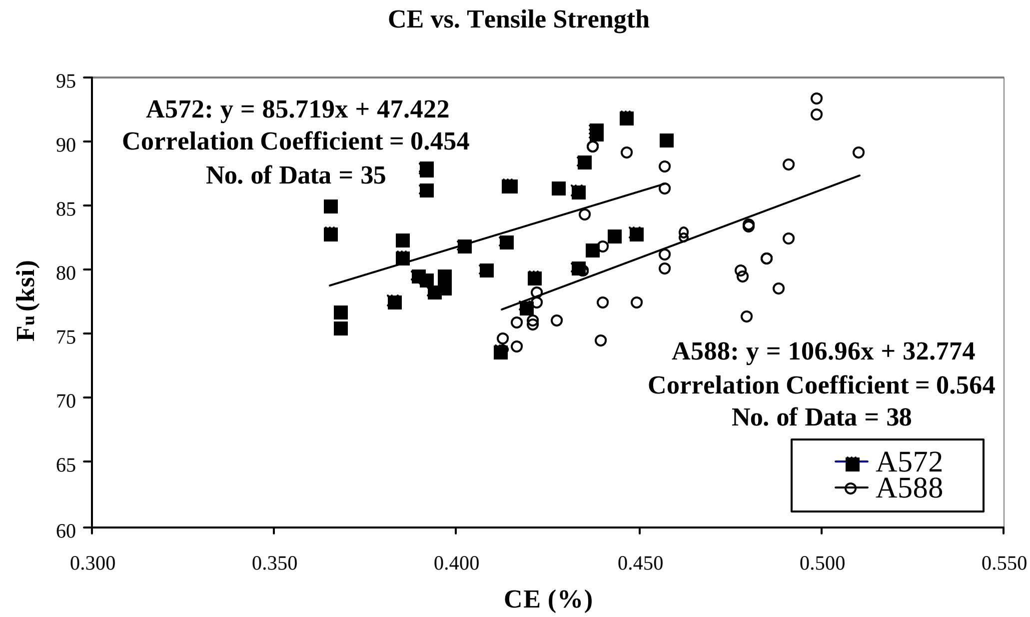


Figure 3.2: CE versus Tensile Strength for the 4-Mill Group.

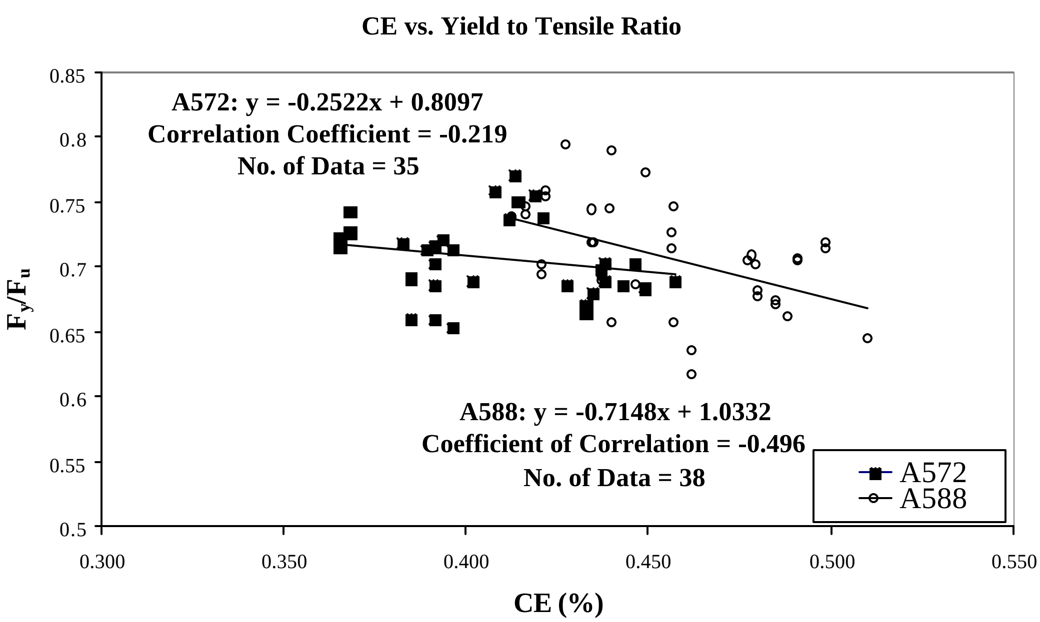


Figure 3.3: CE versus Yield to Tensile Ratio for the 4-Mill Group.

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.

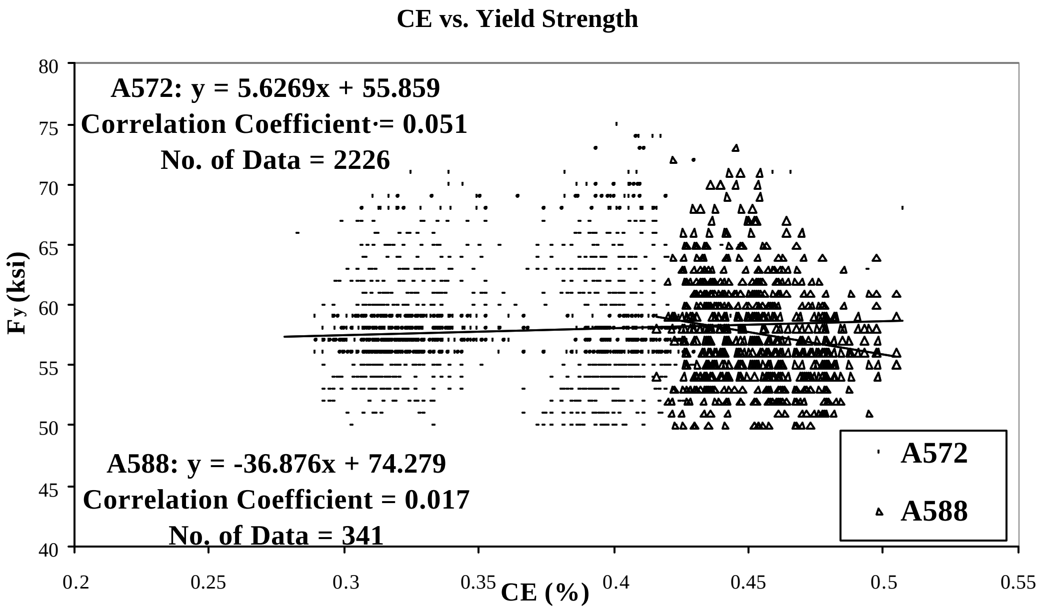


Figure 3.4: CE versus Yield Strength for the 2-Mill Group.

CE vs. Tensile Strength

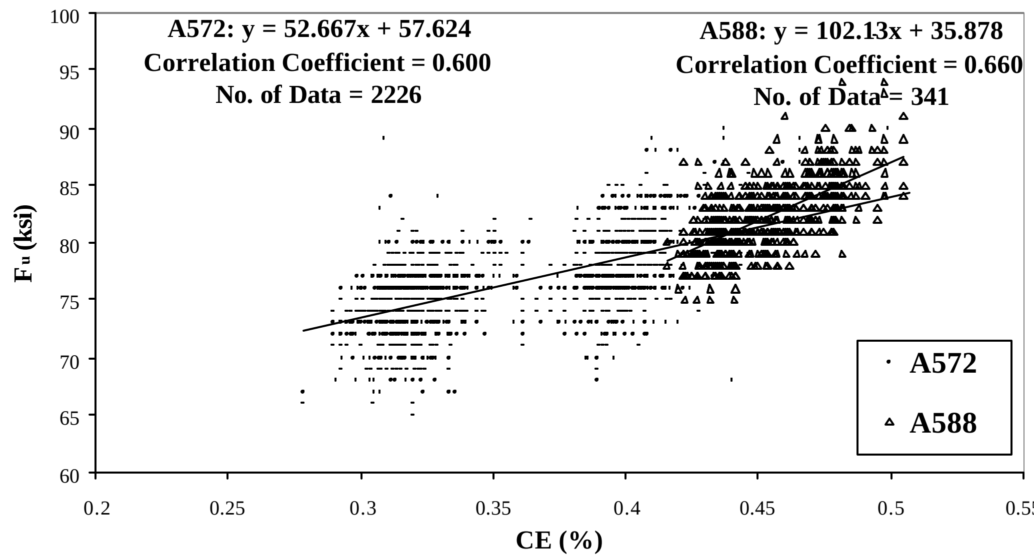


Figure 3.5: CE versus Tensile Strength for the 2-Mill Group.

CE vs. Yield to Tensile Ratio

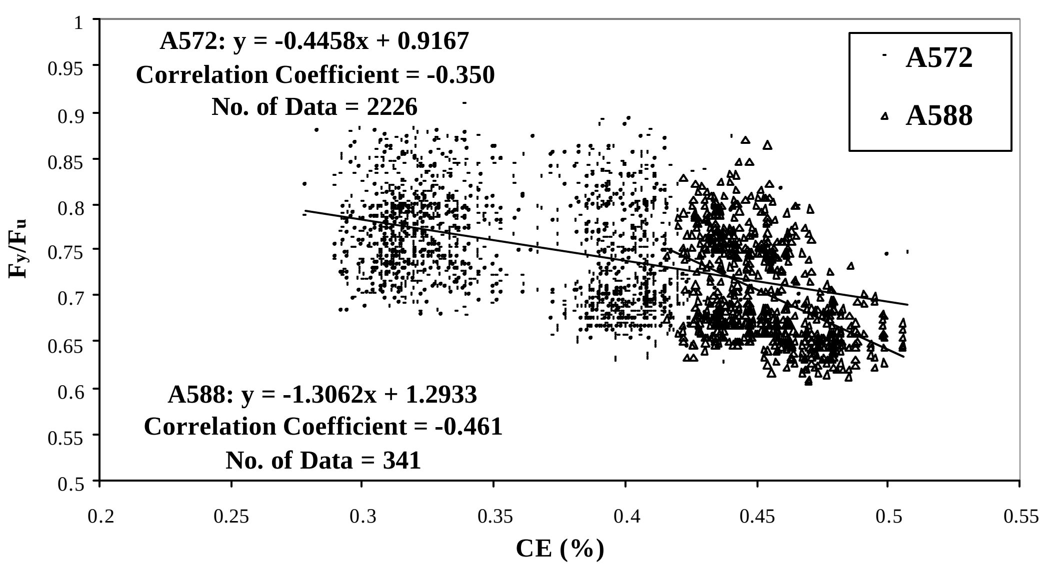


Figure 3.6: CE versus Yield to Tensile Ratio for the 2-Mill Group.

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.