MTR Survey of Plate Material Used in Structural Fabrication

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ABSTRACT

A statistical survey was made for a broad sample of mill test reports (MTR) of plate grades typically used in building construction including A36, A572, A588, A852, and A514 steels. Tensile properties, impact properties, and chemical compositions were analyzed. The tensile statistics agreed with assumptions made in the development of the AISC *Load and Resistance Factor Design Specification for Structural Steel Buildings* (LRFD *Specification*) (AISC, 1999). The yield-tensile ratios varied from 0.61 to 0.94, following the typical trend of increasing yield-tensile ratio with increasing strength level. The mean CVN values at 70ºF were generally over 100 ft-lbs. for all the steels, which is attributable to the fact that the toughness data were generally reported for product with specified minimum values. The minimum CVN values at 70ºF all met or exceeded the 20 ft-lbs. value specified by AISC for plate material over 2 in. thick used for built-up cross sections spliced with complete-joint-penetration groove welds and subjected to tension. The statistical analysis of composition generally indicated good weldability, particularly for A36 and A572 Grade 50.

INTRODUCTION

Periodic statistical analyses are useful in assessing the variability of mechanical properties, toughness, and chemical composition. An up-to-date knowledge of these properties is essential to the development of improved design specifications. For example, in the area of seismic design, inelastic behavior is anticipated and the expected level of the yield point of the various steels is important. Also, in the LRFD design of all structures, the variability of properties must be carefully evaluated to make sure the ϕ-factor is rationally selected. Consequently, AISC sponsored a statistical survey of mill test reports (MTR) for plate grades typically used in building construction. Included were tensile properties (yield point, tensile strength, yield-tensile ratio, and percent elongation), impact properties (Charpy V-Notch toughness), and chemical composition (carbon equivalent, AWS composition parameter P_{cm}, and sulfur content). Commercially available software was used for the data analyses, and comparisons were made to ASTM specification limits where applicable. The following steels over a thickness range of 0.188 to 4.00 in. were included: A36, A572 (Grades 50, 60, 65), A588, A852, and A514. The raw data were provided by three domestic steel producers for a one-year production period. In general, only representative data sets are provided in this paper. The complete data are available in final reports made to AISC.

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TENSILE PROPERTIES

A total of 38,575 sets of tensile data were included in the study. Table 1, which is for A36 steel over a thickness range of 0.188 to 0.75 in. (14,900 items), shows a typical set of statistical data generated. Figure 1 shows the accompanying histogram for yield point. The vertical bars indicate the frequency of occurrence in the sample, and the plotted points show the cumulative percent occurrence. The histograms generally trended toward bell-shaped distributions, but there were exceptions where the data covered a large thickness range.

Table 2 provides a summary of the statistics for yield point and yield-tensile ratio for all the steels and thickness ranges studied. It may be seen that the ratio of the mean yield point to the specified minimum varied with both grade and thickness. For example, for the two thickness ranges listed it was 1.3/1.2 for A36, 1.2/1.1 for A572 Grade 50 and A588, and 1.1/1.2 for A514. Figure 2 illustrates the variation in this ratio. The coefficient of variation (COV) ranged

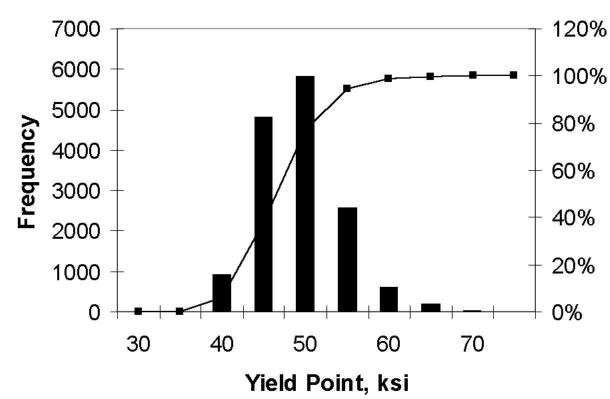

Fig. 1. Histogram for Yield Point of A36 Steel, 0.188 to 0.75 in. Thick (14,900 Values).

Table 1. Summary Statistics of Tensile Data for A36 Steel 0.188 to 0.75 in. Thick

Statistic	Yield Point, ksi	Tensile Strength, ksi	Yield-Tensile Ratio	Percent Elongation in 2 in.	Percent Elongation in 8 in.
Mean	46.88	67.89	0.6894	35.50	22.95
Standard Error	0.0395	0.0305	0.000376	0.1420	0.0303
Median	46.3	67.8	0.6833	33	22
Mode	46	68	0.6667	50	20
Std. Deviation	4.8265	3.7192	0.0459	8.0788	3.3761
Sample Variance	23.2954	13.8327	0.00211	65.2666	11.3977
Kurtosis	0.8129	0.4015	1.9787	-0.7248	1.8044
Skewness	0.6491	0.3941	0.8461	0.8048	0.9029
Range	35.6	28	0.4329	29	37
Minimum	36.0	58	0.5019	21	18
Maximum	71.6	86	0.9348	50	55
Sum	698522	1011674	10272	114835	285579
Count	14900	14900	14900	3235	12441
Confidence Level (95.0%)	0.0775	0.0597	0.000738	0.2785	0.0593
COV*	0.1030	0.0548	0.0666	0.2276	0.1471
Mean + 2SD	56.53	75.34	0.7813	51.66	29.71
Mean - 2SD	37.23	60.46	0.5976	19.34	16.20
Specified	*36 min.*	*58/80 min/max*	-	*24 min*	*20 min*

* COV = Coefficient of Variation.

Table 2. Mean Yield Point and Yield-Tensile Ratio for All Steels*

Steel	Nominal Thickness Range, in.	Specified Yield Point, Min, ksi	Specified Tensile Strength, Min/Max,ksi	Mean Yield Point*, ksi	COV for Yield Point	Mean Yield-Tensile Ratio	COV for Y-T Ratio
A36	0.188-0.75	36	58/80	46.9	0.103	0.69	0.067
A36	>0.75-4.00	36	58/80	43.1	0.088	0.61	0.080
A572-50	0.188-0.50	50	65	58.3	0.052	0.75	0.035
A572-50	>0.50-4.00	50	65	56.8	0.063	0.72	0.052
A572-60	0.375-1.25	60	75	67.8	0.060	0.74	0.048
A572-65	0.312-1.25	65	80	74.3	0.062	0.83	0.039
A588	0.312-2.00	50	70	59.1	0.090	0.74	0.066
A588	>2.00-4.00	50	70	55.5	0.059	0.67	0.038
A852	0.50-3.25	70	90/100	88.2	0.092	0.87	0.074
A514	0.188-2.50	100	110/130	113.6	0.051	0.94	0.017
A514	>2.50-4.00	90	110/130	109.0	0.056	0.90	0.022

* For A852 and A514 steel, replace Yield Point with Yield Strength.
COV = Coefficient of Variation.

from 0.05 to 0.10. These statistics appear to be in line with assumptions made in the development of the AISC LRFD *Specification*, where the mean yield point for plate material was taken as 1.10 times the specified value and the COV was taken as 0.11.

The yield-tensile ratios varied from 0.61 for A36 to 0.94 for A514, following the typical well-known trend of increasing yield-tensile ratio with increasing strength level. The yield-tensile ratio is a consideration in achieving plastic moment in flexural members and in net section criteria for tension members. The mean values of percent elongation were all well above specification minimum values.

IMPACT PROPERTIES

A total of 6,671 sets of Charpy V-Notch (CVN) data for longitudinal specimens were included. In accordance with ASTM A673, each data item for the statistics represents the

Table 3. Summary Statistics of Impact Data for A36 Steel

Temp., ºF	-20	-10	10	32	40	70
Thickness, in.	0.375-2.00	0.250	0.312-2.88	0.50-1.50	0.250-3.50	0.394-4.00
Mean	63.11	65.47	67.93	127.12	105.02	122.01
Standard Error	6.6329	1.8069	1.3611	6.0214	1.7703	4.3356
Median	59.01	62.06	62.00	123.33	94.67	112.5
Mode	59.01	54.97	46.33	98.33	78.33	151.0
Standard Deviation	35.72	11.14	31.89	44.66	49.16	53.10
Sample Variance	1276	124	1017	1994	2416	2820
Kurtosis	-1.0824	-0.5902	1.6034	-0.7825	0.2701	0.2178
Skewness	0.2576	0.6339	1.1061	0.3873	0.8112	0.7974
Range	123.0	44.3	198.3	169.7	264.9	215.0
Minimum	9.7	47.9	15.7	57.7	22.7	47.0
Maximum	139.6	92.2	214.0	227.3	287.6	262.0
Sum	1830	2488	37296	6991	80967	18301
Count	29	38	549	55	771	150
Confidence Level (95.0%)	13.59	3.66	2.67	12.07	3.48	8.57
COV	0.5660	0.1701	0.4694	0.3513	0.4681	0.4352
Mean + 2SD	134.54	87.75	131.72	216.43	203.33	228.21
Mean - 2SD	-8.33	43.20	4.15	37.80	6.70	15.81

average CVN toughness of three test specimens. The data are generally for full-size specimens with correction factors based on A673 applied where sub-size specimens were tested. Table 3, which is for A36 steel (1592 items) at the various test temperatures and thickness ranges indicated, illustrates the statistical data generated. Figure 3 shows the histogram for the CVN of A36 steel at 70ºF. In most cases the CVN histograms suggested a bell-shaped distribution, although some spikes were noted. It is important to note that the CVN data were generally only reported for materials with specified minimum toughness, so the data may not represent typical material without specified toughness. Some material received special processing such as controlled rolling or normalizing, and some was produced to additionally meet the A709 specifications for bridge steel.

Figures 4 through 9 show how the average CVN varied with thickness for three steels (A36, A572 Grade 50, and A588) at 40ºF and 70ºF. These plots also serve to illustrate the range of the CVN values and the distribution of thickness for those data groups. Although the scatter is rather large, there is an indication of decreasing CVN with increasing thickness for A36 and A572 Grade 50 steel. However, there is no discernable trend for A588 steel. Table 4 shows the mean values at 0ºF, 40ºF, and 70ºF determined in the present study for all the steels. In addition, mean values for A572 Grade 50 steel and A588 steel determined in earlier surveys of typical product are shown for comparison. In light of the fact that the present data are mostly for material ordered to a specified minimum toughness, it is not surprising that the values determined in the present study for

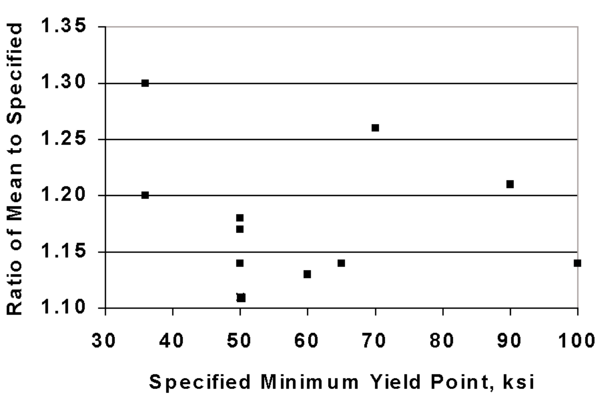

Fig. 2. Ratio of Mean to Specified Yield Point (38,575 Values).

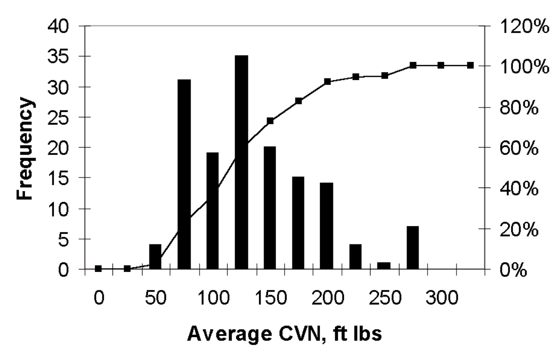

Fig. 3. Histogram for Average CVN of A36 Steel at 70ºF, 0.394 to 4.00 in. Thick (150 Values)

Table 4. Mean CVN Values (ft-lb)

Study	Steel	0ºF Test Temperature	40ºF Test Temperature	70ºF Test Temperature
Present	A36		105	122
Present	A572-50	94	118	138
Present	A588		133	141
Present	A852		141	105
Present	A514	94		82
1973-74*	A572-50	21	37	55
1983-84**	A572-50	21	36	54
1983-84**	A588	41	63	85

* For 1973-74 study, see "The Variation of Product Analysis and Tensile Properties - Carbon Steel Plates and Wide Flange Shapes," AISI, Washington, D.C., September 1979.

** For 1983-84 study, see "The Variations in Charpy V-Notch Impact Test Properties in Steel Plates," AISI, Washington, D.C., July 1989.

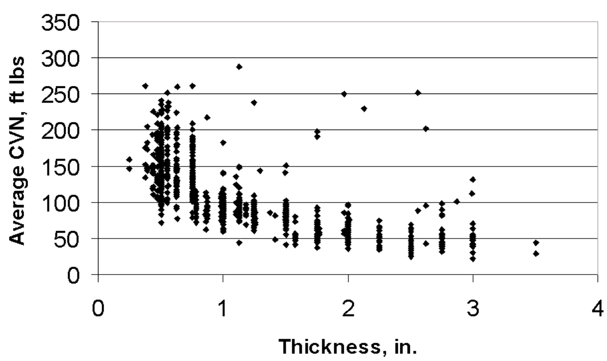

Fig. 4. CVN Trend with Thickness for A36 Steel at 40ºF (771 Values).

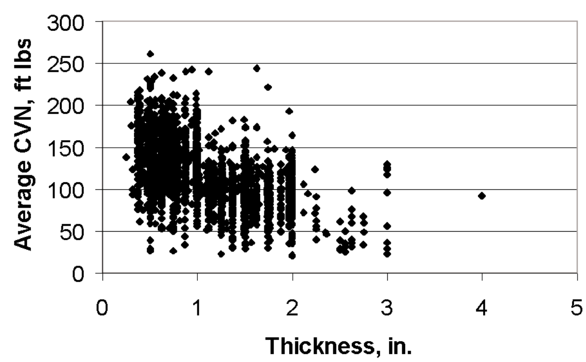

Fig. 6. CVN Trend with Thickness for A572-50 Steel at 40ºF (2400 Values)

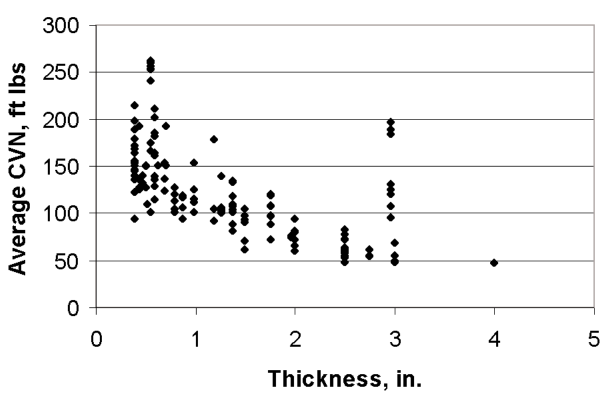

Fig. 5. CVN Trend with Thickness for A36 Steel at 70ºF (150 Values).

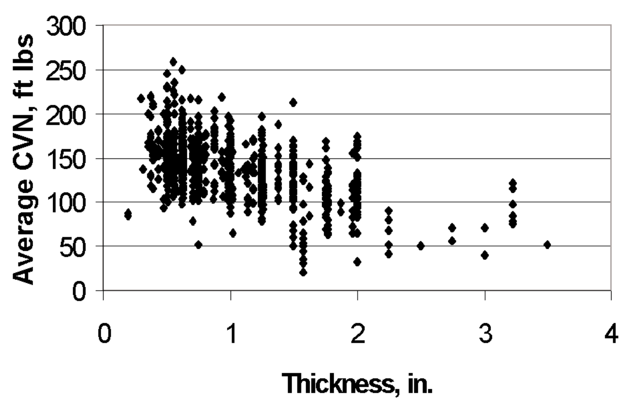

Fig. 7. CVN Trend with Thickness for A572-50 Steel at 70ºF (863 Values).

Table 5. Minimum CVN Values at 70ºF from Present Study

Steel	Thickness Range, in.	CVN, ft-lbs.
A36	0.39 - 4.00	47
A572-50	1.97 - 3.00	20
A588	0.50 - 2.25	67
A852	1.10 - 2.36	63
A514	2.36	75

Table 6. Summary Statistics for Composition of A36 Steel

Statistic	Carbon Equivalent, *CE*, %	Composition Parameter, P_{cm}	Sulfur Content, %
Mean	0.3533	0.2437	0.01254
Standard Error	0.000174	0.000137	0.0000240
Median	0.3483	0.2393	0.013
Mode	0.3383	0.2357	0.012
Standard Deviation	0.0234	0.0183	0.00322
Sample Variance	0.000547	0.000336	0.0000104
Kurtosis	2.9823	6.6773	0.35580
Skewness	0.8740	0.5070	0.07201
Range	0.3054	0.2185	0.02600
Minimum	0.1625	0.1028	0.00100
Maximum	0.4679	0.3212	0.02700
Sum	6360	4387	226
Count	18003	18003	18003
Confidence Level (95.0%)	0.000342	0.000268	0.0000471
COV	0.0662	0.0752	0.2572
Mean+2SD	0.4000	0.2803	0.0190
Mean-2SD	0.3065	0.2070	0.0061

those grades are much higher than those from the previous survey.

In the AISC LRFD and Allowable Stress Design (ASD) *Specifications* (AISC, 1999 and 1989), impact properties need only be specified for plate material over 2 in. thick used for built-up cross sections spliced with complete-joint-penetration groove welds and subjected to tension, and certain connections of such material. In these cases, a minimum CVN of 20 ft-lbs. at 70ºF must be specified (longitudinal specimens). Such properties are also required by the AISC *Seismic Provisions for Structural Steel Buildings* (AISC, 2002) in built-up cross sections of members in

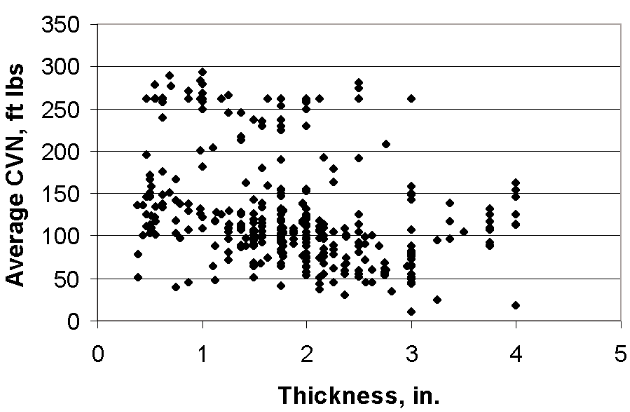

Fig. 8. CVN Trend with Thickness for A588 Steel at 40ºF (377 Values).

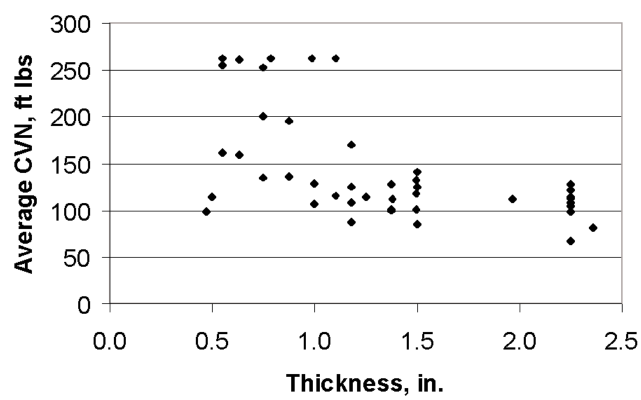

Fig. 9. CVN Trend with Thickness for A588 Steel at 70ºF (48 Values).

Table 7. Summary of Mean Composition Values for All Steels*

Steel	Carbon Equivalent, *CE*, %	Composition Parameter, P_{cm}	Sulfur Content, %
A36	0.35	0.24	0.013
A572-50	0.40	0.26	0.010
A572-60	0.46	0.31	0.007
A572-65	0.43	0.25	0.008
A588	0.46	0.25	0.007
A514-F	0.59	0.31	0.007
A514-B	0.49	0.29	0.008
A514-H	0.57	0.31	0.006
A514-Q	0.80	0.36	0.006
* Composition data for A852 steel was not available.			

Table 8. Summary of Mean + Two Standard Deviations for All Steels

Steel	Carbon Equivalent, *CE*, %	Composition Parameter, P_{cm}	Sulfur Content, %
A36	0.40	0.28	0.019
A572-50	0.46	0.31	0.016
A572-60	0.51	0.33	0.013
A572-65	0.45	0.27	0.010
A588	0.52	0.30	0.012
A514-F	0.62	0.33	0.011
A514-B	0.56	0.32	0.011
A514-H	0.59	0.33	0.008
A514-Q	0.83	0.37	0.009

the seismic load resisting system. Table 5 summarizes the minimum values at 70ºF from the present study for steels that were tested at that temperature. All met or exceeded the 20 ft-lb value.

CHEMICAL COMPOSITION

A total of 21,716 compositions were included in the study, which was focused on carbon equivalent (CE), composition parameter (P_{cm}), and sulfur content. Table 6, which is for A36 steel (18,003 items), illustrates the statistical data generated. Figures 10, 11, and 12 show the accompanying histograms. Table 7 provides the mean values of *CE*, P_{cm}, and sulfur content for all the steels, while Table 8 provides the Mean + 2SD (mean plus two standard deviations).

It should be noted that the typical chemical composition may vary with the steel making process. Shapes are most often made with electric arc furnaces (EAF) whereas plates are made with either basic oxygen furnaces (BOF) or EAF. The data included herein is mainly for BOF steel.

The carbon equivalent, *CE*, is considered to be an index of weldability, that is, the ability to weld a steel without cracking. It is defined in ASTM A6 by the following equation based on the percent of the indicated elements in the composition:

$$CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 \quad (1)$$

Decreasing values of *CE* indicate increasing weldability. However, the *CE* increases as carbon and/or alloying elements are added to increase tensile and other properties. The latest ASTM specification for structural shapes for building framing, A992/A992M with a specified minimum yield point of 50 ksi, sets a maximum *CE* of 0.47 percent for Group 4 and 5 shapes and 0.45 percent for other shapes. The *CE* is not usually specified for the other structural steels discussed herein, but the 0.45–0.47 percent level may be used as a reference point in discussing the present data.

Referring to Table 7, the mean *CE* was 0.35 percent for A36 steel, 0.40 percent for A572 Grade 50 steel, 0.46 percent for A572 Grade 60 steel, 0.43 percent for A572 Grade 65 steel, 0.46 percent for A588 steel, and 0.49 to 0.80 percent for the four grades of A514 steel. (The fact that the *CE* of A572 Grade 60 was less than that of A572 Grade 65 may seem atypical but the data are limited; 9 and 34 values, respectively.) Thus all fell at or below the 0.47 percent level discussed above except for the highest strength steel, A514. A review of the values of Mean + 2SD in Table 8 shows that only A36, A572 Grade 50, and A572 Grade 65 fell below the 0.47 percent level. Of course, both A36 and A572 Grade

50 have long been the most widely used steels in building construction.

The composition parameter, P_{cm}, is a similar type of index used to evaluate the susceptibility of cracking in welds. It is defined by the American Welding Society (AWS) by the following equation, also based on the percent of the indicated elements in the composition:

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5\,B \qquad (2)$$

Decreasing values of P_{cm} also indicate increasing weldability. For example, AWS D1.1 and D1.5 provide a "susceptibility index grouping" showing levels of susceptibility to cracking that depend on both the hydrogen level in the weld consumables and the P_{cm} of the steel. The P_{cm} values listed, indicating low to higher susceptibility, are as follows:

<0.18 %, <0.23 %, <0.28 %, <0.33 %, <0.38 %

Hydrogen control methods become increasingly important as the P_{cm} increases.

Referring to Table 7, the mean P_{cm}, was 0.24 percent for A36 steel, 0.26 percent for A572 Grade 50 steel, 0.31 percent for A572 Grade 60 steel, 0.25 percent for A572 Grade 65 steel, 0.25 percent for A588 steel, and 0.29 to 0.36 percent for the four grades of A514 steel. Thus, based on the mean values, most would fall in the middle AWS category discussed above (<0.28 percent), except for A572 Grade 60 and three of the four A514 steels, which would move up one category (<0.33 percent). A514-Q would move up two categories (<0.38 percent). A review of the values of Mean + 2SD in Table 8 shows that A36 and A572 Grade 65 would still fall in the <0.28 percent category, and all others would fall in the <0.33 percent category except for A514-Q in the <0.38 percent category.

The sulfur content is important in structural steels because it is known to decrease ductility, toughness, and weldability. Maximum levels are set by ASTM specifications as follows:

A36, A572, A588	0.05 %
A852	0.04 %
A514	0.035 %
	(lower for grades S and T)

Significantly, all sulfur levels were well below the specification limits. The means were all 0.013 percent or less for all steels and the Mean + 2SD values were all 0.019 percent or less.

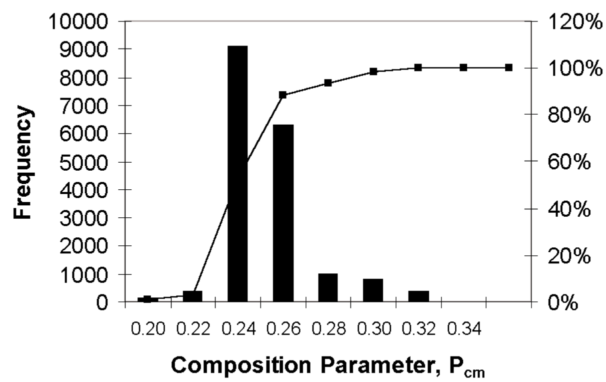

Fig. 11. Histogram for Composition Parameter of A36 Steel (18,003 Values).

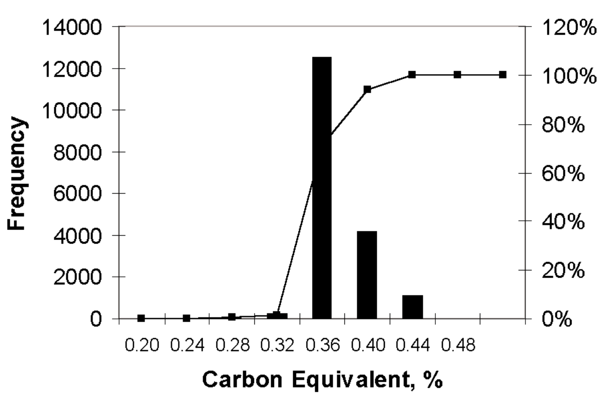

Fig. 10. Histogram for Carbon Equivalent of A36 Steel (18,003 Values).

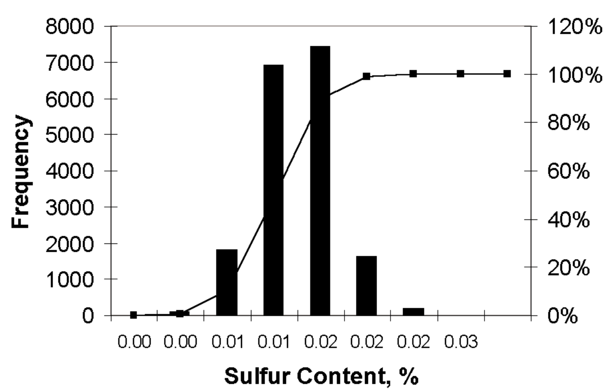

Fig. 12. Histogram for Sulfur Content of A36 Steel (18,003 Values).

CONCLUSIONS

The statistical analysis of tensile properties showed that the ratio of the mean yield point to the specified minimum varied from 1.1 to 1.3, while the COV for the yield point varied from 0.05 to 0.10. These statistics appear to be in line with assumptions made in the development of the AISC LRFD *Specification*, where the mean yield point for plate material was taken as 1.10 times the specified value and the COV was taken as 0.11. The yield-tensile ratios varied from 0.61 for A36 to 0.94 for A514, following the typical well-known trend of increasing yield-tensile ratio with increasing strength level. The mean values of percent elongation were all well above specification minimum values.

The statistical analysis of impact properties showed that the mean CVN values at 7 ºF were generally over 100 ft-lbs. for all the steels. This relatively high level is attributable to the fact that the data were mainly for product that had been ordered with specified toughness values. The minimum values at 70ºF all met or exceeded the 20 ft-lbs. value specified by AISC for plate material over 2 in. thick used for built-up cross sections spliced with complete-joint-penetration groove welds and subjected to tension.

The statistical analysis of composition indicated good weldability. The mean CE for all steels desirably fell at or below a reference value of 0.47 percent level except for the highest strength steel, A514. Also, the mean P_{cm} for most of the steels fell in the middle AWS category except for A572 Grade 60 and most A514 steels. All sulfur levels were well below specification limits.

ACKNOWLEDGMENTS

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