Study of the Material Properties Associated with the Web – Flange Transition Region of Rolled Shapes

by

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Study of the Material Properties Associated with the

Web – Flange Transition Region of Rolled Shapes

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Chapter 1: Project Overview

1.1 PROJECT INTRODUCTION

The SAC Steel Project has funded research into the material properties of rolled shapes in part to understand the impact that tremendous changes in the manufacturing process have had, and in response to the cracking problems in the K-line region that have been experienced in recent earthquakes. The research project conducted by Jasquess (1998) entitled "Characterization of the Material Properties of Rolled Sections" studied the general properties including dimensions, toughness, tensile strength, and chemical composition of several rolled shapes from four producers. This project focused on the material properties associated with the web–flange transition region where cracking problems have been observed. The testing conducted in this project was performed on the same rolled shapes used in the Jasquess study allowing direct comparison and utilization of data from both projects.

1.2 OVERVIEW

This project studied the material properties of the web–flange transition regions of eighteen rolled shapes produced by four mills. The first phase of the project was to investigate the hardness characteristics of this region. Hardness testing was conducted on thirty-four "T – shaped" specimens – two specimens each (top and bottom) from 16 rolled shapes along with one specimen each from two additional rolled shapes. The study focused on the changes in hardness near the web and flange surfaces and with changes occurring through the flange thickness.

The second phase investigated the Charpy V-Notch toughness characteristics of the peak hardness regions discovered in the first phase. Nine rolled shapes were identified as having a peak hardness near the K-line region sufficiently high enough to warrant further investigation. One additional rolled shape, demonstrating uniformity in hardness, was selected as a base for comparison. Six to eight specimens were machined from three locations of each rolled shape: the top and bottom K-line regions and the center region of the web. A total of 214 specimens, each oriented in the transverse-longitudinal (T-L) direction, were tested. A comparison between the longitudinal-transverse (L-T) and the T-L direction was made.

The third phase of the project was an investigation of the tensile properties in the K-line region of the W24x62 rolled shapes. These shapes demonstrated high peak hardness and poor toughness. Also investigated were the tensile properties at the standard one-quarter flange thickness (t/4) and center flange locations of wide flange shapes produced using the Quenched Self Tempered (QST) process by Mill T. The hardness study of these shapes showed a considerable difference in hardness between the high hardness regions near the flange surfaces and low hardness regions in the center of the flange. Table 1.2.1 summarizes the tests performed for each particular shape and producer.

	Test Performed	Rolled Shape							
		W14x211	W14x311	W24x62	W24x162	W27x84	W30x211	W36x150	W36x300
Mill B	Hardness	X	X					X	X
	Toughness	X							
	Tensile	X							
Mill C	Hardness			X					
	Toughness			X					
	Tensile			X					
Mill N	Hardness	X		X		X	X	X	X
	Toughness			X		X		X	
	Tensile			X					
Mill T	Hardness	X	X		X		X	X	X
	Toughness	X	X		X		X		X
	Tensile	X	X				X		X

Table 1.2.1: Shapes, Producers, and Tests Performed in Project

Chapter 2: Hardness Testing of Web-Flange Transition Area

2.1 INTRODUCTION

The hardness characteristics of the web – flange transition regions of the rolled shapes in this study were obtained from the Rockwell Hardness Test procedure described in ASTM E18. The testing program consisted of 34 “T” shaped specimens with approximately 6 inches of flange, 3 inches of web, and the web-flange transition region produced from 8 different sized rolled shapes obtained from 4 different mills. Table 2.1.1 shows the mill and rolled shape that each specimen was taken from. The first digit of the nomenclature identifies the Mill (with the exception of M – a beam from Mill N obtained from Michigan). The second digit was randomly assigned. The last digit refers to the top and bottom K-line regions and labeled 1 and 3 respectively.

Rolled Shape	Mill B	Mill C	Mill N	Mill T
W14x211	B1-1 B1-3		N4-1 N4-3	T4-1 T4-3
W14x311	B2-1 (one only)			T6-1 T6-3
W24x62		C1-1 C1-3	N1-1 N1-3	
W24x162				T1-1 T1-3
W27x84			M1-1 M1-3	
W30x211			N2-1 N2-3	T2-1 T2-3
W36x150	B4-1 B4-3		NA-1 NA-2 N5-1 N5-3	T5-1 T5-3
W36x300	B3-1 B3-3		N3-1 (one only)	T3-1 T3-3

Roller Straightened
Quenched Self Tempered - QST

Table 2.1.1: Hardness Testing Program by Mill and Rolled Shape

2.2 INSTRUMENT CALIBRATION

The Rockwell Hardness Testing Machine used in the testing program was serviced and certified by a qualified independent source. At the beginning of each testing day, the procedure for periodic checks by the user in conformance with ASTM E18 sections14.1.1-3 was performed. The standardized test block used for this test had a mean hardness value of 97.0 HRB. The tolerance for this test block was ± 1.0 HRB. All checks performed met this criterion. The instrument was equipped with a B scale standard indenter and a 1½ inch diameter flat plate anvil.

2.3 SPECIMEN GEOMETRY AND LOCATION

Each of the 34 specimens was cut from a section of the rolled shape. Figure 2.3.1 shows the location and geometry of the "T" shaped specimens used. Specimens were taken from the top and bottom of each rolled shape tested (with the exception of one each from B2 and N3) for further comparison. The approximate size of each "T" specimen was $6 + t_w$ inches in the flange portion by $3 + t_f$ inches in the web direction by 7/16 inches thick. This size was determined to be adequate to study the variation in hardness along lines in the web as well as lines through the flange. Variations in hardness tended to settle down well before reaching the extent of the sample size. Initially, larger sample sizes were tried and found to be both cumbersome and unnecessary. A specimen thickness of much less than 7/16 inches could have been used and still comply with ASTM 318 specification. The 7/16 inch thickness was selected since it was easier to fabricate.

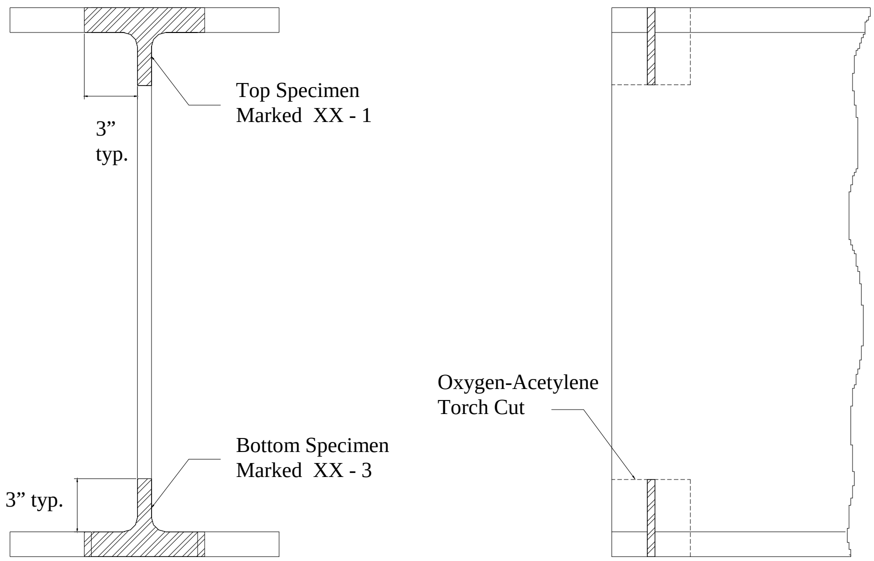

Figure 2.3.1: Location and Geometry of Typical Hardness Specimen

2.4 SPECIMEN MANUFACTURE

The specimens were cut out of the rolled sections using an Oxygen-Acetylene torch while keeping the cut at a minimum of 2 inches from the faces of the specimen. No specification was found for this minimum distance parameter with respect to hardness testing; however, the concept of reducing the effect on test results caused by torch cutting was adapted from the ASTM E23 specifications for Charpy V-Notch bar specimens.

The specimens were sliced out of the larger torch cut blocks using a horizontal band saw. The resulting saw cut faces on each side of the specimen were ground in accordance with sections 6.1-3 of ASTM E18.

2.5 LAYOUT OF TEST SPECIMEN

The research focused on the areas nearest to the surfaces of the rolled shapes in both the web and flange portions. It is in this area that the higher hardness values in a section are generally found. Also, the effects of the final roller straightening process (accomplished with or without surface deformations) would be prominent near the surfaces. A 0.2 inch grid spacing provided a reasonable and smooth representation of the hardness variations within the specimen while conforming to the minimum space requirements as set forth in ASTM E18 section 7.9. This grid was centered on each specimen such that a minimum edge distance of 1/8 inch was maintained (in conformance with ASTM E18 section 7.9.1). Flange through-thickness lines of data spaced 1 inch apart and maintaining the aforementioned grid spacing were taken and evaluated when the near surface test data warranted a further investigation.

Templates were made for each rolled shape tested. These templates consisted of full-scale drawings of each section with holes punched out for each data point. The data points were transferred to each section by aligning the template on the section and using a felt tip marker to mark the locations. Figure 2.5.1 shows a typical specimen layout.

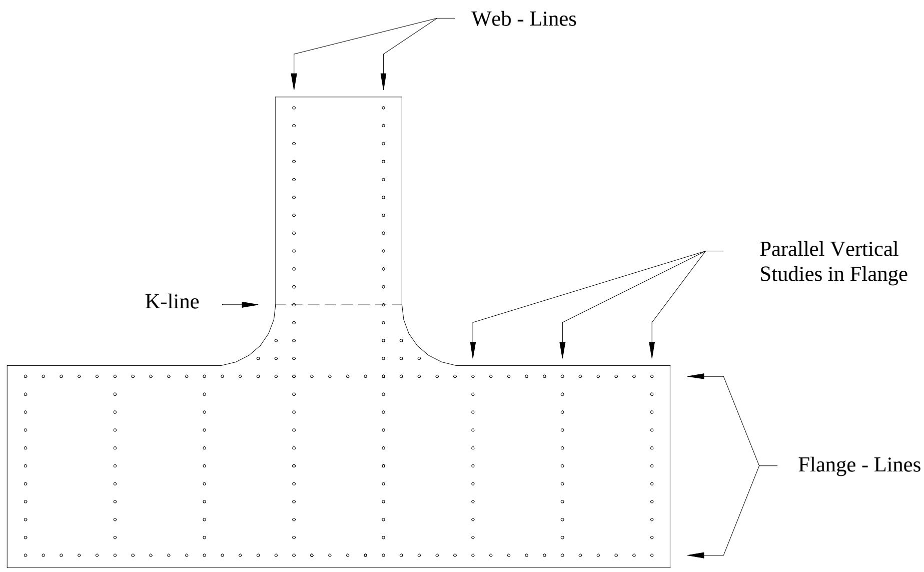

Figure 2.5.1: Typical Hardness Specimen Data Point Layout

2.6 SCOPE OF ANALYSIS

The hardness testing conducted encompassed eight different sized rolled shapes. With each shape having different web and flange thickness and different web to flange thickness ratios, factors which may have a bearing on the outcome (due primarily to the final straightening process), comparisons will initially be made on a per shape basis. The four mills supplying shapes to this project employed two different manufacturing methods. For this reason, a comparison by mill will follow the shape comparison.

2.7 METHODOLOGY OF ANALYSIS

Test data was taken as stated in section 2.5 on a 0.2 inch grid layout. Data was viewed as being in one of three groups, lines of data parallel to the web, lines parallel to the flange, and a survey of vertical parallel lines within the flange. Two lines of data parallel to the face of the web were taken (the W24x62 rolled shape had only one line of data due to its small web thickness). Two lines of data parallel to the flange face were also taken. Four lines of data through the flange thickness parallel to the web and spaced one inch on center from the web data lines were taken on the rolled shapes that were greater than 150 pounds per linear foot. Figure 2.5.1 identifies these three groups of data.

Figure 2.7.1 is a typical plot of Rockwell hardness versus position within data lines that are parallel to the web. A plot for each specimen tested can be found in Appendix B. The plot contains a vertical axis of hardness values with a set range of 60 to 100 HRB units. HRB units are used for all hardness tests and only the number will be used in the subsequent paper. The distance in inches from the outside flange face is plotted on the horizontal axis. A solid vertical line and a dashed vertical line are plotted indicating the inside flange face and the K-line positions respectively. The data along the web-lines are plotted as small filled circles. The average of this data is shown as a solid line going through the data points plotted. The four parallel vertical surveys within the flange are plotted as small filled triangles, the average of this data being represented with a dashed line. The hardness values obtained from specimen B1 from Mill B shown in Figure 2.7.1 exhibits considerable uniformity. Careful examination of the filled circle data points (especially toward the right side of the graph) will show that two data points exist for each position. Much of the data overlaps making it difficult to discern that there are two web-lines of data represented. The solid line is an average of these two web-lines.

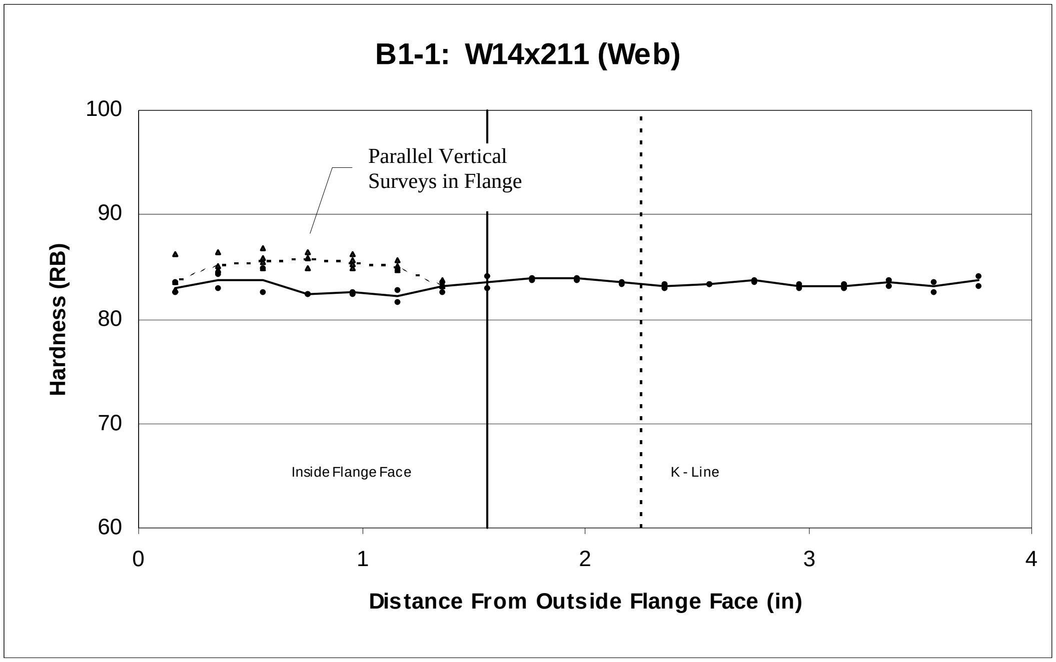

Figure 2.7.1: Typical Web Region Rockwell Hardness Plot

Figure 2.7.2 is a typical graph showing each mill's performance for the same rolled shape. The vertical and horizontal axis, along with the inside flange face and the K-line are presented in the same manner as the individual specimen graphs represented by Figure 2.7.1 and contained in Appendix B. The web-line averages of individual specimens (represented by solid lines in the previously noted figures) have been plotted together for each rolled shape. The top and bottom of most of the rolled shapes were tested (all but B2 and N3 where only the top was tested). Plotting the averages of each specimen in this manner allows a direct comparison between the top and bottom of a particular rolled shape to be made along with comparisons between mills. The three pairs of web-line averages depicted in Figure 2.7.2 show good uniformity between the top and bottom of each rolled shape tested. The top and bottom nomenclature was instigated for record keeping. Distinguishing between the top and bottom web-line averages in this graph was deemed unimportant.

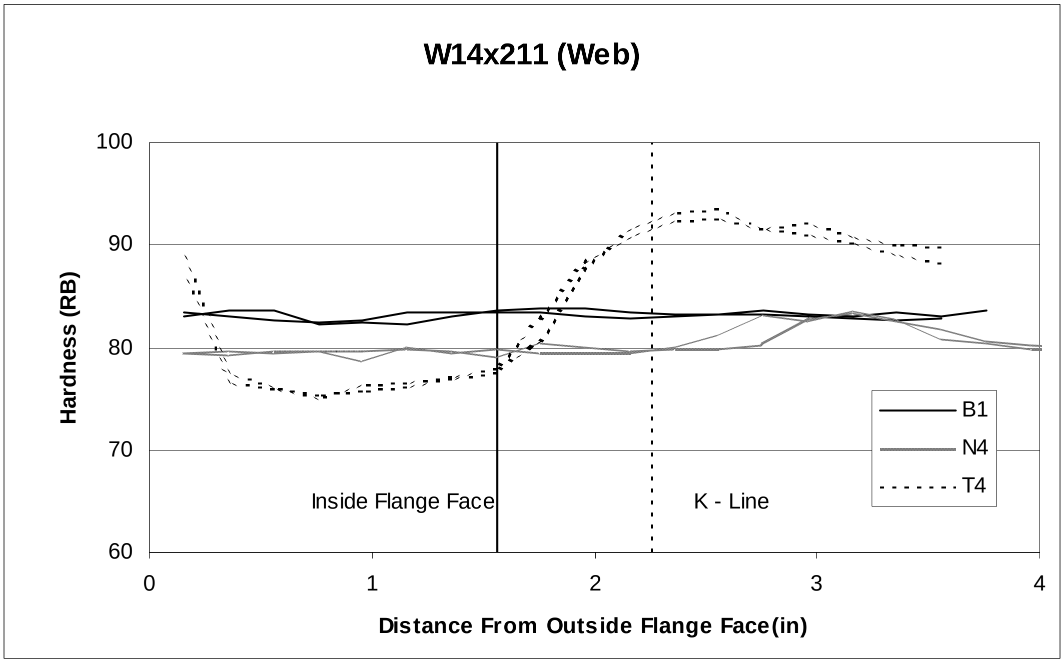

Figure 2.7.2: Typical Web Region Rockwell Hardness Test Results by Shape

Typical representation of the two lines of data going through and parallel to the flange is shown in Figure 2.7.3. The vertical axis is the same as in Figure 2.7.1. The horizontal axis depicts the distance in inches from the center (shown as a centerline) of the web. The two solid vertical lines in the figure depict the theoretical web face locations or web thickness. The data points and average line are shown in the same manner as in Figure 2.7.1.

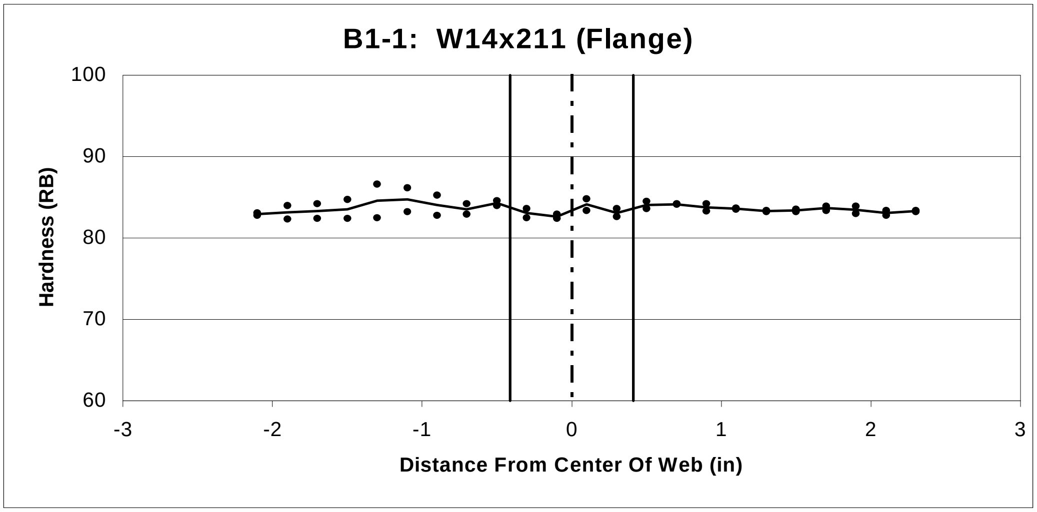

Figure 2.7.3: Typical Flange Region Rockwell Hardness Plot

Figure 2.7.4 shows a typical plot for the flange region showing the top and bottom flange-line averages per shape and mill in the same manner as was done for the web region in Figure 2.7.2.

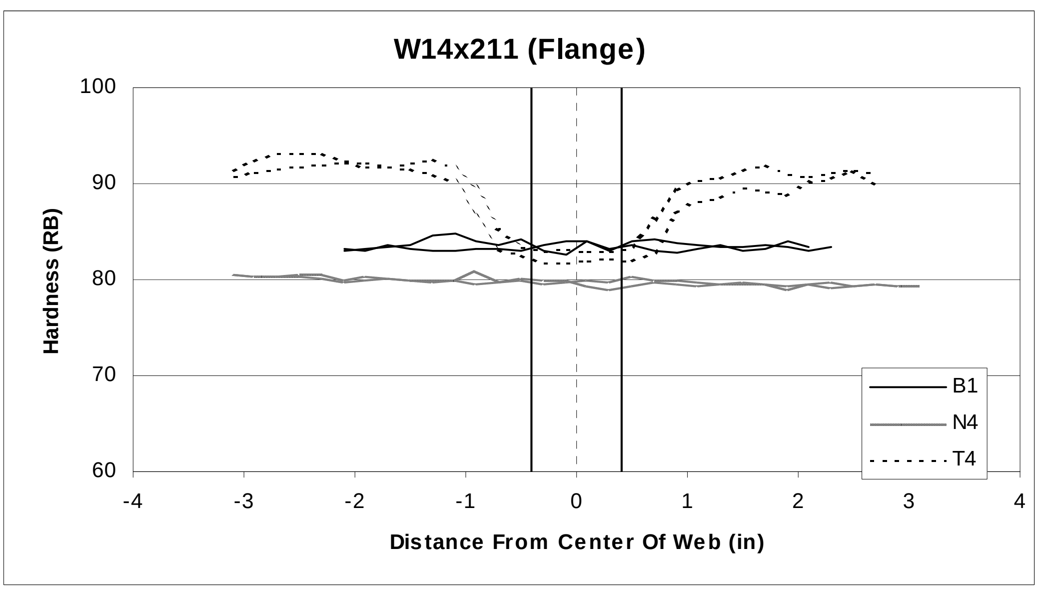

Figure 2.7.4: Typical Flange Region Rockwell Hardness Test Results by Shape

2.8 ANALYSIS OF HARDNESS TEST RESULTS

Figures 2.8.1 through 2.8.16 summarize graphically the results by rolled shape as described in section 2.7. Several observations become apparent when viewing the graphs for the W14x211 shape (Figures 2.8.1 and 2). Mill B is quite uniform in both the web and flange regions showing no unusual areas and an average of approximately 84. Mill N exhibits virtually the same behavior as mill B except for a slightly higher hardness region around an inch past the K-line into the web. This region peaks at about 85, 5 units above the web average of 80. The results for Mill T, however, vary extensively. The specimens demonstrate a substantial peak at the K-line region and a marked trough in the through thickness of the flange. A peak value of about 94 and a low value of 73 in the trough area (throughout the flange – see Appendix B) were found. This gives the range from the trough to the peak of 21 over a distance of less than 1 ½ inches. The skin areas of both the web and flange outside of the transition zone remain high in the region of about 90 to 94.

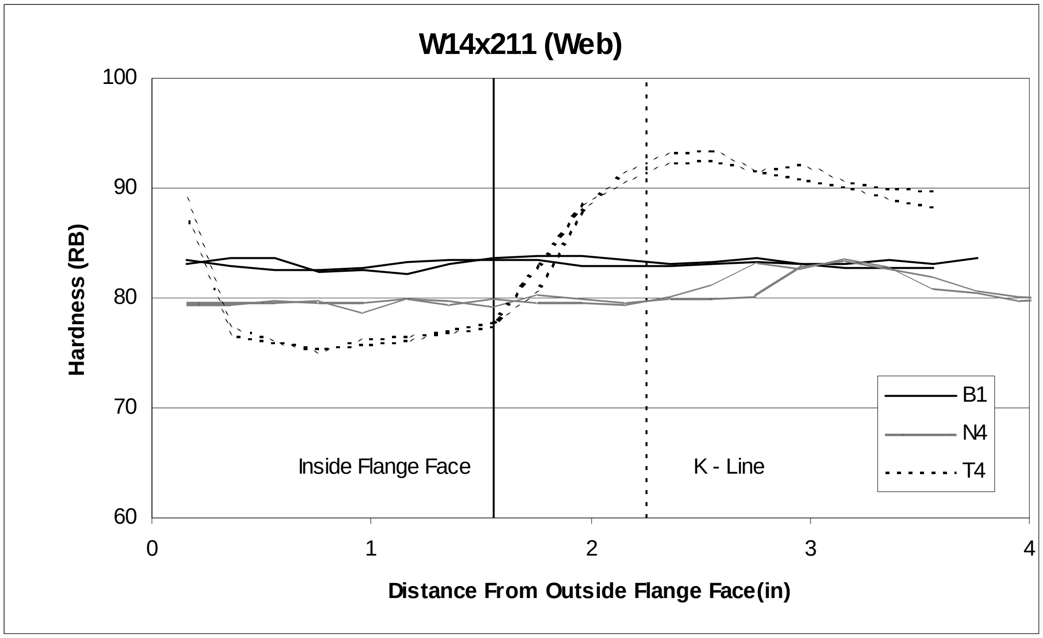

Figure 2.8.1: Web Region Rockwell Hardness Test Results for W14x211

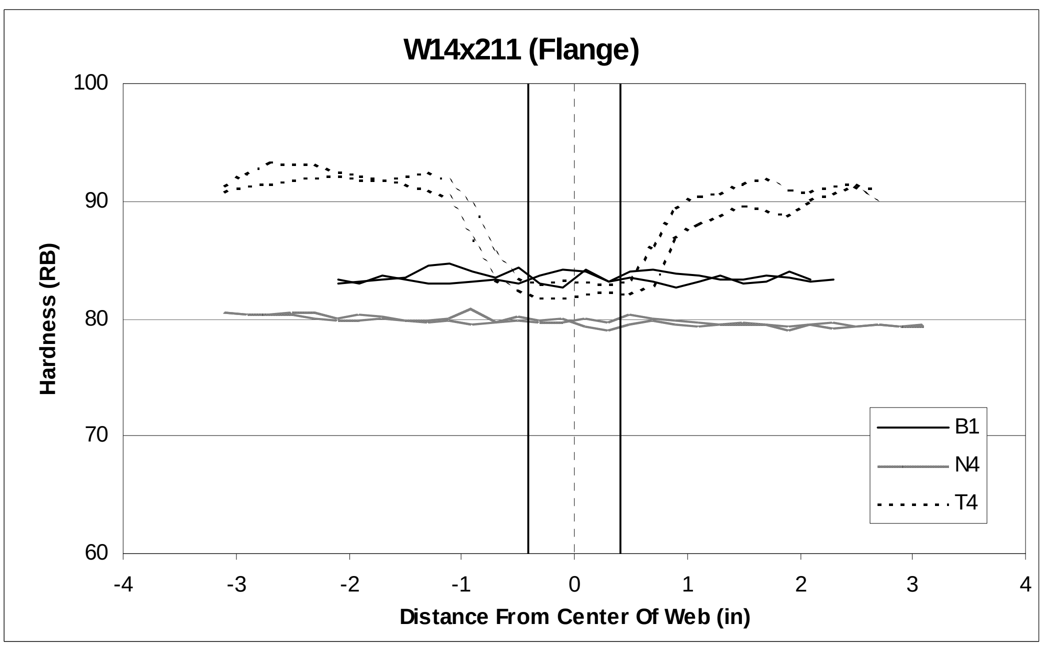

Figure 2.8.2: Flange Region Rockwell Hardness Test Results for W14x211

Figures 2.8.3 through 10 show the results of the W14x311, W36x300, W30x211, and W24x162 shapes respectively. The results tend to be a duplicate of the W14x211 shape in that mills B and N (where applicable) demonstrate a general uniformity throughout the web and flange regions with narrow maximum to minimum range of 5 or less. Average hardness values for mills B and N for these shapes fall between about 81 to 85 with the exception of mill N for the W30x211 shape at 88. Mill T exhibits the same general trough and peak shapes found in the W14x211 rolled shape. What varies for Mill T are the range and the vertical shift. The ranges vary from 18 to 22 in the web regions and from 18 to 25 in the flange regions.

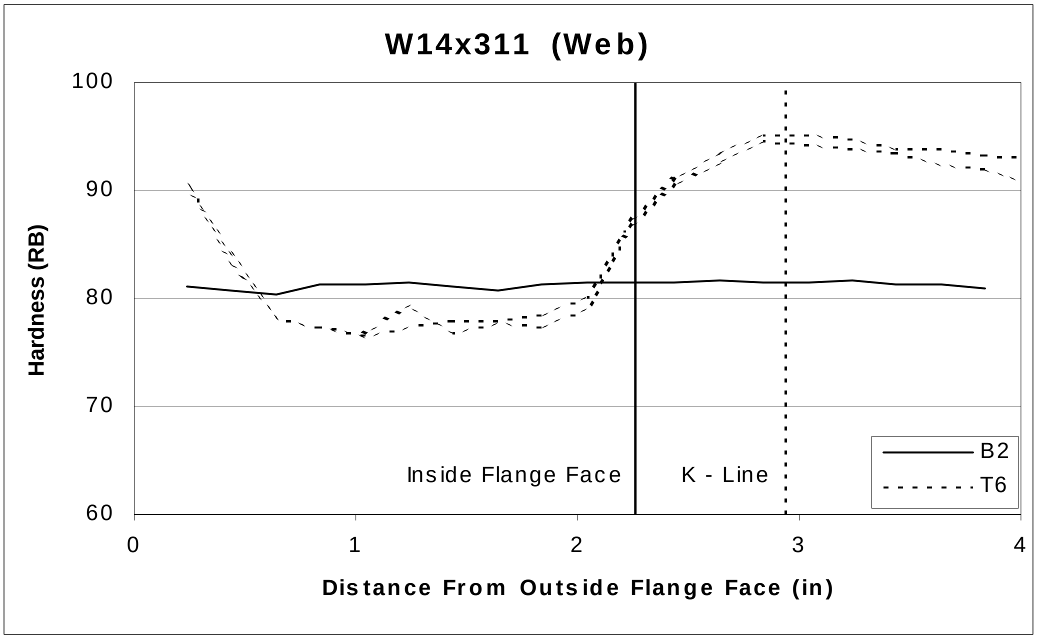

Figure 2.8.3: Web Region Rockwell Hardness Test Results for W14x311

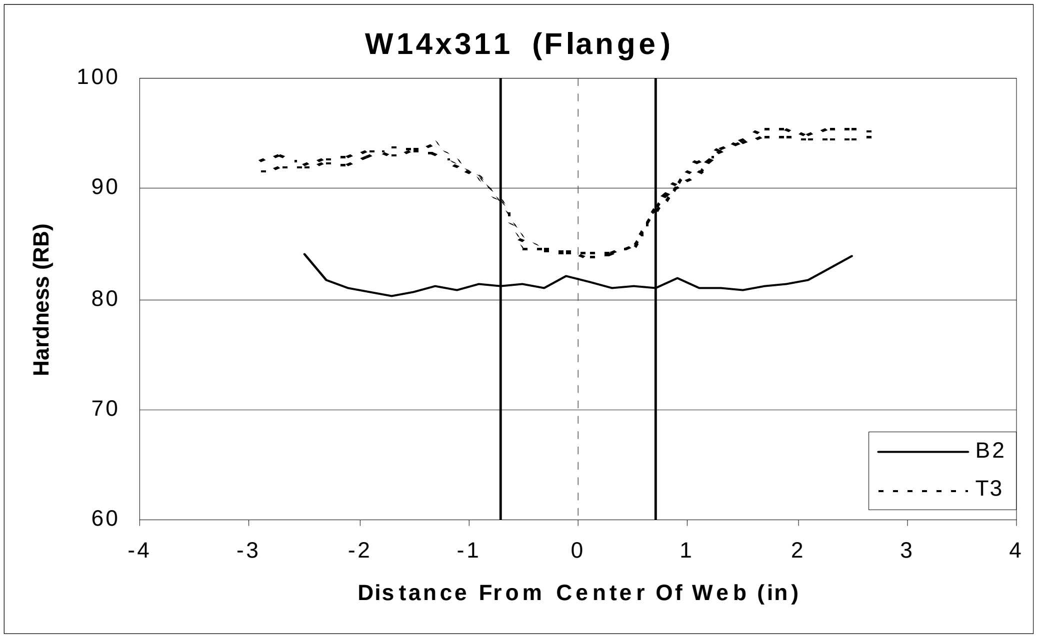

Figure 2.8.4: Flange Region Rockwell Hardness Test Results for W14x311

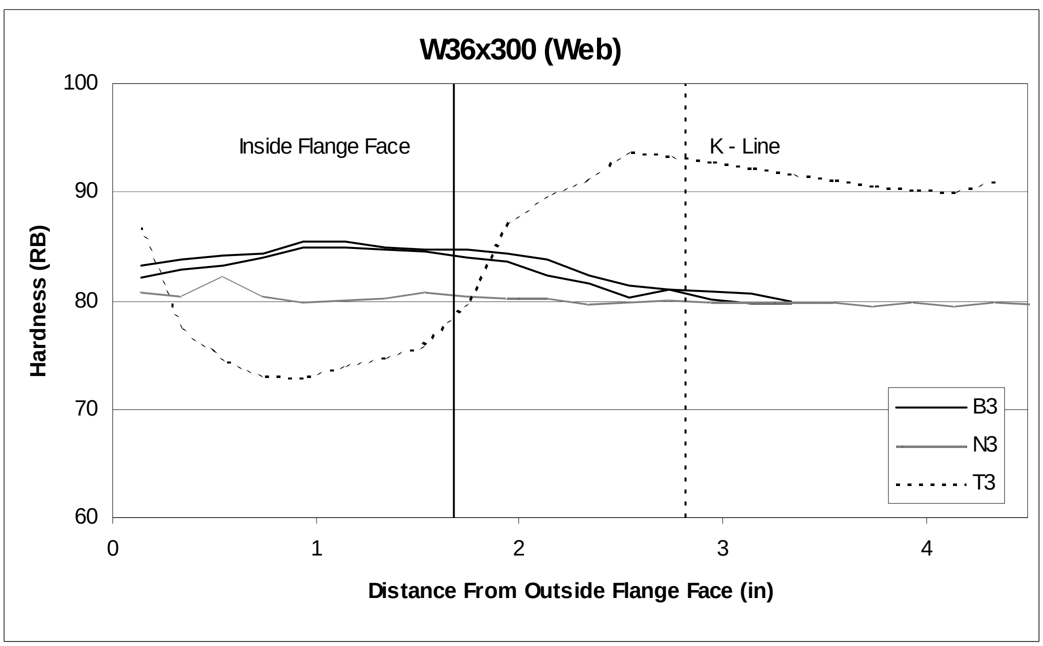

Figure 2.8.5: Web Region Rockwell Hardness Test Results for W36x300

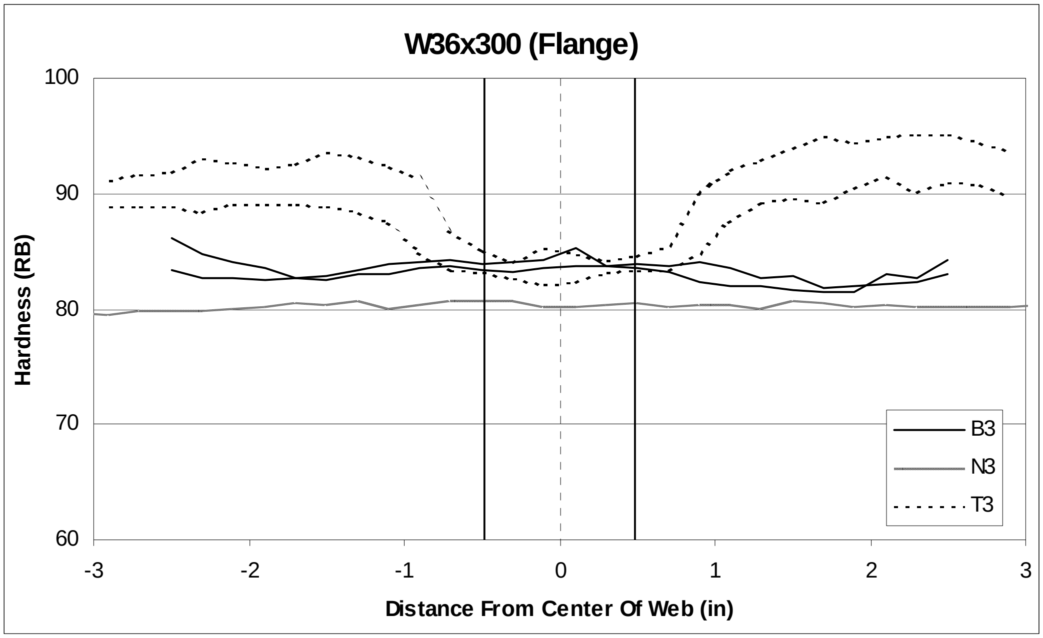

Figure 2.8.6: Flange Region Rockwell Hardness Test Results for W36x300

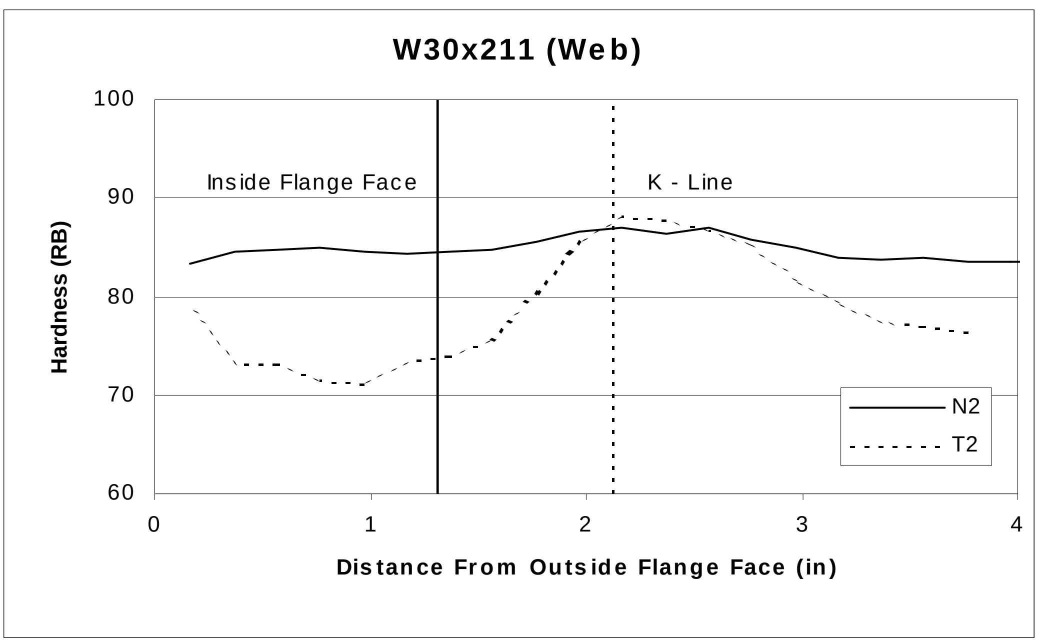

Figure 2.8.7: Web Region Rockwell Hardness Test Results for W30x211

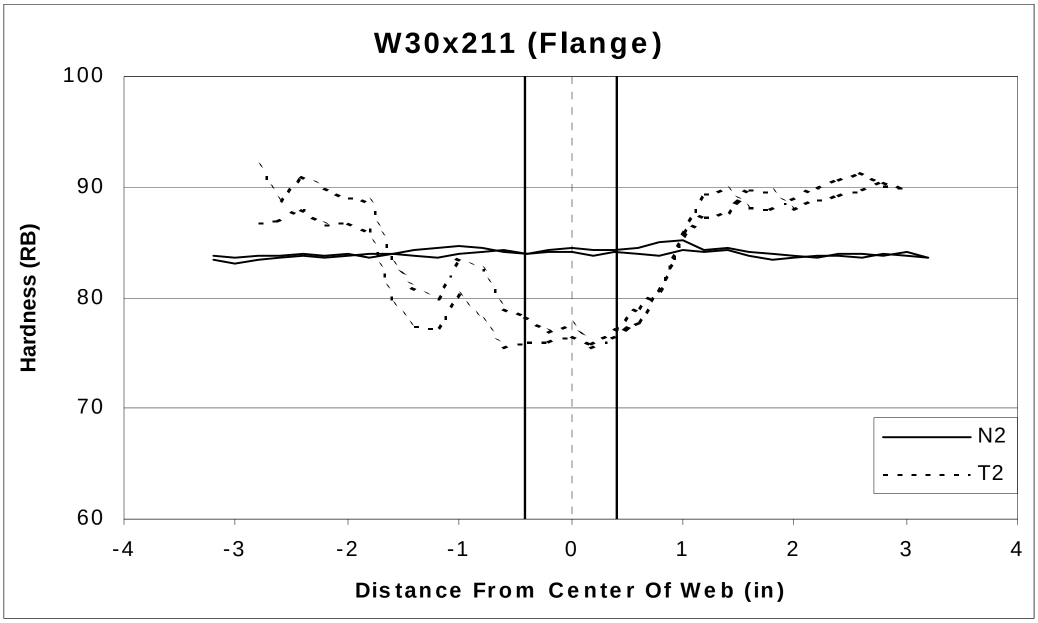

Figure 2.8.8: Flange Region Rockwell Hardness Test Results for W30x211

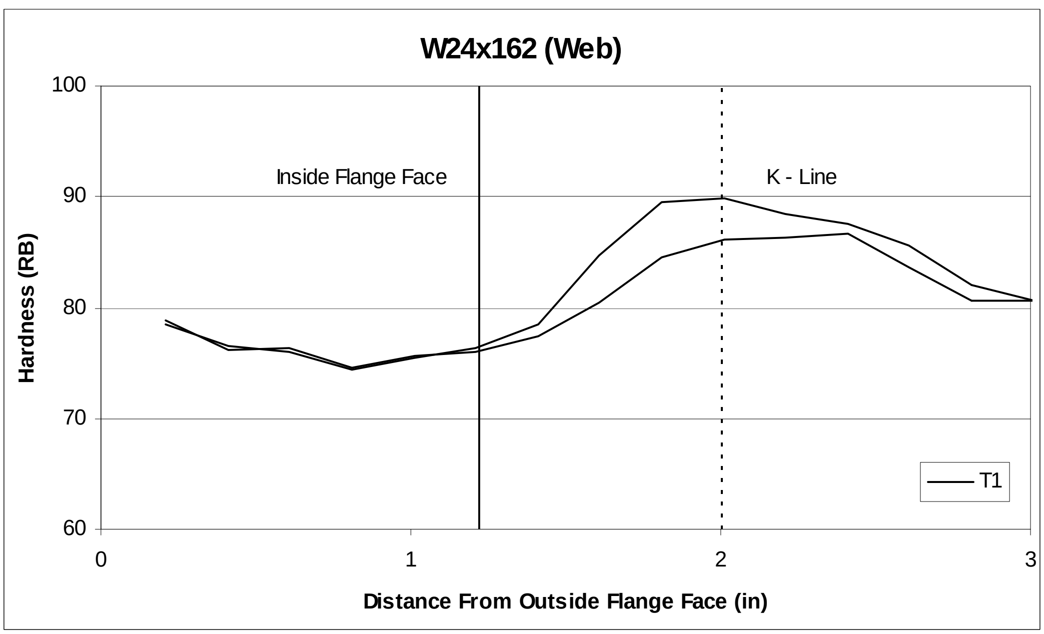

Figure 2.8.9: Web Region Rockwell Hardness Test Results for W24x162

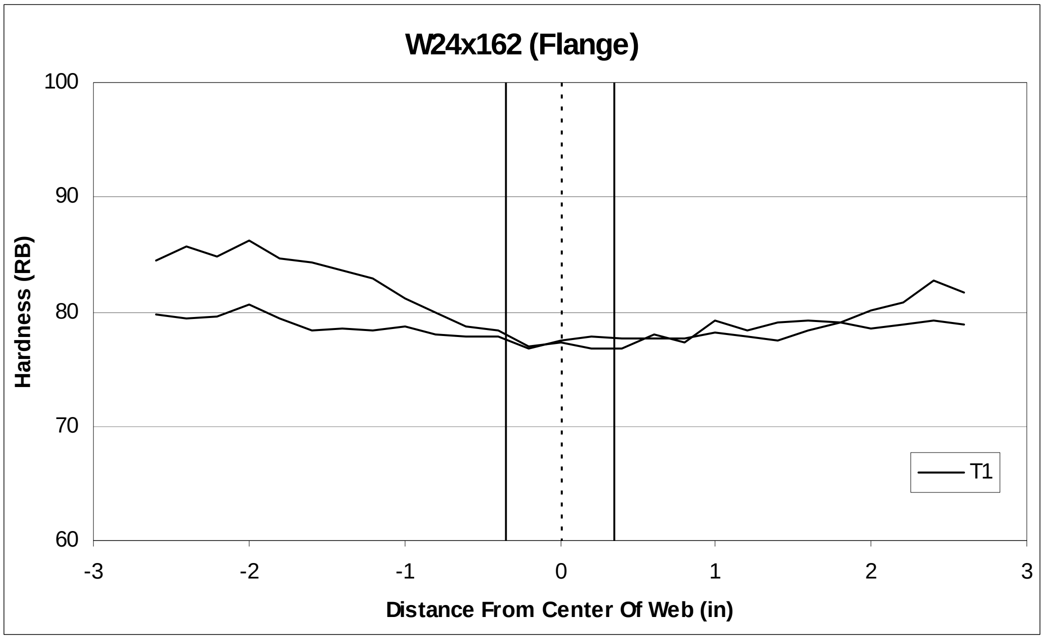

Figure 2.8.10: Flange Region Rockwell Hardness Test Results for W24x162

The results of the hardness testing for the W24x62 and the W27x84 rolled shapes are presented in Figures 2.8.11 through 2.8.14. These figures show hardness values peaking at the K-line. The values for the web region beyond about one to two inches from the K-line tend to level out. The flange regions for the W24x62 shape also seem to be fairly uniform (small range) for both mills. The W27x84 shape has a higher flange range but tends to level out after about an inch away from the centerline of the web.

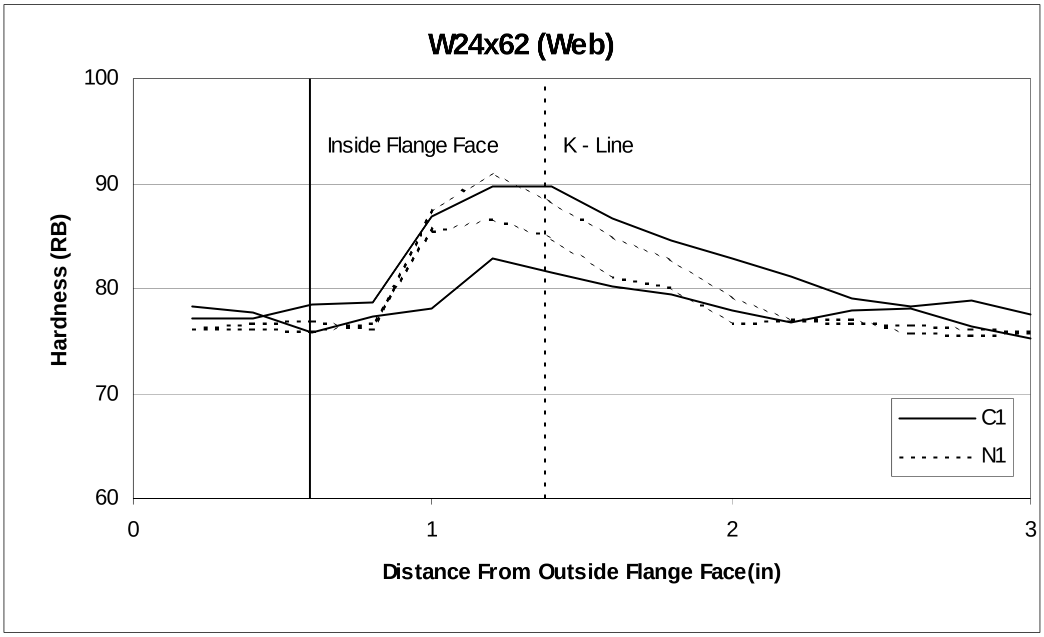

Figure 2.8.11: Web Region Rockwell Hardness Test Results for W24x62

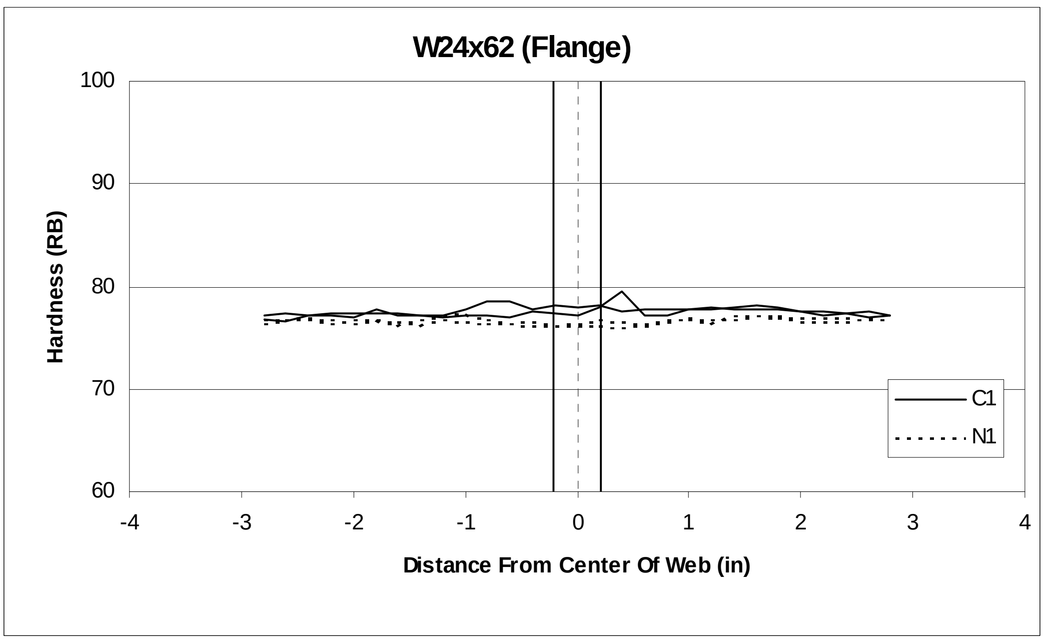

Figure 2.8.12: Flange Region Rockwell Hardness Test Results for W24x62

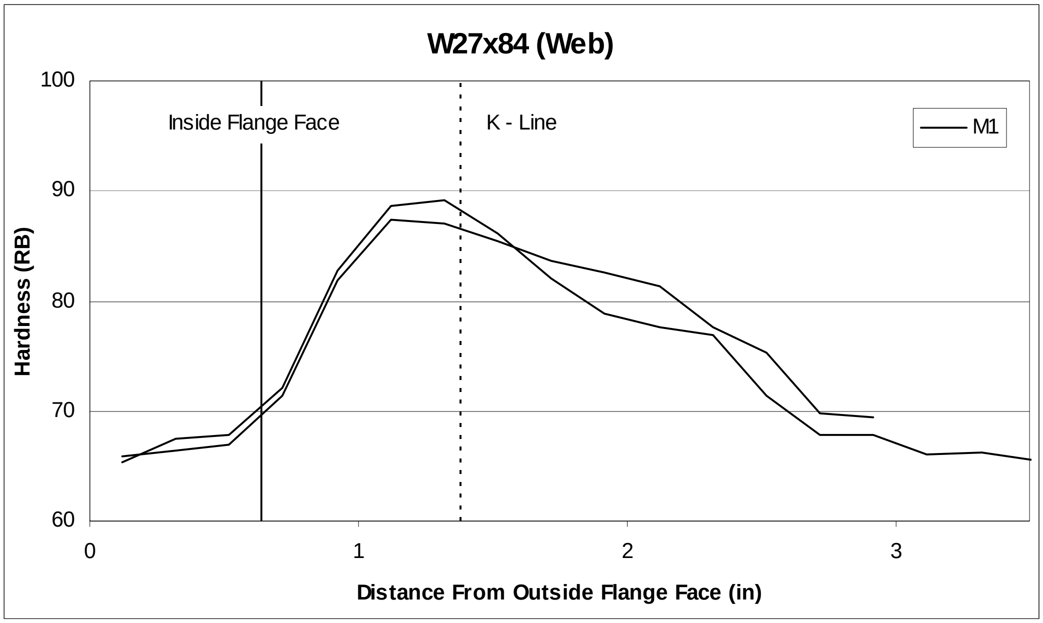

Figure 2.8.13: Web Region Rockwell Hardness Test Results for W27x84

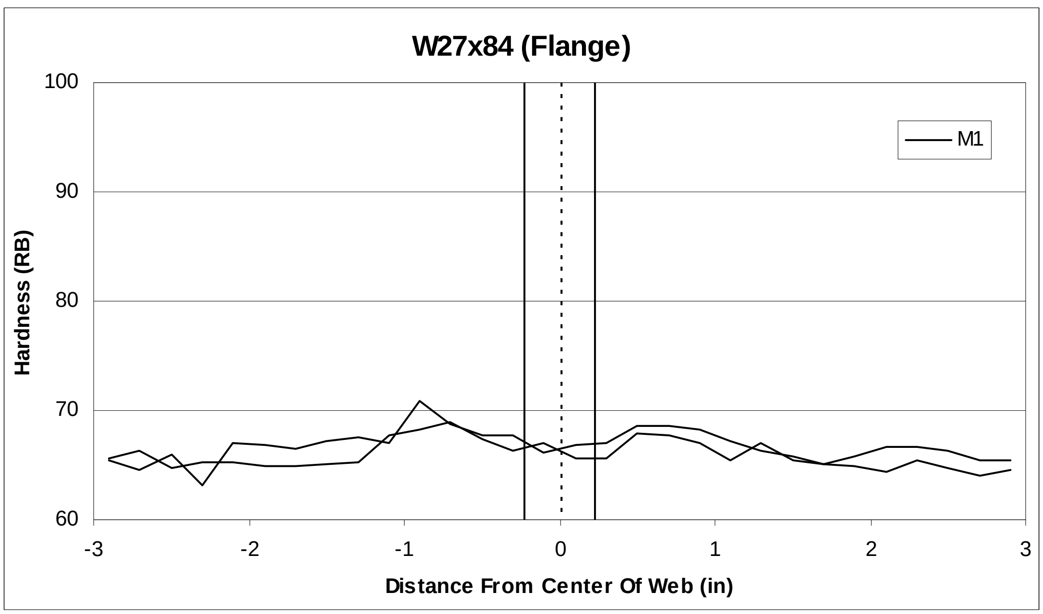

Figure 2.8.14: Flange Region Rockwell Hardness Test Results for W27x84

Figure 2.8.15 and 2.8.16 show the results of the W36x150 rolled shape. Mill T exhibits its characteristic trough and peak curves for the web region. In this case, however, the curves are considerably flattened out with a range of about 5 or less. The flange region has a range of about 17 (values used in the figure show a considerably smaller range than that obtained for this specimen due to averaging). Mill B exhibits uniformity with a small range in both the flange and web regions.

Two rolled shapes from mill N from different heats were tested. Both shapes were roller straightened. The web thickness up to and including the K-line was uniform for sample N5 (variance <0.005 inches). Specimen NA, however, had a visually noticeable reduction in the web thickness at the K-line (variance in thickness at the K-line as compared to one inch into the web from the K-line of approximately 0.017 inches). As Figure 2.8.15 depicts, both shapes tested from mill N demonstrate a peak hardness at or near the K-line followed by a leveling off in the flange and web areas. The difference is in the severity of the ranges. Specimen NA had a range of about 20 compared to 9 for specimen N5.

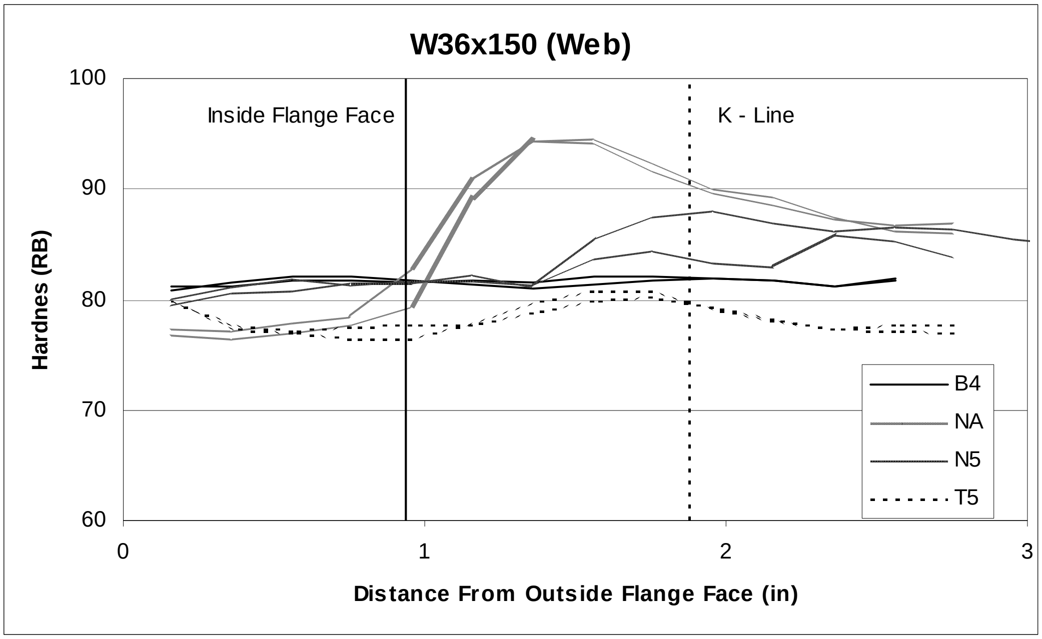

Figure 2.8.15: Web Region Rockwell Hardness Test Results for W36x150

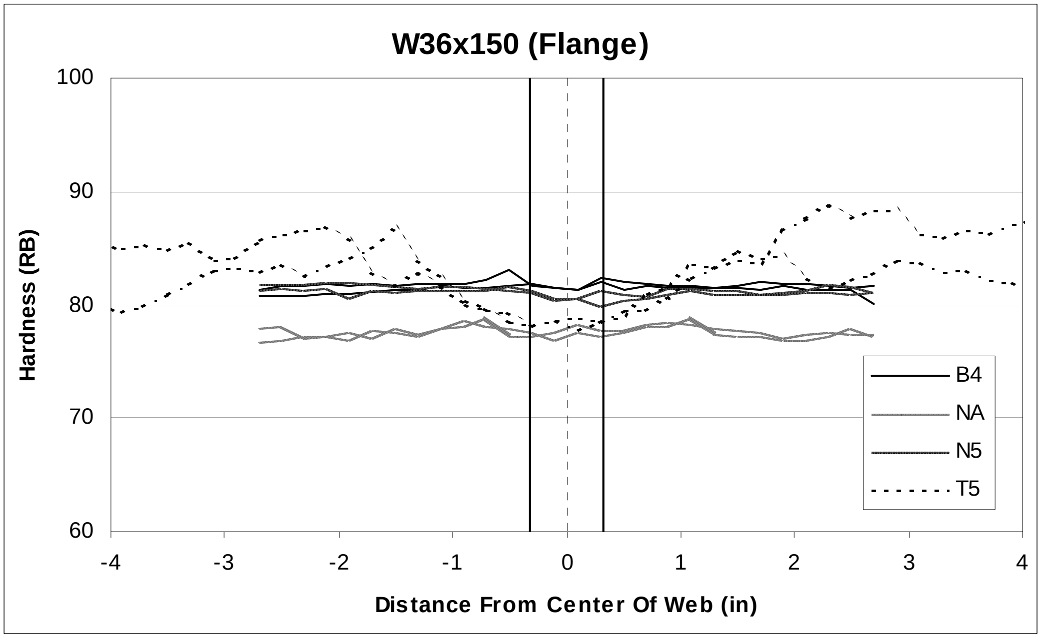

Figure 2.8.16: Flange Region Rockwell Hardness Test Results for W36x150

2.9 CONCLUSIONS

Figures 2.9.1 and 2.9.2 summarize the hardness ranges found in the web and flange regions respectively of all the rolled shapes tested in this program. The mottled textured columns in these figures represent the rolled shapes that were roller straightened. While only specimen NA was identified as having a reduced web thickness at the K-line, all roller straightened specimens produced high hardness ranges in the web region. These specimens, with the exception of M1, showed moderate hardness ranges in the flange region. The low peak hardness but large range in hardness of M1 is unexplained. This specimen came from a girder that had demonstrated the 'smiling column' phenomena of cracking longitudinally in the vicinity of the K-line. Also unexplained is the relatively high hardness of N2. It is noticeably higher than the rest of the shapes produced without roller straightening or QST.

The Quenched Self Tempered production method used only on the shapes produced by Mill T (shown as cross hatched on Figures 2.9.1 and 2.9.2) seems to be the cause of large variations in hardness in both the web and flange regions. In each case, the hardness values for the transition region is considerably lower than the rest of the web and flange areas. This difference occurs over a relatively short distance. The toughness and tensile strengths in hard areas was examined and will be presented in the following chapters.

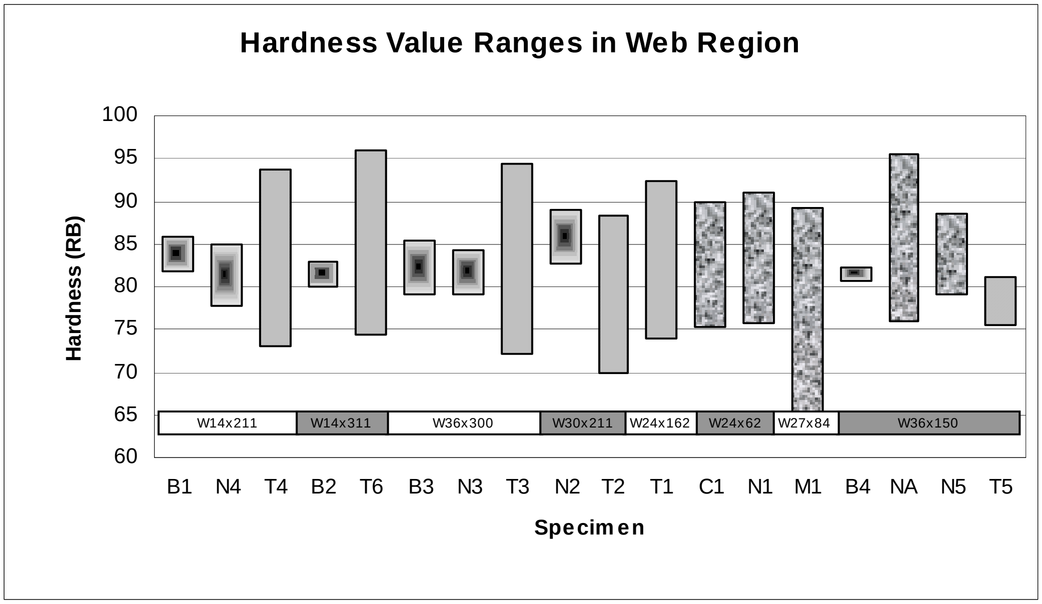

Figure 2.9.1: Summary of Hardness Ranges in the Web Region

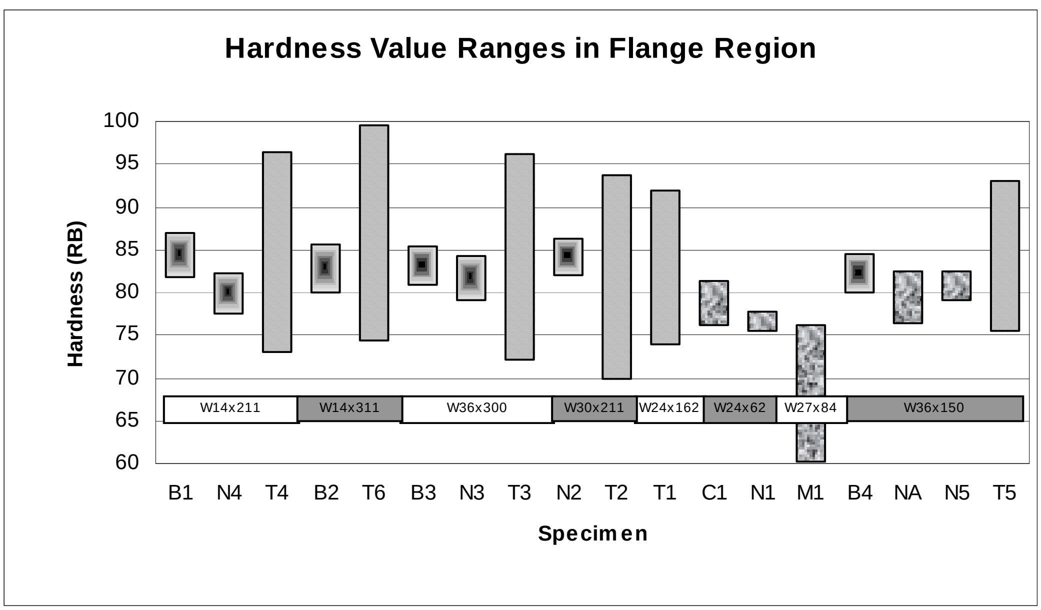

Figure 2.9.2: Summary of Hardness Ranges in the Flange Region

Chapter 3: Charpy Testing of K-line and Web Center Area

3.1 INTRODUCTION

Charpy V-Notch Impact Testing was conducted in accordance with ASTM E23 to determine the toughness characteristics of the rolled shapes in the testing program. Upper and lower shelf energies for each area of rolled shape tested were identified. Also obtained for each area of rolled shape tested was the energy at room temperature along with the temperature corresponding to a 15 ft-lb energy. The shapes tested were those demonstrating high peak hardness values in the K-line region and one shape of uniform hardness, B2. Table 3.1.1 identifies the shapes tested.

Rolled Shape	Mill B	Mill C	Mill N	Mill T
W14x211	B1			T4
W14x311				T6
W24x62		C1	N1	
W24x162				T1
W27x84			M1	
W30x211				T2
W36x150			NA	
W36x300				T3

Roller straightened
Quenched Self Tempered - QST

Table 3.1.1: Charpy Testing Program by Mill and Rolled Shape

3.2 INSTRUMENT CALIBRATION

A pendulum-type testing machine was used for all impact testing. This machine was tested and found to be in conformance with ASTM E23 Sections 5 and 6 by Jaquess (1998) at the beginning of joint SAC II materials testing program conducted within the same time frame as the current program. A windage test was performed at the beginning of each testing day. A zero value was obtained for each windage test.

3.3 SPECIMEN GEOMETRY AND LOCATION

Standard Type A Charpy specimens were used in all impact tests. The dimensions of the simple beam V-notch impact specimens were kept within the tolerances stated in ASTM E23.

Six to Eight Specimens were obtained from each of the peak hardness areas (top and bottom) and the center of the web of each rolled shape. The T-L orientation and V-notch of these specimens was in accordance with ASTM E399. The top, bottom and center web specimens were centered within the web thickness. The top and bottom specimens were positioned such that the V-notch would be at the location of peak hardness. These locations were correlated with the hardness test results for each rolled shape. Figure 3.3.1 shows a typical Charpy specimen layout for the rolled shapes tested.

Specimens from the center of the web, away from the high hardness regions, were tested for comparison purposes using the same alignment. Hardness testing of broken Charpy specimens in the web regions confirmed that the web center and the inner web portions of the T-shaped specimens were uniform (hardness ranges less than 5) with one exception. M1 had a range of 18 between the web center and the T specimens (RHB = 68 and 86 respectively).

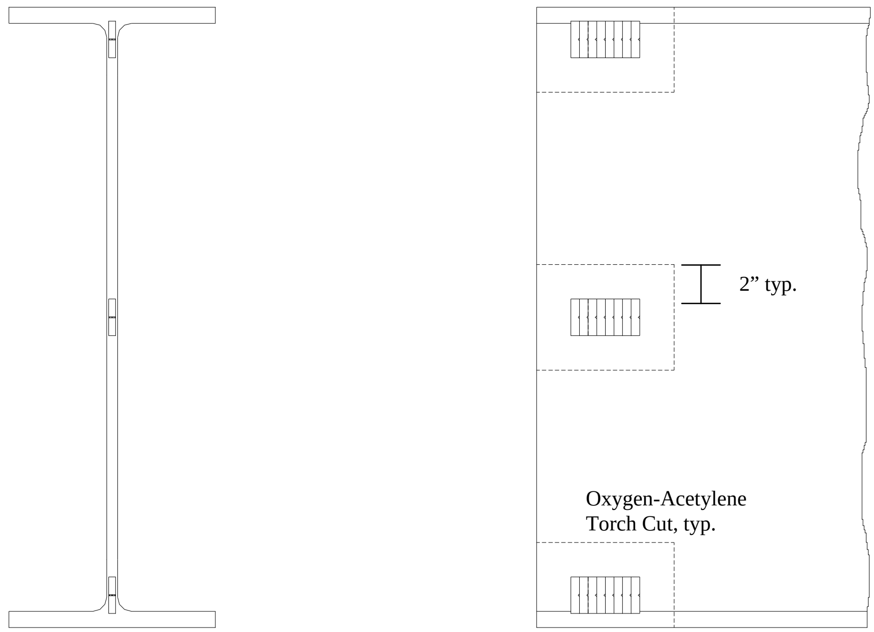

Figure 3.3.1: Typical Charpy Specimen Layout

3.4 COMPARISON OF T-L AND L-T CHARPY DIRECTIONS

The normal alignment for Charpy specimens is L-T, which is parallel to the longitudinal axis of rolled shapes. The intent of this study was to place the V-notch in the hardest area of the rolled shape such that the hardness would decrease from the notch to the ends of each specimen. This would permit the direct study of the effects of hardness on toughness. This alignment is considerably weaker than the normal alignment due to the elongated grain structure of steel. In the normal alignment, the elongated grains are oriented along the length of the specimen. Breakage occurs across the grain. The elongated grains in the chosen specimen alignment are in the narrow dimension of the sample thereby causing the breakage to occur with the grain which normally requires less energy.

Comparisons were made between the T-L and L-T Charpy directions of specimens from the center web regions using the T-L Charpy results obtained from the current study and L-T Charpy results obtained from the joint SAC II materials testing program which utilized the same rolled shapes. Figure 3.4.1 through Figure 3.4.6 are graphs of energy versus temperature comparing the two directions. Figure 3.4.6 shows that the L-T direction has a slightly but notably higher upper shelf energy. The remainder of these figures shows that the L-T direction upper shelf energies are at least 2 ½ times higher than the T-L direction. Observed in all six figures is that the transition between lower and upper shelf energies are shifted to lower temperatures for the L-T direction. Also to be noted from these figures is that the lower shelf energies are essentially independent of Charpy specimen direction.

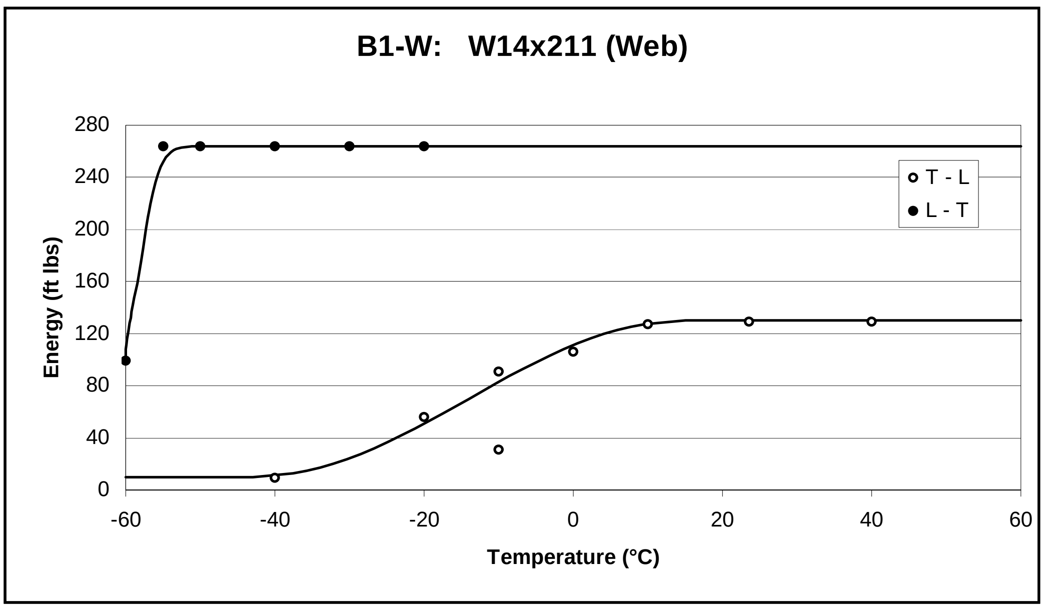

Figure 3.4.1: Comparison of Charpy Direction in Web of Specimen B1

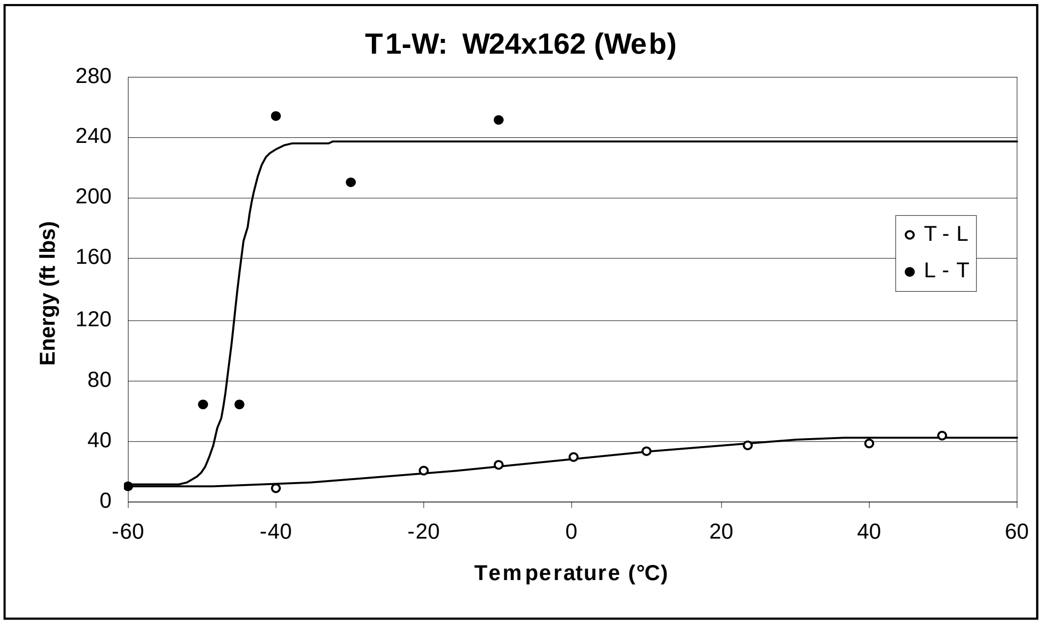

Figure 3.4.2: Comparison of Charpy Direction in Web of Specimen T1

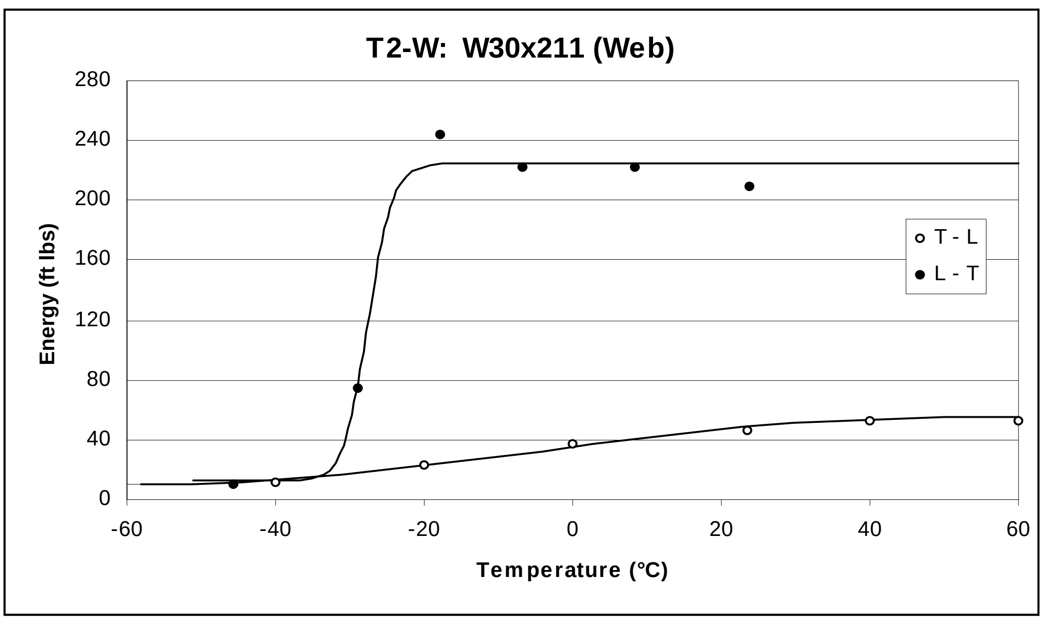

Figure 3.4.3: Comparison of Charpy Direction in Web of Specimen T2

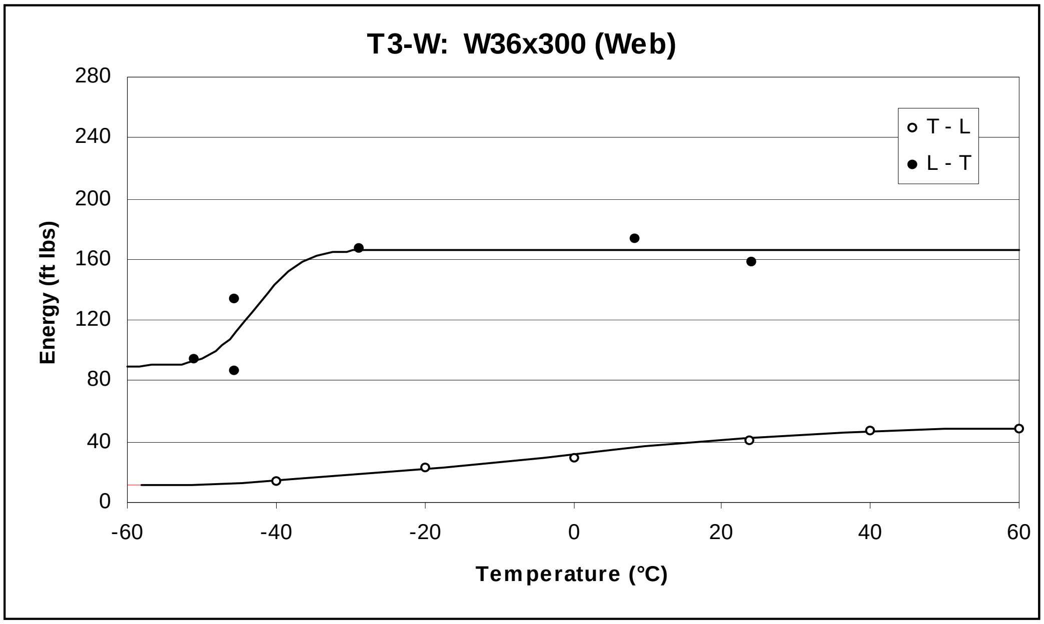

Figure 3.4.4: Comparison of Charpy Direction in Web of Specimen T3

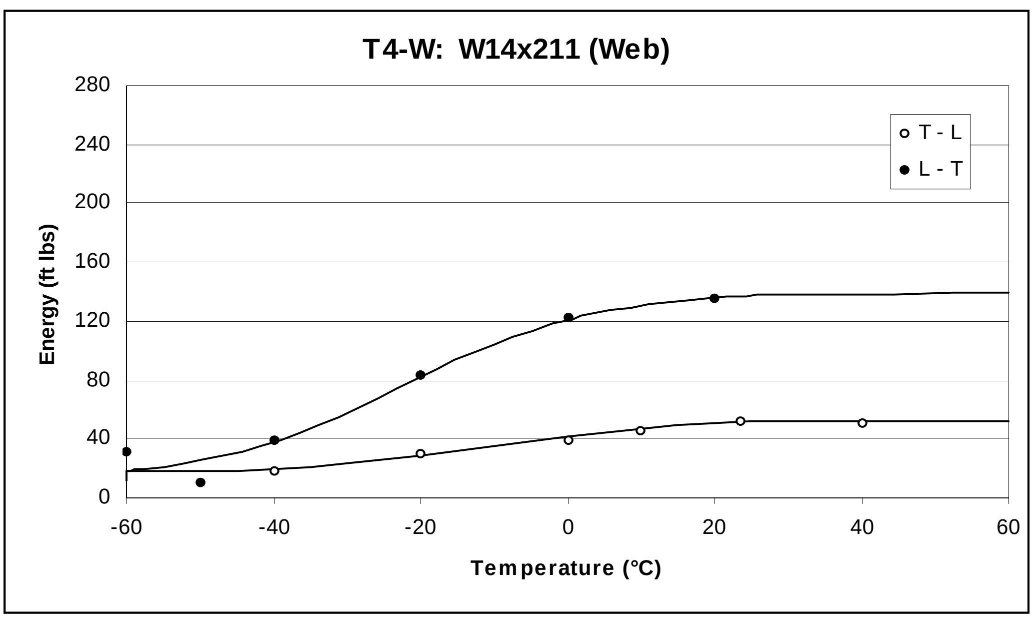

Figure 3.4.5: Comparison of Charpy Direction in Web of Specimen T4

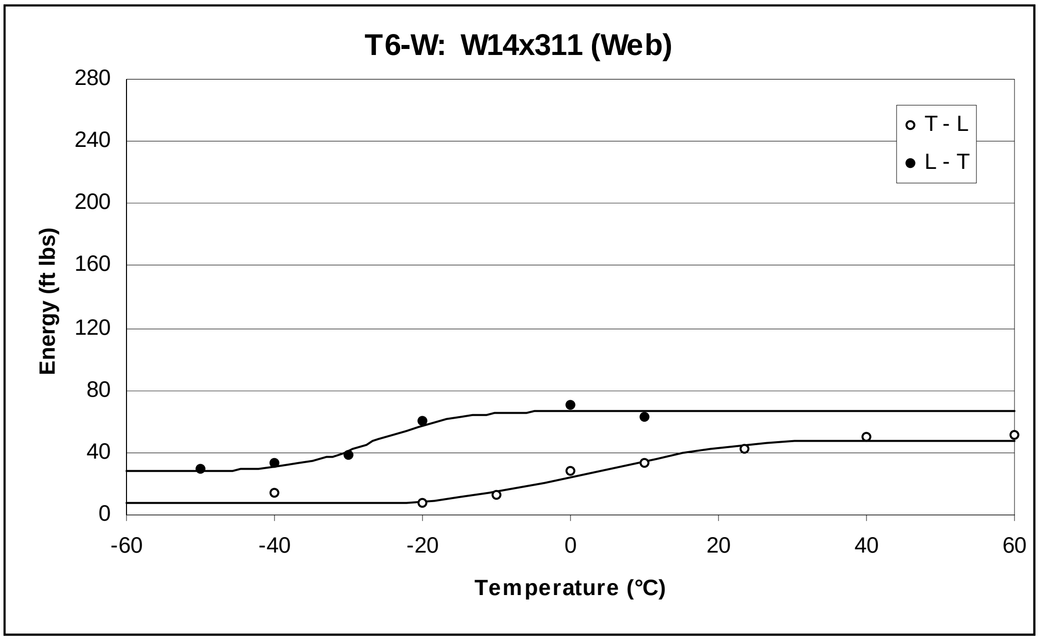

Figure 3.4.6: Comparison of Charpy Direction in Web of Specimen T6

3.5 SPECIMEN MANUFACTURE

The specimens were cut out of the rolled sections using an Oxygen-Acetylene torch while keeping the cut to a minimum of 2 inches from the faces of the specimen (in compliance with ASTM E23). A horizontal bandsaw was used to rough cut the specimens from the torch cut blocks. Specimens were then milled oversized by 0.015 inches in width and thickness. The required cross-sectional dimensions were achieved by surface grinding. A mini-broach was used to notch the specimens.

3.6 METHODOLOGY OF ANALYSIS

Specimens were tested at various temperatures as needed to clearly define the three regions of a graph of energy versus temperature for each area tested. These regions are the upper and lower shelf regions and the transition region between the upper and lower shelves. A plotted trendline consisting of two straight portions for the upper and lower shelf areas and a sinusoidal portion for the transition region was visually best fit to the data by adjusting the energy and temperature ranges of the transition region. Figure 3.6.1 is a graph of energy versus temperature generated from the data of a typical tested region. The best fit line for the data (labeled in the legend as Trend) along with the data itself are plotted. Also shown on this graph are the energy level at room temperature (taken as 21°C) and the temperature at a15 ft-lb energy level. Graphs for each region tested can be found in Figures C.1.1 through C.10.3 in Appendix C.

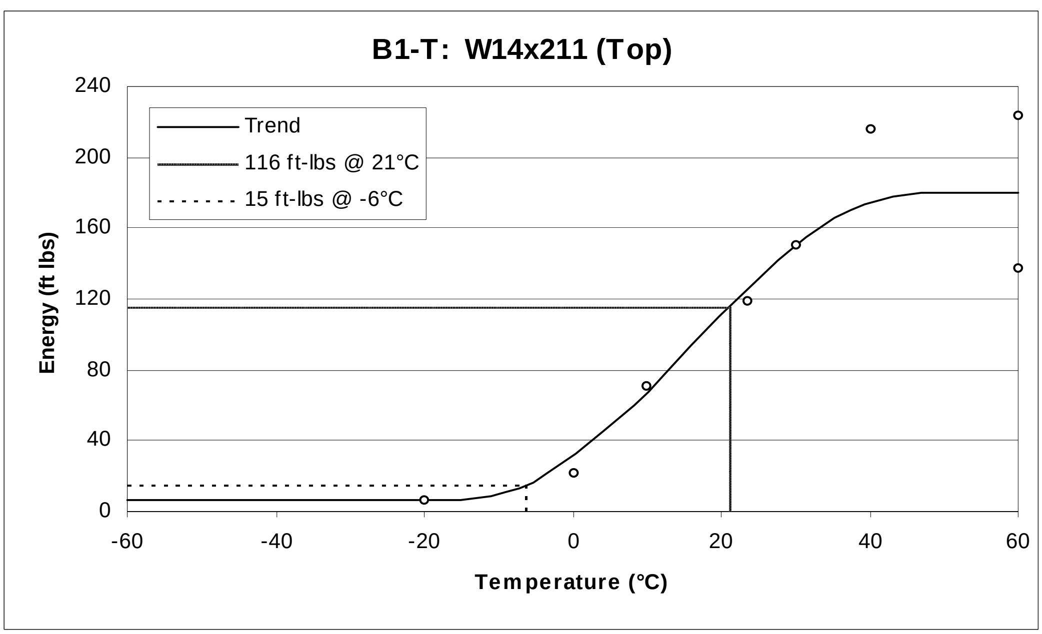

Figure 3.6.1: Typical Graph of Charpy Impact Test Results for a Region

The trend lines and data for the top, bottom, and center web regions were combined into graphs for each of the shapes tested and are presented in the following section. This allowed for comparisons between the three regions of a particular shape to be made by inspection. The criteria for comparison hinges on the desire to have rolled shapes behave in a ductile manner within expected temperature ranges. With this in mind, curves on an energy versus temperature graph of a shape that will perform more desirably will demonstrate the following characteristics:

- Higher upper and lower shelf energies – curves shifted upward
- Lower transition temperatures – curves shifted to the left
- Transition from ductile to brittle behavior over a larger temperature range

Also used for comparison purposes are the energy level at room temperature (21°C) and the temperature at a 15 ft-lb energy level. Figure 3.6.2 is a typical combined graph. The data from the top K-line region is shown in a filled circle. An open circle and open triangle are used for the bottom K-line and center web regions respectively.

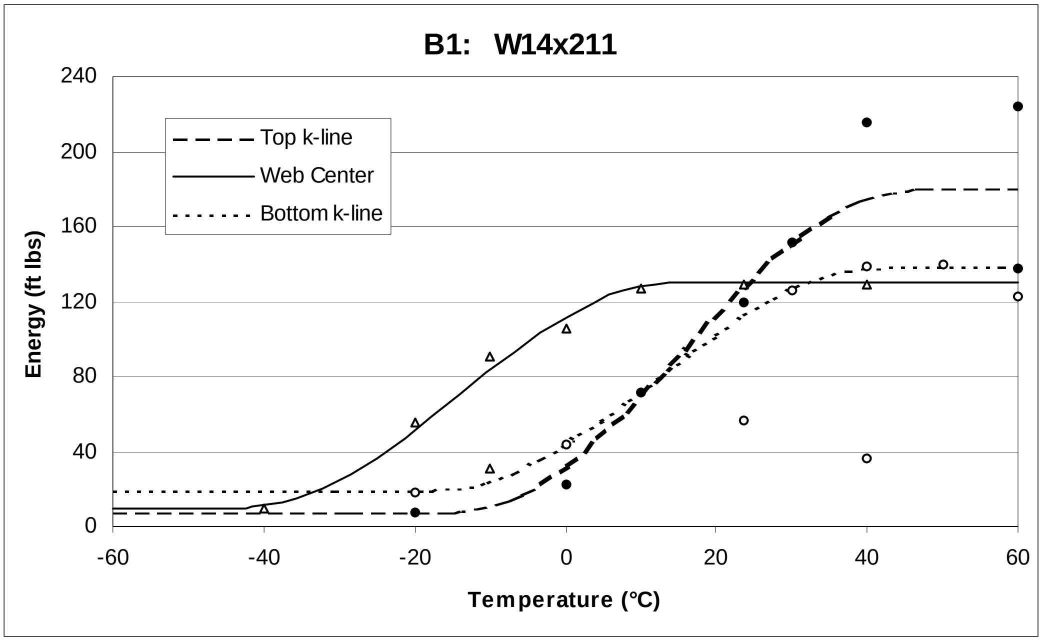

Figure 3.6.2: Typical Graph of Charpy Impact Test Results for a Rolled Shape

3.7 ANALYSIS OF CHARPY IMPACT TEST RESULTS

Figures 3.7.1 through 3.7.10 show the Charpy Impact test results for the three regions of each rolled shape tested. Figure 3.7.1 is of Mill B. This shape was produced without roller straightening or a QST process. The hardness testing for this shape was quite uniform throughout the entire specimens tested. For these reasons, this shape was used as a base line in the impact testing. The upper and lower shelf energies were in excess of about 130 and 7 ft-lbs respectively. The temperatures at a 15 ft-lb energy level were at –6°C or less. Energies at room temperature were in excess of 105 ft-lbs for each region. Figure 3.7.1 shows that the top and bottom curves are in relatively good agreement with each other. The figure also shows that the web region is performing better than the top and bottom regions as noted by the leftward shift of the web curve. This shape demonstrated favorable toughness in all three regions as expected.

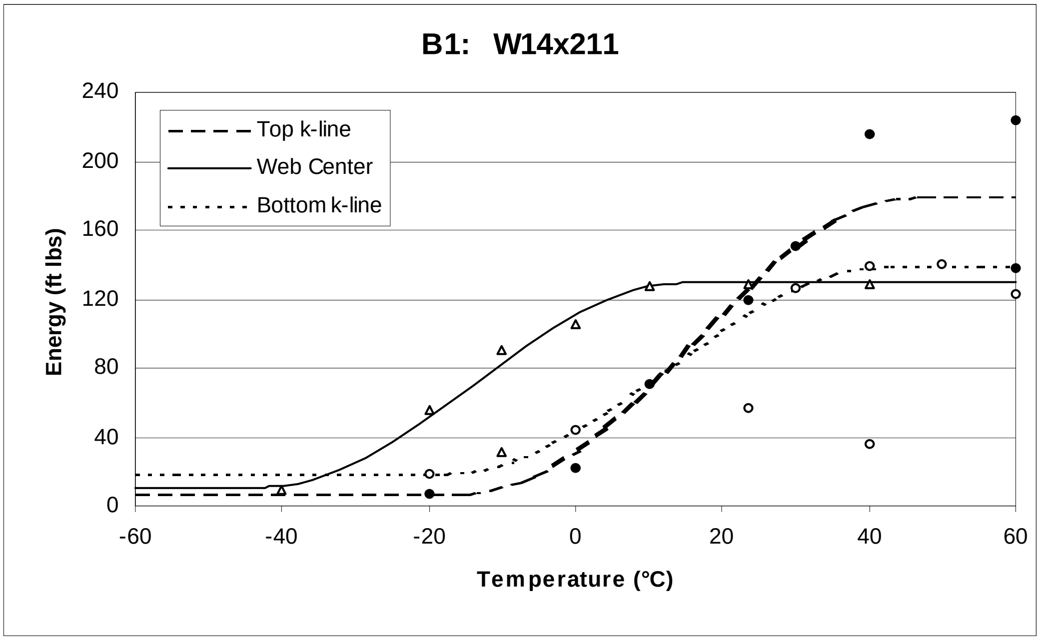

Figure 3.7.1: Charpy Impact Test Results for B1

Figures 3.7.2 through 3.7.5 show the results for the rolled shapes subjected to roller straightening. The toughness in the regions tested also share some common traits. Immediately noticeable from these figures is the contrast in behavior between the results of the K-line regions (top and bottom) and that of the center web region. In each case, the center web region curve is shifted upward and to the left. These web regions have a minimum lower shelf energy of 10 ft-lbs and an upper shelf energy of at least 43 ft-lbs occurring at near or above room temperature. The web regions demonstrated adequate toughness. The same cannot be said about the top and bottom regions.

The top and bottom regions performed uniformly within each shape and quite poorly as a whole. The upper shelf energy was less than 20 ft-lbs. for all but N1 which had values of 31 and 23 for the top and bottom respectively. The lower shelf energies ranged from 1.5 to 5 ft-lbs for all but the top region of N1, which was 11 ft-lbs. The 15 ft-lb energy levels occurred at temperatures of 4°, 26°, and

21°C for the top and bottom of N1 and the bottom of C1 respectively. The minimum temperatures for all other regions in this group were at least 43°C.

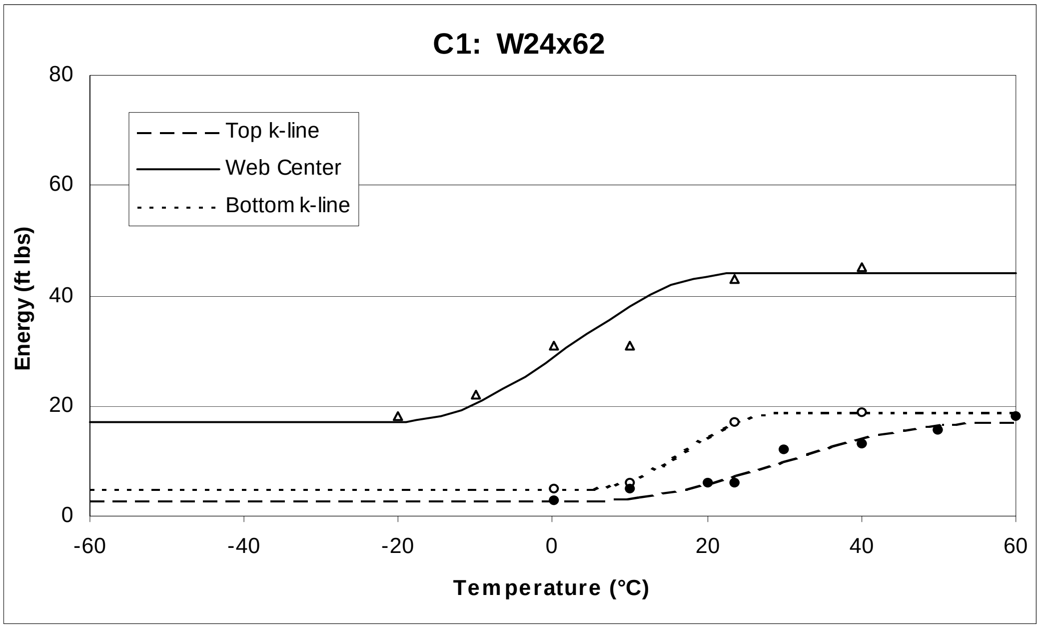

Figure 3.7.2: Charpy Impact Test Results for C1

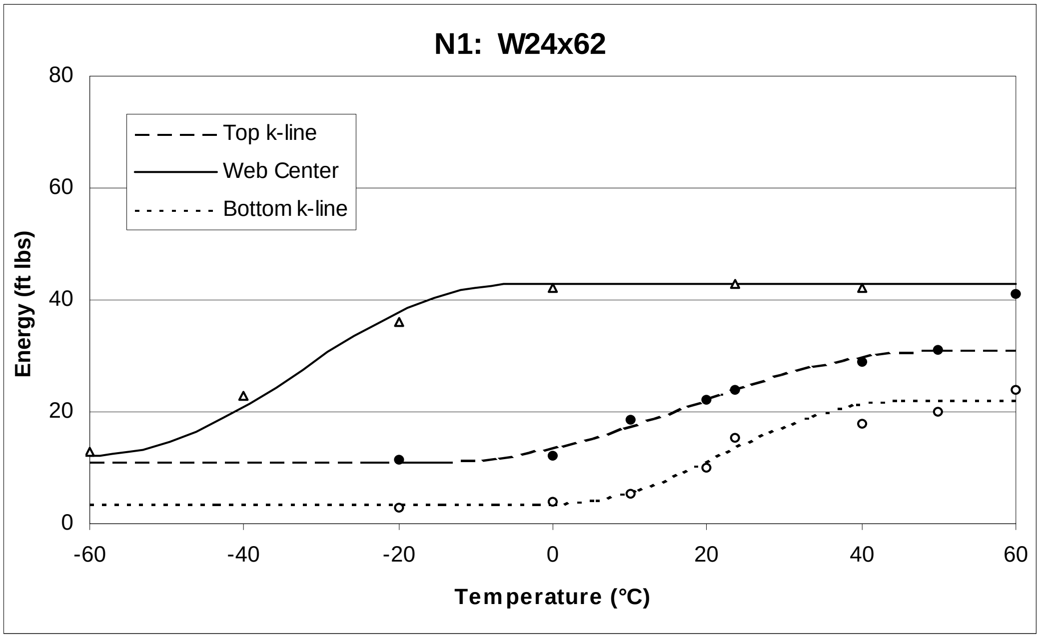

Figure 3.7.3: Charpy Impact Test Results for N1

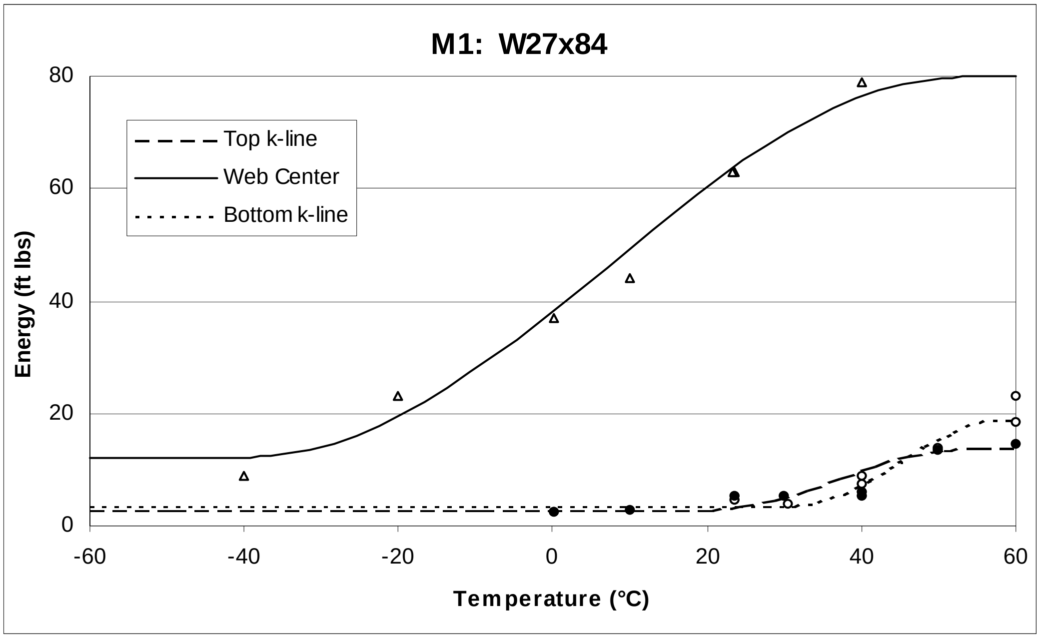

Figure 3.7.4: Charpy Impact Test Results for M1

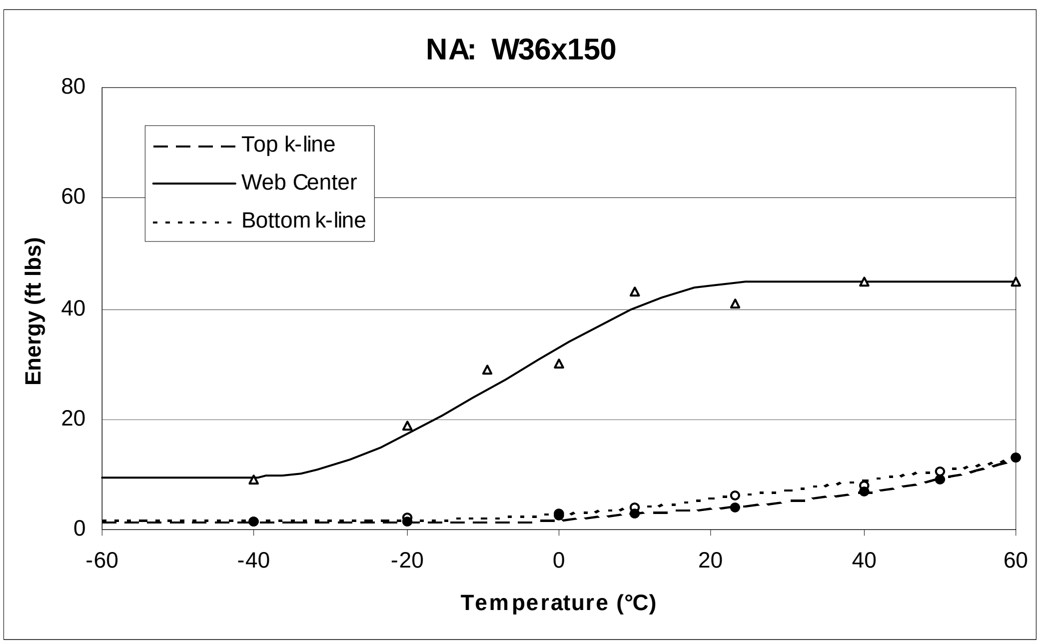

Figure 3.7.5: Charpy Impact Test Results for NA

Figures 3.7.6 through 3.7.10 show the toughness results for the rolled shapes manufactured by Mill T. These shapes had a substantial hardness value range between the characteristic trough and peak variation through the web-flange transition region. This characteristic is thought to be caused by the QST process employed by Mill T. The general observation to be made from these figures is that the toughness curves for the top, bottom, and center web regions are essentially uniform within each rolled shape. The lowest toughness values obtained for these five shapes for the lower and upper shelf energies were 8 and 35 ft-lbs respectively. The lowest room temperature energy was found to be 32 ft-lbs. The highest temperature at 15 ft-lb was determined to be –10°C. Most of the 15 ft-lb temperatures were below –30°C. All of the limiting values of the group occurred in the heaviest shape (W14x311). The toughness performance of the shapes produced by Mill T was good and the hardness variation did not produce a significant toughness difference.

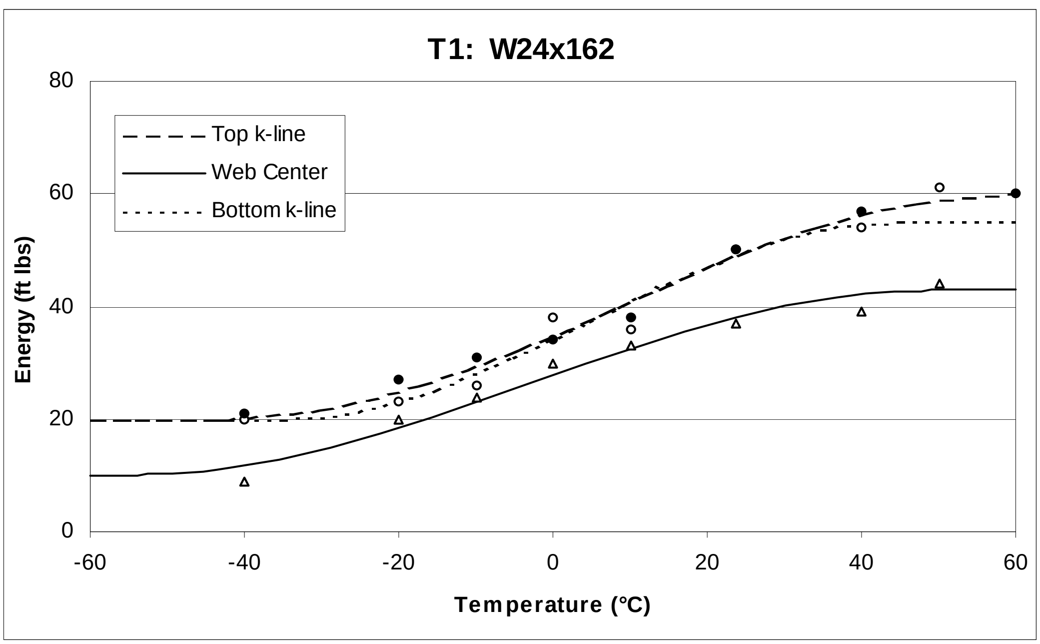

Figure 3.7.6: Charpy Impact Test Results for T1

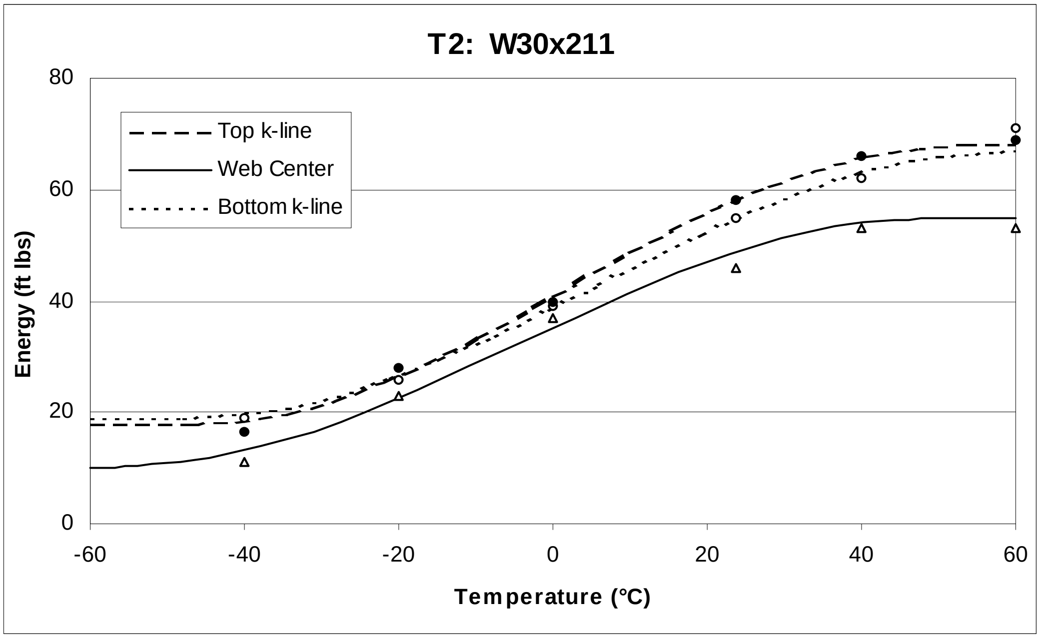

Figure 3.7.7: Charpy Impact Test Results for T2

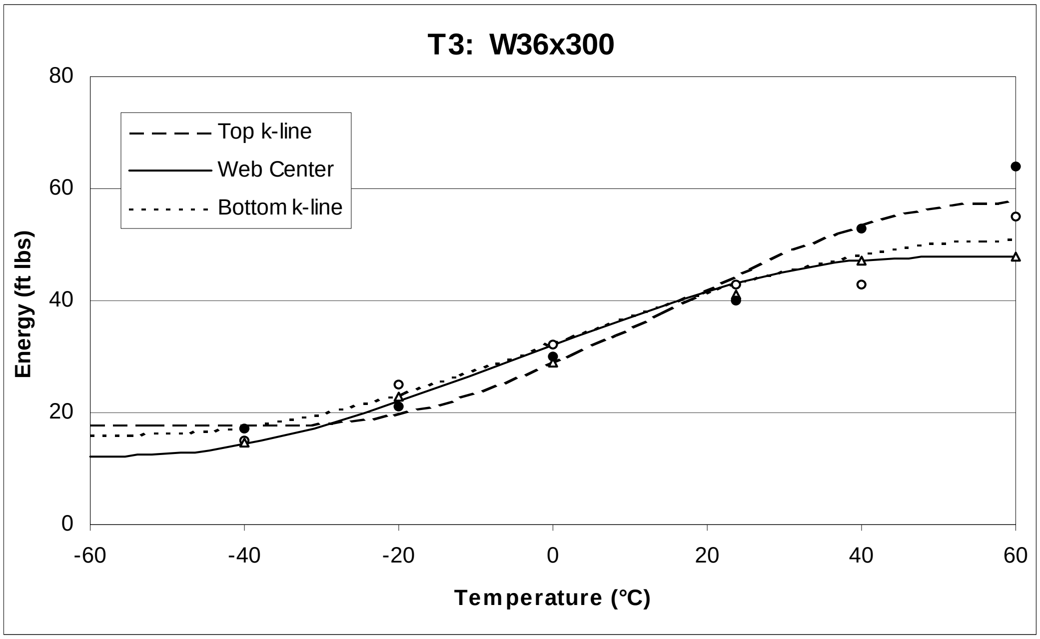

Figure 3.7.8: Charpy Impact Test Results for T3

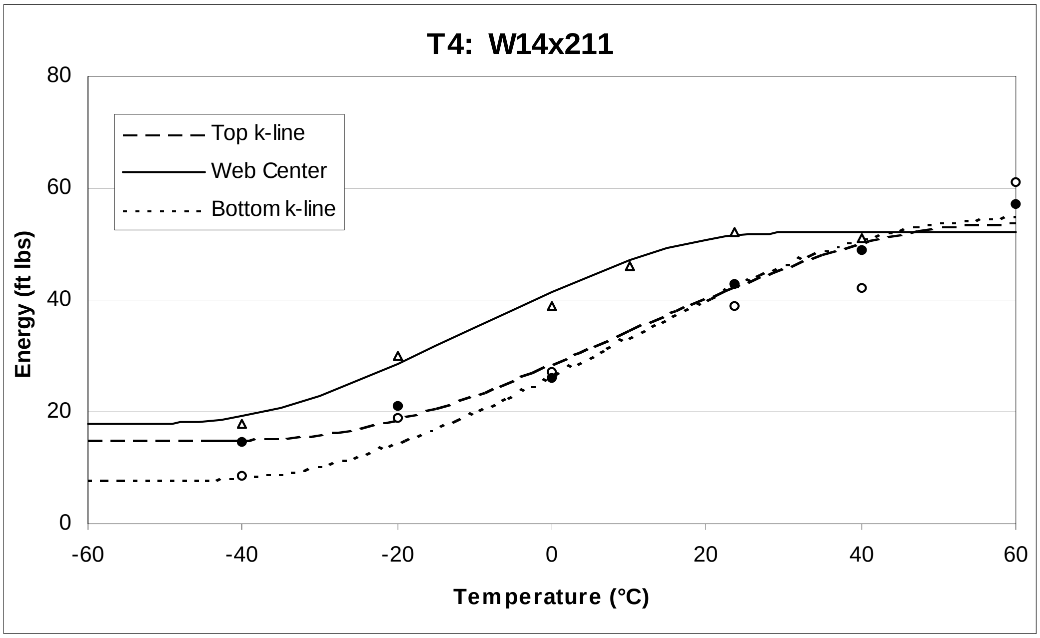

Figure 3.7.9: Charpy Impact Test Results for T4

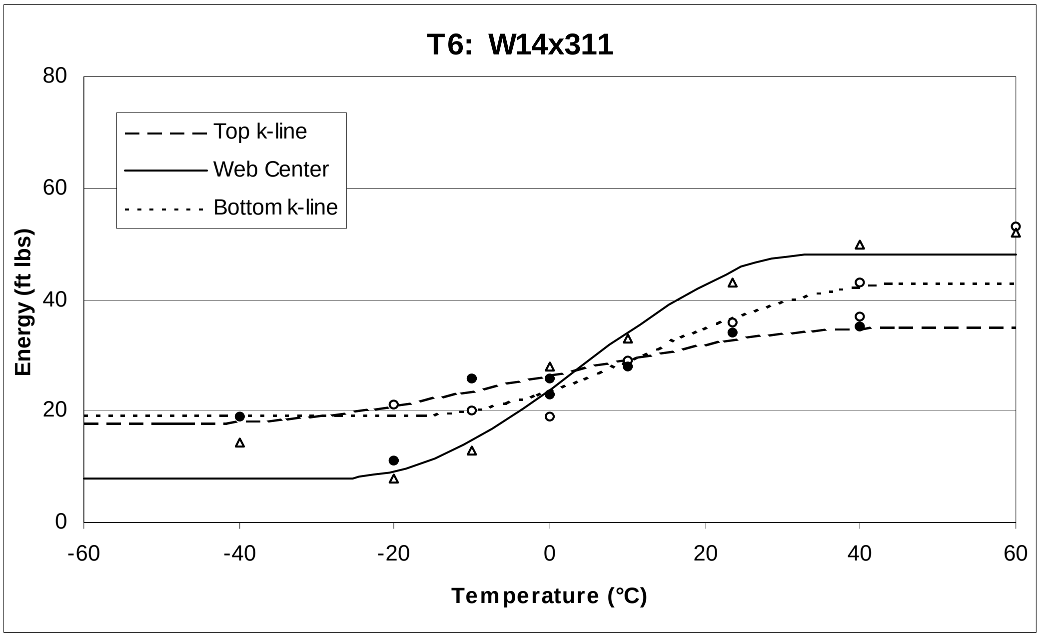

Figure 3.7.10: Charpy Impact Test Results for T6

Figure 3.7.11 shows a comparison of hardness versus upper shelf toughness for the roller straightened and QST methods of production. HRB is plotted on the vertical axis and the upper shelf energy is plotted on the horizontal axis. A general trend of decreasing toughness (upper shelf energy) with increasing hardness can be observed from the data of the roller straightened process. The QST process does not exhibit any noticable trend.

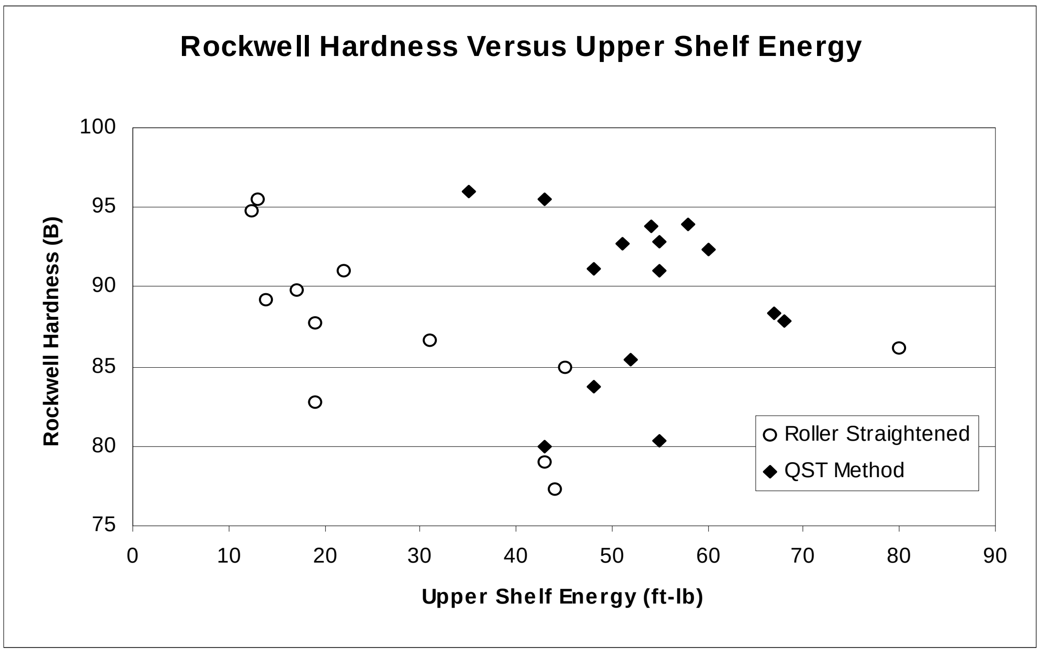

Figure 3.7.11: Comparison of Hardness Versus Toughness

3.8 CONCLUSIONS

The roller straightening process creates an unacceptably low toughness region around the K-line as seen in all shapes tested that were produced in this manner. These results were consistently poor on the shapes tested regardless of the presence or absence of a noticeable K-line area reduction in web thickness. Also observed in the roller straightened shapes was an inverse relationship between the toughness and hardness characteristics.

Chapter 4: Tensile Testing

4.1 INTRODUCTION

Tensile testing of two areas was conducted based on the hardness test results. Hardness variations in through the thickness of the flange resulting in a trough effect for rolled shapes produced by Mill T prompted a tensile study. One-half inch round Tensile specimens machined from the flange centers and the t/4 standard location as specified in ASTM A6 were machined from five rolled shapes (B1 for control, T2, T3, T4, and T6).

The W24x62 shape showed high peak hardness combined with low toughness in the k-line region. Four sheet type tension coupons (top and bottom from C1 and N1) centered at the peak hardness were tested and compared to the web and flange tensile results conducted by Timothy Kyle Jaquess.[1]

4.2 INSTRUMENT CALIBRATION

A 220 kip capacity closed loop tensile testing machine was used for all tests conducted. This machine was calibrated by Jaquess at the beginning of joint SAC II materials testing program conducted within the same time frame as the current program.

4.3 SPECIMEN GEOMETRY AND LOCATION

Four ½ inch round specimens were machined out of one of two flanges from five rolled shapes. The typical layout is shown in Figure 4.3.1. Two of the four specimens (labeled xx-BB and xx-CC) per rolled shape were machined from the center of the flange. The centerline of the other two specimens (labeled xx-AA and xx-DD) were located as close as possible to the ¼ thickness of the flange.

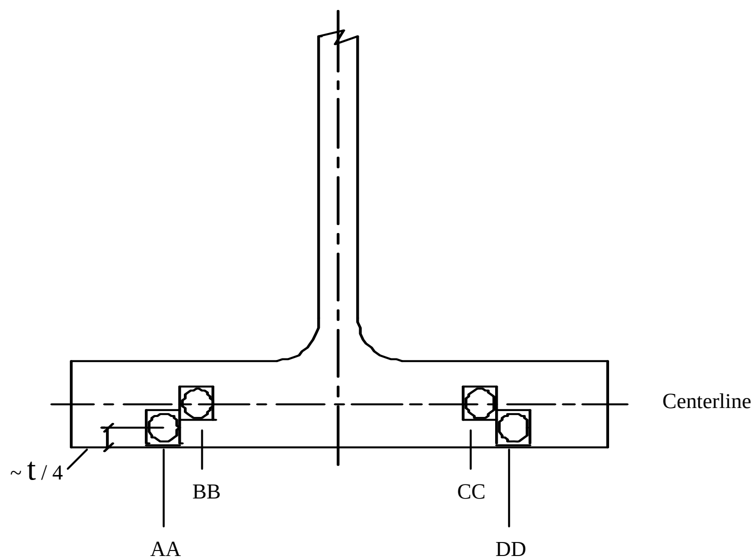

Figure 4.3.1: Half Inch Round Specimen Layout for Flange Study

The web thickness of the W24x62 shape did not permit the use of a standard ½ inch round tensile specimen. Sheet type specimens were machined from the four k-line areas tested. The fillets were removed providing a uniform specimen thickness equal to the web thickness. The overall width was one inch, ½ inch at the reduced section. These specimens were cut 16 inches long for gripping purposes. A two-inch extensometer was used in the narrow portion.

4.4 ANALYSIS OF TENSILE TEST RESULTS

Figure 4.4.1 is a column graph summarizing the tensile test results of the flange study for five rolled shapes. The static and dynamic yield stresses along with the dynamic ultimate stresses are shown. Each column represents an average tensile strength per rolled shape obtained from two specimens tested either at the center of the flange or at the standard t/4 location. The data is presented in pairs of columns. The left column of the pair is the average of the t/4 results for the rolled shape. The right column represents the average of the results from the center of the flange. The pairs of columns are arranged from left to right in the order of increasing flange thickness. The distances between centers of the t/4 and center flange specimens ranged from 0.22 to 0.56 inches.

The least variation in stress between the t/4 and center locations occurred in the B1 shape. This behavior was expected do to the uniformity in hardness throughout the flange thickness. The remainder of the shapes tested had trough shaped hardness variations through the flange thickness. This trend of lower hardness in the center flange region translates to lower static and dynamic stress capacities in the center flange region as well. The differences between the strength capacities in the t/4 and center specimens increase with increasing flange thickness. The variation in hardness follows the same trend. The dynamic yield stresses for these shapes, which were produced by Mill T, fall short of the 50 ksi mark for the specimens tested in the center. The range for the center specimens is from 45 to almost 50 ksi. These shapes performed within industry standards at the standard t/4 locations, however.

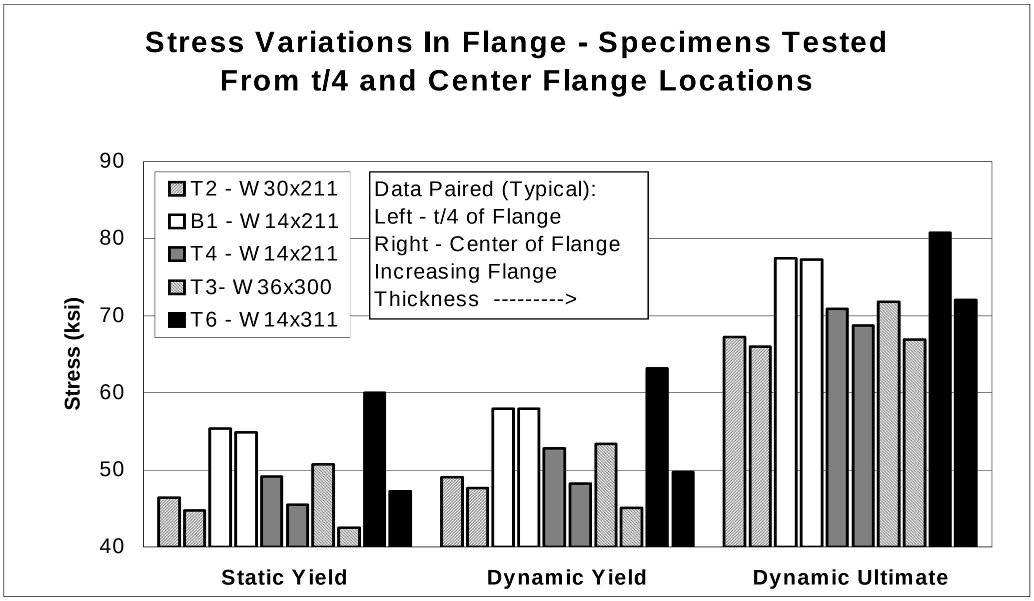

Figure 4.4.1: Stress Variation Through The Flange Thickness

The results of the tensile study conducted on both W24x62 shapes are presented in Figure 4.4.2. The ultimate, dynamic yield, and static yield stresses along with percent elongation of specimens taken from the web, flange, and peak hardness near the k-line are graphed in columnar form for comparison. The data for the flange and web regions were obtained from Jaquess (1998). Uniformity for each of the strengths and the percent elongation can be observed between the flange and web regions from both mills. The dynamic yield stresses for the specimens machined from the peak hardness regions near the k-line was approximately 15 ksi higher than the average flange and web regions. The increase in ultimate stress for the same regional comparison was only about 9 ksi. A reduction of 7 percent in the elongation for the k-line region as compared to the web and flange regions was observed.

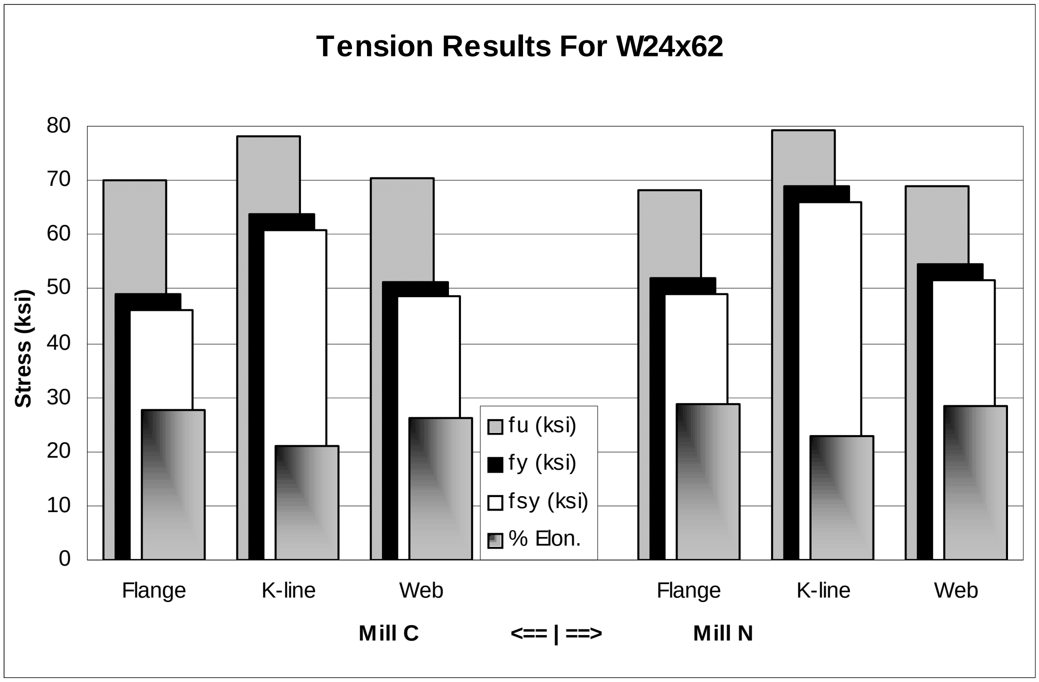

Figure 4.4.2: Tensile Strength Results for W24x62

The applicable hardness values (data from the areas that the tension specimens were obtained) were plotted against the tensile strength test results in Figure 4.4.3. The hardness versus dynamic yield stress data had slightly more scatter than the ultimate tensile strength data for the web and flange regions. Also plotted in this figure are the correlation of Rockwell B hardness and tensile strength given in Table 2B of ASTM A370. A least squares line was fit to the values and is plotted in the figure. The ultimate tensile strength data compares relatively well with the ASTM A370 data at lower hardness values. The two trendlines diverge at higher hardness values. This divergence is due to the four higher values, all of which were obtained from the k-line regions. While the general trend of increasing hardness resulting in increasing ultimate tensile strength is shown, the discrepancy could easily be attributed an averaging of strength due to the width of the specimens.

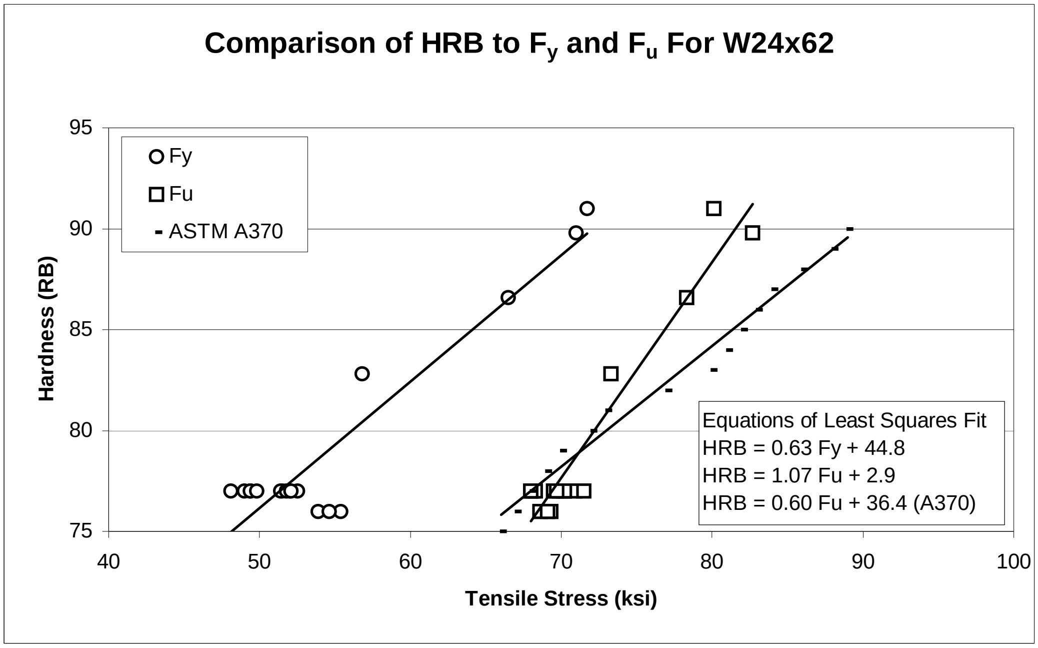

Figure 4.4.3: HRB, Fy, and Fu Comparison for the W24x62 Rolled Shape

4.5 CONCLUSIONS

The yield strengths in the center of flanges experiencing trough-like hardness effects produced by the QST method of manufacture were found to be as much as 10 percent below the standard set for the t/4 location. The thicker flanges produced by the QST method show a larger range in hardness and tensile strength between the higher t/4 regions and the center of the flange. The general trend of increasing tensile strength with increasing hardness occurred in all shapes tested.

Chapter 5: Conclusions

5.1 OVERALL PROJECT ASSESSMENT

The results of the testing conducted in this project suggest that the characteristics of the rolled shapes tested are particular to the manufacturing process. For this reason, the summaries that follow have been categorized by the process. The manufacturing processes involved in the production of the rolled shapes tested were 1) Quenched Self Tempered, 2) Roller Straightened, and 3) Shapes produced without roller sraightening or heat treatment.

5.2 QUENCHED SELF TEMPERED

The rolled shapes in this study that were produced using the Quenched Self Tempered process were produced by Mill T. These shapes demonstrated a trough and peak hardness pattern in the flange and at the web lines. High hardness occurred in the k-line region and near the flange faces. Low hardness was typical in the web-flange transition region and throughout the center of the flange. The hardness ranges for these specimens were typically in excess of 15 HRB in the web lines and 20 HRB in the flanges.

The high peak hardness shown in the k-line regions prompted a further toughness study of the region. Charpy studies (T – L orientation) in this region indicated that the rolled shapes had good toughness properties. These properties were comparable to, and in some cases better than, the results obtained for the web at the center of the rolled shape.

Variation in hardness in the through thickness of the flange prompted a tensile strength study comparing the standard t/4 specimen location (location of higher hardness) and the flange center (location of low hardness). It was determined that thicker flanges, having largest hardness ranges, had the largest tensile strength variations between the two areas. The trend of increasing hardness resulting in increasing tensile strengthes was observed. More importantly, however, was the observation that while all of the dynamic yield stress specimens at the t/4 location passed the standard, none of the center specimens passed the standard with some failing by as much as 10 percent.

5.3 ROLLER STRAIGHTENED

Mill C and Mill N used the roller straightening process for the lighter rolled shapes including the beam from Michigan (M1). The results of the web-line hardness testing for all of these shapes showed pronounced peak hardness in the k-line regions. The hardness tapered off from the peaks and settled down within a short distance away from this region. The variation in hardness for the web-line studies was from 10 to 25 HRB. The variation in hardness in the flange-line was negligible with one exception – the W27x84 shape had a 16 HRB range, the peak of which was low at 76 HRB.

The toughness study (Charpy impact in the L – T orientation) showed that all of the roller straightened shapes had inadequate toughness in the k-line region while performing satisfactorily in the web region at the center of the rolled shape. The k-line regions had low upper shelf energies, typically less than 20 ft-lbs, and the transition temperatures were high, typically greater than room temperature.

Tensile testing was performed on the W24x62 rolled shape at the k-line region and compared to the web and flange regions. The results showed that the k-line had higher dynamic yield and ultimate tensile strengthes. The increases were disproportionate between the dynamic yield and ultimate tensile strengthes with the former increasing about twice as much as the latter. This increase indicates a reduction in ductility, which was confirmed by reduced elongation results.

5.4 NON ROLLER STRAIGHTENED OR QST

The rolled shapes that were produced by Mill B and Mill N without roller straightening or quenched self tempering methods were found to have uniform hardness (ranges of 7 HRB or less) in both the flange-lines and web-lines. For this reason, only one shape (B1 – W14x211) was selected to do Charpy and Tensile testing for comparison.

The B1 shape had k-line upper shelf energies in excess of 120 ft-lbs which was the upper shelf for the web region. The transition for both areas was gradual, spanning approximately 40°C at a transition temperature less than room temperature. The tensile testing of this shape was uniform between the t/4 and center flange locations and easily met the minimum dynamic yield requirements.

5.5 CONCLUSIONS

The results from the shapes produced by the Quenched Self Tempered method indicate that the standard t/4 flange specimen location for minimum tensile strength does not adequately represent but can overestimate the shapes tensile strength. A solution to this would be to change the standard tensile specimen location to the center of the flange or require full thickness testing.

The roller straightening process introduces into the shape a condition of high hardness, low toughness, and reduced ductility at the k-line. This combination can lead to catastrophic failures such as seen in the ‘smiling column’ phenomenon.

High hardness was also found in the rolled shapes produced by the QST process. No reduction in toughness was observed. Therefore, hardness testing cannot be used as a sole indication to determine low toughness regions.

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Vita

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