Characterization of Material Properties of HPS-485W (70 W) TMCP for Bridge Girder Applications

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Abstract: There are currently two methods of production for A 709 Grade HPS-485W (70 W)—quenching and tempering (Q&T) and thermomechanical controlled processing (TMCP). The TMCP enables plates to be rolled in longer lengths than is possible with Q&T; however, because of its recent introduction and a lack of material testing, relatively little is known concerning the effect of this new production method upon the intraplate variability of both tensile strength and toughness. Data from 96 tensile tests show that yield and ultimate strengths of HPS-485W (70 W) TMCP may be dependent upon plate thickness and orientation. The average yield strength was found to be lower than the 485 MPa (70 ksi) limit, while the average ultimate strength was within acceptable limits. Seventy-five Charpy V-Notch (CVN) specimens were tested, and all met the 48 J at −23°C (35 ft-lb at −10°F) AASHTO Zone III requirement for minimum toughness. Overall it was seen that HPS 485W (70 W) TMCP shows promise for bridge girder applications, but thicker plates do not currently meet all the *ASTM A 709* standards, and should be reevaluated before being used in bridge construction on a large scale.

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CE Database subject headings: Bridges, steel; Tensile strength; Toughness; Construction materials; Girders.

Introduction

Since first efforts were made toward developing high performance steel (HPS) in 1992 through a joint collaboration of the American Iron and Steel Institute (AISI), the Federal Highway Administration (FHWA), and the U.S. Navy, HPS has become increasingly common for bridge girder applications. Because of the higher yield strength associated with *ASTM A 709* Grade HPS-485W (70 W), as well as its increased ductility, toughness, weldability, and improved weathering ability, this newly developed grade of steel is highly attractive for applications in bridges. As a result of its increased strength when compared to conventional 345 MPa (50 ksi) steel, HPS-485W (70 W) enables lighter sections to be used, leading to sizable cost savings in overall construction. Lighter bridge girders often equate to shallower sections, which provide greater clearances for the roads underneath. The reduction of carbon within the chemistry of the steel has produced better toughness and weldability characteristics, which translate to better fatigue details and cost savings. The enhanced weathering capability of HPS-485W (70 W) is also an attractive feature as reduced corrosion damage translates to lessened life-cycle costs. These benefits have prompted the use of HPS bridge girders to grow considerably—currently there are more than 200 HPS bridges under design or construction in 39 states (AISI 2004).

Length of HPS plate is currently limited by choice of production process, of which there are two available: quenching and tempering (Q&T) and a thermomechanical controlled process (TMCP). The Q&T procedure allows plates up to 102 mm (4 in.) thick to be created in lengths limited to 15.24 m (50 ft), which can cause a great deal of undesirable splices in longer girders. HPS-485W (70 W) can be produced in sheets up to 38.1 m (125 ft) in length and 51 mm (2 in.) thick by using TMCP (ISG 2003). Given the increased plate length, this manufacturing process could potentially be a great improvement over Q&T due to the exclusion of splices over a greater length of material. Because of its recent introduction and a lack of material testing, relatively little is known concerning the effect of this new production method upon the intraplate variability of both tensile strength and toughness.

As a part of the FHWA's initiative to use innovative materials in bridge design and construction, the Ohio Department of Transportation (ODOT 2002) has constructed a HPS-485W (70 W) TMCP four-span, five-girder highway bridge in Lancaster, Ohio. Research concerning that bridge has been ongoing, part of which has been to adequately characterize the HPS-485W (70 W) TMCP steel used in its construction. Because of the promise that HPS-485W (70 W) TMCP appears to demonstrate with respect to bridge girder applications, it is important that the behavior of the material, as well as the entire bridge as a structural system, is well understood. This paper focuses on material aspects of the HPS-485W (70 W) TMCP bridge girders.

Background

A great deal of attention has been devoted to HPS since its development in 1992, but only a limited amount of research has been directed toward its material properties, most of which has

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focused on the Q&T-produced grade. Research which has been directed toward HPS-485W (70 W) TMCP has been primarily investigative in nature; Manganello (1995), Krouse (1999), Focht and Manganello (1996), Bodnar (1995), and Chilton and Manganello (1996) all discussed the efforts to develop a non-Q&T HPS, but none of those early candidates were ever made available to the bridge-building industry. HPS-485W (70 W) TMCP is currently being used in bridge construction across the United States. Unfortunately, very little literature has been published on the version of HPS-485W (70 W) TMCP that is currently in production and use.

Early development of a non-Q&T, TMCP, version of HPS-485W (70 W) failed primarily due to difficulty obtaining the required 485 MPa (70 ksi) yield strength. "Roundhousing" problems were encountered, wherein the tensile tests exhibited continuous yielding behavior, and no well-defined yield point was present. When the 0.2% offset method was used to find the apparent yield stress, those values obtained were lower than 485 MPa (70 ksi). Bodnar (1995) explained the continuous yield behavior as caused by the presence of large volume fractions of bainite. It was suggested by many writers that more work be done to develop a more successful HPS-485W (70 W) TMCP candidate (Chilton and Manganello 1996; Focht and Manganello 1996; Krouse 1999; Wilson 1999).

Chen et al. (2003) recently performed a study in which toughness strength and tensile strength of HPS-485W (70 W) TMCP were examined. Properties for both 6.4 mm (0.25 in.) and 51 mm (2 in.) plates were studied. The investigation into the tensile strength of the two plate sizes revealed that static yield strengths for both plate thicknesses were somewhat below *ASTM A 709* (ASTM 2001a) specified bounds. The average strength for the 6.4 mm (0.25 in.) plate with coupons oriented transverse to the direction of rolling was 446 MPa (64.7 ksi), and was found to be 438 MPa (63.5 ksi) for the 6.4 mm (0.25 in.) plate with coupons oriented parallel to the direction of rolling. The average yield strength for the 51 mm (2 in.) plate coupons, all of which were oriented longitudinal to the direction of rolling, was found to be 453 MPa (65.7 ksi). The average ultimate strength for the 6.4 mm (0.25 in.) plate was above the specified bound, with the strength of transverse coupons measured at 641 MPa (92.96 ksi) and those oriented parallel to the direction of rolling averaging at 653 MPa (94.7 ksi). However, the average ultimate strength for the 51 mm (2 in.) plate coupons was found to be 518 MPa (75.1 ksi), which is lower than that mandated by *ASTM A 709* (ASTM 2001a). The investigation also revealed that the 6.4 mm (0.25 in.) plate was considerably less tough than the 51 mm (2 in.) plate.

Seradj (2004) reported low yield strengths and scattered toughness values for HPS-485W (70 W) TMCP plates used in a new bridge construction project near Portland, Ore. The Oregon DOT (ODOT 2002) required that sample testing be completed on the HPS-485W (70 W) TMCP plates before the bridge was fabricated to ascertain that the material could achieve properties specified by *ASTM A 709* (ASTM 2001a). The tests concluded that mechanical properties of a few as-rolled plates were less than the 482.6 MPa (70 ksi) mandated by *ASTM A 709* (ASTM 2001a). In addition to this, there were problems with some plates achieving the required toughness values. The plates were subsequently heat treated to correct the low strength problem, and then easily met the material property requirements for HPS-485W (70 W). Even after the heat treating, it was found that the toughness of HPS-485W (70 W) TMCP was considerably more scattered than that of HPS-485W (70 W) Q&T, and the yield strength for the TMCP-produced steel was considerably less than that produced by the Q&T method.

Objectives

The objective of this study is to characterize material properties of HPS-485W (70 W) TMCP. This includes performing tensile and toughness tests, and comparing results to existing *ASTM A 709* (ASTM 2001a) requirements for HPS-485W (70 W).

Tensile and toughness testing are necessary to investigate whether or not this material performs to the same standard as it is held to in design. It is also important to investigate the presence of any notable intraplate variability for either tensile or toughness strength, which could conceivably be an issue due to possible uneven cooling present in TMCP production as opposed to the more uniform cooling found in Q&T.

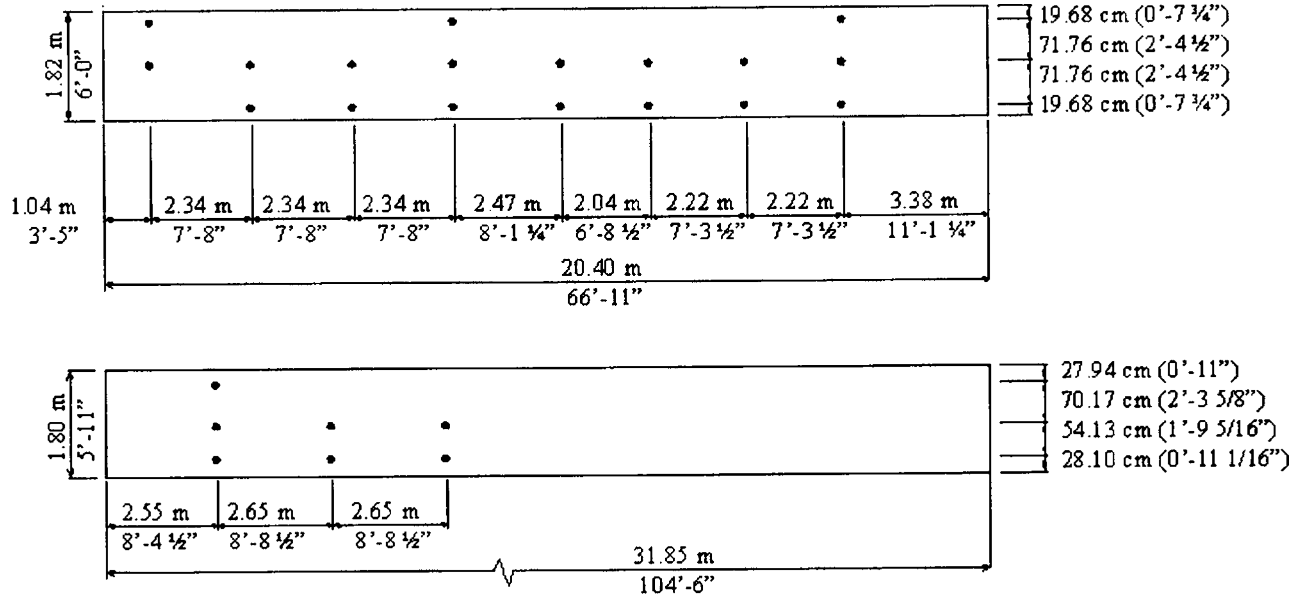
Experimental Setup

Two large HPS-485W (70 W) TMCP plates were obtained from Bethlehem Steel, one 22 mm (7/8 in.) thick and the other 51 mm (2 in.) thick, for the purpose of fabricating the flanges of the Lancaster bridge girders, as well as supplying enough steel with which to perform adequate material testing. Gross dimensions of the plates were 1.8 m×20.4 m×22 mm (6 ft−0 in. ×66 ft−11 in.×7/8 in.) and 1.8 m×31.9 m×51 mm (5 ft−11 in. ×104 ft−6 in.×2 in.). The two large HPS plates were cut into multiple smaller plates, from which the bridge girder flanges were cut. Tensile and Charpy V-Notch (CVN) specimens were machined. Dimensions of the plates, as well as the location of the CVN and tensile specimens are shown in Fig. 1. The CVN and tensile specimens were taken in groups from each location with three CVN samples being cut from each location, and the number of tensile specimens varying between three and four.

A total of 96 tensile tests were completed to investigate characteristics of the material's stress–strain curves and to examine differences in strength due to thickness, plate orientation, and location. Seventy-five CVN tests were performed to determine if HPS-485W (70 W) TMCP meets the toughness requirements set forth by *ASTM A 709* (ASTM 2001a), and to investigate any variation in toughness within the two plates.

Tensile Testing

To examine the effect of plate thickness on tensile strength and variability, 70 of the 96 tensile coupons were machined from 22 mm (7/8 in.) thick plate, while the remaining 26 specimens originated from 51 mm (2 in.) thick plate. Thirty-five of the 22 mm (7/8 in.) thick coupons were oriented such that their longitudinal axis was transverse to the direction of rolling, with the other 38 specimens oriented parallel to the direction of rolling. The 51 mm (2 in.) thick coupons were divided such that 12 were oriented transverse to rolling, and 14 oriented parallel to the direction of rolling. The governing specification for tensile testing was *ASTM E 8* (ASTM 2001b). A sheet-type coupon was chosen for the shape of all tensile tests, as is shown in Fig. 2.



LEGEND

- Origination location of tensile and CVN specimens.
  Three to four tensile specimens were obtained from each location denoted by a dot.
  Three CVN specimens were obtained from each location denoted by a dot.

Fig. 1. Sample locations of Charpy V-Notch and tensile specimens from 7/8 and 2 in. plates (not to scale)

Tensile specimens were tested in a MTS 312 load frame, with a maximum load capacity of 245 kN (55 kips) and a 220 kN (50 kips) capacity load cell. A strain-extensometer with a range of ±500,000 μstrain was used to measure strain in the specimens. The coupons were tested axially under stroke control, loaded at a rate of 0.38 mm (0.015 in.) per minute [corresponding to an elastic rate of 345 MPa (50 ksi) per minute], up to 2.5 mm (0.10 in.) of stroke displacement, upon which the loading rate was increased to 3.3 mm (0.13 in.) per minute until fracture (Dues et al. 2002).

The load rate of 0.38 mm/min (0.015 in./min) up to and through the onset of yield is in accordance with *ASTM E 8* (ASTM 2001b) and *ASTM A 370* (ASTM 2002), which require a stress rate between 68.9 MPa/min (10,000 psi/min) and 689 MPa/min (100,000 psi/min), the former of which states that "The speed of the testing machine shall not be increased in order to maintain a stressing rate when the specimen begins to yield. In practice, it is simpler to use either a strain rate, a rate of separation of the heads, or a free-running crosshead speed which approximates the desired stressing rate" [*ASTM E 8* (ASTM 2001b)]. After yielding was reached, the strain rate was increased to 3.3 mm/min (0.13 in./min), which is less than the *ASTM E 8* suggested rate of 1.27–12.7 mm (0.05–0.5 in./in.) per millimeter of the reduced section per minute, corresponding to a rate 3.81–38.1 mm/min (0.15–1.5 in./min) for the 76.2 mm (3 in.) reduced section being examined. This rate was used to ensure machine stability while specimens were being held in strain control for the purpose of determining static stresses. While this discrepancy should be recognized, it must also be noted that the slightly slower test rate used affects only the ultimate strength results, and will always provide more conservative results than if a faster test rate was used. This point will be discussed further in the "Results and Discussion" section, and it will be shown that the experiment's validity did not suffer as a result of this incongruity.

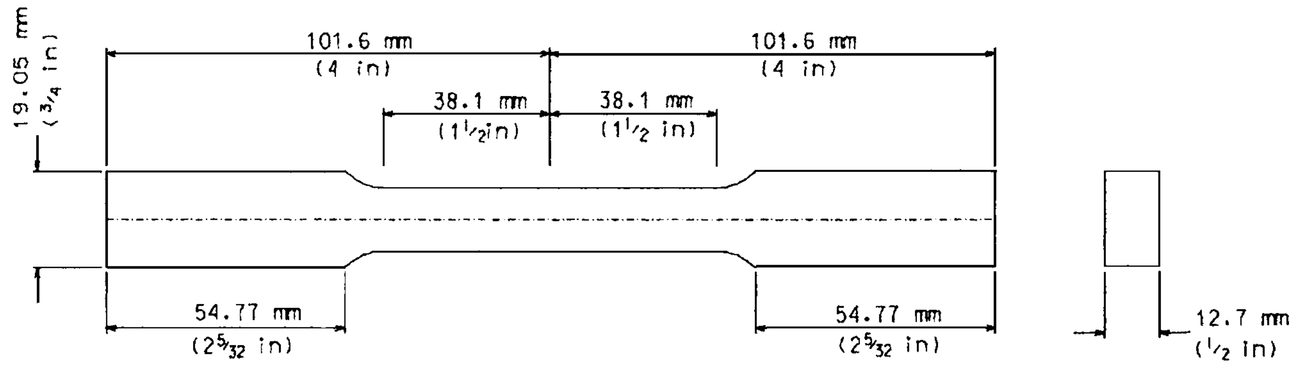


Fig. 2. *ASTM-E 8* sheet-type coupon specimen, dimensions typical for all tensile tests

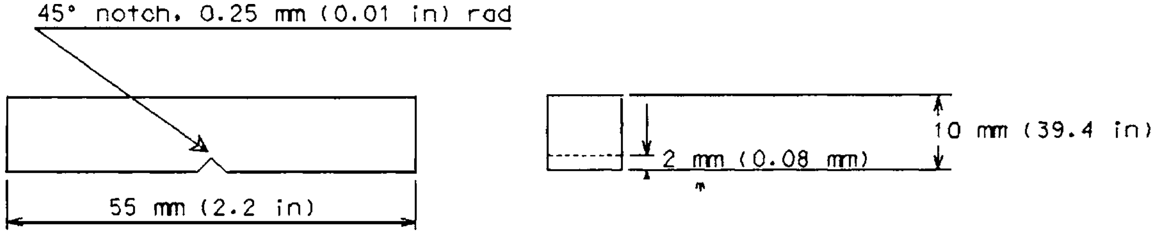


Fig. 3. Charpy V-Notch specimen, dimensions typical for all toughness tests

A stress–strain diagram was plotted for each tensile coupon, and from these plots, the coupons' moduli of elasticity, dynamic yield stresses, static yield stresses, dynamic ultimate strengths, static ultimate strengths, and percent elongations were determined. The modulus of elasticity, E, was determined by fitting a straight line to the data points composing the elastic portion of the stress–strain diagram, up to the data point corresponding with approximately 50% of the mill-certified yield strength. This limitation helped to ensure that the modulus of elasticity was indeed being calculated within the elastic region of the curve. The 0.2% offset method was used to determine the dynamic yield stress, F_{yd}. The static yield stress, F_{ys}, was found for each specimen to provide a more normalized comparison between these tensile tests and those performed by others. Strain was held constant for 30 s twice during the testing to establish the difference between dynamic and static stresses. These two differences were then averaged, finding $(\sigma_d - \sigma_s)$ for each coupon. The static yield stress was then calculated by subtracting this difference, $(\sigma_d - \sigma_s)$, from the dynamic yield stress, F_{yd}, as shown in the following equation:

$$F_{\mathrm{ys}} = F_{\mathrm{yd}} - (\sigma_d - \sigma_s) \tag{1}$$

The dynamic ultimate strength, F_{ud}, of each coupon was taken as the maximum stress resisted by that coupon during loading. The same methodology used to find the static yield stress was used to determine static ultimate strength, F_{us}. Here the quantity $(\sigma_d - \sigma_s)$ was subtracted from F_{ud}, as shown in the following equation:

$$F_{\mathrm{us}} = F_{\mathrm{ud}} - (\sigma_d - \sigma_s) \tag{2}$$

Finally, percent elongation was measured for each specimen, using two sets of center-punched gage marks for each sample (Dues et al. 2002). The distance between the gage marks for both pairs was measured before and after testing; two sets of marks were used in case fracture were to occur at one of the marks.

Toughness Testing

To examine plate toughness, 75 CVN specimens from the HPS-485W (70 W) TMCP plates were tested in accordance with *ASTM E 23* and *ASTM A 370* (2002). Fifty-four of the toughness specimens were cut from the 22±mm (7/8 in.) plate, while the remaining 21 were taken from the 51 mm (2 in.) plate; all were oriented parallel to direction of rolling. Fig. 3 shows the dimensions of the CVN specimens. The 75 CVN specimens were tested at −23°C (−10°F) to facilitate an easy comparison to the AASHTO-LRFD Zone III requirement for 48 J (35 ft-lb) of impact resistance at −23°C (−10°F) (AASHTO 2004). The specimens were taken in groups of three from various locations along the length and width of the two large plates, as shown in Fig. 1, which closely corresponded to locations for the tensile specimens from those same plates. It was hoped that, as for the tensile specimens, by cutting the toughness specimens from varying locations along the HPS-485W (70 W) plate, a general trend could be established for variation of toughness across or along a plate.

Table 1. Average Tensile Testing Results

	E [GPa (ksi)]		**F$_{\mathrm{yd}}$** [MPa (ksi)]		**F$_{\mathrm{ys}}$** [MPa (ksi)]		**F$_{\mathrm{ud}}$** [MPa (ksi)]		**F$_{\mathrm{us}}$** [MPa (ksi)]		Elongation (%)
Average experimental values											
All coupons	213.4	(30,958)	470	(68.2)	448	(65.0)	656	(95.1)	634	(91.9)	27.4
22 mm (7/8 in.) thick coupons	213.5	(30,970)	490.2	(71.1)	468.8	(68.0)	653.6	(94.8)	631.6	(91.6)	26.3
51 mm (2 in .) thick coupons	213.2	(30,925)	415.1	(60.2)	392.3	(56.9)	661.2	(95.9)	638.5	(92.6)	30.7
ASTM A 709 required values for HPS-70W (Q&T)	—		485	(70)	—		585–760	(85–110)	—		19
Standard deviation											
All coupons	6.03	(874)	37	(5.3)	37	(5.4)	21	(3.0)	21	(3.0)	3.5
22 mm (7/8 in.) thick coupons	6.5	(943)	13.1	(1.9)	13.1	(1.9)	13.1	(1.9)	13.8	(2.0)	2.6
51 mm (2 in .) thick coupons	4.6	(668)	20.7	(3.0)	21.4	(3.1)	32.4	(4.7)	33.8	(4.9)	3.5
Coefficient of variation											
All coupons	2.8%		7.9%		8.3%		3.2%		3.3%		12.8
22 mm (7/8 in.) thick coupons	3.0%		2.7%		2.8%		2.0%		2.2%		9.9
51 mm (2 in .) thick coupons	2.2%		5.0%		5.4%		4.9%		5.3%		11.4

Table 2. Mill Certificate for 22 mm (7/8 in.) HPS-485W (70 W) Plate

Bethlehem Steel Corporation Report of Tests and Analysis

Bethlehem Lukens plate Shipment No. 803-13038 Date shipped: 7/30/01

		Size and quantity								
Serial number	Heat number	Number of Pieces	Thickness (in.)	Width (in.)	Length (in.)	Weight (lb)	Yield point (psi)	Tensile strength (psi)	Elongation (in.)	Elongation (%)
A256321	822T40710	1	7/8	72	803	14,347	77,700	95,800	2	26
							94,100	96,700	2	40
A256504	823T73000	1	7/8	63.25	865.5	13,584	77,600	92,200	2	38
							77,800	92,900	2	39

Charpy impact

Serial number	Heat number	Bend	Type	Size	Direction	Test Temperature (°F)	Energy (ft-lb) 1	2	3
A256321	822T40710	T	V	Full	L	−25	113	118	105
		B	V	Full	L	−25	118	130	51
A256504	823T73000	T	V	Full	L	−25	149	117	163
		B	V	Full	L	−25	177	105	161

Chemical analysis

Heat number	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Al	B	Cb	N
822T40710	0.10	1.21	.013	0.005	0.389	0.321	0.32	0.55	0.057	0.058	0.002	0.032	—	0.003	0.008
823T73000	0.10	1.19	.012	0.006	0.414	0.355	0.29	0.55	0.056	0.059	0.003	0.032	—	0.003	0.010

Results and Discussion

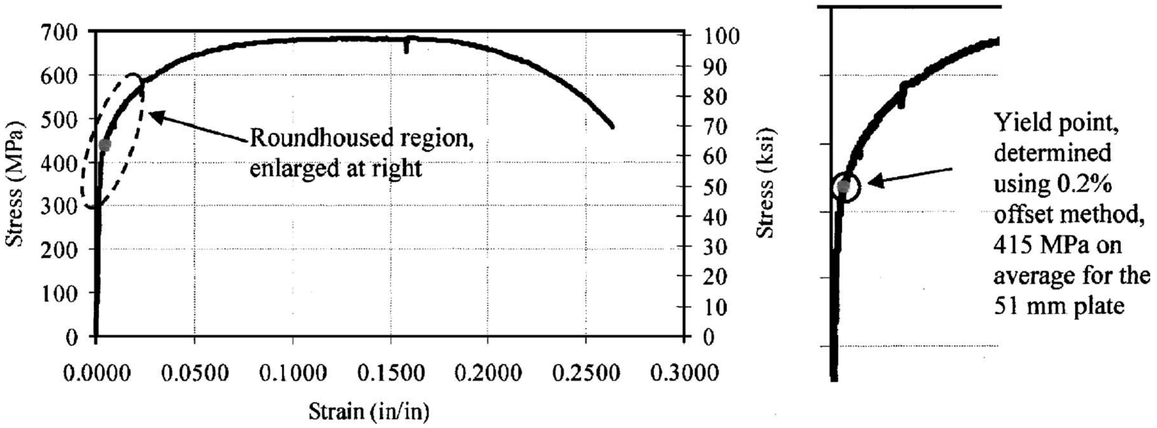
Tensile Testing

Averaged tensile test results for each of the measured parameters are shown in Table 1. They show that the average static and dynamic yield stresses are both below the 485 MPa (70 ksi) minimum set forth by *ASTM A 709* (ASTM 2001a) for HPS-485W (HPS-70 W) Q&T. The low yield stresses can be partially explained by the stroke test rate used through the yield region, which is near the middle of the range mandated by *ASTM E 8*. Lower testing rates provide more conservative values for strengths. Unfortunately, *ASTM A 709* (ASTM 2001a) provides both upper and lower bounds for the rate of crosshead separation within which tensile tests are deemed acceptable. This creates a problematic situation when comparing results to other work, for test rates are rarely published along with the tensile results. Therefore, although these yield stresses appear to be low, it is difficult to accurately compare them to previous work, or even to mill certificates that describe tensile properties of the original plates, as are shown in Tables 2 and 3. Static yield stresses can be calculated if the specimens are held in strain control to provide consistent information for the sake of comparison (Galambos 1998), but static yield values are also often not published in previous work; the required values from ASTM are for dynamic testing only. For these reasons, it is unlikely that the rate of crosshead separation is the sole explanation for the low yield stresses. For the results to be ASTM acceptable, they must pass at any test rate within the aforementioned limits, including the more conservative values that were used herein.

Another reasonable explanation for the low yield stresses becomes apparent when tensile results are examined in relation to the thickness of the plates from which they originated. The average yield strength for the 22 mm (7/8 in.) plate was found to be 490 MPa (71.1 ksi) and the average yield strength for the 51 mm (2 in.) plate was 415 MPa (60.2 ksi). The difference between the results from the 22 mm (7/8 in.) plate and the 51 mm (2 in.) plate is quite significant −75 MPa (10.9 ksi), or a 15.3% difference. Upon examination of the 51 mm (2 in.) plate coupons, it can be seen that almost all of the specimens exhibited roundhousing, or continuous yielding behavior, as is shown in Fig. 4. Very few of the 22 mm (7/8 in.) coupons exhibited the same phenomena, with a typical stress–strain diagram for those coupons shown in Fig. 5. Comparison of these data shows that there may be some inherent difficulties in the TMCP method when producing plates of greater thickness.

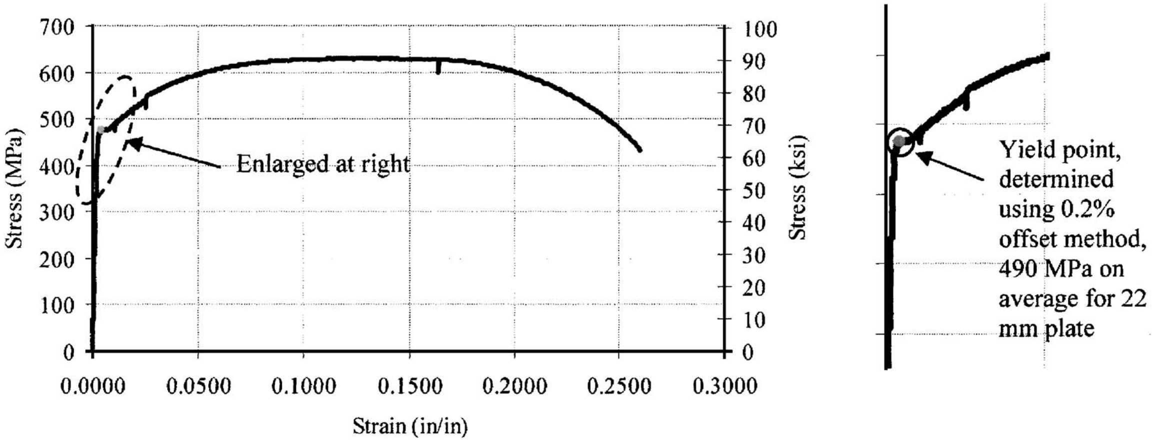
The ultimate strengths for both plate thicknesses, however, fell within reasonable limits. *ASTM A 709* (ASTM 2001a) imposed limits are 585–760 MPa (85–110 ksi), and measured averages for dynamic and static ultimate strengths were found to be 655.7 MPa (95.1 ksi) and 633.6 MPa (91.9 ksi), respectively. It is doubtful that a higher rate of crosshead separation would cause the average ultimate strength to exceed the 760 MPa (110 ksi) limit, but testing should be conducted at the high end of the *ASTM E 8* test rate range to verify this hypothesis. Thus, even with the conservative test rate used for the postyield regions, ultimate strengths lie within an acceptable range according to *ASTM A 709* (ASTM 2001a).

Mill certificates (Tables 2 and 3) reported higher values for yield and ultimate strengths of both plates than were found in this study, providing an average yield strength of 564.0 MPa (81.8 ksi) for the 22 mm (7/8 in.) plate, which is 13.1% higher than the experimental results of the current study, and 557.4 MPa (80.85 ksi) for the 51 mm (2 in.) plate, which is 25.6% higher than the results determined in this study. It should be noted that



Yield point, determined using 0.2% offset method, 415 MPa on average for the 51 mm plate

Fig. 4. Typical stress–strain curve for thermomechanical controlled process 70 W coupon from 51 mm (2 in.) plate



Yield point, determined using 0.2% offset method, 490 MPa on average for 22 mm plate

Fig. 5. Typical stress–strain curve for thermomechanical controlled process 70 W coupon from 22 mm (7/8 in.) plate

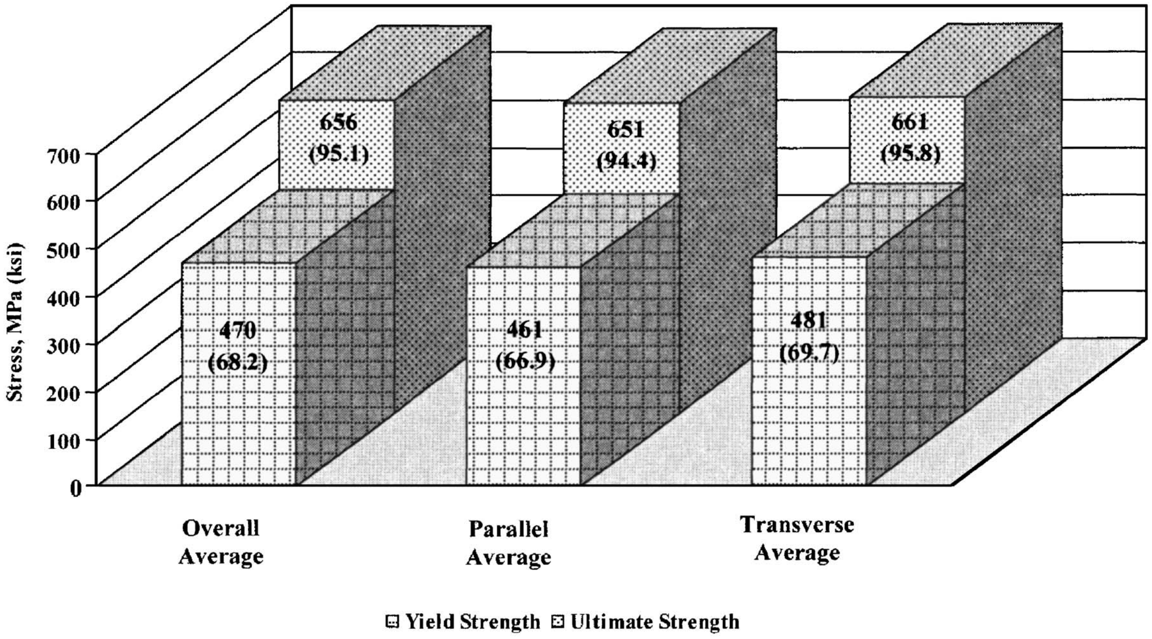


Fig. 6. Coupon strength averages for orientation parallel and transverse to direction of rolling

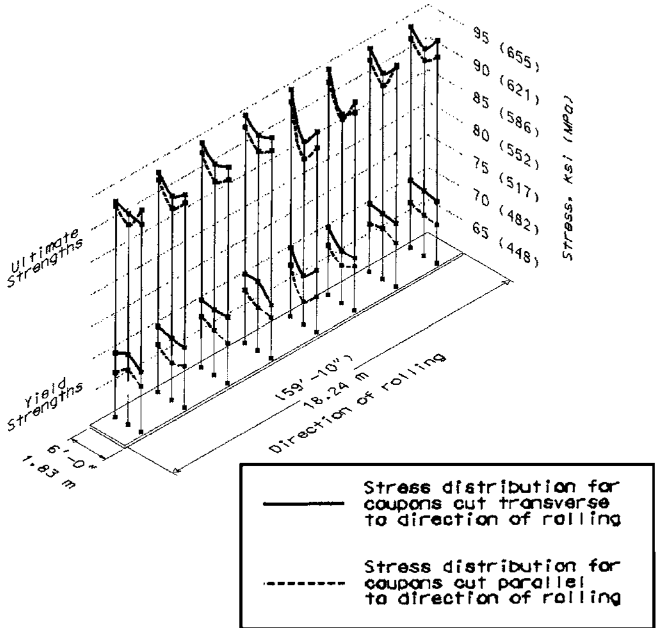


Fig. 7. Tensile stress distribution over cross sections of 22 mm (7/8 in.) thick plate

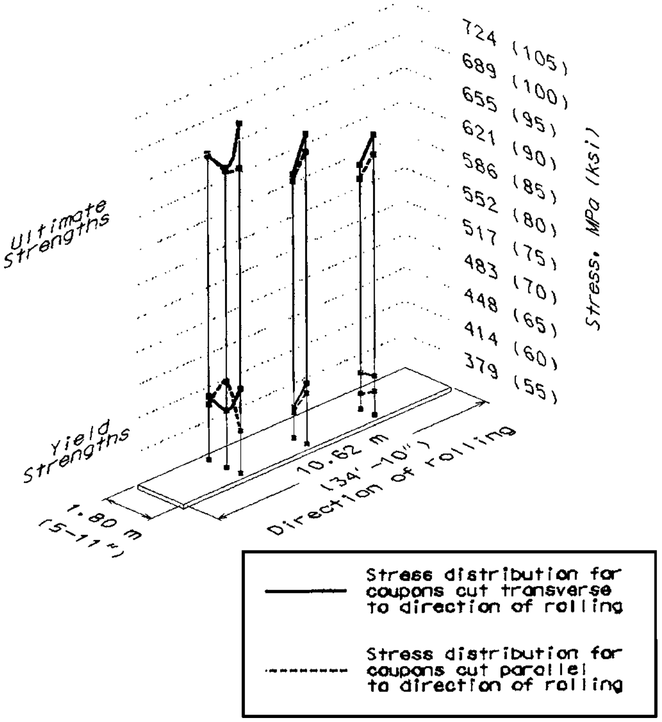


Fig. 8. Tensile stress distribution over cross sections of 51 mm (2 in.) thick plate

plate producers are generally perceived to test at the upper end of the ASTM test rate range, which may explain this discrepancy.

Remaining tensile properties measured for this investigation also fell within acceptable limits. The coupons exhibited excellent ductility characteristics; percent elongation was experimentally found to be 27.4%, which is 44% larger than the *ASTM A 709* (ASTM 2001a) required 19% elongation. The modulus of elasticity was also found to be reasonable, at 213.5 GPa (30,958 ksi).

An interesting phenomenon becomes apparent when coupon strengths are examined in relation to the orientation of those coupons. Orientation of the coupon has a discernible effect upon the strength of the specimen, and is more notable for yield strength than ultimate strength, as is shown in Fig. 6. For almost all cases coupons cut transverse to the direction of rolling exhibited higher strengths than those cut parallel. One possible explanation for this occurrence might be that the microstructure tends to align itself perpendicular to the direction of rolling during the cooling process (Dues et al. 2002). There is a larger disparity in yield strength between the two orientations than there is for ultimate strength; a 4.2% difference in yield strength exists between transverse and parallel coupons, while there is a 1.5%

Table 3. Mill Certificate for 51 mm (2 in.) HPS-485W (70 W) Plate

Bethlehem Steel Corporation Report of Tests and Analysis

Bethlehem Lukens plate — Shipment No. 803-13047 — Date shipped: 7/30/01

Serial number	Heat number	Size and quantity Number of Pieces	Thickness (in.)	Width (in.)	Length (in.)	Weight (lb)	Yield point (psi)	Tensile strength (psi)	Elongation (in.)	Elongation (%)
X400215	601C15310	1	2	71	1,254	50,500	74,400	98,300	2	25
							87,300	108,700	2	22

Charpy impact

Serial number	Heat number	Bend	Type	Size	Direction	Test Temperature (°F)	Energy (ft-lb) 1	2	3
X400215	601C15310	T	V	Full	L	–25	53	39	47
		B	V	Full	L	–25	39	23	37

Chemical analysis

Heat number	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Al	B	Cb	N
601C15310	0.09	1.23	0.011	0.002	0.420	0.320	0.34	0.55	0.060	0.060	0.004	0.023	0.0002	0.001	0.007

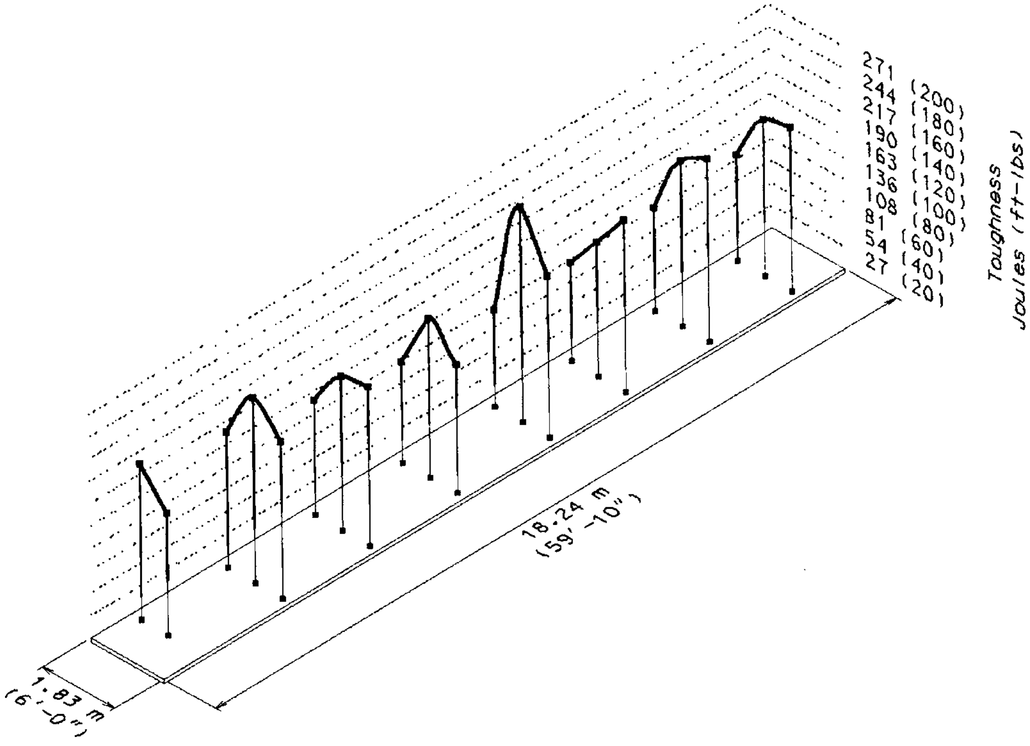


Fig. 9. Toughness distribution over cross sections of 22 mm (7/8 in.) plate

difference in ultimate strengths of those same coupons. This effect is considerably more pronounced for the 22 mm (7/8 in.) coupons than for the 51 mm (2 in.) coupons, which can be noted by examining Figs. 7 and 8. One potential reason for this is that the 22 mm (7/8 in.) plate cooled more quickly and uniformly than the 51 mm (2 in.) plate, leading to a more homogenous distribution of the microstructure, which is seemingly oriented transverse to the direction of rolling. This explanation also helps to clarify why the strength is greater for the 22 mm (7/8 in.) plate than for the 51 mm (2 in.) plate, since faster cooling rates often produce steel of higher strength.

It has been questioned whether the cooling process inherent in TMCP causes any intraplate variation across the plates' dimensions. Upon examination, the data does show noticeable intraplate variation in yield and ultimate strengths for both the 22 mm (7/8 in.) and the 51 mm (2 in.) plates, shown in Figs. 7 and 8. For both thicknesses, the HPS-485W (70 W) TMCP plates exhibit higher yield and ultimate strengths toward the plate edges than they do along their central longitudinal axis. For a majority of the cases, minimum strengths were found to lie along the centerline of the plates' longitudinal axes, while higher tensile strengths were observed to lie nearer the plates' width boundaries, leading to a "cupped" shape for the tensile stress distribution across the plates' widths. This trend is manifested most clearly by ultimate strengths of coupons taken from plates of both thicknesses, but is also valid for the yield strengths. Also, while the cupped tensile stress distributions are more apparent for the 22 mm (7/8 in.) plate than for the 51 mm (2 in.) plate because of the larger number of samples, a similar trend can be identified for the 51 mm (2 in.) plate tensile stress distributions where, except for a single data point, the centerline tensile strengths are lower than those along the edge.

It should be noted that five of the data points on the far edge of the 22 mm (7/8 in.) plate, shown in Fig. 7, were not directly measured from experimental data, but were interpolated from three other data points lying in the same rear line of sampling locations. The inclusion of the interpolated points enabled examination of a greater number of complete stress distributions for the 22 mm (7/8 in.) plate. The fact that the data on the far edge of the plate is fairly symmetrical with the data for the near edge is a good indicator that the interpolated values are reasonable approximations for the actual tensile data. Only one data point was available in the rear line of samples for the 51 mm (2 in.) plate so interpolation was not possible. Therefore, Fig. 8 shows one three-point stress distribution and two two-point distributions.

Toughness Testing

Three CVN samples were machined from each small plate cut from the two large, rolled plates (Fig. 1). The three results at each particular location were averaged to plot the results along the plate dimensions, as is shown in Fig. 9 for the 22 mm (7/8 in.) plate and in Fig. 10 for the 51 mm (2 in.) plate. The average toughness for the 22 mm (7/8 in.) plate was found to be 187.9 J (138.6 ft-lb) with a standard deviation of 42.6 J (31.4 ft-lb), and the average toughness for the 51 mm (2 in.) plate was seen to be 115.4 J (85.1 ft-lb) with a standard deviation of 37.1 J (27.4 ft-lb). Sixty-eight percent of all the CVN specimens fell within 1 SD of the mean, and 96% of the total test sample fell within 2 SD of the mean.

While both of these averages well exceed the AASHTO-LRFD (AASHTO 2004) required value of 48 J at −23°C (35 lbf at −10°F), the large difference in average toughness between the 22 mm (7/8 in.) plate and the 51 mm (2 in.) plate is worth noting. The sizeable variation in toughness reveals a potential limitation of TMCP, as well as a reason why plate thickness created by this process is currently constrained to 51 mm (2 in.). If the current results are linearly extrapolated to obtain a fictional toughness strength for a 76 mm (3 in.) thick plate, a toughness of 50.8 J (37.5 ft-lb) is obtained; if extrapolated further to explore a poten-

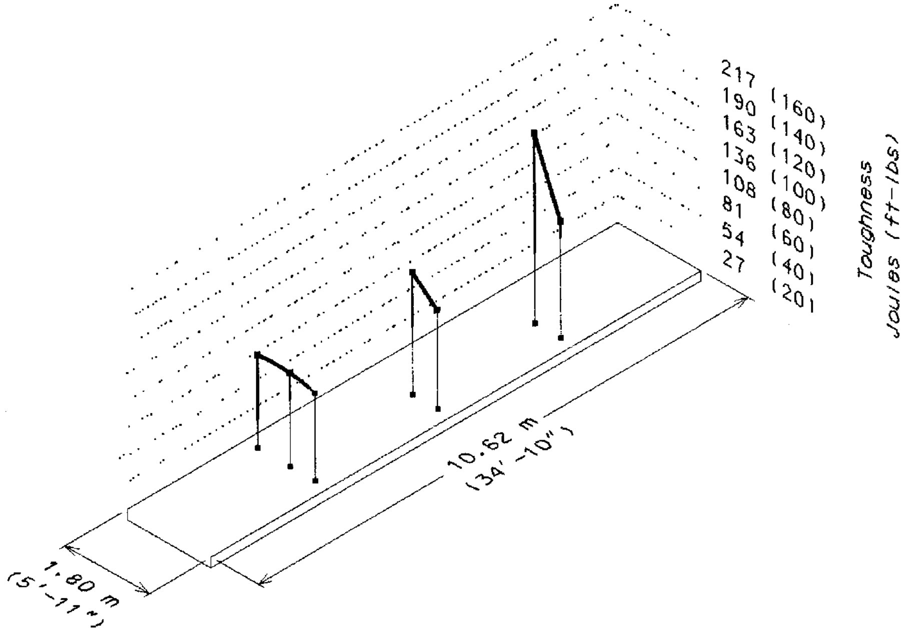


Fig. 10. Toughness distribution over cross sections of 51 mm (2 in.) plate

tial 102 mm (4 in.) thick plate, a negative value for the toughness is obtained. The latter case is obviously under strength with respect to the AASHTO requirements, but even the fictional 76 mm (3 in.) plate with its apparent "passing" toughness of 50.8 J (37.5 ft-lb) is close enough to the limiting envelope to potentially be unreasonable without further refinement to the TMCP process.

As there were more samples taken from the 22 mm (7/8 in.) plate than for the 51 mm (2 in.) plate (Fig. 1), a more complete distribution was obtained for the former, but again, a similar trend can be noted for both cases, as is shown in Figs. 9 and 10. As was the case for the tensile data, four data points lying in the rear line of sampling locations in Fig. 9 were interpolated from the other three data points lying within that same section in order to obtain a more complete plot. Distributions for both plate thicknesses suggest a concave down shape across the cross section of the plates, where the maximum toughness strength is found along the centerline of the plates' longitudinal axes, and the minimum toughness strengths exist on the edges.

The shape of the toughness distribution is worth noting, because it is exactly opposite from that for tensile strength distribution. This suggests that there is an inverse relationship between tensile and toughness strengths for these specimens; as tensile strength increases, toughness decreases, with the opposite holding true as well. While this in itself is not uncommon for high strength steel, Bodnar (1995) attributed a similar inverse relationship to the presence of bainite in his progress report on as-rolled Nb–V weathering steel for bridge applications. This seems to be a reasonable conclusion for the cause of the inverse relationship seen in the present study as well. Bodnar also attributed low yield strengths seen in that investigation to the presence of large fractions of bainite; the same issue has occurred in this research. Although the 51 mm (2 in.) plate coupons exhibited low yield stresses, they also exhibited the highest ultimate strengths and the lowest toughness strengths. Further study should be performed on current HPS-485W (70 W) TMCP to determine whether bainite is the root cause of low yield strength and toughness in the thicker plates.

Conclusion

HPS-485W (70 W) TMCP is a promising grade of bridge steel, but its usefulness seems to be limited by plate thickness. Experimentally, it meets or exceeds many of the required properties described in *ASTM A 709* (ASTM 2001a), regardless of plate thickness. It certainly meets the requisites for toughness and ultimate strengths, and the intra-plate variability of tensile strength and toughness for the thicknesses tested does not seem to be a great concern. However, HPS-485W (70 W) TMCP does not meet the yield strength criterion when examining the 51 mm (2 in.) plate. The experimentally found average dynamic yield strength of 470 MPa (68.2 ksi) is below the required 485 MPa (70 ksi), and this should be recognized by designers and dealt with in the steel-making industry. Further research should be conducted to determine the cause of the roundhousing phenomena in thicker plates.

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