Production Experience with New Heavy Plate Grades for Bridges and Shipbuilding Using Microalloying

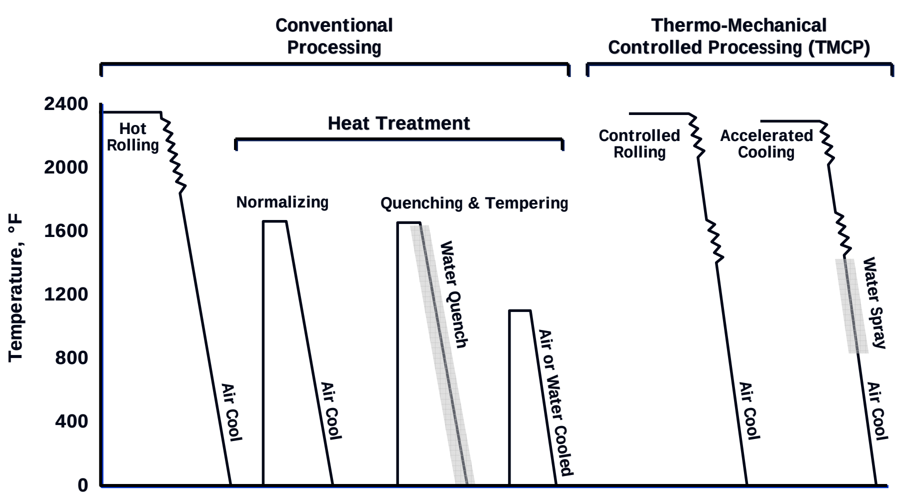
Alexander D. Wilson
Mittal Steel USA
139 Modena Road
Coatesville, PA 19320
Tel.: 610-383-3105
Fax: 610-383-2175
Email: alex.wilson@arcelormittal.com

Key words: High Performance Steel (HPS), High Strength Low Alloy (HSLA)
Quenching and Tempering (Q&T), Thermal-Mechanical-Controlled Processing (TMCP), Microalloy, Weldability, Bridges, Shipbuilding

INTRODUCTION

Over the past decade, research and development activities in the steel bridge and Navy shipbuilding industries have led to the implementation of improved high strength plate steels. With improved weldability and toughness, microalloying additions were an important part of the alloy design of these grades. The development of these new grades started with a requirement of low sulfur levels, as low as 0.002% maximum, with calcium inclusion shape control. This helped provide a basis for improved toughness in all orientations with resistance to lamellar tearing during welding. Plate production of these improved grades also utilized the optimum processing for high strength plate steels using either/or/both quenching and tempering (Q&T) and thermal-mechanical-controlled-processing (TMCP). These processes are schematically shown in Figure 1. The grades that were developed used V, Cb and/or Ti for strengthening and grain refinement characteristics. The grades that were developed were as follows:

Figure 1 - Processes for Producing Plate Steels



Navy Shipbuilding
ASTM A945 Grade 65 (HSLA-65)

- Up to 1-1/4” (32 mm) produced by TMCP from continuous cast slabs
- Over 1-1/4” (32 mm) to 2-1/2” (64 mm) Q&T for ingots

Steel Bridges
ASTM A709 Grades

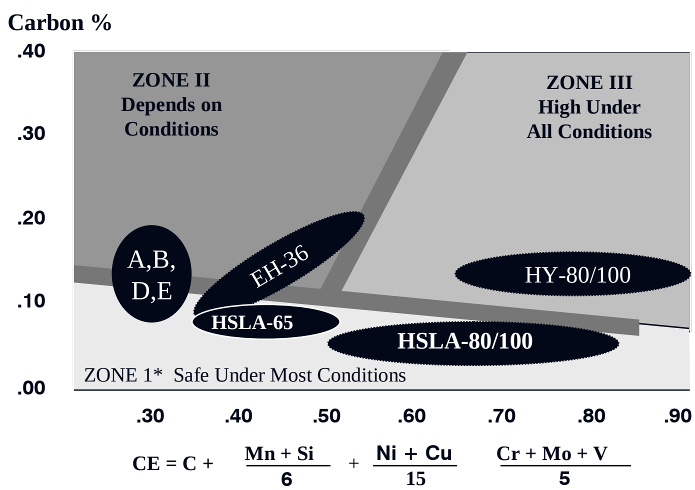
- HPS 70W – TMCP to 2” (51 mm); Q&T to 4” (102 mm)
- HPS 100W – Q&T to 4” (102 mm)

A separate discussion of the development of these new grades and recent production experience will be provided in the following sections.

NEW NAVY STEELS

The U.S. Navy has been using HSLA-80/100 grades on their surface vessels for over 20 years. These grades were developed to replace HY-80/100 because of improved weldability[1]. This is demonstrated in Figure 2 [2]. Subsequently, the need for improved weldability to replace the traditional American Bureau of Shipping (ABS) grades was identified. Also, a slightly higher yield strength would be provided by an HSLA-65 grade. This resulted in a call to industry for grades that would satisfy these needs. Existing line pipe grades for X65 were chosen as the initial candidates. These C-Mn steels have varying microalloyed additions of V, Cb, and Ti. Both TMCP and Q&T processing were evaluated.

Figure 2 - The Graville Weldability Diagram
Susceptibility to HAZ Cracking of Navy Steels



***High Strength Welding Consumables May Require Additional Care**

Thin HSLA-65
The final specification for HSLA-65 was developed as a commercial specification as ASTM A945[3]. The chemistry for plates to 1-1/4” (32 mm) is shown in Figure 3. A Ti addition was made to improve weldment toughness properties. Although the specification allows alternative processing of HSLA-65, plates in this thickness range are most often produced by TMCP. The tensile properties for the grade are 65 ksi (450 MPa) min. yield strength and 78-100 ksi (540 – 690 MPa) ultimate tensile strength. Recent production data is summarized in Figures 4 and 5. These graphs demonstrate that the tensile strength controls the specification, particularly for thinner plate. Also, the Charpy-V-Notch (CVN) impact toughness requirement of 70 ft-lbs.(95 J) @ -40^{o}F (-40 C) is readily met. The microstructure of HSLA-65 is shown in Figure 6, which shows the ferrite-pearlite structure typical of a control-rolled plate.

Figure 3 – A945 Grade 65 Chemistry
(max. if no range shown)

	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	Cb	Al	Ti	N
To 1-1/4”	.10	1.10	0.25	.010	.10	.40	.20	.08	.35	.10	.05	.08	.007	.012
(32 mm)		1.65			.40								.020	
Over 1-1/4” - 2.5”	.10	1.10	.055	.010	.10	.50	.20	.08	.35	.10	.05	.08	.007	.012
(32 mm) (64 mm)		1.65			.40	1.00							.020	

Figure 4 - HSLA-65 TMCP Tensile Data

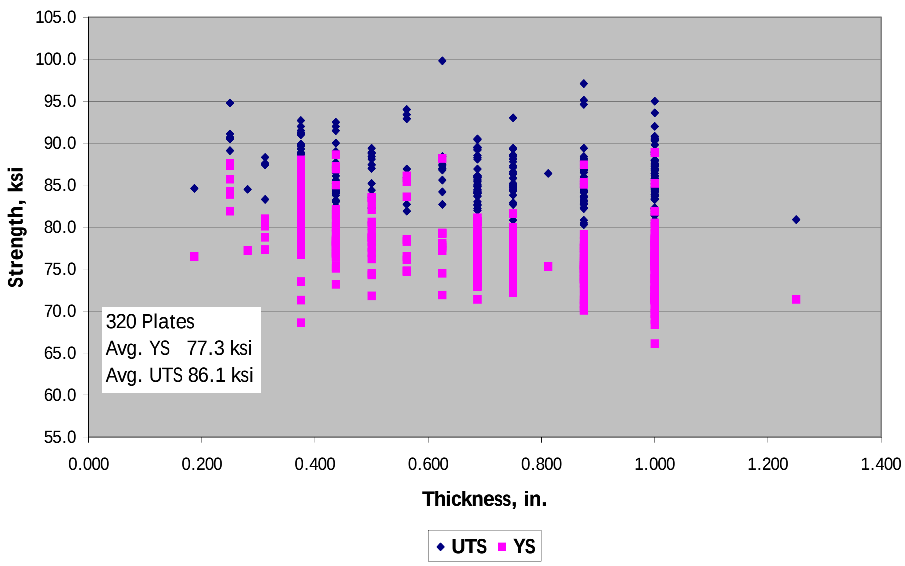


Figure 5 - HSLA-65 TMCP CVN Data

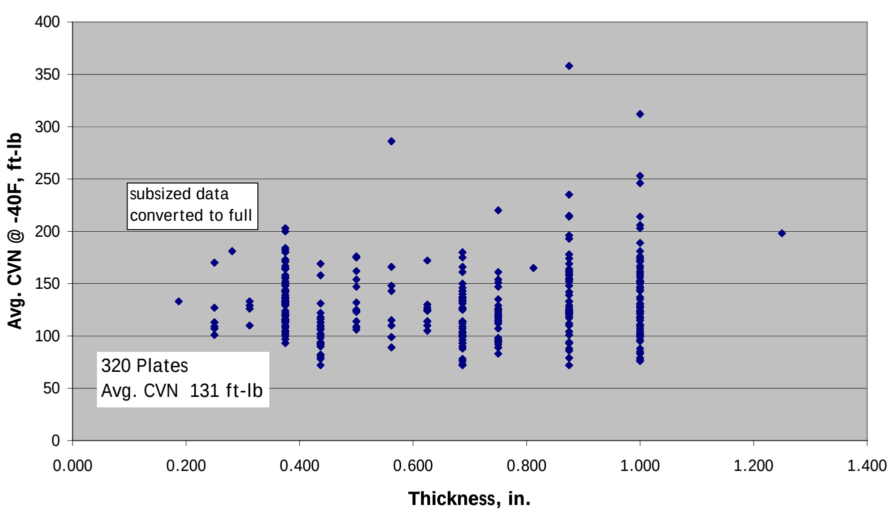
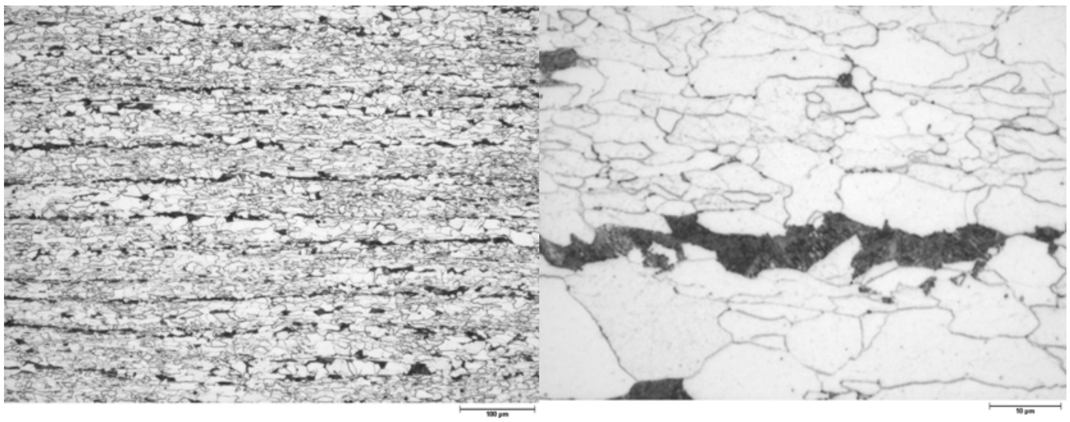
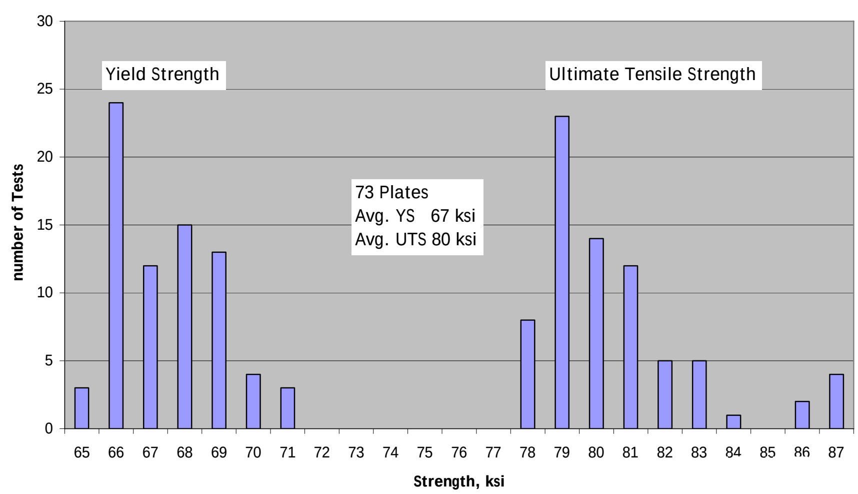


Figure 6 - HSLA-65 – thinner plates to 1¼” Microstructure



5/8 “ Thick Plate

Figure 7 - HSLA-65, Q&T 1.5-2.5" Thick, Tensile Data



An additional Navy requirement for HSLA-65 that is often added is a "precise weight" or "weight controlled" plate. This requirement dictates that plate thickness is controlled very accurately. This is possible at the Mittal Steel USA Burns Harbor, IN 160" plate mill because of 93 isotope thickness gauges that provide immediate feedback of plate thickness across the plate width. Rolling schedules are controlled to produce campaigns of similar width and thickness plates, so that consistent thickness during a mill run is possible.

Thick HSLA-65

The success of the thin HSLA-65 development raised interest in a thicker high strength product to provide weight savings on aircraft carrier construction. Once again, an existing grade was considered for this application. API-2Y-60 is a Q&T grade used in offshore platforms. An existing chemistry for up to 3" (76 mm) was available from ingot cast applications. Ingot casting is required because of the very large plates often required for platforms and ship structures. This grade was evaluated to 2.5" (64 mm) and met the 65 ksi (450 MPa) yield strength requirements, as well as CVN specifications. The chemistry is shown in Figure 3 and is identical to the thinner chemistry - except for the higher nickel level allowed.

The tensile and CVN impact properties for recent production are shown in Figures 7 and 8. Consistent tensile properties have been achieved and excellent toughness demonstrated. The microstructure of this grade is shown in Figure 9. A very refined ferrite-pearlite structure is achieved as a result of the Q&T of this Cb containing chemistry. Both HSLA-65 grades are being widely used in the current construction of aircraft carriers and other surface ships.

Figure 8 - HSLA-65, Q&T, 1.5-2.5", CVN Data

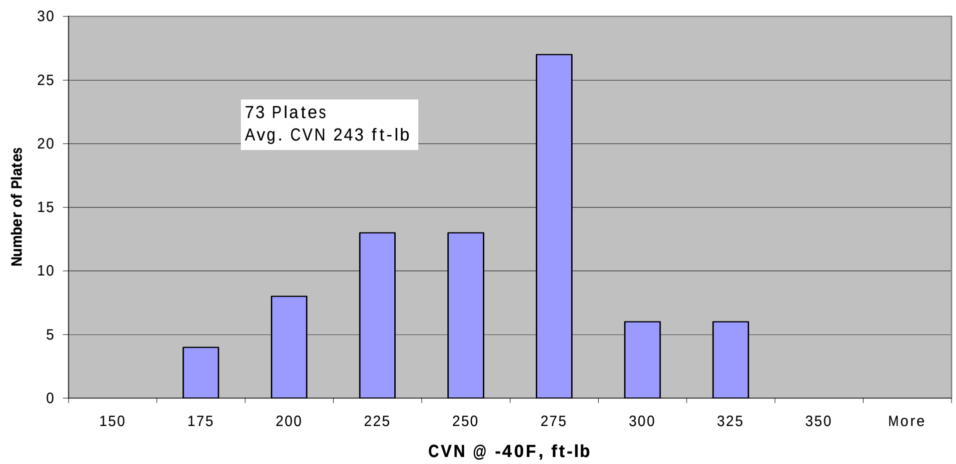
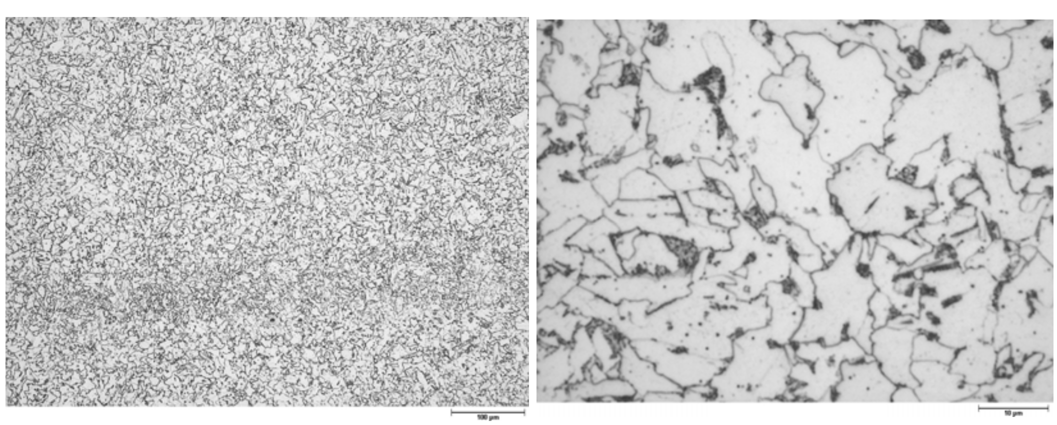


Figure 9 - Thick HSLA-65 to 2½" Microstructure



NEW BRIDGE STEELS

Similar to the Navy applications, the U. S. steel bridge industry, together with the Federal Highway Administration (FHWA) has been active over the past 15 years in developing high strength steels with high toughness and improved weldability, referred to as high performance steels (HPS) [4]. These grades are shown in Figure 10. The improved weldability is demonstrated in Figure 11. More details of these grades are reviewed below.

HPS 70W

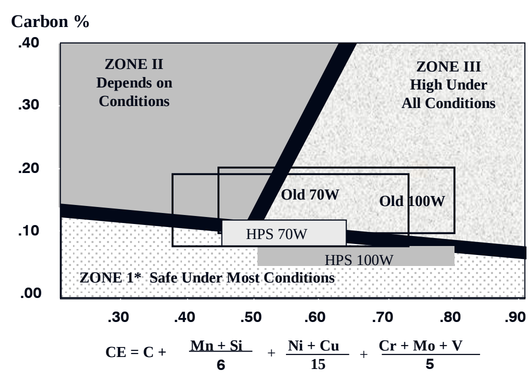
The chemistry of ASTM A709 HPS 70W [3] is shown in Figure 12. The new grade HPS 70W was an improvement upon a former grade 70W. Lower carbon and sulfur levels, as well as tighter chemistry ranges are required, including a significant V addition to help with strength. The chemistry is used to achieve properties to 2" (51 mm) using TMCP and to 4" (112 mm) using Q&T. A ferrite-pearlite microstructure is shown for both processes, as demonstrated in Figures 13 and 14. The mechanical properties using either processing routes are remarkably similar and robust as noted in Figures 15-17. The only major property challenge has been achieving strength for thicker plate as shown in Figure 18. This led to an increase in the allowed Mn level in thicker plates.

Figure 10 - Property Requirements for Current HPS Grades

	HPS 50W Up to 4" (101 mm)	HPS 70W Up to 4" (101 mm)	HPS 100W Up to 2.5" (64 mm)
Yield Strength, ksi (MPa) minimum	**50** (345)	**70** (485)	**100** (690)
Ultimate Tensile Strength, ksi (MPa)	**70** min. (485)	**85-110** (586-760)	**110-130** (760-895)
CVN of 35 ft.-lbs. (48 J) FCM	**+10°F** (-12°C)*	**-10°F** (-23°C)	**-30°F** (-34°C)

** 30 ft-lbs. (41J)*

Figure 11 - The Graville Weldability Diagram
Susceptibility to HAZ Cracking of HPS Bridge Steels



***High Strength Welding Consumables May Require Additional Care**

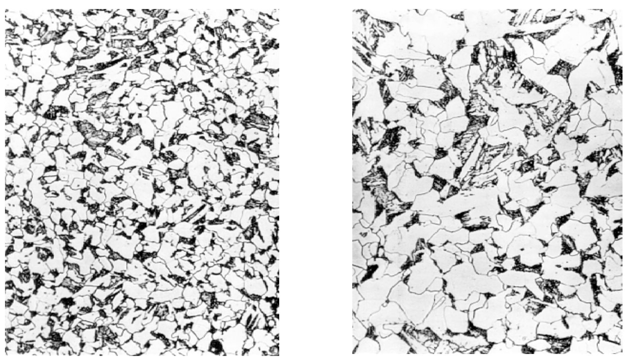
Figure 12 - Chemistries for HPS 70W
Specification Modification

		C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V
Old 70W	Min.	-	.80	-	-	.25	.20	-	.40	-	.02
	Max.	.19	1.35	.035	.04	.65	.40	.50	.70	-	.10
HPS 70W [1]	Min.	-	1.10	-	-	.30	.25	.25	.45	.02	.04
	Max.	.11	1.35[2]	.020	.006	.50	.40	.40	.70	.08	.08

[1] Calcium treated for inclusion shape control, also requires .010 - .040 Al and .015 N max.

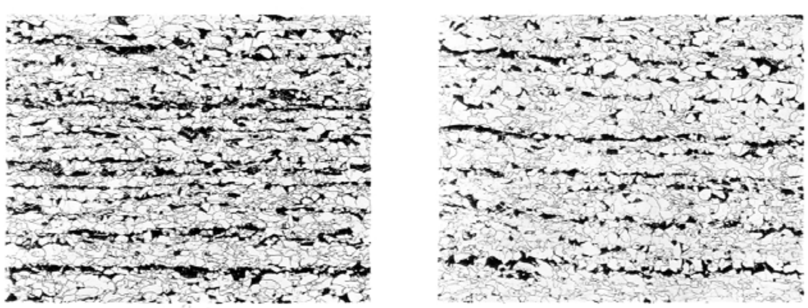
[2] Mn max. to increase to 1.50 for plate over 2.5" thick

Figure 13 - Microstructure of ASTM A709 HPS-70W Q&T Plate Comparison at Quarterline



25 mm Plate ASTM No. 12.3 | 80 mm Plate ASTM No. 11.2

Figure 14 - TMCP HPS-70W Control-Rolled, Q&T Chemistry



3/4 in. (19mm) plate | **1 in. (25 mm) plate, approx. ASTM No. 9**

Figure 15 - Comparing Q&T and TMCP HPS 70W; .5 - 2 " thick

	No.	YS ksi	s.d.	UTS ksi	s.d.	LCVN @-25 ft-lb.	s.d.
TMCP	1,365	78.6	4.8	96.0	5.3	129	45
Q&T	424	83.9	6.2	95.9	3.9	141	43

Figure 16

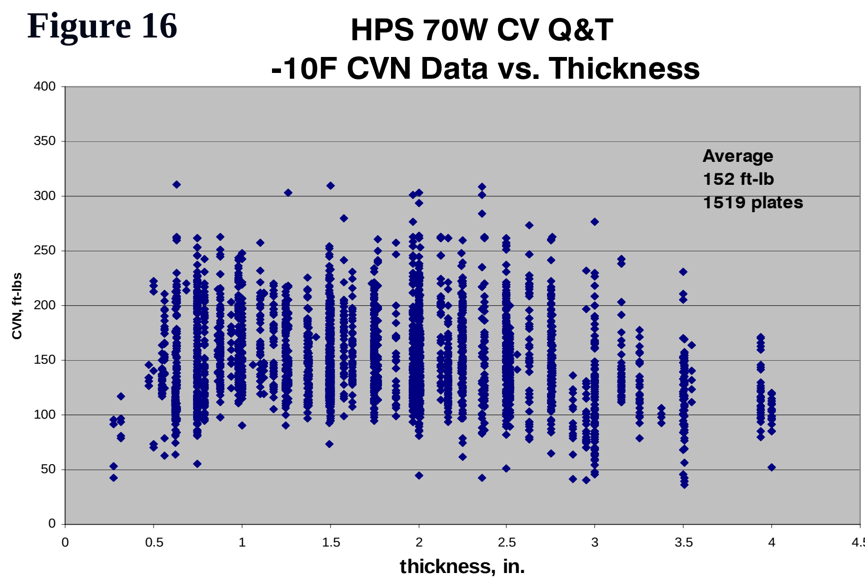
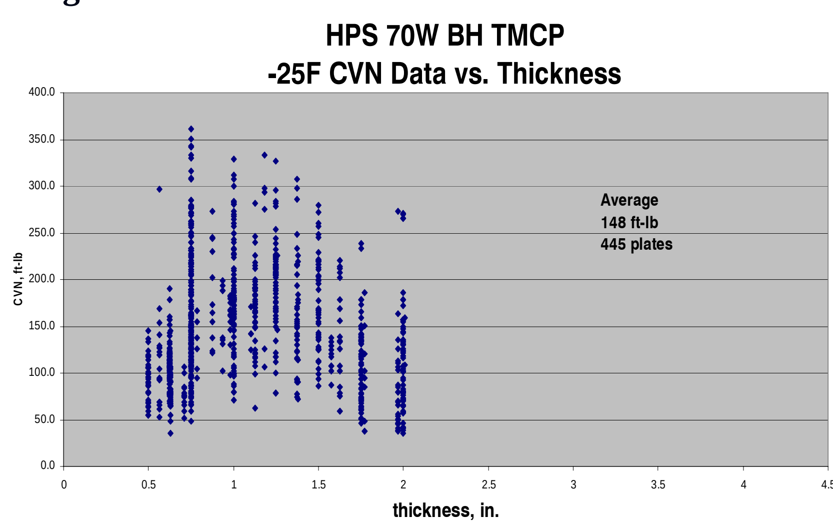


Figure 17



HPS 100W

The development of the HPS 100W grade was again an industry joint activity [(5)]. The development was based upon the Navy work on HSLA-100 using Cu-Ni alloying with other alloy additions. HPS 100W has a Cb addition for grain refinement and V addition to smooth out the tempering curve in this Q&T alloy. Figure 19 shows the chemistry of the specification. A range of microstructures can be found in the alloy ranging from martensite in thin/surface locations and acicular ferrite in the thicker locations, as shown in Figure 20. Figure 21 demonstrates that good properties are achievable through 4" (102 mm). The excellent properties on an initial application for the grade are summarized in Figures 22 and 23.

Figure 18

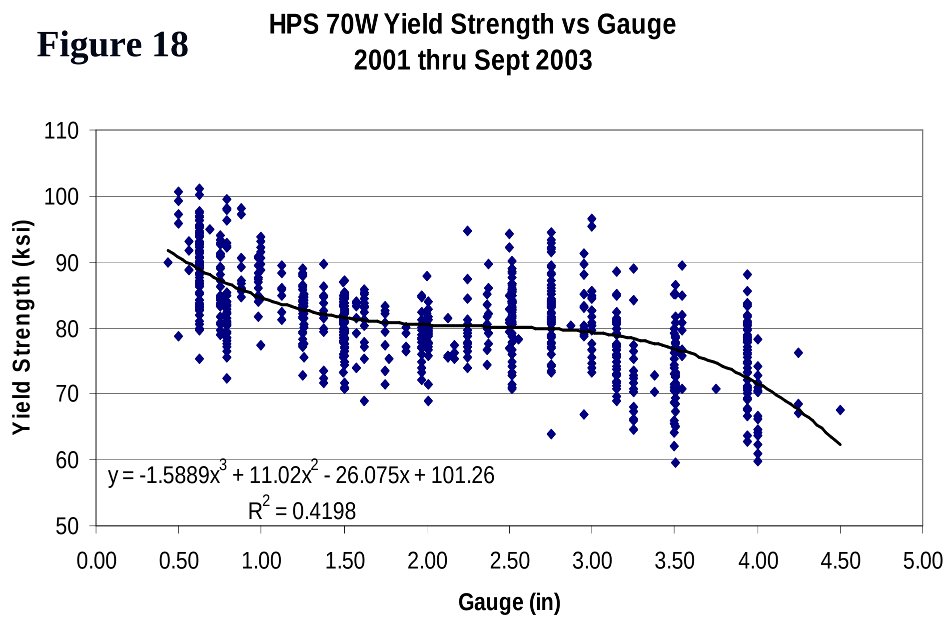


Figure 19 - Comparison of Chemistries for Traditional and HPS Versions of 100W

		C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V
Traditional 100W [(2, 3)]											
	Min.	.10	.60	-	-	.15	.15	.70	.40	.40	.03
	Max.	.20	1.00	.035	.035	.35	.50	1.00	.65	.60	.08
HPS 100W [(1,2,4)]											
	Min.	-	.95	-	-	.15	.90	.65	.40	.40	.04
	Max.	.08	1.50	.015	.006	.35	1.20	.90	.65	.65	.08

(1) Calcium treated for inclusion shape control
(2) 2-1/2" (65 mm) max. thickness
(3) contains .001B
(4) contains .01/.03 Nb, .02/.05 Al and .015 max. N

Figure 20 - Jominy Test Microstructures of Production Heat - As-Quenched

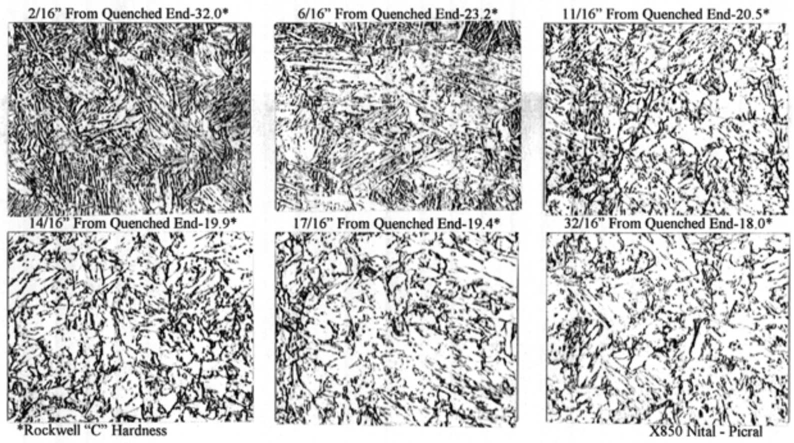


Figure 21 - HPS 100W Production Results

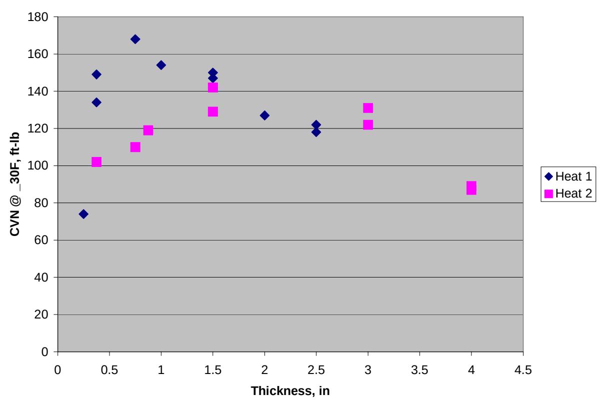


Figure 22 - HPS 100W – Tensile Data

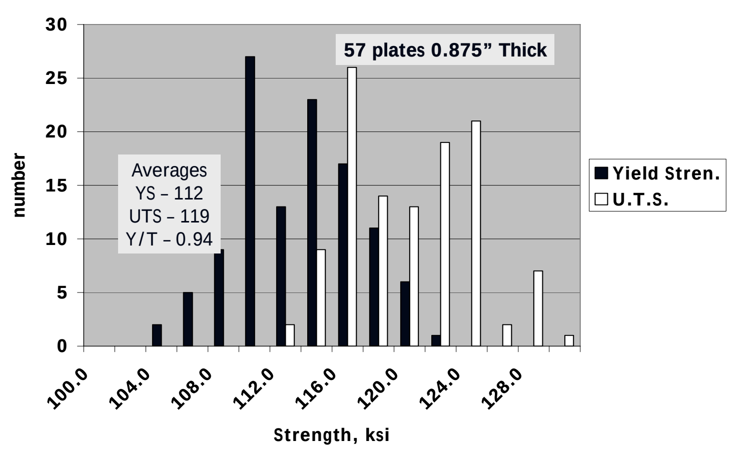
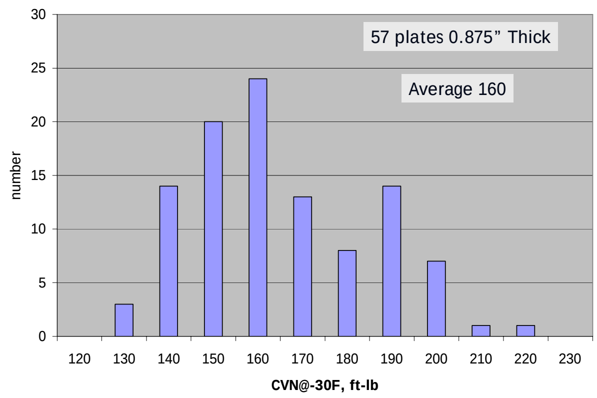


Figure 23 - HPS 100W – CVN Data



SUMMARY

The value of microalloyinig additions of Cb, V and Ti are shown for new grades of high strength, welded plate steels for uses in U. S. Navy shipbuilding and for steel bridges. The benefits included refined microstructures and improved strength in both TMCP and Q&T produced grades of steel. These grades are all being widely used today throughout the U.S.A. in steel bridges and Navy shipbuilding.

ACKNOWLEDGEMENTS

A portion of the research work reported herein was carried out under the guidance of the FHWA/AISI/Navy High Performance Steel Steering Committee. Some of the research work was reported to the Carderock Division, Naval Surface Warfare Center and was sponsored by the Federal Highway Administration. The commercial plate production was carried out at Mittal Steel USA plate facilities in Burns Harbor, IN, Coatesville, PA and Conshohocken, PA. The author would like to acknowledge the input and assistance of the staffs of the Mittal Burns Harbor, Coatesville and Conshohocken plate mills and Mittal Steel Research Laboratories.

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