Carderock Division
Naval Surface Warfare Center
Bethesda, Md. 20084-5000

CARDIVNSWC-TR-61—95/16 August 1995

Survivability, Structures, and Materials Directorate

Technical Report

Development of High Performance Steels for Bridge Construction

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FIGURES

ABBREVIATIONS

ASTM	American Society for Testing and Materials
Ar_3	Upper Critical Temperaure (upon cooling)
CDNSWC	Carderock Division Naval Surface Warfare Center
CE	Carbon Equivalent
CR	Controlled Roll
CVN	Charpy "V" Notch
DQ	Direct Quench
DQT	Direct Quench and Temper
FHWA	Federal Highway Administration
FRT	Finish Rolling Temperature
GMAW	Gas Metal Arc Welding
HAZ	Heat Affected Zone
HPS	High Performance Steel
HSLA	High Strength Low Alloy
IAC	Interrupted Accelerated Cool
IACT	Interrupted Accelerated Cool and Temper
LCS	Lower Critical Stress
PAG	Prior Austenitic Grain
RCR	Recrystallization Controlled Roll
RQT	Reheat Quench and Temper
SCT	Stop Cooling Temperature
TMCP	Thermomechanically Controlled Processing
T_{GC}	Austenite Grain Coarsening Temperature
T_{RXN}	Austenite Recrystallization Stop Temperature
T.S.	Tensile Strength
Y.S.	Yield Strength

CONVERSION FACTORS

To Convert From:	To:	Divide by:
mm	in.	25.4
MPa	ksi	6.894757
J	ft-lbs	1.355818
		Apply:
degrees Celsius	degrees Fahrenheit	$T_{°F} = (T_{°C} \times 1.8) + 32$

ABSTRACT

High strength steels that are used in bridge construction (ASTM A709) have yield strengths in the 50 to 100 ksi range and allow for carbon levels to reach as high as 0.23 wt.%. For good weldability, the carbon content in HSLA steels used by the Navy is usually restricted to a maximum of 0.10 wt.%. The Navy is working with industry to develop new high performance steels for bridges with improved weldability and toughness at the 485 MPa and 690 MPa yield strength levels. The experimental steels developed by the Navy had a maximum allowable carbon content of 0.10 wt.%. Alloying levels typical of bridge steels were employed. The chemical compositions were also designed to meet the weathering requirements of ASTM G101. Processing techniques such as recrystallization controlled rolling, controlled rolling, accelerated cooling and direct quenching were employed to achieve good combinations of mechanical properties and weldability.

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ADMINISTRATIVE INFORMATION

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INTRODUCTION

ASTM A709 [1] summarizes the grades of steels available for bridge construction. The yield strengths of the steels range from 250 MPa to 690 MPa and three weathering grades are available. Some of the features of each grade are given below, and in each case, the steel grade designates the minimum yield strength requirement in units of thousand pounds per square inch. Grade 36 (ASTM A36) and Grade 50 (ASTM A572) allow for carbon levels of 0.28 wt% and 0.23 wt%, respectively, for plates up to 100 mm thick. Grades 50W (ASTM A588) and 70W (ASTM A852), where the "W" designates a weathering grade, have lower allowable maximum carbon levels of 0.20 wt% and 0.19 wt%, respectively, for plates up to 100 mm thick. There are ten different types of Grade 100 (ASTM A514), including four weathering grades, where the allowable carbon levels range from 0.10 to 0.21 wt%, but the specific range for each type depends on the maximum plate thickness.

The toughness requirements for each grade depends on the service temperature and plate thickness. In ASTM A709, three minimum service temperature "zones" are defined for impact testing of fracture critical components: Zone 1 for service temperatures down to -18°C, Zone 2 for service temperatures from below -18°C to -34°C and Zone 3 for service temperatures from below -34°C to -51°C. The most stringent toughness requirements are for Zone 3 service temperatures. See ASTM A709 for the specific toughness requirements for each grade and thickness of the steels.

High Performance Steels. The current interest in developing high performance steels (HPS) has focussed development on steels with yield strengths of 485 MPa and 690 MPa. An HPS is one that demonstrates improved performance over current grades of steels with respect to properties such as strength, toughness, weldability, ductility and weathering characteristics, to name a few. ASTM A709 requires that Grades 70W, 100, and 100W be reheat, quenched and tempered to meet the strength and toughness requirements. The heat treating requirements impose restrictions on plate length and, thereby, require the use of more critical butt-welds. The relatively high allowable carbon levels of the steels render them susceptible to heat affected zone (HAZ) cracking [2] and, thus, fabrication costs due to restrictions on the welding process may be higher compared to a steel that shows low susceptibility to HAZ cracking. Strict fabrication requirements imposed by steels with a high susceptibility to HAZ cracking may also lead to high repair rates, further increasing the cost of the total structure. An HPS developed for bridge construction would demonstrate primarily improved weldability.

Secondary improvements may include increases in strength, toughness, weathering characteristics and plate length.

The application of thermomechanical controlled processing (TMCP) in combination with microalloying has proven to reduce alloying requirements for high strength steels [3] and, thus, improve the steel's weldability and meet or exceed the strengths and toughness of conventionally processed steels. The improved performance of TMCP steels is also an added benefit with regards to the reliability of the structure. There are numerous approaches to TMCP and the details of each may be found in several review articles [3-6].

Thermomechanical Processing. Recrystallization controlled rolling (RCR) is a technique that involves rolling the steel in a temperature range bounded by the austenite grain coarsening temperature (T_{GC}) and the temperature below which austenite does not recrystallize following deformation called the recrystallization stop temperature (T_{RXN}) [7]. Within this temperature range, austenite will recrystallize following deformation. By repeating the deformation/recrystallization process and limiting grain growth following deformation, the austenite grain size can be reduced significantly compared to conventional hot rolling. Therefore, RCR is an attractive advanced processing alternative to conventional hot rolling because finer austenite grains may be obtain prior to cooling, resulting in a finer transformed microstructure. Fine transformed microstructures yield higher strengths and toughness compared to coarser microstructures.

The temperature difference, (T_{GC}-T_{RXN}), defines the RCR processing window and may be expanded by utilizing microalloying elements to either promote or prevent the formation of specific precipitates. Microalloying elements such as Ti, V, and N have been shown to be effective at widening the RCR processing window [7,8].

Low temperature controlled rolling (CR) usually involves rolling the steel in a temperature range bounded by the T_{RXN} and Ar_3. In this temperature range, austenite does not recrystallize following deformation within the time it takes to send the plate back through the rolls for the next pass. CR produces a pancaked austenitic grain structure that possesses a high surface area of substructure made up of slipbands and dislocations that act as nucleation sites for the transformed microstructure. If the density of the substructure is high, very fine transformed microstructures may be obtained. The advantages of CR are that it can increase the strength and toughness of steels at lower levels of alloying elements compared to quench and tempered steels [3]. Some disadvantages include prolonged plate rolling schedules and non-uniform properties throughout a single plate.

The temperature difference, (T_{RXN}-Ar_3), defines the single-phase CR window. Certain microalloying elements have shown to raise the T_{RXN}, and the one most effective is Nb. Nb exhibits limited solubility in austenite and will form strain-induced Nb(CN) precipitates during controlled rolling [9,10,11]. The Nb(CN) particles are effective at pinning deformed austenite grain boundaries and preventing them from recrystallizing. After repeated rolling passes, the resulting prior austenitic grain (PAG) structure is pancaked prior to transforming and can contain a high volume of substructure.

Once the desired prior austenitic grain structure is obtained through RCR or CR, further improvements in mechanical properties may be realized by utilizing controlled cooling techniques such as interrupted accelerated cooling (IAC) or direct quenching (DQ). IAC involves water cooling the plate immediately following rolling to a specific temperature and then allowing the plate to air cool down to ambient temperature. DQ also involves water cooling after rolling, but the plate is continuously cooled to ambient temperature. The high cooling rates make it possible for a variety of transformed microstructures to be obtained. Therefore, with knowledge of the continuous cooling transformation behavior of the steel, a particular microstructure and its associated properties can be obtained through controlled cooling methods such as IAC and DQ.

This research project was aimed at developing 70W and 100W HPS's to be used for highway bridge construction. The goals were to improve weldability and meet or exceed the mechanical properties of the current 70W and 100W bridge steels. The Charpy impact toughness goals corresponded to the Zone 3 toughness requirements for fracture critical components per ASTM A709 and were 40 J at -23°C for the 70W grade steels and 47 J at -34°C for the 100W grade steels. Advanced processing techniques such as RCR, CR, interrupted accelerated cooling and direct quenching were used in an attempt to meet these goals. This paper covers mainly the approaches used to develop the HPS's and the resulting microstructures and mechanical properties. An investigation into the effects of chemistry and processing on the physical metallurgy of these steels and their optimization is still underway.

EXPERIMENTAL PROCEDURE

Materials. Five 500 lb vacuum-induction heats, with the chemical compositions shown in Table 1, were melted and cast into 175 mm x 290 mm x 575 mm big-end-down, hot-topped slab ingots[1]. The first three heats listed were modified ASTM A852 (70W) steels with lower carbon and added Ti and N. The heats were given the identifications of V, Ti-V and Ti-V-N, respectively. When referred to collectively, they will be designated as the "70W" heats. The fourth heat listed, DU65, was a Nb-V microalloyed steel designed to meet the requirements of a 70W grade, as well. The fifth heat, 100W, was a modified ASTM A514 Type F steel with lower carbon and added Nb and Ti.

Processing. The ingots were slabbed to a thickness of about 100 mm and then sectioned into three equal lengths. All of the slabs were reheated to 1175°C and either RCR or CR. The

[1] The steels were melted and thermomechanically processed at the U.S. Steel Technical Center, Monroeville, PA.

RCR practice consisted of reductions of about 13% per pass with a finish rolling temperature (FRT) of 940°C. The CR practice consisted of roughing passes of about 12% reduction per pass and finishing passes of about 9% to 12% reduction per pass with an FRT of 815°C.

The 70W slabs were RCR to 50 mm thick plates. Following rolling, the plates were either air cooled to ambient temperature, IAC or DQ. The average cooling rates were about 5°C/s for IAC and 10°C/s for DQ when measured at the centers of the plates. The stop cooling temperature (SCT) for IAC was 565°C. The DU65 slabs were CR to 50 mm thick plates and were cooled using the same parameters as the 70W described above. The 100W slabs were CR. Two of the slabs were CR to plates 38 mm thick. One plate was air cooled while the other was DQ. The third slab was CR to 50 mm thick and DQ.

Heat Treating. Specimens from the air cooled plates were re-austenitized at 900°C for one hour and water quenched. Then, along with specimens from the IAC and DQ plates, they were tempered for one hour at 620°C, 650°C, 677°C, 705°C, respectively. Quarter thickness, hardness tempering results were evaluated to choose the appropriate tempering temperatures for the plates. Based on the tempering study, all of the air cooled plates were re-austenitized at 900°C for one hour, water quenched and tempered (RQT) at 650°C. The IAC 70W plates were tempered (IACT) at 665°C. The DQ 70W plates and the IAC and DQ DU65 plates were all tempered at 690°C. The DQ 100W plates were tempered (DQT) at 693°C. All of the plates were tempered for one hour. Plate which were either RQT or tempered following IAC or DQ processing will be referred to collectively as "heat treated" in this paper to distinguish them from as-air cooled, as-IAC or as-DQ processed plates.

Mechanical Property and Weldability Testing. Tensile and Charpy "V" notch impact tests were performed on all of the plates in both the as-cooled (air, IAC, and DQ) and heat treated (RQT, IACT and DQT) conditions. The tensile specimens were machined parallel to the rolling direction (longitudinal) and the Charpy specimens were tested in the TL orientation. Tensile specimen geometry conformed to an ASTM E8 proportional tensile specimen with a gauge section of 25 mm (1 in.) and a diameter of 6.4 mm (0.252 in.). Impact tests were performed using standard sized Charpy "V" notched specimens.

Implant weldability tests were performed on a per heat basis on specimens from the IACT 70W and DU65 plates and on the 38 mm DQT 100W plate. The implant specimen geometry and test configuration are shown in Figure 1. The welding wire was a 1.6 mm (1/16 in.) diameter, L-Tec 120S consumable, and the weld was made using the GMAW process with a heat input of 1.6 kJ/mm with ambient preheat. One specimen was tested at its yield stress and a second was tested at 0.5(Y.S. + T.S.). The diffusible hydrogen level for these tests was 7.8 ml/100g. The tests were conducted for 1000 minutes or until the specimens failed. Implant tests were also performed on sample plates of A852 and A514 for comparison.

RESULTS

Tensile Properties. *As-Cooled Plates.* The results of the tensile and impact tests are shown in Table 2. None of the as-air cooled plates met the minimum yield strengths. The IAC plates of the V, DU65 and 100W heats met the minimum yield strength requirements, but the Ti-V and Ti-V-N steels fell short in the as-IAC condition. The yield strengths of all of the as-DQ plates for each heat met the minimum requirements. The yield strength-to-tensile strength ratios for all as-cooled 70W and DU65 plates ranged from 0.63 to 0.71, and from 0.66 to 0.77 for the 100W plates. Refer to Table 2 for the actual values and the processing conditions.

Heat Treated Plates. Following RQT, IACT and DQT processing described above, all of the plates, except for the RQT DU65 plate, met the minimum yield strength goals for each strength level. However, the yield strength of this plate was only about 10 MPa below the

485 MPa minimum. The RQT treatments resulted in increases in the yield and tensile strengths for most of the steels compared to the as-air cooled values. The only exception was that the tensile strength of the air cooled DU65 plate decreased following RQT. Tempering reduced the tensile strengths of all of the IAC and DQ processed 70W and the DU65 plates, resulting in an increase in the yield strength-to-tensile strength ratios. Figure 2 shows the yield strength-to-tensile strength ratio versus the yield strength for the 70W and the DU65 plates and how each was affected by RQT, IACT, and DQT.

RQT and tempering of DQ 100W plates resulted in an average increase in the yield strengths of about 103 MPa. Tempering of the DQ 100W plates resulted in a significant drop in the tensile strengths. The yield strength-to-tensile strength ratios of the heat treated 100W plates were fairly constant at about 0.96. Figure 3 shows the yield strength-to-tensile strength ratio versus the yield strength for the 100W plates.

Impact Toughness. *As-cooled Plates.* Table 2 shows that the toughness of the as-air cooled 70W plates were significantly higher than those of the IAC and DQ plates. The as-air cooled and IAC 70W plates passed the Zone 3 toughness requirements, but the DQ plates failed. On the other hand, the only as-cooled DU65 plate that passed Zone 3 requirements was the DQ plate. The as-air cooled 100W plate exhibited very poor toughness. In fact, the only 100W plate that passed the Zone 3 requirements in the as-cooled condition was the 38 mm DQ plate.

Heat Treated Plates. Table 2 also shows the effect of heat treatments on the impact toughness of the plates. All of the air cooled plates were RQT while the IAC and DQ plates were only tempered. The tempering temperatures are given in Table 2. In general, the RQT plates exhibited the highest toughness values; however, they were not as high as the respective values in the (lower strength) air cooled condition. After tempering, the DQT

70W and DU65 plates exhibited higher toughness than the respective IACT plates. Tempering had little effect on the toughness of the IACT 70W Ti-V-N. The toughness of the air cooled 100W plate increased significantly following RQT. The toughness of the 38 mm DQ plate remained higher than that of the 50 mm DQ plate following tempering. There was little effect of tempering on the toughness of the 50 mm DQT 100W plate. All of the heat treated plates, at both the 485 MPa (70 ksi) and 690 MPa (100 ksi) yield strength levels met the Zone 3 toughness requirements except for the 50 mm DQT 100W plate.

Figure 4 shows the CVN energy versus yield strength for the 70W and the DU65 plates. Figure 5 shows the CVN energy versus yield strength for the 100W plates. Both figures show that tempering plates that are IAC or DQ tends to increase toughness. Also, the tempering temperatures used increased the yield strengths of all of the IAC and DQ plates except for the DQ V-steel. The RQT treatments employed for the 70W plates resulted in decreases in toughness for the V and Ti-V-N steels and an increase for the Ti-V steel. However, as mentioned earlier, they all met the Zone 3 toughness requirements. Following heat treating, the only plates that did not simultaneously meet the required yield strength and toughness requirements were the RQT DU65 and 50 mm DQT 100W plates.

With respect to processing, as-cooled DQ plates exhibited higher yield and tensile strengths than the air cooled and IAC plates, with the strengths decreasing with decreasing cooling rate. However, the DQ plates generally had lower percent elongations and impact toughness than other plates. DQT resulted in higher yield and tensile strengths compared to RQT and IACT, but, in some cases, only slightly.

Weldability. Table 3 lists the stresses and results of the implant weldability tests performed on the experimental steels. The only specimen that fractured was one of the 100W steel specimens tested at a stress equal to 0.5(Y.S. + T.S.). However, fractography of the fracture surface showed no evidence of either intergranular fracture or cleavage fracture, typical of hydrogen cracking in the HAZ, but rather showed microvoid coalescence which is typical of ductile tensile overload. Table 4 lists the results of implant tests on ASTM A852 and A514 steels as a comparison with the experimental steels. This table also shows the chemical composition of the specific ASTM steels tested. All of the implant data per yield strength level are plotted in Figures 12 and 13 for comparison. The experimental steels are clearly more resistant to hydrogen cracking in the HAZ than A852 and A514, respectively.

Microstructure. *As-Cooled Plates.* Figures 6 through 8 show the microstructures of the plates in the as-cooled condition. Figure 6 is representative of the 70W steels since there were only minor differences in the microstructures. Generally, the air cooled 70W plates exhibited a combination of equiaxed ferrite and pearlite while the IAC and DQ plates were primarily bainitic with ferrite at equiaxed prior austenite grain boundaries. The DQ plates contained some martensite and also less grain boundary ferrite than the IAC plates. The prior austenitic grain (PAG) sizes of the 70W steels were measured per ASTM E112 and were as follows: V steel, 44 μm; Ti-V steel, 37 μm ; Ti-V-N steel, 44 μm.

The air cooled DU65 plate exhibited a ferrite/pearlite microstructure, but contained less carbide than the air cooled 70W plates. The IAC and DQ DU65 plates were predominantly bainitic with ferrite at elongated prior austenite grain boundaries. The DQ DU65 plate appeared to contained less grain boundary ferrite than the IAC DU65 plate. Because the grains were pancaked, the PAG thickness was measured using the lineal intercept method and was 63 μm.

The air cooled 100W plate appeared to be entirely bainitic. The elongated PAG's can be seen Figure 10, and are indicative of a controlled rolled steel. The 38 mm and 50 mm DQ 100W plates were composed of a mixture of bainite and martensite. The PAG thickness was 34 μm.

Heat Treated Plates. Figures 9 through 11 show the microstructures of the plates following heat treating. The 70W and DU65 RQT plates appear to be fully bainitic while the IACT and DQT microstructures remained a mixture of ferrite and bainite. The RQT 100W microstructure exhibited equiaxed prior austenite grains and appeared to be bainitic. The 38 mm and the 50 mm DQT 100W microstructures consisted mainly of bainite with some tempered martensite present as well.

DISCUSSION

The yield strength of the 70W steels was influenced significantly by the cooling rate following RCR. IAC and DQ resulted in about a 135 MPa and 200 MPa increase in yield strength, respectively, over air cooling. This effect was attributed to the increased amounts of bainite and martensite in the steel.

Typically, thermomechanically processed Ti-V-N microalloyed low carbon steels exhibit microstructures that contain combinations of ferrite, pearlite and bainite [8,12,13]. However, the ferrite/pearlite microstructures are most common due to the relatively low hardenability of typical Ti-V-N steels. In order to meet the requirements of HPS's for bridge construction, Si, Ni, Cr, and Cu were added for increased atmospheric corrosion resistance (See Table 1). Along with Mo and C, these weathering elements also increase the hardenability of the steels [14]. As shown by the microstructures in Figures 6 through 8, IAC and DQ appear to have provided cooling rates faster than the critical rate for the pearlite transformation, and sufficient to limit ferrite nucleation and growth. Ferrite nucleation and growth may have also been limited by a large austenitic grain size [14]. Due to the hardenability of the 70W steels and the resulting predominantly bainitic microstructure, the effect of V and N on precipitation strengthening of ferrite was not observed. On the other hand, it appears that the plates with a ferrite/pearlite microstructure could not meet the requirements of a 70W in the as-air cooled condition. Therefore, the higher hardenability proved beneficial with regards to strength during IAC and DQ.

The results regarding the 70W steels indicated that RCR plus IAC is a viable processing route for obtaining an as-cooled grade. Optimization of the process to reduce the austenite grain size and control the final microstructure may provide further improvements in strength and toughness properties. PAG sizes of 20 μm have been achieved using RCR in laboratory simulations and in the production of full-scale plates [8,15].

The DU65 steel did not meet the strength and toughness requirements of a 70W steel in the as-air cooled condition. In the IAC and DQ conditions, it met the strength requirements of a 70W steel but not those for toughness. The RQT, IACT and the DQT plates did meet the specifications of the ASTM A709 70W steels.

The DU65 steel derived its properties from a combination of microalloying with Nb and V, controlled rolling and controlled cooling. Figures 7(b) and 7(c) shows that the PAG's were pancaked prior to cooling and is typical of a CR PAG structure. This steel also had enough hardenability to form bainite and/or martensite upon IAC or DQ which appeared to be necessary to attain the mechanical properties. The hardenability resulted from the alloying employed to meet the chemical composition requirements of a weathering grade.

The 100W steel conforms closest to a low carbon ASTM A514 Grade F with added Ti and Nb. The high hardenability of this steel was attributed partly to the B normally present in this grade of steel. The chemistry of this 100W steel may have actually been too rich, leading to the very high yield and tensile strengths following heat treating. Lowering the strength through tempering, decreasing hardenability or decreasing carbon content may help to improve toughness.

The weldability of the candidate HPS's can be compared to that of A852 and A514 by reviewing Tables 3 and 4 and Figures 12 and 13, respectively. A852 has a specified yield strength of 485 MPa, but the yield strength for the plate subjected to implant testing had a yield strength of 572 MPa, and exhibited a lower critical stress (LCS) of about 550 MPa. The carbon equivalent (CE) for the tested A852 was 0.58 with 0.16 wt% C as compared to the CE of the 70W and DU65 steels which were 0.53 and 0.50 at C levels of 0.10 wt% and 0.08 wt%, respectively, as shown in Table 1. Based on the weldability diagram in Figure 14 from Graville [2], the difference in CE does not seem significant enough to account solely for the lower weldability of A852. It appears as though the higher C content of A852 placed it into Zone III of the diagram where steels are considered "difficult to weld". The CE and C content of A514 also placed it into Zone III. The positions of the candidate HPS's are shown on the weldability diagram and indicate that reducing the carbon to 0.10 wt% or below places them into Zone I, making them easy to weld.

CONCLUSIONS

The results of this study indicated that:

(1) The mechanical properties of the current 70W and 100W bridge steels can be met with lower carbon steels by using TMCP,

(2) For the 70W steels, which had a predominantly bainitic microstructure, Ti and N additions did not significantly improve the mechanical properties,

(3) Controlled rapid cooling methods such as IAC or DQ were required to obtain sufficient strength for an as-cooled 70W grade,

(4) RQT processing of air cooled plates and tempering of IAC and DQ plates improved the strength/toughness properties,

(5) The weldability of the candidate low carbon HPS's was considered superior to that of A852 and A514.

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Table 1. Chemical compositions of developmental HPS for bridge construction.

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Nb	B	Al	N	CE
V	0.10	1.15	0.013	0.004	0.40	0.35	0.30	0.55	0.05	0.07	---	---	---	0.025	0.006	
	0.10	1.13	0.012	0.004	0.40	0.33	0.3	0.54	0.05	0.065	0.003	<.002	---	0.026	0.0056	0.53
Ti-V	0.10	1.15	0.013	0.004	0.40	0.35	0.3	0.55	0.05	0.07	0.012	---	---	0.025	0.006	
	0.095	1.16	0.011	.00039	0.40	0.35	0.31	0.55	0.052	0.068	0.015	<.002	---	0.027	.0056	0.53
Ti-V-N	0.10	1.15	0.013	0.004	0.40	0.35	0.30	0.55	0.05	0.07	0.012	---	---	0.025	0.012	
	0.10	1.14	0.012	0.004	0.37	0.33	0.19	0.54	0.05	0.068	0.015	<.002	----	0.024	0.0092	0.52
DU65	0.08	1.40	0.011	0.003	0.40	0.35	0.40	0.20	0.05	0.07	---	0.04	---	0.025	0.006	
	0.082	1.43	0.012	0.0033	0.40	0.34	0.40	0.20	0.051	0.07	0.003	0.04	---	0.025	0.006	0.50
100W	0.085	1.00	0.012	0.008	0.30	0.35	0.75	0.55	0.5	0.05	0.03	0.015	0.0015	0.025	0.006	
	0.086	0.99	0.014	0.0034	0.30	0.34	0.75	0.55	0.49	0.048	0.033	0.015	0.0015	0.025	0.0063	0.59

$$CE = C + \frac{Mn+Si}{6} + \frac{Ni+Cu}{15} + \frac{Cr+Mo+V}{5}$$

Table 2. Strength and toughness properties of developmental HPS for bridge construction.

						CVN Energy (J)		
Heat ID	Processing	Y.S. (MPa)	UTS (MPa)	YS/UTS	% elong.	-23°C	-7°C	10°C
V	RCR + Air Cooled	352	522	0.68	36.6	142	159	168
	RQT: 650°C[1]	505	596	0.85	32	98	138	136
	RCR + IAC	503	705	0.7	25.8	50	69	85
	Tempered: 665°C	537	638	0.84	27	73	103	117
	RCR + DQ	581	835	0.7	25.8	26	54	61
	Tempered: 690°C	557	648	0.86	28	118	110	159
Ti-V	RCR + Air Cooled	330	527	0.63	33.1	92	119	176
	RQT: 650°C[1]	501	572	0.88	33	129	89	182
	RCR + IAC	481	676	0.71	26.6	43	45	77
	Tempered: 665°C	532	634	0.84	28.5	102	103	134
	RCR + DQ	532	780	0.68	25.9	37	52	66
	Tempered: 690°C	538	634	0.85	27	76	126	138
Ti-V-N	RCR + Air Cooled	345	528	0.65	33.7	220	260	262
	RQT: 650°C[1]	490	586	0.84	29	152	167	201
	RCR + IAC	437	658	0.66	29.9	45	54	83
	Tempered: 665°C	530	631	0.84	29.5	46	79	100
	RCR + DQ	527	804	0.66	25.9	35	57	80
	Tempered: 690°C	558	645	0.87	28.5	84	95	126

Table 2. (Cont.) Strength and toughness properties of developmental HPS for bridge construction.

						CVN Energy (J)		
Heat ID	Processing	Y.S. (MPa)	UTS (MPa)	YS/UTS	% elong.	-23°C	-7°C	10°C
DU65	CR + Air Cooled	397	615	0.65	26.7	16	42	43
	RQT: 650°C[1]	475	558	0.85	33	169	188	247
	CR + IAC	506	721	0.7	26.4	31	71	81
	Tempered: 690°C	556	652	0.85	28	91	114	114
	CR + DQ	540	772	0.7	26.5	41	50	89
	Tempered: 690°C	590	676	0.87	28.5	99	114	127
						-34°C	-18°C	10°C
100W	CR + Air Cooled[2]	557	842	0.66	19.9	4	7	8
	RQT: 650°C[1]	834	872	0.96	23	72	99	127
	CR + DQ[2]	729	982	0.73	19.8	58	65	84
	Tempered: 693°C	869	896	0.97	23.5	76	89	100
	CR + DQ	787	1018	0.77	18.9	14	41	57
	Tempered: 693°C	865	900	0.96	22.5	22	77	91

1 Air Cooled plates were re-austenitized at 900°C and water quenched.
2 Plates were 38 mm thick

Table 3. Results of implant weldability tests on developmental HPS for bridge construction.

Specimen I.D.	Stress (MPa)	Time to Failure (min.)
V 24	538	Run Out
V 25	587	Run Out
Ti-V 24	532	Run Out
Ti-V 25	583	Run Out
Ti-V-N 24	530	Run Out
Ti-V-N 25	586	Run Out
DU65 24	558	Run Out
DU65 25	607	Run Out
100W 24	869	Run Out
100W 25	883	391

Table 4. Chemical composition and implant weldability test results for ASTM A852 and ASTM A514 tested for comparison to the experimental high performance steels.

Chemical Composition (wt%)		
Element & CE	ASTM 852	ASTM 514
C	0.16	0.19
Mn	1.2	0.88
Si	0.38	0.24
Cu	0.27	0.29
Ni	0.31	0.84
Cr	0.52	0.50
Mo	...	0.43
V	0.061	0.05
B	...	0.002
CE	0.58	0.65
Results of Implant Weldability Tests		
Applied Stress (MPa)	Time-to-Failure (min.)	
638	107	*not tested*
638	64	*not tested*
627	45	*not tested*
621	Run Out	Run Out
621	35	67
586	15	51
552	184	26
517	Run Out	*not tested*
485	Run Out	73
448	*not tested*	Run Out
415	*not tested*	Run Out

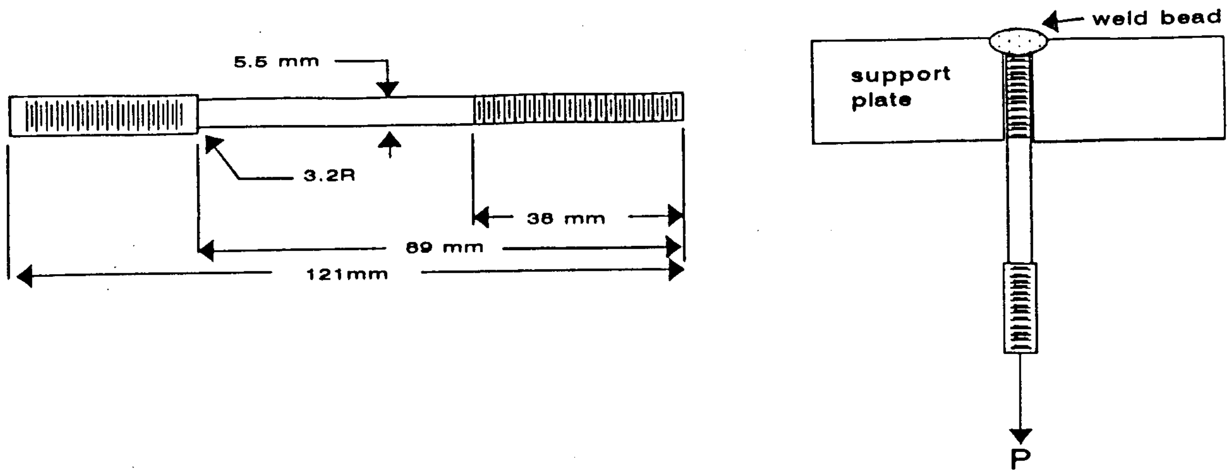


Figure 1. Implant specimen and test configuration.

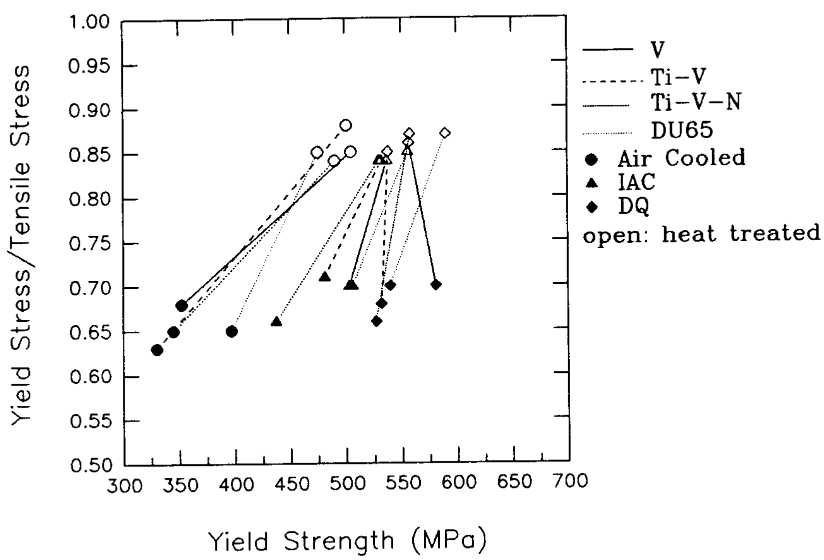


Figure 2. Yield strength-to-tensile strength ratios versus yield strength of 70W and DU65 HPS.

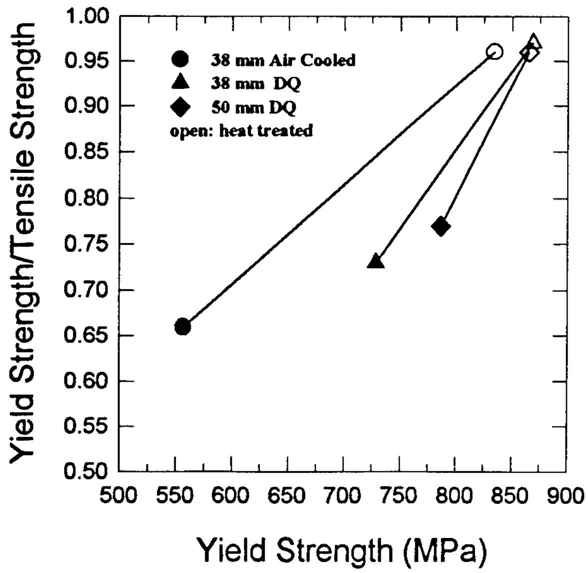


Figure 3. Yield strength-to-tensile strength ratios versus yield strength of 100W HPS.

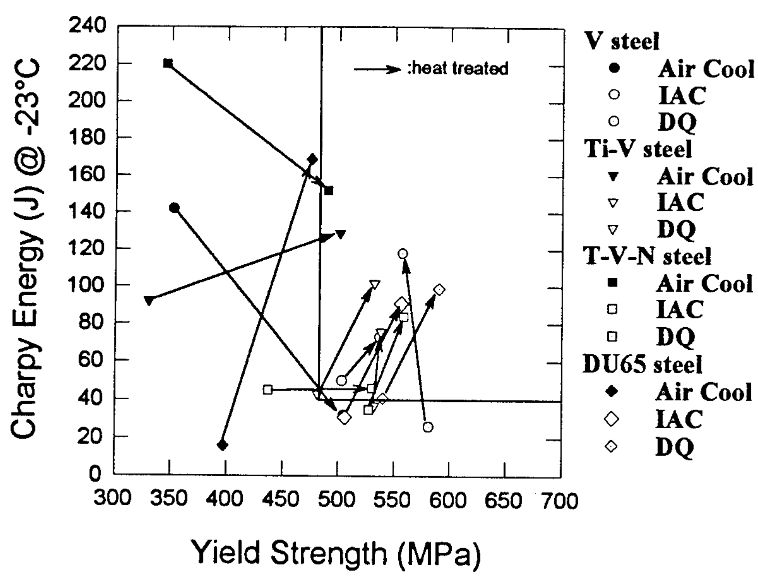


Figure 4. Charpy "V" notch energy versus yield strength of 70W and DU65 HPS.

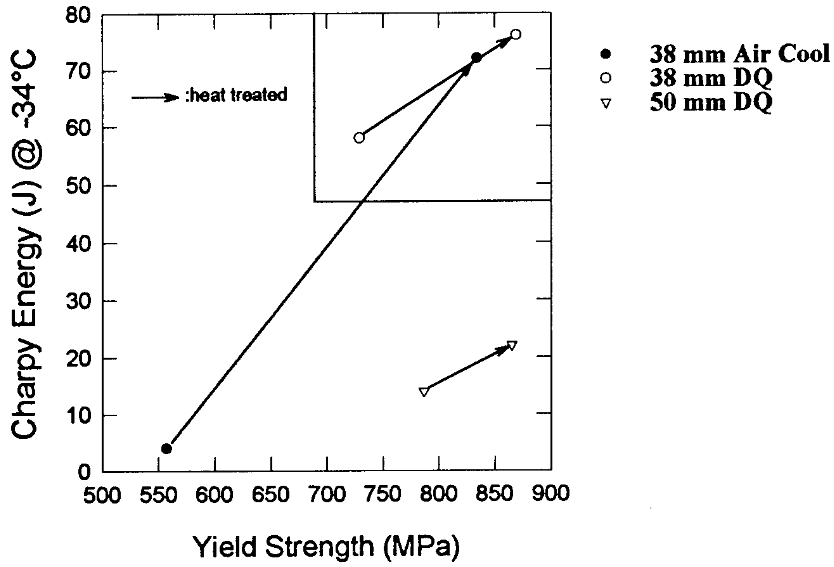
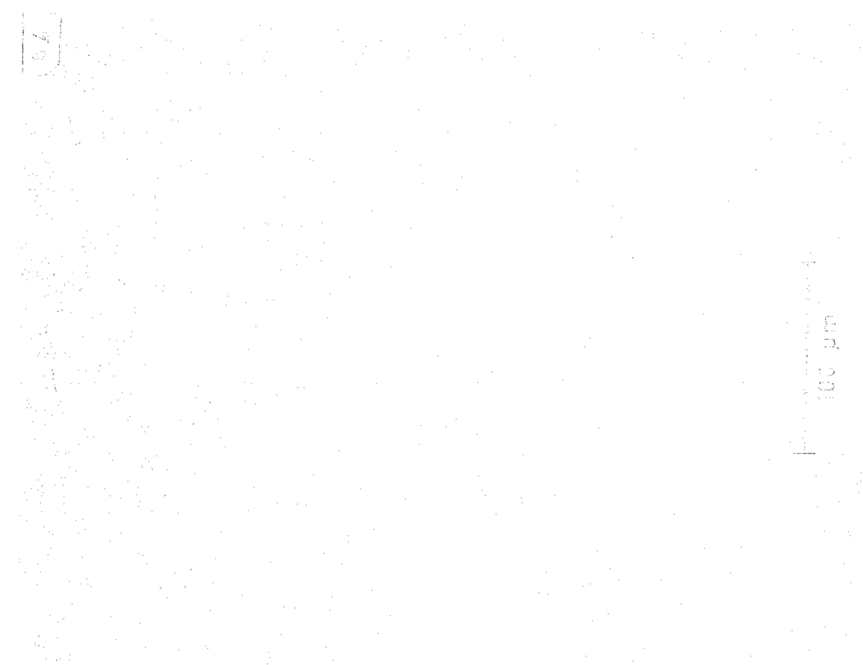


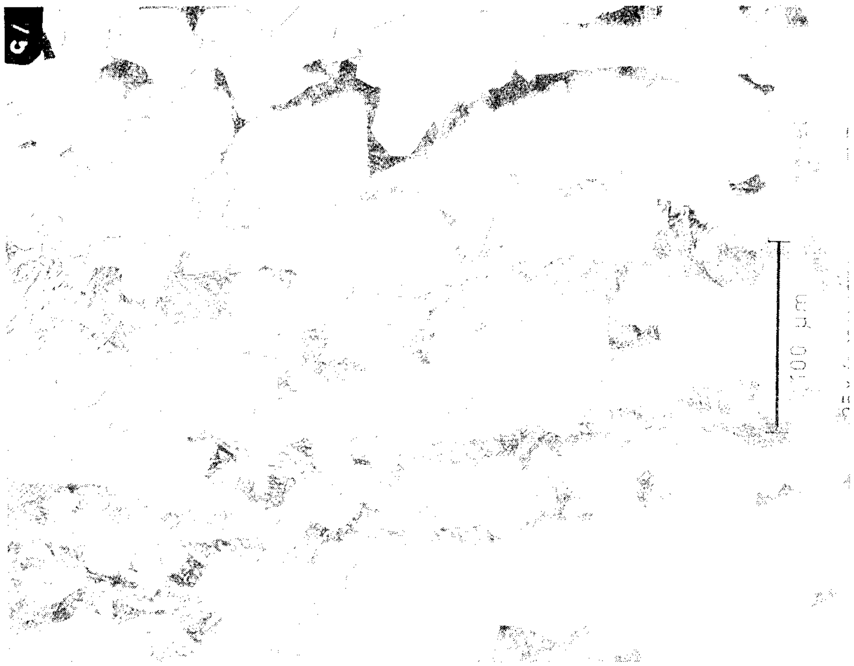
Figure 5. Charpy "V" notch energy versus yield strength of 100W HPS.

(b)

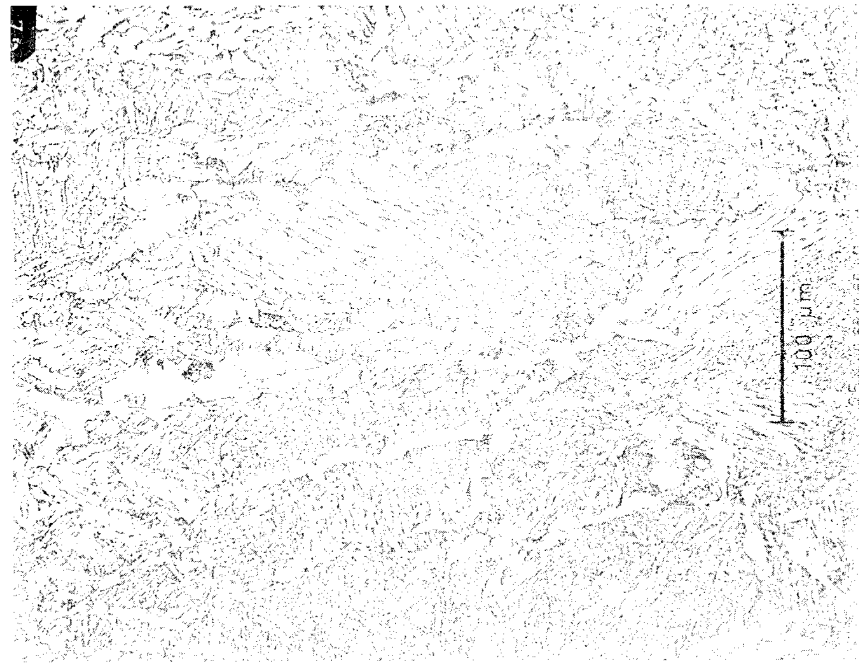


(c)

Figure 6. Microstructure of the V microalloyed HPS in the (a) as-rolled condition, (b) as-IAC condition and (c) the as-DQ condition.



(a)

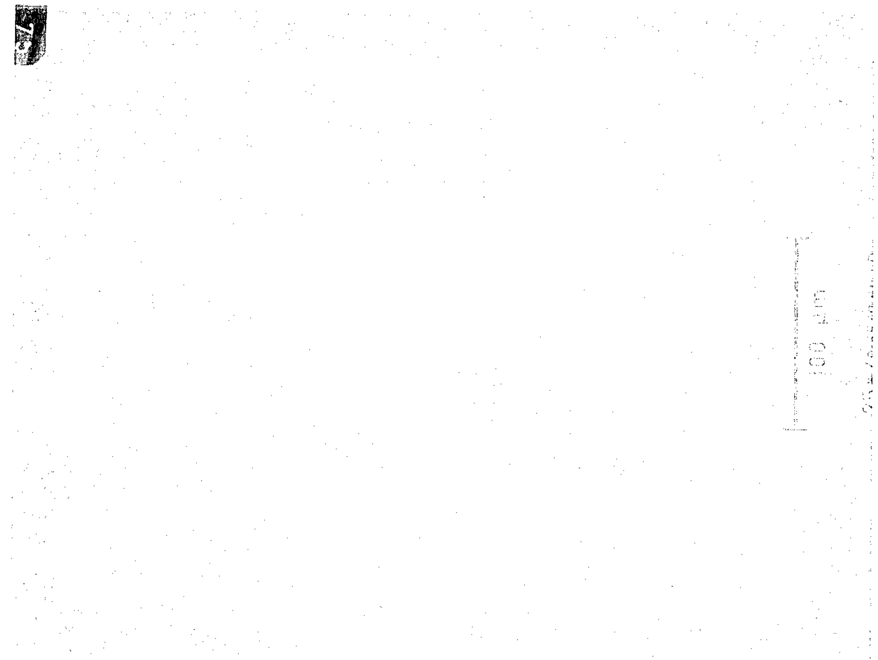


(b)

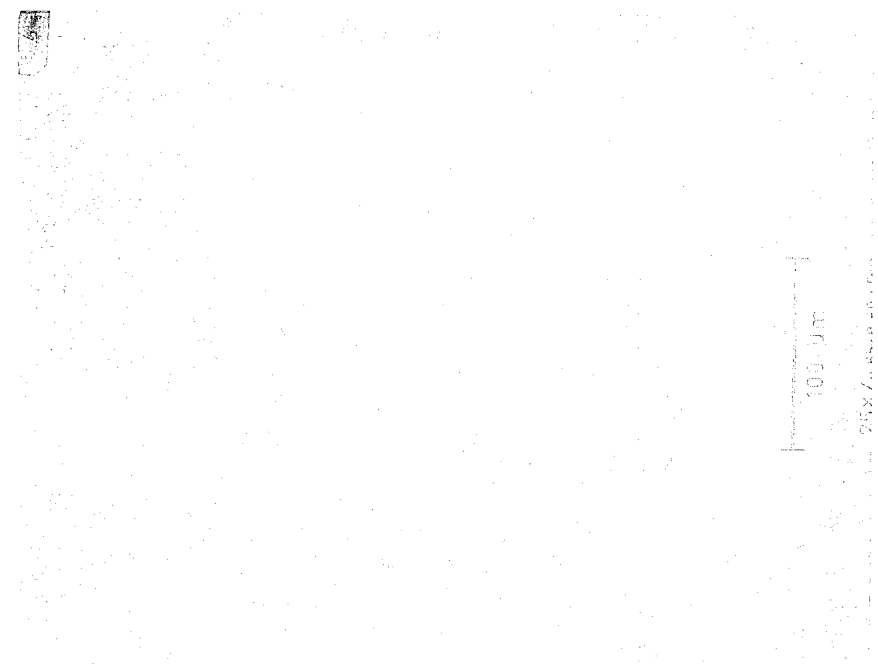
(c)

Figure 7. Microstructure of the DU65 HPS in the (a) as-rolled condition, (b) as-IAC condition and (c) the as-DQ condition.

(a)

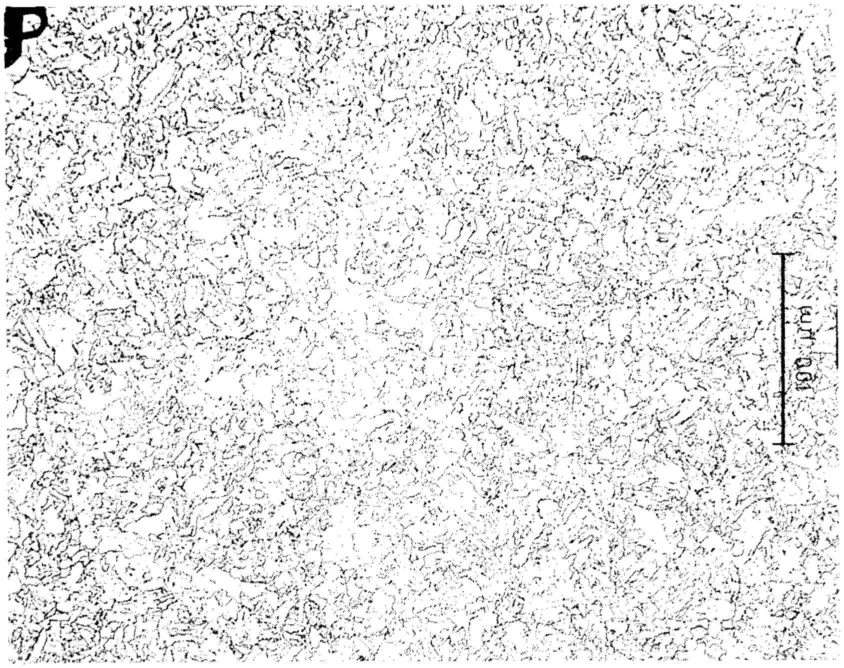


(b)

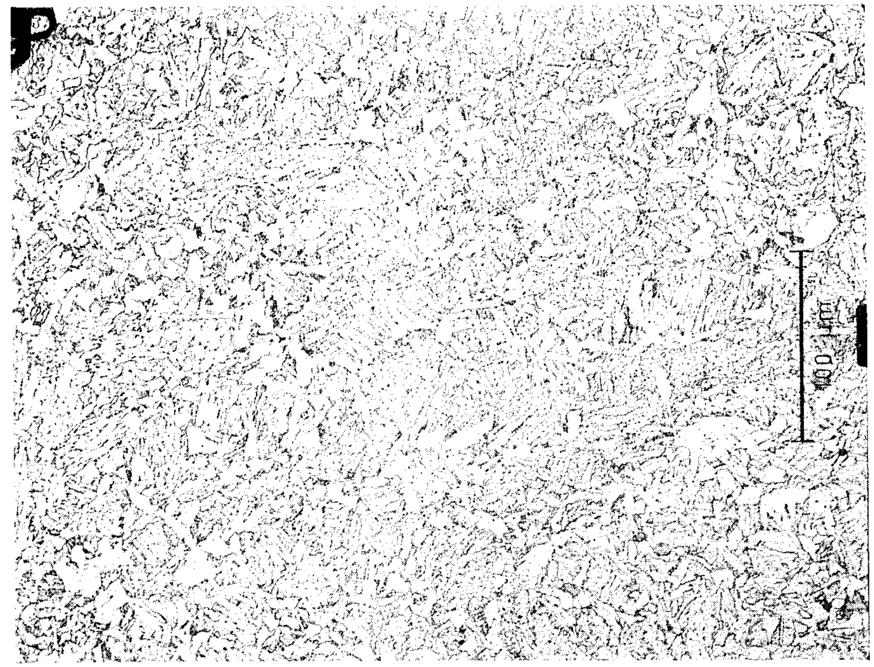


(c)

Figure 8. Microstructure of the 100W HPS in the
(a) 38mm thick plate in the as-air cooled condition,
(b) 38mm thick plate in the as-DQ condition and
(c) 50mm thick plate in the as-DQ condition.



(a)



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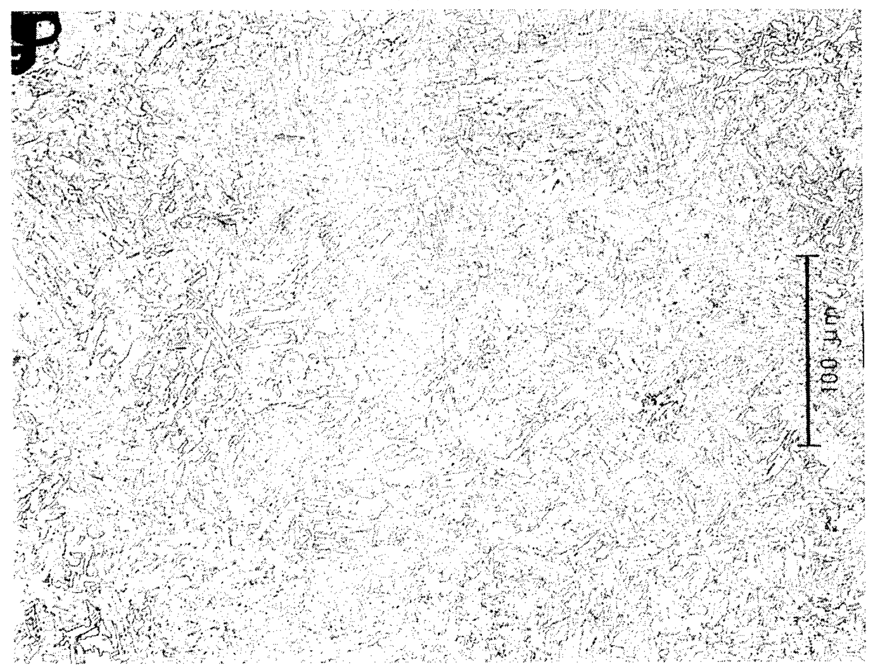
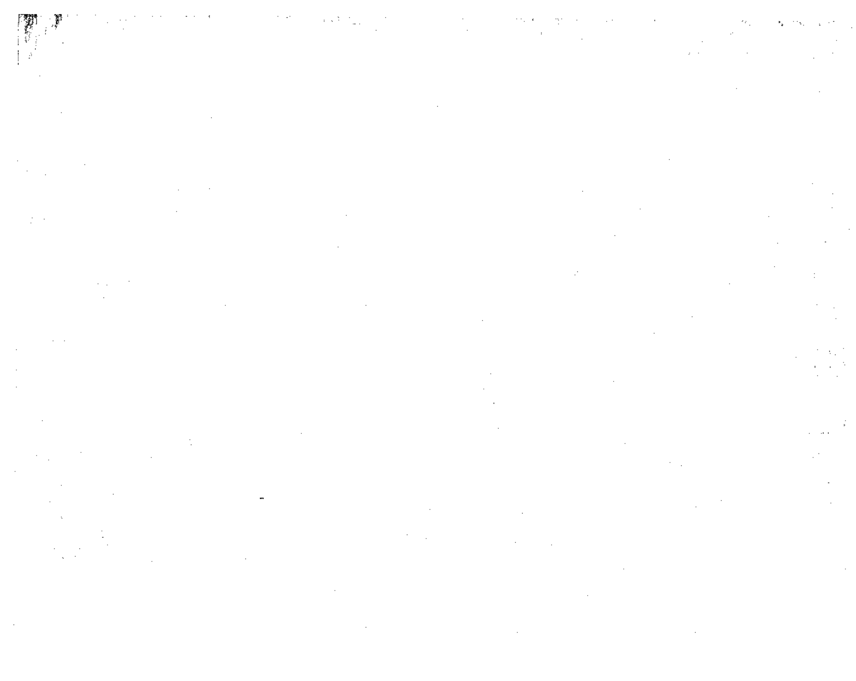


(c)

Figure 9. Microstructure of the V microalloyed HPS in the (a) RQT condition, (b) IAC and tempered condition and (c) DQ and tempered condition.

(a)



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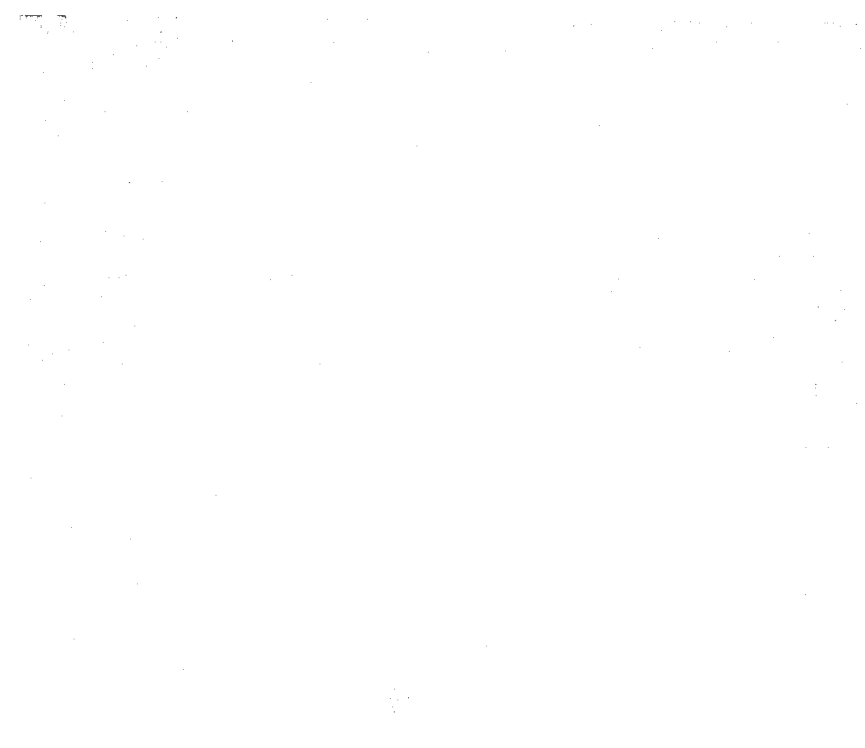
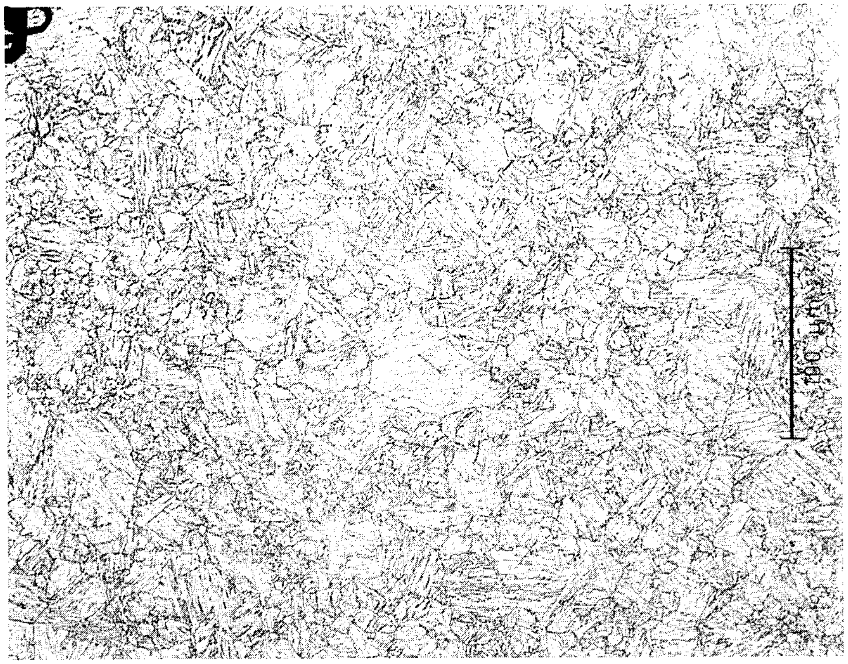


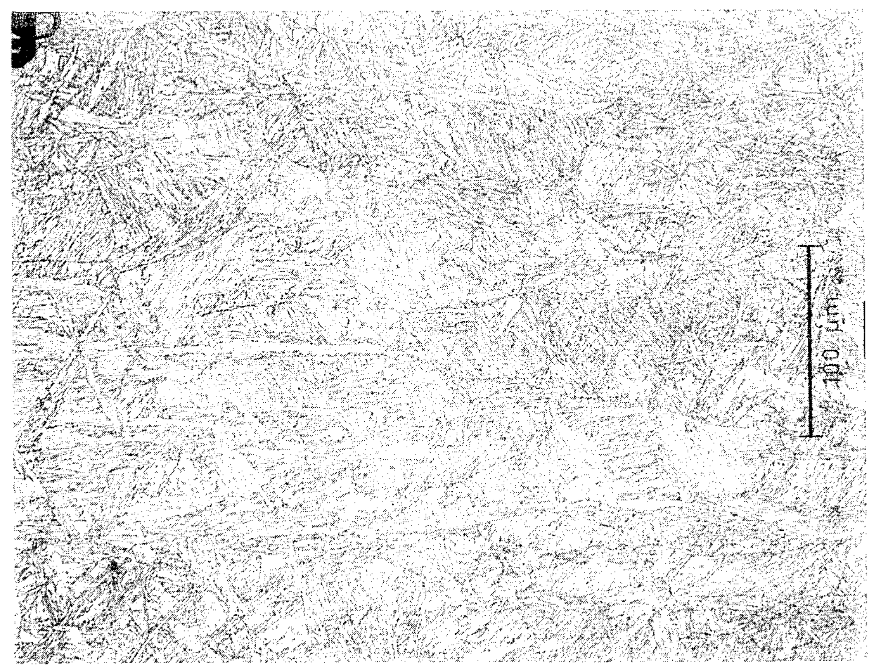
Figure 10. Microstructure of the [illegible] HPS in the (a) RQT condition, (b) IAC and tempered condition and (c) DQ and tempered condition.



(a)

(b)

Figure 11. Microstructure of the 100W HPS in the (a) 38mm thick plate in the RQT condition, (b) 38mm thick plate in the DQ and tempered condition and (c) 50mm thick plate in the DQ and temperedcondition.



(c)

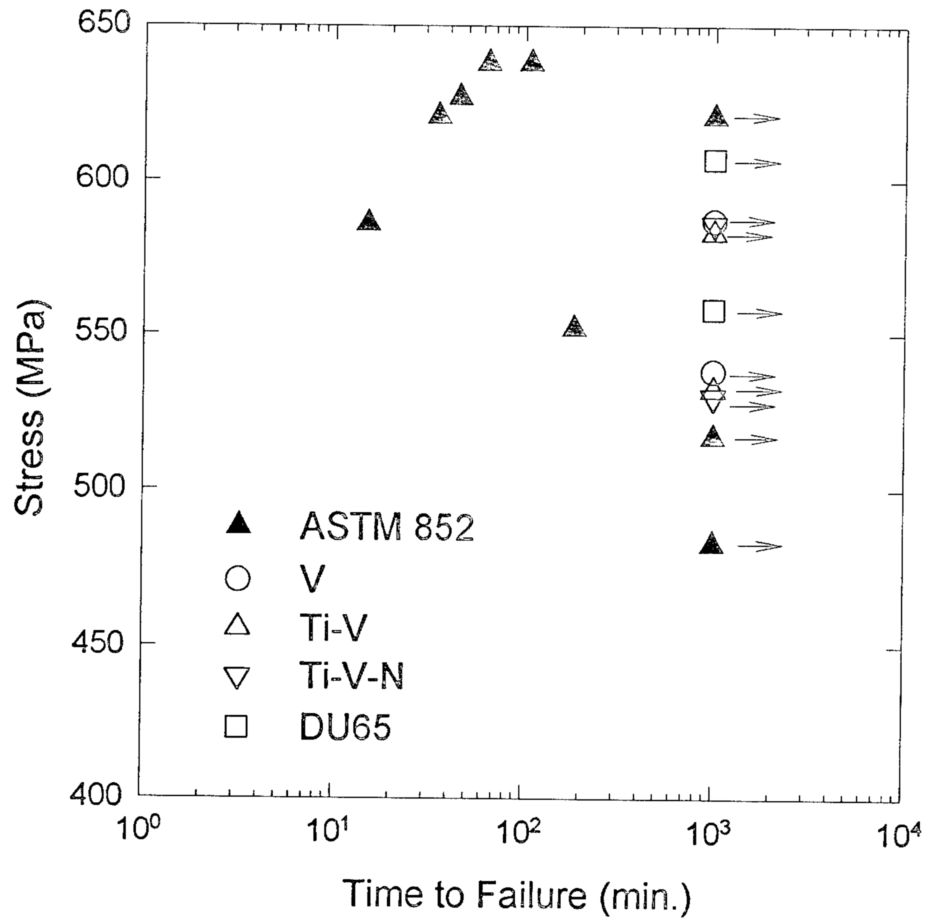


Figure 12. Results of implant weldability tests for ASTM A852 and the candidate 70W HPS's.

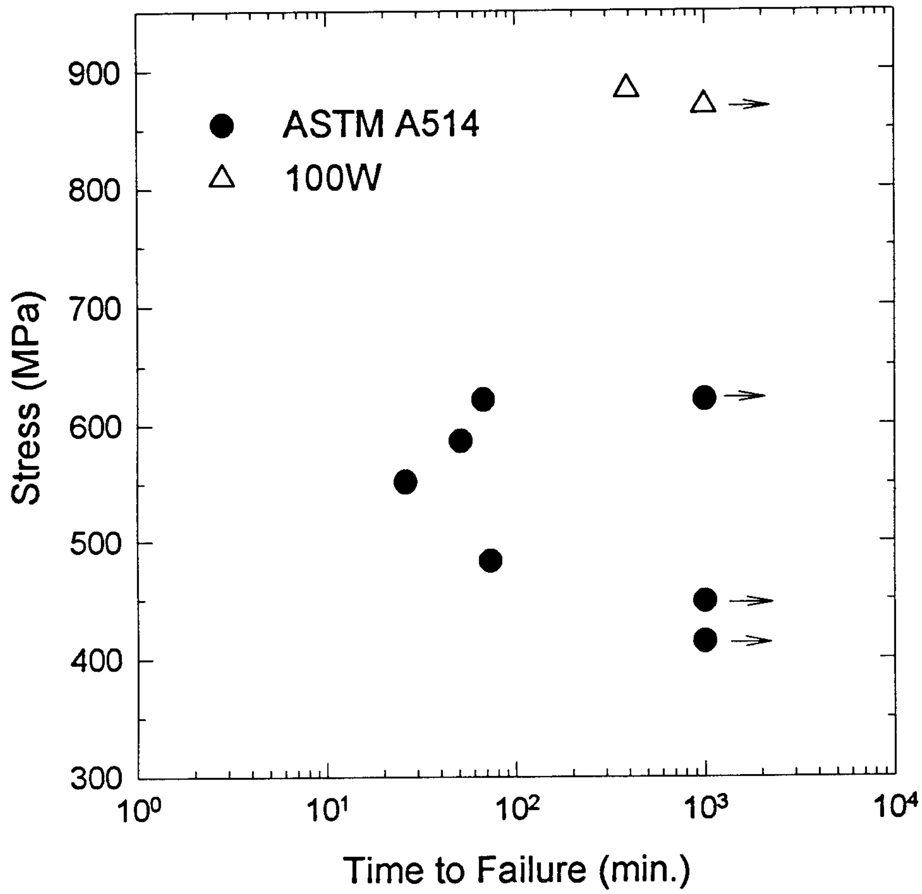


Figure 13. Results of implant weldability tests for A514 and the candidate 100W HPS's.

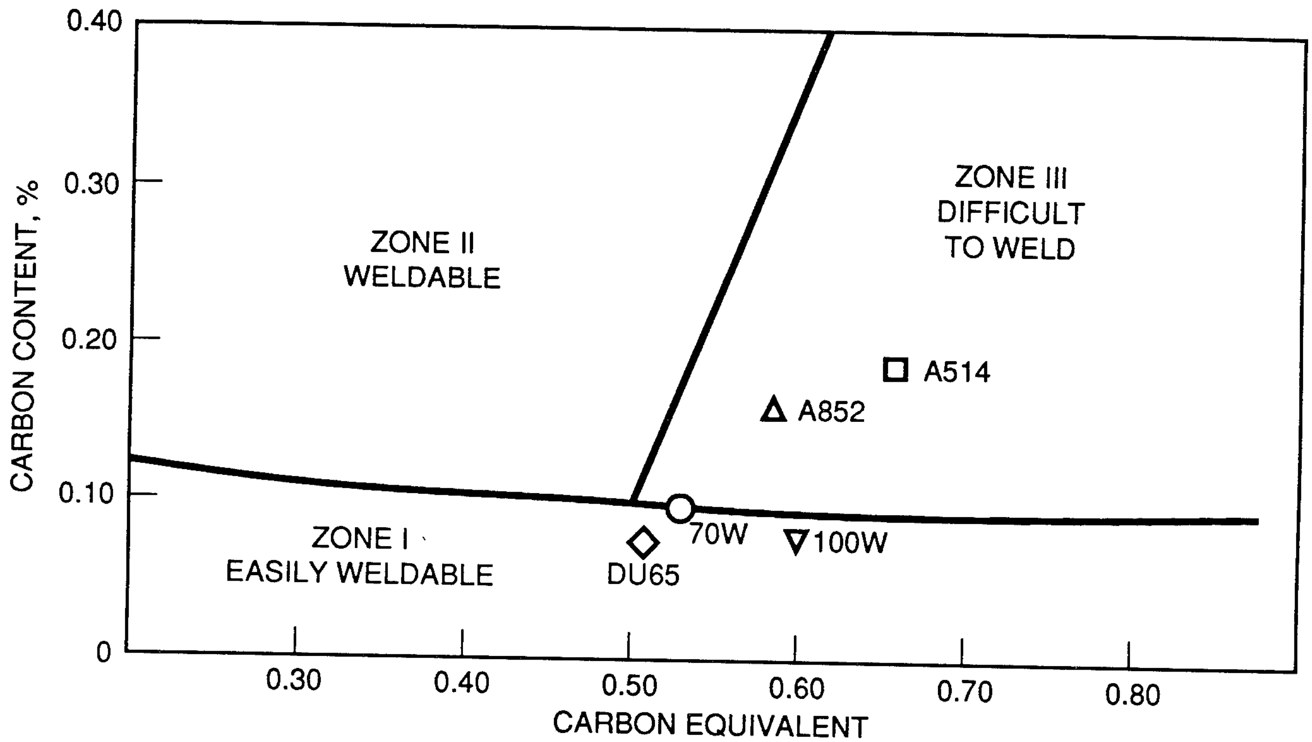


Figure 14. Weldability diagram for HSLA steels. [2]

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13. ABSTRACT *(Maximum 200 words)*

High strength steels that are used in bridge construction (ASTM A709) have yield strengths in the 50 to 100 ksi range and allow for carbon levels to reach as high as 0.23 wt.%. For good weldability, the carbon content in HSLA steels used by the Navy is usually restricted to a maximum of 0.10 wt.%. The Navy is working with industry to develop new high performance steels for bridges with improved weldability and toughness at the 480 MPa and 690 MPa yield strength levels. The experimental steels developed by the Navy had a maximum allowable carbon content of 0.10 wt.% and low alloying levels for good weldability and high low-temperature toughness. The chemical compositions were designed to meet the weathering requirements of ASTM G101. Processing techniques such as recrystallization controlled rolling, controlled rolling, accelerated cooling and direct quenching were employed to achieve good mechanical properties and weldability.

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