

Naval Surface Warfare Center

Carderock Division

West Bethesda, Maryland 20817-5700

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Survivability, Structures and Materials Directorate
Technical Report

High Performance Steel Development for Highway Bridge Construction: A Cooperative Effort

by

E. M. Focht

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ADMINISTRATIVE INFORMATION

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GLOSSARY

AASHTO	American Association of State Highway Transportation Officials
AISC	American Institute of Steel Construction
AISI	American Iron and Steel Institute
Al	Aluminum
ASTM	American Society for Testing and Materials
AWS	American Welding Society
B	Boron
C	Carbon
CE	Carbon Equivalent
CFT	Controlled Finish Temperature
Cr	Chromium
CR	Controlled rolling
Cu	Copper
DQ	Direct Quenching
FHWA	Federal Highway Administration
HAZ	Heat Affected Zone
HPS	High Performance Steel
GMAW	Gas Metal Arc Welding
IAC	Interrupted Accelerated Cooling
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Ni	Nickel
P	Phosphorus
RCR	Recrystallization-Controlled Rolling
RQT	Reheat, Quench and Tempering
S	Sulphur
Si	Silicon
Ti	Titanium
TMCP	Thermomechanical Controlled Processing
T _{RXN}	Recrystallization Stop Temperature
V	Vanadium

ABSTRACT

High Performance Steels (HPS) for highway bridge applications are being developed under a cooperative agreement between the FHWA, the AISI and the U. S. Navy. This combined and coordinated effort has culminated in the production of low carbon weathering steels which exhibit excellent strength, toughness and weldability at the 485 MPa (70 ksi) and 690 MPa (100 ksi) yield strength levels. The production heats of these HPS's meet the current mechanical property requirements of ASTM A709 Grades 70W and 100W. This paper presents the development of the steels produced under the FHWA Program on High Performance Steels for Bridge Construction.

INTRODUCTION

The Federal Highway Administration is sponsoring a program to develop new High Performance Steels (HPS) to be utilized in innovative as well as existing bridge designs. The program is a cooperative effort between the American Iron and Steel Institute (AISI), the Federal Highway Administration (FHWA), the American Institute of Steel Construction (AISC), the American Welding Society (AWS) and the U.S. Navy to collectively design and produce candidate steels. The goals of the program are to develop affordable 485 MPa (70 ksi) and 690 MPa (100 ksi) yield strength weathering steels that meet the American Association of State Highway Transportation Officials (AASHTO) M270/ American Society for Testing and Materials (ASTM) A709 mechanical property requirements and provide excellent weldability. The initial phases of the program included initial screening studies of several possible chemistries for both A709 70W and 100W grades.

Several experimental heats of steel were produced in the first phase of the program to screen possible chemistries and processing approaches to produce 50 mm (2 in.) thick plates. After the initial screening process was completed, one heat at each strength level was chosen as primary candidates for the 70W grade and the 100W grade. Then, an additional heat of the 70W grade was melted, rolled and characterized to optimize the carbon level. The chemical composition and processing of the 100W heat melted as part of the first phase were considered adequate. Full size heats were melted and processed to demonstrate whether or not the steels could be produced in large quantities so large scale structural beam testing could be performed.

The amount of work performed in the initial screening studies was extensive and the details are too voluminous to report herein. However, several reports and papers have

been prepared and presented at conferences which include all of the experimental details and results (1-6). This paper summarizes the major accomplishments of the FHWA Program on High Performance Steels for Bridges with respect to steel development.

BACKGROUND

A high performance steel (HPS) for bridge construction may be described as having tensile properties that meet or exceed application requirements while exhibiting high toughness in fracture critical applications with respect to ASTM A709, good atmospheric corrosion resistance per ASTM G-101, and excellent resistance to heat affected zone (HAZ) cold cracking following welding without preheat. (The criteria for a steel's resistance to heat affected zone cold cracking may vary depending on the test performed.) ASTM A709 is a compilation of several grades of steels appropriate for use in the fabrication of bridges. The specification covers the chemical, mechanical property and toughness requirements for weathering and non-weathering grades at the 248 MPa (36 ksi), 345 MPa (50 ksi), 485 MPa (70 ksi) and 690 MPa (100 ksi) minimum yield strength levels.

The mechanical property and chemical composition requirements per ASTM A709 for 70W and 100W Type F steels are shown below:

Mechanical Property Requirements of ASTM A709 70W and 100W Steels

Grade	Plate Thickness, mm	Y.S., MPa	T.S., MPa	% elongation in 50 mm	Reduction of area, min, %
70W	to 100 incl.	485	620-760	19	not specified
100W	to 65 incl.	690	760-896	18	50

Chemical Composition Requirements of ASTM A709 70W and 100W Type F Steels

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	B
70W	0.19	<u>0.80</u>	0.035	0.04	<u>0.20</u>	<u>0.20</u>	0.50	<u>0.40</u>	...	<u>0.02</u>	...	...
	max	1.35	max	max	0.65	0.40	max	0.70		0.10		
100W	<u>0.10</u>	<u>0.60</u>	0.035	0.035	<u>0.15</u>	<u>0.15</u>	<u>0.70</u>	<u>0.40</u>	<u>0.40</u>	<u>0.03</u>	...	<u>0.0005</u>
Type F	0.20	1.00	max	max	0.35	0.50	1.00	0.65	0.60	0.08		0.006

Since the carbon levels in the steels shown above can exceed 0.10 wt. %, HAZ resistance to cold cracking may be diminished unless preheat is employed (7). Therefore, a HPS should have carbon levels below or only slightly above 0.10 wt. % to avoid cold cracking when welded using ambient preheat. Alloying elements used to increase weathering resistance may also decrease HAZ resistance to cold cracking. The HPS's developed in this program maintained the level of elements used to provide weathering resistance, but decreased carbon to below 0.10 wt. % for the 70W steel and 0.12% for the 100W steel, resulting in an overall decrease in hardenability compared to higher carbon versions of these steels.

Good toughness is also expected of HPS to provide resistance to brittle fracture. The HPS's developed in this program were intended to meet or exceed the AASHTO M270/ASTM A709 Zone 3 Charpy impact requirements for fracture critical members given below:

<i>AASHTO M270/ASTM A709 Zone 3 Fracture Critical Impact Requirements</i>			
Grade	Thickness, mm	Minimum Energy, J	Test Temperature, °C
70W	to 40 incl.	41	-23
100W	to 65 incl.	47	-34

Reducing carbon levels in steels provides certain beneficial effects with respect to weldability and toughness but with such benefits comes the trade off of decreased strength. To maintain strength in low-alloy steels, thermomechanical controlled processing (TMCP) techniques can be employed to achieve finer grain sizes. There are review articles that explain TMCP techniques and how they are applied to different types of steel as well as the benefits that can be achieved (8-11).

The primary objective of TMCP is to condition the austenite during high temperature rolling to achieve a fine transformed microstructure. Tanaka (9) has identified regions in which controlled rolling can be performed with each yielding a different result based upon the condition of the austenite prior to its decomposition (**Figure 1**). Rolling above the recrystallization stop temperature, or T_{RXN} , is known as recrystallization controlled rolling (RCR) and is employed to yield equiaxed austenitic grain structures that are finer than those obtained via hot rolling. Rolling below the T_{RXN} is known as controlled rolling (CR) and results in a pancaked austenitic grain structure. The transformed microstructures obtained from pancaked austenite are typically finer than those obtained from equiaxed structures giving better toughness and higher strength, but rolling below T_{RXN} requires higher mill loads and longer hold times to reach the lower temperatures.

Controlled cooling practices such as interrupted accelerated cooling (IAC) and direct quenching (DQ) may be used to cool the plates at desired rates immediately after rolling. IAC involves cooling the plate using water curtains or sprays down to a specified temperature and then allowing it to air cool to ambient temperature. DQ is a more severe cooling practice than IAC whereby the plate is cooled rapidly to ambient temperature from or near the finish rolling temperature. Utilizing such on-line cooling practices eliminates the need for off-line reheating and quenching prior to tempering in most cases. Obviously, the TMCP route employed will depend on the requirements of the steel. As will be shown, a variety of TMCP techniques were used in this program to produce experimental HPS's.

EXPERIMENTAL PROCEDURE

70W Grades

Five 227 kg (500 lb) vacuum induction melted experimental heats of the 70W grade were studied in the first round of screening. Two of the heats were designed to be heat treated following rolling while three heats were designed to be as-rolled. Table 1 gives the chemical compositions of each heat. The processing details for the plates from each heat used to produce the heat treated 70W grade are given in Table 2. The processing details for the as-rolled grades are given by Bodnar and Hansen (1). The ingots from each heat were sectioned into several pieces and rolled to either 25 mm (1 in.) or 50 mm (2 in.) thick plates. A total of 30 70W grade plates were produced. Fifteen of the as-rolled grade plates were 25 mm (1 in.) thick and the other nine plates were 50 mm (2 in.) thick. All six of the heat treated grade plates were rolled to 50 mm (2 in.) thick. TMCP techniques such as recrystallization controlled rolling (RCR), controlled finish temperature (CFT) rolling, controlled rolling (CR), IAC and DQ were employed as well as conventional hot rolling (HR). The effects of various heat treatments such as reheat, quench and tempering (RQT) and tempering as-cooled plates following IAC or DQ were studied. For clarification, the use of the term "as-rolled" refers to plates that have been rolled and air cooled, whereas, the term "as-cooled" encompasses plates that have been rolled and either air cooled or subjected to some variety of controlled cooling such as interrupted accelerated cooling or direct quenching.

Preliminary studies were performed to determine the proper tempering temperature for plates designated for heat treating. Sections of air cooled plates from heats 8054 and 8055 were reheated to 1650°F (900°C), water quenched and then tempered at several different temperatures. IAC and DQ plate sections were tempered (IAC & DQT, respectively) in the as-cooled condition. The sections were tempered at 590°C (1100°F), 620°C (1150°F), 650°C (1200°F), 675°C (1250°F), and 700°C (1300°F). Following tempering, hardness measurements were made near the surface, and at the quarter- and mid-thickness of the plate. The remaining plate sections were tempered for one hour at temperatures chosen based upon the results of the tempering study and are shown in Tables 2.

The evaluation of each plate consisted of longitudinal tensile tests using standard 12.7 mm (0.500 in.) diameter specimens and longitudinal Charpy impact testing at various temperatures that ranged from -100°C to +100°C (-145°F to +210°F) using standard sized specimens as well as metallography. All mechanical property specimens were removed from the quarter thickness. Through-thickness hardness measurements were made on the as-rolled plates but will not be reported here. Refer to Bodnar and Hansen (1) for details.

Implant weldability tests were performed on the heat treated 70W heats to determine their susceptibility to hydrogen assisted heat affected zone cracking. An L-Tec 120S electrode was deposited in a single pass using Gas Metal Arc Welding (GMAW) with ambient preheat. The heat input was 1.6 kJ/mm. **Figure 2** shows the specimen and

the experimental setup for the implant test. Duplicate tests were performed at the yield stress and the flow stress for each steel as determined from the standard tensile properties.

100W Grades

Four different experimental heats were studied as potential 100W HPS candidates. All of the experimental heats were vacuum induction melted and cast as 227 kg (500 lb) ingots with the compositions shown in Table 3. In ASTM A709, Types E, F, P and Q are considered weathering grades and the carbon level may range from 0.10 wt. % to 0.21 wt. %, depending on the Type. The experimental steel compositions had lower carbon levels that ranged from 0.086 to 0.13 for improved weldability. Other alloying elements such as molybdenum, vanadium, titanium and boron are contained in each steel for strength following heat treating and nickel, chromium and copper for atmospheric corrosion resistance.

A variety of processing techniques were employed to produce 25-mm (1 in.) and 51-mm (2 in.) thick plates. The processing techniques used were designed for each heat of steel and are shown in Table 5. TMCP approaches such as CR and CFT rolling coupled with air cooling or DQ were used, as well as conventional hot rolling and air cooling. The air cooled plates were reheated, quenched and tempered while the DQ plates were tempered in the as-cooled condition.

Tempering studies were performed on each plate to determine the optimum tempering temperature(s) to obtain the mechanical properties required by A709. Once the plates were heat treated, tensile tests at ambient temperatures were performed using longitudinal 12.7-mm (0.500 in.) diameter tensile specimens. Charpy V-notch impact tests were performed using longitudinal standard sized specimens at temperatures that ranged from -101°C to 149°C (-150°F to +300°F). All of the mechanical property specimens were removed from the quarter-thickness position of the plates. Implant weldability testing were performed on the heat that contained the highest level of carbon using the same filler metal, procedure, and conditions outlined above for the 70W steels.

RESULTS AND DISCUSSION

70W Steels - Screening Study to Production Heat

The results of the tensile and Charpy impact tests for the heat treated 70W steels are shown in Table 5. For brevity, only the mechanical property results of the heat treated 70W grade will be presented because it proved to be the most promising HPS candidate at this point in the program. See Bodnar and Hansen (1) and Chilton and Manganello (2) for excellent reviews of the work performed on the as-rolled 70W steels.

Heat Treated 70W Steels

All of the heat treated 70W steels met the minimum yield strength and toughness requirements of A709 (2). The tensile strengths were occasionally low, but this was due to tempering at too high of a temperature. The yield/tensile ratio of the hot rolled, reheat quenched and tempered plates ranged from 0.84 to 0.87 and were considered typical for an A709 70W steel. The highest yield/tensile ratio obtained was 0.93 and was for the 0.13 wt. % carbon, recrystallization-controlled rolled and direct quenched plate tempered at 621°C (1150°F). **Figure 3** shows that the strength and toughness of the steels were affected by the chemical composition (particularly the carbon level) and the processing. The 0.08% carbon steel (heat 8054) exhibited better combinations of strength and toughness than the 0.13% carbon steel (heat 8055). The hot-rolled, reheat, quenched and tempered 0.08% carbon plate had better overall properties than the other plates. For both carbon levels, the direct quenched plates had higher strengths and lower toughness when tempered at 621°C (1150°F) than the reheat, quenched and tempered plates with the same carbon levels. However, the toughness of the direct quenched plates was improved significantly when tempered at 677°C (1250°F) but the yield strength decreased. Recrystallization-controlled rolling resulted in slightly lower strengths than hot rolling at the same tempering temperature.

As-rolled 70W Steels (1)

Only one of the 25 mm (1 in.) thick as-rolled 70W steels met the minimum yield strength requirements of A709 while none of the 51 mm (2 in.) thick plates met the requirements in the as-rolled condition, but most plates met the tensile strength requirements. The inability of the as-cooled steels to meet the minimum yield strength requirements was attributed to continuous yielding behavior due to the partially bainitic microstructures (1). The alloying elements present in the steels to meet the requirements of a weathering grade increased the hardenability such that bainite formed during accelerated cooling whereas a ferrite/pearlite microstructure may have been more suitable

because they typically exhibit yield point behavior. More information on the effects of alloying elements such as Si, Cu, Ni and Cr on the microstructural evolution during accelerated cooling following controlled rolling is needed to produce and optimize an as-rolled 70W grade bridge steel (1).

The initial screening study to produce 70W steels showed that the carbon could be reduced below 0.10 wt. % and still meet the mechanical property requirements of A709 using conventional hot rolling and heat treating practices. The lower carbon contents should provide improved weldability over A709 70W steels with higher carbon contents. In fact, implant weldability testing of the heat treated 70W steels proved to be superior to the A709 70W steels used to establish the baseline. None of the specimens from the experimental heats failed due to hydrogen induced heat affected zone cracking under the conditions imposed during the tests.

The heat treated 70W grade steel was chosen as the candidate steel to be used for further optimization and production. Selection of the 70W composition was made based on the screening studies and, except for the carbon content, was the same as heat 8054. It was thought that the carbon content could be lowered to a level below 0.08 wt. %. Thus, two 227 kg (500 lb.) heats (8012 & 8013) were vacuum-induction melted with chemical compositions the same as heat 8054, but one had a carbon content of 0.073 wt. % and the other was at 0.095 wt % carbon (6). The 127-mm (5 in.) thick slabs from each heat were reheated to 1245°C (2275°F), straight-away-rolled to 51-mm (2 in.) thick with a finish rolling temperature of approximately 1040°C (1900°F) and air-cooled on edge. The plates were then reheated to 900°C (1650°F), and immersion water quenched. The 0.073 wt. % carbon plate was tempered at 635°C (1175°F) and the 0.095 wt. % carbon plate was tempered at 650°C (1200°F), both for one hour. The tempering temperatures were determined by hardness tempering studies performed on plates from each heat.

The results of the mechanical testing performed on the 0.073 wt. % showed that the yield strength was 435 MPa (63 ksi) in the longitudinal direction at the quarter-thickness location in the plate and did not meet the minimum requirements. However, the mechanical properties of the 0.095 wt. % carbon steel met the minimum requirements with a yield strength of 498 MPa (72 ksi), a tensile strength of 596 MPa (86 ksi), % elongation in 51 mm of 27.1, % reduction in area of 76.7 and a yield/tensile ratio of 0.83. The toughness also met the AASHTO M270/ASTM A709 requirements with an impact toughness of 209 J (154 ft-lb) at -23°C (-10°F). The quoted properties were measured in the longitudinal direction and at the quarter-thickness location. This study showed that the carbon level in this steel should not be lower than 0.08 wt. % in order to meet the 485 MPa (70 ksi) yield strength requirements. Furthermore, it was recommended (6) that the commercial melting range of 0.08 to 0.11 wt. % carbon be used for optimum properties.

Production Heat

A production heat of the heat-treated 70W steel was melted and rolled into plates with thickness ranging from 9.5 mm (0.375 in.) to 63.5 mm (2.5 in.). The chemical composition was as follows:

Heat ^(a)	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Al
U5191	0.10	1.20	0.006	0.001	0.39	0.33	0.31	0.52	0.06	0.06	0.013

(a) Information was provided by Mr. A. D. Wilson of Lukens Steel Co., Coatesville, PA

Table 6 shows the mechanical properties exhibited by the plates from the production heat of the 70W steel. The minimum yield strength and impact toughness requirements were met by all plates up to and including the maximum thickness of 63.5 mm (2.5 in.). Table 6 also shows some typical values of strength and toughness of an A709 70W steel with higher carbon content (2). The plates from the production heat of the heat-treated 70W steel are currently being fabricated into girders and will be tested by the FHWA. Also, numerous weldability tests are being performed to characterize the production heat's suitability for welding without preheat.

100W Steels (3,4)

The four heats melted to produce the experimental 100W steels were similar to ASTM A709/A514 Type F steels but the level of the alloying elements were adjusted to examine the effects of lowering the levels of carbon, silicon, nickel, and chromium. The chemical compositions of the four heats are shown in Table 3. Heats 8057 and 8058 examined the effects of carbon while heats 704K047 and 704K048 (abbreviated 47 and 48, respectively) investigated the possibility of completely eliminating chromium from the steel.

The results of the mechanical properties of the 100W steels examined in the screening study are shown in Table 7 and some of the results are plotted versus carbon content and carbon equivalent (CE) in **Figures 4 and 5**, respectively. **Figure 4** shows that plates tempered at the same temperature, both the yield strength and the toughness of the steels (heats 8057 & 8058) increased with increasing carbon content. This may have occurred due to the refinement of the microstructure as a result of increasing amounts of martensite relative to the amount of bainite. All of the plates from heats 8057 and 8058 met the minimum yield strength of 690 MPa (100 ksi) and the tensile strength range of 758-896 MPa (110-130 ksi) at one or more of the tempering temperatures. The yield/tensile ratios ranged from 0.92 to 0.98. The lower carbon heat (heat 8057) exhibited sub-par toughness in all but two plates while all of the higher carbon plates (heat 8058) met the minimum toughness requirements. The results also show that controlled rolling followed by direct quenching and tempering provided the best combinations of strength

and toughness at both carbon levels. The weldability of the 0.13 wt. % carbon steel was tested using the implant test. No failures were exhibited in the heat affected zone at stresses up to the flow stress (i.e., the maximum stress tested). Based upon the results of the screening study of heats 8057 and 8058, Manganello (3) believed that the optimum chemistry was not evaluated and suggested that a carbon level of around 0.10 wt. % to 0.11 wt. % would give the best properties.

The results of the mechanical properties (4) of the two heats (heats 47 & 48) designed to determine if chromium could be eliminated from the steel and still meet the minimum requirements for strength and toughness are shown in Table 7 and Figure 5. Plates with thickness of 25 mm (1 in.) and 51 mm (2 in.) were investigated. The data in Figure 5 is plotted versus the CE value for each chemistry because carbon was not adjusted but other elements that affect strength and toughness were. The expression for determining the CE is shown in Table 3. All but one of the plates met the minimum strength requirements (plate K47J) for both thickness levels and had yield/tensile ratios that ranged from 0.91 to 0.98. The 25-mm (1 in.) thick plates tended to have higher yield strengths than the 51-mm (2 in.) thick plates, as shown in Figure 5, but the difference in strength between all of the plates decreased at the higher carbon equivalent value. In most cases, the strength of the *direct quenched* and tempered plates decreased slightly with increasing CE while the strength of the reheat, quenched and tempered plates increased with CE. The controlled finish temperature rolled plates exhibited the highest yield strengths, whereas the hot rolled plate exhibit the lowest yield strengths per thickness. Direct quenching tended to increase the yield strength of the hot rolled plates due to either a refinement of the bainitic structure or the formation martensite.

In general, the toughness of the plates increased with increasing carbon equivalent and was probably due to the refinement of the transformed microstructure. The hot rolled, air cooled and tempered plates exhibited the lowest toughness compared to the other processing techniques while controlled finish temperature rolling followed by direct quenching provided better toughness. In the chromium-free steel (lower CE), none of the plates met the minimum toughness requirements. However, the addition of chromium, and other elemental level adjustments, seemed to increase the toughness considerably except in the case of one 25-mm (1 in.) plate (K47H). The trends in toughness may be attributed to the condition of the austenite prior to cooling. The hot rolled plates had a coarser prior austenitic grain structure resulting in lower toughness than the controlled finish rolled plates that exhibited a pancaked, thus a finer, austenitic structure. Overall, the best combinations of both yield strength and toughness were obtained in the controlled finish temperature rolled plates. Additional work to investigate the effect of other alloy additions such as Ni and Mo in a Cr-free steel are warranted.

Production Heat

Based upon the results of the screening study for the 100W steels, a production heat of a low carbon A514 Type F steel was melted with the composition given below. The following information was provided by the U.S. Steel Technical Center, Monroeville, PA:

C	Mn	P	S	Si	Cu	Ni
0.11	0.85	0.015	0.003	0.30	0.33	0.85
Cr	Mo	V	Ti	Al	B	N
0.54	0.46	0.04	0.03	0.03	0.0011	0.005

This heat was vacuum-degassed and calcium-treated for sulfide shape control and had a carbon equivalent value of 0.59. The mechanical properties of this heat of steel are currently being characterized. The plates produced from the production 100W heat will be used to fabricate full-scale girders for fatigue and fracture analysis.

CONCLUSIONS

The cooperative effort between AISI, FHWA and the U. S. Navy to develop excellent candidate high performance steels for bridges was considered to be very successful. Efforts are still underway to fully characterize the steels and provide them on a production basis for immediate implementation.

The following conclusions were made based upon the work performed during the initial screening studies:

1. A low carbon A709 Gr. 70W steel processed via hot rolling, reheat quench and tempering was found to provide mechanical properties that met the requirements of AASHTO M270 and ASTM A709 and exhibited good weldability based on the implant weldability test. This type of steel was used to produce a production heat for full scale girder fabrication and testing,
2. The low carbon Nb-V weathering steels possessed too high of a hardenability to produce an as-rolled 70W grade,
3. A low carbon A709 Gr. 100W steel provided mechanical properties that met the requirements of AASHTO M270 and ASTM A709 and exhibited good weldability using the implant weldability test. This type of steel was used for a production heat that will be fully characterized in the program.
4. The chromium-free 100W candidate steel provided adequate strength in most cases but did not provide sufficient toughness.

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Table 1 Chemical Composition of Experimental 70W High Performance Steels for Bridge Construction (1,2)

Heat ID	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al	Ti	N	CE
Heat Treated 70W Steels															
8054	0.082	1.24	0.014	0.005	0.40	0.33	0.30	0.53	0.05	0.06	<0.005	0.027	0.002	0.0058	0.53
8055	0.140	1.25	0.016	0.005	0.40	0.34	0.31	0.55	0.051	0.069	0.006	0.029	0.002	0.0058	0.59
As-Rolled 70W Steels															
704K044	0.14	1.12	0.022	0.011	0.45	0.34	0.25	0.50	---	0.078	0.04	0.048	---	0.0085	0.55
704K045	0.083	1.28	0.021	0.011	0.46	0.35	0.26	0.50	---	0.079	0.039	0.038	---	0.0086	0.52
704K046	0.053	1.39	0.019	0.01	0.45	0.35	0.25	0.49	---	0.079	0.039	0.035	---	0.0076	0.53
ASTM A709 Grade 70W	0.19 max	0.8 1.35	0.04 max	0.05 max	0.20 0.65	0.20 0.40	0.50 max	0.40 0.70	---	0.02 0.10	---	---	---	---	---

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

Table 2 Plate Processing Details for the Heat Treated Experimental 70W Grade High Performance Steels for Bridge Construction (2)

Plate Code	Plate Thickness, mm	Slab Reheating Temp., °C	Processing	Finish Rolling Temp., °C	Cooling Stop Temp., °C	Reaustenitizing Temp., °C	Tempering Temps., °C
8054A	50	1260	HR+Air Cool	---	---	900	620, 650
8054B	50	1175	RCR+DQ	945	ambient	---	620, 675
8054C	50	1175	RCR+Air Cool	945	---	900	620, 650
8055A	50	1260	HR+Air Cool	---	---	900	620, 650
8055B	50	1175	RCR+DQ	945	ambient	---	620, 675
8055C	50	1175	RCR+Air Cool	945	---	900	620, 650
8056A	50	1260	HR+Air Cool	---	---	900	620, 675
8056B	50	1175	RCR+IAC	945	590	---	620, 690
8056C	50	1175	CR+Air Cool	815	---	900	620, 675

Table 3 Chemical Composition of Experimental 100W Grade High Performance Steels for Bridge Construction (3,4)

Heat	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Al	B	N	CE
8057	0.086	0.95	0.014	0.0034	0.31	0.36	0.77	0.55	0.50	0.043	0.033	0.030	0.0014	0.0056	0.59
8058	0.130	0.96	0.016	0.0032	0.31	0.35	0.79	0.55	0.49	0.040	0.030	0.025	0.0015	0.0058	0.63
704K047	0.11	1.33	0.021	0.009	0.57	0.33	0.26	---	0.49	0.049	0.031	0.029	0.0020	0.0078	0.57
704K048	0.11	1.33	0.018	0.009	0.11	0.31	0.41	0.51	0.50	0.050	0.031	0.032	0.0020	0.0078	0.61

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

Table 4 Plate Processing Details for the Experimental 100W Grade High Performance Steels for Bridge Construction (3,4)

Plate Code	Thickness, mm	Slab Reheat Temp., °C	Processing	Finish Rolling Temp., °C	Cooling Rate, °C/s	Reaustenitizing, °C	Tempering Temp., °C
8057A	51	1260	HR+Air Cool	1038		900	620, 675
8057B	51	1176	CR+DQ	815			620, 675
8057C	51	1176	CR+Air Cool	815		900	620, 675
8058A	51	1260	HR+Air Cool	1038		900	675, 690
8058B	51	1176	CR+DQ	815			675, 704
8058C	51	1176	CR+Air Cool	815		900	675, 690
K47G	25	1260	HR+Air Cool	1027		900	662
K47H	25	1260	HR+DQ	1027			675
K47I	25	1150	CFT+DQ	871			675
K48G	25	1260	HR+Air Cool	1027		900	662
K48H	25	1260	HR+DQ	1025			675
K48I	25	1150	CFT+DQ	868			675
K47J	51	1260	HR+Air Cool	1071		900	650
K47K	51	1260	HR+DQ	1093			675
K47L	51	1150	CFT+DQ	871			675
K48J	51	1260	HR+Air Cool	1099		900	650
K48K	51	1260	HR+DQ	1099			675
K48L	51	1150	CFT+DQ	871			675

HR = Hot Rolling CR = Controlled Rolling CFT = Controlled Finish Temperature Rolling

Table 5 Mechanical Properties of 51 mm (2 in.) Thick Heat Treated 70W Grade High Performance Steels for Bridge Construction (2)

Plate Code	Processing	Tempering Temp., °C	Y.S., ¹ MPa	T.S., ¹ MPa	% El. in 51mm,	% R.A.	Y.S/ T.S	CVN Energy, Joules ²			CVN 47J TT, °C
								-23°C	-7°C	10°C	
8054A	1260+HR+RQT	621 649	560 512	659 609	26.0 27.4	74.8 76.8	0.85 0.84	150 203	155 231	182 230	<-73 -90
8054B	1177+RCR+DQT	621 677	638 579	725 665	23.5 23.3	76.1 73.1	0.91 0.87	117 196	137 235	165 228	-70 -40
8054C	1177+RCR+RQT	621 649	544 491	646 532	28.0 27.9	74.2 77.2	0.84 0.92	158 186	170 209	190 203	-62 -90
8055A	1260+HR+RQT	621 649	646 592	741 698	25.5 23.2	71.3 70.0	0.87 0.85	69 98	87 150	107 152	-54 -51
8055B	1177+RCR+DQT	621 677	753 634	806 725	22.5 22.2	66.3 69.6	0.93 0.88	54 141	52 150	91 184	-32 -51
8055C	1177+RCR+RQT	621 649	637 572	735 682	23.3 23.8	69.4 70.6	0.87 0.84	77 94	101 139	120 145	-37 -54
ASTM A709- Gr. 70W			482 min.	620-758	19 min.			41 min			

1. MPa = 6.894 ksi 2. Joule = 1.355 ft-lbf

Table 6 Mechanical Properties of 70W Grade High Performance Steel Production Heat¹

Slab Code	Thickness, mm	Location	Y.S., MPa ²	T.S., MPa ²	Y.S./T.S.	CVN @ -23°C, J (long.) ³
3A	9.5	Top	564	654	0.86	255 ⁴
		Bottom	585	668	0.87	265 ⁴
87A	38.1	Top	548	635	0.86	196
		Bottom	556	661	0.84	275
5	51	Top	554	643	0.86	279
		Bottom	552	656	0.84	281
6A	51	Top	549	649	0.85	249
		Bottom	573	638	0.90	289
6B	51	Top	526	636	0.83	304
		Bottom	529	635	0.83	352
2	63.5	Top	491	627	0.78	266
		Bottom	559	654	0.86	269
ASTM A709 Gr. 70W			482 min.	620-758	---	41 min.

1. Information provided by Mr. A. D. Wilson, Lukens Steel Co., Coatesville, PA.

2. MPa = 6.894 ksi

3. Joule = 1.355 ft-lbf

4. ¾ sized Charpy specimens

Table 7 Mechanical Properties of 100W Grade High Performance Steels for Bridge Construction (3,4)

Plate Code	Plate t, mm	Tempering Temp., °C	Y.S., ¹ MPa	T.S., ¹ MPa	% El.	% R.A.	Y.S./T.S.	CVN Energy, Joules ²			CVN 47J TT, °C
								-34°C	-18°C	21°C	
8057A	51	620 675	836 759	888 809	21.5 20.6	72.0 72.2	0.94 0.94	12 35	18 53	75 169	2 -23
8057B	51	620 675	817 779	876 838	22.5 20.6	73.3 72.6	0.93 0.93	43 53	24 145	107 77	-4 -40
8057C	51	620 675	855 760	905 799	21.5 20.8	71.7 71.8	0.95 0.95	27 144	58 169	125 205	-23 -65
8058A	51	675 690	843 747	883 810	21.0 21.2	70.8 71.6	0.95 0.92	66 98	89 144	157 188	-51 -57
8058B	51	675 704	942 828	963 869	20.0 20.4	69.5 67.1	0.98 0.95	95 122	107 157	126 180	<-73 -87
8058C	51	620 690	820 755	856 815	21.3 21.2	72.4 71.7	0.96 0.93	72 138	122 150	171 199	-65 -65
K47G	25	662	725	794	21.8	66.1	0.91	10	20	14	22
K47H	25	675	801	853	20.0	63.7	0.94	7	9	19	74
K47I	25	675	831	852	20.8	65.3	0.98	28	38	47	-4
K48G	25	662	745	775	22.0	70.9	0.96	54	92	123	-36
K48H	25	675	780	831	20.3	68.3	0.94	9	19	16	6
K48I	25	675	787	818	22.0	70.1	0.96	65	102	103	-46
K47J	51	650	672	741	21.5	65.9	0.91	4	5	8	76
K47K	51	675	735	798	21.0	64.9	0.92	33	31	23	7
K47L	51	675	771	809	20.8	64.2	0.95	34	31	50	-5
K48J	51	650	750	782	21.3	69.9	0.96	45	69	103	-34
K48K	51	675	720	777	20.5	69.7	0.93	60	49	51	-29
K48L	51	675	780	798	21.5	69.0	0.98	96	118	134	-52
ASTM A709 Gr. 100W								47			

1. MPa = 6.894 ksi

2. Joule = 1.355 ft-lbf

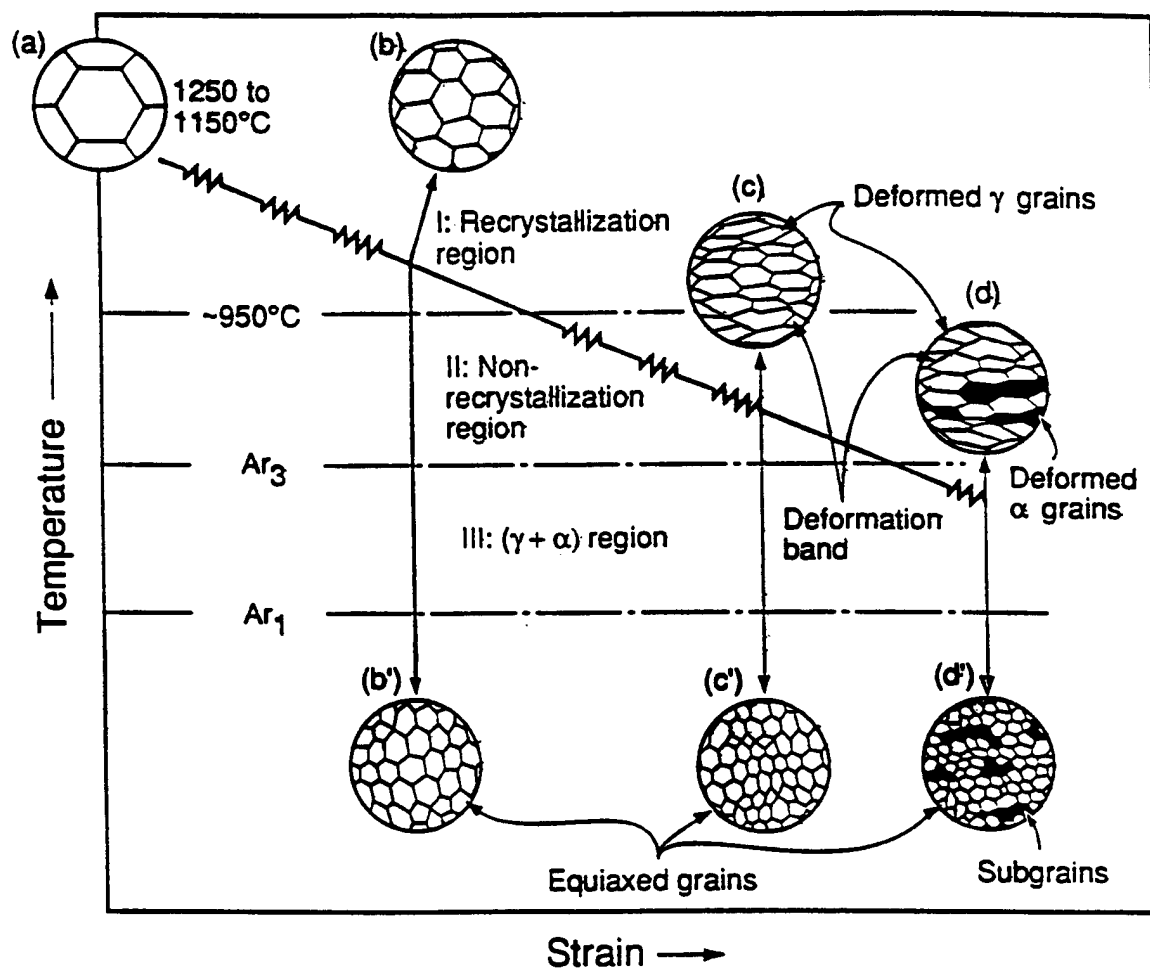


Figure 1. A schematic representation of the effect of temperature and strain on the condition of austenite during controlled rolling and the resulting transformed microstructures. After Tanaka (9).

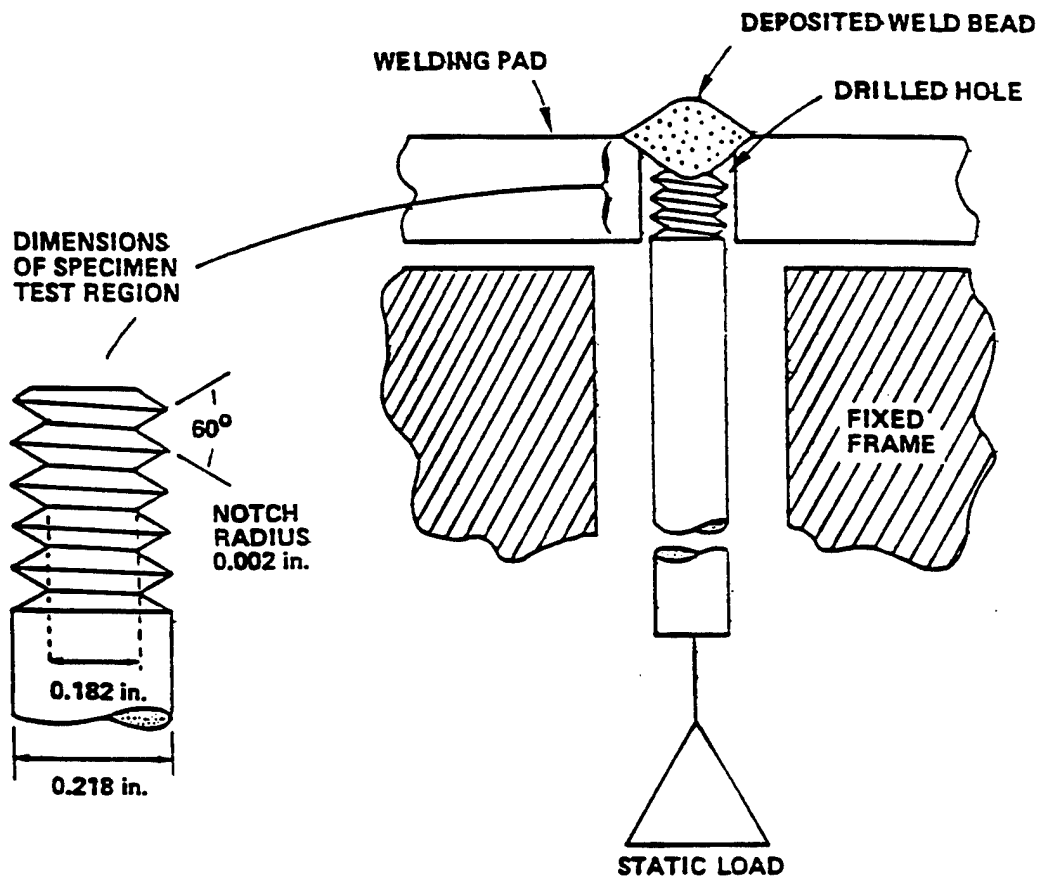


Figure 2. Specimen design and test setup for implant weldability tests.

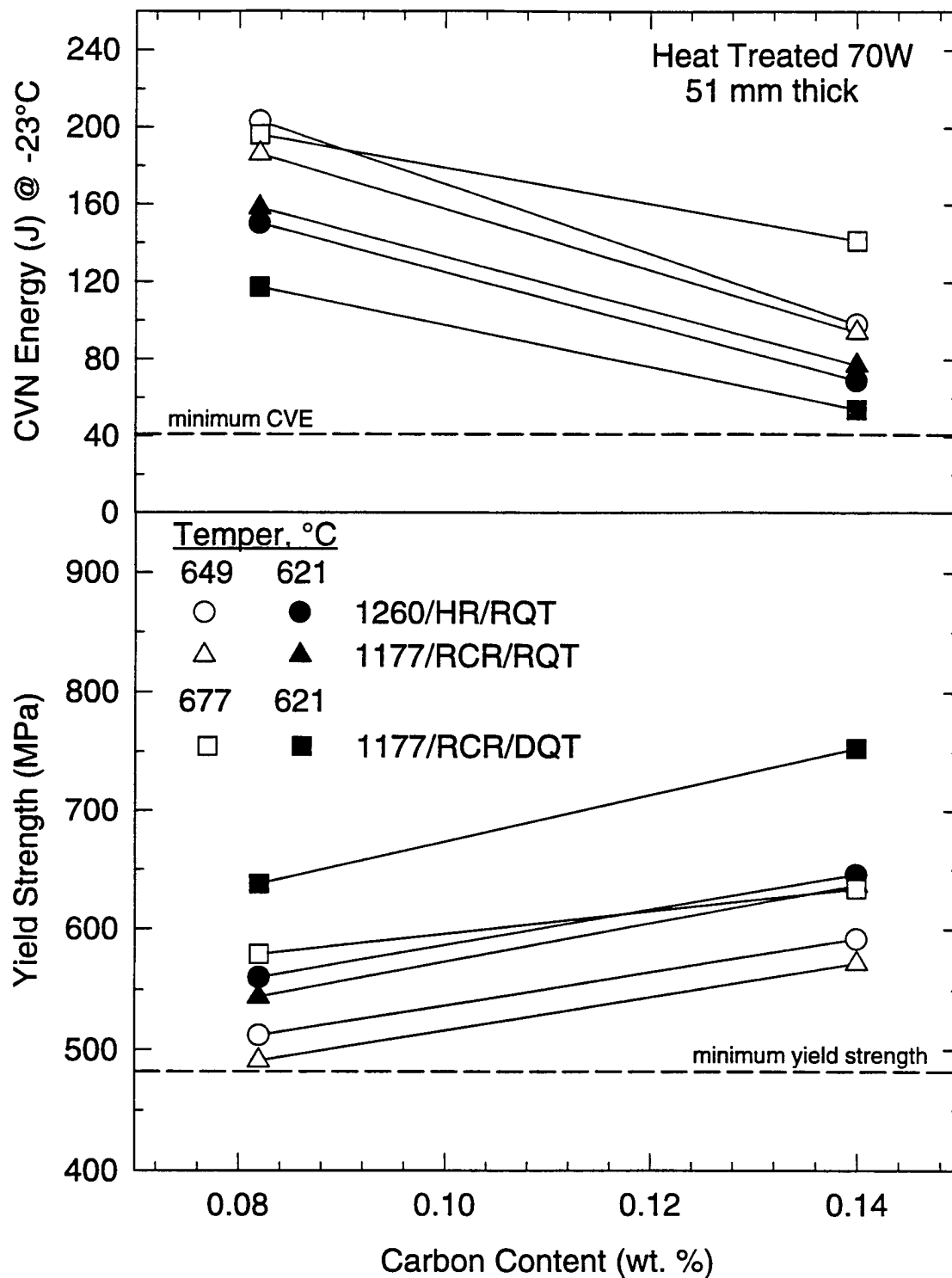


Figure 3. Strength and toughness as a function of the carbon content of heat treated 70W steels. Data from (2,3). HR=Hot Rolling RCR=Recrystallization Controlled Rolling RQT=Reheat, Quench and Temper

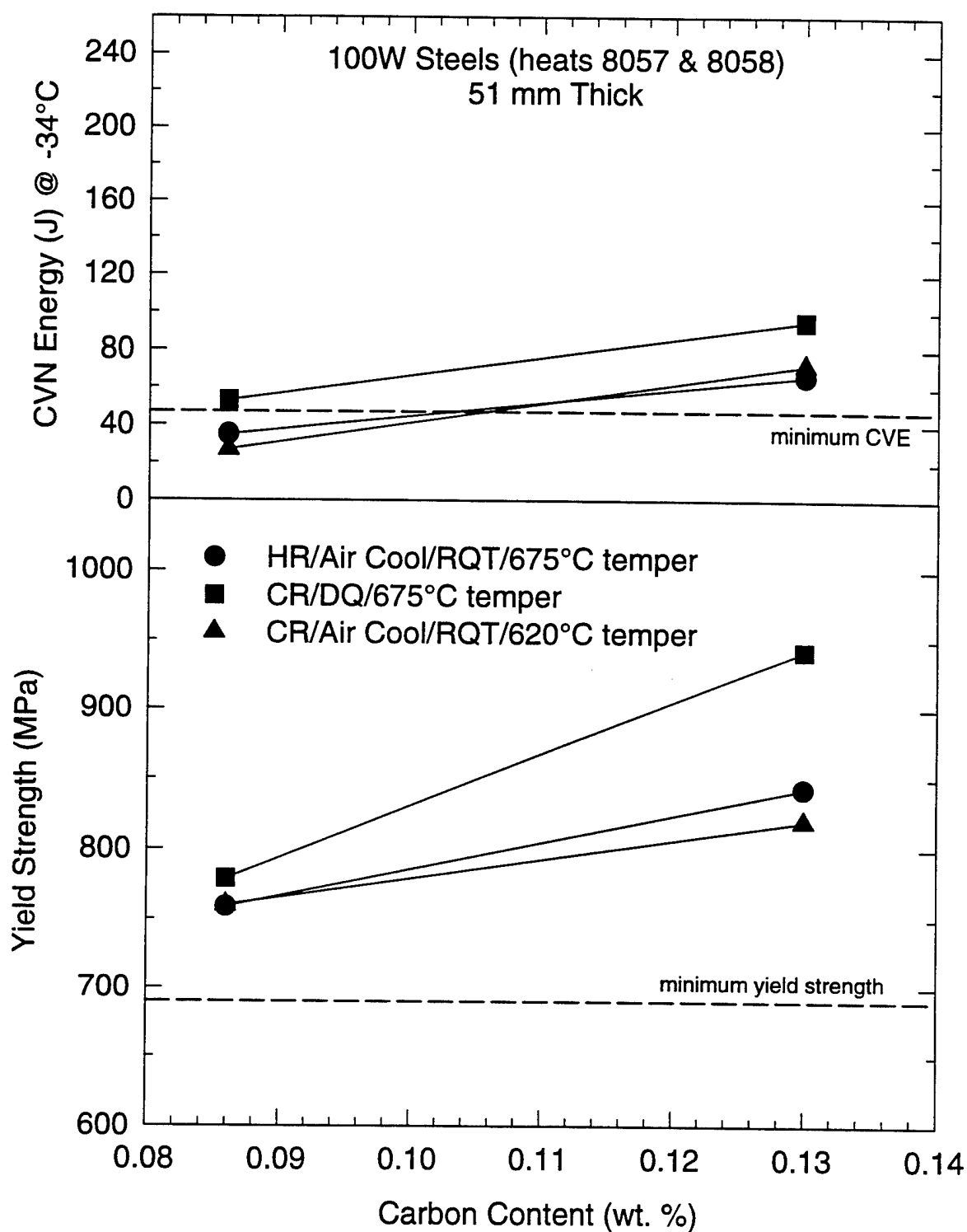


Figure 4. Strength and toughness as a function of the carbon content of 100W steels. Data from (3). HR = Hot Rolling CR = Controlled Rolling RQT = Reheat, Quench and Temper DQ = Direct Quench

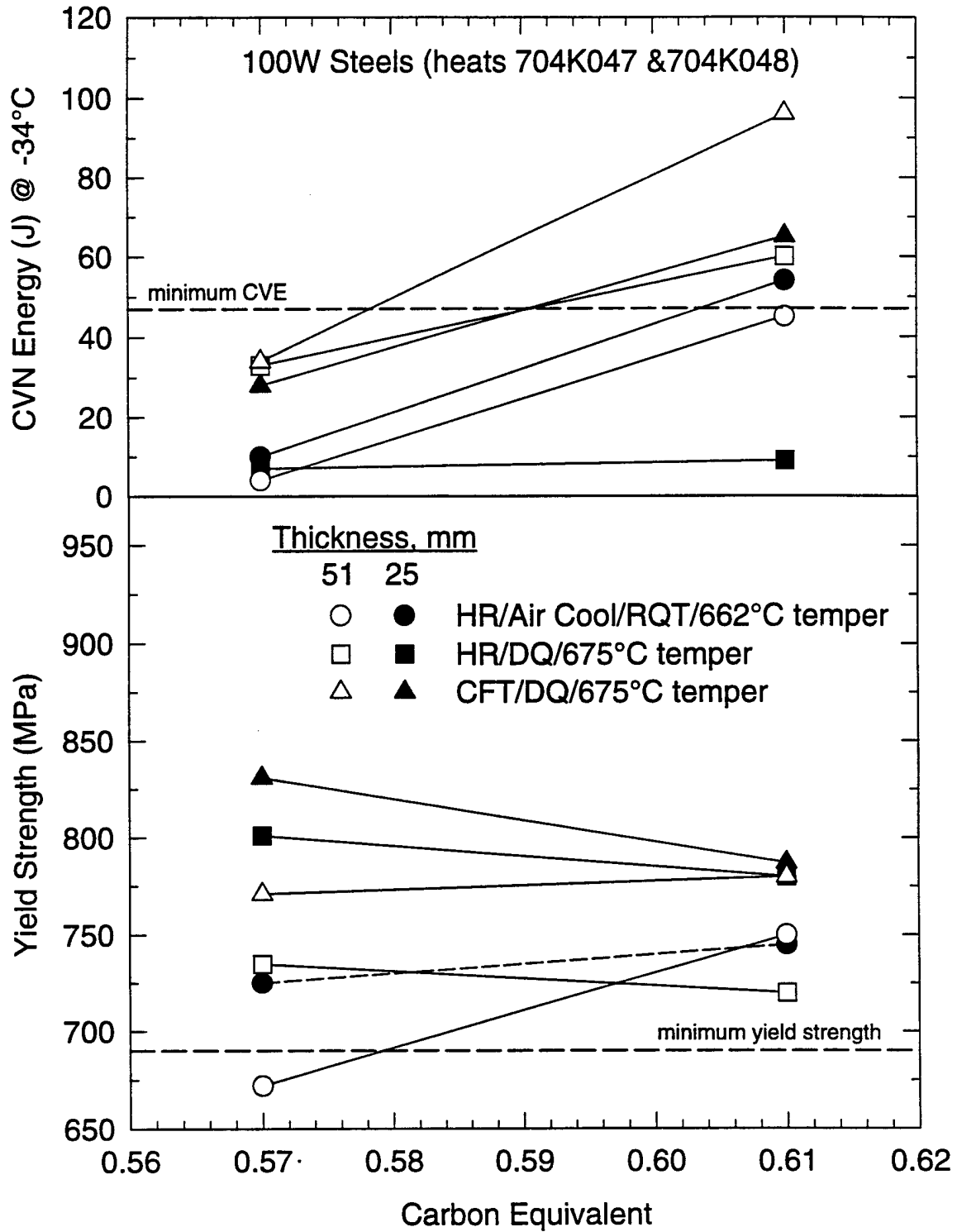


Figure 5. Strength and toughness as a function of the carbon equivalent of 100W steels. Data from (4). HR=Hot Rolling RQT=Reheat, Quench and Temper DQ=Direct Quench CFT=Controlled Finish Temperature Rolling

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