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DEVELOPMENT OF COMPOSITIONS OF Cu-Ni HIGH-PERFORMANCE STEELS WITH YIELD STRENGTHS OF 100- TO 130-KSI AND EXCELLENT TOUGHNESS

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DEVELOPMENT OF COMPOSITIONS OF Cu-Ni HIGH-PERFORMANCE STEELS WITH YIELD STRENGTHS OF 100- TO 130-KSI AND EXCELLENT TOUGHNESS

ABSTRACT

On the basis of extensive investigations, the Lehigh University ATLSS Center recommended the chemical composition for a Cu-Ni HPS-100W steel for bridges and similar infrastructure applications. The composition was based on a factorial study optimizing the carbon, manganese, and molybdenum contents at a nickel content of 0.75% and 1.0% copper. Commercial heats of this HPS 100-W have been produced and product has been fabricated and erected into bridges. To determine the potential for greater yield strength and plate thickness for steels having the same carbon, manganese, and molybdenum contents at 2.5% nickel, laboratory heats of the compositions but with only the highest and lowest hardenability were melted and evaluated.

The conclusions of the program for HPS-100W steel with 2.5% nickel were as follows:

1. The hardenability was increased such that heavier sections can be fully hardened with the desired improvement in strength and toughness.
2. The HPS-100W steel composition with increased nickel may be suitable as an HPS-120W steel for bridges and similar infrastructure applications.
3. Its suitability for Items 1 and 2 should be confirmed by producing a commercial heat of the steel, evaluating its metallurgical characteristics, and conducting large-scale weldability and full-scale prototype tests.

INTRODUCTION

The Lehigh University ATLSS Center has been developing high-performance steels (HPS) with improved fracture toughness and weldability at yield strengths of 70 to 130 ksi (490 to 910 MPa) for civilian and military applications. The results of these investigations* indicate that the Cu-Ni alloy-steel system is significantly superior to other alloy-steel systems for the intended applications. This occurs because strengthening by copper-rich precipitates permits the carbon content to be reduced from the typical 0.15 percent for constructional alloy steels to 0.06 to 0.08 percent. This reduction in carbon content greatly improves both fracture toughness and weldability. Initial studies involved optimizing the manganese, nickel, and molybdenum content in the following full factorial composition study:

Full-Factorial Program Steel Compositions, %

Steel	Mn	Cu	Ni	Cr	Mo	V	Cb
A	1.00	1.00	0.75	0.50	0.25	0.06	0.015
B	1.00	“	0.75	“	0.50	“	“
C	1.00	“	2.50	“	0.25	“	“
D	1.00	“	2.50	“	0.50	“	“
E	1.50	“	0.75	“	0.25	“	“
F	1.50	“	0.75	“	0.50	“	“
G	1.50	“	2.50	“	0.25	“	“
H	1.50	“	2.50	“	0.50	“	“

The previously completed programs* involved Steels A, B, E, and F, which are the low nickel (0.75%) steels, intended for applications, such as bridges. The results have been summarized in a series of ATLSS reports[1-11], and the Cu-Ni HPS 100W steel specification considered to be optimum is as follows:

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al	N
0.050	0.95	0.015	0.003	0.15	0.90	0.65	0.40	0.40	0.040	0.010	0.020	0.015
0.080	1.50	max	max	0.35	1.20	1.00	0.65	0.65	0.080	0.030	0.050	max

Commercial heats of the Cu-Ni HPS 100W have been produced, plate product has been fabricated and erected into bridges, primarily interstate, and the proposed specification is being reviewed for inclusion in ASTM A709, “Standard Specification for Structural Steel Bridges”. Its broader use as a 100-ksi minimum yield-strength steel is expected because its

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*See references

weldability and fracture toughness are far better than any of the A514 structural steels. It also is expected to replace the A517 steels.

The successful performance of the 0.75% nickel composition as a Cu-Ni HPS 100W steel for structural applications suggests that similar success might be expected for a 2.50% nickel steel within the specification composition to obtain fracture-toughness down to temperatures as low as -120F (-85C) and to extend the range of applications requiring heavier sections, both with improved weldability. Therefore, the ATLSS Center studied the properties of only the lowest hardenability (Steel C) and the highest hardenability (Steel H), with nickel at 2.5 percent.

EXPERIMENTAL PROCEDURE

Melting and Rolling - 300-pound heats of Steels C and H were melted and poured into three 100-pound slab ingots at aim carbon contents of 0.04, 0.06, and 0.08 percent. The ingots were rolled to 1.1-inch-thick plate. The compositions of all steels are listed in Table I to IV.

Jominy Tests - Six Jominy end-quench-hardenability test specimens for each steel composition were machined and tested in accordance with ASTM A255. After hardness testing, one specimen for each steel was reheated at 950F, 1050F, 1150F, or 1250F (510C, 565C, 620C, or 675C, respectively), aged for one hour, hardness tested, and plotted. The Jominy specimens were polished, etched, and examined metallographically: and various locations along the length were photographed. Results are reported in Reference 6.

Mechanical-Property Tests - For each steel composition, an 8"x12"x1" plate was austenitized at 1650F (900C) and quenched in an agitated water bath (H=1.5@50F/sec.) A second 1-inch-thick plate was similarly austenitized and quenched in agitated water containing 4.75% polyalkylene glycol to simulate the cooling of a 3-inch-thick commercially-quenched plate (H=1.5@9F/sec.) Tensile and Charpy V-notch specimens were machined from each quenched plate after temper-aging at 1150 and 1250F (620 and 675C).The tensile specimens were tested to obtain strength and ductility values, and the Charpy specimens were tested to obtain transition-temperature behavior.

Weldability Tests - As for Steels A, B, E, and F, evaluation of their weldability was implied from small-scale implant tests, followed by larger-scale tests when the commercial heat was produced. For this study, implant tests were conducted on Steel H, the steel with the highest hardenability and carbon equivalent, and thus the least weldable steel.

Testing of Large Prototypes - The suitability of the 0.75% nickel Cu-Ni HPS-100W steel for structural applications was established by fabricating and testing prototype girders with plates from the first production heat (Lukens R8660) to demonstrate (1) strength and ductility and (2) resistance to fatigue and fracture. The tests were conducted by the ATLSS personnel identified in References 7-11.

Tests for strength and ductility were conducted on I-girders fabricated from 3/4- and 1-inch-thick flanges and 1/4- and 3/8-inch-thick webs, respectively. The I-girders with 3/4-inch flanges were 21 and 27 inches deep and those with 1-inch flanges were 24-, 33-, and 42-inches deep. The girders with a compression tubular flange were fabricated from seamless 10-inch-diameter by 0.30-inch-thick-wall heat-treated tubes.

Tests for fatigue and fracture investigations involved eight girders – six were 1-inch-thick by seven inch-wide flanges with 3/8-inch-thick webs that were 30 inches deep; the other two were similar flanges and webs but were 33 inches deep. Ultrasonic-impact-test treatments were imposed on the stiffener fillet welds.

RESULTS AND DISCUSSION

Mechanical Properties - The mechanical properties of the lowest hardenability 0.75% nickel steel, Steel A, are listed in Table I for comparison with those for the corresponding 2.5% nickel steel, Steel C, Table II. The mechanical properties for the highest hardenability 0.75% nickel steel, Steel F, are listed in Table III for comparison with those for the corresponding 2.5% nickel steel, Steel H, Table IV. The specific strength and toughness criteria of interest are compared in Table V for the preferred carbon content, 0.06%. The comparisons of Steel A with Steel C and Steel F with Steel H reveal the effect of increasing nickel content from 0.75% to 2.50% on the mechanical properties of the Cu-Ni steels. There is a significant increase in the yield and tensile strength provided by the increased nickel in Steel C over Steel A, without detriment to the Charpy V-notch transition temperatures. In the case of Steel F compared with Steel H, there is essentially no effect on the mechanical properties for the water-quenched 1-inch-thick plates; however, at the slower cooling rate for the polymer-quenched plates, equivalent to commercially quenched 3-inch-thick plates, both the strength and the toughness are significantly enhanced by the increased nickel content. Moreover, the higher strength obtained by the nickel addition and the polymer-quenching is accompanied by a significant lowering of the Charpy V-notch transition temperatures. It should be noted that Steel C and Steel F have similar mechanical properties, probably because the alloying effects of 1.5% Mn, 0,5%Mo, and 0.75%Ni parallel those of 1.0%Mn, 0.25%Mo, and 2.5%Ni.

Another comparison based on the chemical composition of the four steels is shown below for (1) hardenability, based on the ASTM calculation of the ideal-critical diameter, D_i, and (2) susceptibility to welding hydrogen-assisted cracking (HAC), using the IIW formula to calculate the carbon equivalent, CE, both at the preferred carbon content of 0.06%.

Steel	A6	P*	C6	F6	H6
Hardenability, D_i	1.20	1.60	2.18	2.30	4.12
Carbon Equivalent, CE	0.55	0.56	0.67	0.64	0.80

* Production heat

As the above values suggest, increasing the nickel content from 0.75 to 2.50% almost doubles the hardenability, based on the ASTM formula. Thus, the thickness of plates that can be quenched to full midthickness hardness is greatly increased. However, the increased nickel content also increases the susceptibility to HAC.

Testing of Large Prototypes

Strength and Ductility - I-Girder Flexural - Tests and finite-element simulations have shown that the behavior of HPS-100W steel with bridge I-girders in flexure to the behavior of I-girders made of conventional-strength steel[7]. In particular, when the difference in steel ongoing.

Strength and Ductility – Tubular – Additional tests and finite-element simulations have investigated the use of HPS-100W steel in innovative I-girder tube-shaped concrete-used is taken into account, the flexural strength and ductility of HPS-100W steel I-girders is similar to that of conventional steel I-girders; that is, there is no reduction in behavior from the high yield stress of HPS-100W steel as previously observed for other high-strength structural steels. . In addition, the structural-strength provision of the AASHTO LRFD Bridge Design Specifications (Third Edition 2004) are applicable for the design of HPS-100W I-girders in negative flexure (i.e., controlled by the compression flange). Research on HPS 100-W I-girders in positive flexure (controlled by the tension flange) is filled compression flanges[8]. In this application, the high-strength of HPS-100W steel was successfully exploited because the tube resisted buckling modes that often control the design of high-strength-steel bridge girders. These HPS-100W tubular-flange girders were lighter, required less bracing and construction, and enhanced fatigue resistance.

Fatigue and Fracture - Fatigue and fracture tests of welded details continue to demonstrate that High Performance Steel (HPS) provides the same fatigue resistance for a given detail[9,10,11] as all other structural steels. Test results on HPS-100W girders that were subjected to Ultrasonic Impact Treatment (UIT), demonstrated that Category C stiffener details could have their fatigue limit increased to Category B or better. The web-flange welded detail was found to be the condition limiting the fatigue resistance of welded built-up members and their attachments from further enhancement. The high toughness of HPS 100W eliminates susceptibility to plane-strain fracture from defects and consequential catastrophic failure. Thus failure occurs under plane-stress conditions when the load exceeds the yield strength of the remaining net section.

CONCLUSIONS

Increasing the nickel content of HPS-100W experimental steels from 0.75% to 2.5% resulted in the following effects:

1. The hardenability of HPS-100W type steels was increased such that heavier sections can be fully hardened with the desired improvement in strength and toughness.
2. The HPS-100W steel composition with increased nickel resulted in a steel that may be suitable as HPS-120W for bridges and similar infrastructure applications

ATLSS tests of large-scale prototypes of HPS-100W steel demonstrated its suitability for structural applications.

RECOMMENDATIONS

The suitability of HPS-100W with increased nickel for thicker plate gauges and as an HPS-120W steel for bridges and similar infrastructure applications should be confirmed by producing a commercial heat of the steel, evaluating its metallurgical characteristics, and conducting large-scale weldability and full-scale prototype tests.

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Table I - Mechanical Properties of Steel A After Various Treatments

Processing Condition Temperature, °F	Codes	Tensile Properties					Hard.	Charpy V-Notch Transition Temp., °F					Charpy V-Notch Energy ft-lb				
		Y.S. ksi	T.S ksi	EL. %	R.A %	Y.S./T.S.	HRc	20 ft-lb	35 ft-lb	60 ft-lb	15 mils	50% FAT	70°F	0°F	-40°F	-80°F	-120°F
A4 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.045	1.00	0.012	0.003	0.23	1.02	0.75	0.50	0.24	0.057	0.015	0.022			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	A4AB	101	111	26	75	0.91	22.5	-130	-110	-100	-125	20	----	135	130	110	30
Temper @ 1150 °F	A4AD	96	106	26	78	0.90	19.5	-120	-110	-100	-120	-90	----	195	175	140	15
Temper @ 1250 °F	A4AF	91	99	28	79	0.92	17.0	-150	-130	-120	-130	-90	----	205	205	205	60
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	A4BB	90	106	27	76	0.85	20.0	-130	-120	-110	-130	-20	----	160	125	110	35
Temper @ 1150 °F	A4BD	86	98	31	76	0.88	18.5	-110	-100	-90	-110	-70	----	210	180	20	10
Temper @ 1250 °F	A4BF	81	91	28	81	0.89	13.5	-135	-125	-120	-130	-125	----	240	195	185	60
A6 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.064	1.01	0.013	0.003	0.23	1.02	0.74	0.50	0.24	0.056	0.015	0.020			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	A6AB	105	118	26	74	0.89	24.0	-140	-125	-115	-130	30	----	125	110	90	40
Temper @ 1150 °F	A6AD	99	109	25	75	0.91	21.0	-130	-125	-120	-120	-40	----	190	180	170	60
Temper @ 1250 °F	A6AF	96	103	26	78	0.92	17.0	-130	-125	-120	-145	-100	----	220	190	155	60
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	A6BB	98	112	24	74	0.87	21.5	-120	-100	-80	-105	40	----	130	115	65	20
Temper @ 1150 °F	A6BD	94	106	24	76	0.88	19.5	-115	-110	-105	-115	-30	----	175	150	120	10
Temper @ 1250 °F	A6BF	83	95	28	79	0.86	15.0	-150	-145	-140	-140	-100	----	210	195	175	125
A8 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.082	1.00	0.013	0.003	0.24	1.02	0.75	0.50	0.24	0.056	0.015	0.019			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	A8AB	116	129	24	70	0.90	28.0	-160	-130	-90	-140	30	----	100	85	70	40
Temper @ 1150 °F	A8AD	108	117	24	72	0.93	26.0	-130	-100	-110	-130	-50	----	150	130	90	30
Temper @ 1250 °F	A8AF	96	105	24	76	0.92	17.5	-150	-145	-140	-155	-90	----	200	180	150	130
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	A8BB	102	116	24	72	0.88	23.5	-150	-130	-100	-150	30	----	100	90	70	45
Temper @ 1150 °F	A8BD	102	115	24	73	0.89	22.5	-130	-120	-105	-130	-60	----	160	125	90	35
Temper @ 1250 °F	A8BF	95	105	27	77	0.90	19.5	-140	-135	-130	-140	-100	----	210	200	150	120

Table II - Mechanical Properties of Steel C after Varous Heat Treatments

Processing Condition Temperature, °F	Codes	Tensile Properties					Hard.	Charpy V-Notch Transition Temp., °F					Charpy V-Notch Energy ft-lb				
		Y.S. ksi	T.S ksi	EL. %	R.A %	Y.S. / T.S.	HRc	20 ft-lb	35 ft-lb	60 ft-lb	15 mils	50% FAT	0F	-40F	-80F	-120°F	-150°F
C4 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.04	1.01	0.14	0.003	0.24	0.99	2.5	0.51	0.25	0.057	0.015	0.037			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	CC4AD	110	117	25	76	0.94	23.0	<-150	<150	<150	<150	-60		140	110	95	60
Temper @ 1250 °F	CC4AF	91	107	25	77	0.85	19.3	<-150	<-150	<-150	<-150	-120		180	175	50	90
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1150F	CC4BD	98	110	27	75	0.89	21.7	<-150	<-150	<-150	<-150	-40		130	115	90	10
Temper @ 1250F	CC4BF	91	107	25	77	0.85	17.3	<-150	<-150	-140	<-150	-90		200	160	115	45
C6 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.057	1.00	0.014	0.003	0.23	0.99	2.49	0.51	0.25	0.057	0.015	0.039			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	CC6AD	118	124	25	72	0.95	25.6	<-150	<-150	-125	-150	-60		130	100	70	45
Temper @ 1250 °F	CC6AF	90	110	26	75	0.82	20.4	<-150	<-150	-150	<-150	-140		165	140	110	70
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1150 °F	CC6BD	106	116	22	74	0.91	24.4	-120	-100	-90	-120	-50		120	90	45	10
Temper @ 1250 °F	CC6BF	88	106	24	74	0.83	18.2	<-150	<-150	-140	<-150	-100		180	145	85	70
C8 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.074	1.00	0.013	0.003	0.23	0.98	2.48	0.50	0.24	0.057	0.015	0.04			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	CC8AD	123	130	24	74	0.95	27.5	<-150	<-150	-130	<-150	-100		110	85	70	50
Temper @ 1250 °F	CC8AF	99	114	25	74	0.87	22.0	<-150	<-150	<-150	<-150	-130		155	150	110	70
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1150 °F	CC8BD	118	126	24	72	0.94	26.4	<-150	<-150	-145	<-150	-120		130	110	90	55
Temper @ 1250 °F	CC8BF	93	115	26	72	0.81	21.0	<-150	<-150	<-150	<-150	<-150		145	145	135	110

Table III - Mechanical Properties of Steel F after Various Heat Treatments

Processing Condition Temperature, °F	Codes	Tensile Properties					Hard.	Charpy V-Notch Transition Temp., °F					Charpy V-Notch Energy ft-lb				
		Y.S. ksi	T.S ksi	EL. %	R.A %	Y.S./T.S.	HRc	20 ft-lb	35 ft-lb	60 ft-lb	15 mils	50% FAT	70°F	0°F	-40°F	-80°F	-120°F
F4 Steel - Longitudinal			C 0.040	Mn 1.51	P 0.010	S 0.003	Si 0.25	Cu 0.99	Ni 0.78	Cr 0.50	Mo 0.51	V 0.059	Cb 0.017	Al 0.022			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	F4AB	109	121	24	75	0.90	26.5	-65	-60	-55	-65	45	125	100	85	5	----
Temper @ 1150 °F	F4AD	111	120	24	76	0.92	25.0	-75	-70	-65	-75	30	150	125	115	5	----
Temper @ 1200 °F	F4AE	107	112	24	76	0.96	23.0	-95	-90	-85	-95	-30	----	140	130	100	5
Temper @ 1250 °F	F4AF	100	106	25	78	0.94	20.0	-140	-135	-130	-140	-65	----	185	155	80	55
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	F4BB	96	116	24	74	0.83	23.5	-75	-70	-65	-70	70	120	115	105	10	----
Temper @ 1150 °F	F4BD	97	112	24	76	0.87	23.0	-95	-90	-85	-90	5	----	130	125	100	10
Temper @ 1200 °F	F4BE	95	105	26	78	0.90	20.5	-120	-115	-110	-125	-20	----	----	140	120	20
Temper @ 1250 °F	F4BF	92	103	26	80	0.89	19.0	-135	-130	-125	-135	-85	----	180	180	125	60
F6 Steel - Longitudinal			C 0.059	Mn 1.50	P 0.011	S 0.003	Si 0.25	Cu 0.99	Ni 0.78	Cr 0.50	Mo 0.50	V 0.059	Cb 0.017	Al 0.026			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	F6AB	120	130	24	74	0.92	30.0	-130	-110	-70	-120	35	105	85	70	55	25
Temper @ 1150 °F	F6AD	125	131	24	74	0.95	29.0	-180	-160	-120	-170	-15	----	130	100	85	60
Temper @ 1200 °F	F6AE	116	120	26	75	0.97	25.5	-180	-175	-165	-180	-80	----	135	145	115	90
Temper @ 1250 °F	F6AF	109	113	26	76	0.96	23.0	-200	-195	-190	-195	-100	----	165	165	160	115
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	F6BB	114	129	22	70	0.88	26.5	-105	-90	-50	-90	80	95	75	65	40	15
Temper @ 1150 °F	F6BD	110	121	24	73	0.91	25.8.	-130	-105	-90	-115	75	125	120	110	70	25
Temper @ 1200 °F	F6BE	103	111	26	74	0.93	25.5	-130	-115	-105	-125	-50	----	135	145	105	30
Temper @ 1250 °F	F6BF	102	108	26	77	0.94	21.0	-145	-120	-85	-130	-5	----	145	115	65	35
F8 Steel - Longitudinal			C 0.081	Mn 1.49	P 0.011	S 0.003	Si 0.25	Cu 0.99	Ni 0.77	Cr 0.50	Mo 0.50	V 0.059	Cb 0.016	Al 0.025			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	F8AB	137	146	22	70	0.94	33.5	-130	-80	-5	-85	70	75	65	50	35	25
Temper @ 1150 °F	F8AD	132	138	24	68	0.96	31.0	-165	-140	-100	-145	-40	----	110	95	75	50
Temper @ 1200 °F	F8AE	120	124	24	74	0.97	27.0	-180	-170	-140	-180	-80	----	----	120	100	70
Temper @ 1250 °F	F8AF	114	118	24	74	0.97	25.0	-200	-195	-180	-200	-125	----	150	145	135	110
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	F8BB	111	134	23	68	0.83	28.0	-125	-90	-20	-115	70	80	65	50	40	25
Temper @ 1150 °F	F8BD	112	128	24	70	0.88	28.0	-145	-120	-75	-140	30	120	95	75	55	35
Temper @ 1200 °F	F8BE	107	117	24	72	0.91	26.5	-165	-150	-120	-155	-20	----	----	110	95	60
Temper @ 1250 °F	F8BF	107	115	26	76	0.93	21.0	-170	-140	-135	-165	-40	----	145	125	110	75

Table IV - Mechanical Properties of Steel H after Various Heat Treatments

Processing Condition Temperature, °F	Codes	Tensile Properties					Hard.	Charpy V-Notch Transition Temp., °F					Charpy V-Notch Energy ft-lb				
		Y.S. ksi	T.S ksi	EL. %	R.A %	Y.S./T.S.	HRc	20 ft-lb	35 ft-lb	60 ft-lb	15 mils	50% FAT	70°F	0°F	-40°F	-80°F	-120°F
H4 Steel - Longitudinal		C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al				
		0.044	1.50	0.011	0.003	0.24	1.03	2.50	0.49	0.49	0.056	0.016	0.023				
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	H4AD	128	133	24	75	0.96	28.5	-155	-140	-115	-140	-40	----	145	125	90	55
Temper @ 1200 °F	H4AE	120	124	24	74	0.97	27.5	-155	-150	-145	-155	-85	----	----	140	115	100
Temper @ 1250 °F	H4AF	96	119	25	78	0.81	24.0	<-200	<-200	<-200	<-200	-145	----	185	190	180	160
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1150 °F	H4BD	122	130	24	76	0.94	28.0	<-200	<-200	<-170	<-200	-45	----	180	140	120	100
Temper @ 1200 °F	H4BE	116	121	24	76	0.95	26.0	-200	-195	-190	-200	-100	----	----	155	150	120
Temper @ 1250 °F	H4BF	95	118	25	77	0.81	23.0	<-200	<-200	<-200	<-200	-175	----	210	210	200	185
H6 Steel - Longitudinal		C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al				
		0.061	1.51	0.012	0.003	0.24	1.04	2.50	0.49	0.49	0.056	0.016	0.023				
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	H6AD	131	137	23	73	0.96	30.5	-170	-140	-120	-150	-15	----	120	105	80	55
Temper @ 1200 °F	H6AE	121	126	24	73	0.96	27.5	<-200	-150	-135	-60	-60	----		130	110	75
Temper @ 1250 °F	H6AF	100	123	25	74	0.81	25.0	<-200	-190	-160	<-200	-135	----	190	185	165	140
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1150 °F	H6BD	130	137	24	73	0.95	30.5	-170	-150	-120	-140	-70	----	144	115	95	60
Temper @ 1200 °F	H6BE	120	126	24	72	0.96	27.5	<-200	-175	-150	-180	-80	----		150	125	85
Temper @ 1250 °F	H6BF	99	123	26	74	0.81	25.0	<-200	<-200	<-200	<-200	-180	----	190	185	175	150
H8 Steel - Longitudinal		C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al				
		0.080	1.50	0.011	0.003	0.24	1.03	2.53	0.49	0.49	0.056	0.016	0.022				
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	H8AD	138	142	23	70	0.97	32.0	-190	-150	-90	-170	-40	----	90	80	65	50
Temper @ 1200 °F	H8AE	127	134	24	69	0.95	29.0	-190	-150	-130	-185	-100	----	120	100	85	65
Temper @ 1250 °F	H8AF	104	129	24	69	0.80	27.0	<-200	-200	-150	<-200	-100	----	135	130	115	80
Prod. Quench of 3-inch Plate (9 °F/sec.) .)																	
Temper @ 1150 °F	H8BD	136	143	24	69	0.95	32.0	-160	-140	-100	-140	-20	110	90	80	65	50
Temper @ 1200 °F	H8BE	130	135	23	70	0.96	30.0	-190	-160	-130	<-200	-70	----	125	115	100	70
Temper @ 1250 °F	H8BF	104	130	24	69	0.80	26.5	<-200	<-200	-170	<-200	-140	----	140	135	120	100

Table V - Comparison of Low- (0,75%) and High-(2.5%) Nickel Steels with 0.06% Carbon

	Steel A	Steel C	Steel F	Steel H
Yield Strength, ksi				
WQ + 1150F	99	118	125	131
WQ + 1200F			116	121
PC + 1150F	94	106	110	130
PQ + 1200F			103	120
Tensile Strength, ksi				
WQ + 1150F	109	124	131	137
WQ + 1200F			120	126
PQ + 1150F	106	116	121	137
PQ + 1200F			111	126
Charpy Transition, F				
35 ft-lb - WQ+ 1150F	-125	<-150	-160	-140
WQ+ 1200F			-175	-150
PQ+ 1150F	-110	-100	-105	-150
PQ+ 1200F			-115	-175
60 ft-lb - WQ+ 1150F	-120	-125	-120	-120
WQ+ 1200F			-165	-135
PQ+ 1150F	-105	-90	-90	-120
PQ+ 1200F			-105	-150
50%FF - WQ+1150F	-40	-60	-15	-15
WQ+ 1200F			-80	-60
PQ+ 1150F	-30	-50	75	-70
PQ+ 1200F			-50	-80