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EVALUATION OF A PRODUCTION HEAT OF AN IMPROVED Cu-Ni 70W/100W STEEL

by

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Distinguished Research Fellows

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Evaluation of a Production Heat of an Improved Cu-Ni HPS 70W/100W Steel

ABSTRACT

On the basis of extensive laboratory studies, ATLSS recommended a Cu-Ni steel with significantly improved properties for 100W infrastructure applications, such as bridges. To confirm these results, a 165-ton full-scale heat of the recommended composition was electric-furnace melted, bottom-poured into ingots, and converted to plates from ¼ to 2-½ inches thick and 10-inch-diameter seamless tubes. The products were evaluated for 100W applications by quenching and temper-aging and for 70W applications by interrupted-accelerated cooling, control-rolling, or normalizing. The processed materials were characterized by hardenability, tensile, notch-toughness, and weldability tests.

The investigation of the electric-furnace-melted 165-ton heat of a Cu-Ni steel developed by ATLSS as a 100W infrastructure steel may be summarized as follows:

1. The characteristics of the production heat replicate quite faithfully those observed in the 100-pound heat initially studied in the laboratory.

2. Especially useful is the ability of the steel to retain excellent notch toughness over a wide range of plate thicknesses and heat-treatment parameters.

3. The minimum yield strength of 100 ksi required to meet the 100W grade-specification was attained in plates through 2-1/2 inches thick. For the thick plate, an increase in the manganese content to 1.25 percent would provide a larger margin of safety in strength.

4. The implant test confirmed the excellent weldability of the Cu-Ni steel composition, which will permit fabrication with little or no preheating.

5. Adapting this steel composition to 70W-grade applications by means of less costly mill processes, such as interrupted-accelerated-cooling, is feasible.

6. No advantage was observed in using controlled-rolling to obtain the desired properties in this Cu-Ni steel without further processing.

The production material is being evaluated in a number of prototype bridge components in a series of projects also sponsored by FHWA and PITA.

INTRODUCTION

Copper-Nickel (Cu-Ni) structural steels are treated as a separate class of steels for both civilian (ASTM A710) and military (HSLA 80 and 100) applications because of their ability to be strengthened by the precipitation of epsilon copper, which may increase the yield strength by as much as 20 ksi (140 MPa). Consequently, yield strengths of 70 to 130 ksi (485 to 900 MPa) can be obtained at carbon contents of 0.03 to 0.08 percent, far below the usual range for structural steels. This significant reduction in carbon content results in much better fracture toughness and weldability than that of conventional transformation-strengthened structural steels Details of the characteristics of these Cu-Ni steels are contained in several ATLSS investigations[1 to 6]*, which resulted in the development of an optimized composition for a 70W/100W infrastructure bridge steel. Consequently, a 165-ton heat of this composition was melted and evaluated in various product forms by ATLSS and cooperating steel companies, Bethlehem/Lukens Plate and U.S.Steel. The project was funded by the Federal Highway Administration and by the Pennsylvania Infrastructure Technology Alliance. The project was managed by ATLSS with technical oversight by the Steel Advisory Group (SAG) of the AISI High Performance Steel Steering Group.

EXPERIMENTAL PROCEDURE

Melting and Rolling

The 165-ton heat was melted by the Coatesville plant of Bethlehem/Lukens Plate to the aim composition shown in Table I. Also shown are the ladle analysis and plate check analyses. The ladle of steel was calcium-treated and degassed. It was teemed (bottom-poured) into ingot molds, stripped, slabbed, and shipped for further processing as also shown in Table I.

Processing to Plates and Tubes

A. At Homer Research Lab - The 10"x10" blooms were heated, rolled on the Laboratory mill, and quenched to determine the best combination of deformation and quenching temperature to optimize the interrupted-accelerated-cooling practice with respect to strength and toughness. This practice was then used at Burns Harbor.

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*See References

B. At Burns Harbor - The four 10"x76"x100" slabs were heated to 2365F (1300C), rolled on the roughing mill, and finish-rolled on the 160-inch mill, followed by interrupted-accelerated cooling (IAC) in accordance with the following practice:

Gauge,	Passes	Start Roll	Finish Roll	Start Cooling	Finish Cooling
1"	17	1789F(976C)	1601F(872C)	1468F(798C)	955F(513C)
2"	15	1818F(992C)	1653F(900C)	1610F(877C)	955F(513C)

Plate-width samples, two-feet long in the rolling direction, were removed from the 1-and 2-inch IAC plates and the mechanical properties determined. The remaining plates were austenitized at 1650F (900C), aged at 1150F (620C), and the mechanical properties determined.

C. At Gary - The 10"x76"x43" slab was heated to 2300F (1260C) and control-rolled to 1-inch plate with a finishing temperature of 1650F (900C). The 10"x76"x82" slab was heated to 2300F (1260C) and control-rolled to 2-inch plate with a finishing temperature of 1650F (900C). Plate-width samples, one-foot long in the rolling direction, were removed from the as-rolled plates and shipped to ATLSS, where they were normalized and tested. The remaining plates were austenitized at 1650F (900C), spray-quenched, and aged at 1150F (620C), and the mechanical properties determined.

D. At Coatesville:

1. The 62-inch x 28-inch ingot No. 6 was heated to 2300F (1260C) and direct-rolled to a plate, 1-1/2"x84"x600". The plate was cut into two 300-inch-long plates, which were austenitized at 1650F (900C), spray-quenched, and aged at 1150F (620C).

2. The 9"x82"x71" 4C slab from ingot No. 4 was heated to 2300F (1260C) and rolled to a 2-1/2"x80"x200" plate. The plate was austenitized three times at 1650F (900C), spray-quenched after each austenitizing, and aged at 1100F (595C).

E. At Conshohocken:

1. A 9"x82"x100" slab from ingot No. 8 was heated to 2300F (1260C) and rolled on the Steckel Mill to five 1/4-inch plates 80"x600", which were austenitized at 1650F (900C), spray-quenched, and aged at 1150F (620C).

2. A 10"x75"x100" slab from ingot No. 5 was heated to 2300F (1260C) and rolled on the Steckel Mill to four 3/8-inch plates 96"x600", which were austenitized at 1650F (900C), spray-quenched, and aged at 1150F (620C).

3. A 9"x82"x63" slab from ingot No. 4 was heated to 2300F (1260C) and rolled to a 3/4-inch plate 81"x685", which was cut into a plate 433" long and a second plate 252" long. The plates were austenitized at 1650F (900C), spray-quenched, and aged at 1150F (620C).

F. At Fairfield – Three slabs 12"x12"x112" from ingot No. 7 were machined to 11-1/2-inch rounds, heated to 2330F (1275C), pierced and rolled to six seamless tubes, 0.30" wall x 9-7/8" diameter x 564" long. The tubes were heated to 1650F (900C), externally spray-quenched, and aged at 1150F (620C).

Jominy-End-Quench-Hardenability Testing

Six Jominy-end-quench-hardenability test specimens were machined from a 1-inch-thick production-heat plate and tested in accordance with ASTM A255 (austenitized at 1650F (900C). Four of the Jominy bars were then aged at 950, 1050, 1150, or 1250F (510, 565, 620, or 675C) respectively, and the hardness tests repeated after regrinding the hardness-test faces.

The hardness test surface of one of the as-quenched Jominy bars was polished and etched, and micrographs were recorded at distances of 1/, 6/, 11/, 14/, 17/, and 32/16-inch from the quenched end of the bar.

Mechanical-Property Testing

Longitudinal tensile-tests and Charpy V-notch tests of the appropriate size and location were machined from production-heat plates of each thickness.

Weldability Testing

Implant tests were conducted on the production heat in accordance with IIW guidelines ("Cold Cracking Test Methods Using Implants", IIW Document 802-84,1984)

RESULTS AND DISCUSSION

Jominy End-Quench-Hardenability Tests

The response of the production heat to the quenching and aging treatments imposed on the Jominy test specimens is shown in Figure 1. The results were as expected with the plots of hardness vs distance from the quenched end closely replicating those obtained on the original 100-pound laboratory heat, Figure 2 (Heat B6 in ATLSS Report No. 98-02). Comparison of the figures confirms the replication, and thus the consistency of the hardenability and aging behavior between production and laboratory heats. Only the curves for 1250F (675C) aging display some disagreement.

The small changes in hardness as the aging temperature is raised from 950F (510C) to1150F (620C) are explained by the opposing effects of overaging of the copper precipitation and the secondary hardening of the vanadium and molybdenum carbides. The small loss of hardness at 1150F (620C) compared with 950 or 1050F (510 or 565C) is more than balanced by the gain in notch toughness, as shown later.

The micrographs of the as-quenched Jominy bar, Figure 3, essentially replicate those shown for B6 steel in Figure A9 of Reference 2.

Mechanical Properties of Quenched and Temper-Aged Plates

Plates 1/4- to 1-inch Thickness. Table II contains the results of tensile tests and Charpy V-notch tests on all the plate thicknesses produced in the quenched and aged condition. It is evident that the plates from 1/4 to 1 inch in thickness readily met the 100-ksi minimum yield strength with notch toughness values far above those needed for bridges and infrastructure. Note that Charpy values exceeding 100 foot-pounds are exhibited at –120F (-85C).

Plates 1-1/2- to 2-1/2-inch Thickness. The plates in this thickness range that were production quenched and aged met the 100-ksi minimum yield strength for a 100W grade with a relatively small margin. However, the Charpy test values for 1-1/2- and 2-inch plates remained well above 100 foot-pounds at temperatures down to –80F (-60C).

A scan of Table II supports the choice of 1150F (620C) as the optimum aging temperature for both strength and toughness.

In a previous laboratory study, a heat was included which matched the production heat in composition, except that the manganese content was 1.50 percent. This steel developed a yield strength of 110 ksi, when quenched at a cooling rate simulating a production-quenched 4-inch-thick plate and then aged at 1150F (620C). Increasing the manganese content to 1.25 percent would likely be beneficial to the yield-strength level of plates over 1-inch thick.

Mechanical Properties of Interrupted-Accelerated-Cooled Plates.

The possibility was recognized that the Cu-Ni steel developed for the 100W applications might also be amenable to processing to make it suitable for a 70W grade. One such process is interrupted-accelerated-cooling (IAC), in which water is sprayed onto the plate surface as it leaves the hot-rolling mill for a timed quench to a chosen temperature after which the plate is air-cooled. This cooling technique suppresses transformation of soft high-temperature microconstituents, but does not induce full hardening of the steel, as may occur with spray-quenching to room temperature.

In Table III, the response of the 1- and 2-inch-thick plates to the IAC treatment is reported. The yield strengths are higher than needed for a 70W grade but adjustment of the IAC time and temperature when the quench is interrupted would remedy that problem Further mill trials would determine the feasibility of producing a steel ranging from 70W to 100W with uniformly high notch toughness.

Mechanical Properties of Control-Rolled Plates.

Hot rolling steel to a finishing temperature close to the transformation range refines the size of the grains and increases the yield strength and notch toughness of conventional carbon-hardened steels. A trial was undertaken to learn the effects of controlled rolling as a means of by-passing the expense of subsequent heat treatment. Both 1- and 2-inch plates were tested.

The results of the controlled rolling are shown in Table IV, including data from added heat treatments to compare with as-control-rolled plates. The yield strengths conferred by controlled rolling were too low to meet the 70W requirements but notch toughness was higher than that obtained by a normalizing treatment. Aging at 1150F (620C) after controlled-rolling benefitted both yield strenth and Charpy notch toughness.

Implant Weldability Tests.

The results of the implant weldability test series are shown in Figure 4. The threshold of hydrogen-induced delayed cracking was found to be 97 ksi, just short of the minimum-yield-strength specification. The delayed failures progressed through weld metal rather than base-metal heat-affected zone. Cracks likely originated at the thread root coinciding with the weld fusion line but propagated into the weld metal as a 45 degree angle cone.

SUMMARY AND CONCLUSIONS

The investigation of the electric-furnace-melted 165-ton heat of a Cu-Ni steel developed by ATLSS as a 100W infrastructure steel may be summarized as follows:

1. The characteristics of the production heat replicate quite faithfully those observed in the 100-pound heat initially studied in the laboratory.

2. Especially useful is the ability of the steel to retain excellent notch toughness over a wide range of plate thicknesses and heat-treatment parameters.

3. The minimum yield strength of 100 ksi required to meet the 100W grade-specification was attained in plates through 2-1/2 inches thick. For the thick plate, an increase in the manganese content to 1.25 percent would provide a larger margin of safety in strength.

4. The implant test confirmed the excellent weldability of the Cu-Ni steel composition, which will permit fabrication with little or no preheating.

5. Adapting this steel composition to 70W-grade applications by means of less costly mill processes, such as interrupted-accelerated-cooling, is feasible.

6.No advantage was observed in using controlled-rolling to obtain the desired properties in this Cu-Ni steel without further processing.

FUTURE WORK

Larger-scale fracture-toughness and weldability tests are recommended to confirm the results obtained on Charpy V-notch toughness tests and implant weldability tests. These tests would determine the effect of welding fabrication parameters such as section thickness, heat input, post-weld heat treatment, and weld-metal composition on the performance of production-heat weldments.

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Table I-Melting and Rolling of Cu-Ni Production Heat R8660

1. Chemical Composition - 165 ton electric-furnace heat No.R8660, bottom poured ingots

	C	Mn	P	S	Si	Ni	Cu	Cr	Mo	V	Cb	Al
Aim	0.060	1.00	LAP	LAP	0.25	0.75	1.00	0.50	0.50	0.060	0.020	0.030
Ladle	0.060	0.99	0.005	0.002	0.27	0.75	0.98	0.51	0.50	0.059	0.020	0.035
Ing.3*	0.057	1.00	0.005	0.003	0.27	0.74	1.00	0.51	0.49	0.059	0.022	0.033
Ing.3#	0.056	1.00	0.006	0.003	0.27	0.75	1.00	0.51	0.49	0.059	0.022	0.032
Ing.6+	0.059	0.99	0.005	0.003	0.27	0.73	-----	0.52	0.48	0.058	0.022	0.032

*1-inch and #2-inch plate from Ingot 3, and +1-1/2-inch plate from Ingot 6 were analyzed
The steel in the ladle was calcium treated (0.0012%) and vacuum degassed

2. Ingot Provisioning

Ingot No.	Size	Weight-lb	Slab No.	Size-in.	Weight-lb	Recipient
1	82x34	59,000	1A	10x75x115	24,562	Burns Harbor
			1B	10x75x144	30,600	" "
2	82x34	50,000	2A	10x75x110	24,000	Burns Harbor
			2B	10x75x141	29,900	" "
3	62x28	32,400	3A	10x75x53	10,500	Gary Works
			3B	10x75x91	19,500	" "
4	62x28	32,400	4A	9x82x63	12,860	Conshohocken
			4B	9x40x22	2,290	Homer Research
			4C	9x82x71	13,568	Coatesville
5	62x28	25,492	5A	10x75x100	21,300	Conshohocken
6	62x28	25,492		Direct Rolled to1-1/2x84x600	21,875	Coatesville
7.	54x23	22,900	7	12x48x149	24,830	Fairfield Works
8	54x23	22,900	8	9x82x100	21,100	Conshohocken

3. Disposition of Slabs

	Facility	Heat Treatment	Product Sizes	# of Pcs.	# of Slabs	Slab Sizes
A	HRL*	IAC &Aged	Various	4	4	10" x 10" x 22"
B	BH*	IAC/Q&T	1" x 96" x 660"	2	2	10" x 76" x 100"
			2" x 96" x 480"	2	2	10" x 76" x 130"
C	Gary*	Q&T	1" x 96" x 240"	1	1	10" x 76" x 43"
			2" x 96" x 240"	1	1	10" x 76" x 82"
D	CV/CN*	Q&T	1/4" x 80" x 600"	5	1	9" x 82" x 100"
			3/8" x 96" x 600"	4	1	10"x 75" x 100"
			3/4" x 81" x 433"	1	1	9"x 82" x 63"
			3/4" x 81" x 252"	1		
			1-1/2"x 84" x 600"	1	0	Rolled Direct
			2-1/2" x 80" x 200"	1	1	9" x 82" x 71"
E	Fairfield	Q&T	9-7/8" dia. x 0.30" thick x 564" **	6	3	12" x 12" x 112"

*HRL-Homer Research, BH-Burns Harbor, Gary Works, CV/CN-Coatesville or Conshohocken, ** Fairfield Works

Table II - Mechanial Properties of the Quenched and Tempered Plates and Tubes

Plate Thickness	Heat Treatment	Yield Str - ksi	Tensile Str - ksi	Charpy V-notch Toughness, ft-lb @					
				0F	-10F	-30F	-40F	-80F	-120F
1/4 inch				Charpy bars were 1/2 width					
	Mill Q 1650F, TA 1150F	120	125	—	75	74	—	—	—
3/8 inch				Charpy bars were 3/4 width					
	Mill Q 1650F , TA 1150F	116	122	—	137	134	—	—	—
	Mill Q 1650F , Lab TA 1100F	112	120	156	—	—	149	128	113
	Mill Q 1650F , Lab TA 1150F	115	120	180	—	—	166	168	120
	Mill Q 1650F , Lab TA 1200F	107	112	174	—	—	172	182	146
3/4 inch									
	Mill Q 1650F , TA 1150F	112	120	—	176	168	—	—	—
	Mill Q 1650F , Lab TA 1150F	106	114	180	—	—	145	130	110
1 inch									
Plate	Mill Q 1650F , TA 1150F	109	119	—	170	154	—	—	—
400054	Mill Q 1650F , Lab TA 1050F	114	126	135	—	—	124	114	63
	Mill Q 1650F , Lab TA 1150F	114	122	158	—	—	142	132	86
	Mill Q 1650F , Lab TA 1250F	103	109	196	—	—	194	164	135
400055	Mill Q 1650F , Lab TA 1150F	111	122	130	—	—	120	100	40
1-1/2 inch									
Plate 6A	Mill Q 1650F , TA 1150F	102	115	—	148	147	—	—	—
	Lab Test Check	102	112	154	—	—	145	123	55
Plate 6B	Mill Q 1650F , TA 1150F	104	115	—	161	150	—	—	—
	Lab Test Check	100	112	177	—	—	122	130	40
2 inch									
Plate	Mill Q 1650F , TA 1100F	103	115	—	123	127	—	—	—
400057	Mill Q 1650F , Lab TA 1050F	100	116	130	—	—	112	92	15
	Mill Q 1650F , Lab TA 1150F	105	115	170	—	—	132	134	95
	Mill Q 1650F , Lab TA 1250F	96	103	208	—	—	150	158	122
400056	Mill Q 1650F , Lab TA 1100F	102	114	145	—	—	100	80	15
2-1/2 inch									
	Mill Q 1650F , TA 1100F-Head	102	116	—	132	122	—	—	—
	Mill Q 1650F , TA 1100F-Tail	101	116	—	117	118	—	—	—
Tubes				Charpy bars were 2/3 width					
	Mill Q 1650F, TA 1150F	115	124	—	40	—	—	—	—
	Lab Test Check	111	118	75	—	—	58	50	46

Table III - Mechanical Properties of Interrupted-Accelerated-Cooled Production-Heat R8660 Plates

One -Inch-Thick Plate

Heat Treatment	Yield Str - ksi	Tensile Str - ksi	Charpy V-notch Toughness, ft-lb @					
			0F	-10F	-30F	-40F	-80F	-120F
Mill IAC Quench 1468F to 955F	90	106	—	120	110	—	—	—
ATLSS Test Check	78	112	190	—	—	160	80	15
ATLSS Age 1050F	98	123	125	—	—	110	40	15
ATLSS Age 1150F	102	121	150	—	—	140	50	15
ATLSS Age 1250F	100	114	180	—	—	140	75	25

Two-Inch-Thick Plate

Mill IAC Quench 1610F to 955F	104	115	—	130	100	—	—	—
ATLSS Test Check	89	111	177	—	—	83	50	17
ATLSS Age 1050F	101	126	65	—	—	31	15	—
ATLSS Age 1150F	103	121	80	—	—	65	40	15
ATLSS Age 1250F	97	110	192	—	—	112	83	21

Table IV - Mechanical Properties of Control-Rolled Production Heat R8660 Plates

One-Inch Plate

Control-Rolled	62	100	140	—	—	95	60	30
Control-Rolled + Age 1150F	88	106	135	—	—	125	50	25
Control-Rolled + Norm.1650F	61	101	80	—	—	45	25	—
Control-Rolled + Norm. + Age	81	102	200	—	—	150	110	35

Two-Inch Plate

Control-Rolled	66	102	90	—	—	50	25	—
Control-Rolled + Age 1150F	87	108	210	—	—	130	110	15
Control-Rolled + Norm. 1650F	52	94	20	—	—	5	—	—
Control-Rolled + Norm. + Age	72	95	55	—	—	30	—	—

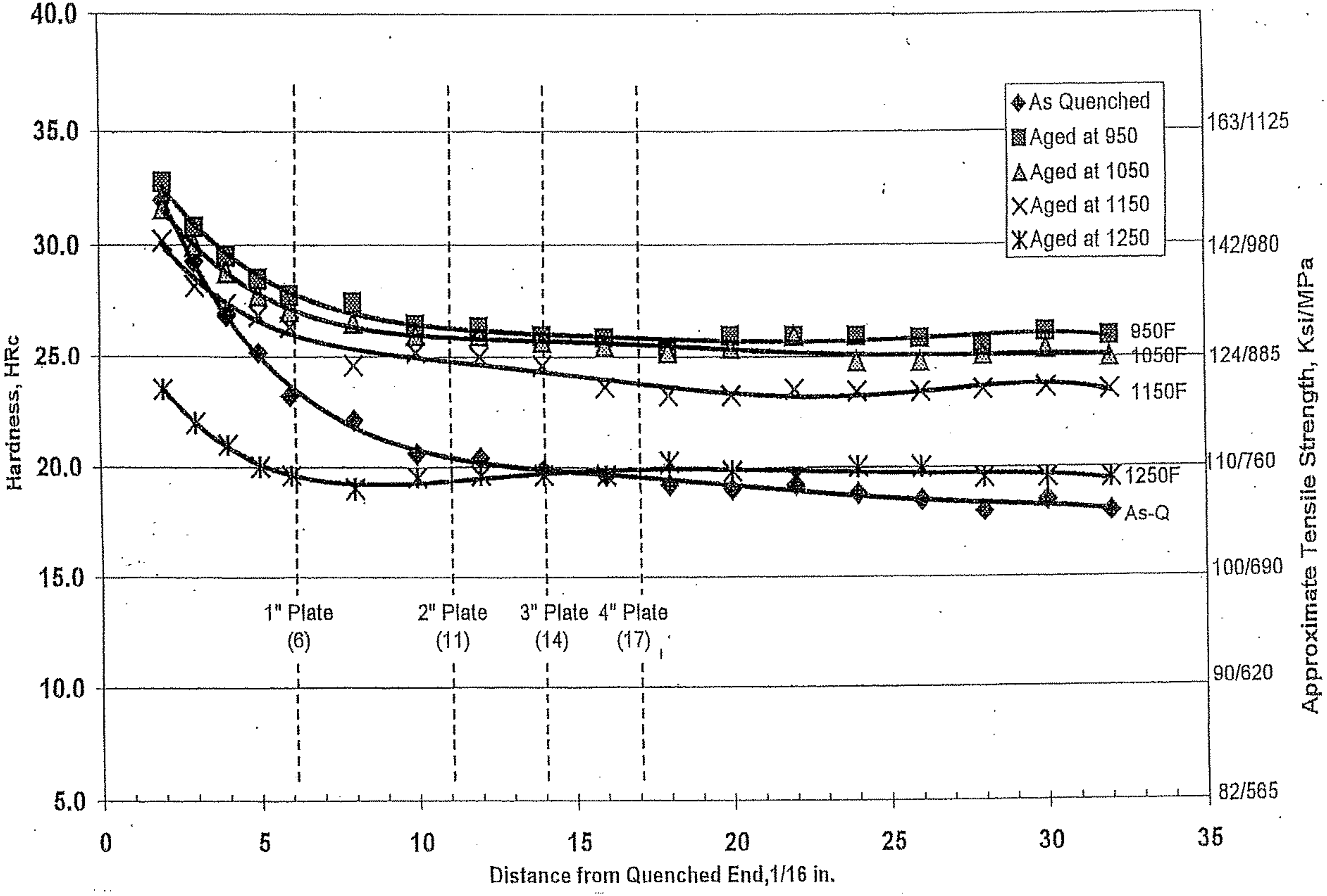


Figure 1 - Averaged Jominy End-Quenched Hardenability Results for Production Heat R8660

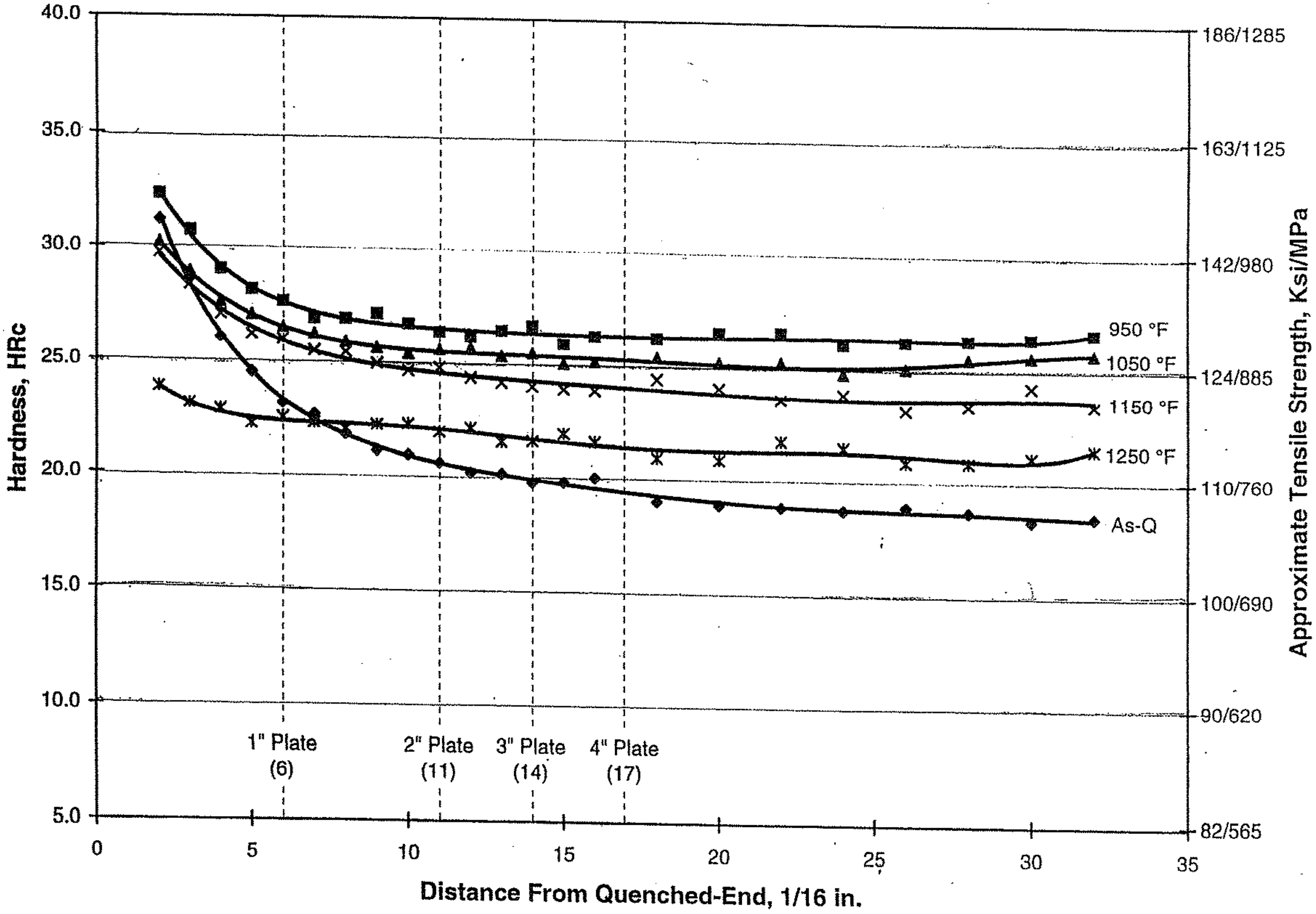
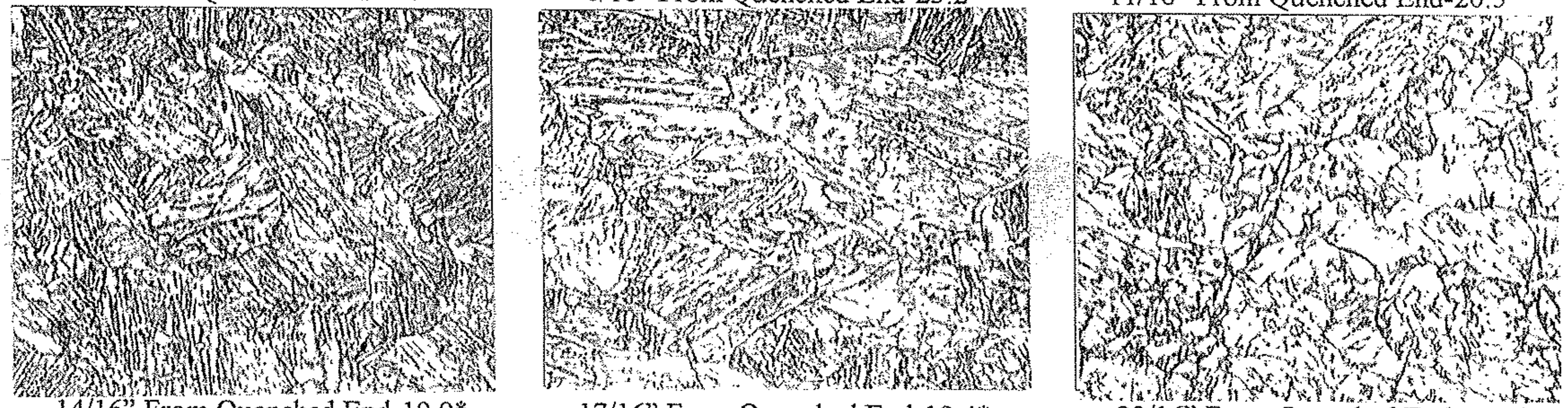


Figure 2 – Averaged Jominy End-Quenched Hardenability Results for Steel B6

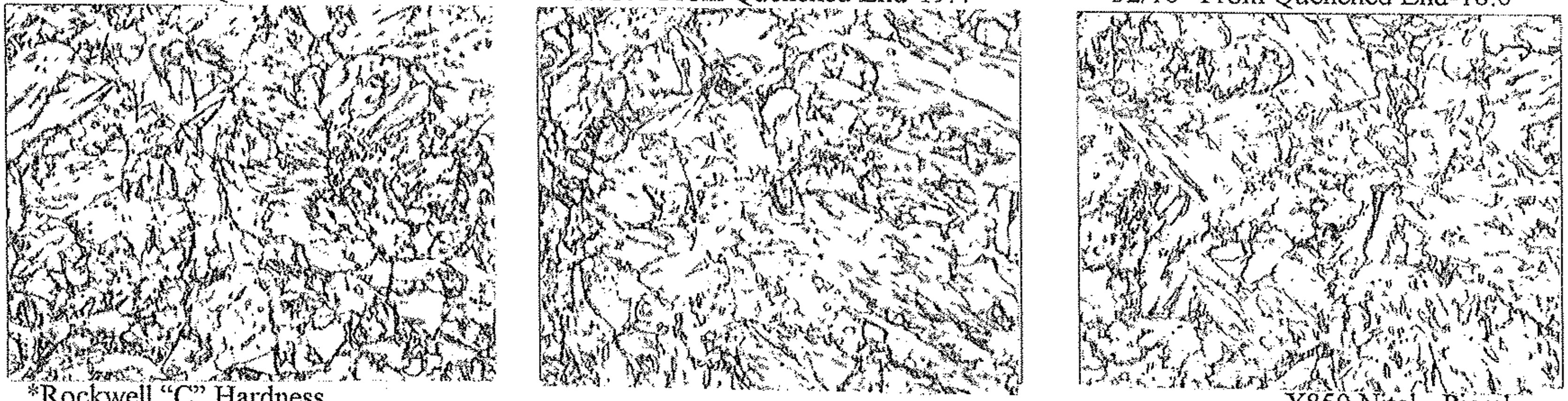
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.060	0.99	0.005	0.002	0.27	0.98	0.75	0.51	0.50	0.059	0.020	0.035



2/16" From Quenched End-32.0*

6/16" From Quenched End-23.2*

11/16" From Quenched End-20.5*



14/16" From Quenched End-19.9*

17/16" From Quenched End-19.4*

32/16" From Quenched End-18.0*

*Rockwell "C" Hardness

X850 Nital - Picral

Figure 3 – Jominy Test Microstructures – As-quenched – Production Heat R8660

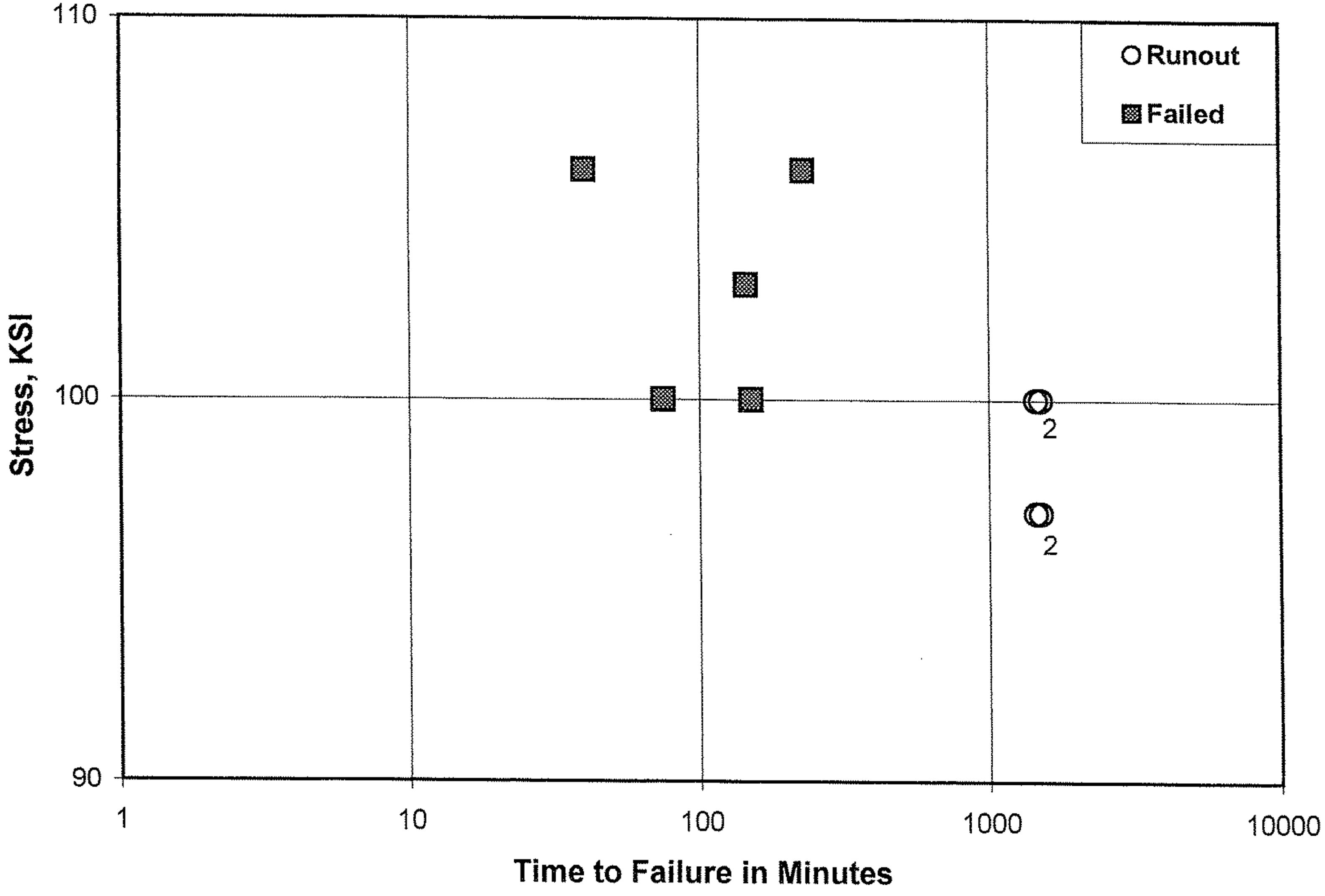


Figure 4 - Implant Test Results for Production Heat R8660