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ATLSS Report No. 99-07

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DEVELOPMENT OF AN IMPROVED HPS 70W STEEL

ABSTRACT

To continue the study of composition effects in Cu-Ni steels, the present project was undertaken to determine the best composition for an improved HPS 70W steel to be produced by hot rolling and quenching and tempering . A second objective was to eliminate chromium from the composition to avoid the formation of hexavalent chromium vapors during welding.

The steel compositions studied were as follows:

Steel	C	Mn	Si	Cu	Ni	Cr	Mo	V	Cb
J1	0.047	1.00	0.25	0.99	0.73	0.005	0.005	0.06	0.014
J2	0.045	1.00	0.26	0.99	0.73	0.005	0.26	0.06	0.015
J3	0.064	1.00	0.26	1.00	0.73	0.005	0.26	0.06	0.015

Tests were conducted to evaluate the hardenability, mechanical properties, metallography, and weldability of the steels in 1-inch-thick and simulated 4-inch-thick quenched and tempered plates.

On the basis of the foregoing evaluation of the prospective 70W J1, J2, and J3 Steels, the results of the study may be summarized as follows:

1. As expected, the Jominy hardenability was progressively lowered by reducing carbon from 0.06 to 0.04%, and by eliminating chromium and molybdenum.

2. At 0.04% carbon and no chromium or molybdenum, the steel met a minimum yield strength of 70 ksi after quenching and tempering 1-inch-thick plate but not in simulated 4-inch-thick plate. With the addition of 0.25% molybdenum, the 70-ksi minimum yield strength was met in simulated 4-inch-thick plate.

3. At 0.06% carbon, 0.25% molybdenum and no chromium, the yield strength was higher than that appropriate for a 70W steel.

4. For all Steel J compositions, the Charpy V-notch energy absorption was far above that specified by AASHTO for a 70W bridge steel.

5. Implant-test results demonstrated that the Steel J compositons could be welded without preheat using a low-hydrogen process.

These results indicate that an improved HPS 70W infrastructure steel with extraordinary toughness can be produced through 4-inch-thick plate in a quenched and tempered Cu-Ni steel containing no chromium.

INTRODUCTION

On the basis of previous ATLSS studies[1,2*], the advantages in fracture toughness and weldability of 80W, 90W, and 100W copper-nickel (Cu-Ni) bridge/infrastructure steels were compared with existing 80-, 90-, or 100-ksi yield strength structural weathering steels. The advantages result from the strengthening of the Cu-Ni steels by precipitation as well as by conventional transformation to low-temperature microconstituents. This dual-strengthening permits a significant reduction in carbon content and the resultant superior toughness and weldability of the Cu-Ni steels. The chemical composition of the small-scale heats of the previously investigated Steels A, B, E, and F are listed in Table I. The study concluded that Steel B6 would be an improved HPS 100W steel, and recommended full-scale production to confirm its commercial suitability.

To continue the study of composition effects in Cu-Ni steels, the present project was undertaken to determine the best composition for an improved HPS 70W steel to be produced by hot-rolling and quenching and tempering. A second objective was the elimination of chromium from the composition to avoid the formation of hexavalent chromium vapors during welding.

EXPERIMENTAL PROCEDURE

MELTING AND ROLLING

A 300-pound (135kg) heat was vacuum-melted and poured into three 100-pound (45kg) ingots with additions to the second and third ingot to obtain the compositions identified as Steels J1, J2, and J3 in Table I. The 100-pound (45kg) ingots were charged into a reheat furnace at 2150F (1175C), rolled in five passes to 1-inch-thick plate with a finishing temperature of approximately 1750F (950C) and air cooled. The rolled plates were sectioned for processing as illustrated in Figure 1. The metallurgical characteristics of the steels are also listed in Table I.

JOMINY END-QUENCH HARDENABILITY TESTING

For Steels J1, J2, and J3, six Jominy specimens were machined from Plate-Section J (Figure 1), and tested in accordance with ASTM A255 [austenitized at 1650F (900C)]. Two opposed longitudinal flats were ground on each specimen and the hardness traverse obtained. Four of the as-quenched Jominy specimens were then tempered (aged**), one at each of the following temperature: 950F (510C), 1050F (565C), 1150F (620C), or 1250F (675C). After tempering, the flat areas were reground to remove all effects of prior hardness testing, and the hardness traverses were repeated.

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*See references

** The words tempering or aging are used to mean the same treatment

METALLOGRAPHIC EXAMINATION

One hardness-test flat on an as-quenched Jominy specimen and on a 1250F (675) tempered specimen was ground, polished, and etched sequentially with picral and nital solutions, and metallographically examined along the length of the specimen. For each of the samples , micrographs were recorded at a magnification of 850X at locations of 1-, 6-, 11-, 14-, and 17-16 inches (1.5, 10, 17, 22, and 27 mm) from the quenched end, corresponding to 1/8-, 1-, 2-, 3-, and 4-inch-thick (3, 25, 50, 75, and 100 mm) production-quenched plates, respectively, and at 32/16 inches (50 mm), corresponding approximately to 1/3-inch-thick (8 mm) normalized plate, cooled at 3 F/second (1.7 C/sec.).

HEAT TREATMENT AND MECHANICAL-PROPERTY TESTING

For each of Steels J1, J2, and J3, Plate Section A (Figure 1) was austenitized at 1650F (900C) and immersion-quenched in a mildly agitated 70F (20C) water bath [H=1.5, cooling rate of 50 F/sec (28C/sec), Figure 2] to simulate production quenching of a 1-inch-thick (25-mm) plate, Figure 3. Similarly for each of the three steels, Plate-Section B was austenitized at 1650F and immersion-quenched without agitation in a water-bath containing 4.75% polyalkalene glycol, cooling rate of 9F/sec (5C/sec), Figure 2, to simulate production quenching of a 4-inch (100-mm) plate, Figure 3. After heat-treatment, three longitudinal subsections were cut from Sections A and B as shown in Figure 4. Two of the subsections were tempered at 1150 or 1250F (620 or 675C). These treatments correspond to conventional austenitizing, quenching, and tempering.

Each subsection was machined into mechanical-test specimens as shown in Figure 4. For the present study, mechanical-property testing consisted of longitudinal tension and Charpy V-notch tests. The tension tests were 0.357-inch-diameter (9-mm) specimens centered at the quarter-thickness location and tested at room temperature. The Charpy tests were also centered at the quarter-thickness location, notched in the plate thickness direction, and tested over a range of temperatures to obtain a full transition curve.

WELDABILITY TESTING

To establish resistance to hydrogen-assisted cracking (HAC) of the heat-affected-zone (HAZ), implant tests for the three steels were machined from Plate-Section D, Figure 1, and tested in accordance with IIW guidelines. The implant test is widely accepted as a means of measuring the susceptibility of steels to HAC when welded. It has the advantage of requiring only a small amount of test material and a simple bead-on-plate weld.

In these tests, welding was performed at room temperature by the shielded-metal-arc process at 200 amps and 8 inches/ min (20 cm/min), a heat input of 35 KJ/inch (1.4 KJ/mm). This heat input was chosen to produce a relatively fast cooling rate and high hardness in the HAZ and induce HAC if the steel was susceptible.The electrode grade, E8018C3 and the loading plate, which was 1-inch-thick HSLA-80 steel, were selected to be compatible with the Cu-Ni test steels. The welded specimens were tested at levels up to and exceeding the yield stress but limited by plastic deformation and ability to maintain the load. The highest stress that could be applied without failure in 24 hours was the measure of the resistance of the steel to HAC.

RESULTS AND DISCUSSION

JOMINY END-QUENCH HARDENABILITY TESTS - AS-QUENCHED

The Jominy curves for the as-quenched J1, J2, and J3 Steels, Figure 5, show the rapidly decreasing hardness from that of martensite at 1/8 inch to that of higher-temperature-transformation microconstituents beyond 1/8 inch, characteristic of a relatively low-hardenability steel. At 0.06 percent carbon, eliminating chromium reduced the hardenability from that for Steel A6 to that for Steel J3. At 0.04 percent carbon, eliminating chromium reduced the hardenability from that for Steel A4 to that for Steel J2. When molybdenum as well as chromium was eliminated at 0.04 percent carbon, the hardenability dropped to that for Steel J1 compared with that for Steel J2. This comparison demonstrates the significant contribution of carbon, chromium, and molybdenum to hardenability.

JOMINY END-QUENCH HARDENABILITY TESTS - TEMPERED (AGED)

The effect of tempering on the Jominy hardenability for Steels J1, J2, and J3 is illustrated in Figures 6, 7, and 8, respectively. Figure 6 for Steel J1 (0.047C, no Cr or Mo) shows that precipitation strengthening markedly increased the overall level of hardness for all tempering temperatures, that precipitation strengthening decreased with increased tempering temperature due the loss of lattice coherency and increased agglomeration of the Cu-rich precipitates, and that essentially no low-temperature transformation products were formed in this very low-hardenability steel that could be softened by tempering. Similar tempering effects were observed for Steel J2 (0.045%C, no Cr, 0.26% Mo) Figure 7, except that the level of all the curves was raised by the addition of 0.26 percent molybdenum, and a further raising of the level of all the curves for Steel J3 (0.064%C, no Cr, 0.26% Mo), Figure 8, as a result of the increase in carbon content .

JOMINY END-QUENCH HARDENABILITY TESTS-METALLOGRAPHIC EXAMINATION

Micrographs of the J Steels at the previously noted distances from quenched end of the Jominy specimen are shown in Figures 9, 10, and 11 for the as-quenched condition. The figures show that martensite formed in all three Steels J1, J2, and J3 at 1-16 inch, corresponding to a cooling rate of 490F/sec (270C/sec) but that at 6/16 inch corresponding to production-quenched 1-inch plate, 50F/sec (28 C/sec), the microstructure was ferrite and bainite. At greater distances from the quenched end, the amount of ferrite increased and bainite decreased. However, when molybdenum was added (Steel J2 and J3) and carbon was increased from 0.04 to 0.06 (Steel J3), the amount of bainite increased significantly and the grain size decreased. Tempering at 1250F (675C), Figures 12, 13, and 14, resulted primarily in some agglomeration of the martensite or bainite.

MECHANICAL-PROPERTY EVALUATION - TENSILE AND TOUGHNESS DATA

The tensile and toughness data for Steels J1, J2, and J3 are listed in Table III and illustrated in Figures 15, 16, and 17, respectively. The mechanical properties for Steel J1 after quenching and tempering indicate that the desired minimum yield strength of 70 ksi (485 MPa) was achieved in the 1-inch plate but not in simulated 4-inch plate. When 0.25 percent molybdenum was added to Steel J1 to produce Steel J2, the 70 ksi (485 MPa) was readily met after tempering at 1150F (620C) and 1250F (675C). When the carbon content was increased from 0.04% for Steels J1 and J2 to 0.06 for Steel J3, the yield strength was much higher , even after the 1250F (675C) temper,than appropriate for a 70W steel.

Thus the standard Cu-Ni steel (1.00Cu and 0.75Ni) at 0.04% carbon containing 1.0% Mn and 0.25% Mo and no chromium has sufficient hardenability when quenched and tempered to be a 70W steel. Moreover, the toughness exceeds 240 ft-lb at -40. If molybdenum as well as chromium was removed from Steel J3 it would probably meet the 70 ksi yield strength at its carbon of 0.06 percent, which would be a more desirable carbon specification from the production standpoint.

WELDABILITY

The results of the implant tests on the J Steels are illustrated in Figure 18 and the resultant threshold values are listed in Table IV. On the basis of these results, all the J Steels had threshold values higher than their corresponding typical yield strengths. Thus the J Steels should be readily weldable without preheat by the the shielded metal-arc process using low-hydrogen electrodes and other processes having similarly low-hydrogen potential.

SUMMARY and CONCLUSIONS

On the basis of the foregoing evaluation of the prospective 70W Steels J1, J2, and J3, the results of the study may be summarized as follows

1. As expected, the Jominy hardenability was progressively lowered by reducing carbon from 0.06 to 0.04% and by eliminating chromium and molybdenum.

2. At 0.04 % carbon and no chromium or molybdenum, the steel met a minimum yield strength of 70 ksi after quenching and tempering 1-inch-thick plate but not in simulated 4-inch-thick plate. With the addition of 0.25% molybdenum, the 70-ksi minimum yield strength was met in simulated 4-inch-thick plate.

3. At 0.06% carbon, 0.25% molybdenum and no chromium, the yield strength was higher than that appropriate for a 70W steel.

4. For all Steel J compositions, the Charpy V-notch energy absorption was far above that specified by AASHTO for a 70W bridge steel.

5. Implant-test results demonstrated that the Steel J compositons could be welded without preheat using a low-hydrogen process.

These results indicate that an improved HPS 70W infrastructure steel with extraordinary toughness can be produced through 4-inch-thick plate in a quenched and tempered Cu-Ni steel containing no chromium.

REFERENCES

1. Dawson, H.M., Gross, J.H., and Stout, R.D., "Copper-Nickel High-Performance 70W/100W Bridge Steels - Part I", ATLSS Report No. 97-10, Lehigh University, August 1997.

2. Dawson, H.M., Gross, J.H., and Stout, R.D., " Copper-Nickel High-Performance 70W/100W Bridge Steels - Part II", ATLSS Report No. 98-02, Lehigh University, May 1998.

ACKNOWLEDGEMENTS

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The steels evaluated were melted and rolled by the U.S.Steel Technical Center, Monroeville, PA.

Table I - Chemical Composition of Steels A, B, E, F, and J

	Steel														
	A4	A6	A8	B4	B6	B8	E4	E6	E8	F4	F6	F8	J1	J2	J3
C	0.045	0.064	0.082	0.043	0.061	0.080	0.042	0.060	0.076	0.040	0.059	0.081	0.047	0.045	0.064
Mn	1.00	1.01	1.00	1.01	1.02	1.01	1.52	1.52	1.50	1.51	1.50	1.49	1.00	1.00	1.00
P	0.012	0.013	0.013	0.010	0.011	0.010	0.011	0.011	0.012	0.010	0.011	0.011	0.011	0.011	0.011
S	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Si	0.23	0.23	0.24	0.26	0.27	0.26	0.25	0.26	0.27	0.25	0.25	0.25	0.25	0.25	0.26
Cu	1.02	1.02	1.02	1.00	1.01	1.00	1.00	1.02	1.02	0.99	0.99	0.99	0.99	0.99	1.00
Ni	0.75	0.74	0.75	0.75	0.77	0.76	0.77	0.80	0.81	0.78	0.78	0.77	0.73	0.73	0.73
Cr	0.50	0.50	0.50	0.51	0.51	0.51	0.51	0.51	0.52	0.50	0.50	0.50	0.005	0.005	0.005
Mo	0.24	0.24	0.24	0.50	0.50	0.50	0.25	0.26	0.26	0.51	0.50	0.50	0.005	0.26	0.26
V	0.057	0.056	0.056	0.054	0.054	0.054	0.059	0.057	0.056	0.059	0.059	0.059	0.058	0.058	0.060
Cb	0.015	0.015	0.015	0.018	0.017	0.018	0.016	0.016	0.016	0.017	0.017	0.016	0.014	0.015	0.015
Al(total)	0.022	0.020	0.019	0.024	0.015	0.012	0.025	0.021	0.019	0.022	0.026	0.025	0.029	0.026	0.024
	Calculated Metallurgical Characteristics														
D_I - ASTM	0.85	1.20	1.56	1.00	1.60	2.20	1.10	1.70	2.30	1.5	2.3	3.2	0.24	0.41	0.62
A_{e1}, F	1325	1325	1325	1320	1320	1320	1305	1305	1305	1305	1305	1305	1305	1305	1305
A_{e3}, F	1560	1540	1525	1565	1545	1530	1540	1525	1510	1540	1530	1510	1565	1565	1550
B_s, F	1195	1185	1175	1260	1240	1230	1210	1200	1190	1180	1170	1150			
M_s, F	900	885	860	895	875	855	895	875	860	890	875	850	910	905	890
C.E. (IIW)	0.53	0.55	0.57	0.54	0.56	0.58	0.57	0.59	0.61	0.62	0.64	0.66	0.38	0.43	0.45

A_{e1}, F = 1333 - 25 x %Mn - 26 x %Ni + 40 x %Si +42 x %Cr

A_{e3}, F = 1670 - (876C - 772C^2) - 45Mn - 36Cu - 40Ni - 20Cr + 108Si +1260P +450Al

B_s, F = 1625 - 485 x %C - 150 x %Mn - 65 x %Ni - 125 x %Cr - 150 x %Mo

M_s, F = 955 - 815 x %C - 31 x %Ni + 27 x %Cr - 17 x %Mo + 390 x %C^2
- 129 (%C x %Mn) - 122 (%C x %Cr)

Extrapolated Martensitic Hardness, HRc*

%C	95% Martensite	99.9% Martensite
0.04	30.0	35.0
0.06	31.2	36.2
0.08	32.5	37.5
0.10	33.8	38.7

*Extrapolated from U.S Steel Carilloy Steels Handbook

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
J1 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.047	1.00	0.011	0.003	0.25	0.99	0.73	0.005	0.005	0.058	0.014	0.029			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	J1AD	75	85	32	82	0.88	10.0	-110	-110	-110	-110	-110	----	240	240	240	15
Temper @ 1250 °F	J1AF	71	81	34	82	0.88	6.0	-140	-140	-140	-140	-140	----	240	240	240	240
Prod. Quench of 4-inch Plate (9 °F/sec.)																	
Temper @ 1150 °F	J1BD	68	79	34	83	0.86	6.0	-110	-110	-110	-110	-110	----	240	240	240	20
Temper @ 1250 °F	J1BF	64	74	37	84	0.86	3.5	-140	-140	-140	-140	-140	----	240	240	240	240
J2 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.045	1.00	0.011	0.003	0.25	0.99	0.73	0.005	0.26	0.058	0.015	0.026			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	J2AD	90	99	31	80	0.91	18.0	-120	-120	-120	-120	-100	----	240	240	240	215
Temper @ 1250 °F	J2AF	82	91	32	82	0.9	18.0	-150	-145	-140	-150	-130	----	----	240	240	240
Prod. Quench of 4-inch Plate (9 °F/sec.)																	
Temper @ 1150 °F	J2BD	80	91	29	81	0.88	13.0	-120	-120	-120	-120	-120	----	240	240	240	125
Temper @ 1250 °F	J2BF	75	86	32	82	0.88	12.0	-150	-150	-145	-150	-130	----	----	240	240	240
J3 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.064	1.00	0.011	0.003	0.26	1.00	0.73	0.005	0.26	0.060	0.015	0.024			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	J3AD	98	106	28	78	0.92	18.5	-145	-140	-125	-145	-125	----	----	240	240	135
Temper @ 1250 °F	J3AF	88	96	28	80	0.92	14.0	-160	-140	-130	-160	-80	----	----	240	200	90
Prod. Quench of 4-inch Plate (9 °F/sec.)																	
Temper @ 1150 °F	J3BD	84	95	28	78	0.88	15.5	-145	-140	-130	-145	-120	----	----	240	240	50
Temper @ 1250 °F	J3BF	79	89	27	81	0.89	12.0	-135	-130	-130	-135	----	----	----	240	240	240

Table II - Mechanical Properties for 1-Inch-Thick Plates of J Steels after Various Heat Treatments (Longitudinal)

Table III Implant Weldability Test Results

Steel	Yield Strength, ksi	Failure Threshold Stress, ksi
J1	71	87
J2	82	100
J3	88	95

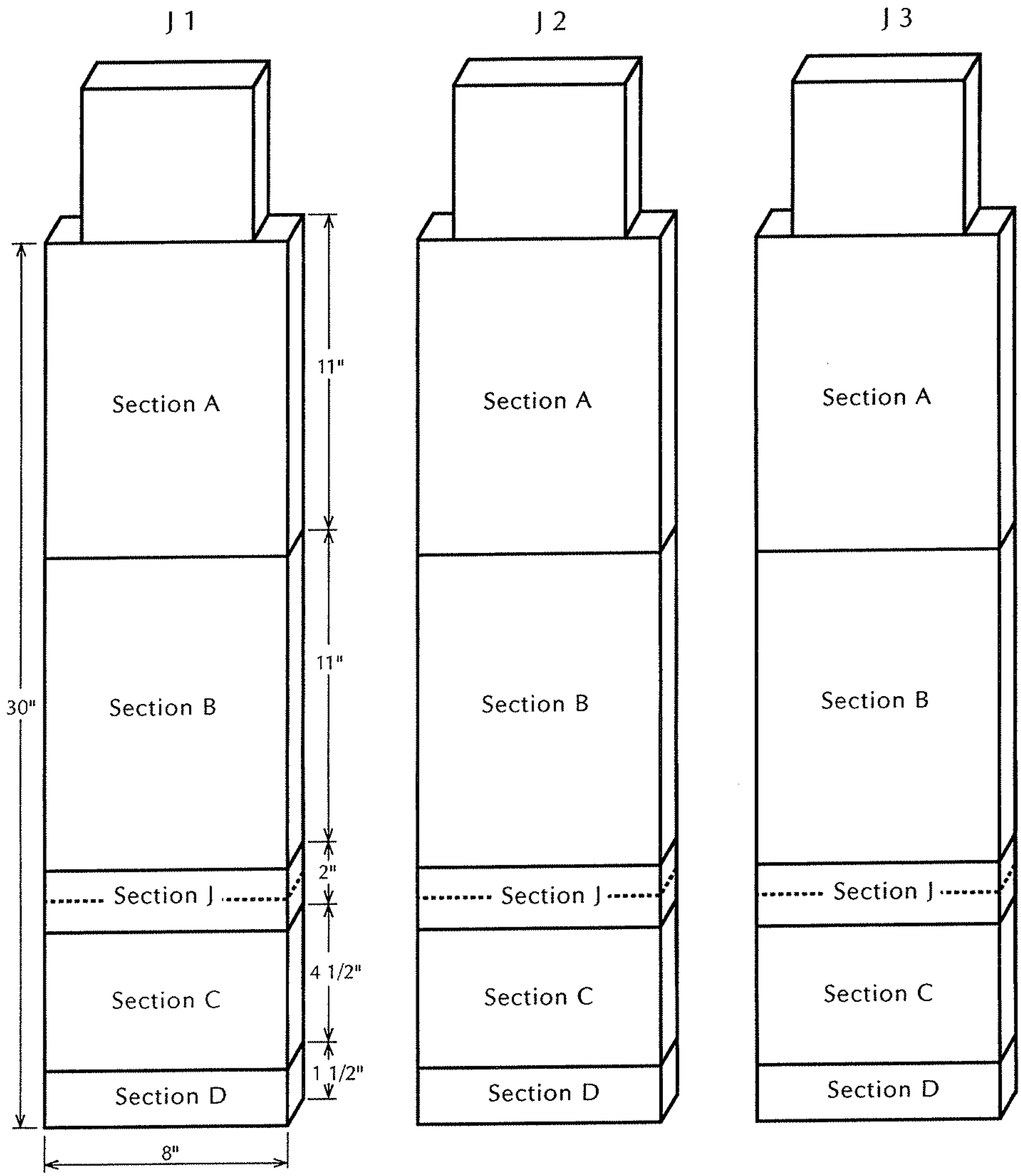

Figure 1 - Sectioning of 100-Pound-Ingot Plates

97-F002

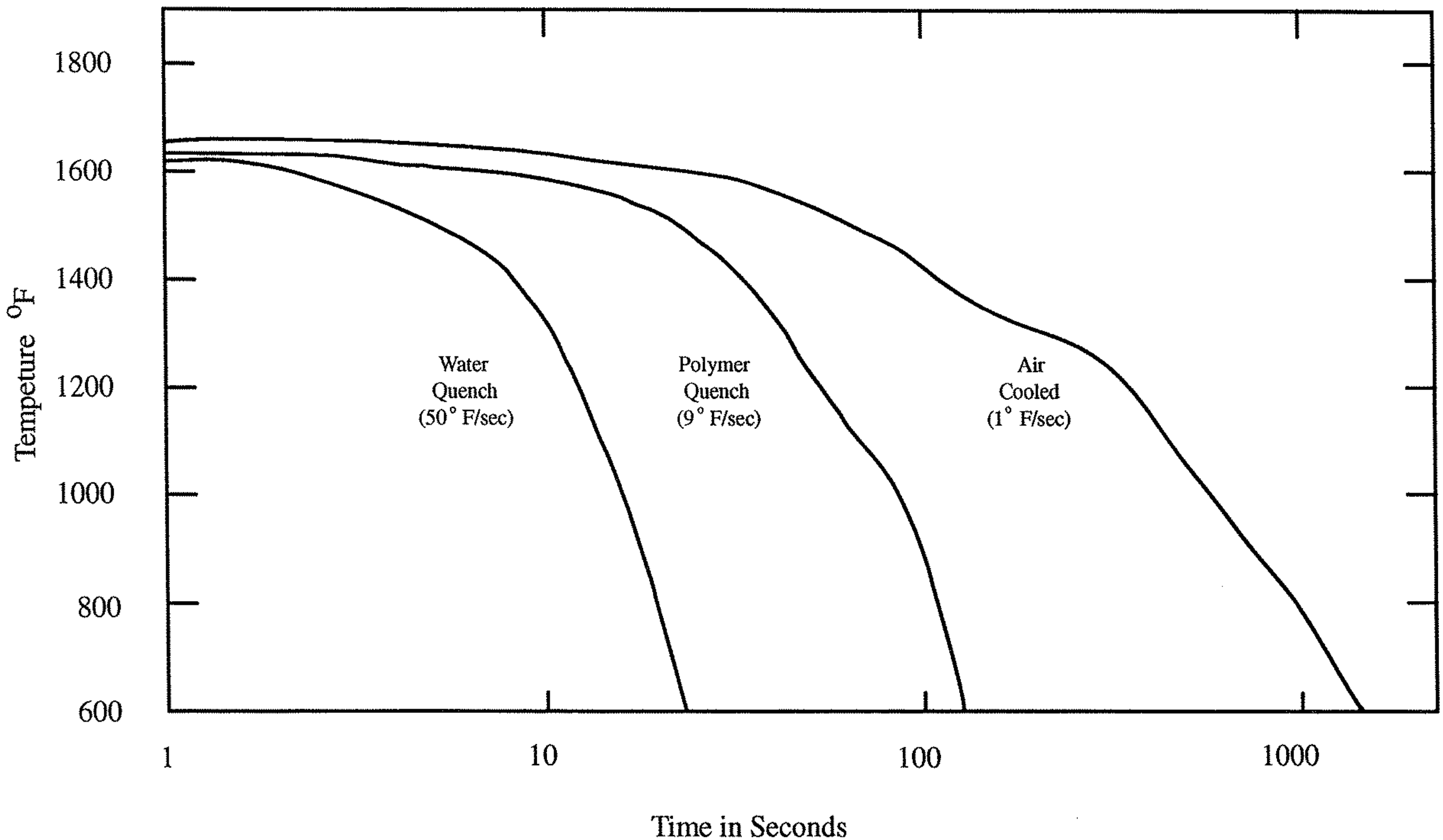

Figure 2 - Cooling Curves for One - Inch Plate

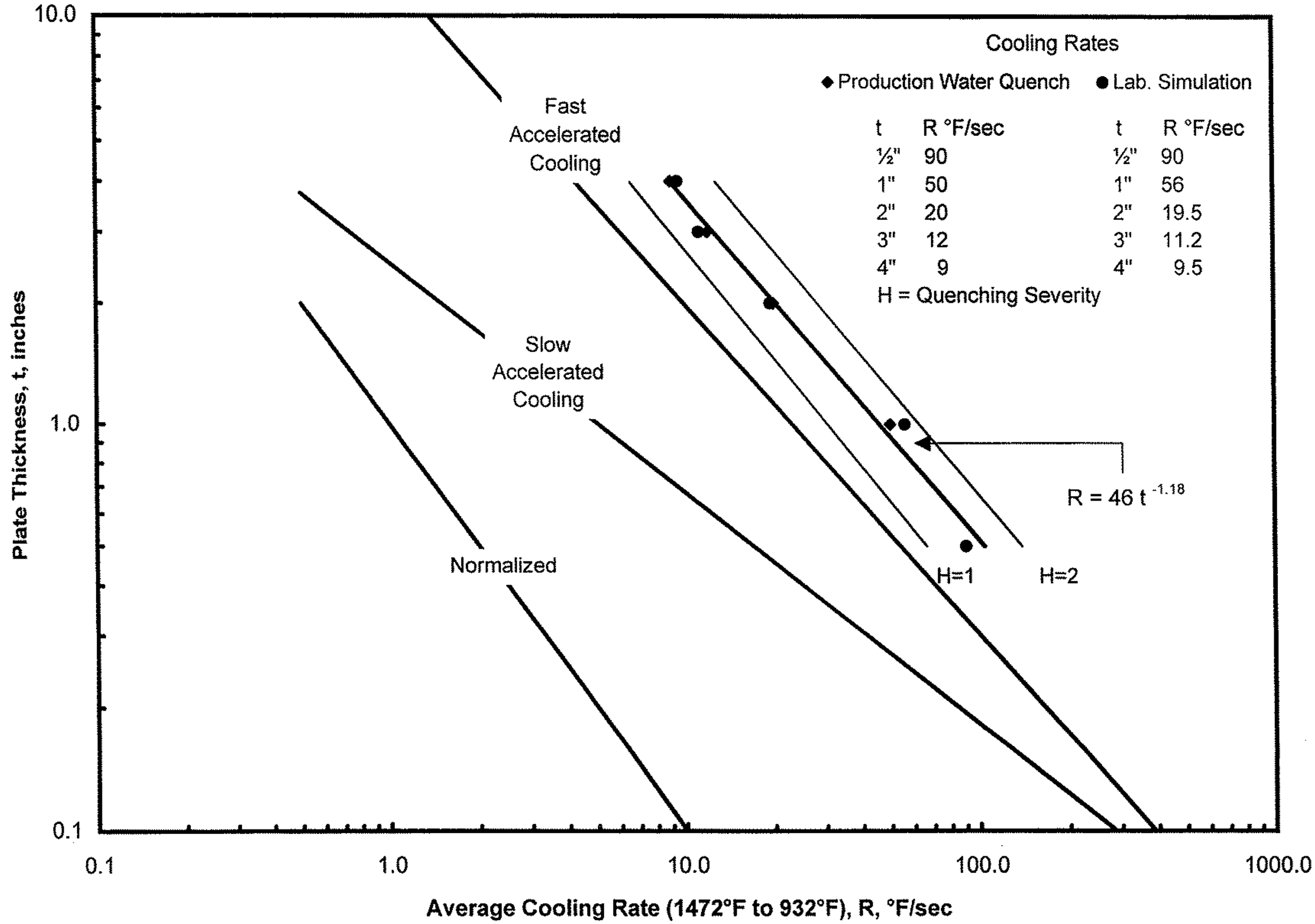

Figure 3 - Comparison of Laboratory and Production Cooling Practices

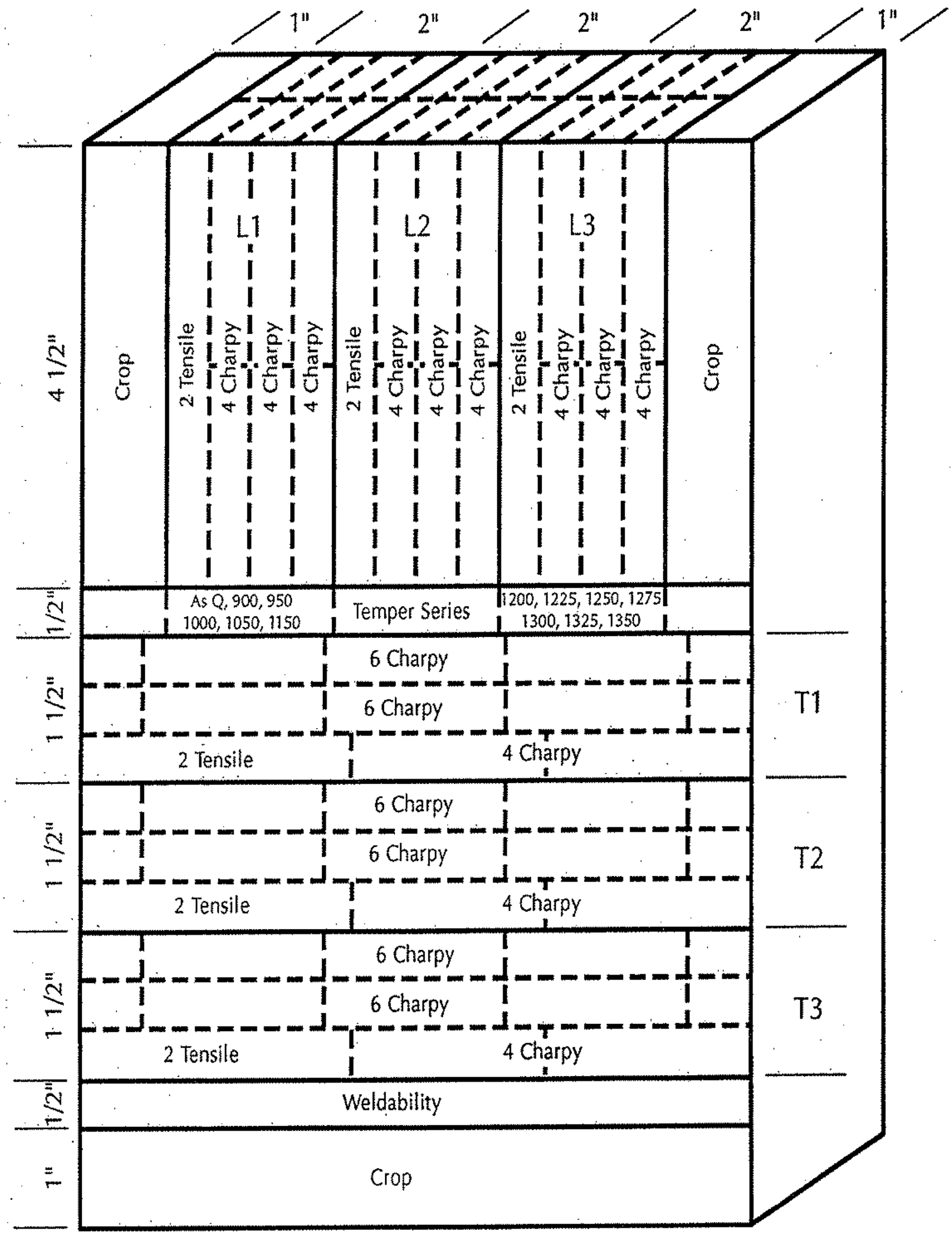

Figure 4 – Machining of Sections A and B from Figure 1 to Test Specimens

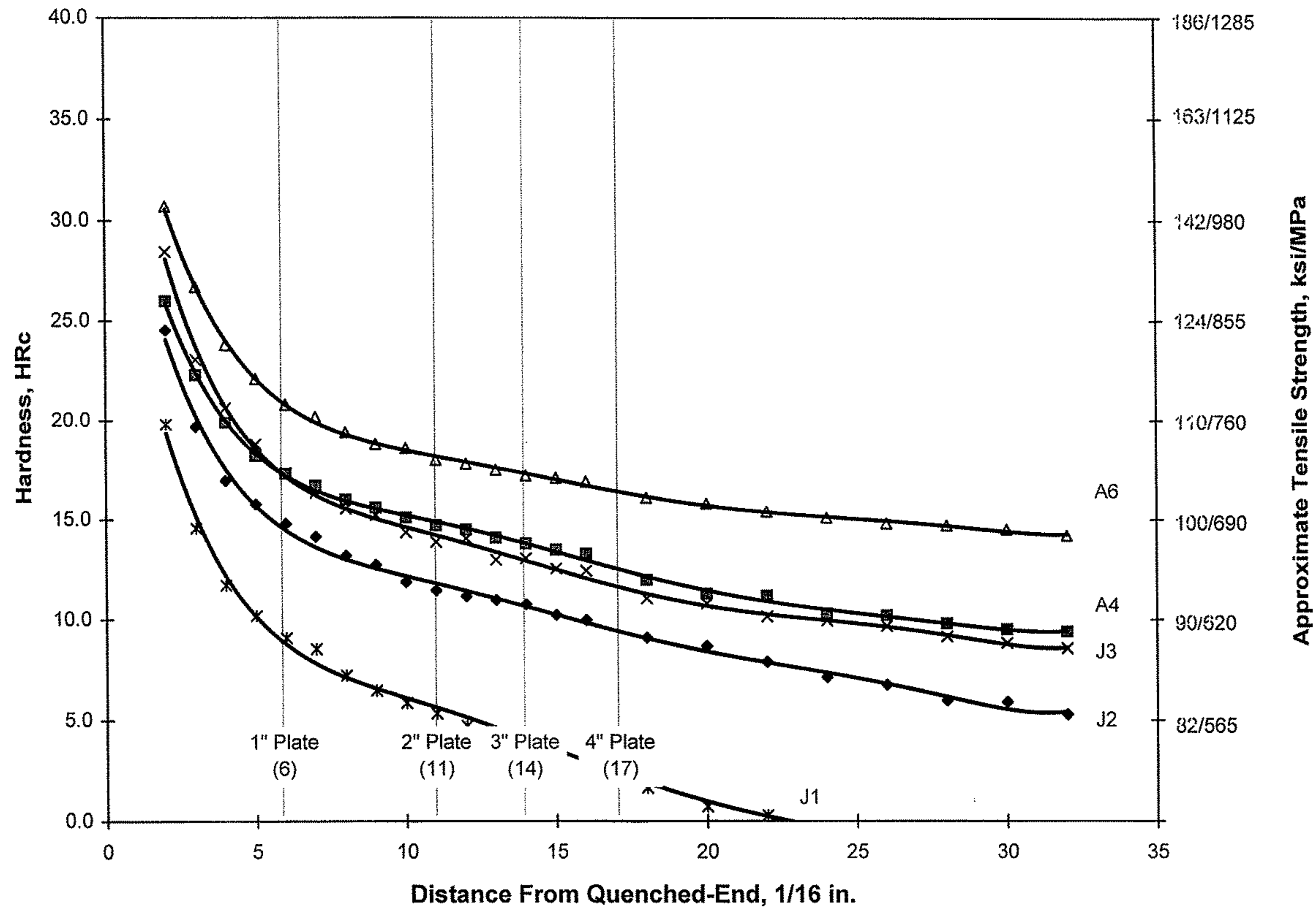

Figure 5 - Averaged Jominy End-Quenched Hardenability Results for Steels J1, J2, J3, B6 - As-Quenched

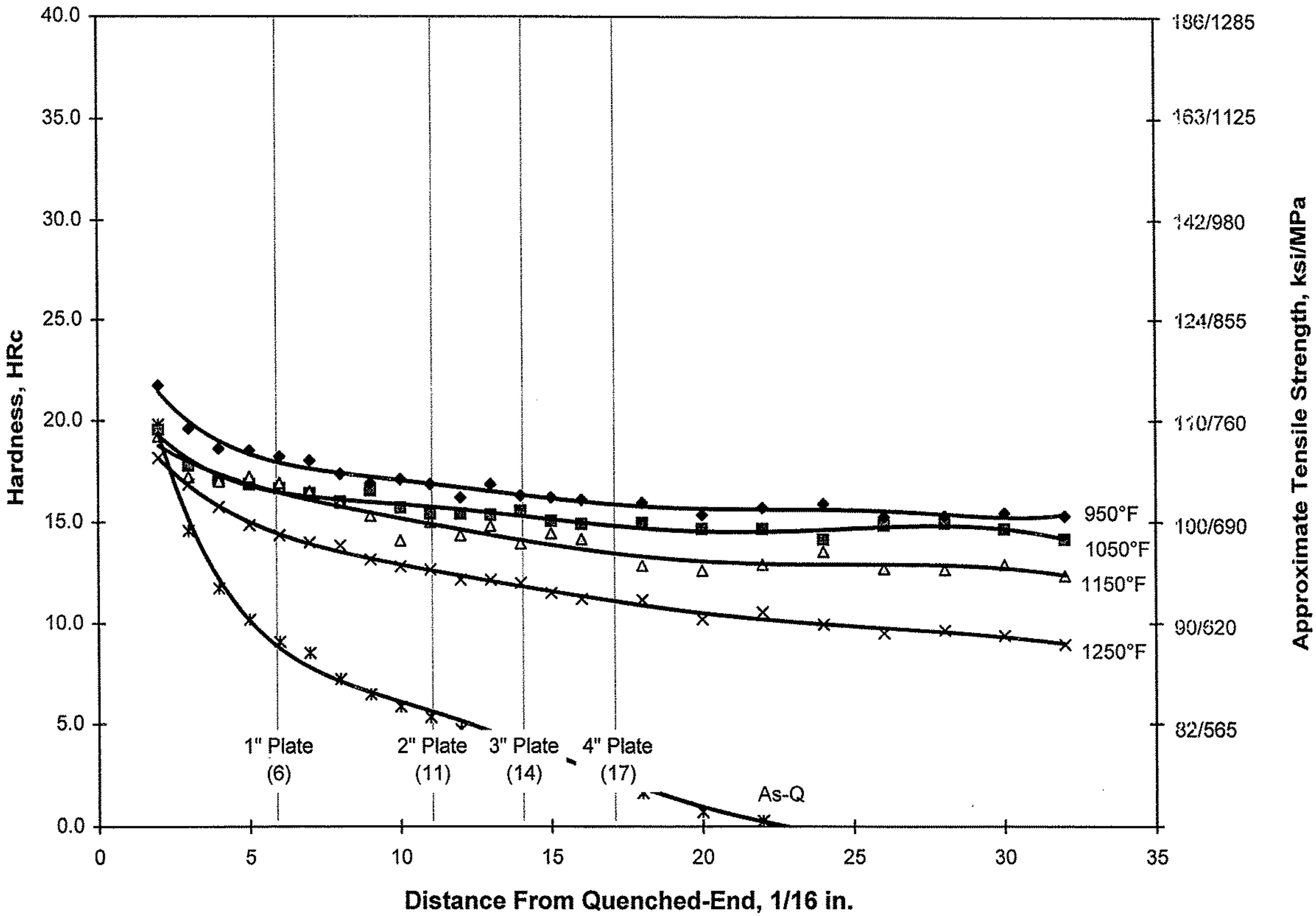

Figure 6 - Effect of Tempering on Jominy End-Quench Hardenability Tests for Steel J1

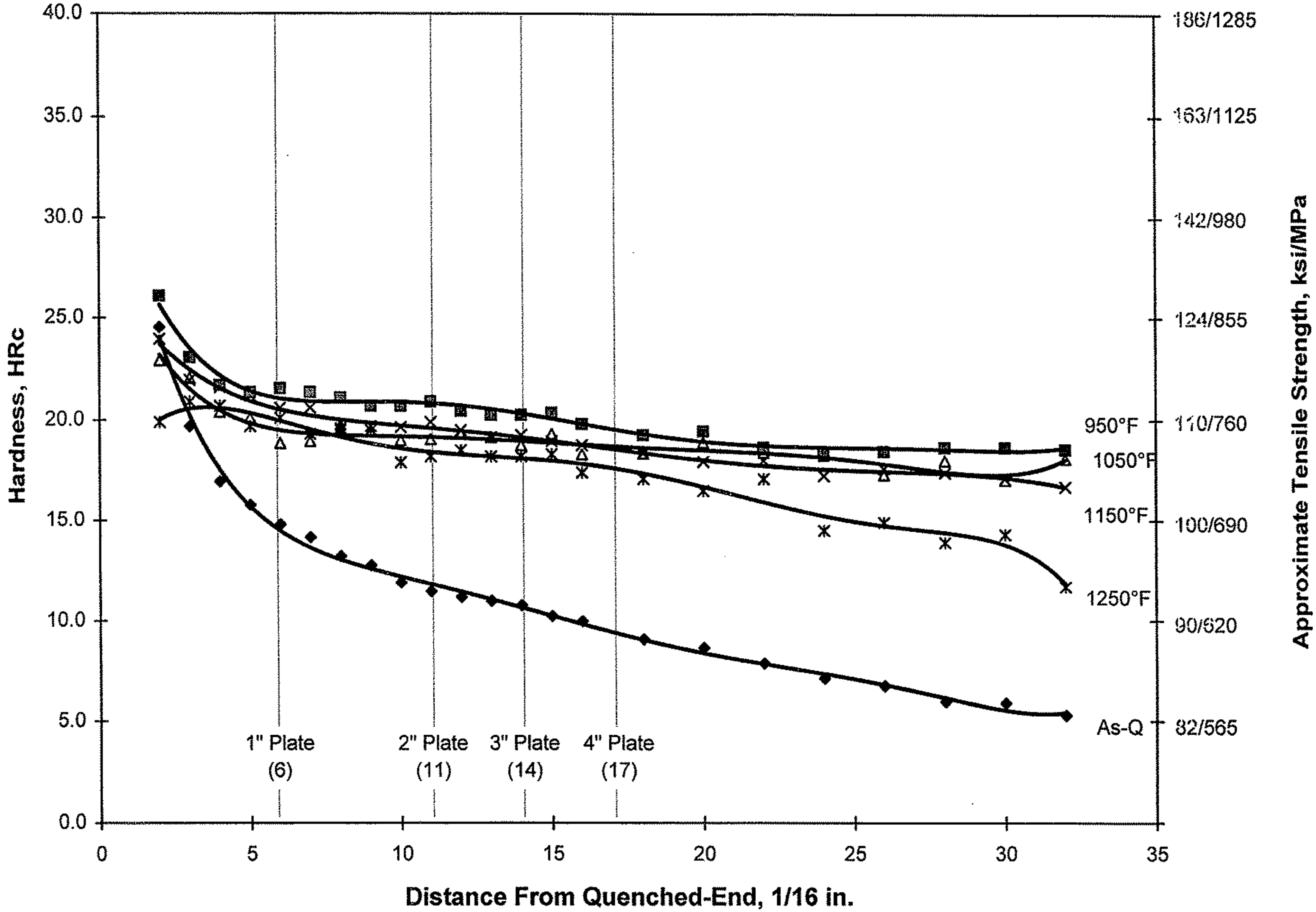

Figure 7 - Effect of Tempering on Jominy End-Quench Hardenability Tests for Steel J2

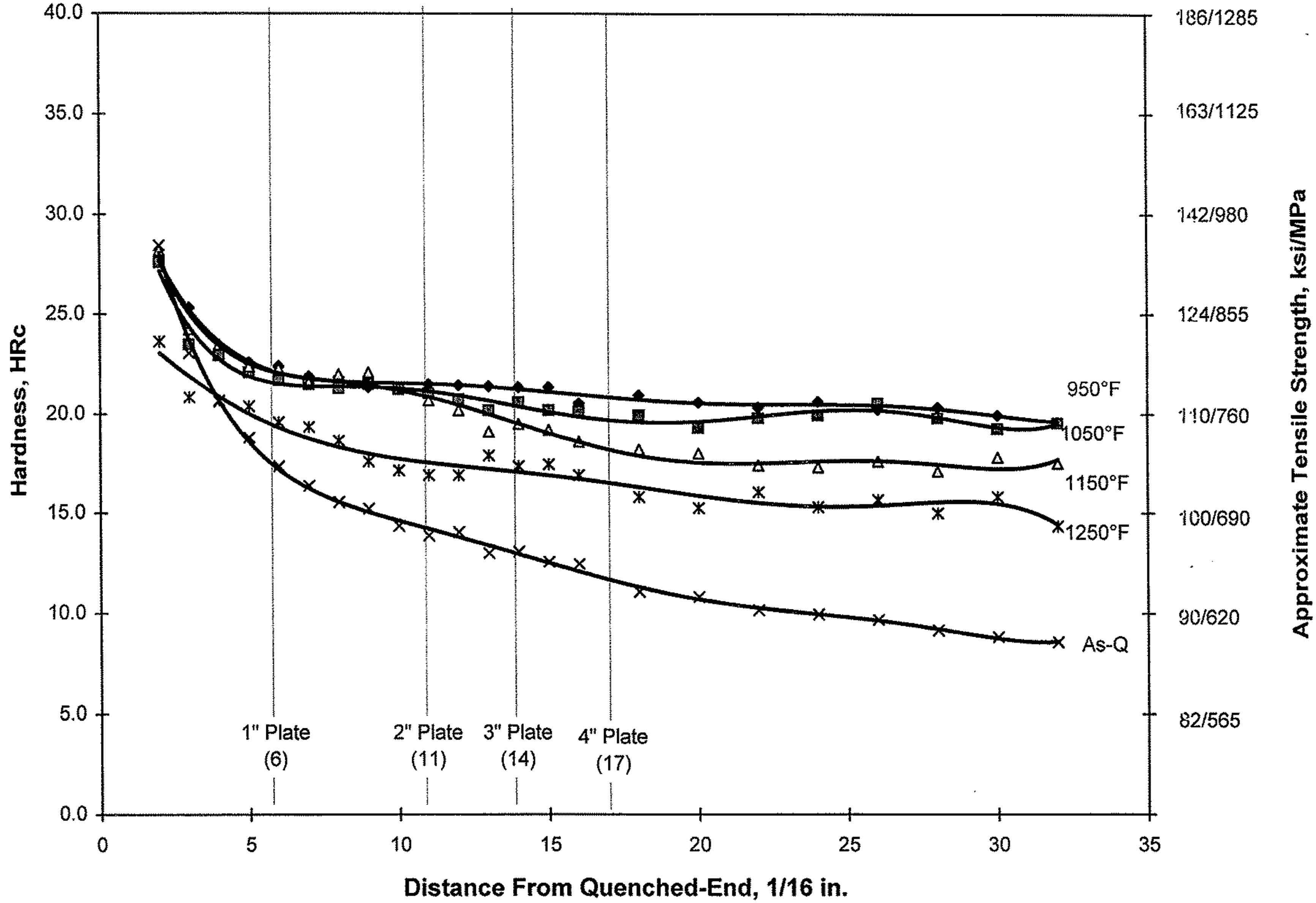

Figure 8 - Effect of Tempering on Jominy End-Quench Hardenability Tests for Steel J3

Steel J1

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.047	1.00	0.011	0.003	0.25	0.99	0.73	0.005	0.005	0.058	0.014	0.029

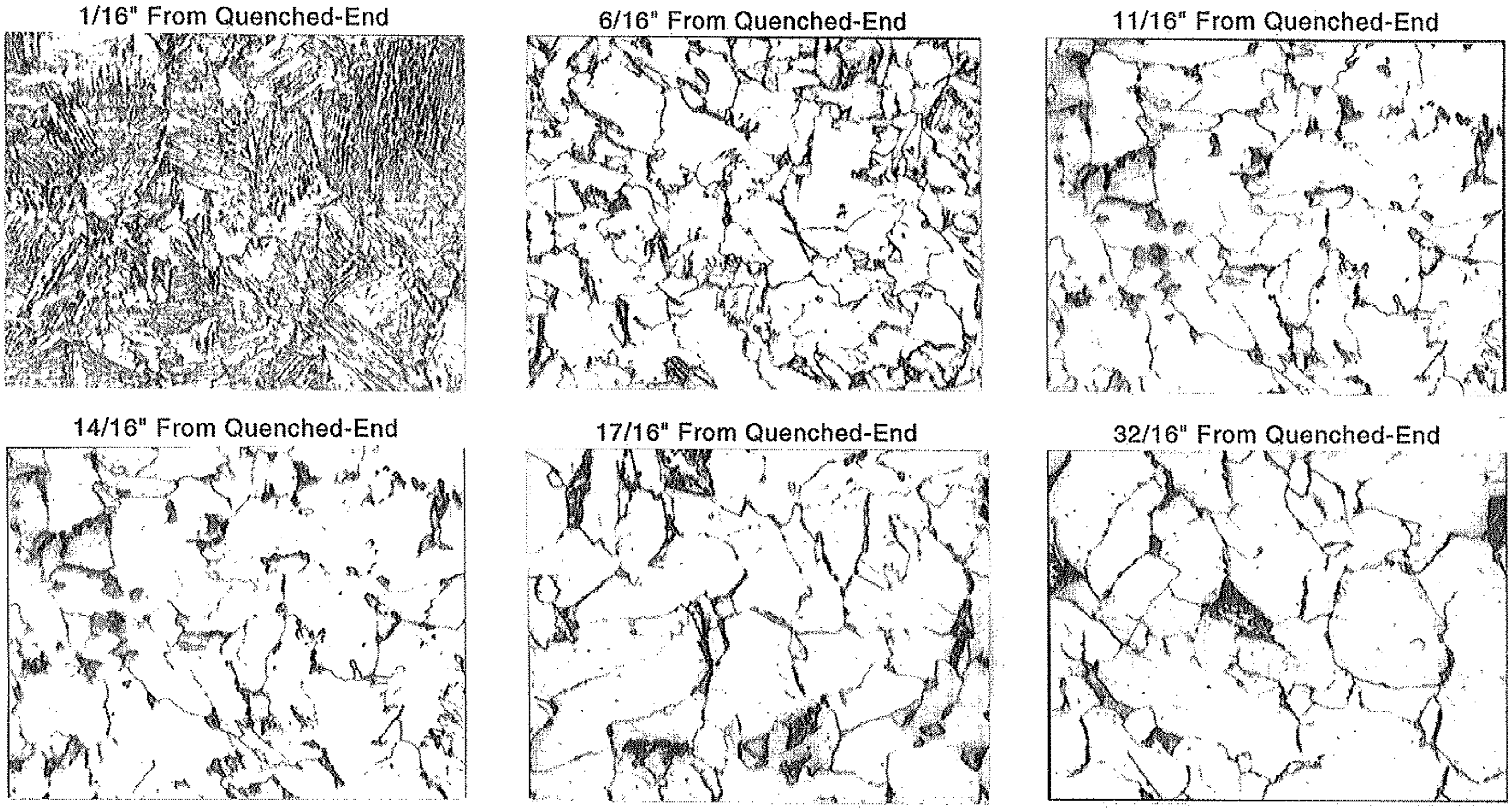

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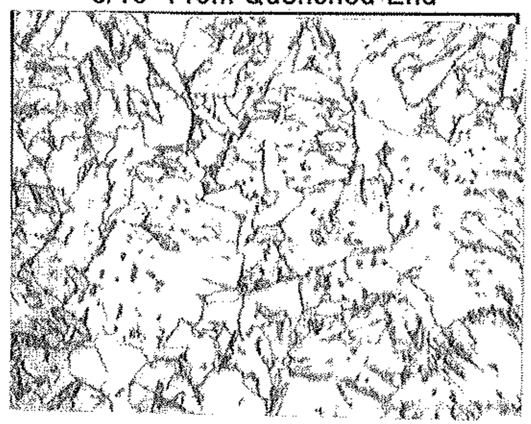
Figure 9 - Steel J1 Jominy End Quenched Hardenability Microstructures - As Quenched

Steel J2

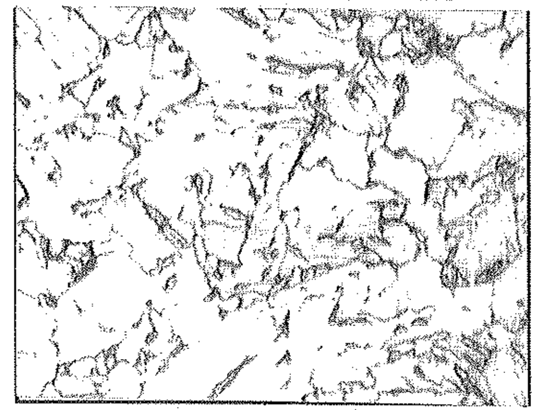
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.045	1.00	0.011	0.003	0.25	0.99	0.73	0.005	0.26	0.058	0.015	0.026

1/16" From Quenched-End

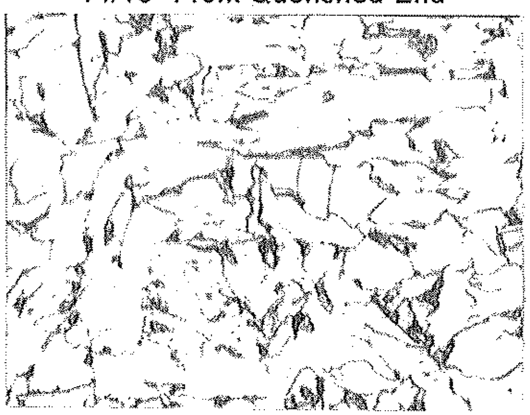
6/16" From Quenched-End



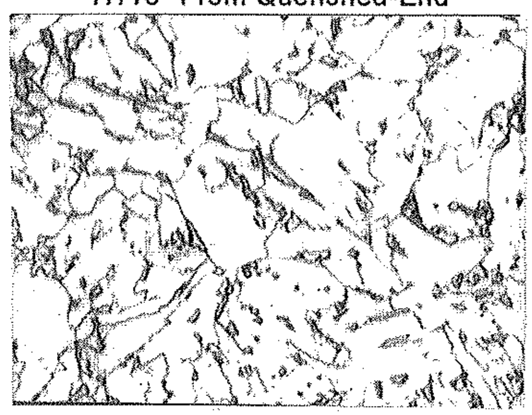
11/16" From Quenched-End



14/16" From Quenched-End



17/16" From Quenched-End



32/16" From Quenched-End

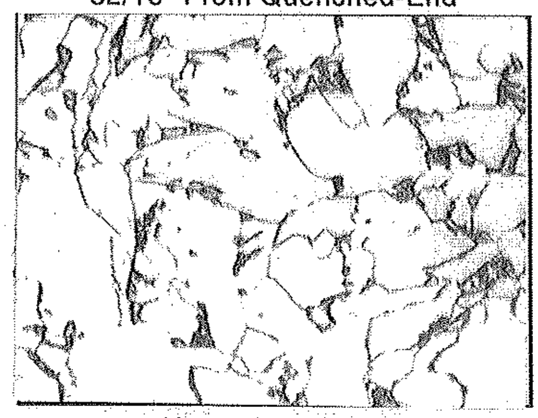


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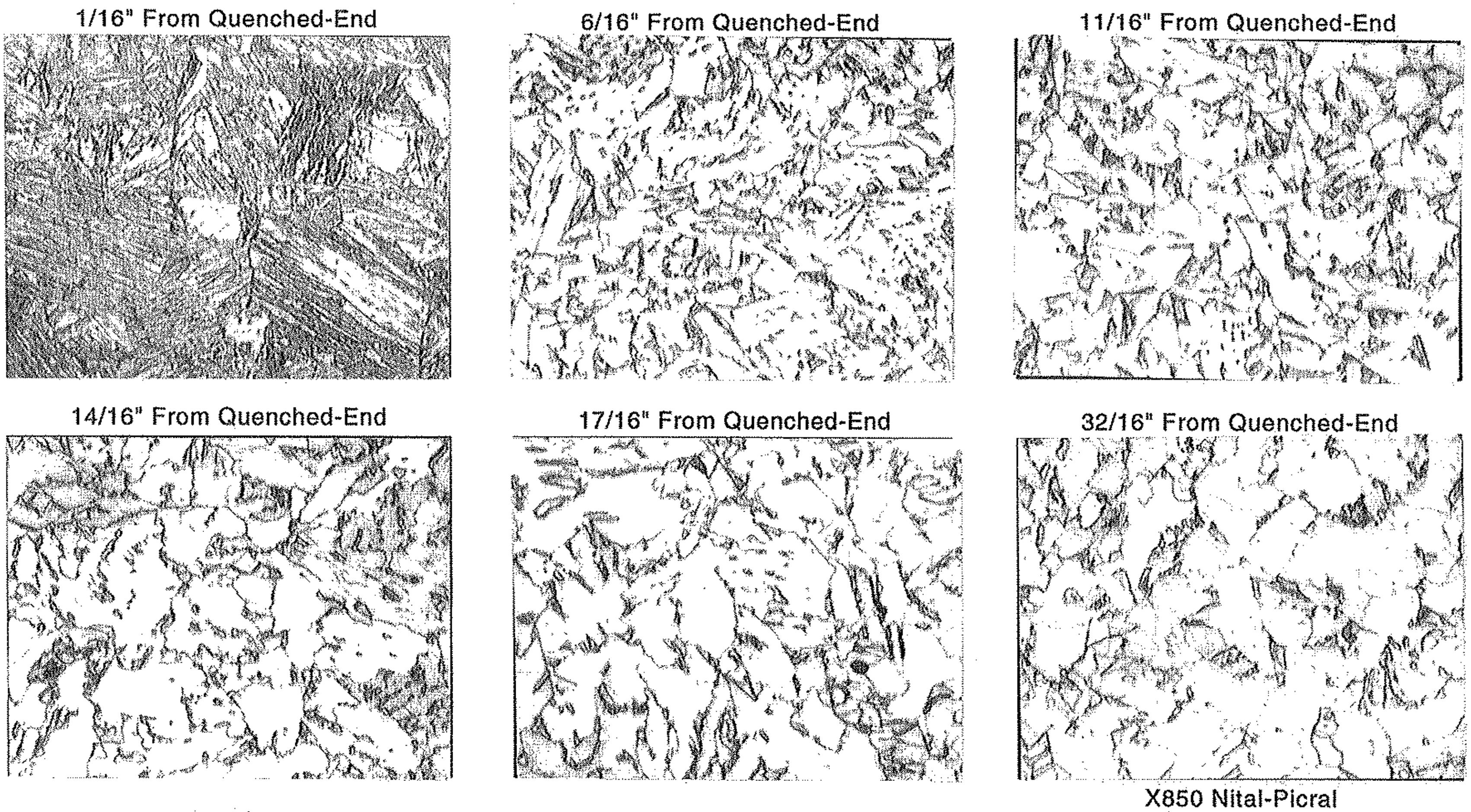
Figure 10 - Steel J2 Jominy End Quenched Hardenability Microstructures - As Quenched

Steel J3

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.064	1.00	0.011	0.003	0.26	1.00	0.73	0.005	0.26	0.060	0.015	0.024



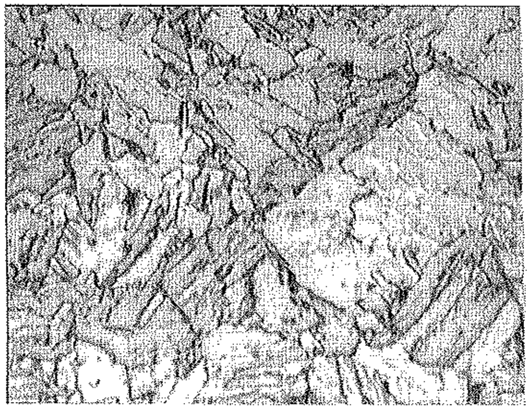
95-D057-19

Figure 11 - Steel J3 Jominy End Quenched Hardenability Microstructures - As Quenched

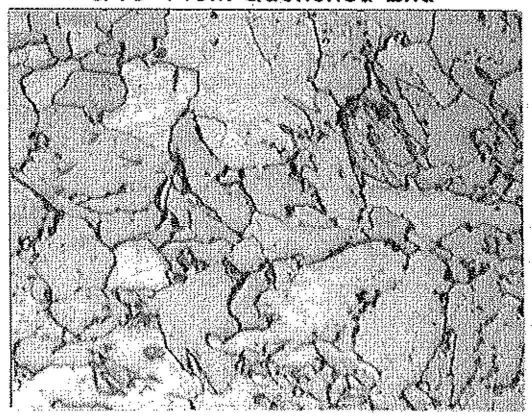
Steel J1

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.047	1.00	0.011	0.003	0.25	0.99	0.73	0.005	0.005	0.058	0.014	0.029

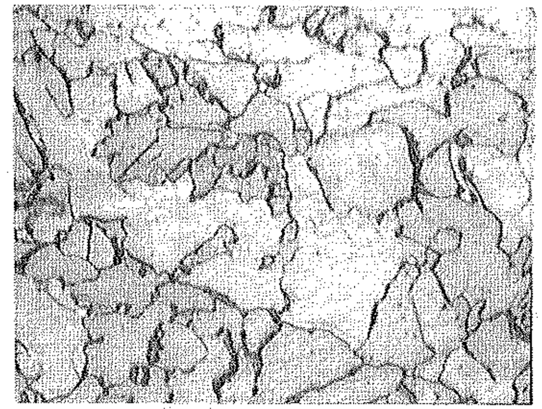
1/16" From Quenched-End



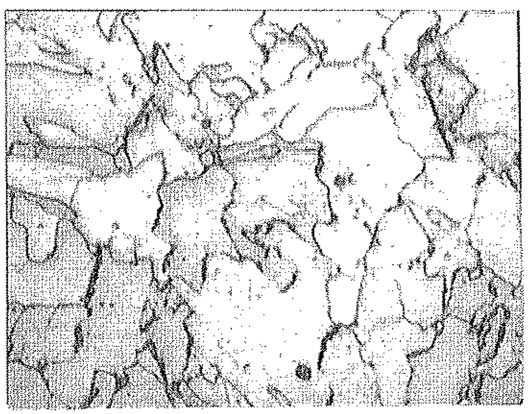
6/16" From Quenched-End



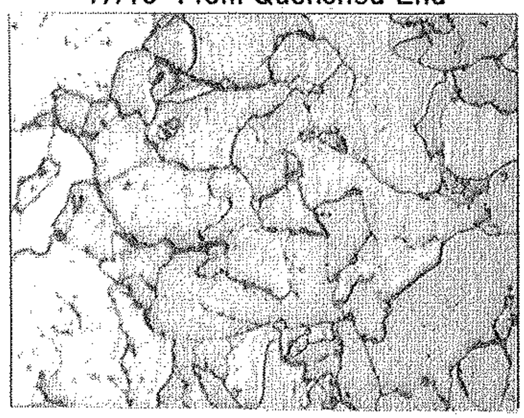
11/16" From Quenched-End



14/16" From Quenched-End



17/16" From Quenched-End



32/16" From Quenched-End

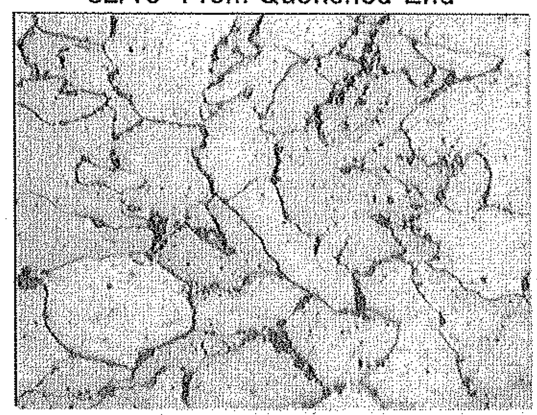


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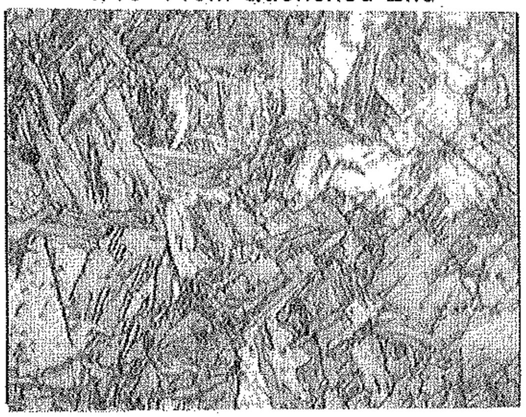
Figure 12, - Steel J1 Jominy End Quenched Hardenability Microstructures - Tempered 1250F (675C)

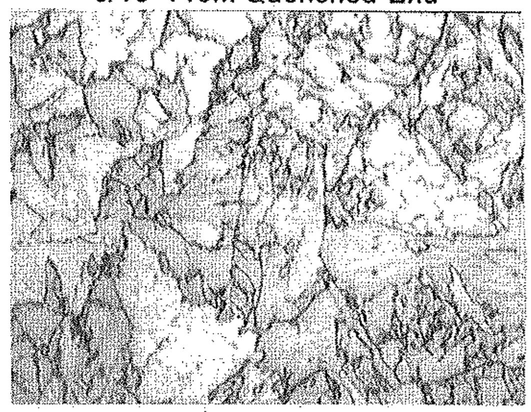
Steel J2

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.045	1.00	0.011	0.003	0.25	0.99	0.73	0.005	0.26	0.058	0.015	0.026

1/16" From Quenched-End



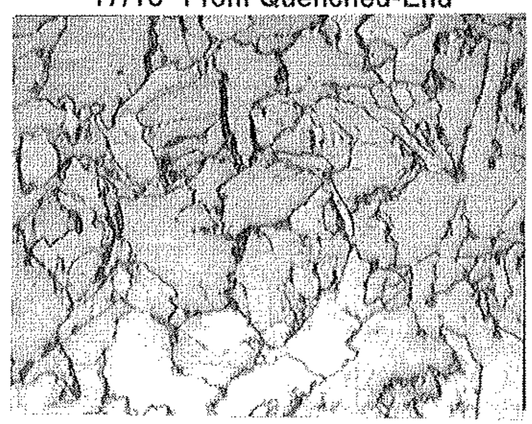
6/16" From Quenched-End



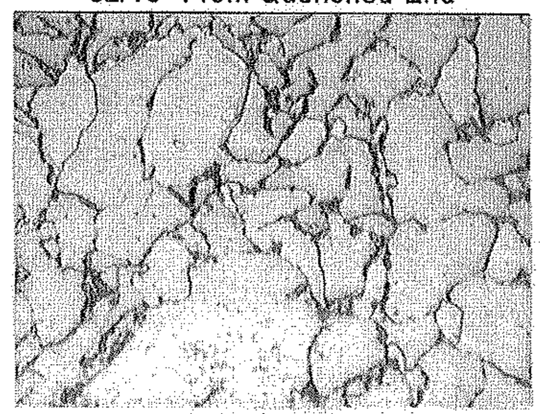
11/16" From Quenched-End

14/16" From Quenched-End

17/16" From Quenched-End



32/16" From Quenched-End



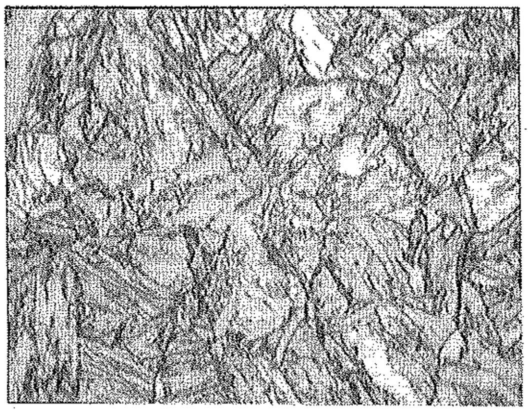
X850 Nital-Picral

95-D057 Figure 13 - Steel J2 Jominy End Quenched Hardenability Microstructures - Tempered 1250F (675C)

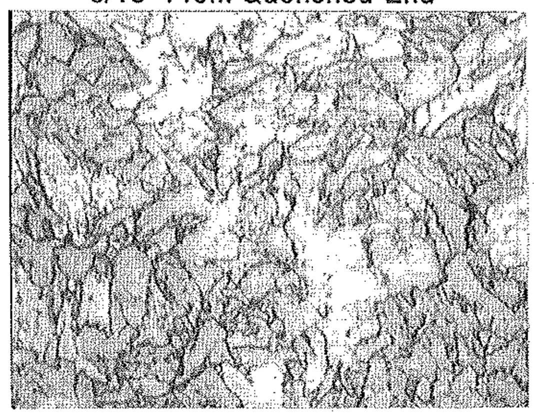
Steel J3

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.064	1.00	0.011	0.003	0.26	1.00	0.73	0.005	0.26	0.060	0.015	0.024

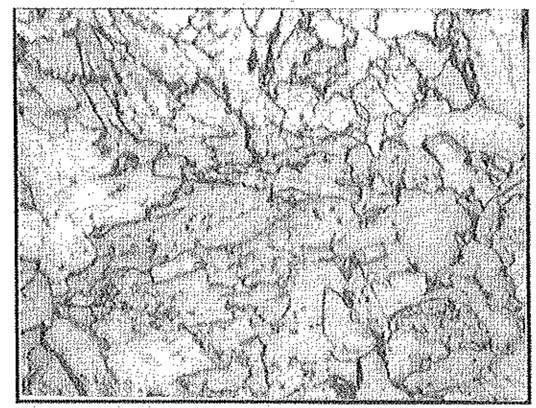
1/16" From Quenched-End



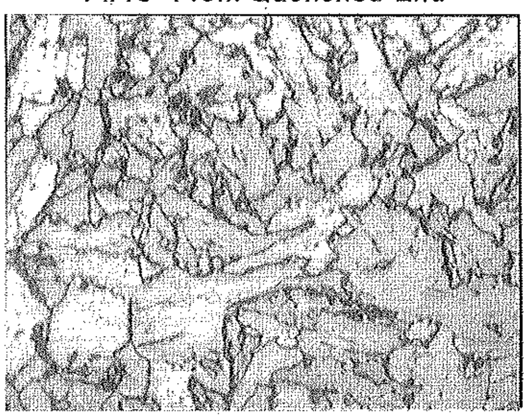
6/16" From Quenched-End



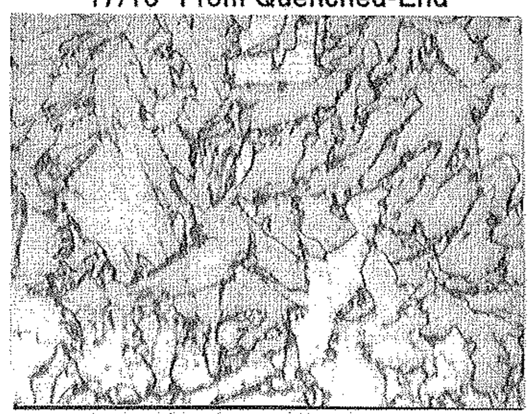
11/16" From Quenched-End



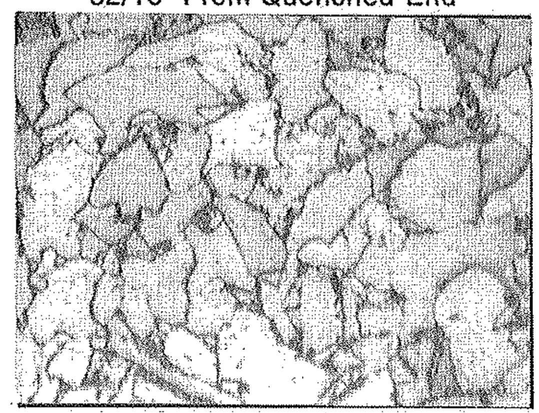
14/16" From Quenched-End



17/16" From Quenched-End

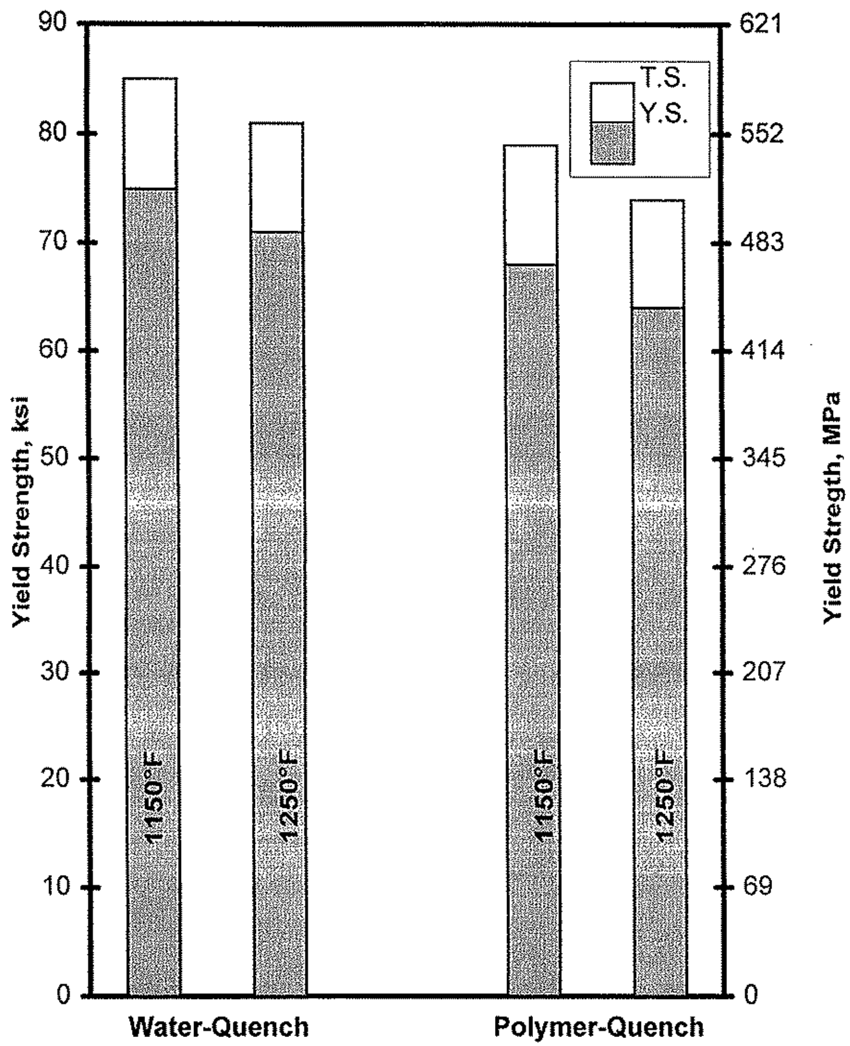


32/16" From Quenched-End



X850 Nital-Picral

95-D057-20 Figure 14 - Steel J3 Jominy End Quenched Hardenability Microstructures - Tempered 1250F (675)



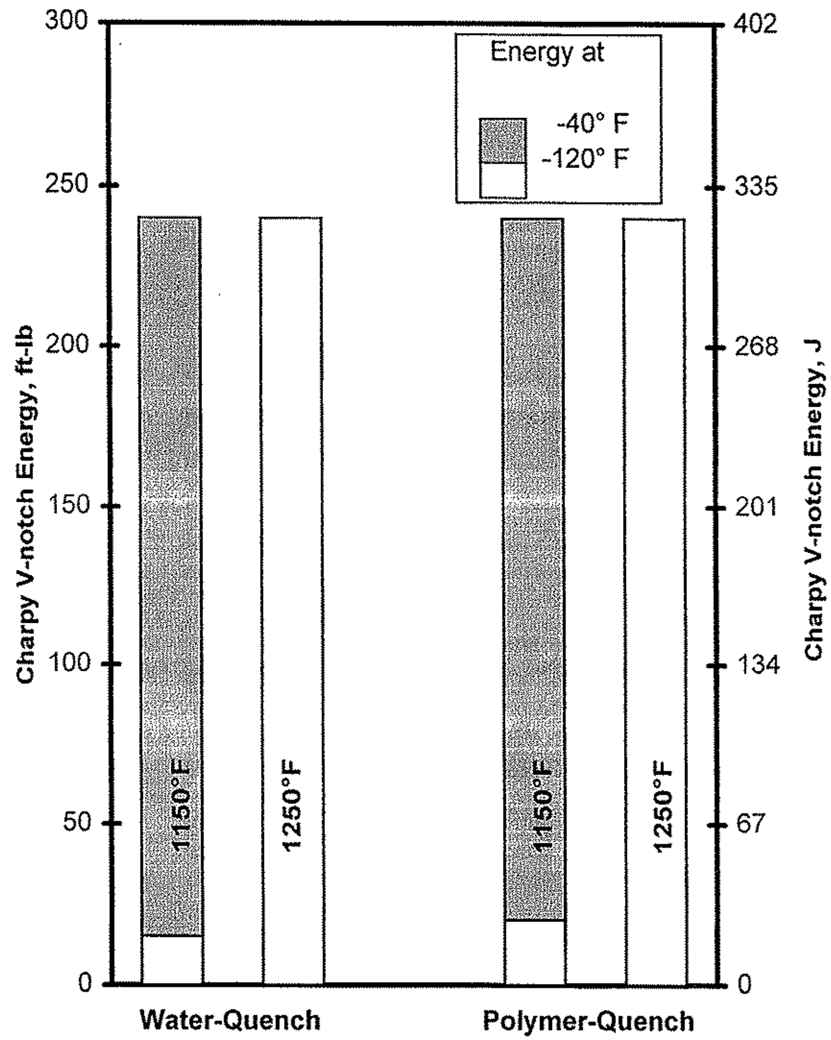


Figure 15 - Strength and Toughness Properties for J1 Steel after Various Heat Treatments (Longitudinal)

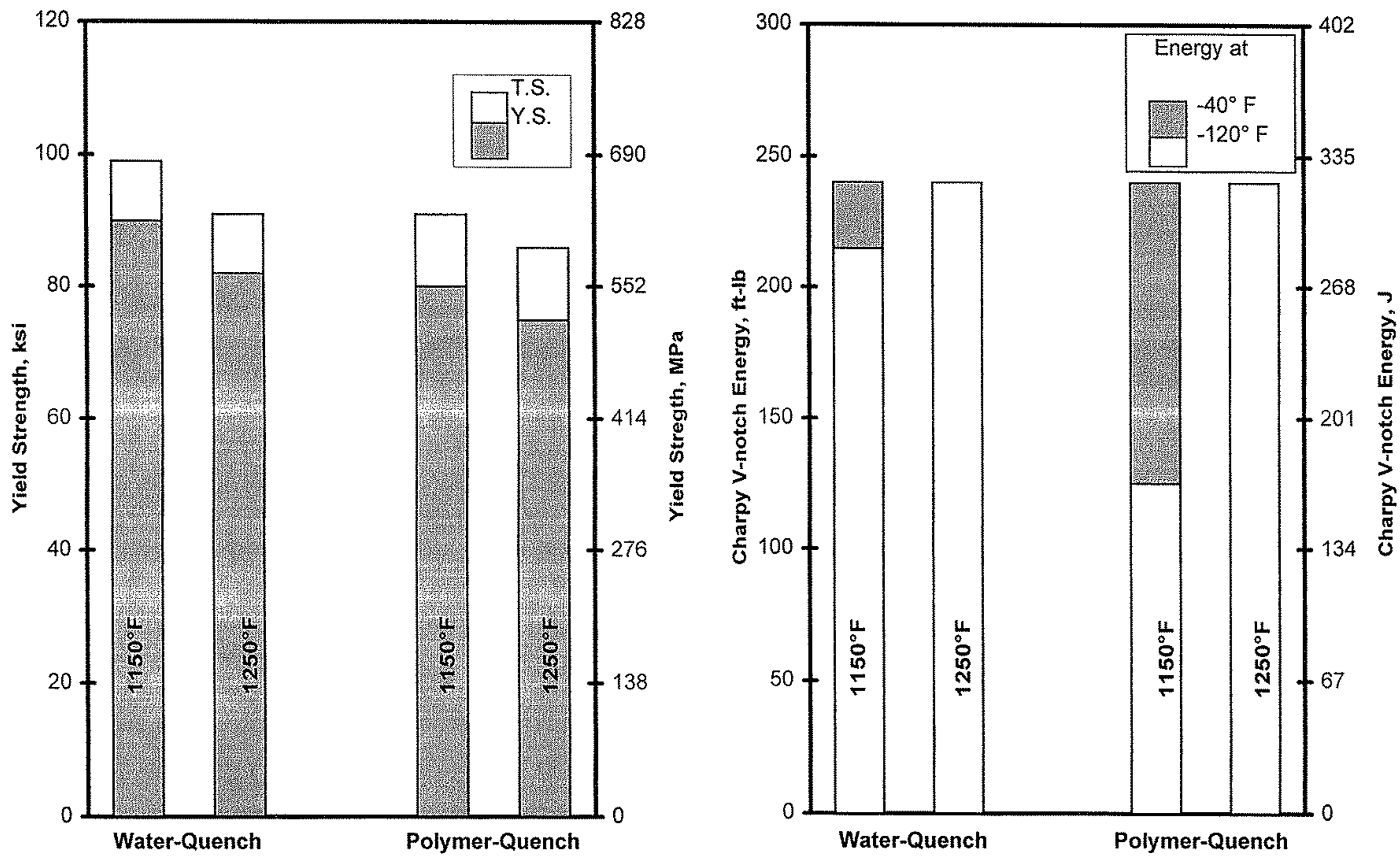


Figure 16 - Strength and Toughness Properties for J2 Steel after Various Heat Treatments (Longitudinal)

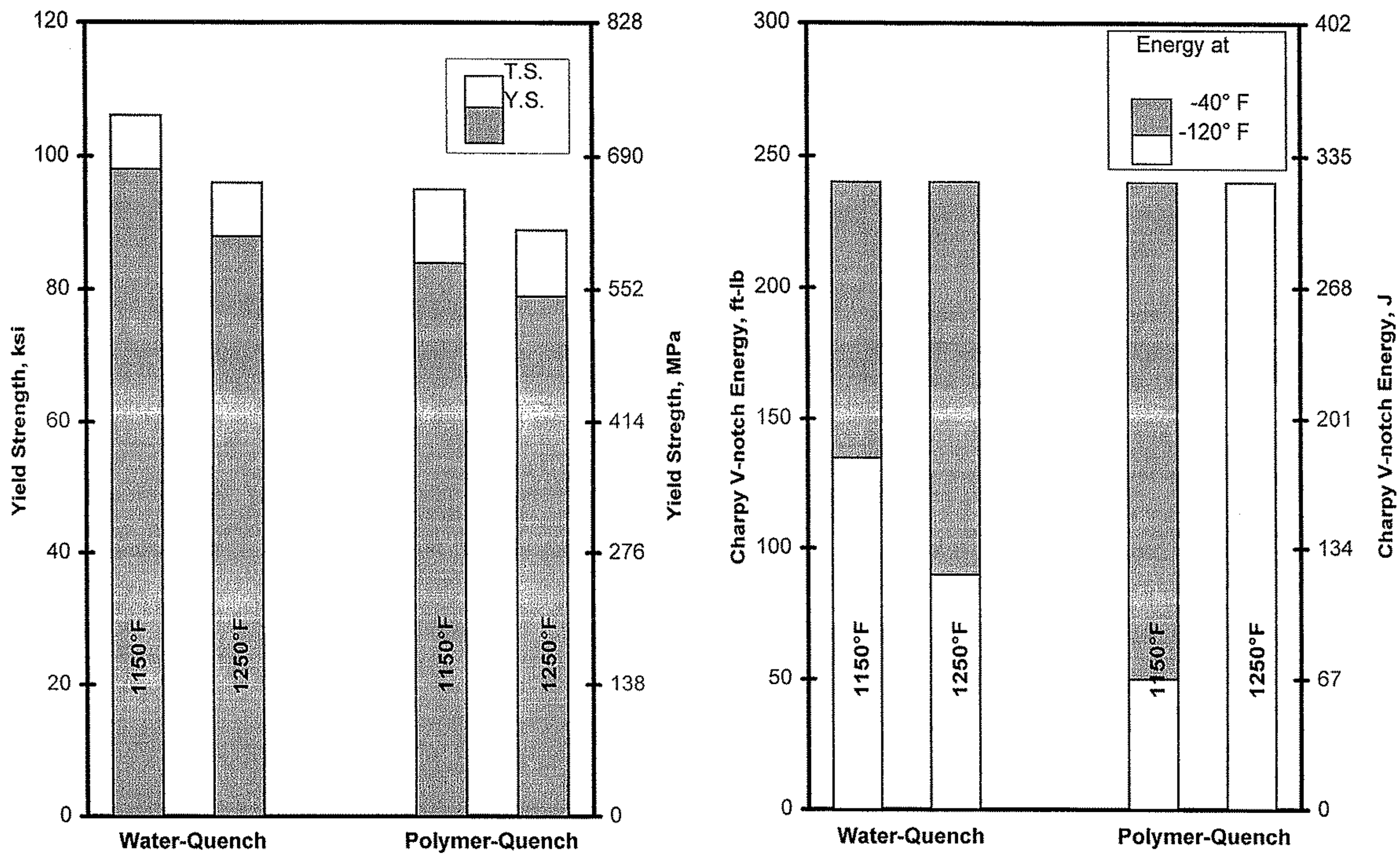


Figure 17 - Strength and Toughness Properties for J3 Steel after Various Heat Treatments (Longitudinal)

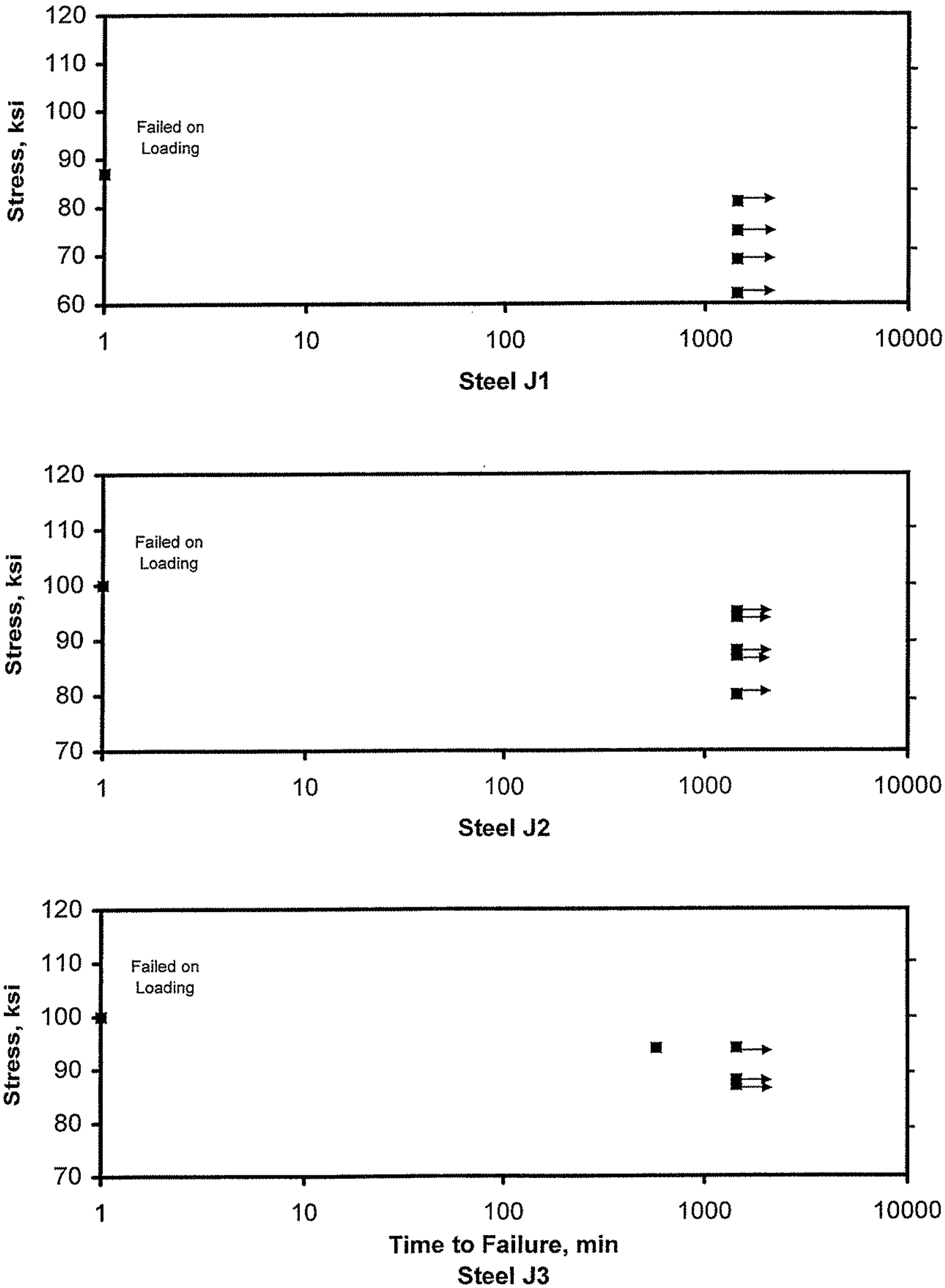


Figure 18 - Results of Implant Tests on J Steels