1-1-2000

Effect of Columbium on the Properties of Cu-Ni Structural Steels

Robert D. Stout

John H. Gross

F. R. Kachele

ATLSS

LEHIGH University

EFFECT OF COLUMBIUM ON THE PROPERTIES OF Cu-Ni STRUCTURAL STEELS

by

R.D. Stout

J.H.Gross

F.R. Kachele

This project was sponsored by the Federal Highway Administration and by the Pennsylvania Infrastructure Technology Alliance through a grant from the Pennsylvania Department of Community and EconomicDevelopment

ATLSS Report No. 99-14

January 2000

ATLSS is a National Center for Engineering Research on Advanced Technology for Large Structural Systems

117 ATLSS Drive
Bethlehem, PA 18015-4729

Phone: (610)758-3525
Fax: (610)758-5553

www.lehigh.edu/~inatl/inatl.html
Email: inatl@lehigh.edu

EFFECT OF COLUMBIUM ON THE PROPERTIES OF Cu-Ni STRUCTURAL STEELS

by

R.D. Stout
J.H. Gross
Distinguished Research Fellows

F.R. Kachele
Student Intern

This project was sponsored by the Federal Highway Administration and by the Pennsylvania Infrastructure Technology Alliance through a grant from the Pennsylvania Department of Community and EconomicDevelopment

ATLSS Report No. 99-14

January 2000

ATLSS is a National Center for Engineering Research on Advanced Technology for Large Structural Systems

117 ATLSS Drive
Bethlehem, PA 18015-4729

Phone: (610)758-3525
Fax: (610)758-5553

www.lehigh.edu/~inatl/inatl.html
Email: inatl@lehigh.edu

ABSTRACT

In recent studies columbium has been observed after heat treatment to markedly increase strength, decrease grain size and thus enhance fracture toughness, and to be effective in avoiding continuous (roundhouse) yielding in as-cooled Cu-Ni steels. For these reasons an investigation was conducted on the effects of columbium on Cu-Ni structural steels.

When the columbium content was increased from 0.015 to 0.030 to 0.045 percent and chromium was eliminated from ATLSS experimental Cu-Ni steels, the following results were observed:

1. The Jominy hardenability was not changed by increasing the columbium content; however, it was markedly reduced by eliminating chromium. Similarly, the yield and tensile strength were not significantly affected by increasing the columbium content; but they were markedly reduced by eliminating the chromium.

2. The effect of columbium on notch toughness appeared to be inconsistent in that increasing columbium from 0.030 to 0.045% in the absence of chromium, (Steel X1 vs Steel X2) was beneficial; whereas increasing columbium from 0.015 to 0.045% at 0.50% chromium (Steel X3 vs Steel B6), was not beneficial.

3. Some of the preceding effects may be related to the lower level of cleanliness in Steels X1, X2, and X3 compared with Steel B6.

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 reports[1 to 5]*.

Another characteristic of Cu-Ni structural steels of interest is their response to columbium. MIL-S-24645 SH for HSLA 80 and 100 specifies 0.02 to 0.06% Cb, higher than that usually specified for structural steels. At the high end of this range, columbium has been observed after heat treatment to markedly increase strength, decrease grain size and thus enhance fracture toughness, and to be effective in avoiding continuous (roundhouse) yielding in as-cooled steels, which are known to be residually stressed and therefore susceptible to continous yielding. For these reasons an experimental program was conducted on the effects of columbium on Cu-Ni structural steels.

EXPERIMENTAL PROCEDURE

MELTING AND ROLLING

A 300-pound (135 kg) heat was vacuum-melted and poured into three 100-pound (45 kg) ingots with additions to the second and third ingots to obtain the compositions shown in Table I and identified as Steels X1, X2, and X3. These steels are modifications of Steel B6, which is considered an excellent candidate for an improved HPS 100W steel. The ingots were charged into a reheat furnace at 2150F (1175C), rolled in five passes to 1-inch-thick (25mm) 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.

---

*See references

JOMINY END-QUENCH HARDENABILITY TESTING

For each of Steels X1, X2, and X3, three Jominy specimens were machined from Plate-Section J (Figure 1), and tested in accordance with ASTM A255 [austenitized at 1650F (900C)]. Two longitudinal flats were ground on each specimen and the hardness traverse obtained. Thee three as-quenched Jominy specimens were then tempered (aged**) at 1050F (565C), 1150F (620C), or 1250F (675C), respectively. After tempering, the flat areas were reground to remove all effects of prior hardness testing, and the hardness traverse was repeated on both sides of each tempered specimen. One hardness-test flat on each as-quenched Jominy specimen was ground, polished, and etched sequentially with picral and nital solutions, and metallographically examined along the length of the specimen. For samples as-quenched and after tempering at 1050, 1150, or 1250F (510, 565, 620, or 675C), micrographs were recorded at a magnification of 850X at locations of 1-, 6-, 11-, 14-, and 17-16 inch (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 the 32/16-inch location (50 mm), corresponding to 1/3-inch-thick (8 mm) normalized plate, cooled at 3F/sec.(1.7 C/sec.).

To evaluate the effect of austenitizing temperature on hardenability, one Jominy specimen for each of Steels X1, X2, and X3 was machined and tested in accordance with ASTM A255 after austenitizing at 1750F (950C).

HEAT TREATMENT AND MECHANICAL-PROPERTY TESTING

For each of the three X steels, 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. For each of the three X steels, Plate-Section B was also austenitized 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 austenitizing and quenching, Sections A and B were cut into subsections as shown in Figure 4, tempered at 1050, 1150 or 1250F (565, 620 or 675C) and machined to the indicated test specimens. Mechanical-property testing consisted of longitudinal tension and Charpy V-notch tests.

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

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.

RESULTS AND DISCUSSION

JOMINY END-QUENCH HARDENABILITY TESTS - AS-QUENCHED

The results of the hardness testing of the as-quenched Jominy tests are illustrated in Figure 5. The curves show that Steels B6 and X3, with the same composition except in the amount of Cb, exhibited essentially identical hardenabilities. Consequently austenitizing at 1650F (900C) resulted in no effect of columbium on hardenability. The same result was observed for Steels X1 and X2, with the same composition except for Cb.Therefore, the difference between the B6/X3 curves and X1/X2 curves is related to the difference in chromium content. The low hardenabilty of Steel J3 compared with Steels X1/X2 is consonant with the absence of chromium in all three steels and the lower molybdenum content of Steel J3. Raising the austenitizing temperature from 1650F to 1750F did not significantly change the Jominy curves. Therefore, the curves are not reported herein.

JOMINY END-QUENCH HARDENABILITY - TEMPERED

The effect of tempering the Jominy bars of the reference Steel B6 is illustrated in Figure 6, which shows that the net strengthening of the as-quenched bar is a competition between strengthening from precipitation of epsilon copper and softening of the transformation products. As expected, the maximum precipitation strengthening and minimum transformation-product softening occurred at 950F (510C), but softening by overaging occurred increasingly as the temperature increased to 1250F (675C). Transformation-product softening occurred primarily near the quenched end of the bar where fast cooling produced the strongest transformation products.

The effect of tempering the Jominy bars of Steels X1, X2, and X3 is shown in Figures 7, 8, and 9, respectively. The curves for all three steels indicate that softening of the transformation products occurred near the quenched end, but that significant net strengthening occurred at and beyond 6/16 inch from the quenched end. The response of Steels X1, X2, and X3 to changes in tempering temperature from !050F to 1150F to 1250F (565C to 620C to 675C) was surprisingly small compared to that for Steel B6.

METALLOGRAPHIC EVALUATION OF JOMINY SPECIMENS

Micrographs for Steels X1, X2, and X3 on as-quenched Jominy specimens at 1-, 6-, 11-, 14-, 17-, and 32-16 inch from the as-quenched end are depicted in Figures 10, 11, and 12, respectively. The three steels show a similar trend of microstructural changes as the cooling rate decreases along the length of the bar from the quenched end.

At the 1/16-inch position, 490 F/sec (270C/sec), the microstructure is fully martensitic, but at 6-16-inch, 56F/sec (30C/sec), the typical cooling rate for a 1-inch-thick (25-mm) production-quenched plate, the microstructure is granular bainite. Thereafter, the second phase (MA constituent) is gradually agglomerated as cooling rates decrease toward the end of the bar. No discernible effect of columbium on the microstructure is evident.

Metallographic examination of the tempered Jominy specimens revealed no significant change in the microstructure other than some spheroidization of the martensite at the quenched end of the specimen. The micrographs of the tempered specimens are presented in the Appendix.

Examination of the etched samples revealed areas containing significant amounts of nonmetallics. These areas were avoided in recording micrographs of the etched samples. However, to illustrate the types of nonmetallics observed, areas containing typical amounts of nonmetallics were recorded as illustrated in Figure 13.

MECHANICAL-PROPERTY EVALUATION

The tensile and toughness properties for Steels X1, X2, and X3 are listed in Table II and illustrated in Figures 14, 15, and 16. Among Steels X1,X2, or X3 after any common heat treatment, Steel X3 exhibited the highest yield and tensile strength. This is consistent with the Jominy-test results, which demonstrated the importance of chromium to increasing hardenability.

The yield and tensile strengths of Steel X3 averaged about 8 ksi lower than the respective values for Steel B6. Both steels are essentially identical in composition except for the columbium content, 0.045% for Steel X3 vs 0.017% for Steel B6.

The notch toughness of Steel X2 was somewhat better than that of Steel X1 and that for Steel X3 was similar to that of Steel B6.

The specific effects of columbium were difficult to deduce because of the possible effect of cleanliness on the properties of the X Steels.

CONCLUSIONS

When the columbium content was increased from 0.015 to 0.030 to 0.045 percent and chromium was eliminated from ATLSS experimental Cu-Ni steels, the following was observed:

1. The Jominy hardenability was not changed by increasing the columbium content; however, it was markedly reduced by eliminating chromium. Similarly, the yield and tensile strength were not significantly affected by increasing the columbium content, but they were markedly reduced by eliminating the chromium.

2. The effect of columbium on notch toughness appeared to be inconsistent in that increasing columbium from 0.030 to 0.045% in the absence of chromium, (Steel X1 vs Steel X2) was beneficial; however increasing columbium from 0.015 to 0.045% at 0.50% chromium (Steel X3 vs Steel B6), was not beneficial.

3. Some of the preceding effects may be related to the lower level of cleanliness in Steels X1, X2, and X3 compared with Steel B6.

REFERENCES

1. Dawson, H.M., Gross, J.H., and Stout, R.D., "Copper-Nickel High Performance 70W/100W Bridge Steels - Part 1", ATLSS Rep[ort No. 97-10, August 1997.
2. Gross, J.H., Stout, R.D., and Dawson, H.M., "Copper-Nickel High Performance 70W/100W Bridge Steels - Part II", ATLSS Report No. 98-02, May 1998.
3. Dawson, H.M.,Gross, J.H., andStout, R.D., "Development of an Improved HPS 70W Steel", ATLSS Report No. 99-07, 1999.
4. Dawson, H.M., Gross, J.H., and Stout R.D., "Effect of Copper on the Properties of Cu-Ni Structural Steels" ATLSS Report No. 99-08, 1999.
5. Dawson, H.M., Gross, J.H., and Stout, R.D., "Effect of Nickel on the Properties of Cu-Ni Structural Steels", ATLSS Report No. 99-09, 1999.

Table I - Chemical Composition of X1, X2, X3. B6, and J3 Steels

	Steel				
	X1	X2	X3	B6	J3
C	0.062	0.062	0.063	0.061	0.064
Mn	1.00	0.98	0.99	1.02	1.00
P	0.013	0.013	0.013	0.011	0.011
S	0.0028	0.0026	0.0028	0.003	0.003
Si	0.22	0.22	0.23	0.27	0.26
Cu	1.01	1.00	1.00	1.01	1.00
Ni	0.73	0.72	0.73	0.77	0.73
Cr	0.004	0.004	0.51	0.51	0.005
Mo	0.49	0.49	0.049	0.50	0.26
V	0.057	0.056	0.057	0.054	0.060
Cb	0.028	0.047	0.045	0.017	0.015
Al(total)	0.034	0.031	0.023	0.015	0.024

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
X1 Steel - Longitudinal			C 0.062	Mn 1.00	P 0.013	S 0.0028	Si 0.22	Cu 1.01	Ni 0.73	Cr 0.004	Mo 0.49	V 0.057	Cb 0.028	Al 0.034			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	X1AB	99	111	27	74	0.89	21.0	-60	-60	-60	-60	40	135	130	120	5	-----
Temper @ 1150 °F	X1AD	99	109	28	76	0.91	21.0	-80	-40	-35	-50	55	160	125	100	20	-----
Temper @ 1250 °F	X1AF	91	100	26	76	0.91	18.0	-85	-80	-80	-85	-40	-----	200	160	80	10
Prod. Quench of 4-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	X1BB	92	107	28	76	0.86	20.0	-80	-70	-70	-75	80	140	135	120	20	5
Temper @ 1150 °F	X1BD	92	103	27	77	0.89	19.0	-60	-60	-55	-60	50	180	160	145	10	-----
Temper @ 1250 °F	X1BF	89	99	28	78	0.90	18.0	-80	-80	-75	-80	-40	-----	185	140	25	10
X2 Steel - Longitudinal			C 0.062	Mn 0.98	P 0.013	S 0.0026	Si 0.22	Cu 1.00	Ni 0.72	Cr 0.004	Mo 0.49	V 0.056	Cb 0.047	Al 0.031			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	X2AB	97	110	26	76	0.88	21.0	-115	-110	-105	-115	-40	-----	180	150	100	10
Temper @ 1150 °F	X2AD	100	108	27	78	0.92	22.0	-95	-90	-85	-85	-40	-----	215	150	70	10
Temper @ 1250 °F	X2AF	92	101	299	79	0.91	18.0	-135	-130	-120	-130	-100	-----	220	220	190	60
Prod. Quench of 4-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	X2BB	92	106	28	76	0.87	19.5	-120	-115	-110	-120	-30	-----	165	130	110	20
Temper @ 1150 °F	X2BD	92	102	29	79	0.90	19.0	-135	-130	-130	-135	-75	-----	230	200	160	125
Temper @ 1250 °F	X2BF	85	96	29	80	0.88	15.5	-120	-115	-110	-120	-80	-----	235	220	140	25
X3 Steel - Longitudinal			C 0.063	Mn 0.99	P 0.013	S 0.0028	Si 0.23	Cu 1.00	Ni 0.73	Cr 0.51	Mo 0.049	V 0.057	Cb 0.045	Al 0.023			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	X3AB	106	118	26	74	0.90	25.0	-70	-60	-55	-60	40	125	115	85	10	-----
Temper @ 1150 °F	X3AD	105	113	25	76	0.93	24.5	-115	-110	-105	-115	40	-----	140	120	110	10
Temper @ 1250 °F	X3AF	94	101	26	78	0.93	21.5	-120	-110	-105	-115	-90	-----	240	240	165	25
Prod. Quench of 4-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	X3BB	94	114	26	73	0.82	22.0	-105	-100	-90	-100	15	165	125	100	75	10
Temper @ 1150 °F	X3BD	96	110	28	78	0.87	21.0	-70	-65	-60	-65	-30	-----	170	110	10	
Temper @ 1250 °F	X3BF	90	101	30	79	0.89	18.0	-120	-115	-110	-120	-40	-----	225	150	110	20
B6 Steel - Longitudinal			C 0.061	Mn 1.02	P 0.011	S 0.003	Si 0.27	Cu 1.01	Ni 0.77	Cr 0.51	Mo 0.5	V 0.054	Cb 0.017	Al 0.015			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	B6AB	116	128	25	72	0.90	28.5	-115	-110	-95	-110	-60	-----	120	90	70	15
Temper @ 1150 °F	B6AD	117	125	25	75	0.93	27.0	-150	-140	-130	-140	-55	-----	130	120	110	85
Temper @ 1250 °F	B6AF	107	112	26	76	0.95	21.0	-175	-170	-165	-170	-80	-----	175	160	140	120
Prod. Quench of 4-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	B6BB	105	119	26	74	0.88	23.0	-85	-75	-65	-85	40	135	120	100	25	5
Temper @ 1150 °F	B6BD	98	115	25	76	0.85	22.5	-115	-110	-105	-115	-65	-----	150	140	130	10
Temper @ 1250 °F	B6BF	94	104	27	76	0.90	19.0	-115	-110	-105	-115	-60	-----	210	180	130	10

Table II - Mechanical Properties of Steels X1, X2, X3, and B6.

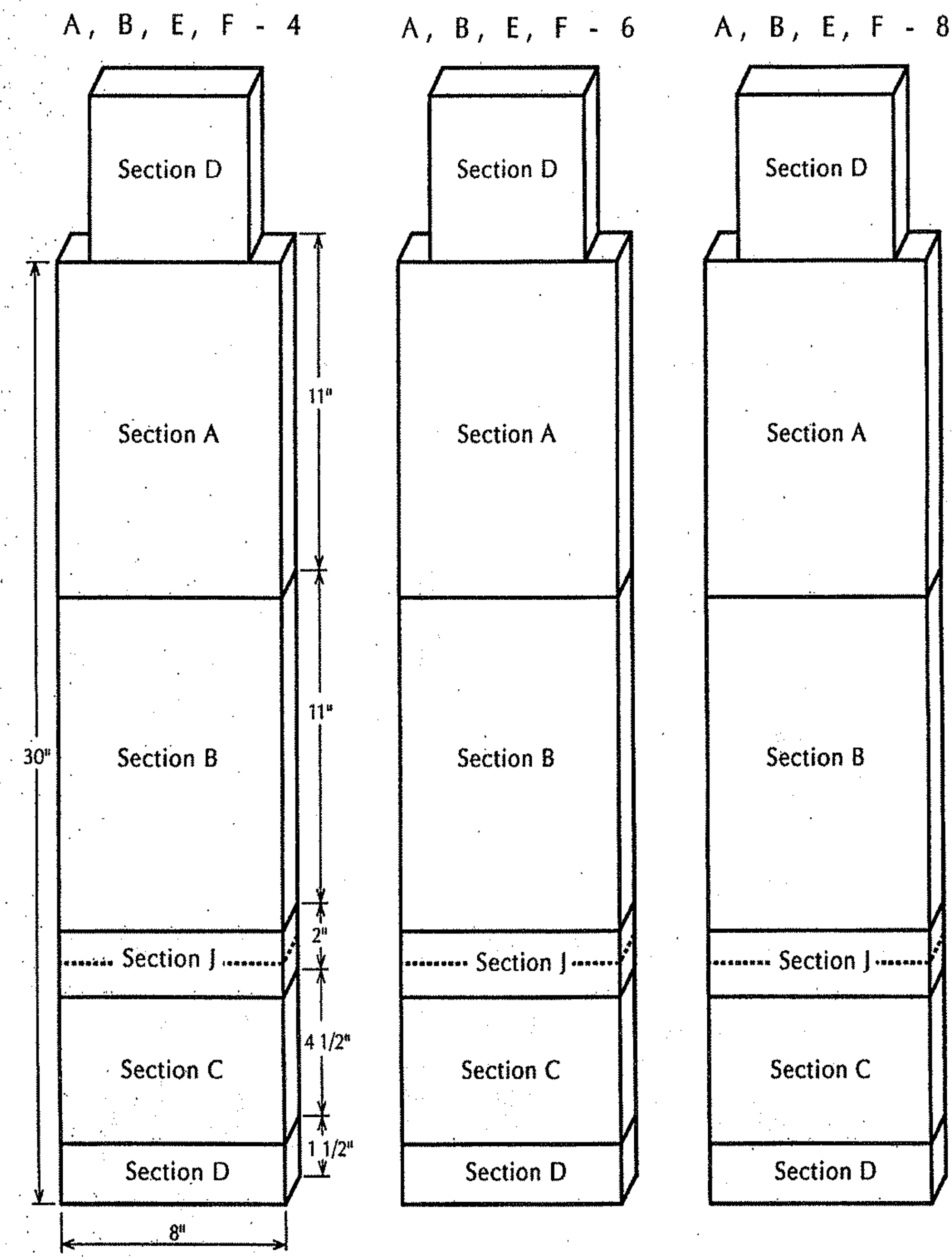


Figure 1 – Sectioning of 100 – Pound – Ingot Plates

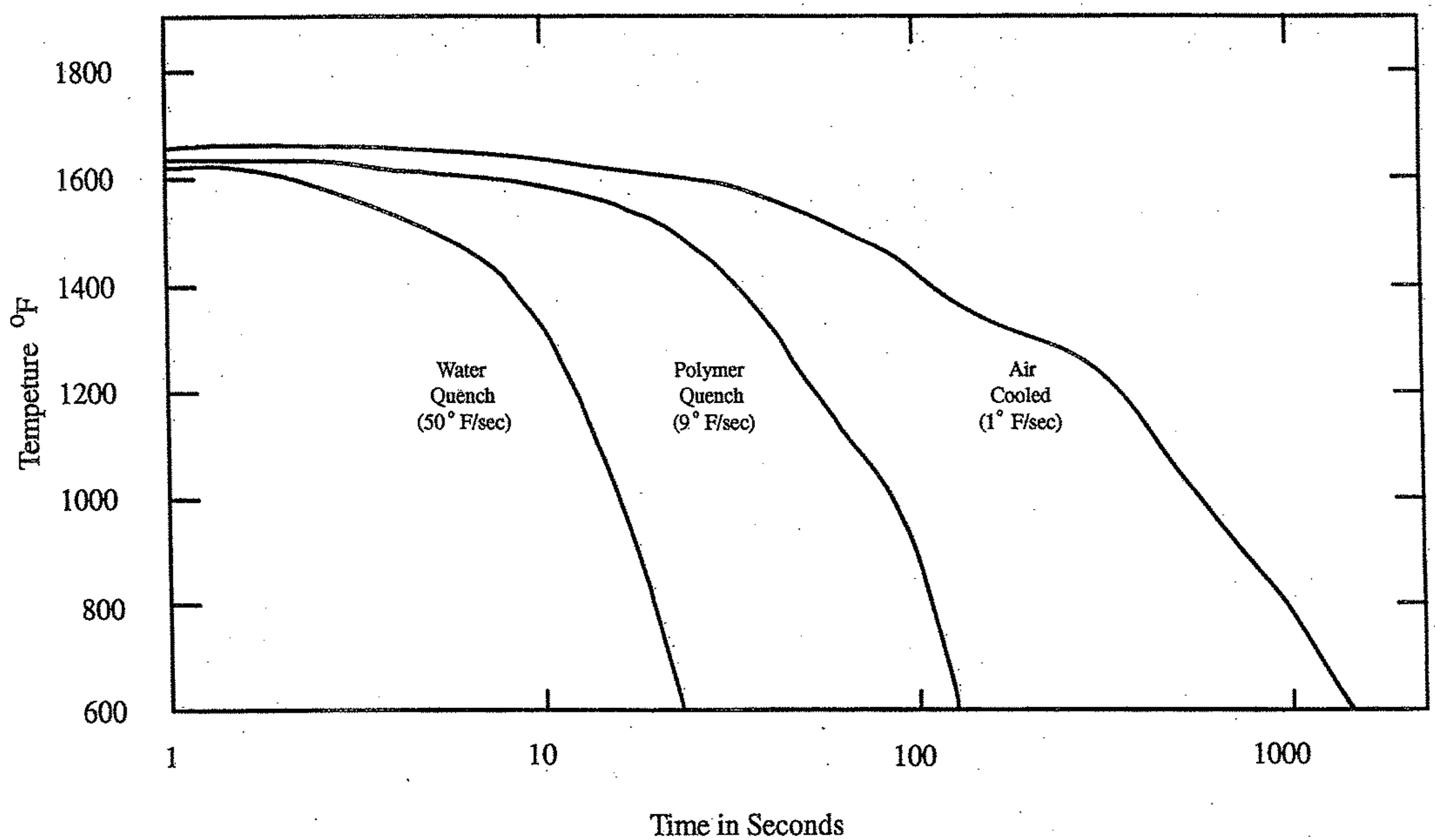


Figure 2 – Cooling Curves for One – Inch Plate

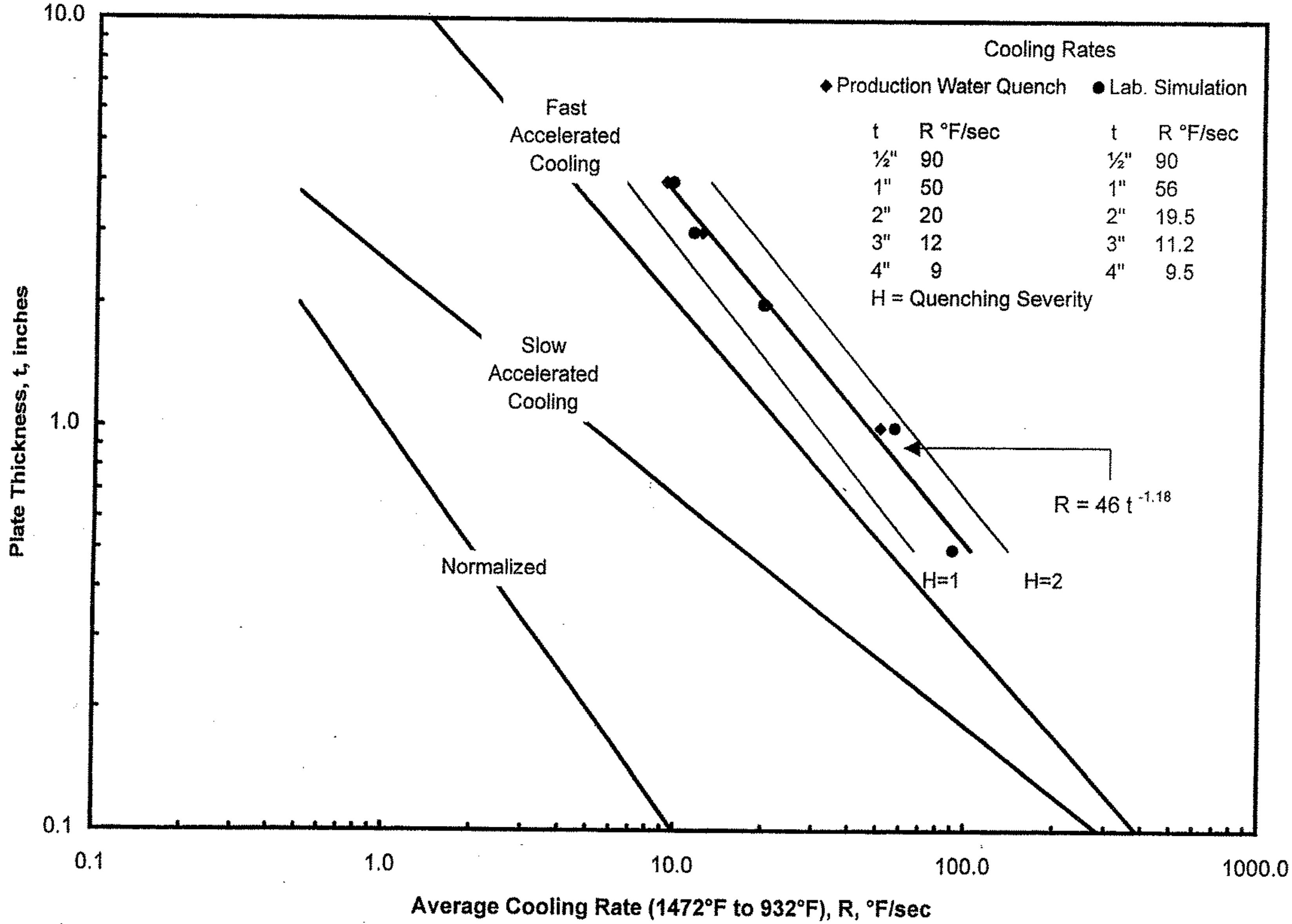


Figure 3 - Comparison of Laboratory and Production Cooling Practices

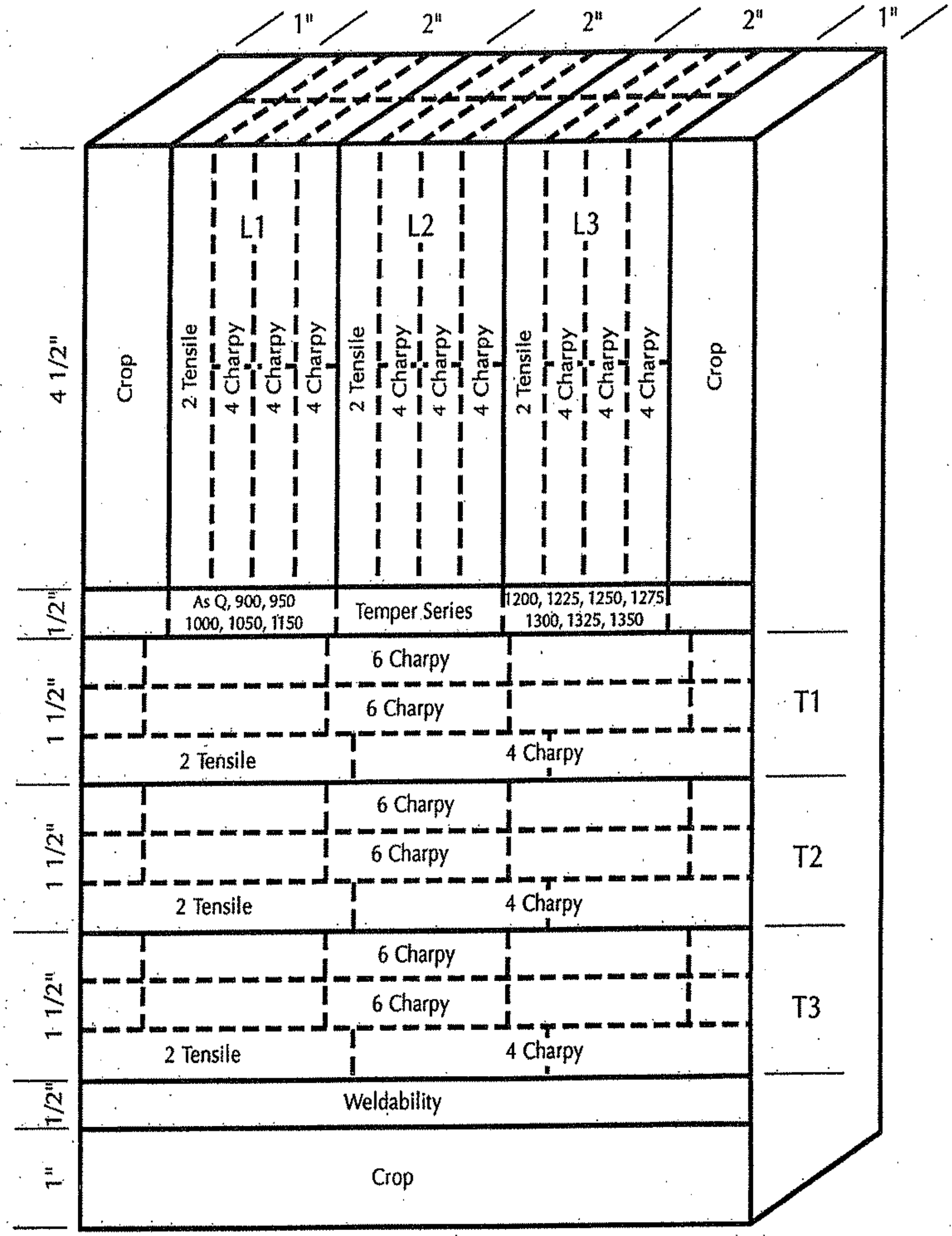


Figure 4 – Machining of Sections A and B from Figure 1 to Test Specimens

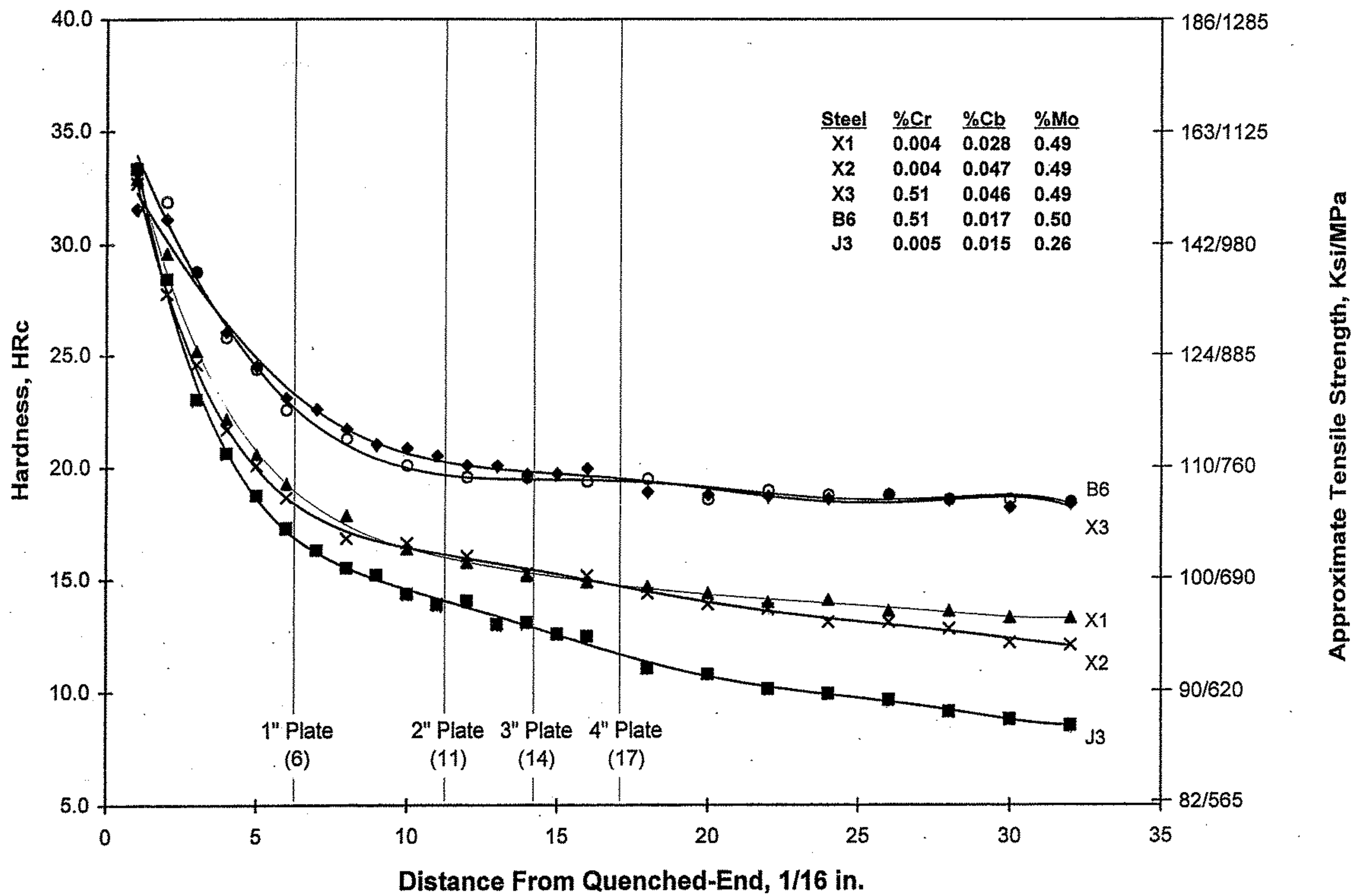


Figure 5 - The Effect of Columbium on Jominy End-Quench Hardenability Tests for X1, X2, X3, B6 and J3 Steel - As-Q

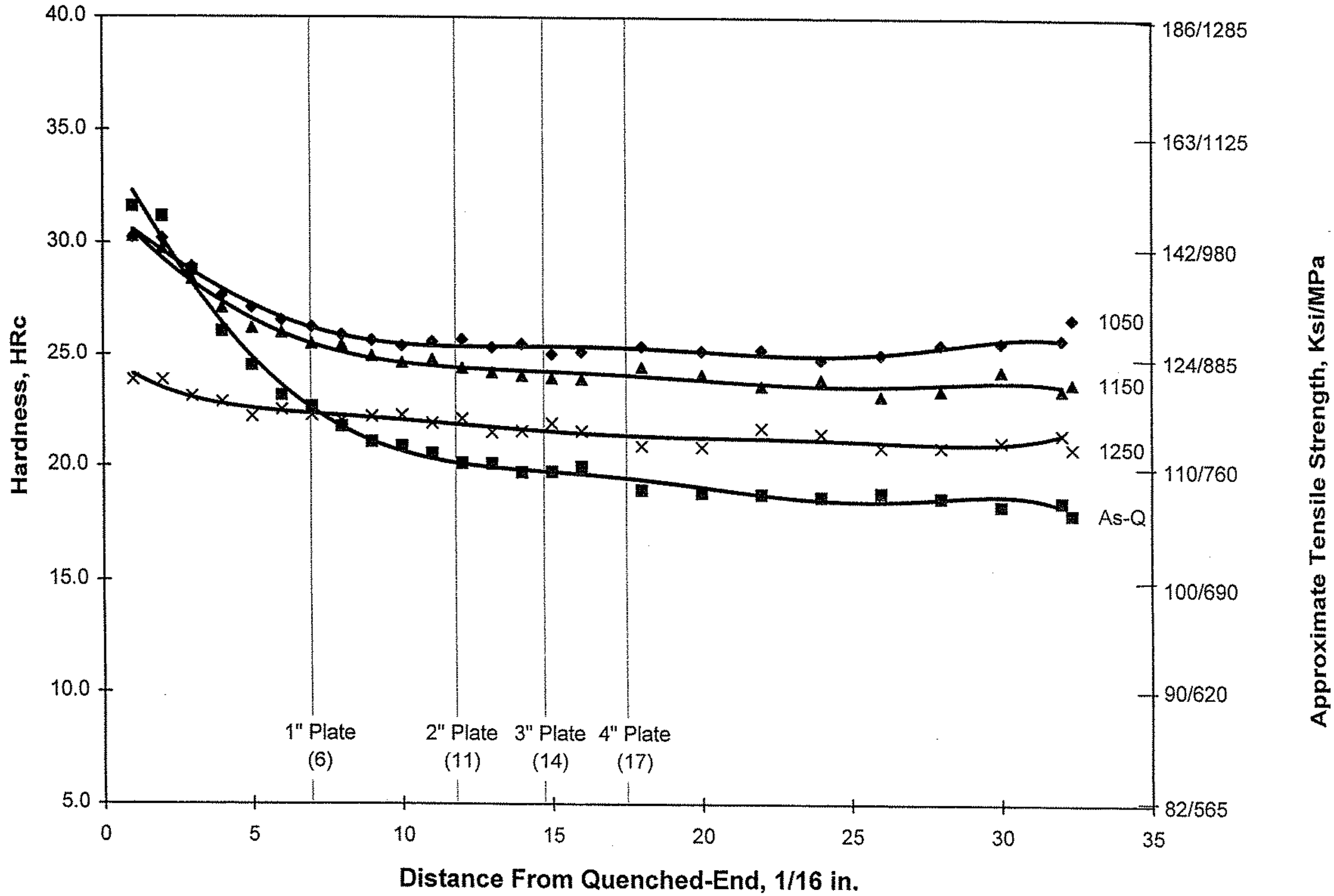


Figure 6 - The Effect of Tempering on Jominy End-Quench Hardenability Tests for B6 Steel

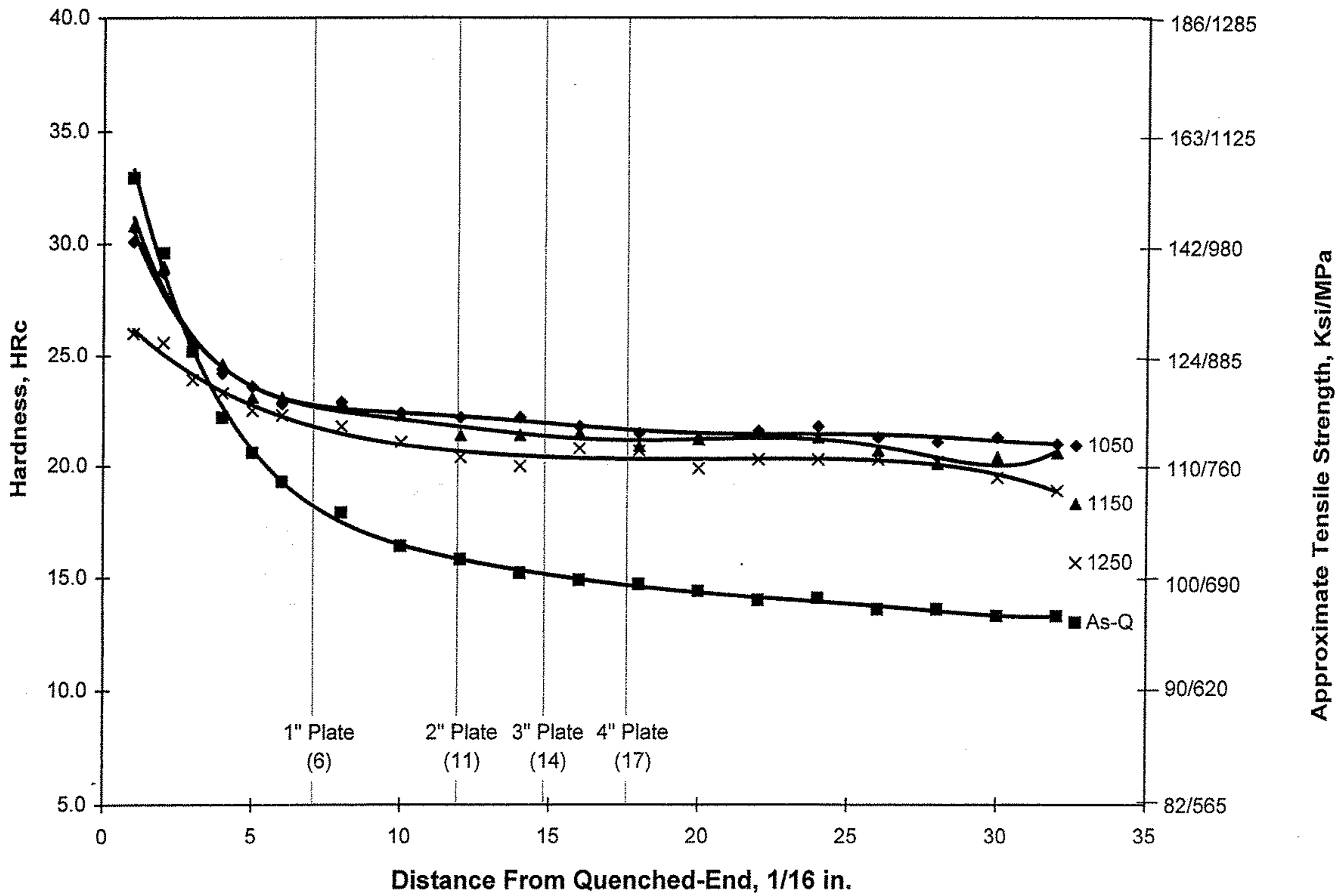


Figure 7 - The Effect of Tempering on Jominy End-Quench Hardenability Tests for X1 Steel

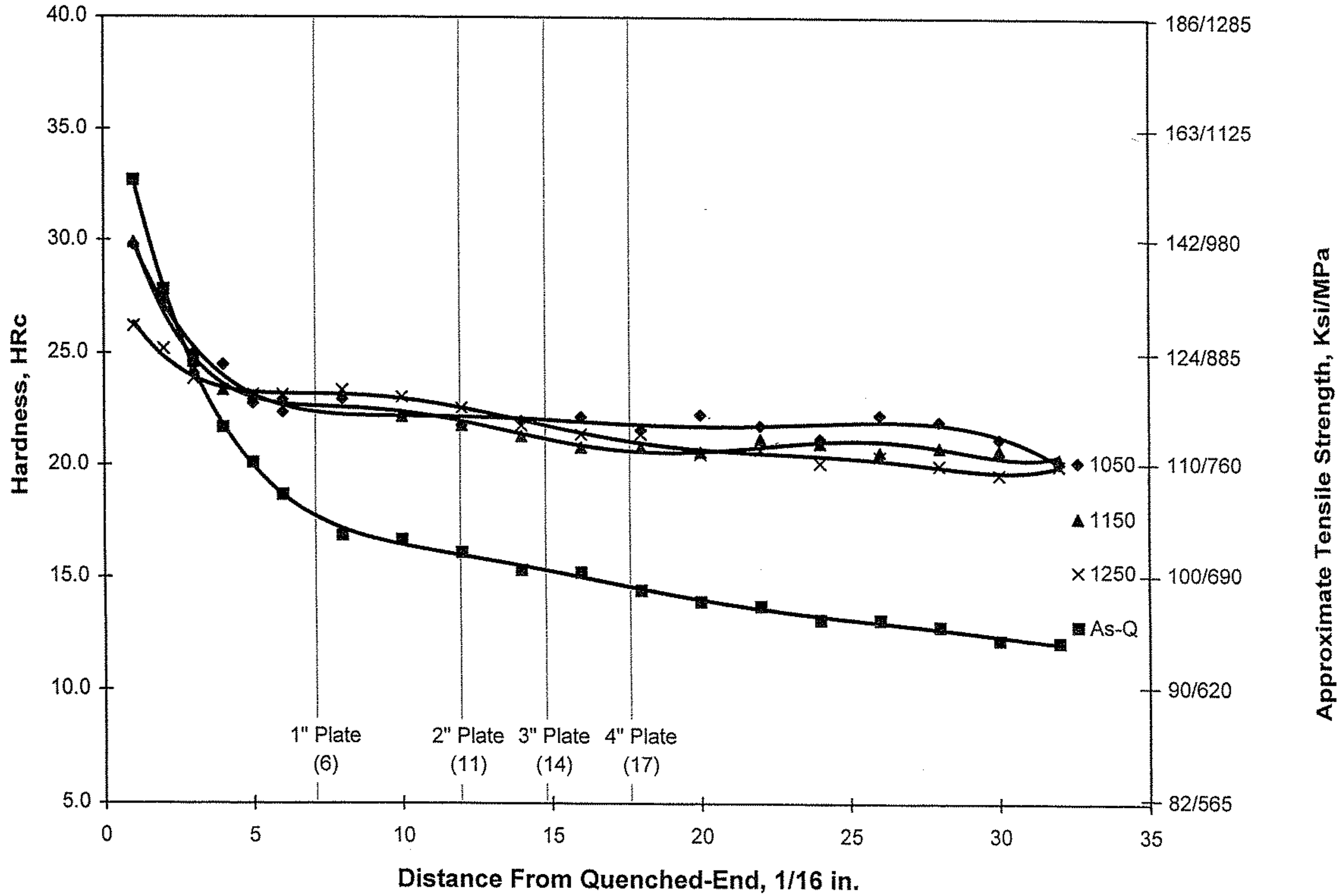


Figure 8 - The Effect of Tempering on Jominy End-Quench Hardenability Tests for X2 Steel

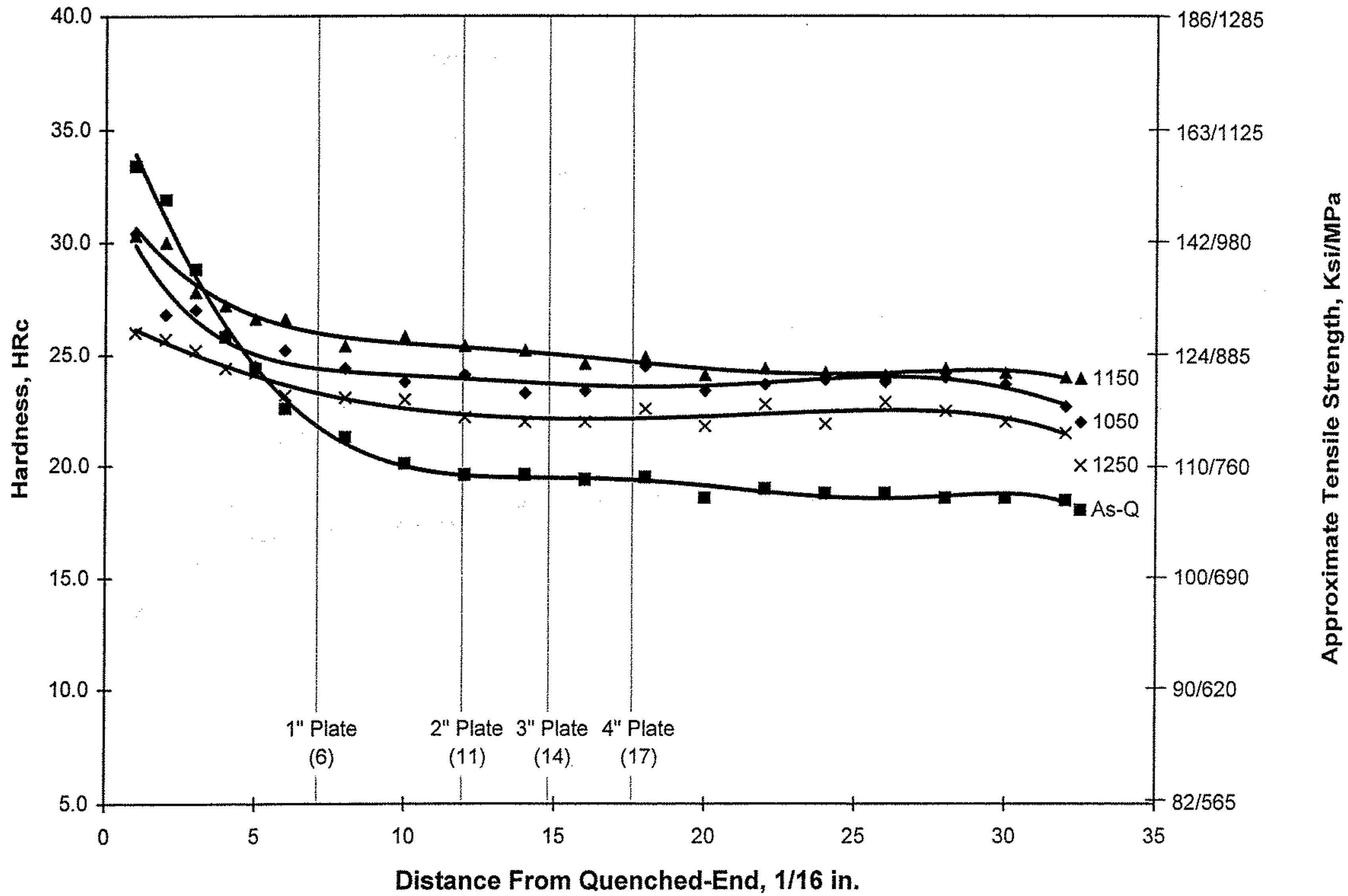


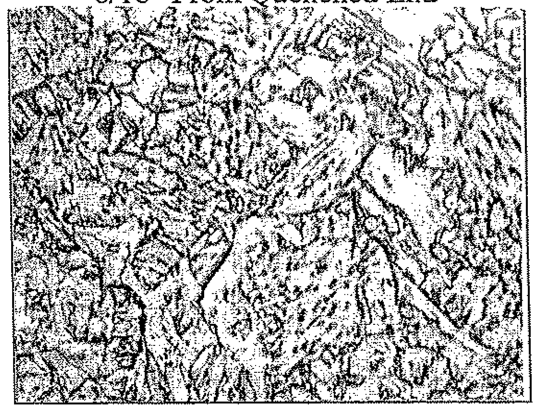
Figure 9 - The Effect of Tempering on Jominy End-Quench Hardenability Tests for X3 Steel

Steel X1

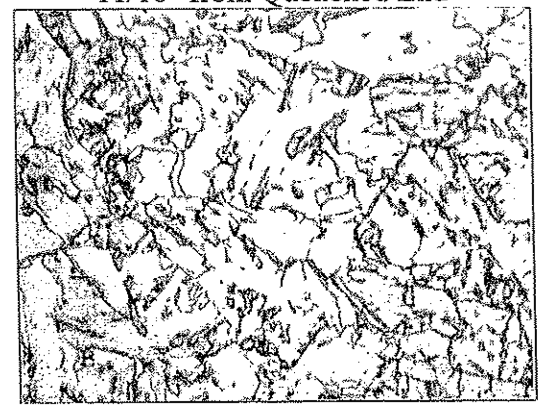
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.062	1.00	0.013	0.003	0.22	1.01	0.73	0.004	0.49	0.057	0.028	0.034

1/16" From Quenched End

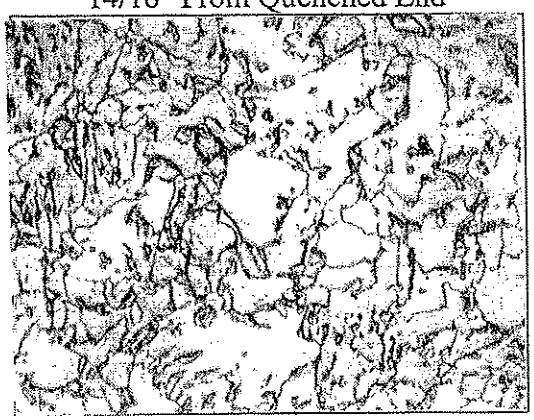
6/16" From Quenched End



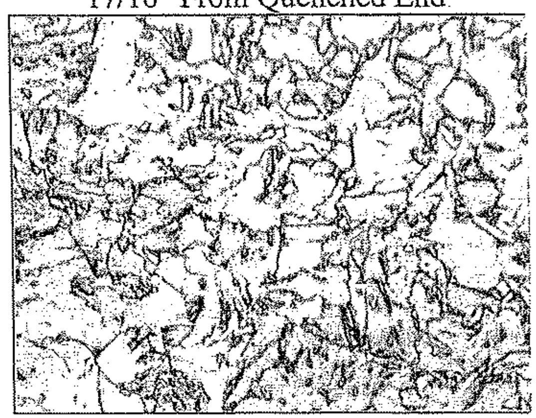
11/16" from Quenched End



14/16" From Quenched End



17/16" From Quenched End



32/16" from Quenched End

X850 Nital-Picral

Figure 10– Steel X1 Jominy End-Quench-Hardenability-Test Microstructures – As Quenched

Steel X2

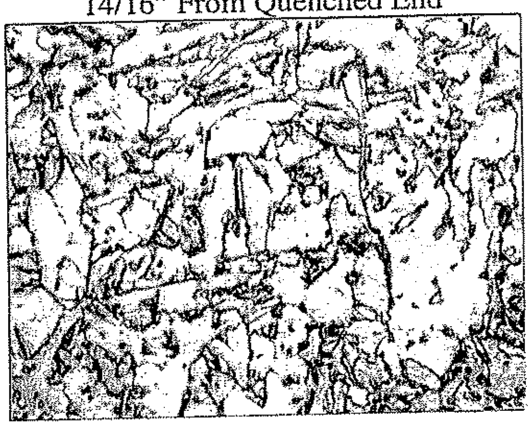
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.062	0.98	0.013	0.003	0.22	1.00	0.72	0.004	0.49	0.056	0.047	0.031

1/16" From Quenched End

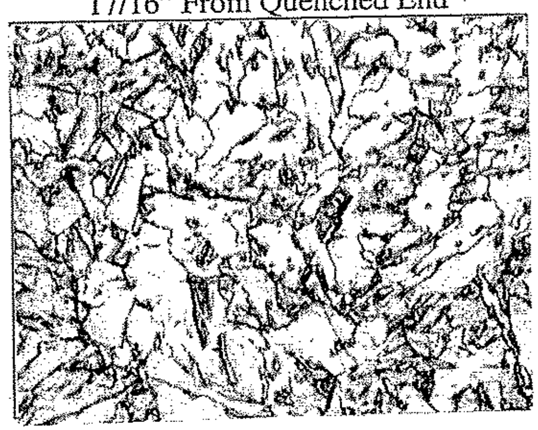
6/16" From Quenched End

11/16" from Quenched End

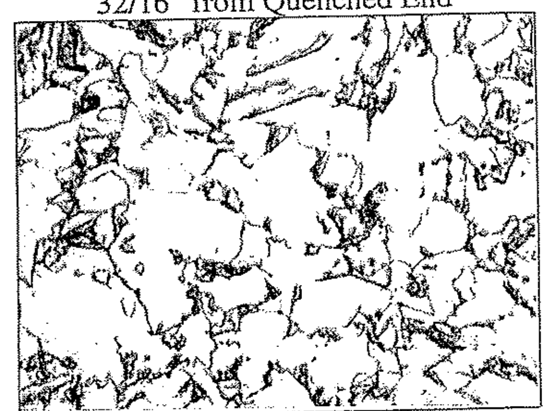
14/16" From Quenched End



17/16" From Quenched End



32/16" from Quenched End



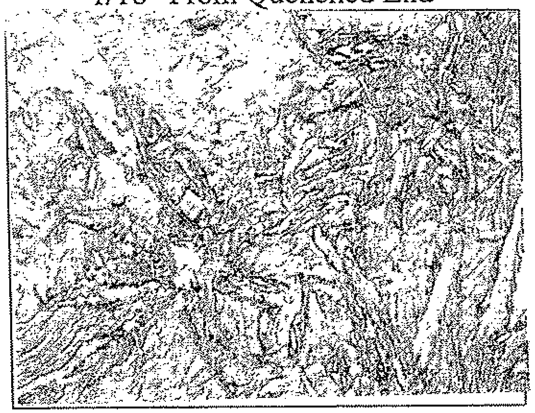
X850 Nital-Picral

Figure 11– Steel X2 Jominy End-Quench-Hardenability-Test Microstructures – As Quenched

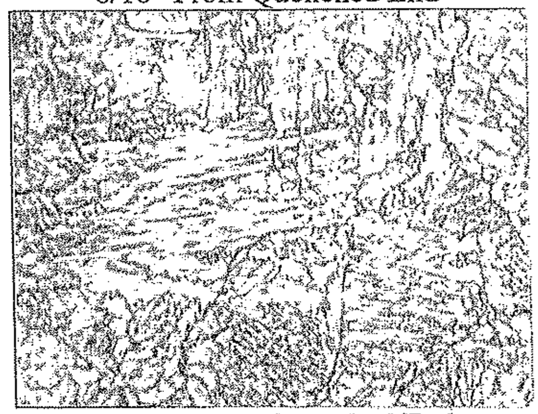
Steel X3

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.063	0.99	0.013	0.003	0.23	1.00	0.73	0.51	0.49	0.057	0.045	0.023

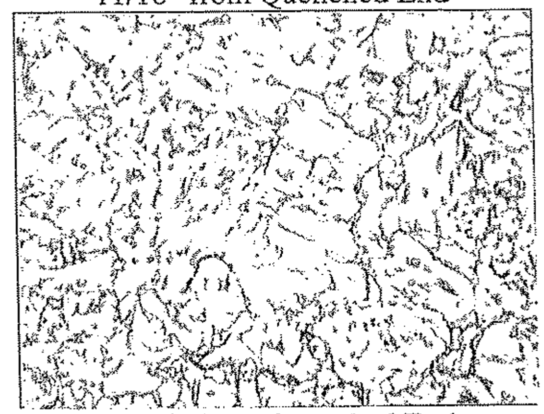
1/16" From Quenched End



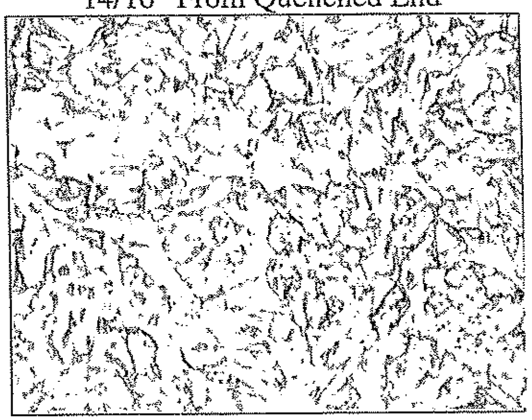
6/16" From Quenched End



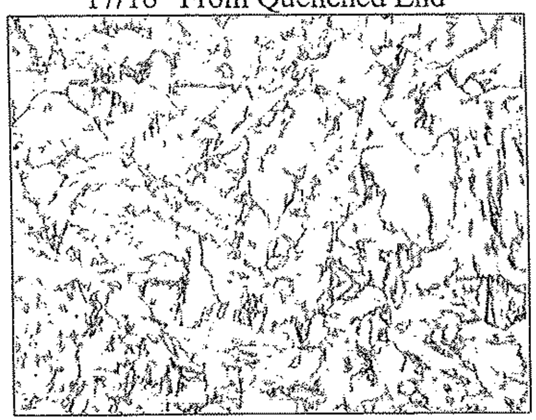
11/16" from Quenched End



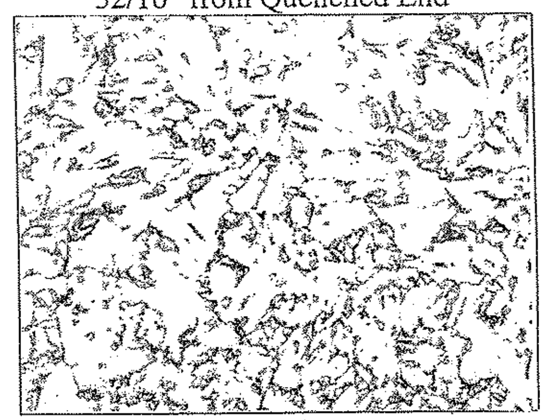
14/16" From Quenched End



17/16" From Quenched End

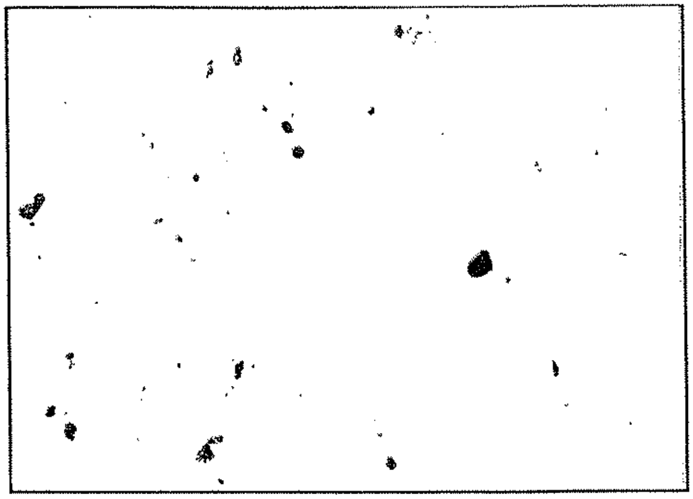


32/16" from Quenched End

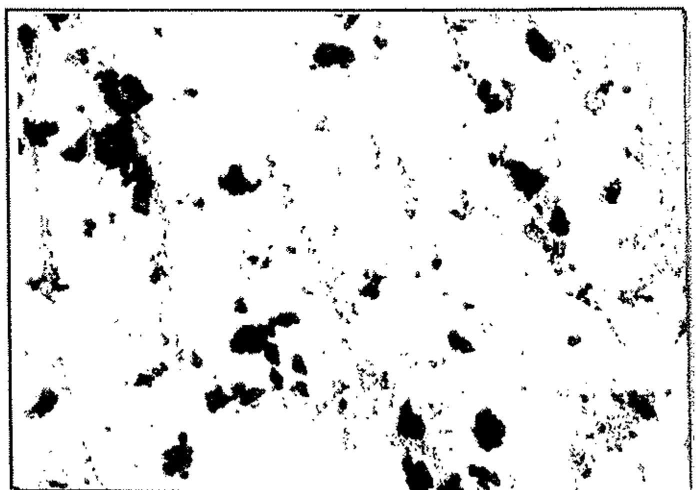


X850 Nital-Picral

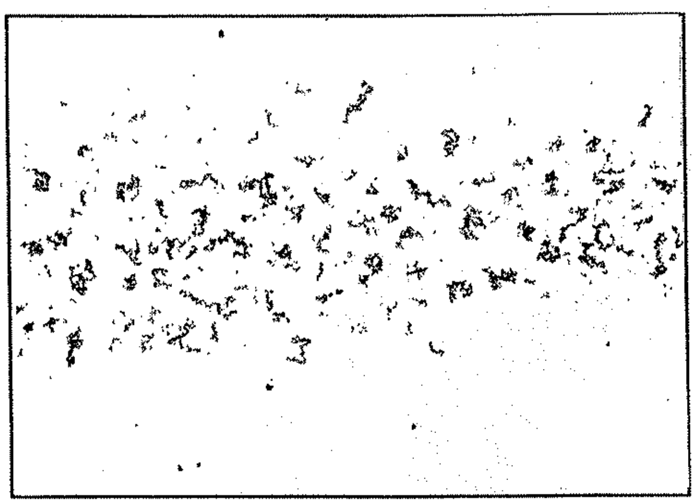
Figure 12– Steel X3 Jominy End-Quench-Hardenability-Test Microstructures – As Quenched



Ingot 1 (8044A)



Ingot 2 (8044B)



Ingot 3 (8044C)

Figure 13 - Selected Areas Illustrating Nonmetallic Inclusions in USS Heat No. 9902-8044. 85X Unetched

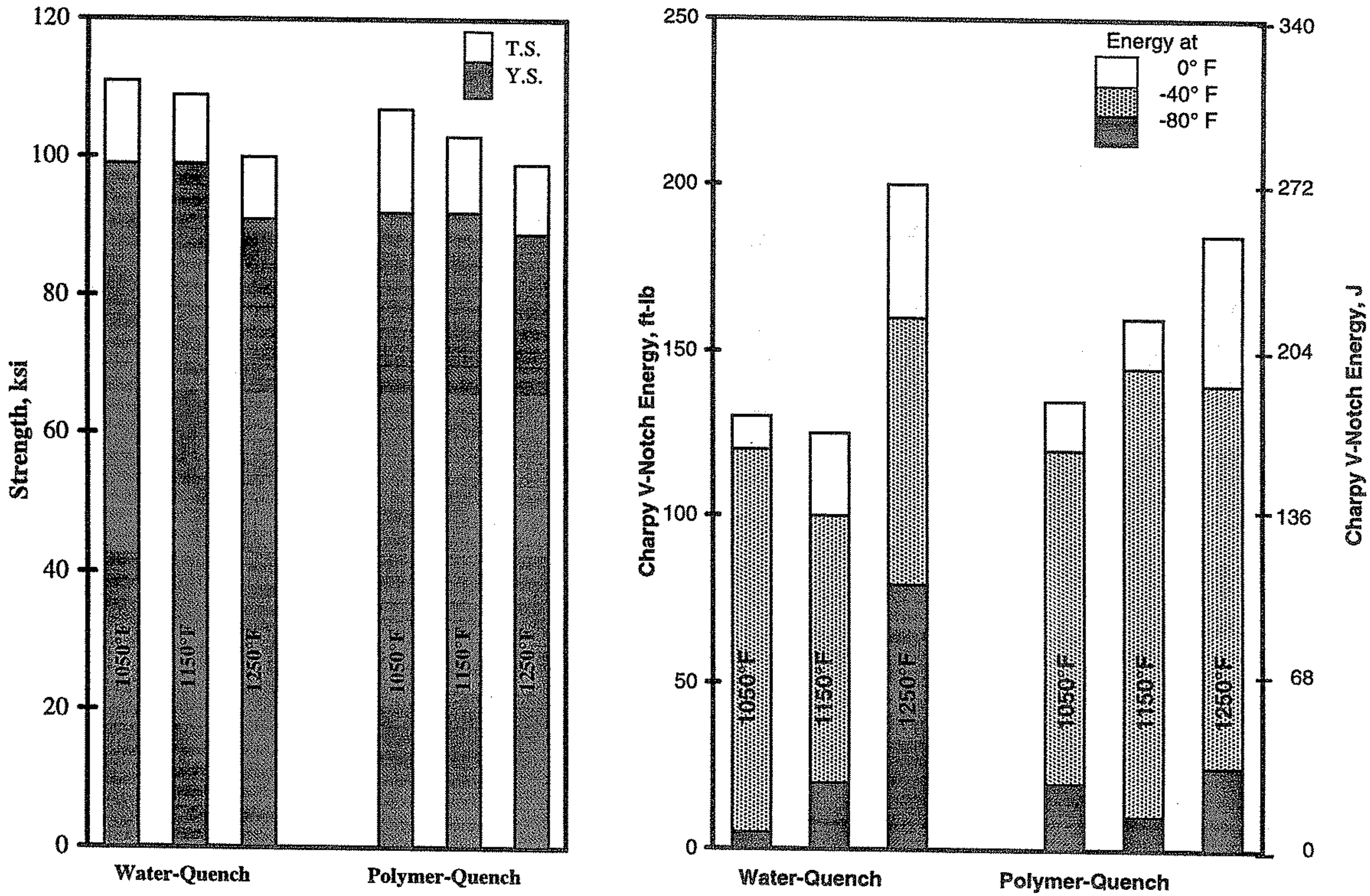


Figure 14 - Strength and Toughness Properties for X1 Steel after Various Heat Treatments

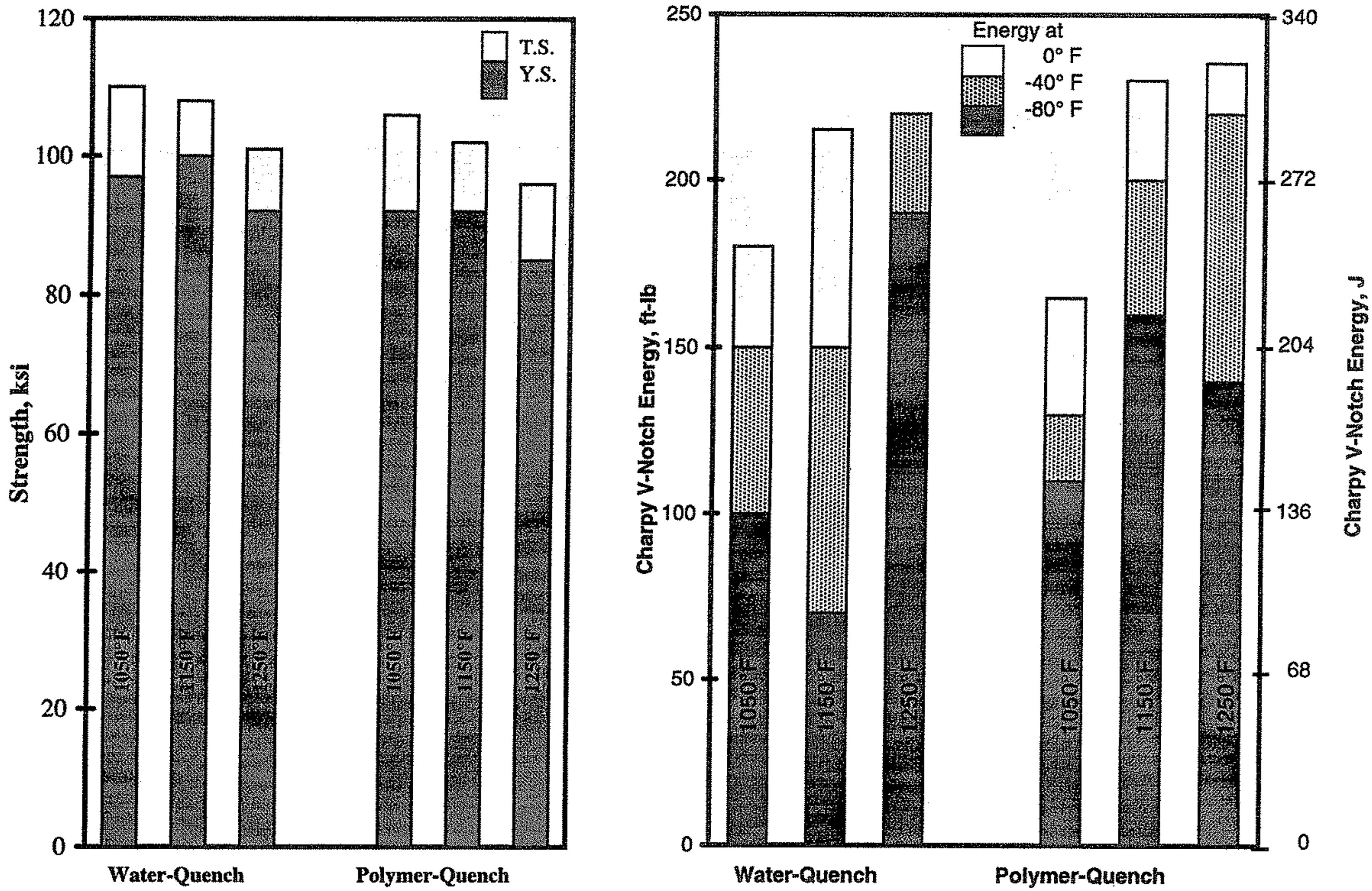


Figure 15 - Strength and Toughness Properties for X2 Steel after Various Heat Treatments

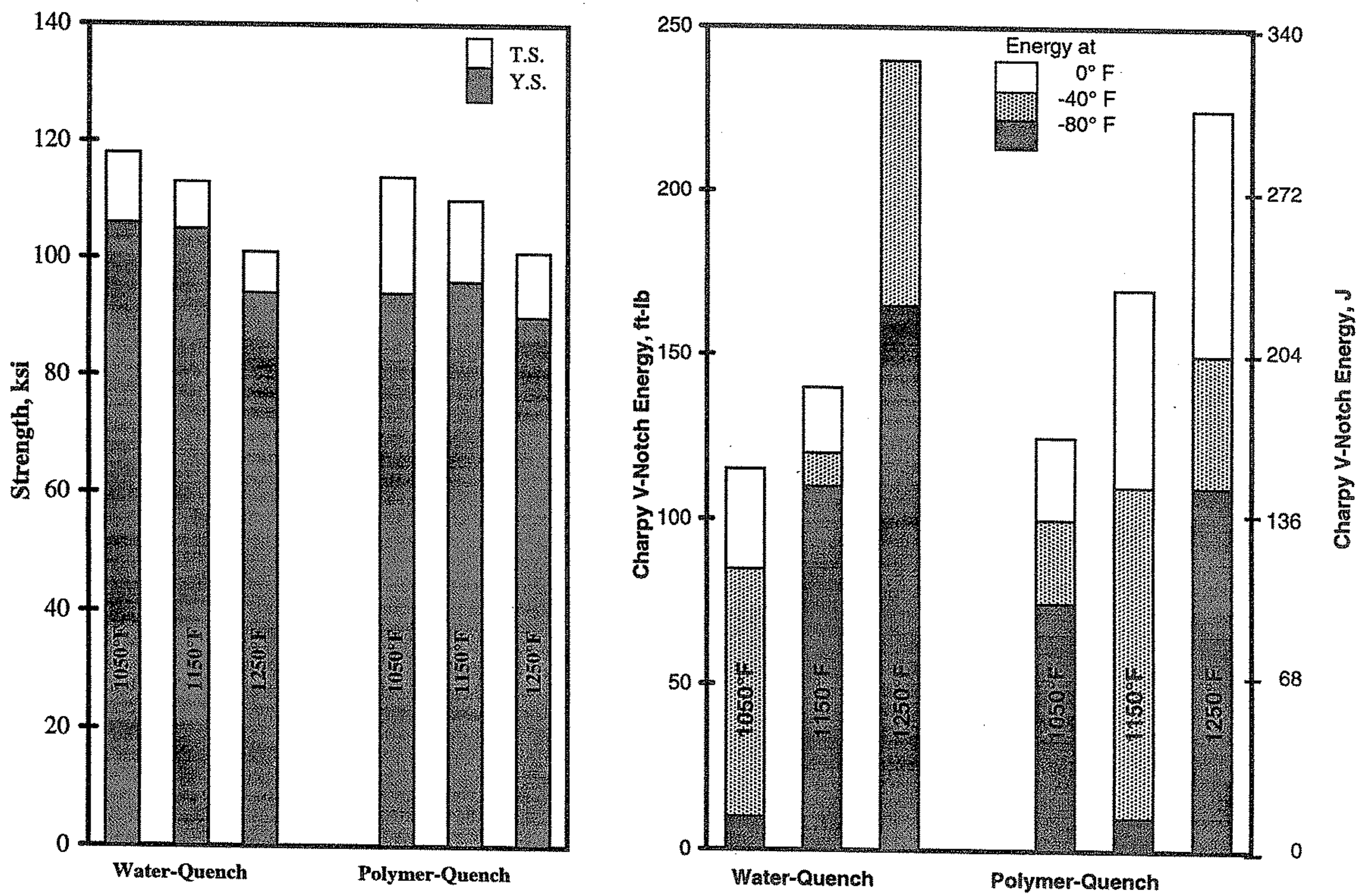
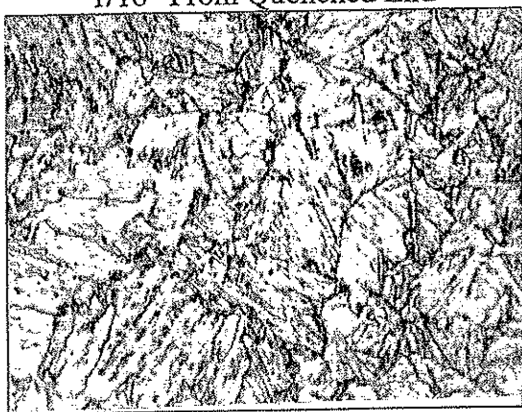


Figure 16 - Strength and Toughness Properties for X3 Steel after Various Heat Treatments

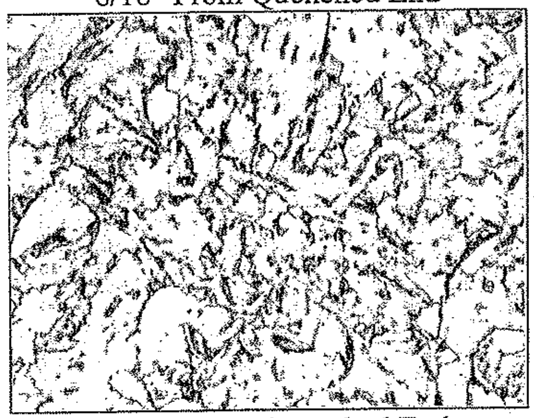
Steel X1

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.062	1.00	0.013	0.0028	0.22	1.01	0.73	0.004	0.49	0.057	0.028	0.034

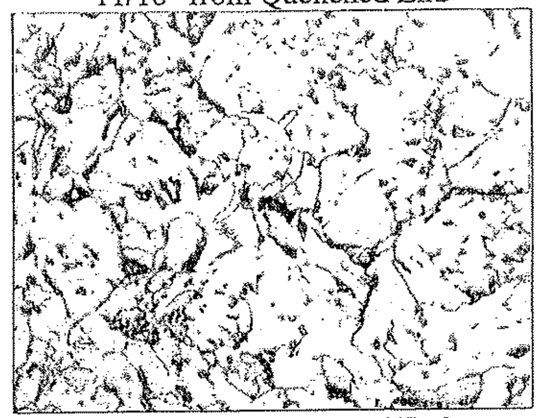
1/16" From Quenched End



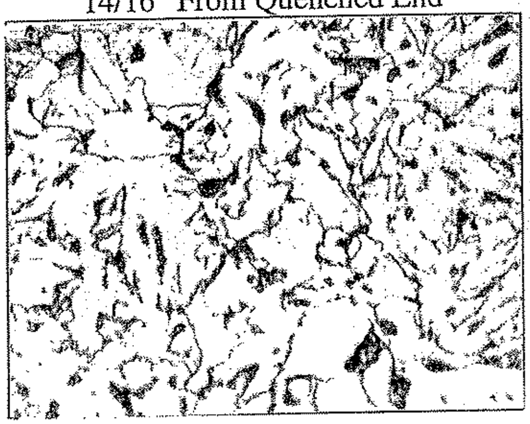
6/16" From Quenched End



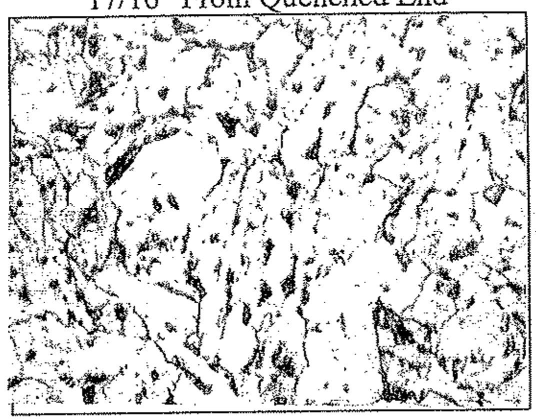
11/16" from Quenched End



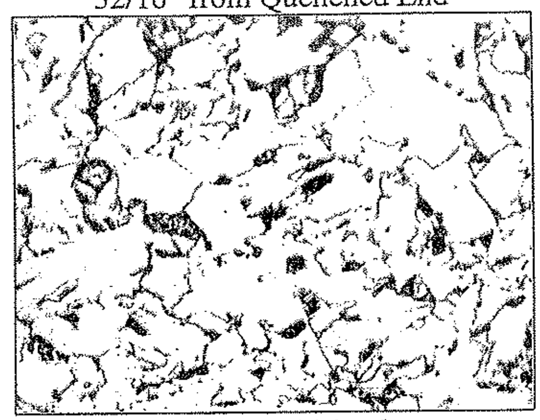
14/16" From Quenched End



17/16" From Quenched End



32/16" from Quenched End



X850 Nital-Picral

Figure A1 – Steel X1 Jominy End Quenched Hardenability Microstructures – Tempered 1050°F (565°C)

Steel X1

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.062	1.00	0.013	0.0028	0.22	1.01	0.73	0.004	0.49	0.057	0.028	0.034

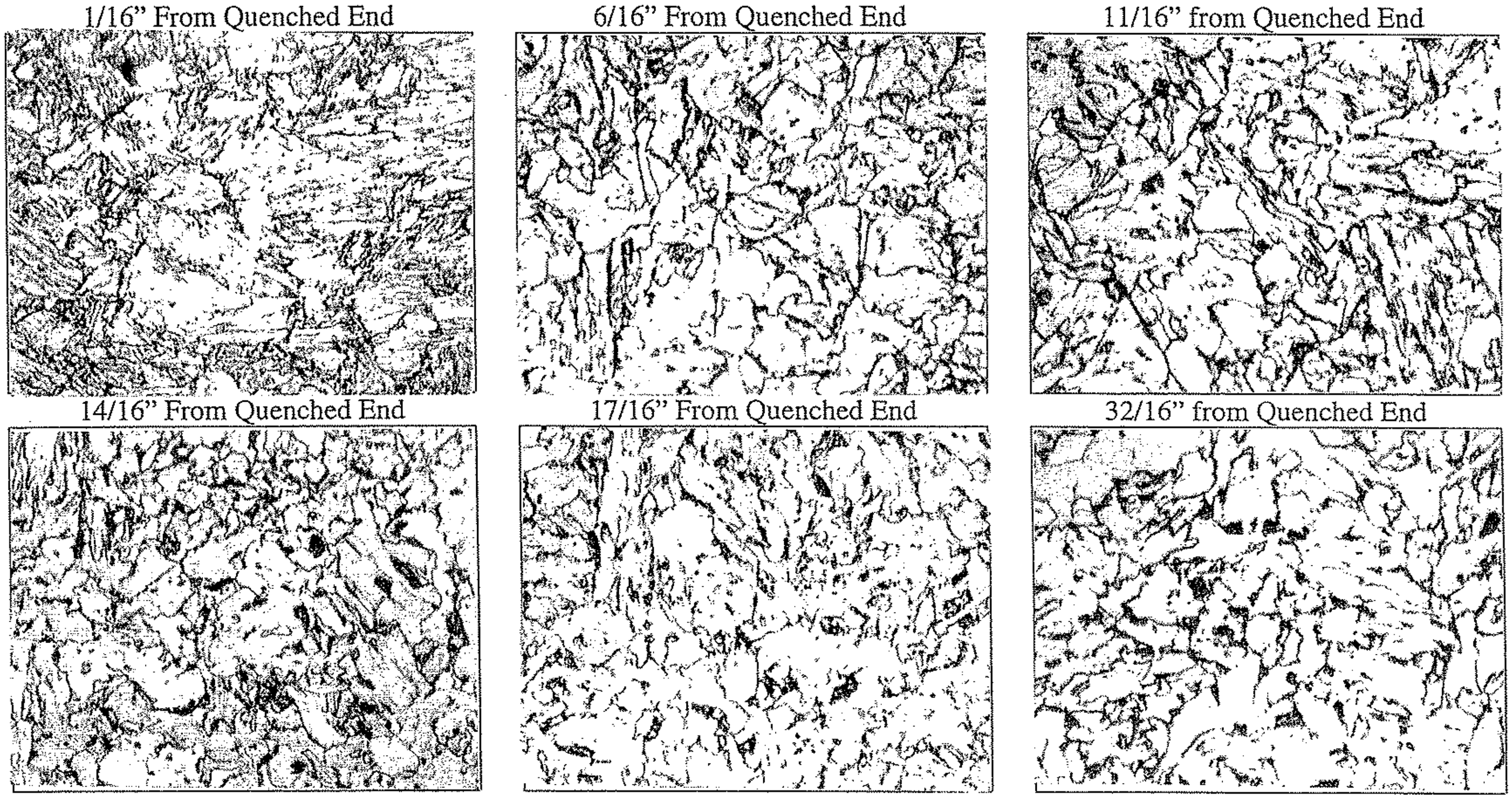


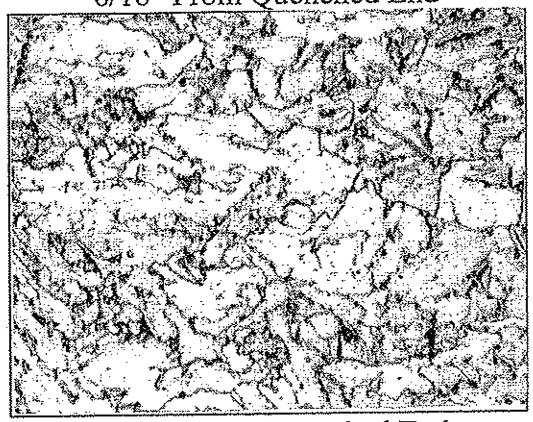
Figure A2 – Steel X1 Jominy End Quenched Hardenability Microstructures – Tempered 1150°F (620°C)

Steel X1

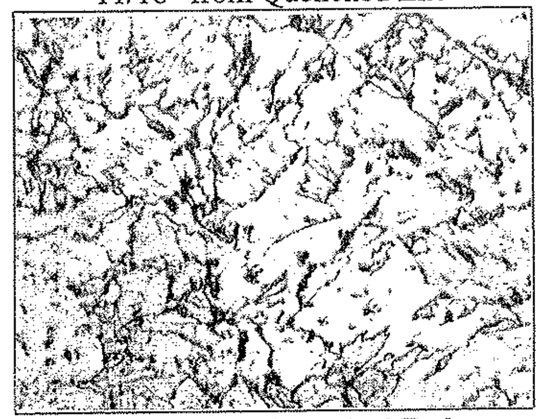
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.062	1.00	0.013	0.0028	0.22	1.01	0.73	0.004	0.49	0.057	0.028	0.034

1/16" From Quenched End

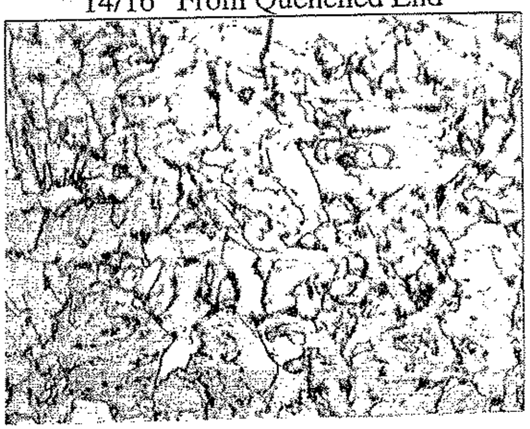
6/16" From Quenched End



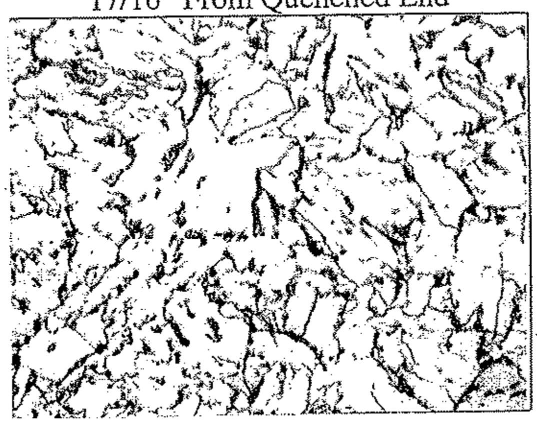
11/16" from Quenched End



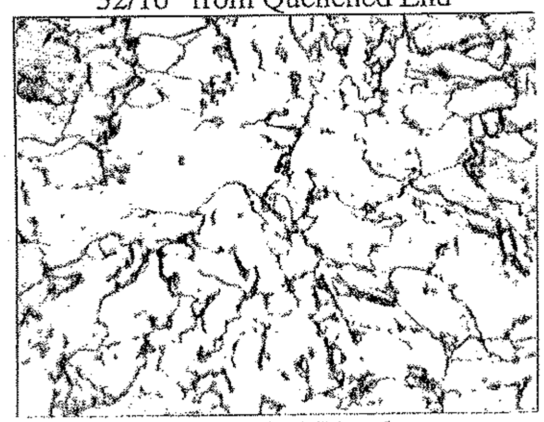
14/16" From Quenched End



17/16" From Quenched End



32/16" from Quenched End



X850 Nital-Picral

Figure A3 – Steel X1 Jominy End Quenched Hardenability Microstructures – Tempered 1250°F (675°C)

Steel X2

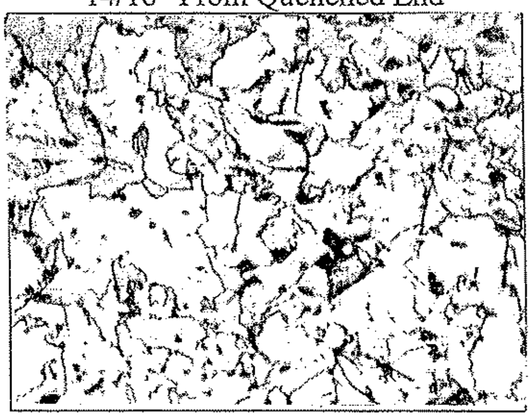
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.062	0.98	0.013	0.0026	0.22	1.00	0.72	0.004	0.49	0.056	0.047	0.031

1/16" From Quenched End

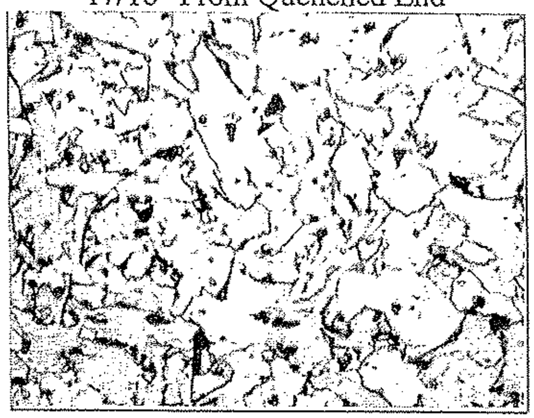
6/16" From Quenched End

11/16" from Quenched End

14/16" From Quenched End



17/16" From Quenched End



32/16" from Quenched End

X850 Nital-Picral

Figure A4 – Steel X2 Jominy End Quenched Hardenability Microstructures – Tempered 1050°F (565°C)

Steel X2

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.062	0.98	0.013	0.0026	0.22	1.00	0.72	0.004	0.49	0.056	0.047	0.031

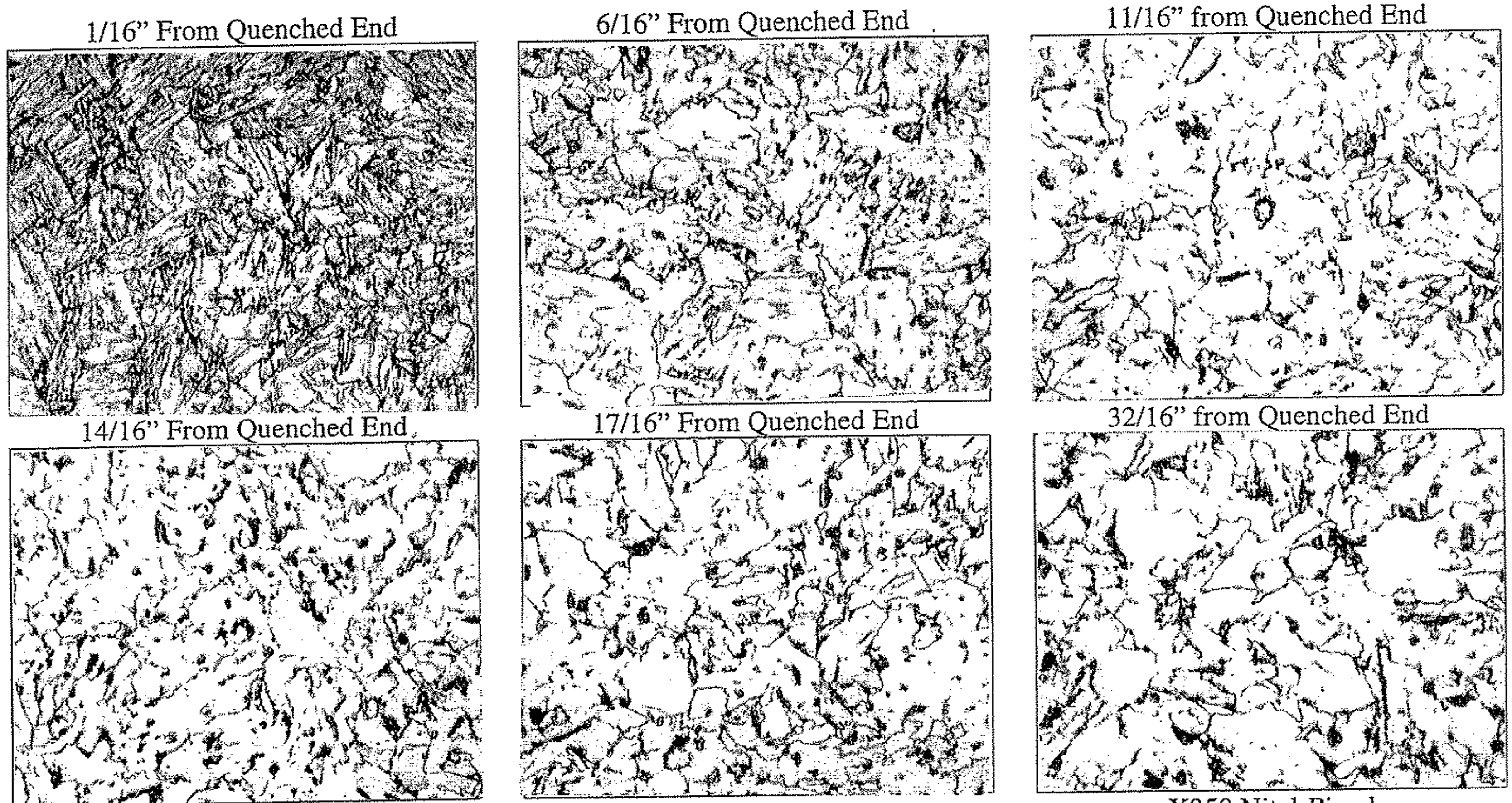


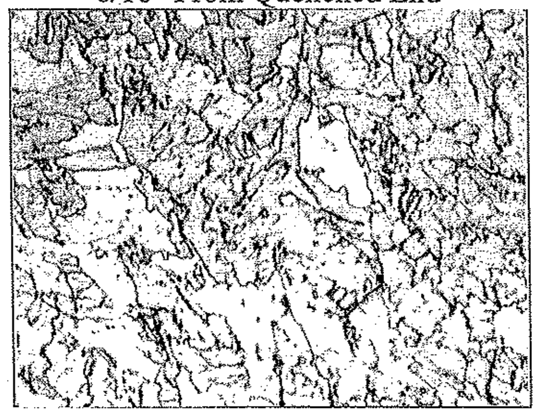
Figure A5 – Steel X2 Jominy End Quenched Hardenability Microstructures – Tempered 1150°F (620°C)

Steel X2

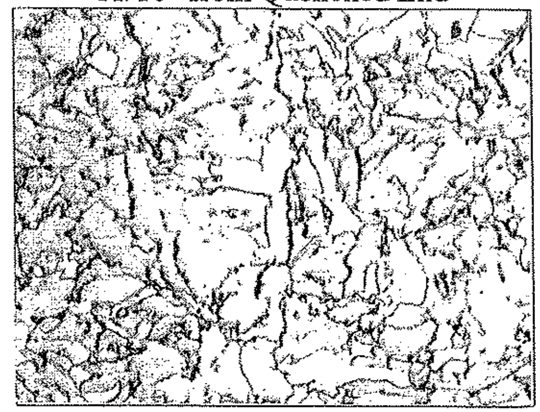
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.062	0.98	0.013	0.0026	0.22	1.00	0.72	0.004	0.49	0.056	0.047	0.031

1/16" From Quenched End

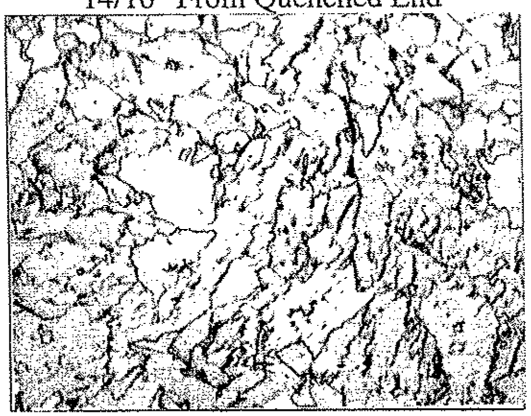
6/16" From Quenched End



11/16" from Quenched End

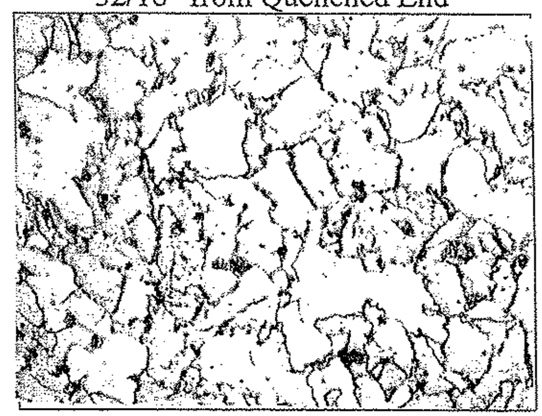


14/16" From Quenched End



17/16" From Quenched End

32/16" from Quenched End



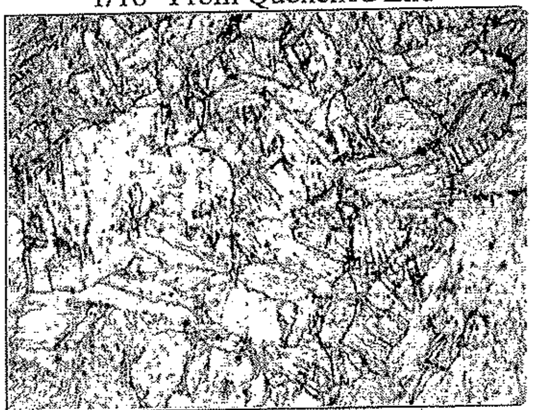
X850 Nital-Picral

Figure A6 – Steel X2 Jominy End Quenched Hardenability Microstructures – Tempered 1250°F (675°C)

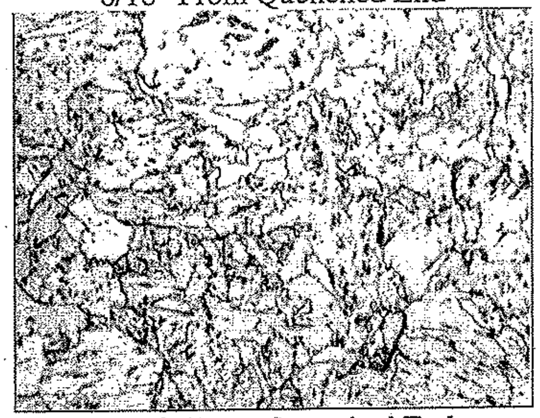
Steel X3

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.063	0.99	0.013	0.0028	0.23	1.00	0.73	0.51	0.49	0.057	0.045	0.023

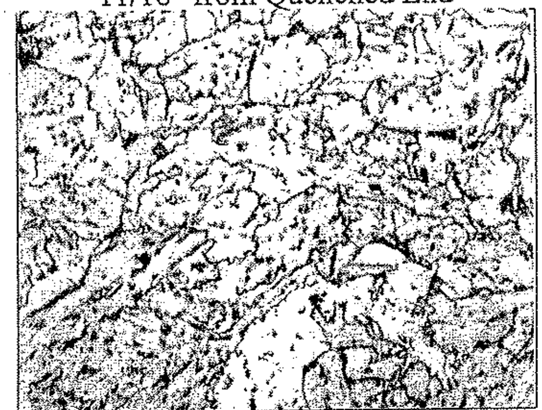
1/16" From Quenched End



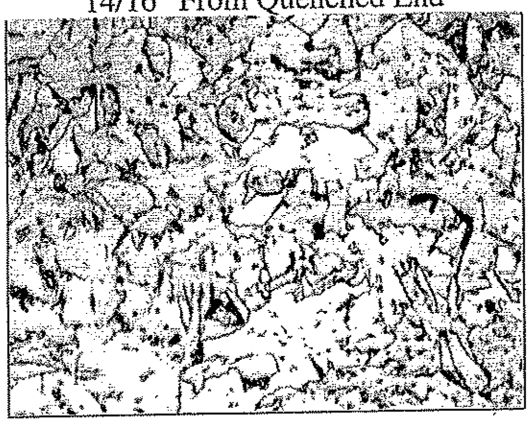
6/16" From Quenched End



11/16" from Quenched End

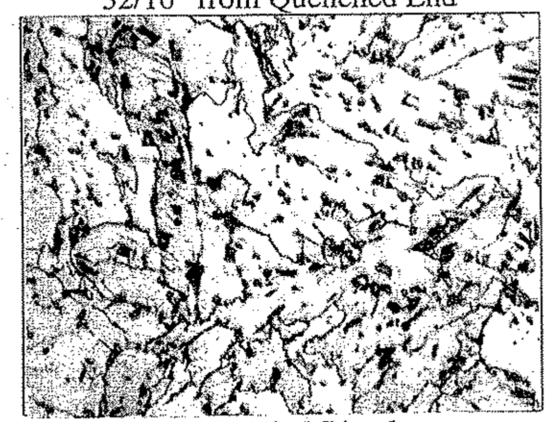


14/16" From Quenched End



17/16" From Quenched End

32/16" from Quenched End



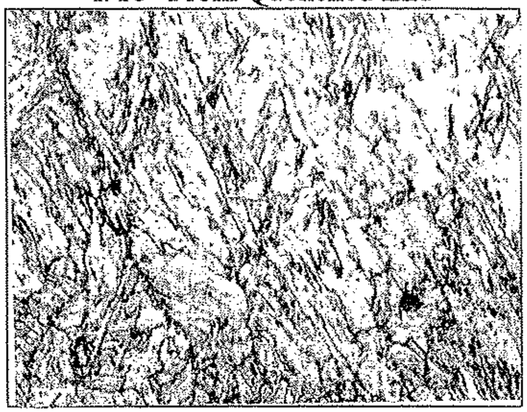
X850 Nital-Picral

Figure A7 – Steel X3 Jominy End Quenched Hardenability Microstructures – Tempered 1050°F (565°C)

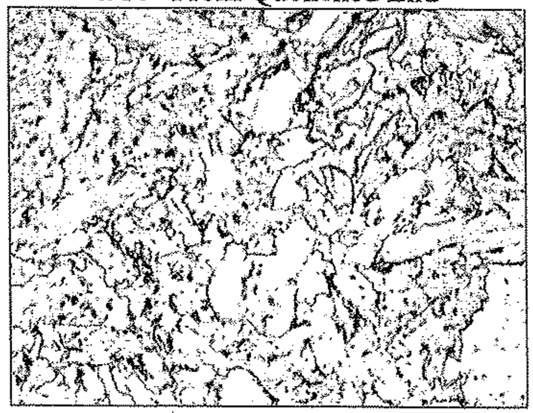
Steel X3

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.063	0.99	0.013	0.0028	0.23	1.00	0.73	0.51	0.49	0.057	0.045	0.023

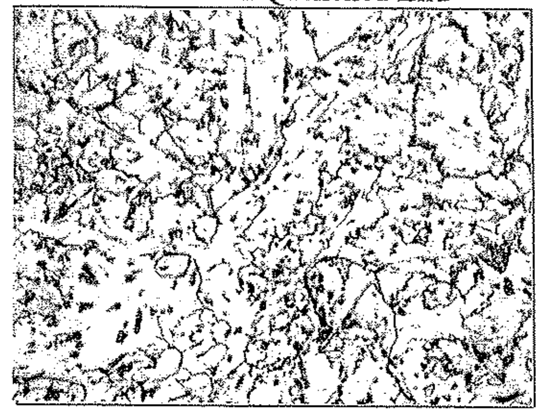
1/16" From Quenched End



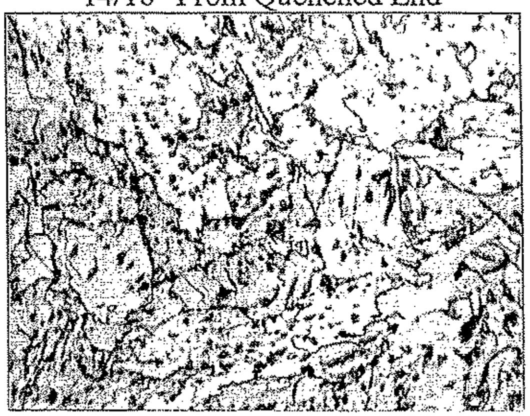
6/16" From Quenched End



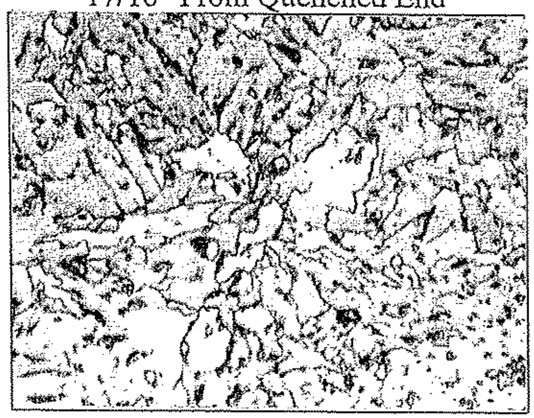
11/16" from Quenched End



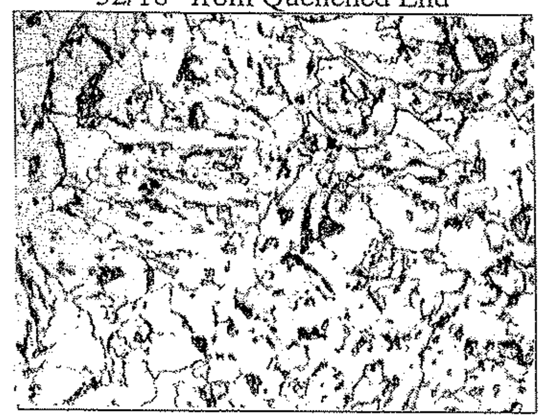
14/16" From Quenched End



17/16" From Quenched End



32/16" from Quenched End



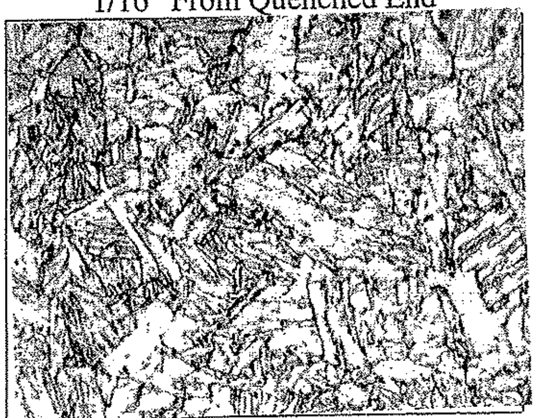
X850 Nital-Picral

Figure A8 – Steel X3 Jominy End Quenched Hardenability Microstructures – Tempered 1150°F (620°C)

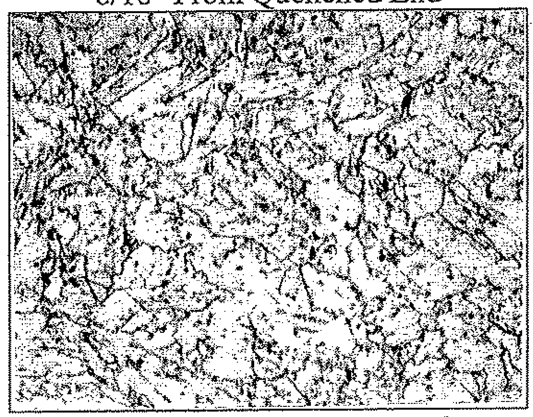
Steel X3

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.063	0.99	0.013	0.0028	0.23	1.00	0.73	0.51	0.49	0.057	0.045	0.023

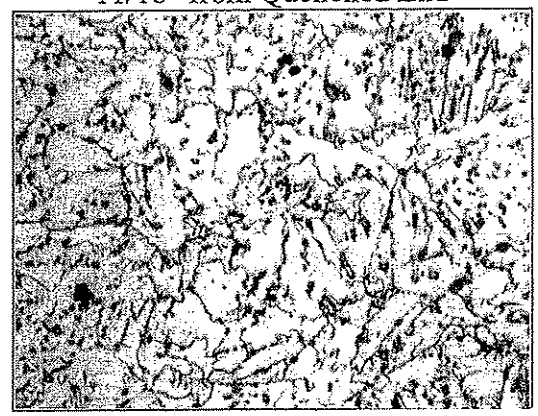
1/16" From Quenched End



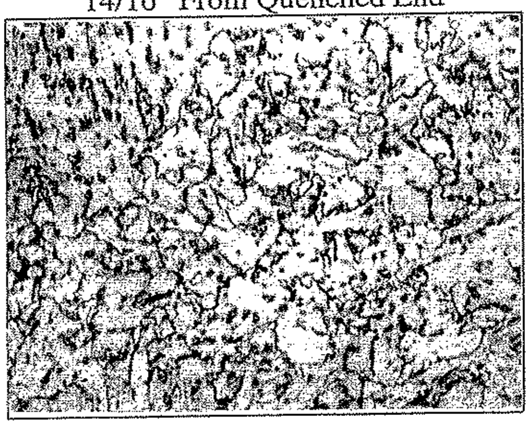
6/16" From Quenched End



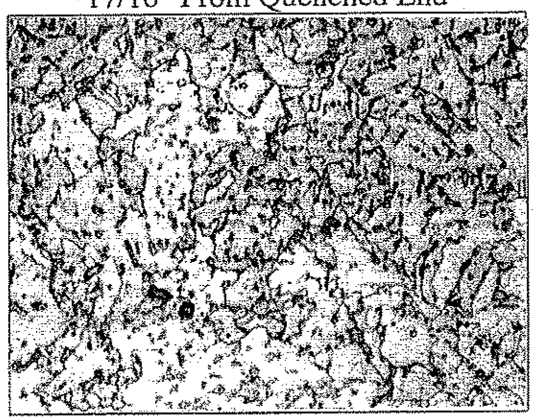
11/16" from Quenched End



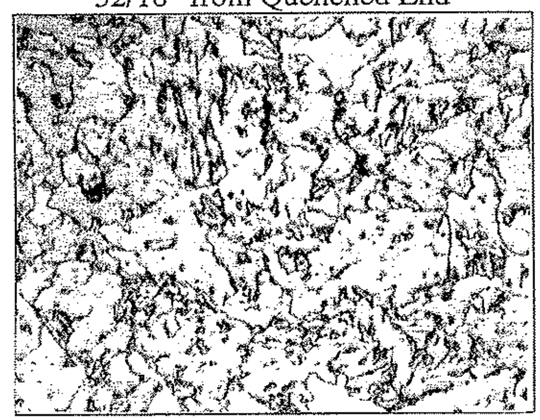
14/16" From Quenched End



17/16" From Quenched End



32/16" from Quenched End



X850 Nital-Picral

Figure A9 – Steel X3 Jominy End Quenched Hardenability Microstructures – Tempered 1250°F (675°C)