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ATLAS of Transformation Characteristics for Precipitation-Strengthened Cu-Ni Infrastructure Steels

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ATLAS OF TRANSFORMATION CHARACTERISTICS FOR PRECIPITATION-STRENGTHENED Cu-Ni INFRASTRUCTURE STEELS

by

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ABSTRACT

The copper-nickel alloy-steel system, which is based on precipitation-strengthening, offers significant potential for a variety of infrastructure applications because of its outstanding weldability and fracture toughness. This occurs because this strengthening mechanism permits the carbon content to be reduced from the typical 0.15 to 0.20 percent for constructional alloy steels to 0.04 to 0.08 percent at yield strengths in the range 90 to 130 ksi (690 to 900 MPi).

To optimize the chemical composition of this system, ATLSS has been studying the performance of experimental Cu-Ni steels. Initial studies involved the 1.0 % Cu-0.75% Ni steels for civilian applications such as bridges at yield strengths of 100 ksi (690 MPi). To demonstrate the suitability of these steels, a 150-ton commercial heat was produced for testing. The mechanical properties of this steel at a minimum yield strength of 100 ksi for plate thicknesses through 2 inches were excellent and plates were tested at ATLSS as various large-scale structural components, and by ATLSS and other laboratories for weldability with favorable results. Plates from a second production heat of Steel B were fabricated into girders for a 190-foot overpass across I-80 near Omaha, Nebraska. These results validated the Cu-Ni HPS 100W steel for civilian infrastructure applications, such as bridges.

Information from these studies is being compiled herein as an atlas to facilitate the selection of compositions and heat treatments for specific applications within the range of compositions evaluated. Included is information on hardenability, mechanical properties, and microstructures.

Recent studies summarized herein suggest that a 2.5 percent nickel Cu-Ni steel may be suitable at yield strengths up to 130 ksi for applications requiring fracture-transition-plastic behavior. Therefore, a program is recommended to produce a commercial heat of this composition for validation tests such as those described for Cu-Ni HPS 100W steel.

INTRODUCTION

The copper-nickel alloy-steel system, which is based on precipitation strengthening, offers significant potential for a variety of infrastructure applications because of its outstanding weldability and fracture toughness. This occurs because this strengthening mechanism permits the carbon content to be reduced from the typical 0.15 to 0.20 percent for constructional alloy steels to 0.04 to 0.08 percent at yield strengths in the range 90 to 130 ksi (690 to 900 MPi). To optimize the chemical composition of this system, ATLSS has been studying* the performance of a number of experimental Cu-Ni steels. Initial studies involved 1.00% copper-0.75% nickel steels (A,B,E,F) having the aim compositions listed below, and were investigated for civilian applications such as bridges at yield strengths of 100 ksi (690 MPi). Recently, Jominy hardenability tests were conducted on 1.00%Cu- 2.50% nickel steels (C,D,G,H) along with the mechanical properties for Steel H for applications requiring fracture-toughness-plastic performance.

Steel+	Mn	Cu	Ni	Cr	Mo	V	Cb	D_i**
A6	1.00	1.00	0.75	0.50	0.25	0.06	0.015	1.20
B6	1.00	"	0.75	"	0.50	"	"	1.60
C6	1.00	"	2.50	"	0.25	"	"	1.90
D6	1.00	"	2.50	"	0.50	"	"	2.53
E6	1.50	"	0.75	"	0.25	"	"	1.70
F6	1.50	"	0.75	"	0.50	"	"	2.30
G6	1.50	"	2.50	"	0.25	"	"	2.69
H6	1.50	"	2.50	"	0.50	"	"	3.75

+The steels were evaluated at a carbon content of 0.06%., **ASTM Formula

Steel B was selected to demonstrate the suitability of the 0.75 percent nickel steels (A,B,E,F) for civilian infrastructure applications, and a 150-ton commercial heat was produced for testing. The mechanical properties of this steel at a minimum yield strength of 100 ksi for plate thicknesses through 2 inches were excellent and plates were tested at ATLSS as various large-scale structural components, and by ATLSS and other laboratories for weldability with favorable results. Plates from a second production heat of Steel B were fabricated without preheat into girders for a 190-foot overpass across I-80 near Omaha, Nebraska. These results validated the Cu-Ni system for civilian infrastructure applications, such as bridges.

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* See References

EXPERIMENTAL PROCEDURE

The eight experimental Cu-Ni steels were melted by the U.S.Steel Technical Center as 300-pound heats that were cast sequentially into three 100-pound molds at carbon contents of 0.04, 0.06, or 0.08 percent. The resultant compositions are listed on the Jominy hardenability figures for the 0.06% carbon steels. The individual ingots were straightaway-rolled to 1-inch-thick (25.4 mm) plates. The plates were austenitized and quenched to simulate production spray-quenching of 1-inch plate-thick plate by water quenching and of 3-inch-thick plate by quenching 1-inch-thick plate in water containing 5% polyglycol.

The plates were tested (1) to establish their hardenability characteristics, and (2) to portray their resultant microstructures and mechanical properties. The cooling rates at the midthickness of plates of various thickness are identified on the Jominy plots by the dashed vertical lines at the corresponding Jominy-test cooling rate.

RESULTS AND DISCUSSION

Curves representing the cooling rates at 1300F (705C) at the midthickness of commercially-quenched (H=1.5) ½-, 1-, 1-1/2-, 2-, and 3-inch-thick plates are illustrated in Figure 1 with the corresponding cooling rates of 195, 56, 32, 16, or 8.5F/sec. (108, 31, 17.7, 8.9, or 4.7 C/sec., respectively). The cooling rates in the Jominy test conducted in accordance with ASTM A255 corresponding to the previously identified plate cooling rates occur at 2.5-, 6-, 8.5-, 11-, or 18-sixteenths of an inch from the quenched end. The Jominy hardenability curves for the 0.06% carbon steels are illustrated in Figures 2, 4, 6, 8, 10, 12, 14, and 16 for Steels A, B, E, F, C, D, G, and H respectively. The mechanical properties for Steels A, B, E, F, and H, are also shown, but at only 0.06 percent carbon because the combination of strength, toughness and weldability was optimal at this carbon content. The microstructures for the eight steels at 2.5-, 6-, 8.5-, 11-, and 18-sixteenths of an inch from the quenched end are shown in Figures 3, 5, 7, 9, 11, 13, 15, and 17.

Jominy End-Quench Hardenability

It is instructive to scan the Jominy Test results to note the changes in hardenability produced by altering the levels of the alloying elements, manganese, molybdenum, and nickel. Copper was not varied because it was previously found[7] that in this group of steels no advantage in mechanical properties was obtained by raising the copper content above one percent. All the elements increase the hardness at the quenched end by aiding martensite formation and the hardness at locations away from the quenched end is also increased, presumably by grain refinement and solution strengthening of the ferrite.

Temper-Aging Effects

Jominy-test curves also reveal the strengthening effect temper-aging produced in these Cu-Ni steels. While the martensite formed near the quenched end softens with tempering, the regions away from the quenched end are strengthened at the aging temperatures by copper precipitation hardening. Above about 1150F (620C), overaging results in a softening of the steel but an enhancement of its toughness.

Mechanical Properties

The effect of alloying elements and temper-aging on the hardness levels of the steels reflects accurately their influence on the tensile strength and the yield strength. All the steels in the group are capable of exceeding 100 ksi yield strength by an appropriate choice of the temper-aging temperature, but the section thicknesses at which this is possible are regulated by the manganese, molybdenum, and nickel content. However, the notch toughness of the steels decreases at the higher hardnesses obtainable by aging in the 950 to 1100F range (510 to 595). Thus the optimum combination of strength and toughness generally is produced by temper-aging around 1150F (620C).

Metallographic Evaluation

The micrographs of the eight as-quenched steels exhibited lath-like martensitic microstructures to varying degrees at 2.5 sixteenth inch from the quenched end, when cooled at 195F/sec (108C/sec.). At greater distances from the quenched end, the microconstituents were various combinations of ferrite, martensite, and MA (martensite-austenite) constituent. These micrographs illustrate the gamut of microstructures to be encountered when these Cu-Ni steels are production-quenched and temper-aged in plates of ¼- to 3-inch-thickness.

SUMMARY AND CONCLUSIONS

The results described herein should provide access to the following information for Cu-Ni steels within the range of compositions evaluated:

1. the Jominy end-quench test provides valid information about the hardenability of Cu-Ni steels, and therefore permits the selection of a heat treatment that will result in a desired hardness and strength,
2. the mechanical-property data permit an estimation of the toughness, which can be expected to be high,
3. the weldability data in the referenced information indicate that consumables are available to match the steels' strength and that can be deposited without requiring preheat.

RECOMMENDATION

Recent studies summarized herein suggest that the 2.5 percent nickel Steel H composition may be suitable for yield strengths up to 130 ksi for applications requiring fracture-transition-plastic behavior. Therefore a program is recommended to produce a commercial heat of this composition for validation tests such as those utilized for the Cu-Ni HPS 100W steel.

REFERENCES

1. Dawson, H.M., Gross, J.H., and Stout, R.D., "Copper-Nickel High Performance 70W/100W Bridge Steels - Part 1", ATLSS Report 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. Gross, J.H. and Stout, R.D., "Evaluation of a Production Heat of an Improved Cu-Ni 70W/100W Steel", ATLSS Report No. 01-10, June 2001.

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ACKNOWLEDGMENTS

Funding by the Federal Highway Administration and the Pennsylvania Infrastructure Technology Alliance is gratefully acknowledged. Oversight of the technical work was provided by the AISI High Performance Steel Steering Committee and its Steel Advisory and Welding Advisory Groups.

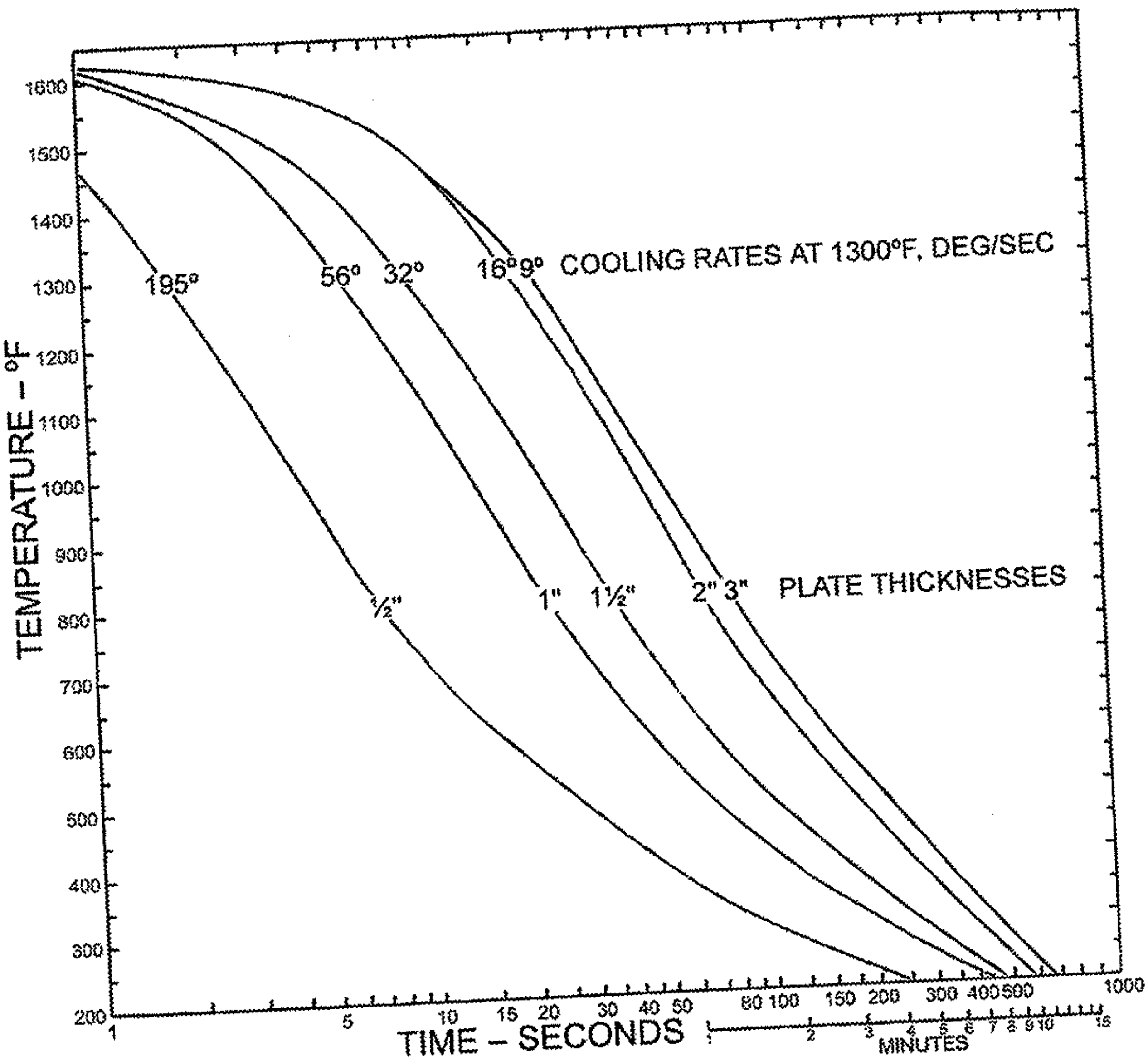
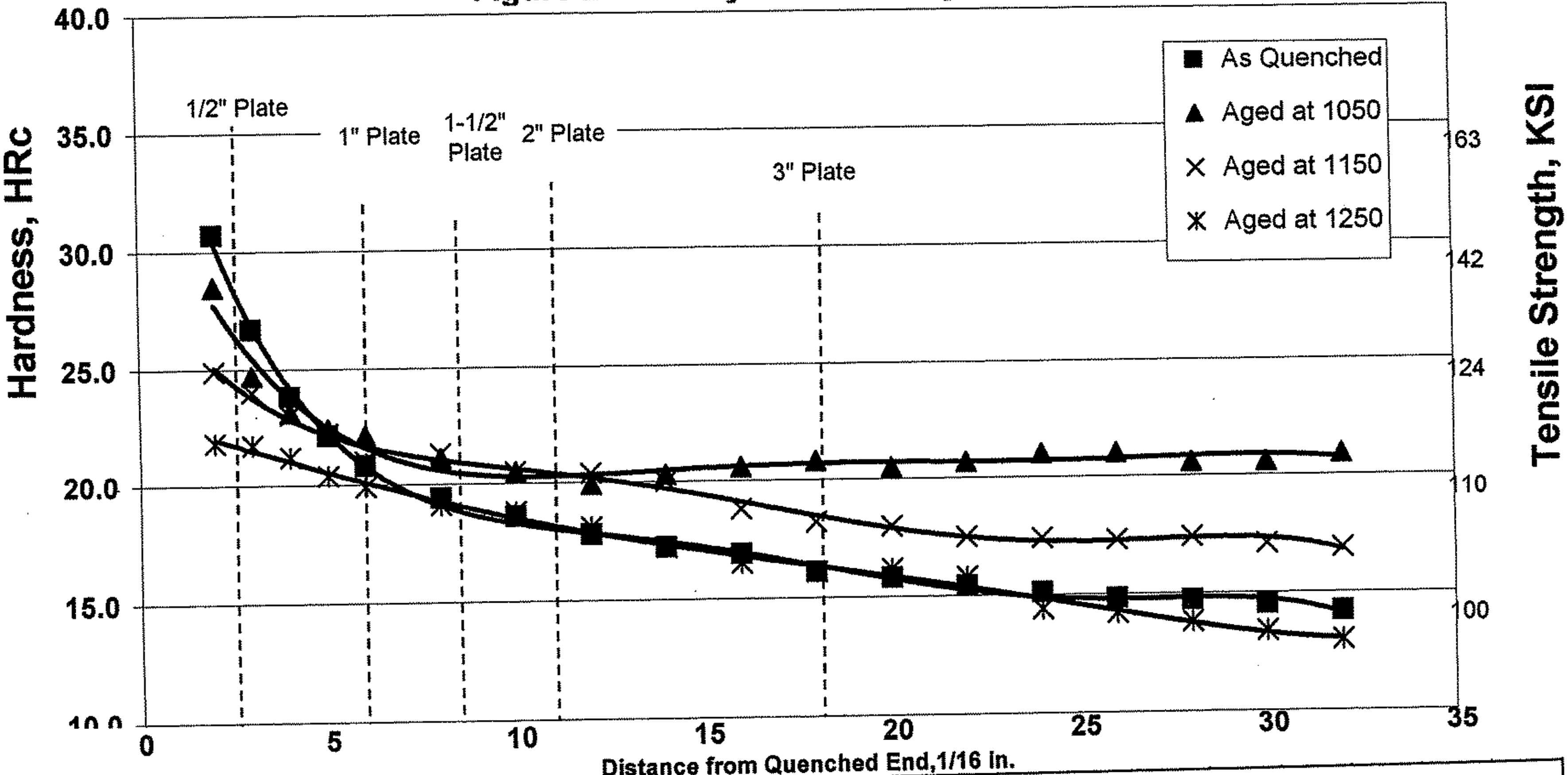


Figure 1 – Jominy End-Quench-Test Cooling Curves

Figure 2 - Jominy Hardenability of Steel A



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

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
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	A6AB	105	118	26	74	0.89	24	-140	-125	-115	-130	30	----	125	110	90	40
Temper @ 1150 °F	A6AD	99	109	25	75	0.91	21	-130	-125	-120	-120	-40	----	190	180	170	60
Temper @ 1250 °F	A6AF	96	103	26	78	0.92	17	-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	-150	-145	-140	-140	-100	----	210	195	175	125

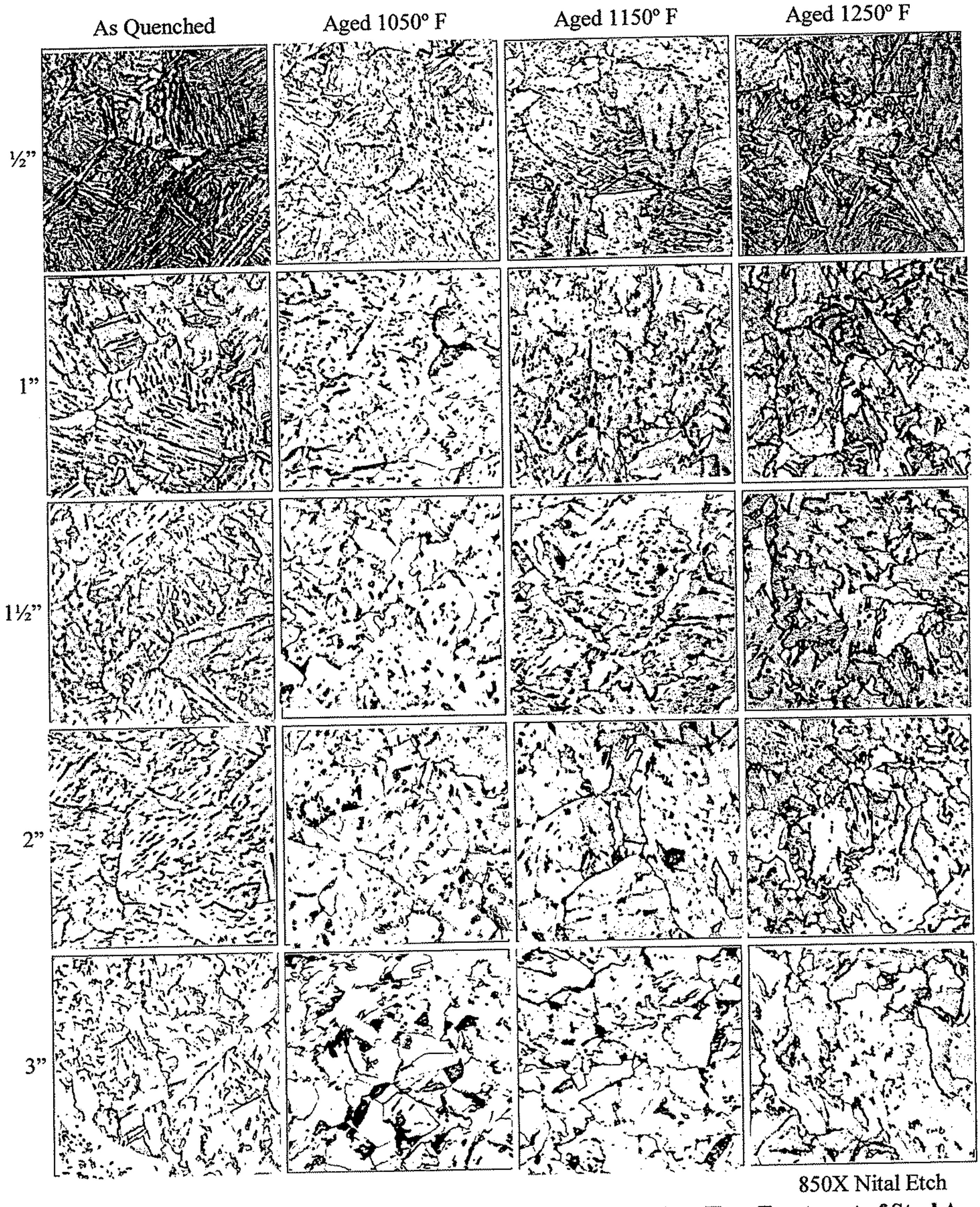
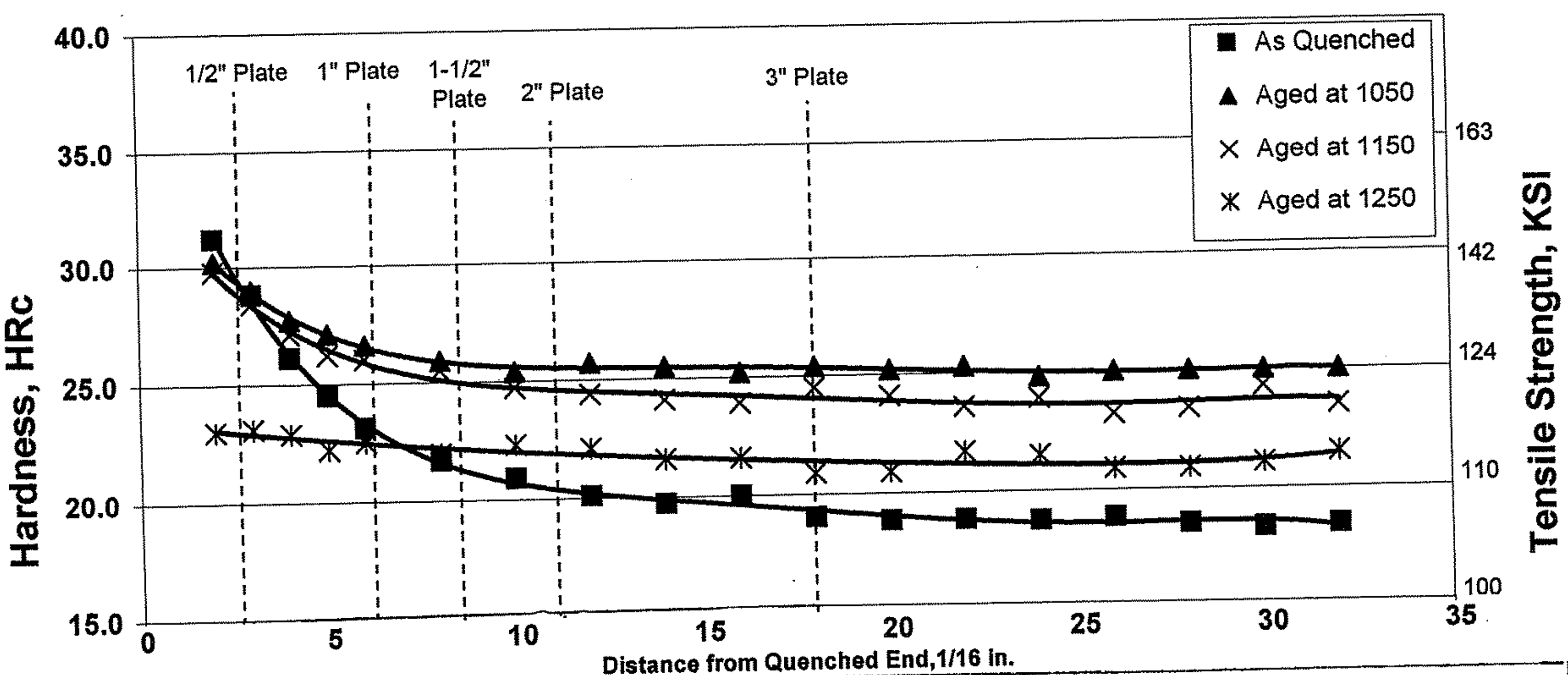


Figure 3 – Microstructures Representative of Commercial Plate Heat Treatment of Steel A

Figure 4 - Jominy Hardenability of Steel B



B6 Steel - Longitudinal

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.061	1.02	0.011	0.0035	0.27	1.01	0.77	0.51	0.50	0.054	0.017	0.015

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
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	-150	-140	-130	-140	-55	----	130	120	110	85
Temper @ 1250 °F	B6AF	107	112	26	76	0.95	21	-175	-170	-165	-170	-80	----	175	160	140	120
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	B6BB	105	119	26	74	0.88	23	-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	-115	-110	-105	-115	-60	----	210	180	130	10

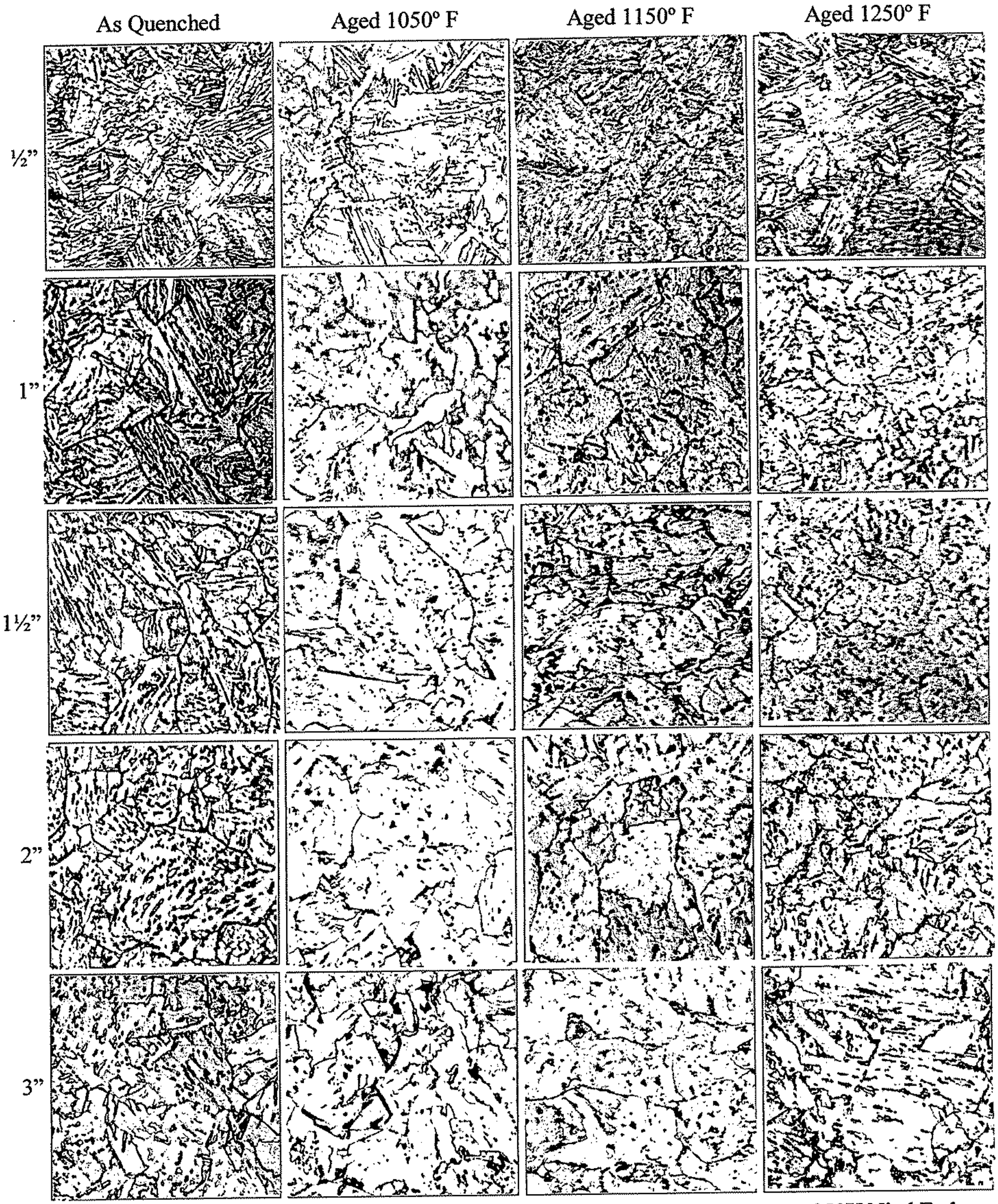


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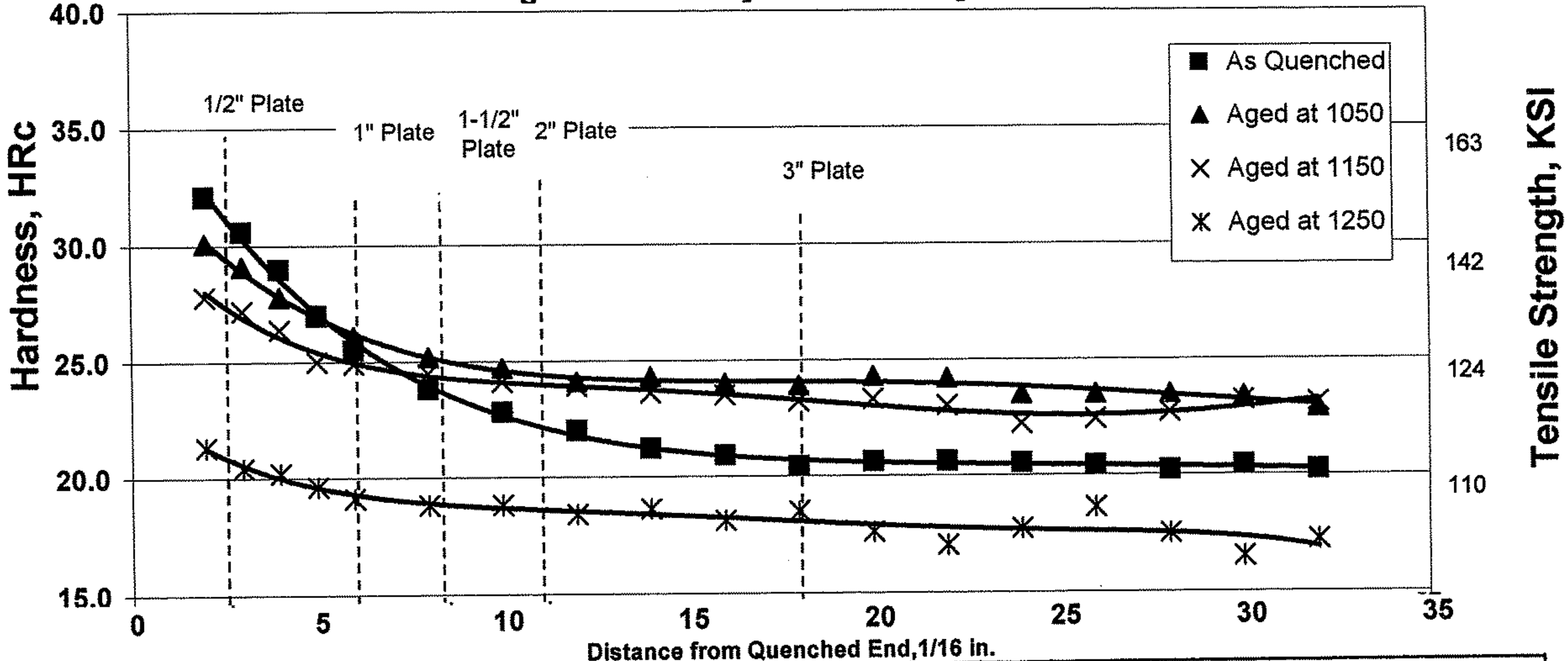
Figure 5 – Microstructures Representative of Commercial Plate Heat Treatment of Steel B

Figure 6 - Jominy Hardenability of Steel E



E6 Steel - Longitudinal

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.060	1.52	0.011	0.003	0.26	1.02	0.80	0.51	0.26	0.057	0.016	0.021

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
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	E6AB	114	123	24	75	0.92	27.5	-115	-90	-70	-110	30	100	85	70	45	15
Temper @ 1150 °F	E6AD	112	118	24	74	0.95	24.0	-170	-145	-125	-160	-20	----	135	110	90	65
Temper @ 1250 °F	E6AF	100	105	26	77	0.95	21.0	-200	-190	-140	-185	-70	----	185	170	140	130
Prod. Quench of 3-inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	E6BB	99	115	24	72	0.86	23.0	-80	-75	-70	-75	65	125	90	80	20	5
Temper @ 1150 °F	E6BD	99	110	24	74	0.90	22.0	-125	-115	-110	-115	5	170	135	110	90	30
Temper @ 1250 °F	E6BF	88	100	27	77	0.88	17.0	-160	-150	-140	-160	-40	----	195	160	135	105

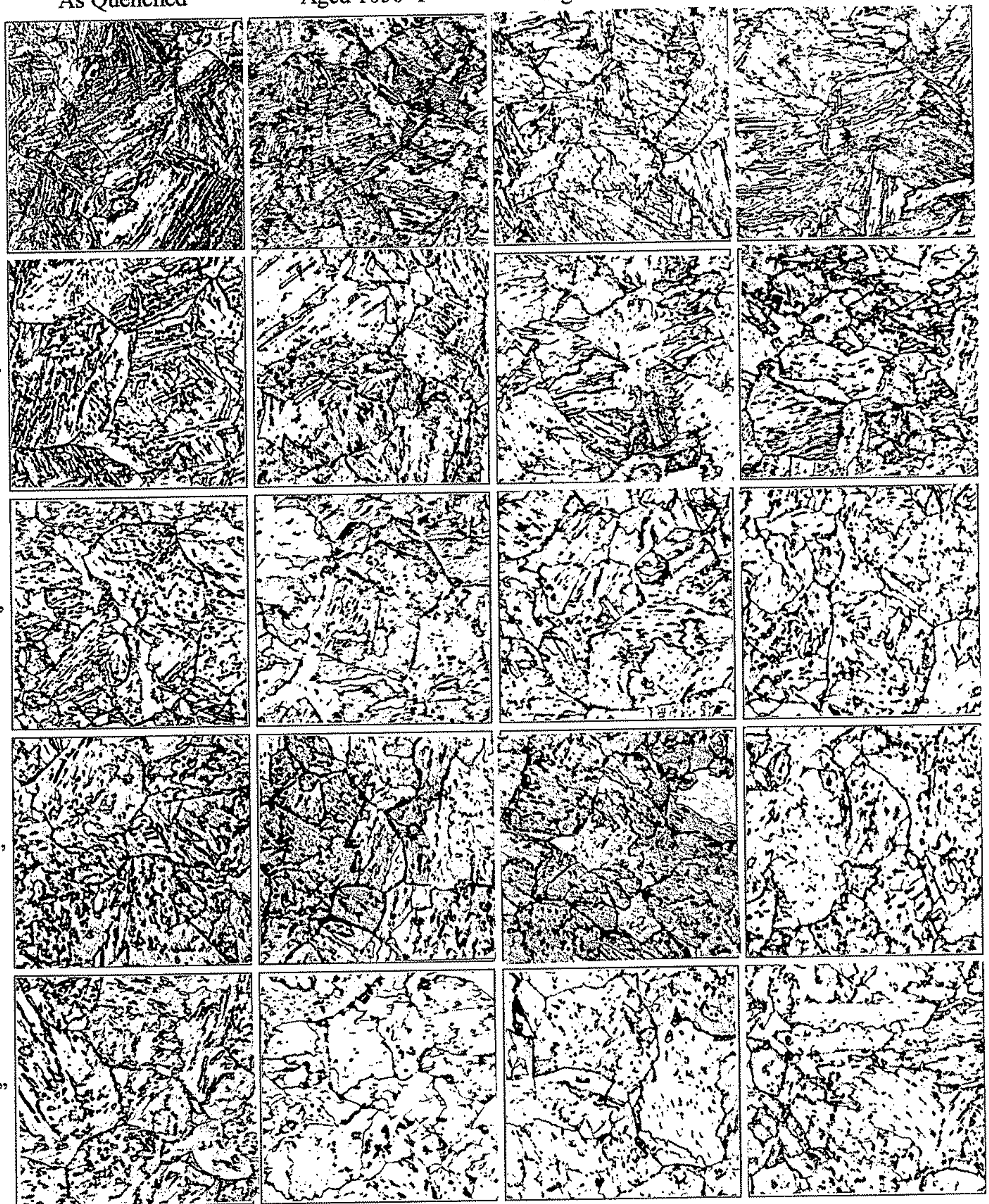


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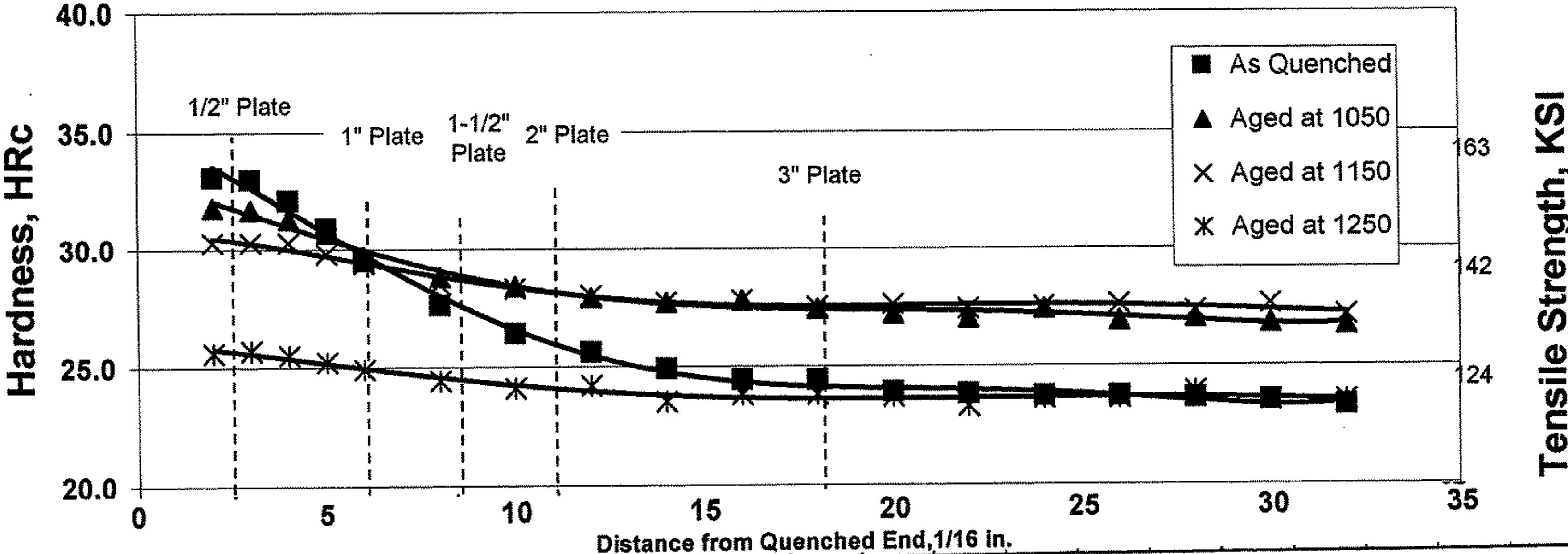
Figure 7 – Microstructures Representative of Commercial Plate Heat Treatment of Steel E

Figure 8 - Jominy Hardenability of Steel F



F6 Steel - Longitudinal

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.059	1.50	0.011	0.003	0.25	0.99	0.78	0.50	0.50	0.059	0.017	0.026

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
Prod. Quench of 1-inch Plate (50 °F/sec.)													105	85	70	55	25
Temper @ 1050 °F	F6AB	120	130	24	74	0.92	30.0	-130	-110	-70	-120	35	----	130	100	85	60
Temper @ 1150 °F	F6AD	125	131	24	74	0.95	29.0	-180	-160	-120	-170	-15	----	165	165	160	115
Temper @ 1250 °F	F6AF	109	113	26	76	0.96	23.0	-200	-195	-190	-195	-100					
Prod. Quench of 3-inch Plate (9 °F/sec.)													95	75	65	40	15
Temper @ 1050 °F	F6BB	114	129	22	70	0.88	26.5	-105	-90	-50	-90	80	125	120	110	70	25
Temper @ 1150 °F	F6BD	110	121	24	73	0.91	25.8	-130	-105	-90	-115	75	----	145	115	65	35
Temper @ 1250 °F	F6BF	102	108	26	77	0.94	21.0	-145	-120	-85	-130	-5					

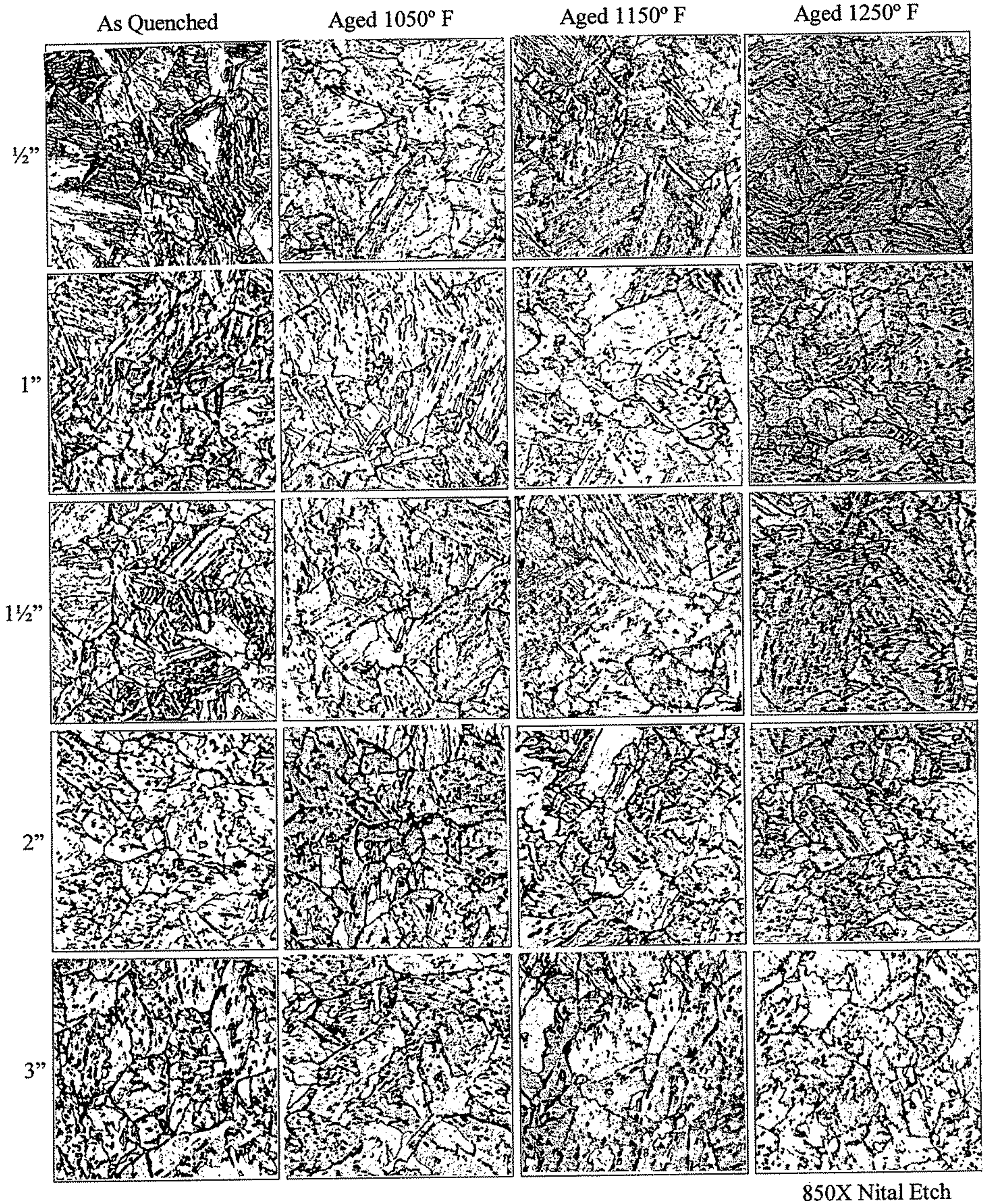
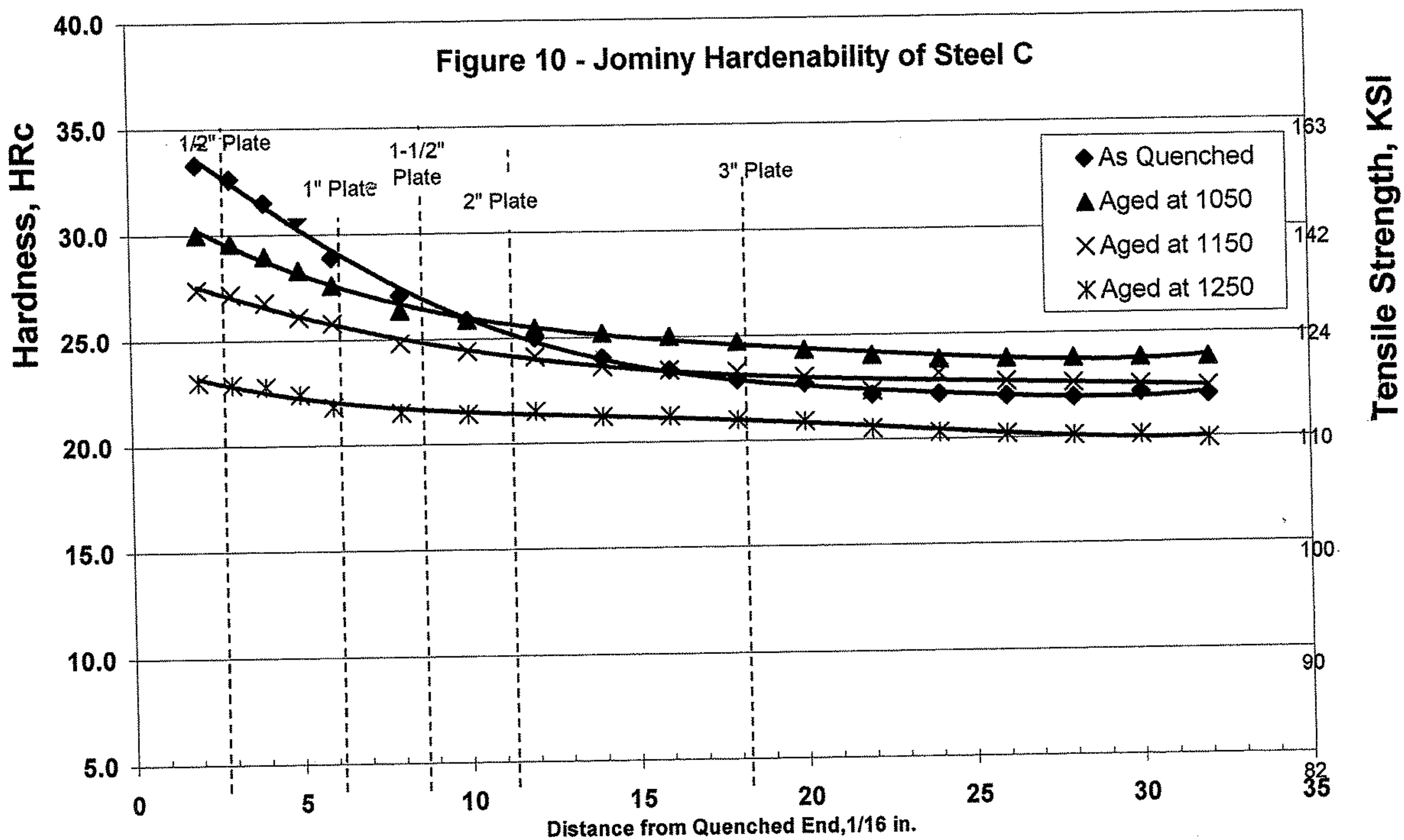


Figure 9 – Microstructures Representative of Commercial Plate Heat Treatment of Steel F



C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.058	0.98	0.016	0.006	0.23	0.92	2.49	0.50	0.25	0.06	0.015	0.03

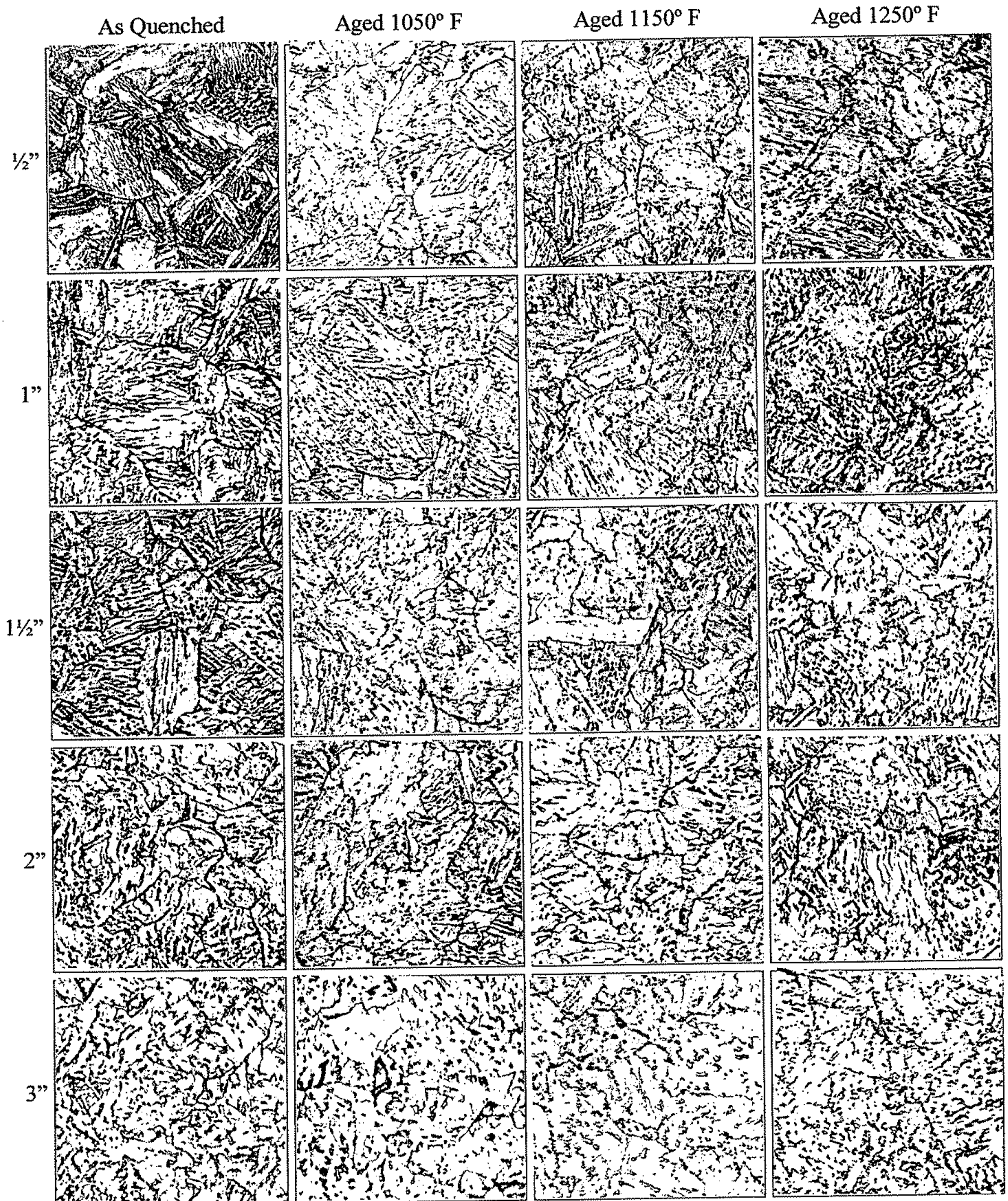


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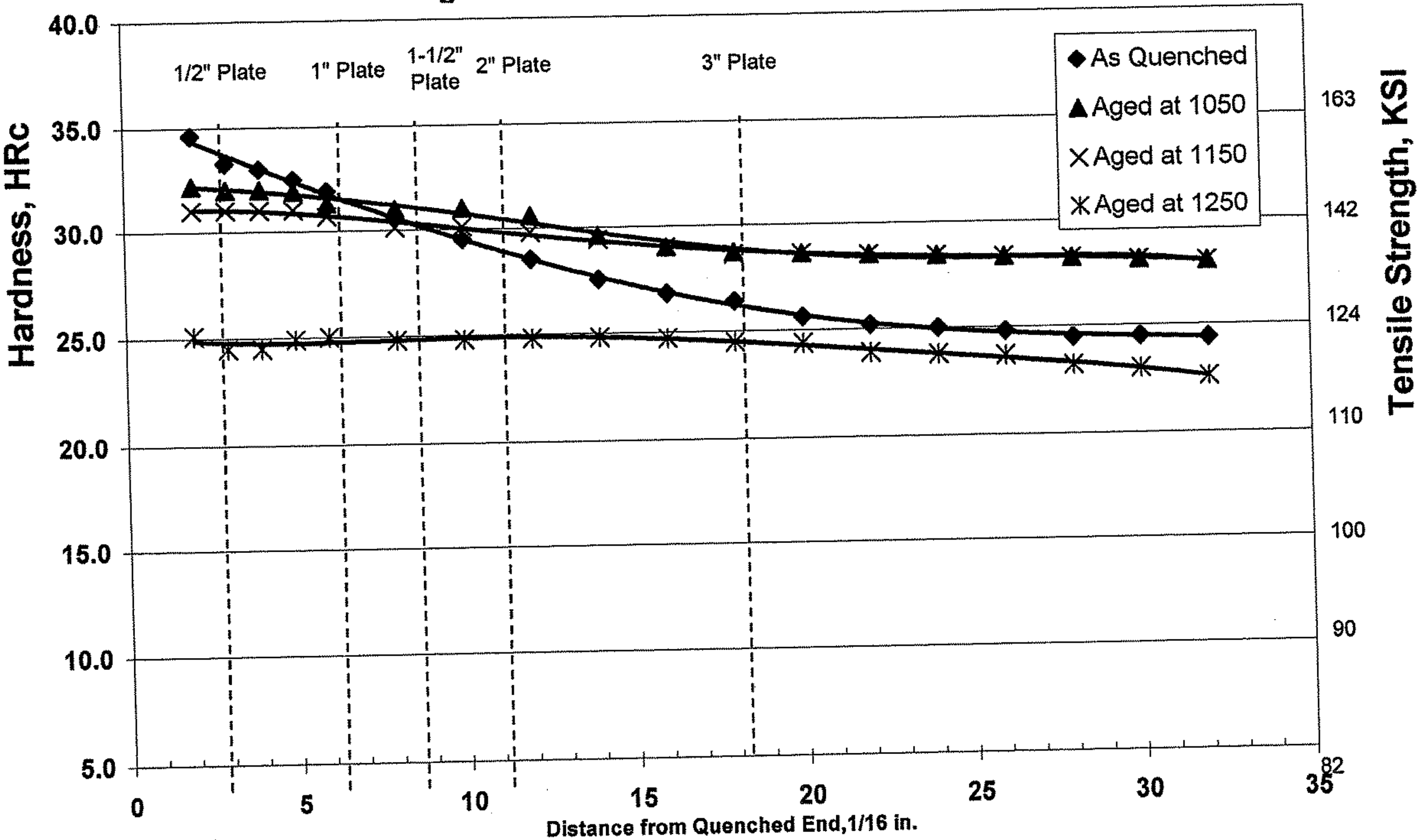
Figure 11 – Microstructures Representative of Commercial Plate Heat Treatment of Steel C

Figure 12 - Jominy Hardenability of Steel D



C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.064	0.99	0.015	0.006	0.22	0.99	2.53	0.50	0.49	0.06	0.015	0.03

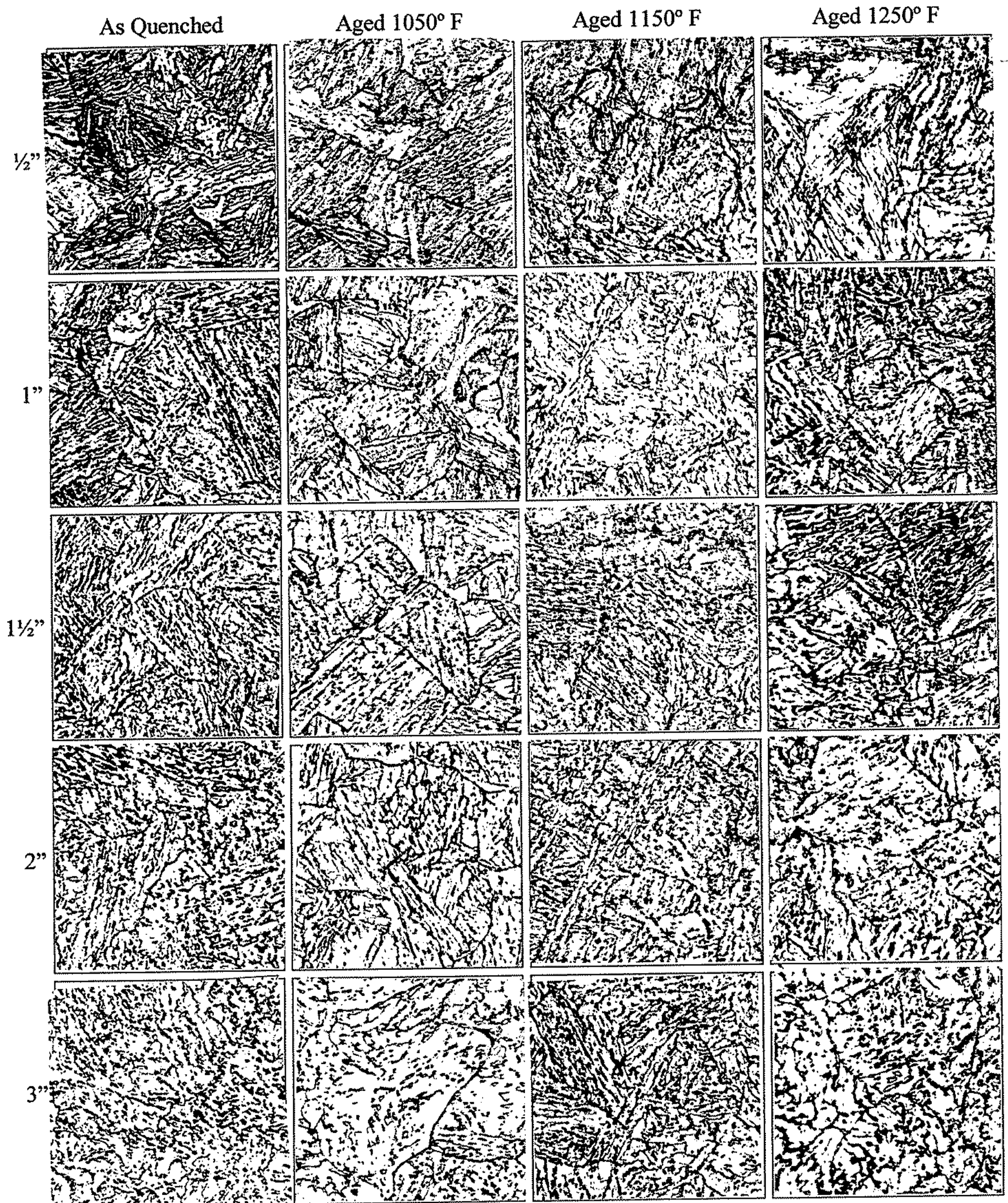


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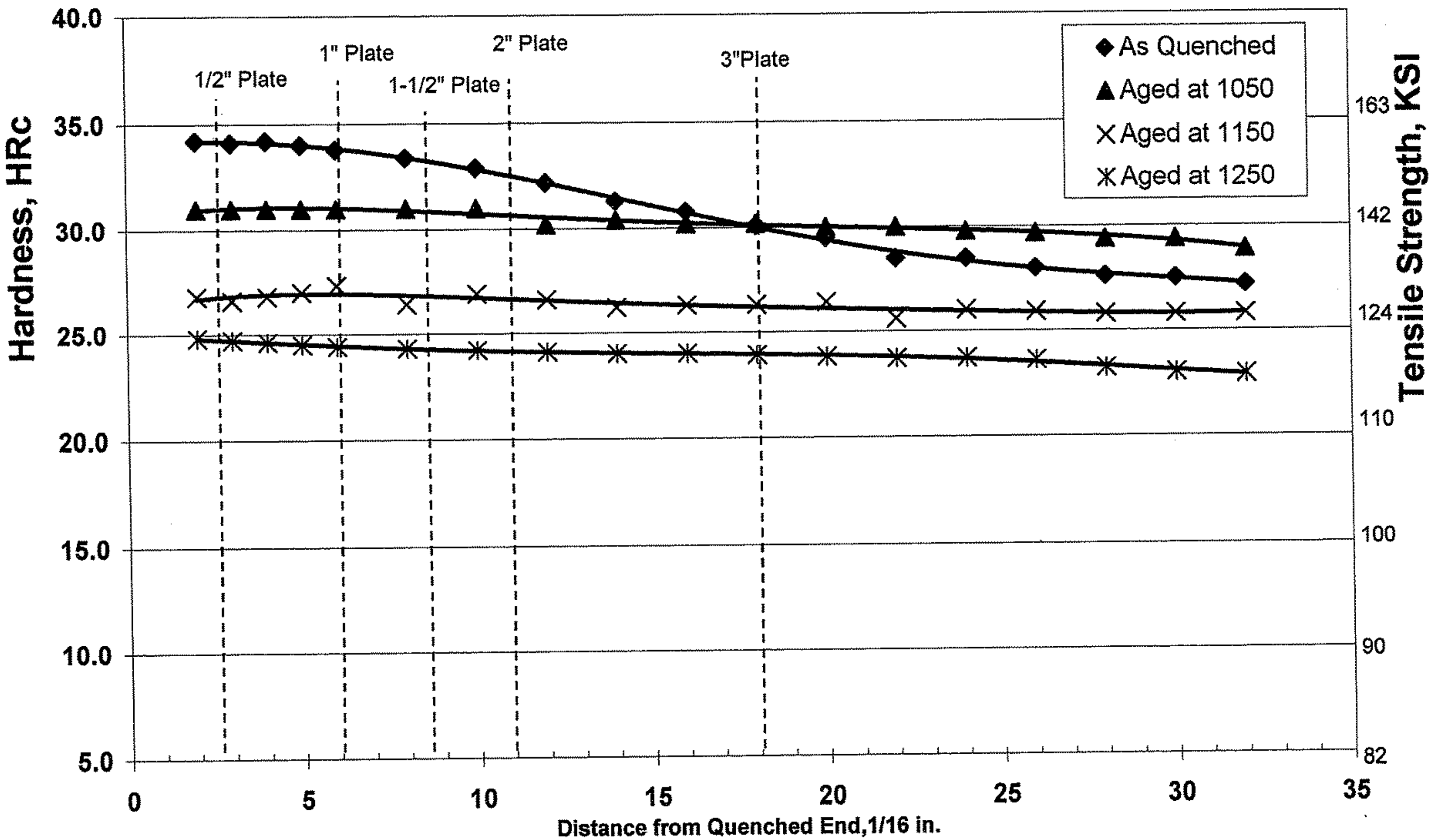
Figure 13 – Microstructures Representative of Commercial Plate Heat Treatment of Steel D

Figure 14 - Jominy Hardenability of Steel G



C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.062	1,52	0.016	0.006	0.26	0.99	2.49	0.50	0.25	0.06	0.015	0.03

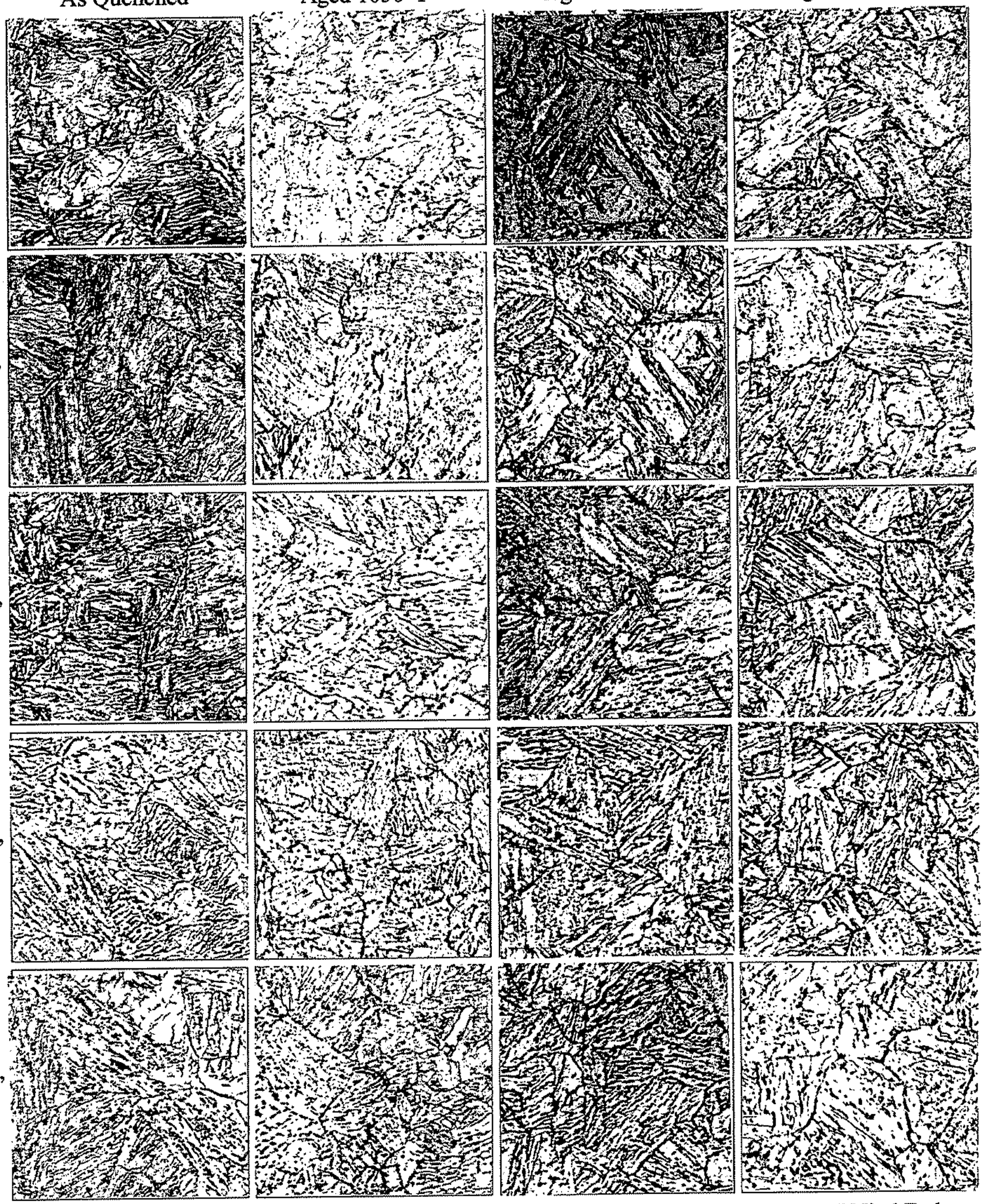


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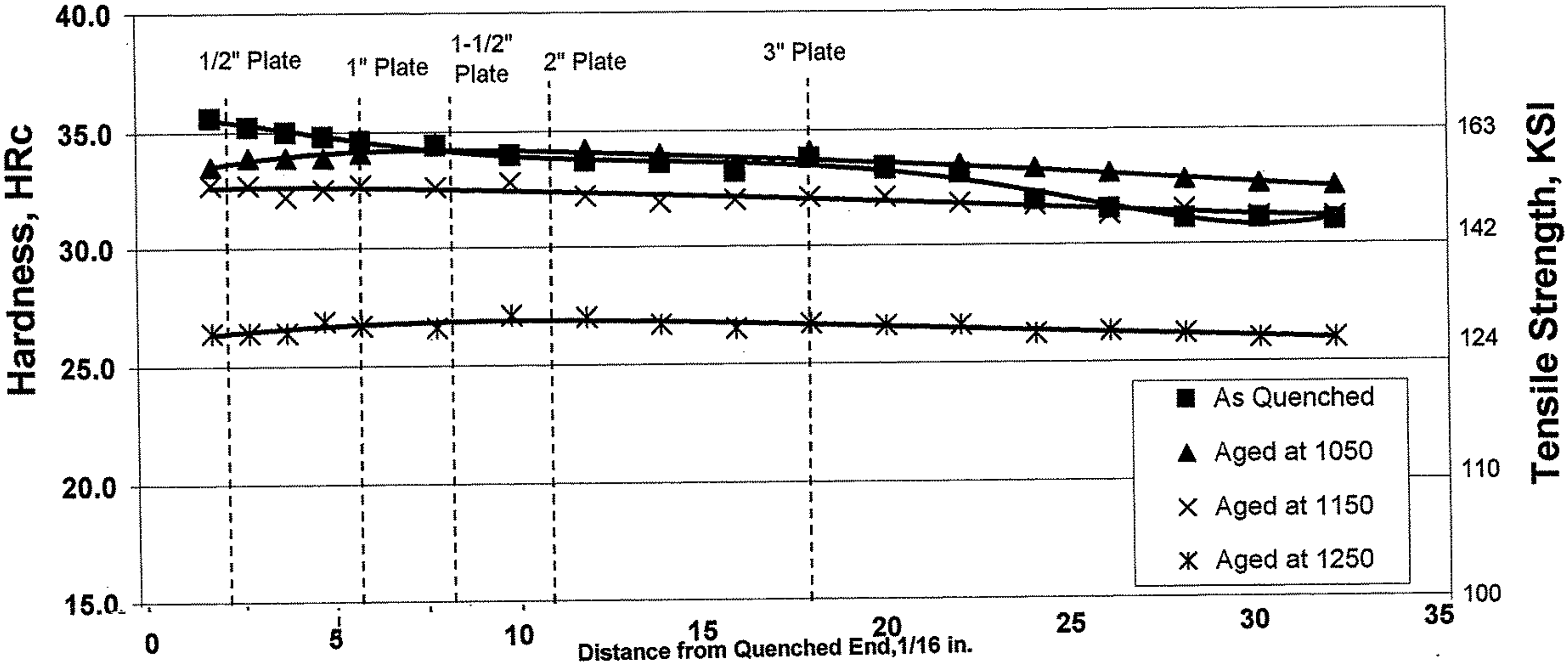
Figure 15 – Microstructures Representative of Commercial Plate Heat Treatment of Steel G

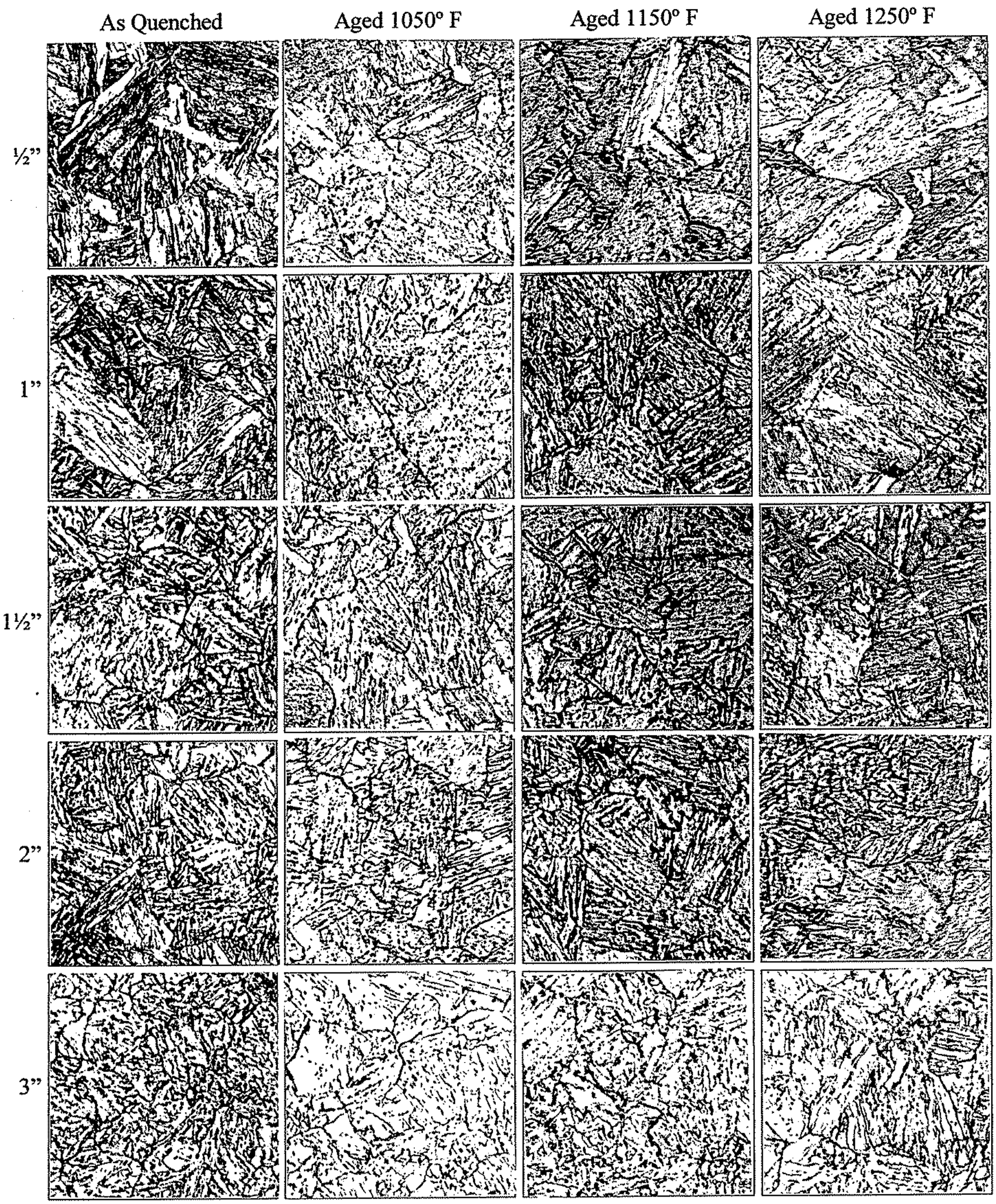
Figure 16 - Jominy Hardenability for Steel H



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

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
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



850X Nital Etch

Figure 17 – Microstructures Representative of Commercial Plate Heat Treatment of Steel H