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THE EFFECT OF INCREASING NICKEL ON THE PROPERTIES OF Cu-Ni STEELS

ABSTRACT

To study further the chemical composition of Cu-Ni steels, the effect of nickel at 0.75% (F Steels) and at 2.5% (H Steels) on the hardenability, mechanical-properties, and weldability was investigated on the following base steel composition (percent):

Mn	Si	Cu	Cr	Mo	V	Cb
1.50	0.25	1.00	0.50	0.50	0.060	0.015

A 300-pound (135-kg) heat of each nickel content was vacuum-melted and poured into 100-pound ingots with additions to the second and third ingot to increase the carbon content from 0.040 to 0.060 and 0.080%, respectively. The ingots were rolled to 1-inch-thick plate, which was heat-treated and machined to provide hardenability, mechanical-property, and implant-test weldability specimens.

The conclusions of the investigation were as follows:

1. The increased nickel content from 0.75% to 2.50% increased the hardenability (DI) by a factor of 1.6, with corresponding changes in the Jominy curves.

2. The hardness of these precipitation-strengthened steels in the as-quenched condition was increased by tempering at 950 to 1150F (510 to 620C) and the increase was inverse to the tempering temperature. Above 1150F (620C), the hardness was decreased by overaging of the copper precipitate and by agglomeration of the second phase.

3. Metallographically, the 2.5% nickel H Steels contained more martensite and/or bainite than the 0.75% nickel F Steels at similar distances from the quenched end of the Jominy specimen.

Tempering was manifested primarily by agglomeration of the second phase.

4. Statistically, the yield strength and the Charpy V-notch energy absorbed at -40 were related to composition, hardenability (DI), tempering temperature (T, °F), and cooling rate (CR, °F/sec) by

$$YS\ (ksi) = 234 + 321C + 7.8Ni - 0.13T + 0.18\ CR\ (R^2 = 92\%),\ \text{and}$$

$$E\text{-}40\ (ft\text{-}lb) = 25Ni - 20\ DI + 0.58T - 542\ (R^2 = 88\%)$$

5. Implant data for Steels F and H suggest that steels with carbon equivalents above 0.50 and carbon contents exceeding 0.06 % may require preheat to avoid HAZ cold cracking. Larger-scale weldability tests are required to confirm these observations and to test Graville diagram predictions.

INTRODUCTION

On the basis of previous ATLSS studies[1,2]* and related papers[3 to 14], the advantages in fracture toughness and weldability of 80W, 90W, and 100W copper-nickel (Cu-Ni) bridge/infrastructure steels were reported 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 compositions of the steels previously investigated are listed in Table I. To further study the composition of Cu-Ni steels, the effect of nickel on the hardenability, mechanical properties, and weldability of Cu-Ni steels was investigated by comparing the properties of Steels F4, F6, and F8 at 0.75 percent nickel with those of Steels H4, H6, and H8 at 2.5 percent nickel, all other chemical elements being the same as illustrated in Table II. The properties of the F Steels were previously reported[2] and are incorporated herein.

EXPERIMENTAL PROCEDURE

MELTING AND ROLLING

A 300-pound (135-kg) heat of steel was vacuum-melted and poured into three 100-pound (45-kg) ingots with additions to the second and third ingot to obtain the compositions shown in Table II for Steels H4, H6,and H8. The 100-pound 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.

JOMINY END-QUENCH HARDENABILITY TESTING

For each of the three steels, six 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. Four of the as-quenched Jominy specimens were then tempered at 950F (510C), 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. As described next, a flat area for each Jominy specimen was prepared for metallographic examination.

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*See references

METALLOGRAPHIC EXAMINATION

As previously noted, one hardness-test flat on each as-quenched Jominy specimen was ground, polished, and etched sequentially with picral and nital and metallographically examined along the length of the specimen. For the as-quenched samples, micrographs were recorded at a magnification of 850X at locations 1-, 6-, 11-, 14-, and 17/16th 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 the 32/16-inch location (50 mm), corresponding approximately to 1/3-inch-thick (8 mm) normalized plate, cooled at 3F/sec. (1.7 C/sec.).

HEAT TREATMENT AND MECHANICAL-PROPERTY TESTING

For each of the three F Steels and H 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. Similarly, for each of the six 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-thick (100-mm) plate, Figure 3. After austenitizing and quenching, Sections A and B were cut into subsections as shown in Figure 4, tempered* at 1150, 1200, or 1250F (620, 675, or 675C), and machined to the indicated test specimens. 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 at temperatures to obtain a full transition curve.

WELDABILITY TESTING

To measure resistance to hydrogen-assisted cracking (HAC) of the heat-affected-zone (HAZ), implant tests for the six steels were machined from Plate Section D, Figure 2, 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

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*The words tempering or aging are used interchangeably to mean the same treatment and induce HAC if the steel was susceptible. The electrode grade, E11018, 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-test curves for the as-quenched Steels H4, H6, and H8, Figure 5, show that the hardness curves are essentially flat, typical for a high-hardenability steel, and also illustrate the strong effect of carbon content on the maximum hardness of martensite and on hardenability. The Jominy curves for the the as-quenched Steels F4, F6, and F8 are also relatively flat but not as flat as the Steel H curves and lie significantly below them. These results indicate that increasing nickel from 0.75 to 2.50 percent strongly increased the hardenability.

JOMINY END-QUENCH HARDENABILITY TESTS - TEMPERED (AGED)

The effect of tempering on the Jominy curves for Steels H4, H6, and H8 is illustrated in Figures 6, 7, and 8 respectively. Figure 6 for Steel H4 (0.044%C) shows that tempering at 950F and 1050F (510 and 565C) increased the hardness from Cu-rich precipitates more than softening of the martensite/bainite microconstituents. At 1150F (620C), the two effects essentially offset each other, but at 1250F (675C), martensite/bainite softening was much greater than precipitation strengthening, which was lessened by overaging of the Cu-rich precipitates. Figure 7 for Steel H6 (0.061%C) shows that the tempering effects were similar to those observed for Steel H4, except that the increased carbon raised the level of all the curves, that precipitation strengthening was more offset by martenite/bainite softening at 950 and 1050F (510 and 565C), and that softening at 1250F (675C) was much greater than precipitation strengthening. Figure 8 for Steel H8 (0.080%C) illustrates the strong effect of carbon in raising the level of all the Jominy curves, and as a result, the response to martensite/bainite softening compared with precipitation strengthening.

The effect of tempering on the Jominy curves for Steels F4, F6, and F8 are shown in Figures 9, 10, and 11, respectively. Figure 9 for Steel F4 (0.040% C) indicates that precipitation strengthening was greater than softening of the observable microconstituents at all tempering temperatures, except 1250F (675C), which showed no change except for some softening for the high-hardness microconstituents near the quenched end. The curves for Steel F6 (0.059% C), Figure 10, were affected by tempering in essentially the same way as those for Steel F4, except for a general upward shift in hardness of the Jominy curves. The curve for Steel F8 (0.081% C) differs from those for Steels F4 and F6 in that tempering at 1250F (675C) lowered the curve below that of the as-quenched specimen The curves for the Steel F8 also lie higher in hardness than those for Steel F6, again illustrating the general strengthening effect of carbon.

METALLOGRAPHIC EVALUATION OF JOMINY SPECIMENS

Typical microstructures observed in the as-quenched Jominy specimens as a function of the distance from the quenched end are shown in Figures 12, 14, and 16 for Steels F4, F6, and F8, respectively, and in Figures 13, 15, and 17 for Steels H4, H6, and H8, respectively.

At the 1/16-inch very rapid cooling rate (450F/sec), all the steels transformed to martensite. However, at distances [6/16 (50F/sec) and 17/16 (9F/sec) inches] equivalent to one- or four-inch-thick production-quenched plates, respectively, the microstructures exhibited differences consistent with the variation in carbon and nickel content among the steels. In the case of the H Steels, the 2.5 percent nickel sufficiently increased the hardenability to produce martensite or bainite at all carbon levels and at the cooling rates for production-quenched 1- and 4-inch-thick plates. In contrast, the F Steels with 0.75 percent nickel exhibited a gamut of microstructures, depending on the carbon content and the cooling rate. At 0.04% carbon, F Steel was bainitic with little acicularity of the second phase in the case of 6/16 inch and none at 17/16, whereas the 0.06 and 0.08 % carbon F Steels showed increasing amounts of acicular second phase consistent with the higher carbon contribution to hardenability.

The micrographs for the Jominy specimens tempered at 1250F (675C) are shown in Figures 18, 20, and 22 for Steels F4, F6, and F8, respectively, and in Figures 19, 21, and 23 for Steels H4, H6, and H8, respectively. For the both steels, the effect of tempering was not very visible and consisted mainly of agglomerating or spheroidizing of the second phase.

Thus the Jominy test can be used to predict with reasonable reliability the response of a steel to both quenching and tempering treatments, including the influence of quenching rate, section size, and tempering temperature.

MECHANICAL-PROPERTY EVALUATION - TENSILE AND TOUGHNESS DATA

The tensile and fracture-toughness data for Steels F4, F6, and F8 are listed in Table III and for Steels H4, H6, and H8 in Table IV. The effect of tempering on the strength and toughness of the F Steels is compared in Figures 24, 25, and 26. Figure 24 for Steel F4 shows that the yield strengths varied from 100 to 111 ksi (690 to 765 MPa) for 1-inch production-quenched plate and 92 to 96 ksi (635 to 660 MPa) for simulated 4-inch production-quenched plate. The Charpy V-notch 35 ft-lb transition temperatures were at or below -60F (-50C) for both 1- and 4-inch plate.

For Steel F6, Figure 25, the yield strength ranged from 109 to 125 ksi (830 to 860 MPa) and 102 to 114 ksi (705 to 785 MPa) for 1- and 4-inch-thick plate, respectively. For Steel F8, Figure 26, the yield strengths ranged from 114 to 137 ksi (785 to 945 MPa) and 107 to 111 ksi (740 to 765 MPa) for 1- and 4-inch-thick plate. Both 1-inch F6 and F8 Steels exhibited better toughness than the corresponding F4 Steels, despite their higher strength. This better strength-toughness behavior for the 1-inch F6 and F8 Steels results from their hardenability being sufficient to produce more favorable microstructures,i.e., more martensite and bainite than that for Steel F4. The effects of tempering on Steels F4, F6 and F8 were similar with respect to yield strength and Charpy energy at -40. The authors previously reported[2] that Steels F6 and F8 were excellent candidates for a 100W infrastructure steel through 4 inches.

At 2.5% nickel, the hardenability of the H Steels was sufficient to produce martensite or martensite and bainite at 6/16 and 17/16 inches. Thus after tempering at 1200F (650C), a minimum yield strength of 120 ksi (830 MPa) was readily obtained through 4 inches for Steel H6 and an energy absorption higher than the specified minimum of 60 ft-lb.(80J) at -120F for HSLA 100. Thus Steel H6 could be an excellent candidate for HSLA 120. Correspondingly, Steel H8 could be a candidate for HSLA 130 or an improved HY-130 (40 ft-lb,55J).

The reduced yield strengths and low yield-tensile ratios obtained after tempering of the H Steels at 1250F (675C) were the result of exceeding the A_1 temperature. The results suggest that the calculated A_1 value of 1270F (685C) may be too high, and subsequent careful tempering of a set ofSteel H8 samples at a range of temperatures from the 1200F (675C) to 1350F (730C) confirmed this. Consequently, the H Steels should not be tempered above 1225F (660C) as standard practice.

Exceeding the A_1 resulted in the formation of some austenite during tempering and its transformation upon cooling was the cause of the much lower yield strength and also lower yield-tensile ratio. For those applications where a very high yield-tensile ratio is undesirable, tempering by a controlled amount above the A_1 may be an appropriate practice. It should also be noted that this practice did not adversely affect the toughness. Our previous studies produced similar results, but the full benefit of intercritical tempering requires further study.

The detailed effects of tempering on the strength and Charpy notch toughness properties of the H Steels are illustrated in Figures 27, 28, and 29. The comparison in Figure 27 for Steel H4 shows that the yield strength decreased sharply with increased tempering temperature but with corresponding increases in Charpy energy absorbed at -40 and -120F (-85C). The effects of tempering on the yield strength and toughness for Steels H6 and H8 were quite similar to those for Steel H4.

MECHANICAL -PROPERTY EVALUATION - STATISTICAL ANALYSIS

The mechanical-test data for the F and H Steels can be used to obtain a statistical analysis of the effect of nickel on the toughness and yield strength of these copper-nickel steels. The simplest procedure is to plot the observed toughness against the yield strength to display the displacement of the curves and measure the effect of nickel on the toughness at a given yield strength or vice versa as shown in Figure 30. The displacement of the curves between 90 and 120 ksi (620 and 830 MPa) averaged an increase in toughness of 30 foot-pounds per 1 percent nickel at constant strength or an increase in yield strength of 20 ksi at constant toughness.

An excellent inverse linear relation, $R^2 = 92\%$, occurred between yield strength and notch toughness for Steel H regardless of carbon content, quenching rate or tempering temperature. Steel F, on the other hand, showed a scattered behavior that depended on carbon content and quenching rate and a much poorer regression index, $R^2 = 62\%$. It is noteworthy that the water-quenched 1-inch plates of Steels F6 and F8 attained the same level of properties as the H Steels.

The beneficial effect of nickel on the yield-strength—notch-toughness combination appears to be associated with its contribution to hardenability, as depicted in the Jominy curves in Figure 5. This is a reminder that tempered martensite provides the best combination of strength and toughness and that nickel is most beneficial when complete hardening can not be obtained.

When the effect of the independent variables on the Charpy energy at -40 of Steels F and H was statistically analyzed, the most reliable estimate ($R^2 = 88\%$) was found for the following relationship:

$$E\text{-}40 = 25\,Ni - 20\,DI + 0.58\,T - 542^*$$

The predictability of this equation is illustrated in Figure 31. All the variables of the equation were found to be statistically significant at the 99% confidence level. Note that nickel improves toughness and that its coefficient is similar to that calculated from Figure 30. The negative effect of DI and the positive effect of tempering temperature is consistent with their respective effects on strength, and the effect of strength on toughness. The maximum E-40 changes over the ranges studied are nickel = 44, DI = 78, and tempering temperature = 58.

The regression equation that best explained the variability in yield strength ($R^2 = 92\%$) was

$$YS = 234 + 321C + 7.8Ni - 0.13\,T + 0.18CR^*$$

The maximum effect on yield strengthof the independent variables over the ranges studied was similar: for carbon, it was 13 ksi, for nickel , it was14 ksi, for tempering temperature, it was 13 ksi, and for cooling rate , it was 7 ksi.. All the variables were statistically significant at the 99% confidence level. The predictability of yield strength is shown in Figure 32.

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* Ni in %, DI as calculated hardenability number, T as tempering temperature ^{0}F, C as % carbon, CR as cooling rate (50F/sec for 1-inch plate, 9F/sec for 4-inch plate)

WELDABILITY

The implant-test results for the H Steels are plotted in Figure 33 and the threshold to failure values for the H Steels are listed in Table V along with the data previously reported[2] for the F Steels. The threshold levels for failure observed in the H Steels were well below those of the F Steels and consistently below the nominal yield strengths of the H4, H6, and H8 steels. Thus as nickel and carbon are increased, the resistance to failure in the implant test is also reduced On the basis that HAZ cracking in weldments is more likely as the threshold stress falls below the yield strength, increasing the nickel content from 0.75% for the F Steels to 2.5% for the H Steels, significantly increased potential susceptibility to HAZ cracking for welding by the shielded metal-arc process (SMAW) using low-hydrogen electrodes. Moreover, carbon contents above 0.06% appear similarly detrimental and welding may require preheat. The results further suggest that the Graville diagram may not be conservative for steels with carbon equivalents exceeding 0.50. However definitive conclusions on weldability will require larger-scale weldability tests.

CONCLUSIONS

On the basis of a comparison of the properties of the F Steels containing 0.75 percent nickel with those of the H Steels containing 2.50 percent nickel with other elements the same, the following may be concluded:

1. The increased nickel content increased the hardenability (DI) by a factor of 1.6, with corresponding upward shifts in the as-quenched Jominy curves.

2. The hardness of these precipitation-strengthened steels in the as-quenched condition was increased by tempering at 950 to 1150F (510 to 620C) and the increase was inverse to the tempering temperature. Above 1150F (620C), the hardness was decreased by overaging of the copper precipitate and by agglomeration of the second phase.

3. Metallographically, the 2.5% nickel H Steels contained more martensite and/or bainite than the 0.75% nickel F Steels at similar distances from the quenched end of the Jominy specimen. Tempering was manifested primarily by agglomeration of the second phase.

4. Statistically, the yield strength and the Charpy V-notch energy absorbed at -40 were related to composition, hardenability (DI), tempering temperature (T, °F), and cooling rate (CR) by

$$YS = 234 + 321C + 7.8Ni - 0.13T + 0.18\ CR\ (R^2 = 92\%),\text{ and}$$

$$E\text{-}40 = 25Ni - 20\ DI + 0.58T - 542\ (R^2 = 88\%))$$

5. Implant data for Steels F and H suggest that steels with carbon equivalents above 0.50 and carbon contents exceeding 0.06 % may require preheat to avoid HAZ cold cracking. Larger-scale weldability tests are required to confirm these observations and to test Graville diagram predictions.

6. As previously reported, the mechanical properties for Steel F6 indicate that it would make an extremely tough 100W Steel. Similarly, Steel H6 could be an excellent candidate for HSLA 120 and Steel H8 for HSLA 130 or an improved HY-130.

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

	Steel											
	A4	A6	A8	B4	B6	B8	E4	E6	E8	F4	F6	F8
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
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
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
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
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
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
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
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
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
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
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
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
Calculated Metallurgical Characteristics												
D_I - ASTM	0.85	1.20	1.56	1.00	1.60	2.20	1.10	1.70	2.30	1.50	2.30	3.20
A_{e1}, F	1325	1325	1325	1320	1320	1320	1305	1305	1305	1305	1305	1305
A_{e3}, F	1560	1540	1525	1565	1545	1530	1540	1525	1510	1540	1530	1510
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
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

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

Table II - Chemical Composition of Steels F and H

	Steel					
	F4	F6	F8	H4	H6	H8
C	0.040	0.059	0.081	0.044	0.061	0.08
Mn	1.51	1.50	1.49	1.50	1.51	1.50
P	0.010	0.011	0.011	0.01	0.012	0.011
S	0.003	0.003	0.003	0.003	0.003	0.003
Si	0.25	0.25	0.25	0.24	0.24	0.24
Cu	0.99	0.99	0.99	1.03	1.04	1.03
Ni	0.78	0.78	0.77	2.50	2.50	2.53
Cr	0.50	0.50	0.50	0.49	0.49	0.49
Mo	0.51	0.50	0.50	0.49	0.49	0.49
V	0.059	0.059	0.059	0.056	0.056	0.056
Cb	0.017	0.017	0.016	0.016	0.016	0.016
Al(total)	0.022	0.026	0.025	0.023	0.023	0.022
	Calculated Metallurgical Characteristics					
D_I - ASTM	1.50	2.30	3.20	2.88	4.12	5.38
A_{e1}, F	1305	1305	1305	1270	1270	1270
A_{e3}, F	1540	1530	1510	1495	1480	1465
B_s, F	1180	1170	1150	960	950	940
M_s, F	890	875	850	840	820	800
C.E. (IIW)	0.62	0.64	0.66	0.78	0.80	0.82

Processing Condition Temperature, °F	Codes	Tensile Properties					Hard.	Charpy V-Notch Transition Temp., °F					Charpy V-Notch Energy ft-lb				
		Y.S. ksi	T.S ksi	EL. %	R.A %	Y.S./T.S.	HRc	20 ft-lb	35 ft-lb	60 ft-lb	15 mils	50% FAT	70°F	0°F	-40°F	-80°F	-120°F
F4 Steel - Longitudinal		C 0.040	Mn 1.51	P 0.010	S 0.003	Si 0.25	Cu 0.99	Ni 0.78	Cr 0.50	Mo 0.51	V 0.059	Cb 0.017	Al 0.022				
Prod. Quench of 1-Inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	F4AB	109	121	24	75	0.90	26.5	-65	-60	-55	-65	45	125	100	85	5	----
Temper @ 1150 °F	F4AD	111	120	24	76	0.92	25.0	-75	-70	-65	-75	30	150	125	115	5	----
Temper @ 1200 °F	F4AE	107	112	24	76	0.96	23.0	-95	-90	-85	-95	-30	----	140	130	100	5
Temper @ 1250 °F	F4AF	100	106	25	78	0.94	20.0	-140	-135	-130	-140	-65	----	185	155	80	55
Prod. Quench of 4-Inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	F4BB	96	116	24	74	0.83	23.5	-75	-70	-65	-70	70	120	115	105	10	----
Temper @ 1150 °F	F4BD	97	112	24	76	0.87	23.0	-95	-90	-85	-90	5	----	130	125	100	10
Temper @ 1200 °F	F4BE	95	105	26	78	0.90	20.5	-120	-115	-110	-125	-20	----	----	140	120	20
Temper @ 1250 °F	F4BF	92	103	26	80	0.89	19.0	-135	-130	-125	-135	-85	----	180	180	125	60
F6 Steel - Longitudinal		C 0.059	Mn 1.50	P 0.011	S 0.003	Si 0.25	Cu 0.99	Ni 0.78	Cr 0.50	Mo 0.50	V 0.059	Cb 0.017	Al 0.026				
Prod. Quench of 1-Inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	F6AB	120	130	24	74	0.92	30.0	-130	-110	-70	-120	35	105	85	70	55	25
Temper @ 1150 °F	F6AD	125	131	24	74	0.95	29.0	-180	-160	-120	-170	-15	----	130	100	85	60
Temper @ 1200 °F	F6AE	116	120	26	75	0.97	25.5	-180	-175	-165	-180	-80	----	135	145	115	90
Temper @ 1250 °F	F6AF	109	113	26	76	0.96	23.0	-200	-195	-190	-195	-100	----	165	165	160	115
Prod. Quench of 4-Inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	F6BB	114	129	22	70	0.88	26.5	-105	-90	-50	-90	80	95	75	65	40	15
Temper @ 1150 °F	F6BD	110	121	24	73	0.91	25.8.	-130	-105	-90	-115	75	125	120	110	70	25
Temper @ 1200 °F	F6BE	103	111	26	74	0.93	25.5	-130	-115	-105	-125	-50	----	135	145	105	30
Temper @ 1250 °F	F6BF	102	108	26	77	0.94	21.0	-145	-120	-85	-130	-5	----	145	115	65	35
F8 Steel - Longitudinal		C 0.081	Mn 1.49	P 0.011	S 0.003	Si 0.25	Cu 0.99	Ni 0.77	Cr 0.50	Mo 0.50	V 0.059	Cb 0.016	Al 0.025				
Prod. Quench of 1-Inch Plate (50 °F/sec.)																	
Temper @ 1050 °F	F8AB	137	146	22	70	0.94	33.5	-130	-80	-5	-85	70	75	65	50	35	25
Temper @ 1150 °F	F8AD	132	138	24	68	0.96	31.0	-165	-140	-100	-145	-40	----	110	95	75	50
Temper @ 1200 °F	F8AE	120	124	24	74	0.97	27.0	-180	-170	-140	-180	-80	----	----	120	100	70
Temper @ 1250 °F	F8AF	114	118	24	74	0.97	25.0	-200	-195	-180	-200	-125	----	150	145	135	110
Prod. Quench of 4-Inch Plate (9 °F/sec.)																	
Temper @ 1050 °F	F8BB	111	134	23	68	0.83	28.0	-125	-90	-20	-115	70	80	65	50	40	25
Temper @ 1150 °F	F8BD	112	128	24	70	0.88	28.0	-145	-120	-75	-140	30	120	95	75	55	35
Temper @ 1200 °F	F8BE	107	117	24	72	0.91	26.5	-165	-150	-120	-155	-20	----	----	110	95	60
Temper @ 1250 °F	F8BF	107	115	26	76	0.93	21.0	-170	-140	-135	-165	-40	----	145	125	110	75

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

Processing Condition Temperature, °F	Codes	Tensile Properties Y.S. ksi	T.S ksi	EL. %	R.A %	Y.S./T.S.	Hard. HRc	Charpy V-Notch Transition Temp., °F 20 ft-lb	35 ft-lb	60 ft-lb	15 mils	50% FAT	Charpy V-Notch Energy ft-lb 70°F	0°F	-40°F	-80°F	-120°F
H4 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.044	1.50	0.011	0.003	0.24	1.03	2.50	0.49	0.49	0.056	0.016	0.023			
Prod. Quench of 1-Inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	H4AD	128	133	24	75	0.96	28.5	-155	-140	-115	-140	-40	----	145	125	90	55
Temper @ 1200 °F	H4AE	120	124	24	74	0.97	27.5	-155	-150	-145	-155	-85	----	----	140	115	100
Temper @ 1250 °F	H4AF	96	119	25	78	0.81	24.0	<-200	<-200	<-200	<-200	-145	----	185	190	180	160
Prod. Quench of 4-Inch Plate (9 °F/sec.)																	
Temper @ 1150 °F	H4BD	122	130	24	76	0.94	28.0	<-200	<-200	<-170	<-200	-45	----	180	140	120	100
Temper @ 1200 °F	H4BE	116	121	24	76	0.95	26.0	-200	-195	-190	-200	-100	----	----	155	150	120
Temper @ 1250 °F	H4BF	95	118	25	77	0.81	23.0	<-200	<-200	<-200	<-200	-175	----	210	210	200	185
H6 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.061	1.51	0.012	0.003	0.24	1.04	2.50	0.49	0.49	0.056	0.016	0.023			
Prod. Quench of 1-inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	H6AD	131	137	23	73	0.96	30.5	-170	-140	-120	-150	-15	----	120	105	80	55
Temper @ 1200 °F	H6AE	121	126	24	73	0.96	27.5	<-200	-150	-135	-60	-60	----		130	110	75
Temper @ 1250 °F	H6AF	100	123	25	74	0.81	25.0	<-200	-190	-160	<-200	-135	----	190	185	165	140
Prod. Quench of 4-inch Plate (9 °F/sec.)																	
Temper @ 1150 °F	H6BD	130	137	24	73	0.95	30.5	-170	-150	-120	-140	-70	----	144	115	95	60
Temper @ 1200 °F	H6BE	120	126	24	72	0.96	27.5	<-200	-175	-150	-180	-80	----		150	125	85
Temper @ 1250 °F	H6BF	99	123	26	74	0.81	25.0	<-200	<-200	<-200	<-200	-180	----	190	185	175	150
H8 Steel - Longitudinal			C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al			
			0.080	1.50	0.011	0.003	0.24	1.03	2.53	0.49	0.49	0.056	0.016	0.022			
Prod. Quench of 1-Inch Plate (50 °F/sec.)																	
Temper @ 1150 °F	H8AD	138	142	23	70	0.97	32.0	-190	-150	-90	-170	-40	----	90	80	65	50
Temper @ 1200 °F	H8AE	127	134	24	69	0.95	29.0	-190	-150	-130	-185	-100	----	120	100	85	65
Temper @ 1250 °F	H8AF	104	129	24	69	0.80	27.0	<-200	-200	-150	<-200	-100	----	135	130	115	80
Prod. Quench of 4-Inch Plate (9 °F/sec.)																	
Temper @ 1150 °F	H8BD	136	143	24	69	0.95	32.0	-160	-140	-100	-140	-20	110	90	80	65	50
Temper @ 1200 °F	H8BE	130	135	23	70	0.96	30.0	-190	-160	-130	<-200	-70	----	125	115	100	70
Temper @ 1250 °F	H8BF	104	130	24	69	0.80	26.5	<-200	<-200	-170	<-200	-140	----	140	135	120	100

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

Table V - Implant Test Results

Steel	Typical Yield Strength, ksi	Threshold to Failure, ksi
Steel F - 0.04%C	100	112
0.06%C	105	100
0.08%C	115	94
Steel H - 0.04%C	115	84
0.06%C	120	68
0.08%C	125	66

Note: All tests were conducted on weldments produced with E11018 covered electrodes at a heat input of 35kJ/inch (1.4kJ/mm)

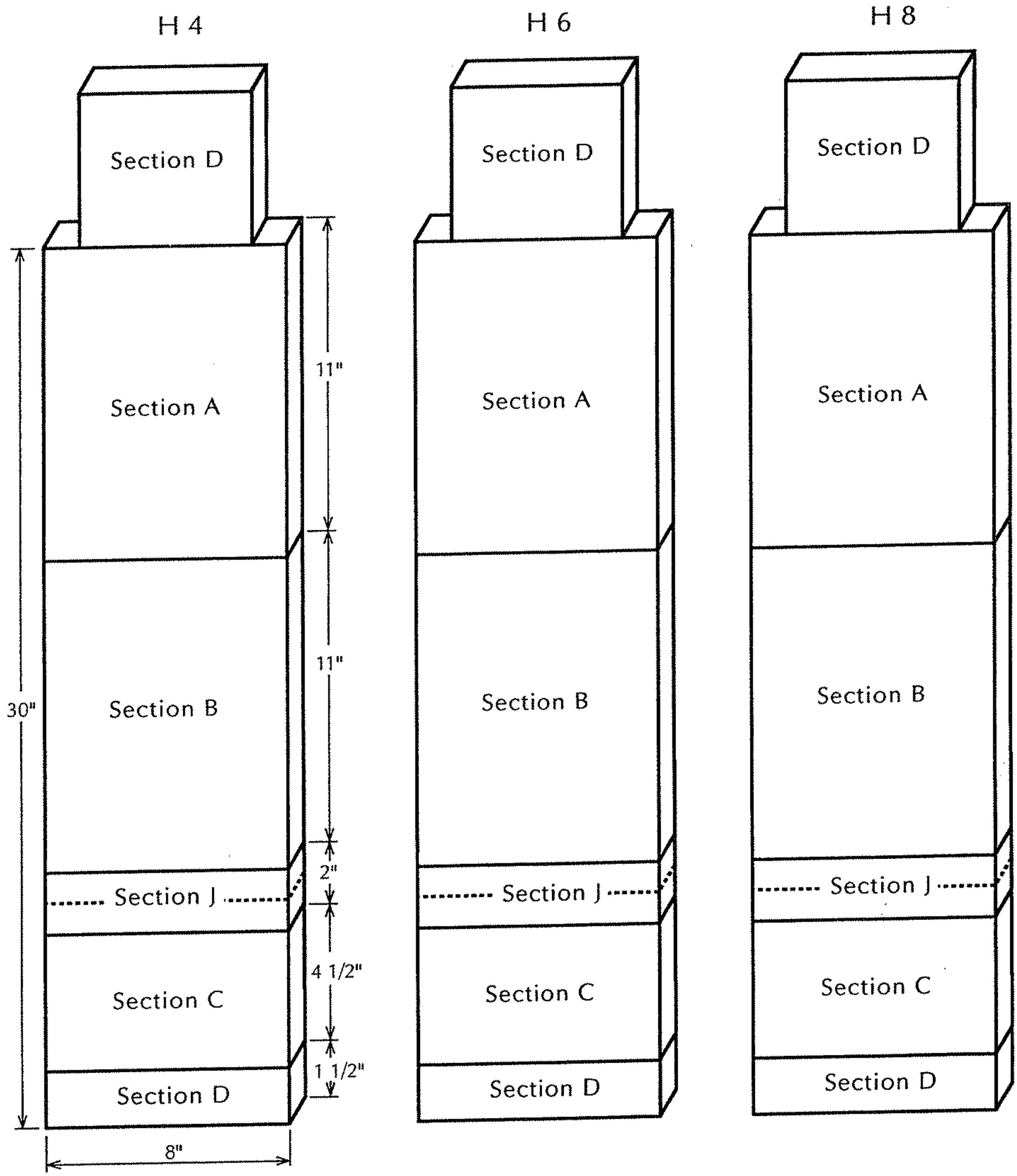


Figure 1 - Sectioning of 100-Pound-Ingot Plates

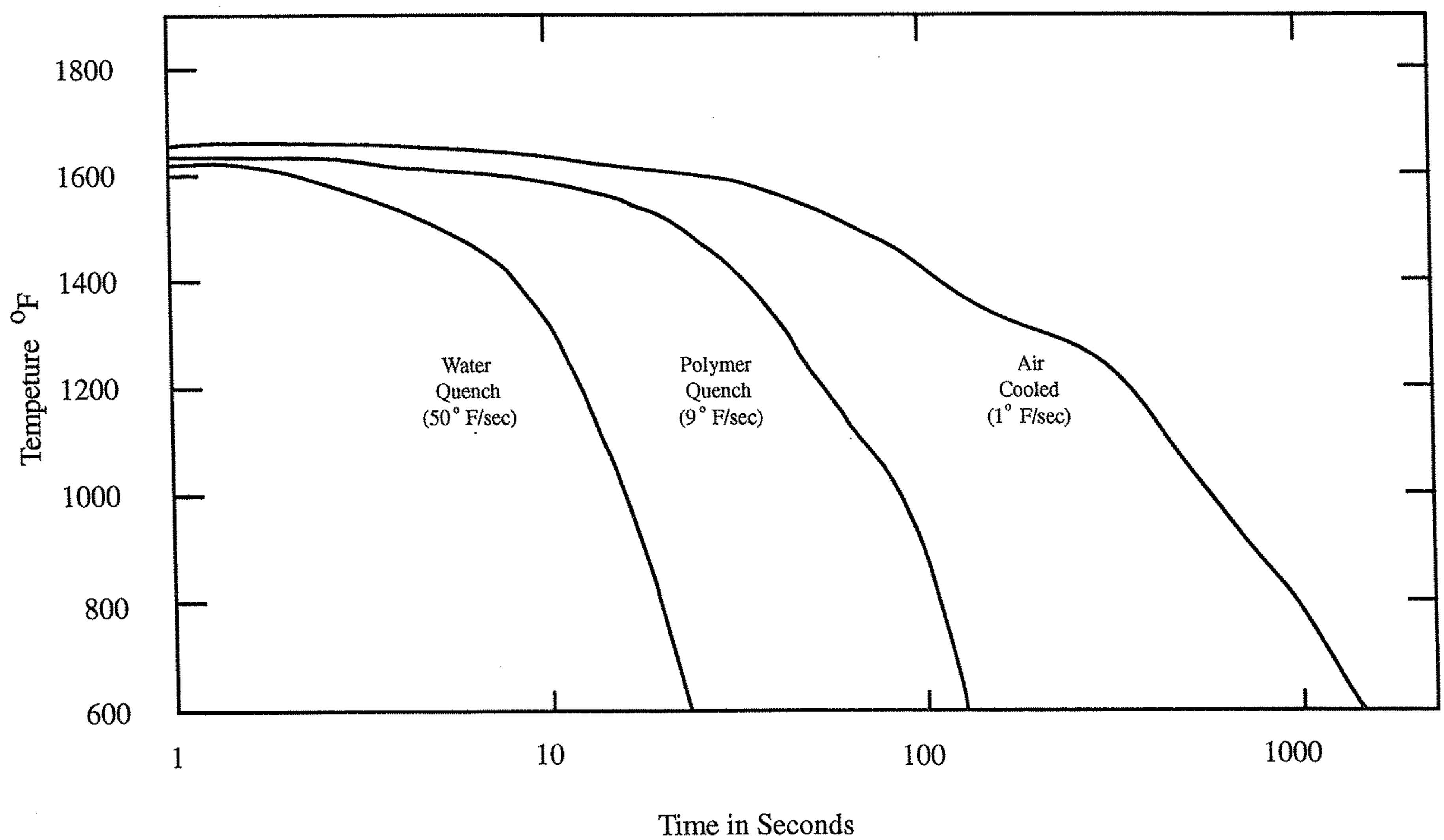


Figure 2 - Cooling Curves for One - Inch Plate

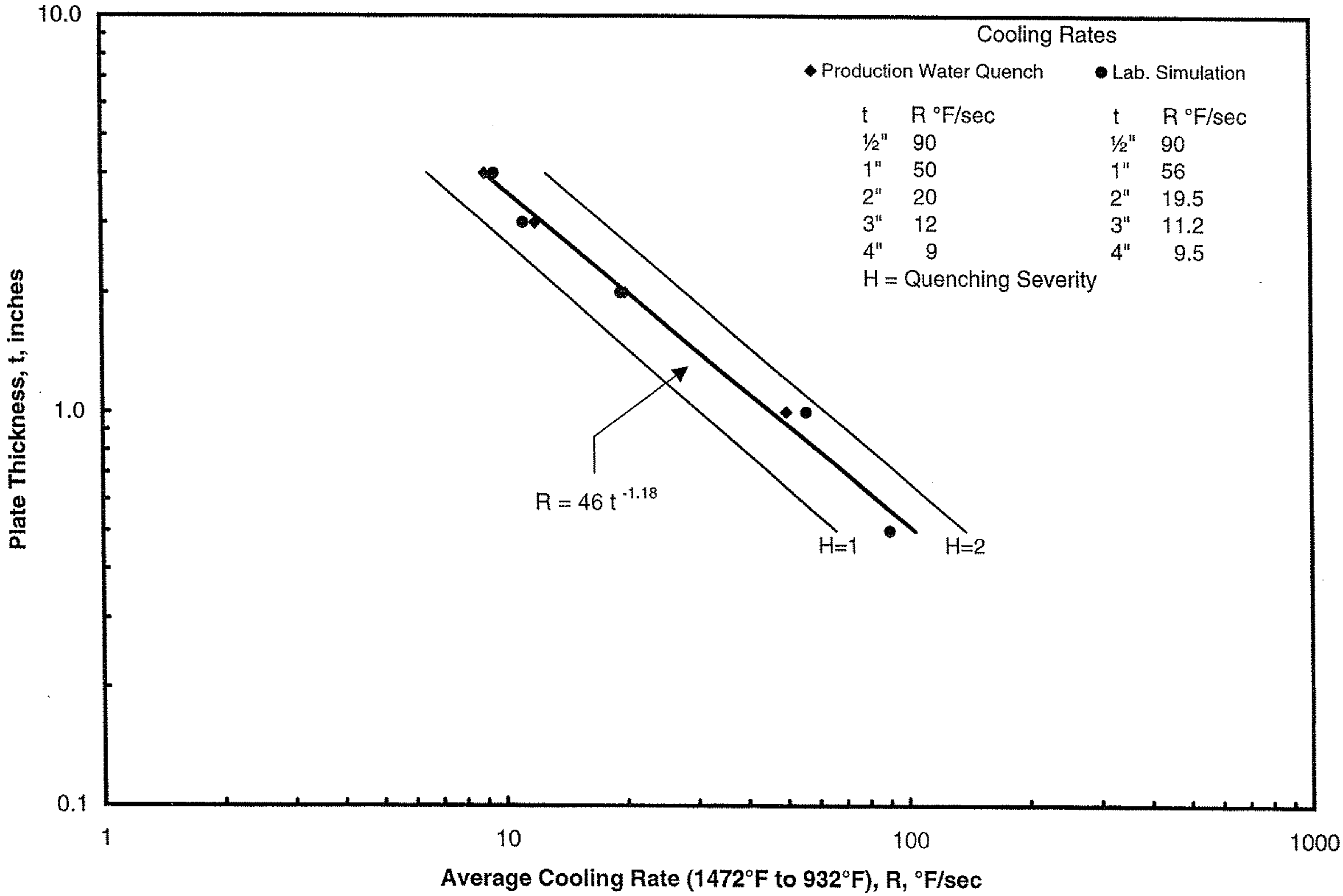


Figure 3 - Comparison of Laboratory and Production Cooling Practices

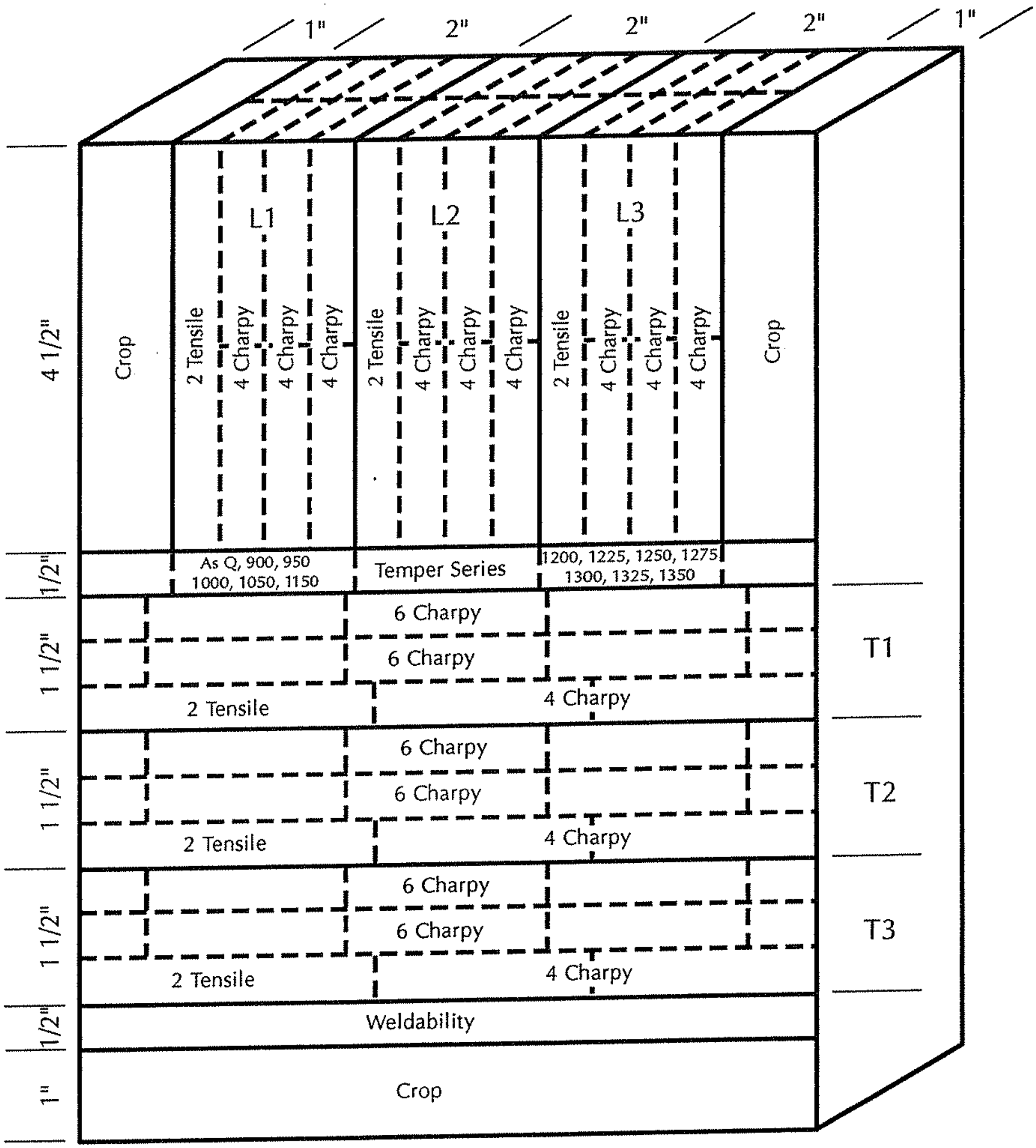


Figure 4 - Machining of Sections A and B from Figure 1 to Test Specimens

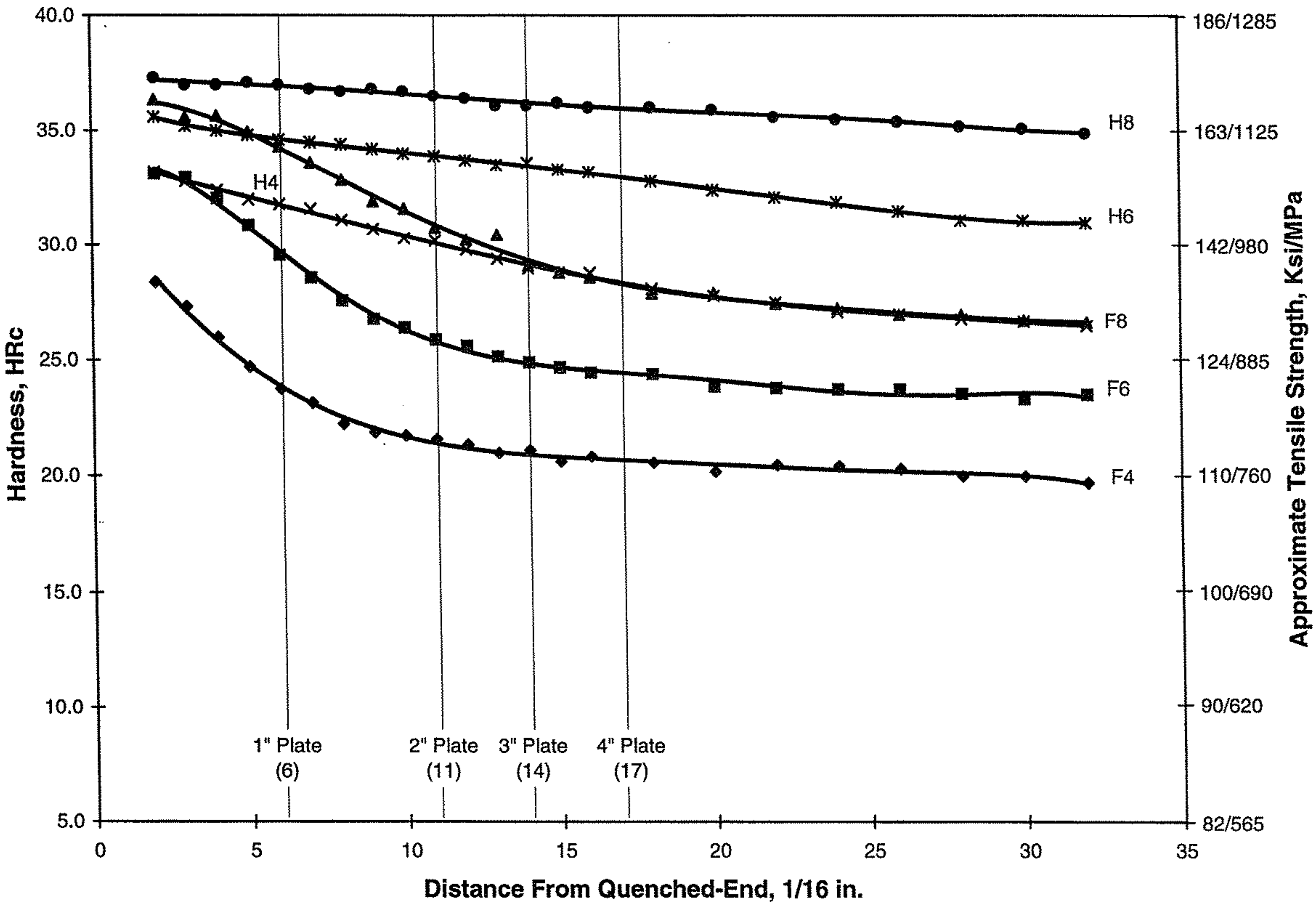


Figure 5 - Averaged Jominy End-Quench Hardenability Results for Steel F and H - As-Quenched

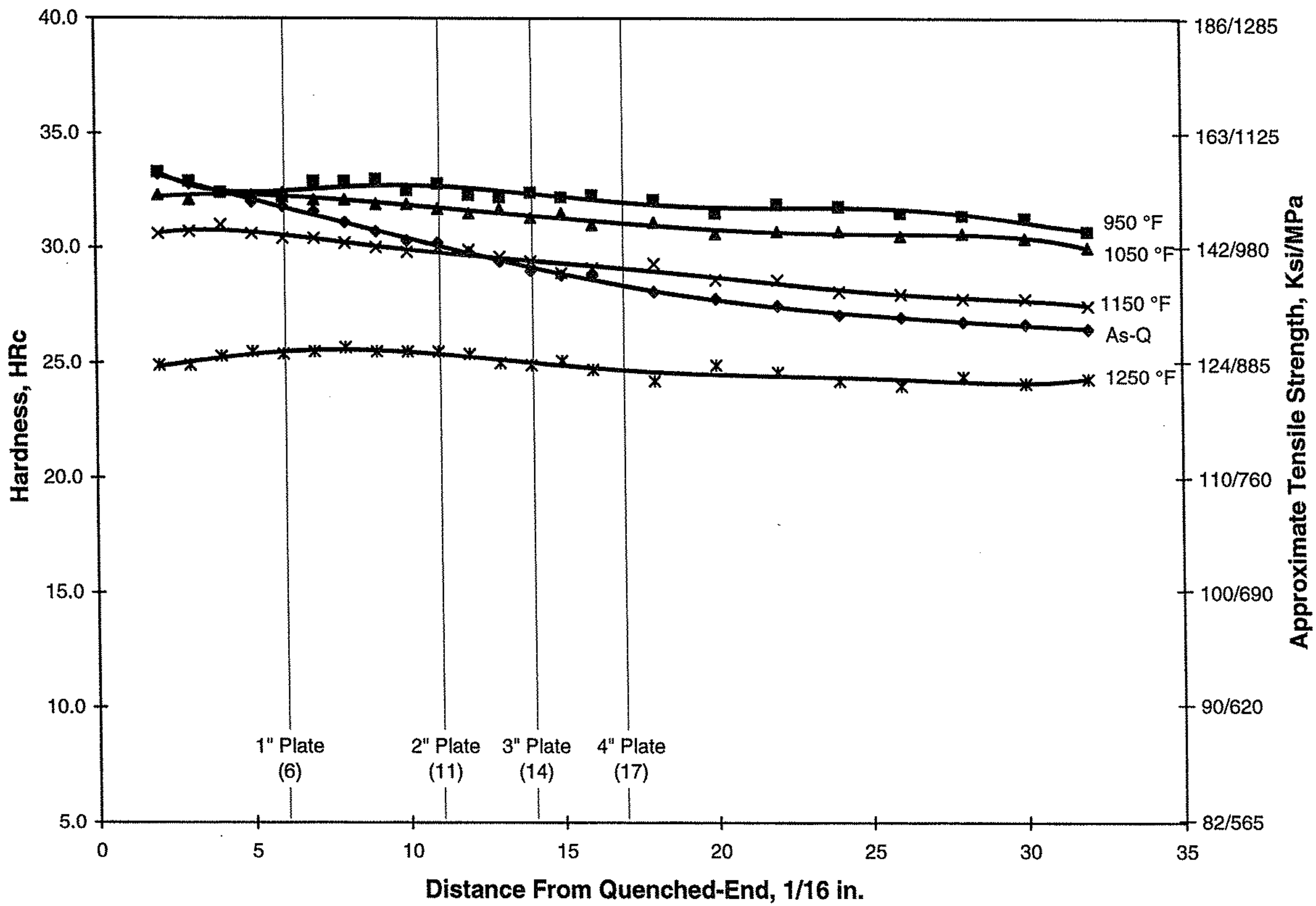


Figure 6 - Averaged Jominy End-Quench Hardenability Results for Steel H4 - Tempered (Aged)

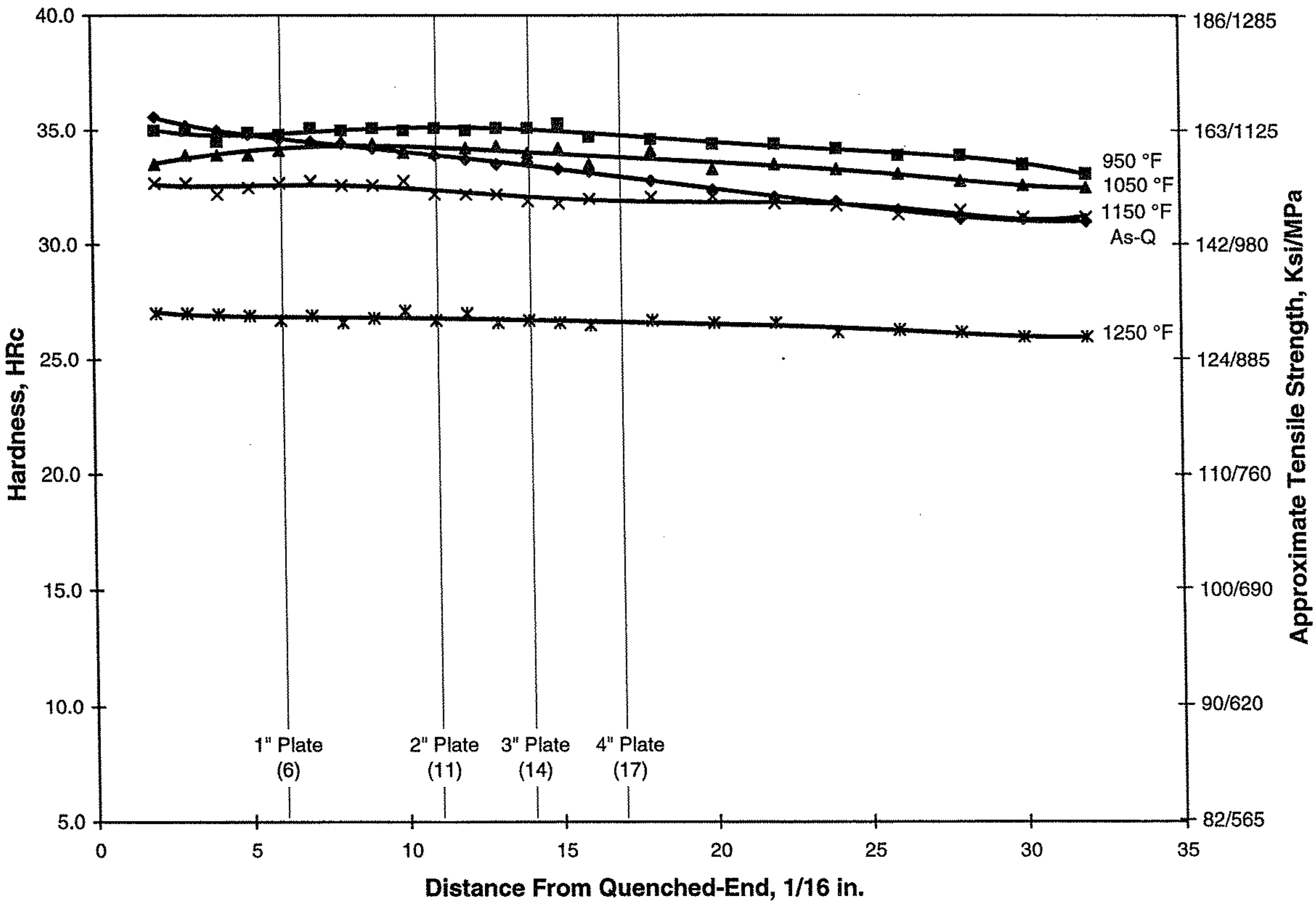


Figure 7 - Averaged Jominy End-Quench Hardenability Results for Steel H6 - Tempered (Aged)

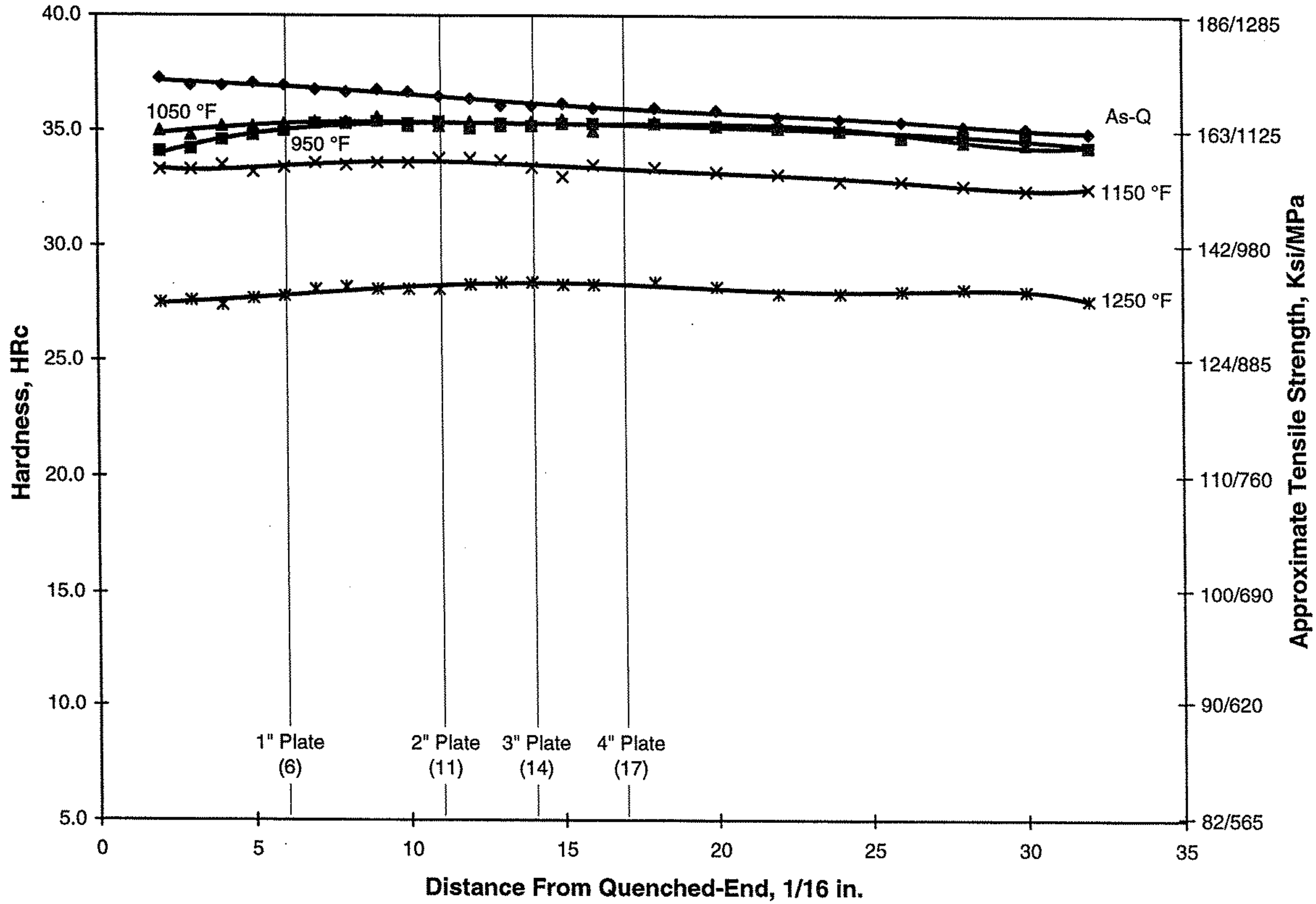


Figure 8 - Averaged Jominy End-Quench Hardenability Results for Steel H8 - Tempered (Aged)

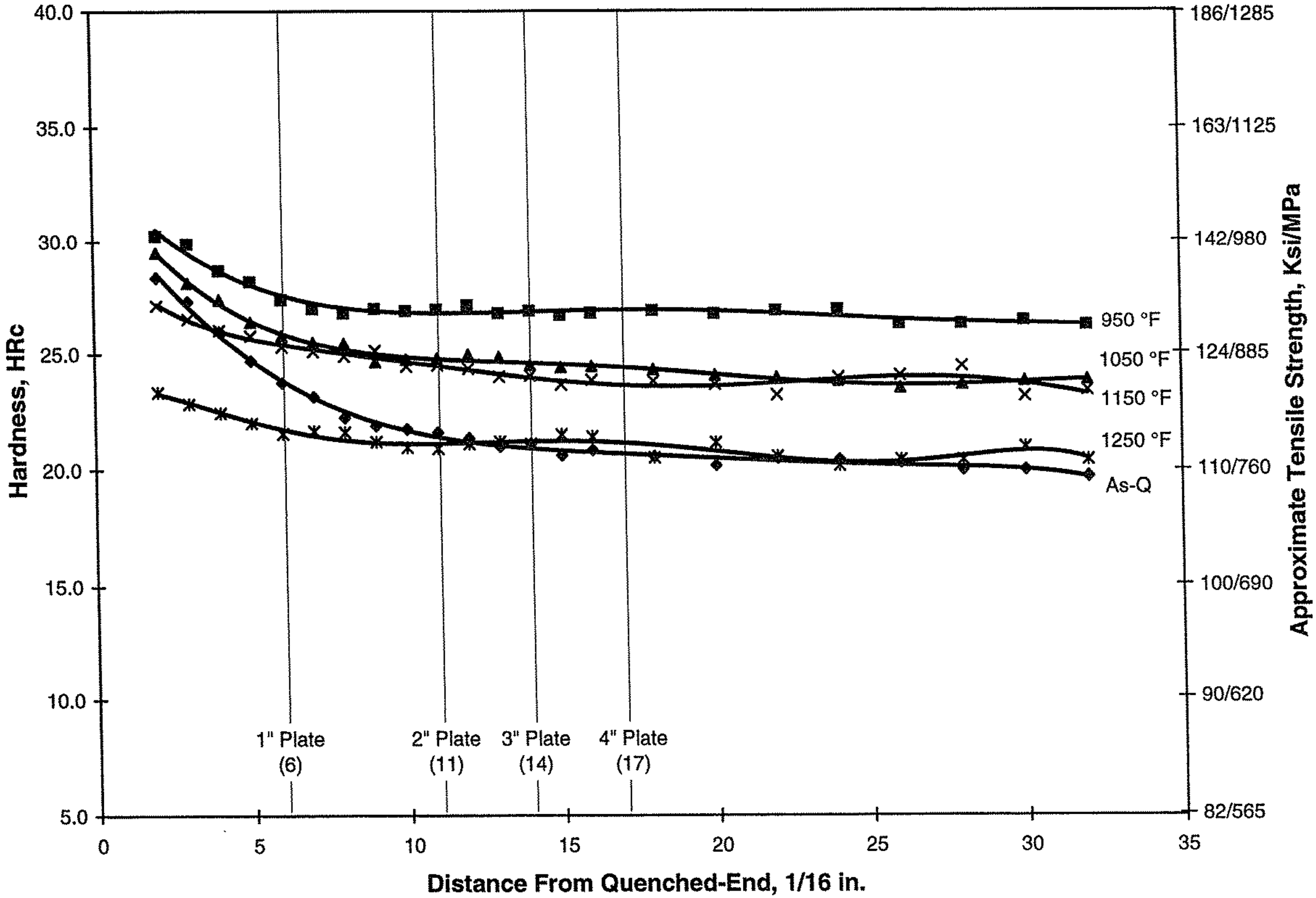


Figure 9 - Averaged Jominy End-Quench Hardenability Results for Steel F4 - Tempered (Aged)

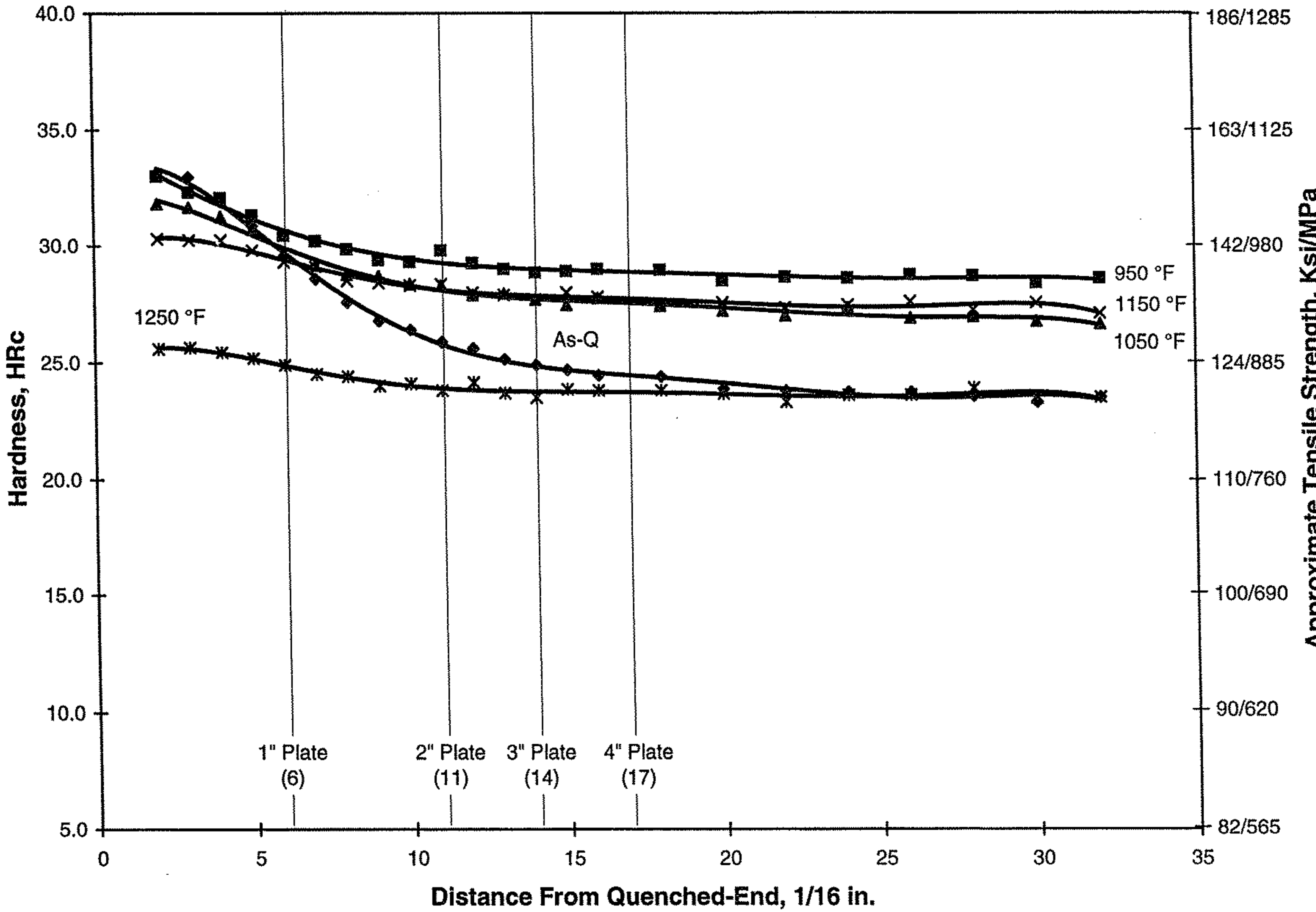


Figure 10 - Averaged Jominy End-Quench Hardenability Results for Steel F6 - Tempered (Aged)

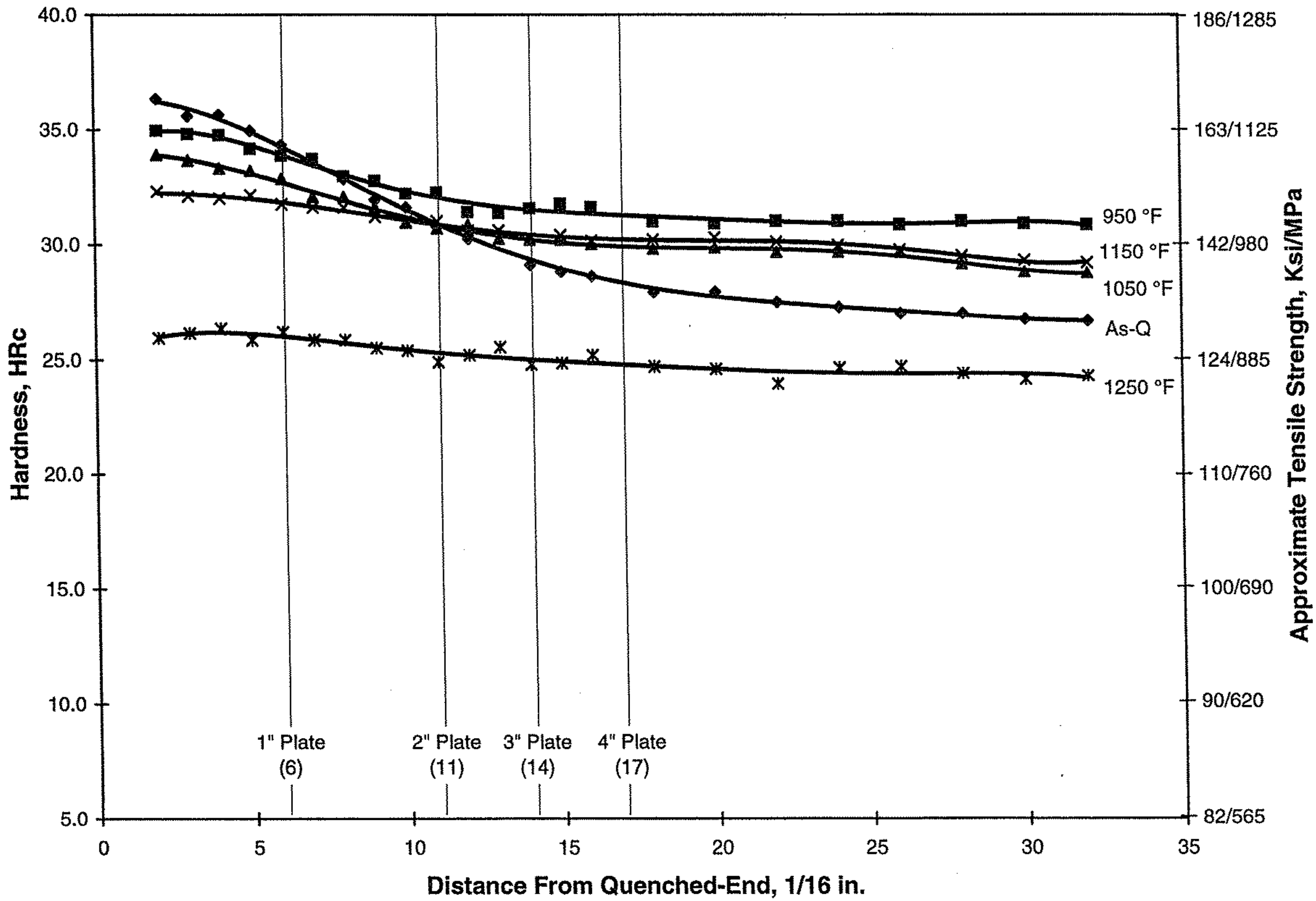
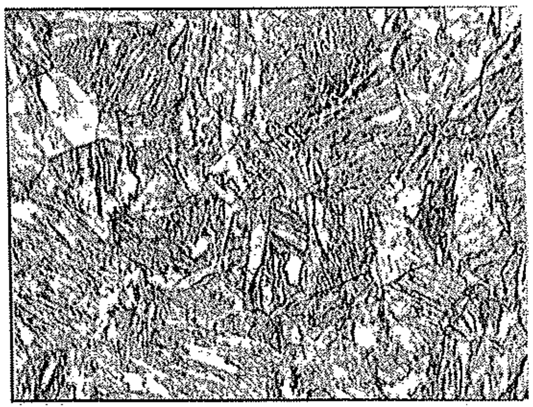


Figure 11 - Averaged Jominy End-Quench Hardenability Results for Steel F8 - Tempered (Aged)

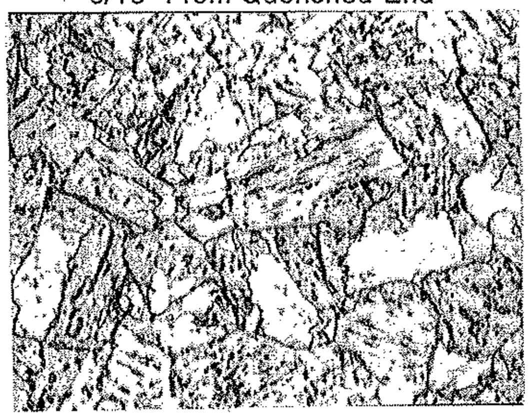
Steel F4

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.040	1.51	0.010	0.004	0.25	0.99	0.78	0.50	0.51	0.059	0.017	0.022

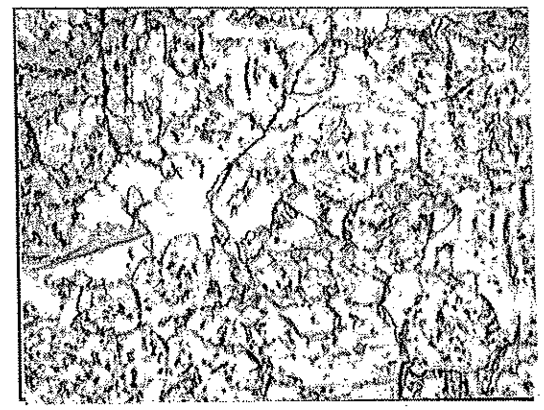
1/16" From Quenched-End



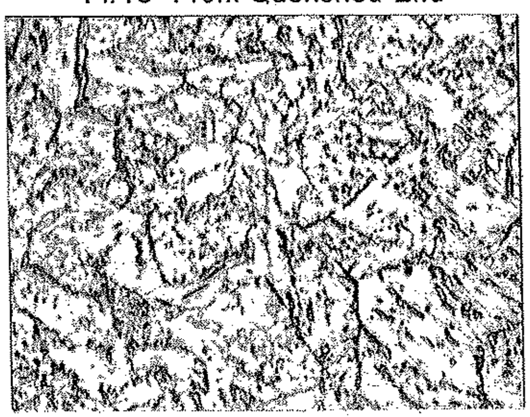
6/16" From Quenched-End



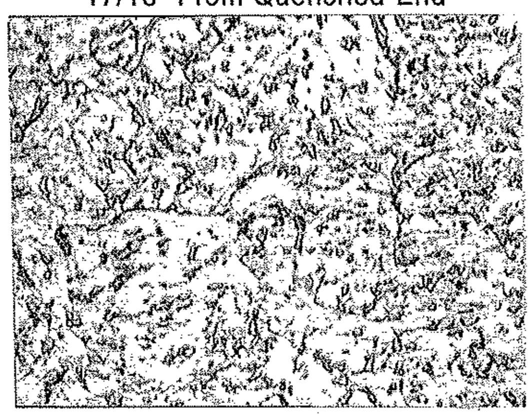
11/16" From Quenched-End



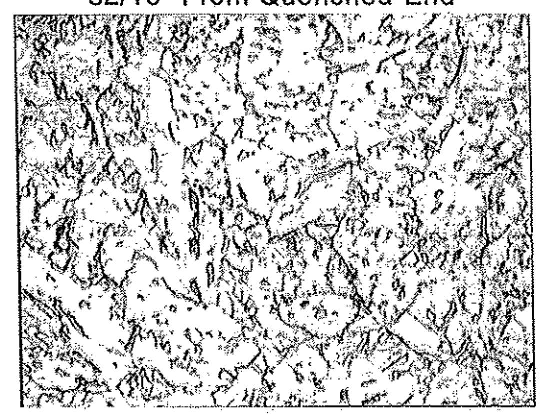
14/16" From Quenched-End



17/16" From Quenched-End



32/16" From Quenched-End



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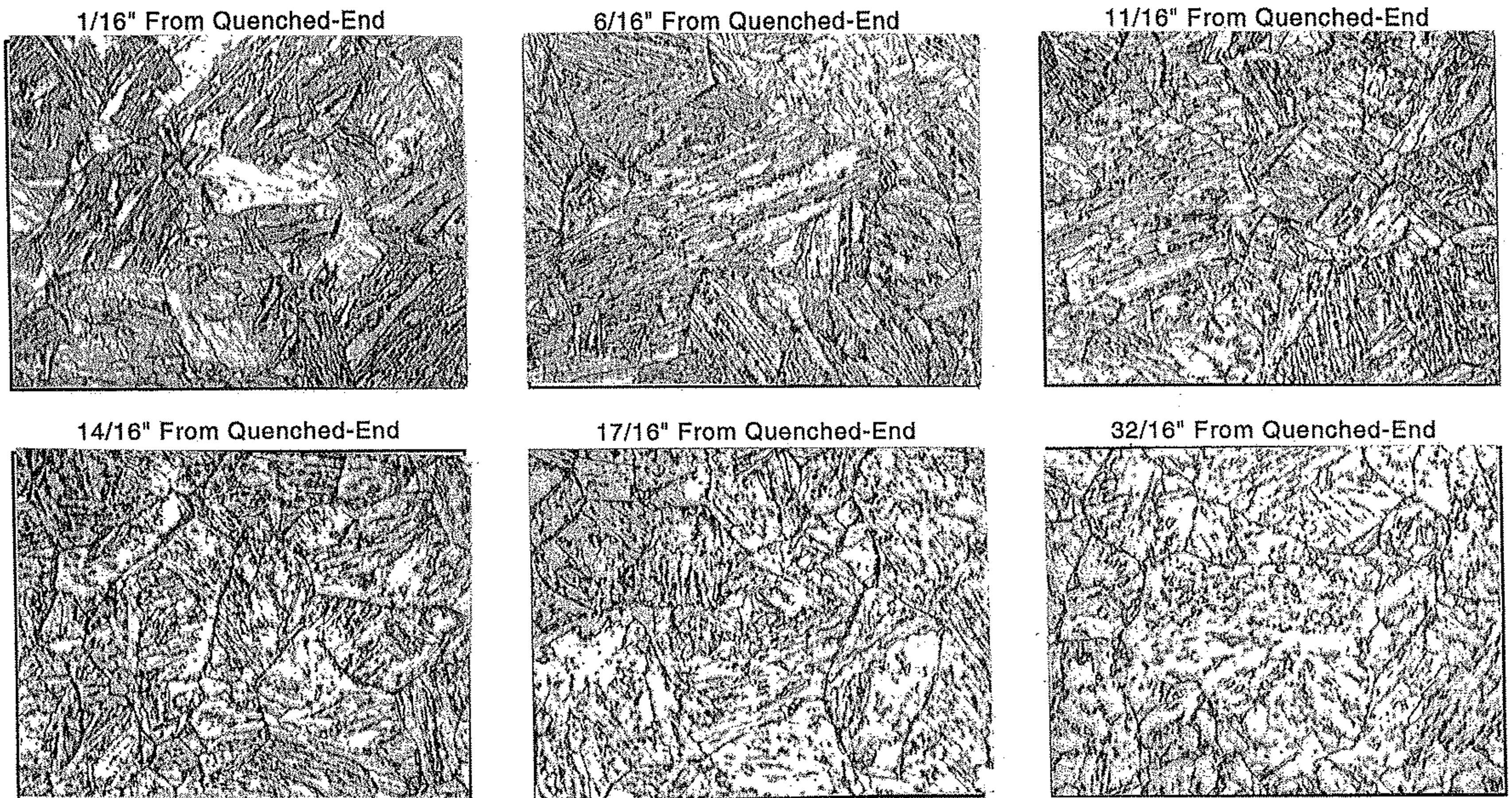
95-D057-14

Figure 12 – Steel F4 Jominy End Quenched Hardenability Microstructures - As-Quenched

Steel H4

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.044	1.50	0.010	0.003	0.24	1.03	2.50	0.49	0.49	0.056	0.016	0.023



X850 Nital-Picral

95-D057-7

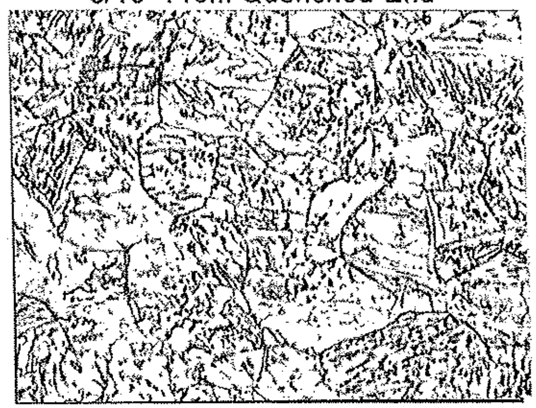
Figure 13 — Steel H4 Jominy End Quenched Hardenability Microstructures - As Quenched

Steel F6

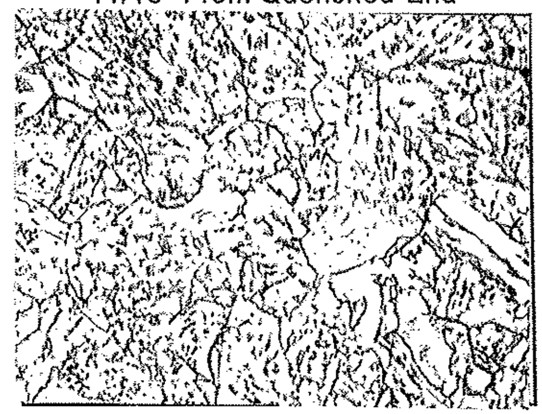
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.059	1.50	0.011	0.004	0.25	0.99	0.78	0.50	0.50	0.059	0.017	0.026

1/16" From Quenched-End

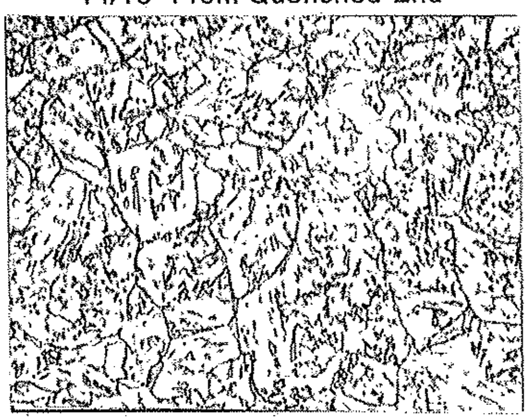
6/16" From Quenched-End



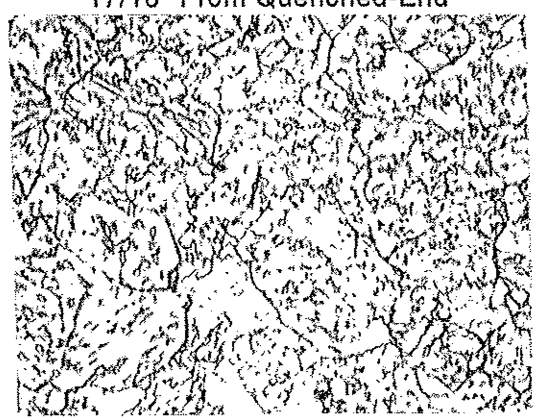
11/16" From Quenched-End



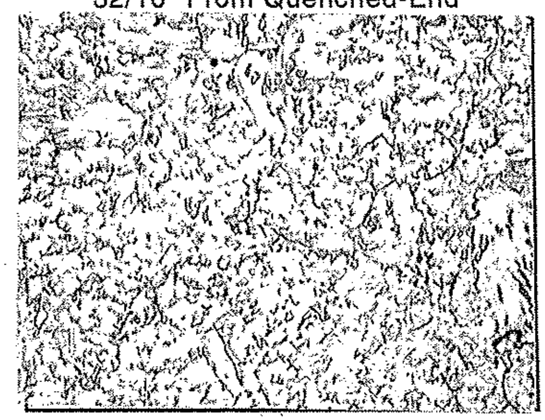
14/16" From Quenched-End



17/16" From Quenched-End



32/16" From Quenched-End



X850 Nital-Picral

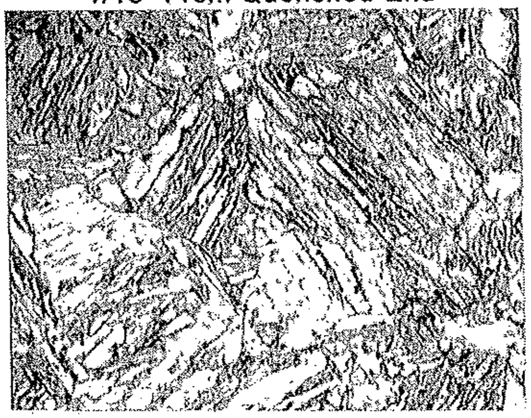
95-D057-15

Figure 14 – Steel F6 Jominy End Quenched Hardenability Microstructures - As-Quenched

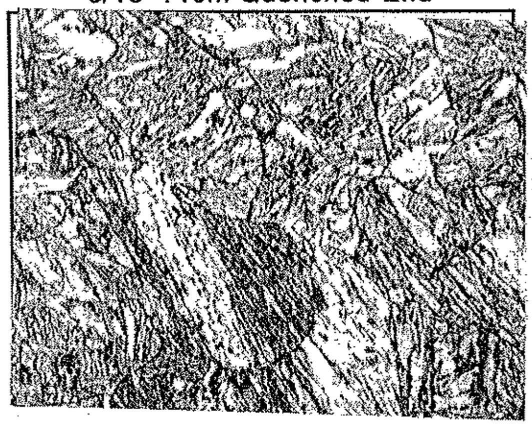
Steel H6

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

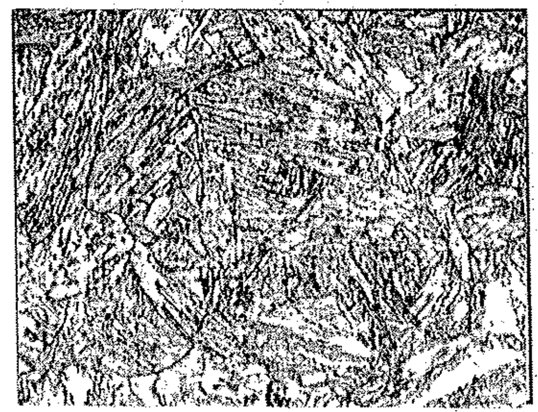
1/16" From Quenched-End



6/16" From Quenched-End

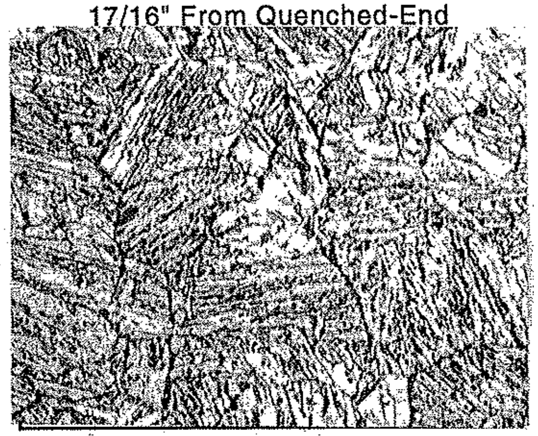


11/16" From Quenched-End



14/16" From Quenched-End

17/16" From Quenched-End



32/16" From Quenched-End

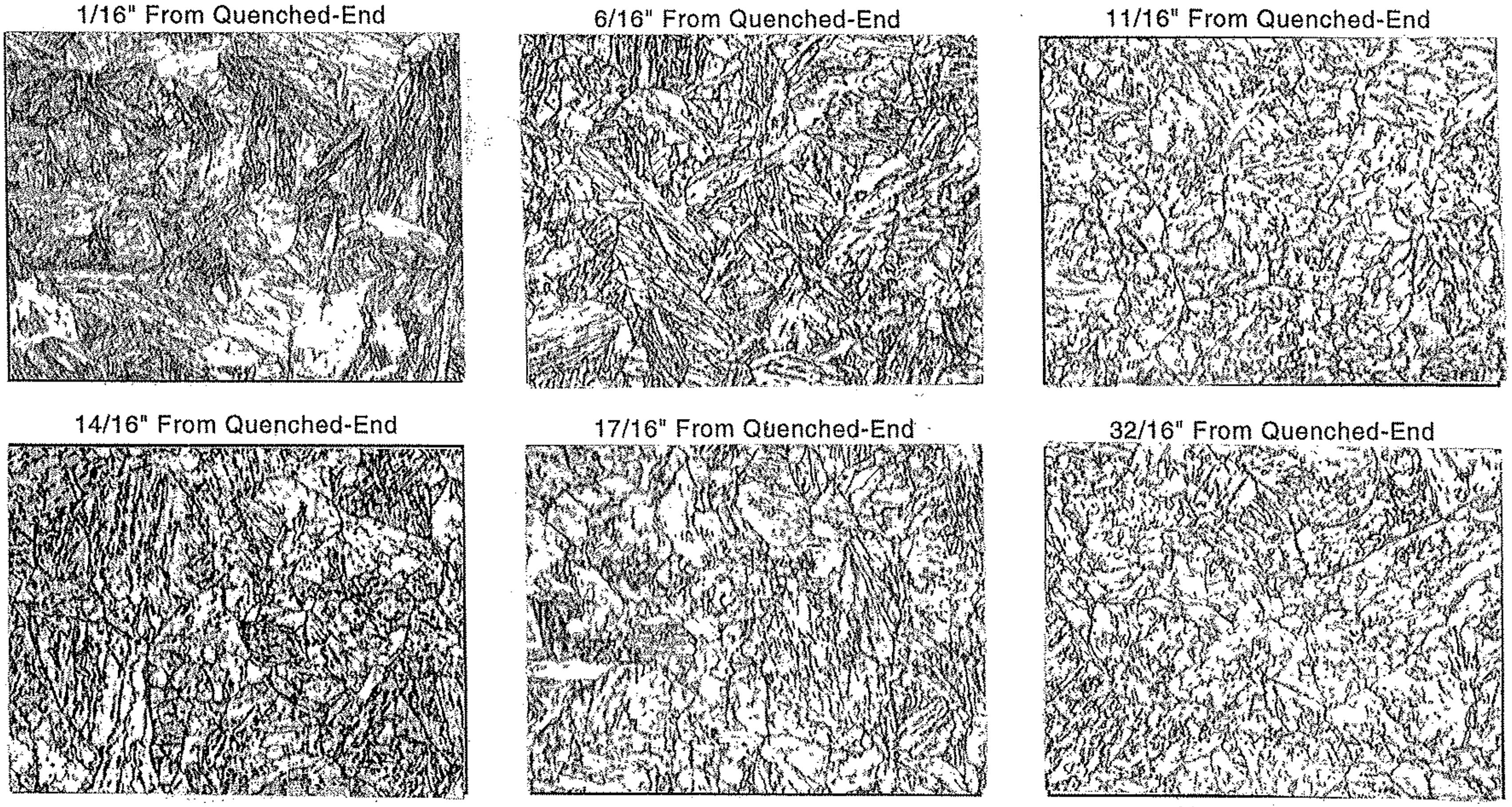
X850 Nital-Picral

95-D057-9

Figure 15 – Steel H6 Jominy End Quenched Hardenability Microstructures - As Quenched

Steel F8

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.081	1.49	0.011	0.003	0.25	0.99	0.77	0.50	0.50	0.059	0.016	0.025



X850 Nital-Picral

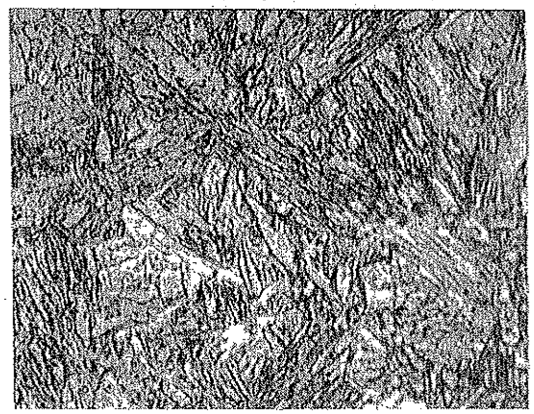
95-D057-16

Figure 16 – Steel F8 Jominy End Quenched Hardenability Microstructures - As-Quenched

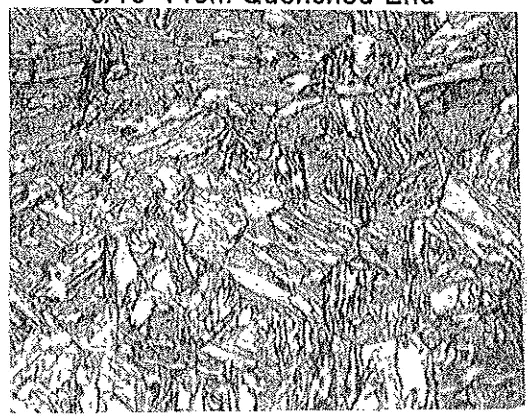
Steel H8

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.080	1.50	0.011	0.003	0.24	1.03	2.53	0.49	0.49	0.056	0.016	0.022

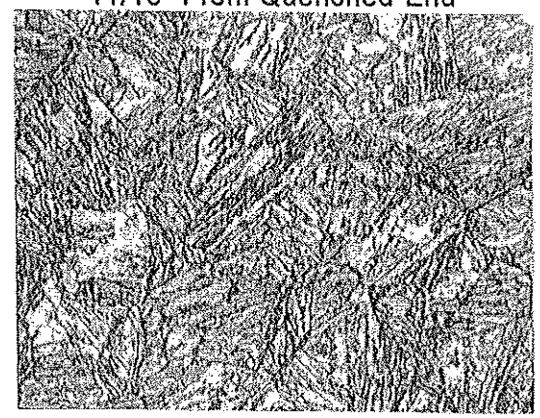
1/16" From Quenched-End



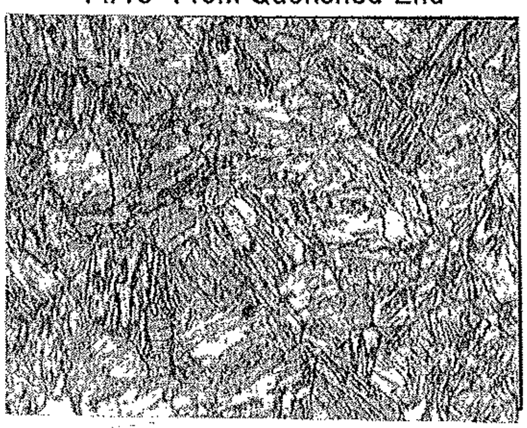
6/16" From Quenched-End



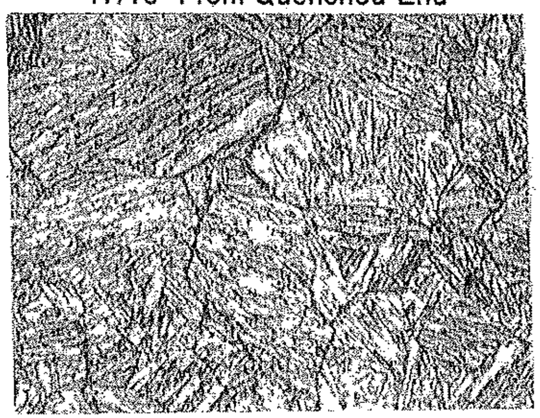
11/16" From Quenched-End



14/16" From Quenched-End



17/16" From Quenched-End



32/16" From Quenched-End

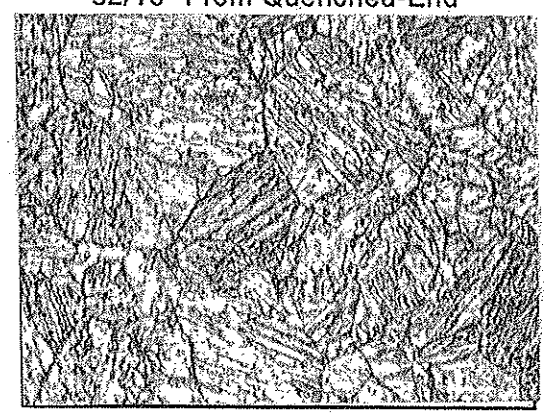


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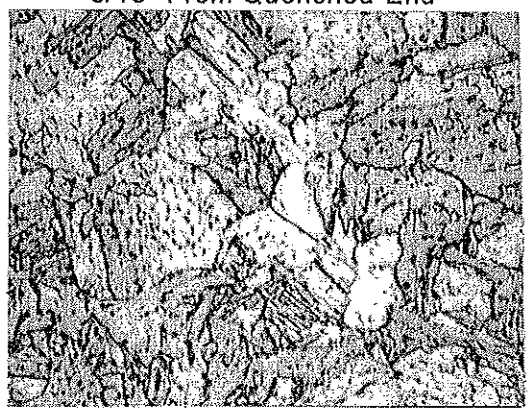
Figure 17 — Steel H8 Jominy End Quenched Hardenability Microstructures - As Quenched

Steel F4

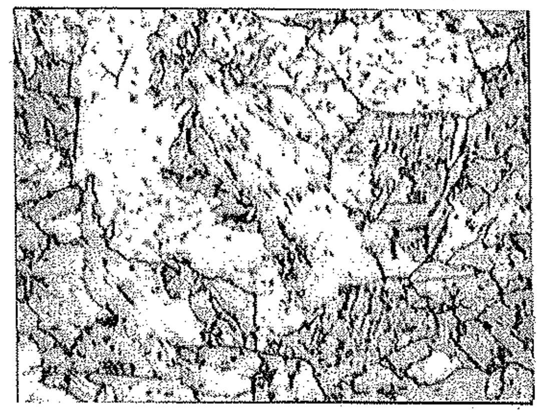
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.040	1.51	0.010	0.0038	0.25	0.99	0.78	0.50	0.51	0.059	0.017	0.022

1/16" From Quenched-End

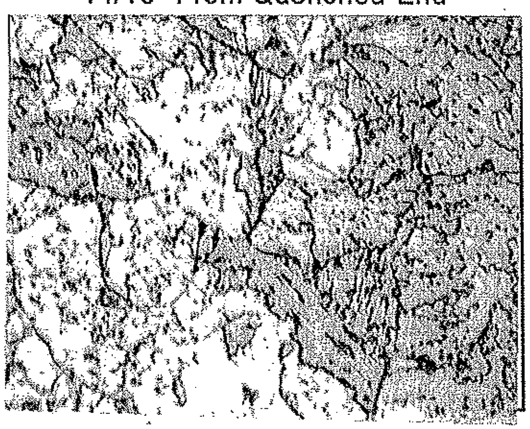
6/16" From Quenched-End



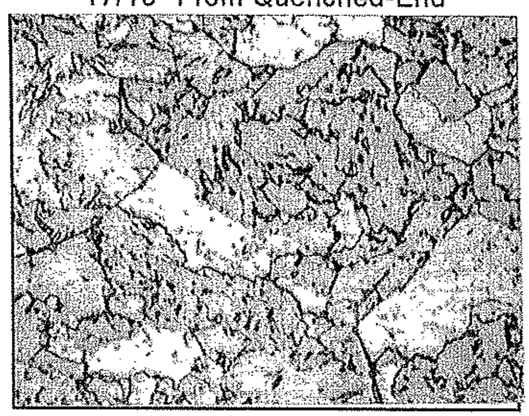
11/16" From Quenched-End



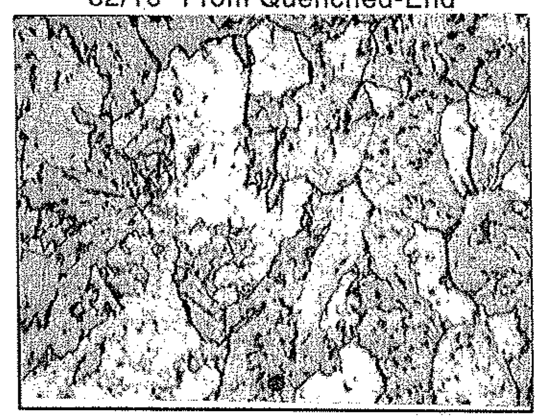
14/16" From Quenched-End



17/16" From Quenched-End



32/16" From Quenched-End



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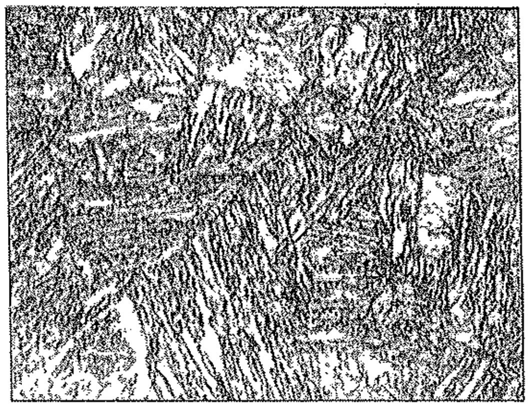
95-D057-I Figure 18 – Steel F4 Jominy End Quenched Hardenability Microstructures - Tempered 1250F (675C)

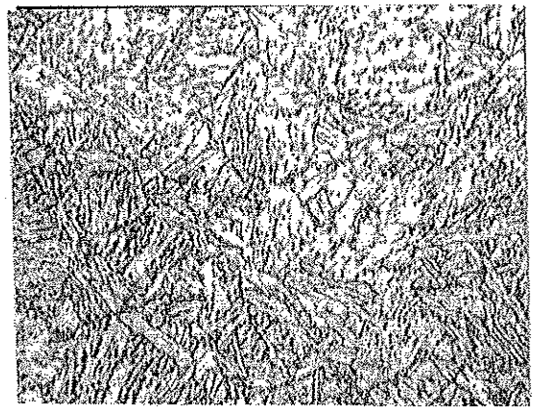
Steel H4

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.044	1.50	0.010	0.003	0.24	1.03	2.50	0.49	0.49	0.056	0.016	0.023

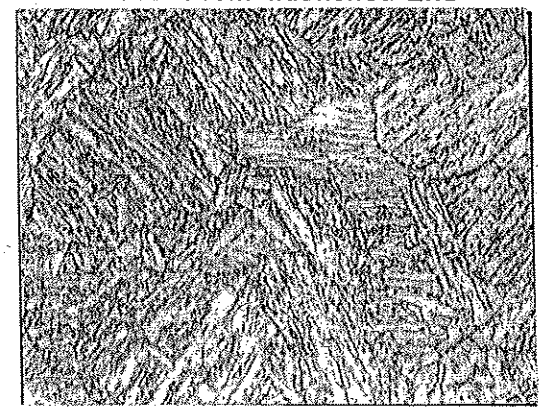
1/16" From Quenched-End



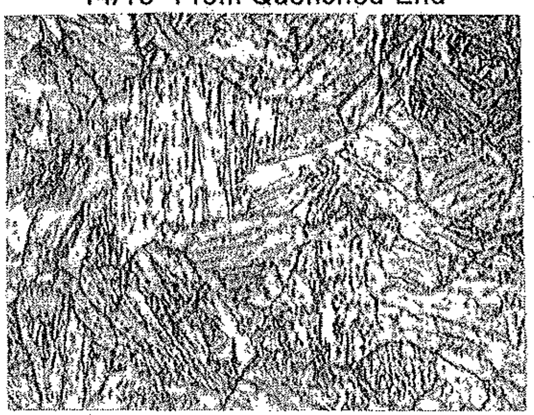
6/16" From Quenched-End



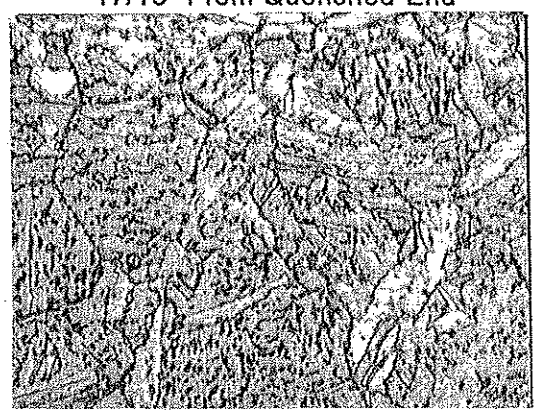
11/16" From Quenched-End



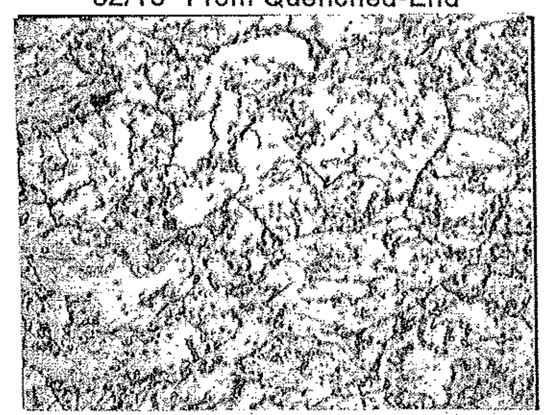
14/16" From Quenched-End



17/16" From Quenched-End



32/16" From Quenched-End



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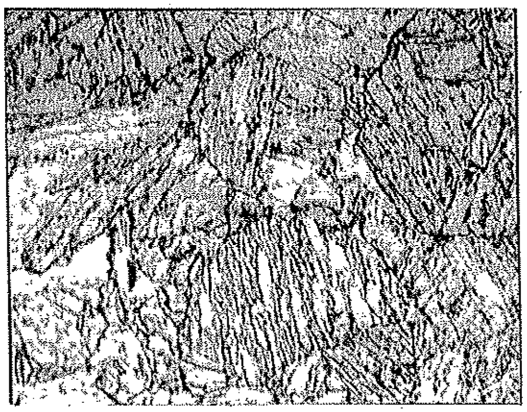
95-D057 Figure 19 — Steel H4 Jominy End Quenched Hardenability Microstructures - Tempered 1250F (675C)

Steel F6

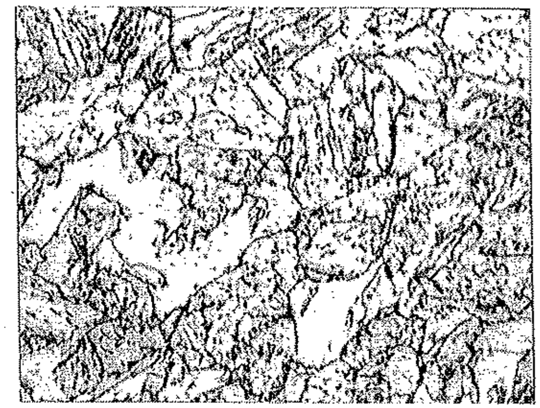
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.059	1.50	0.011	0.0036	0.25	0.99	0.78	0.50	0.50	0.059	0.017	0.026

1/16" From Quenched-End

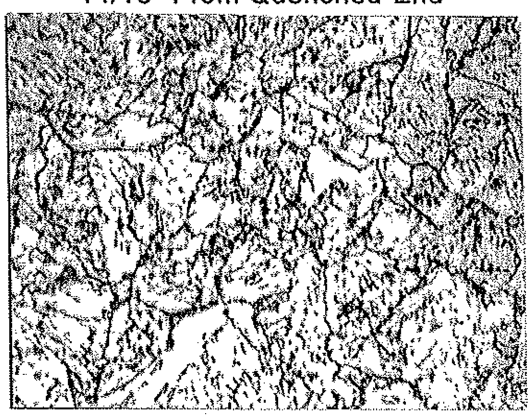


6/16" From Quenched-End

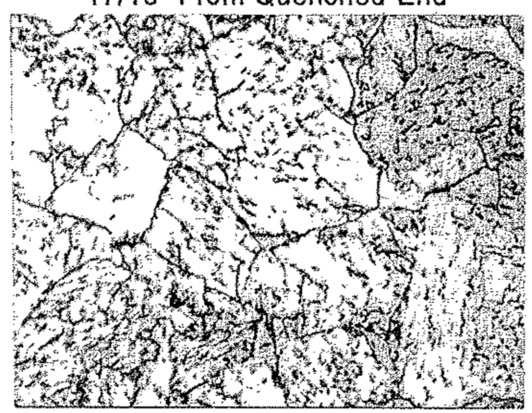
11/16" From Quenched-End



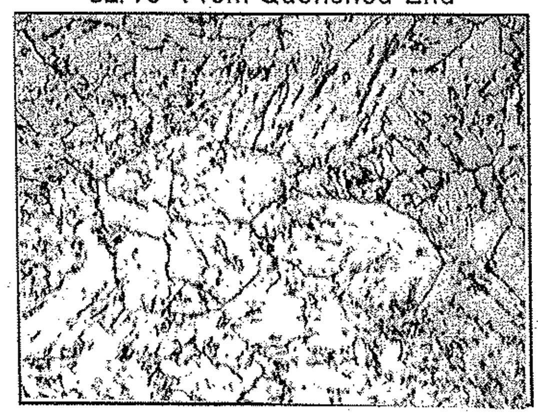
14/16" From Quenched-End



17/16" From Quenched-End



32/16" From Quenched-End



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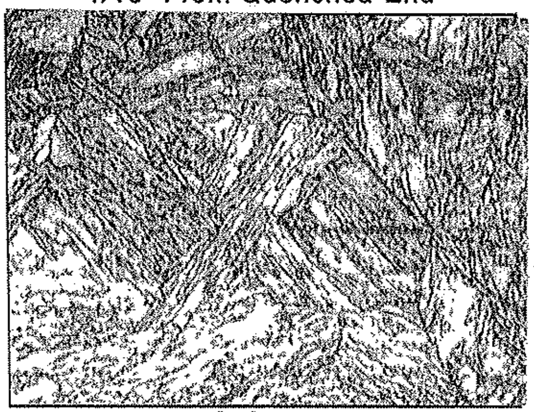
95-D057-39 Figure 20 - Steel F6 Jominy End Quenched Hardenability Microstructures - Tempered 1250F (675C)

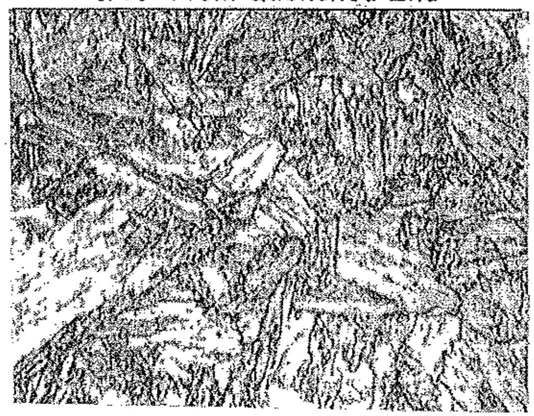
Steel H6

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

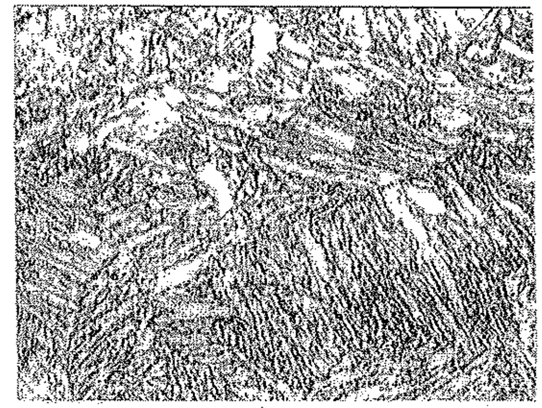
1/16" From Quenched-End



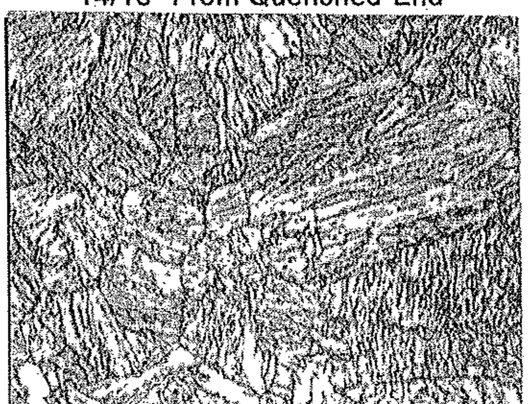
6/16" From Quenched-End



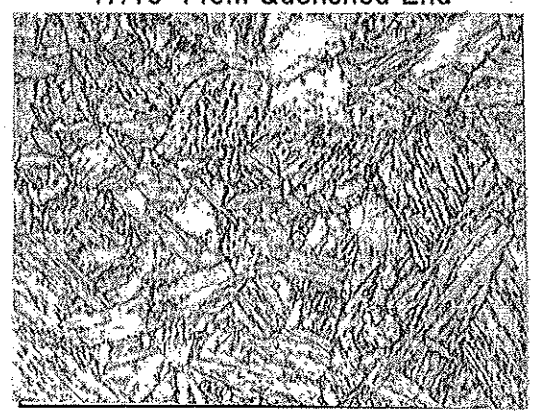
11/16" From Quenched-End



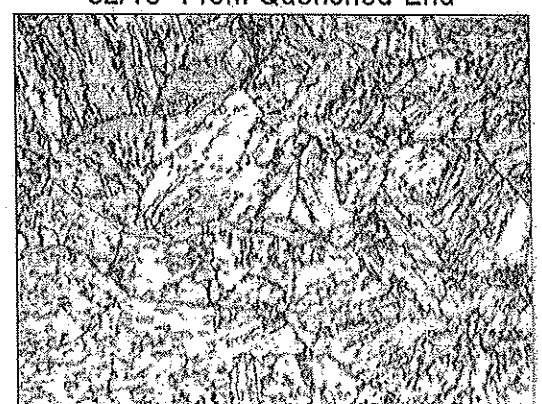
14/16" From Quenched-End



17/16" From Quenched-End



32/16" From Quenched-End



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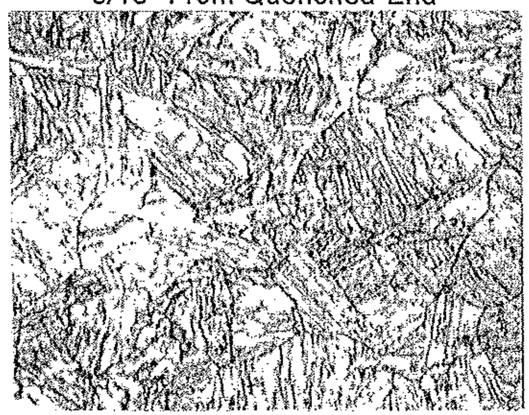
95-D057. Figure 21 - Steel H6 Jominy End Quenched Hardenability Microstructures - Tempered 1250F (675C)

Steel F8

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.081	1.49	0.011	0.0034	0.25	0.99	0.77	0.50	0.50	0.059	0.016	0.025

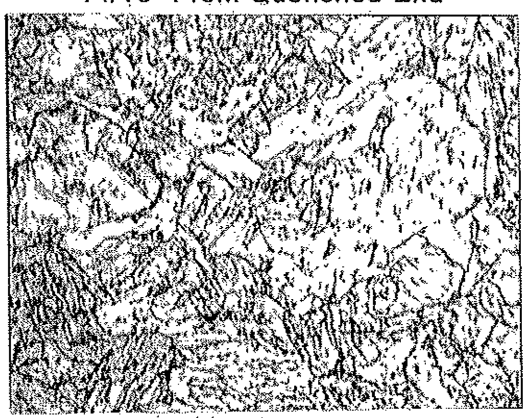
1/16" From Quenched-End

6/16" From Quenched-End

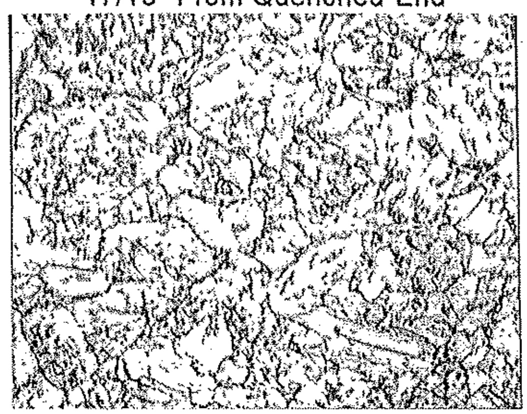


11/16" From Quenched-End

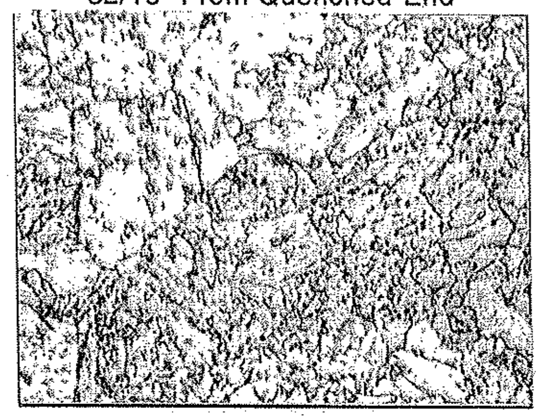
14/16" From Quenched-End



17/16" From Quenched-End



32/16" From Quenched-End



X850 Nital-Picral

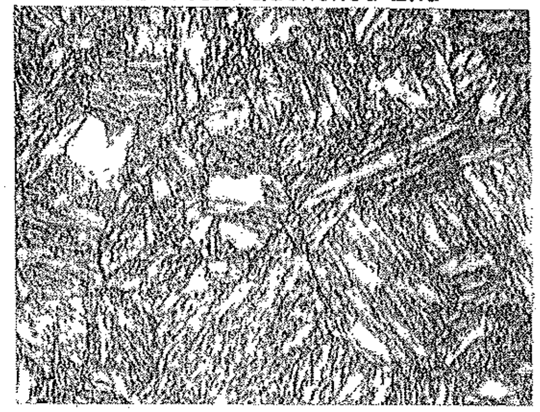
95-D057-40 Figure 22 – Steel F8 Jominy End Quenched Hardenability Microstructures - Tempered 1250F (675C)

Steel H8

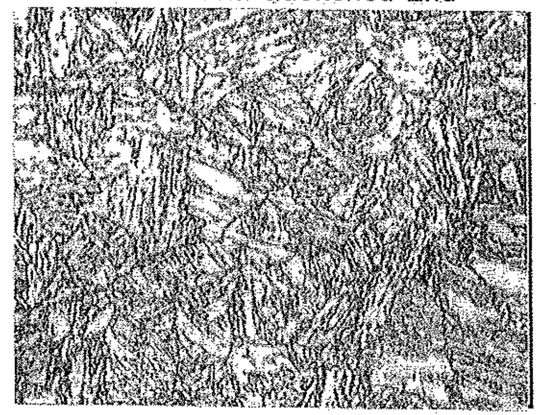
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.080	1.50	0.011	0.003	0.24	1.03	2.53	0.49	0.49	0.056	0.016	0.022

1/16" From Quenched-End

6/16" From Quenched-End

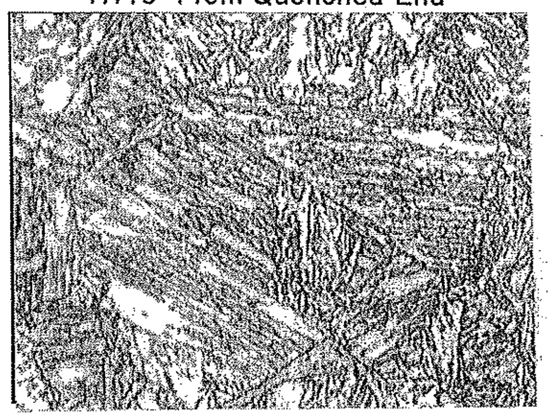


11/16" From Quenched-End

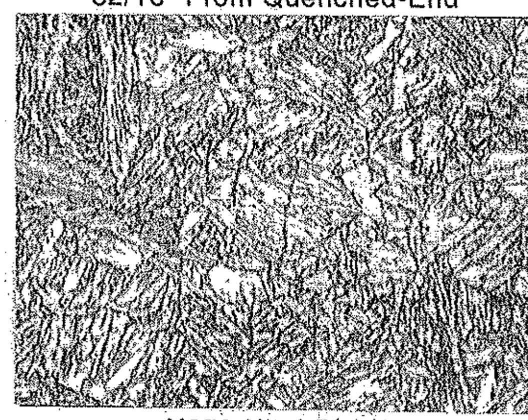


14/16" From Quenched-End

17/16" From Quenched-End



32/16" From Quenched-End



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95-D057-12 Figure 23 – Steel H8 Jominy End Quenched Hardenability Microstructures - Tempered 1250F (675C)

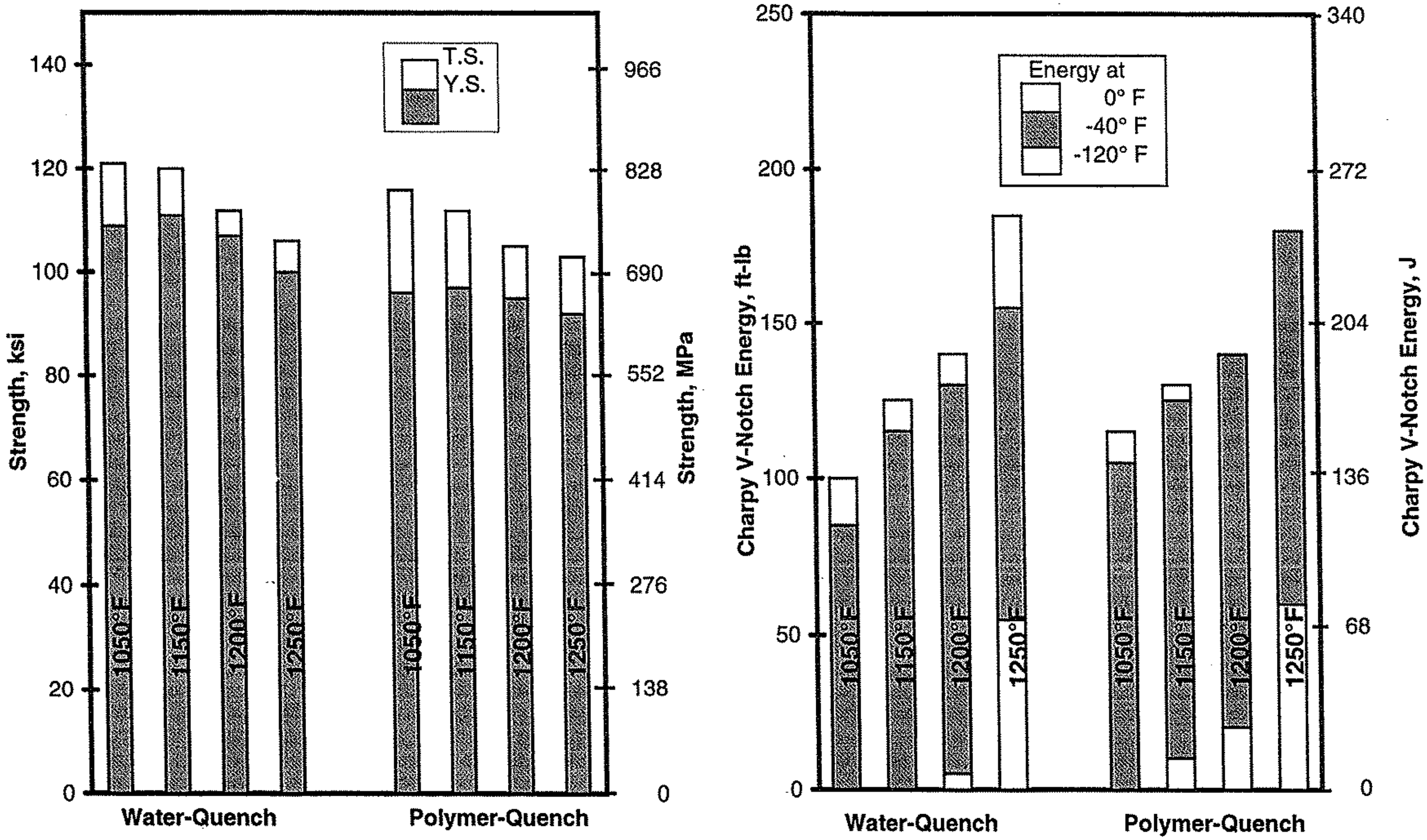

Figure 24 - Strength and Toughness Properties for F4 Steel after Various Heat Treatments (Longitudinal)

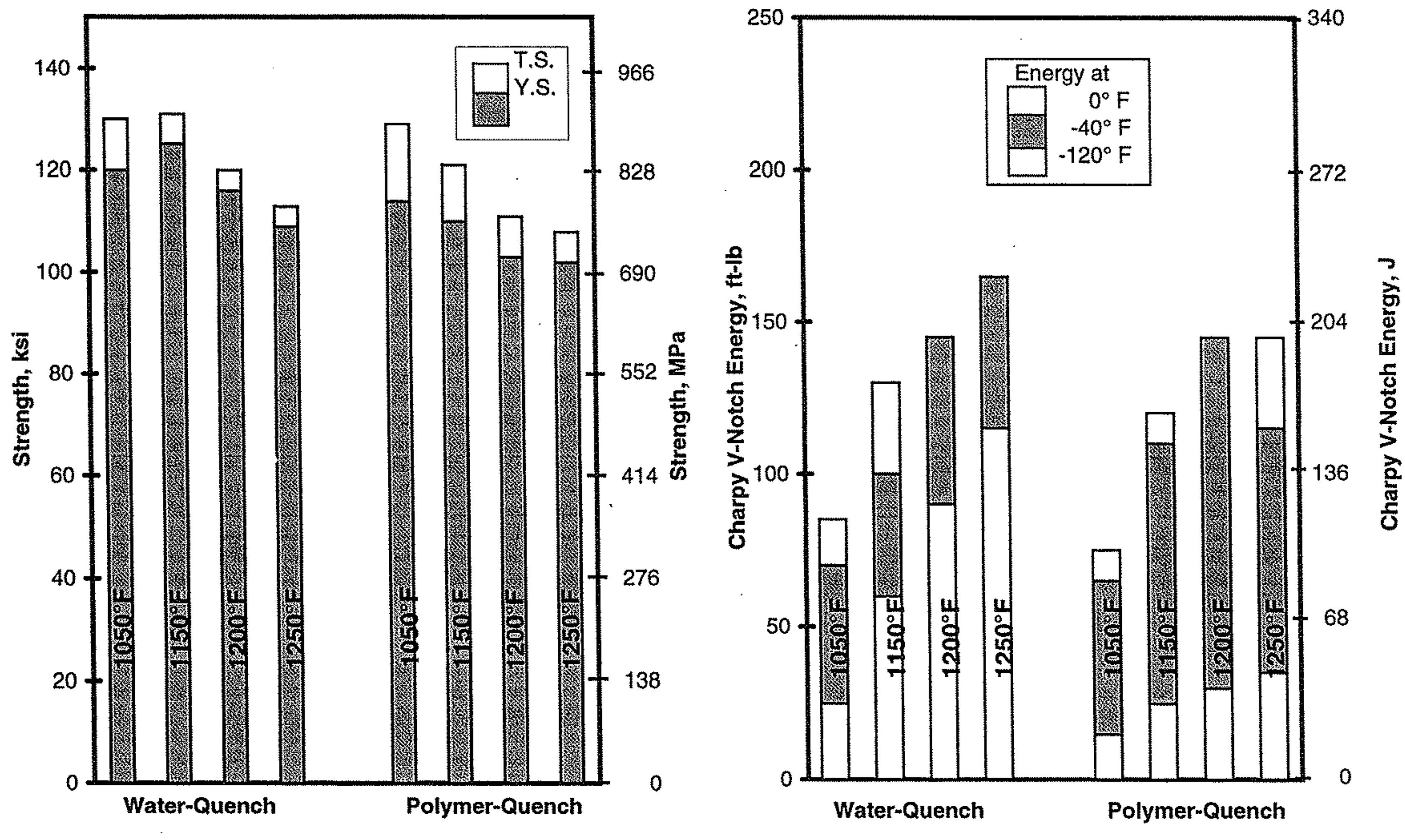

Figure 25 - Strength and Toughness Properties for F6 Steel after Various Heat Treatments (Longitudinal)

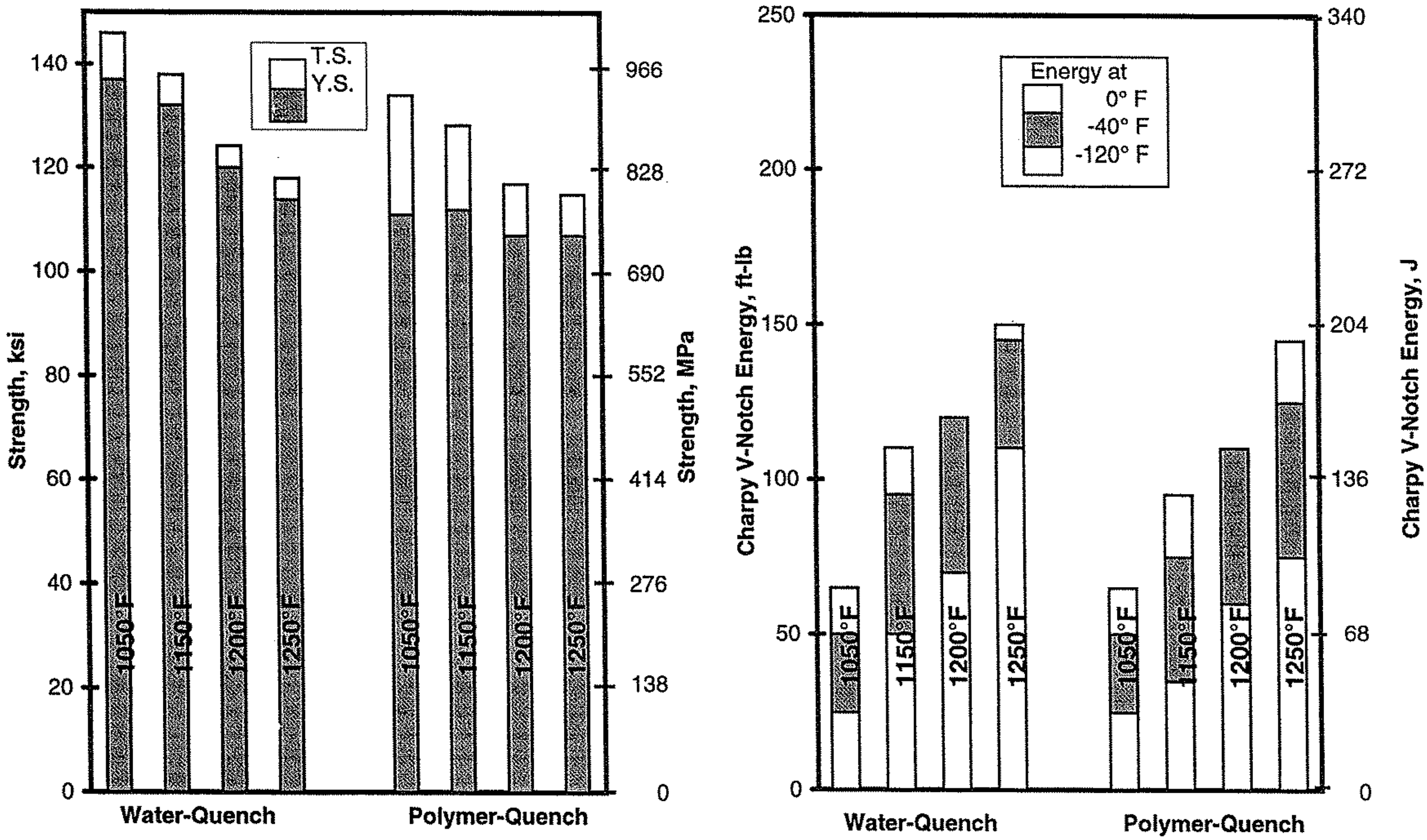

Figure 26 - Strength and Toughness Properties for F8 Steel after Various Heat Treatments (Longitudinal)

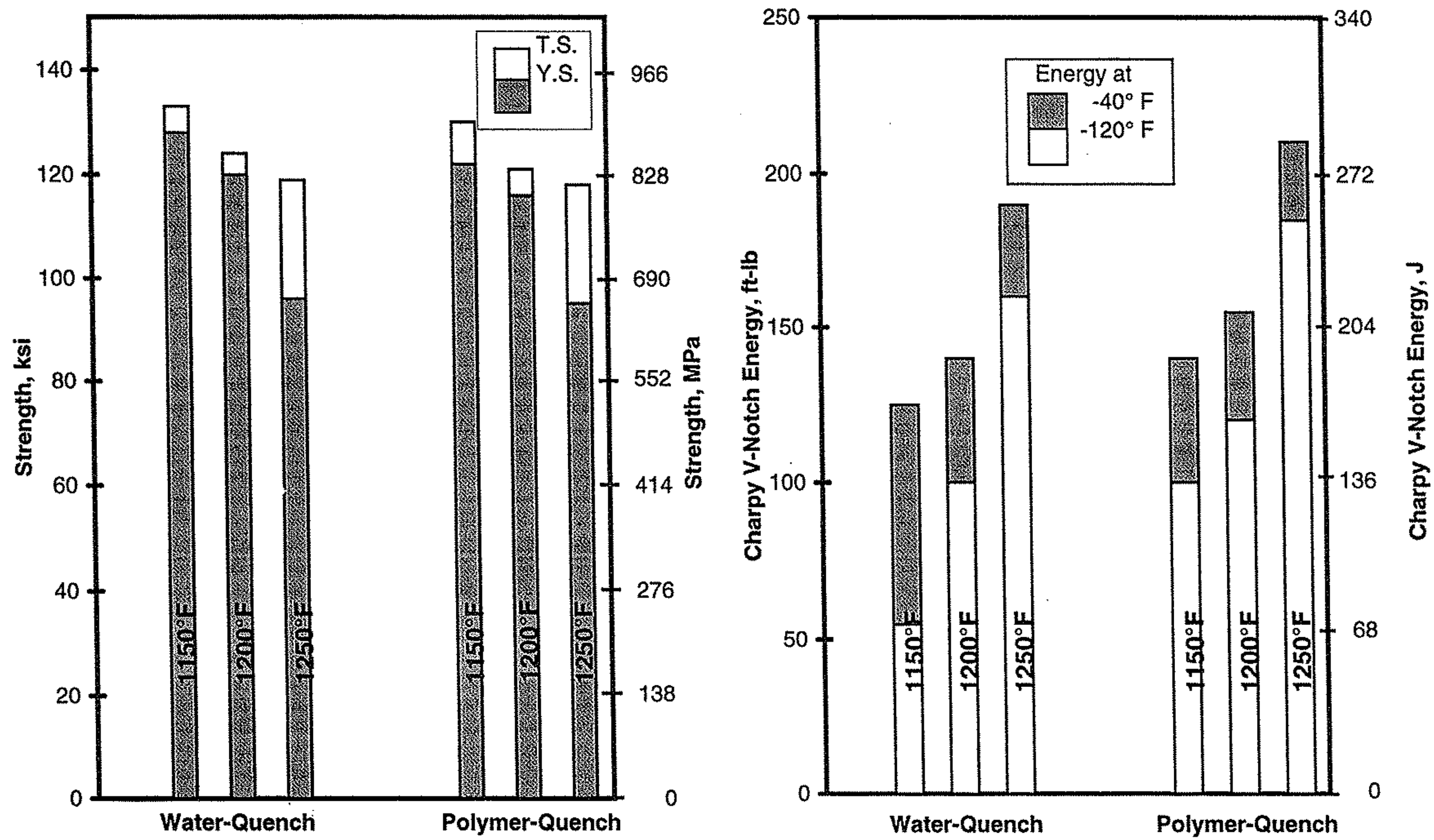

Figure 27 - Strength and Toughness Properties for H4 Steel after Various Heat Treatments (Longitudinal)

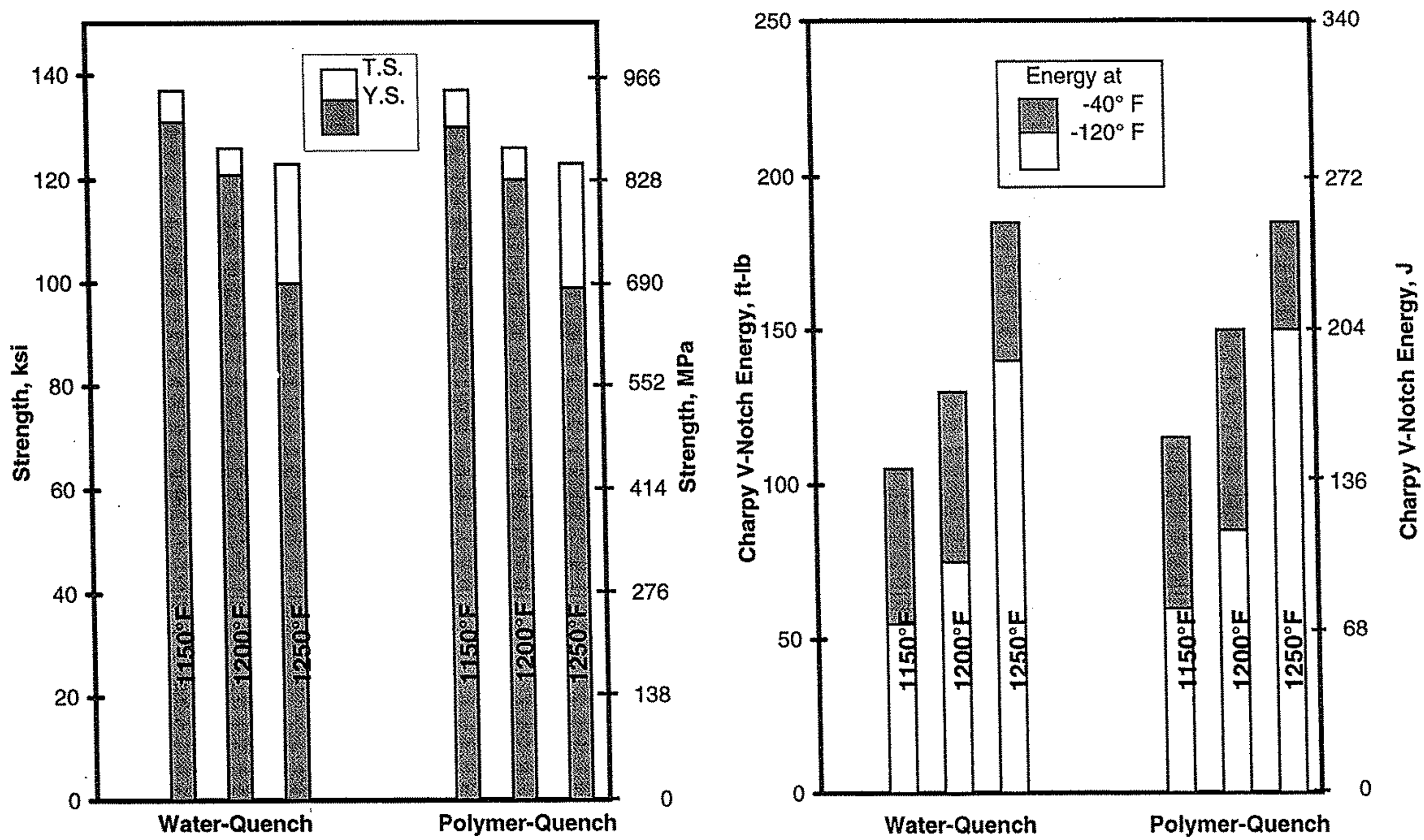

Figure 28 - Strength and Toughness Properties for H6 Steel after Various Heat Treatments (Longitudinal)

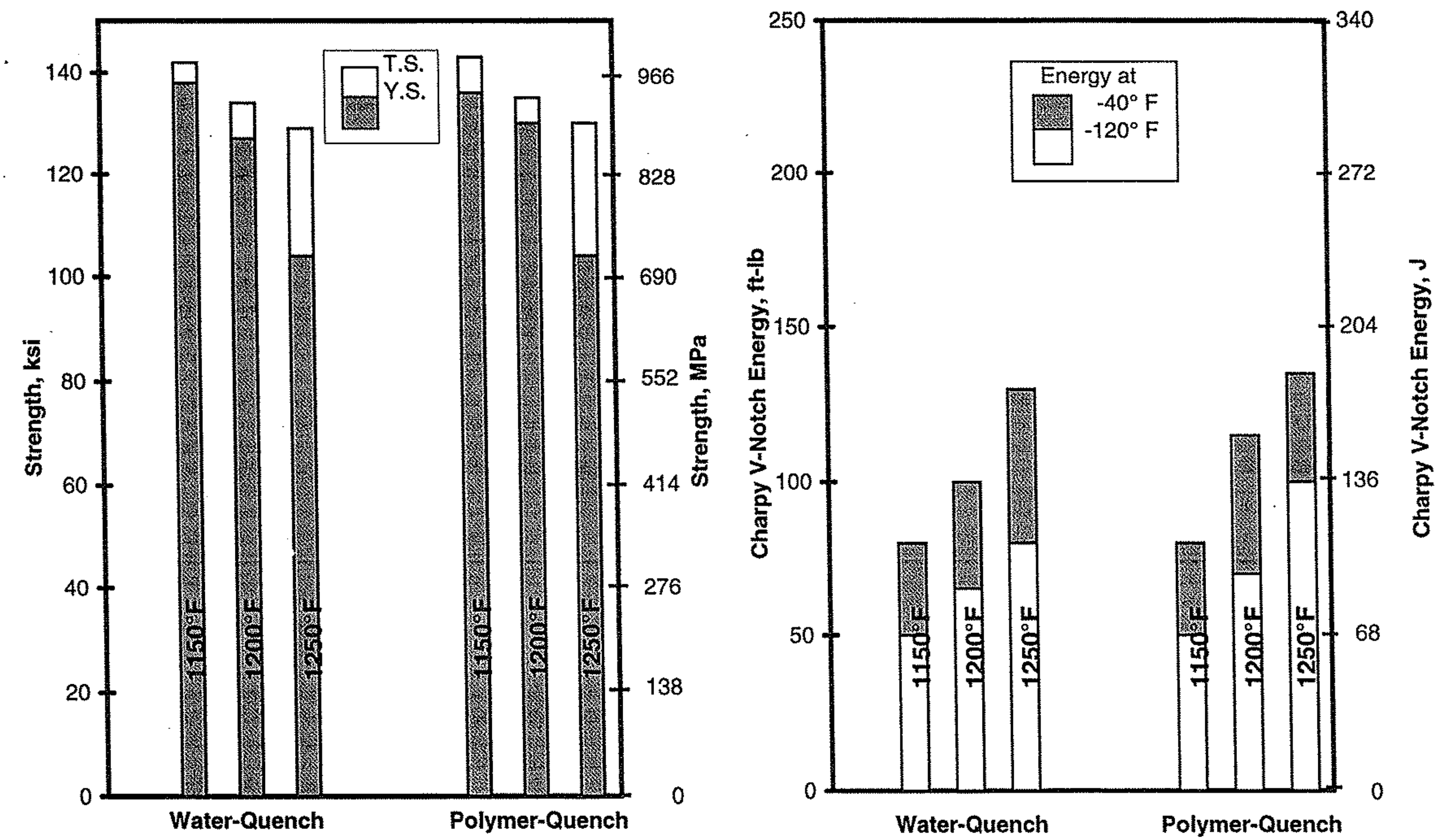

Figure 29 - Strength and Toughness Properties for H8 Steel after Various Heat Treatments (Longitudinal)

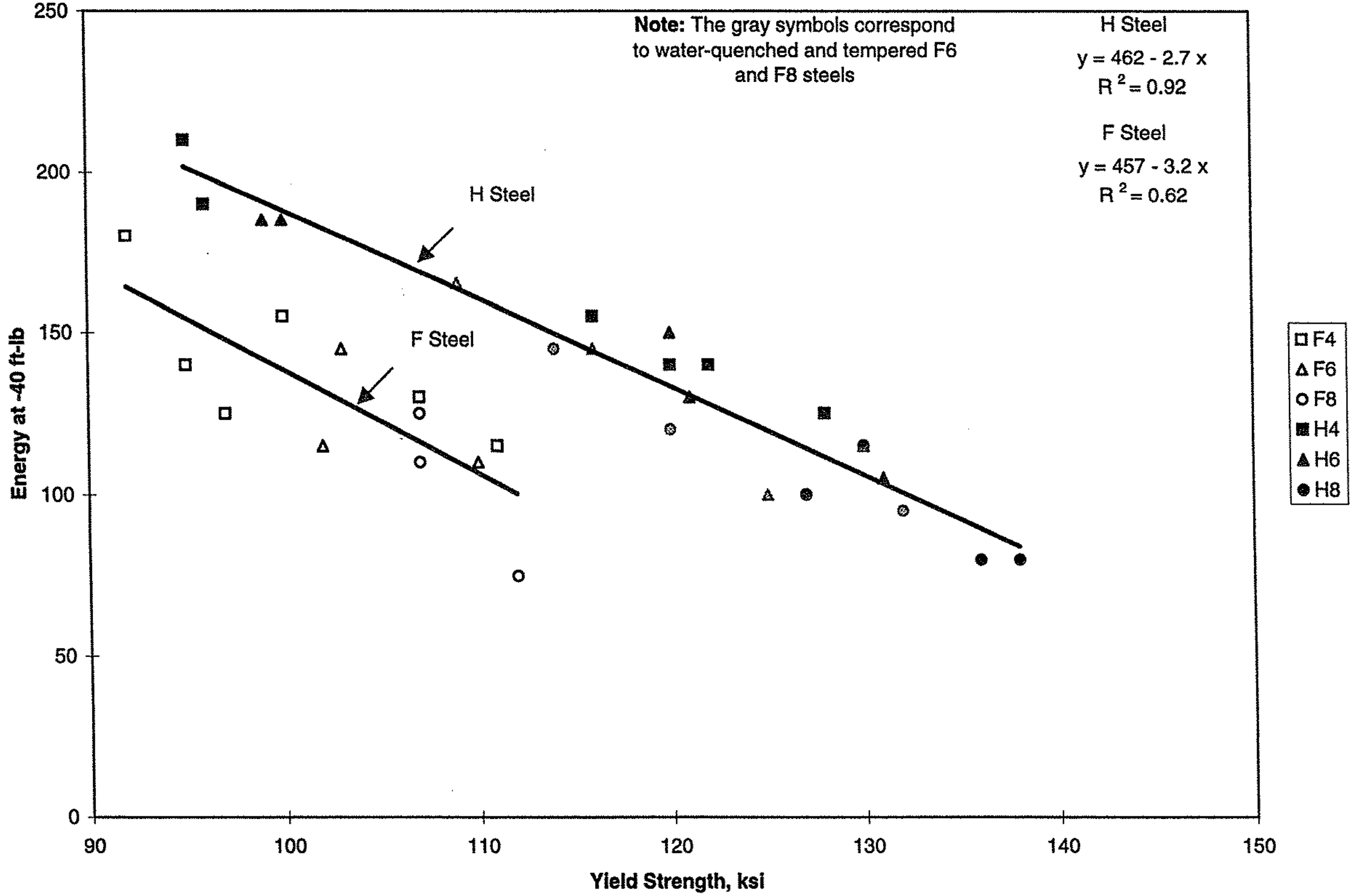

Figure 30 - Energy at -40, ft-lb vs. Yield Strength, ksi

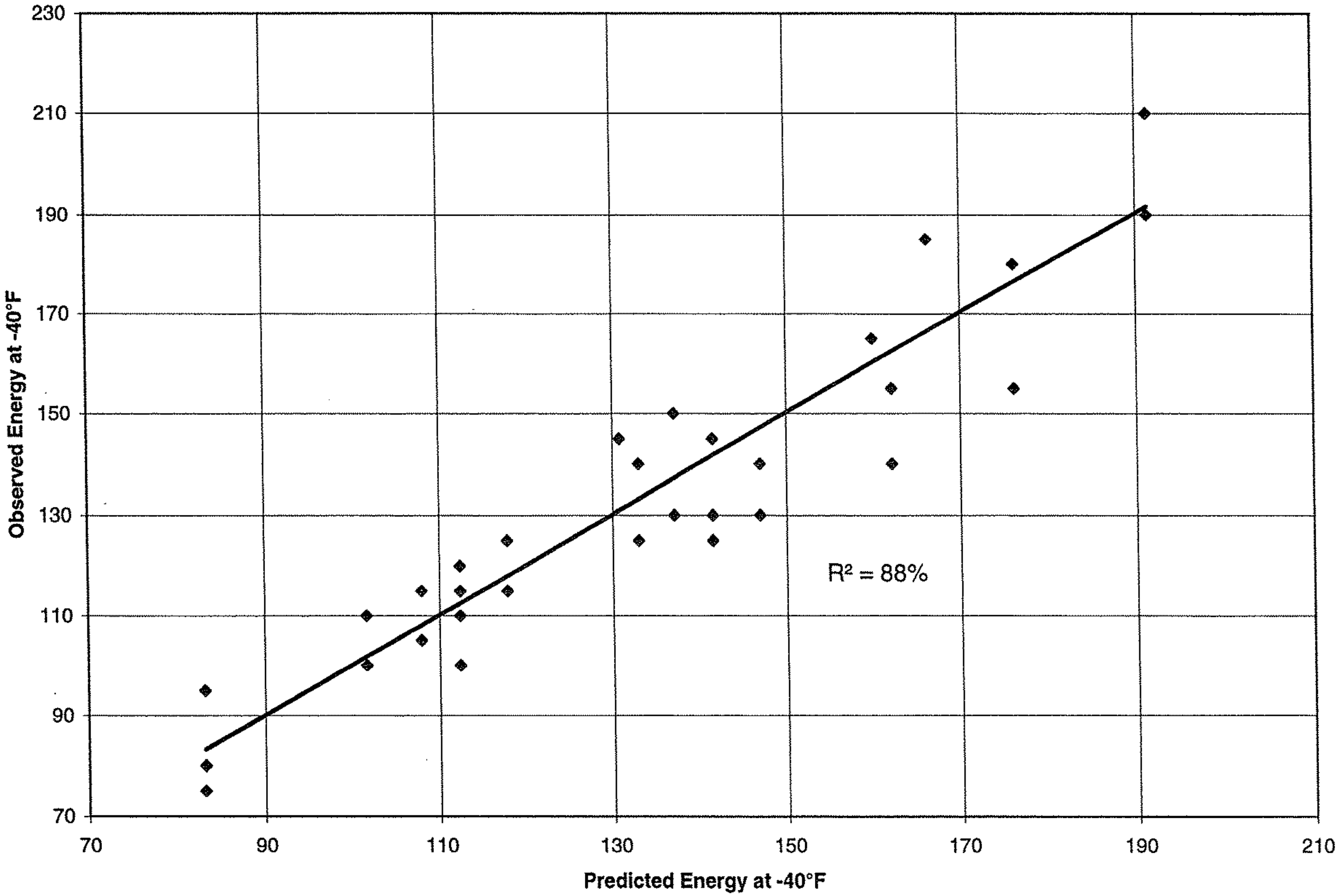

Figure 31 - Predictablility of E-40 = 25Ni - 20DI + 0.58T - 542

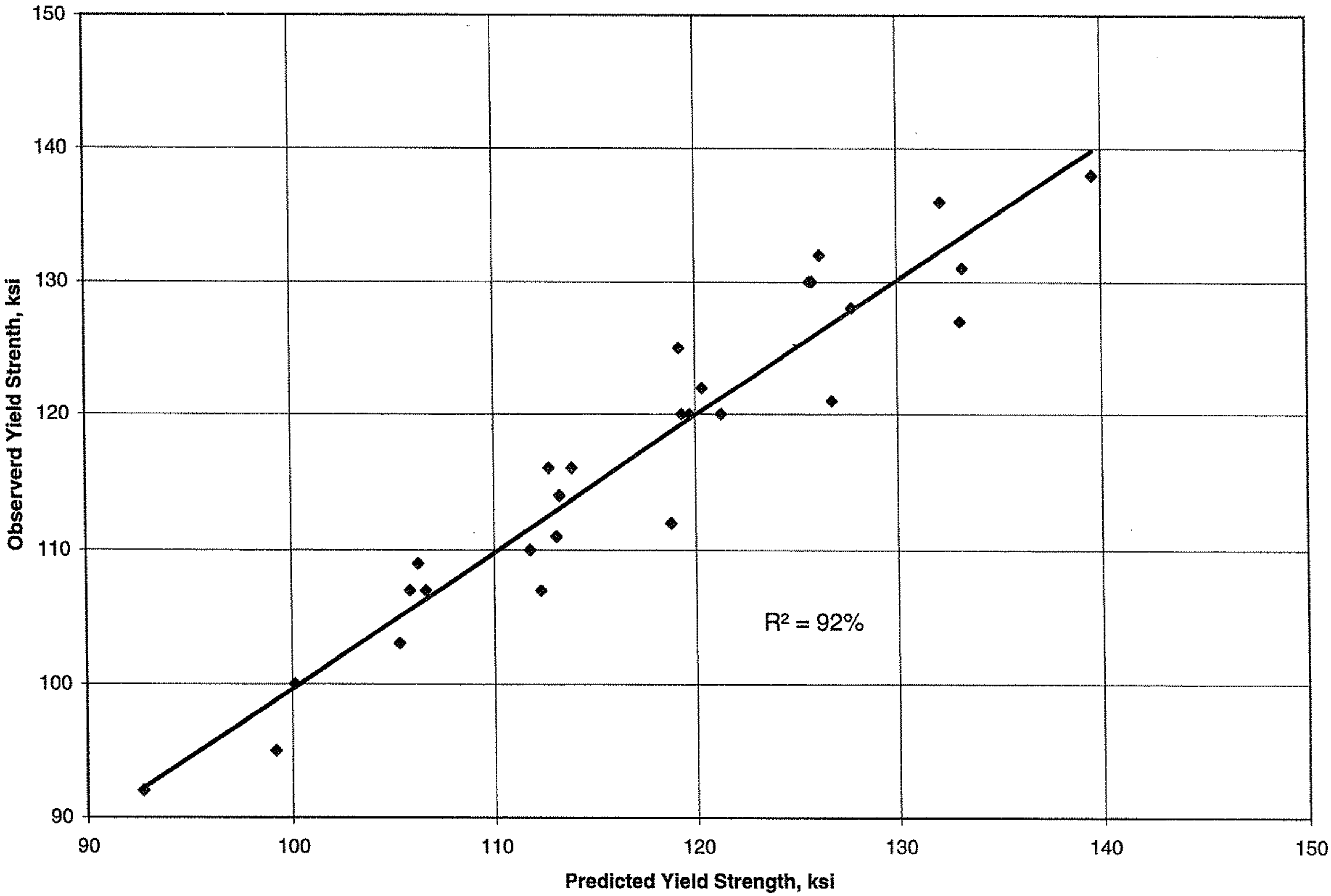

Figure 32 - Predictablility of YS = 2.34 + 321C + 7.8Ni - 0.13T + 0.18CR

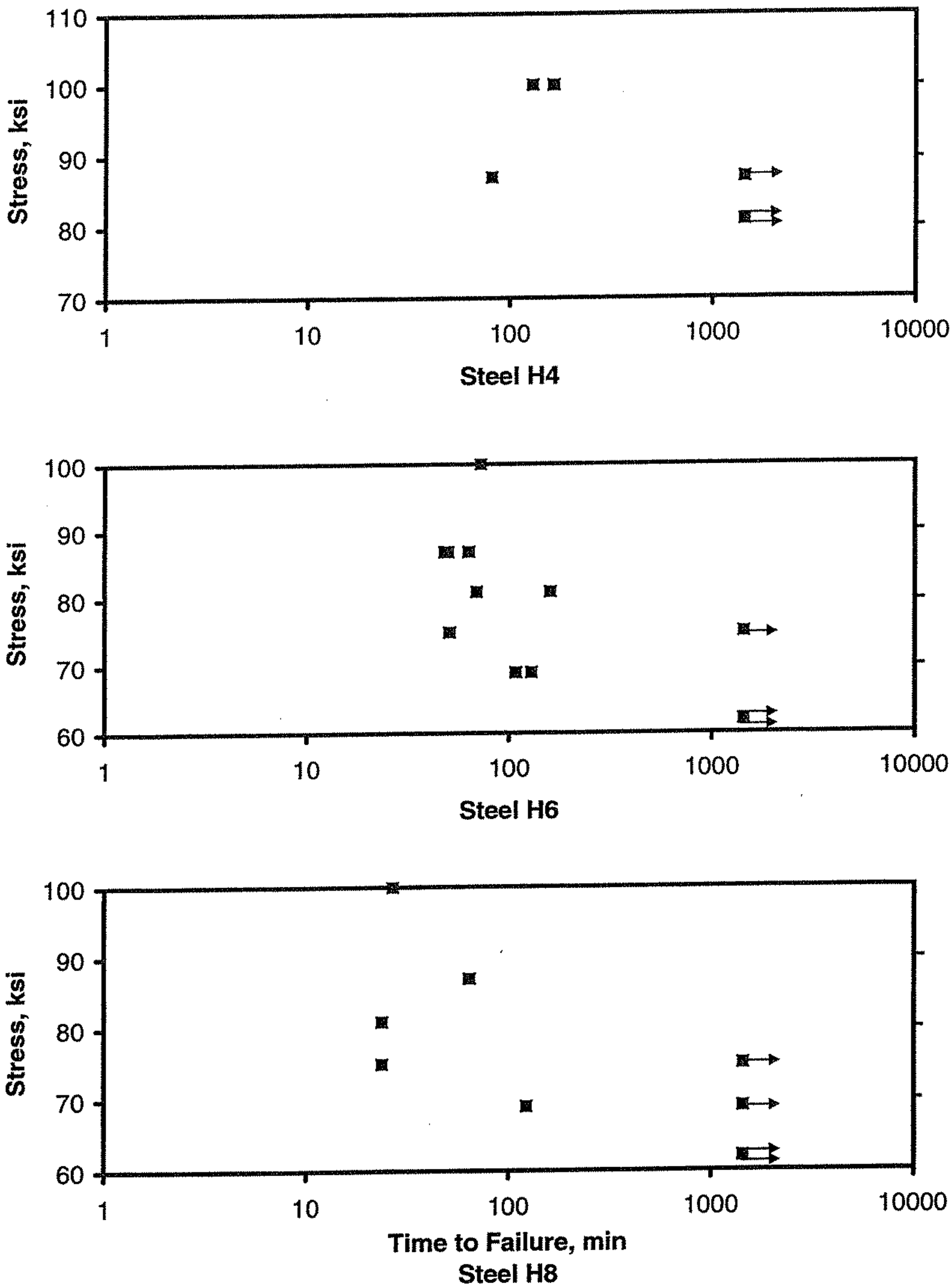

Figure 33 - Results of Implant Tests on H Steels