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ABSTRACT

Previous ATLSS studies of various alloy plate-steel systems to develop high-performance steels (HPS) demonstrated that the Cu-Ni steel system is significantly superior to other known systems. Therefore, ATLSS initiated a statistically designed full-factorial program to predict the hardenability, tensile properties, fracture toughness, and weldability of Cu-Ni plate steels from their chemical composition. The program involves 24 compositions - eight alloying-element variations at carbon contents of 0.04, 0.06, and 0.08 percent . The present study reports the results of Jominy end-quench tests on the most highly alloyed steel - 1.5 Mn, 1.0 Cu, 0.75 Ni, 0.50 Cr, 0.50 Mo, and 0.06 V - for Jominy tests in the as-quenched condition and after tempering at 950, 1050, 1150, and 1250 F (510, 565, 621, and 677 C).

The results showed that the Jominy test is extremely useful in estimating the strength and hardenability for specific plate-steel compositions and heat treatments. The results also indicate that the highest hardenability Cu-Ni steel can meet tensile strengths of 120 to 170 ksi (830 to 1170 MPa) and estimated yield strengths of 100 to 150 ksi (690 to 1035 MPa). The strength and hardenability were markedly influenced by the carbon content and suggest that in production the carbon content must be controlled, probably to ± 0.01 percent.

Results of the complete study represent an opportunity to specify chemical compositions for Cu-Ni HPS that are significantly better than any current plate steels and that will be cost-effective when fabrication, erection, and life-cycle costs are considered.

INTRODUCTION

Over the last two decades, steel producers worldwide have installed new ladle-metallurgy and continuous-casting facilities, which have significantly improved the cleanliness and uniformity of steel products. As a consequence, considerable emphasis has been placed on the development of new and improved plate structural steels, commonly referred to as high-performance steels (HPS). These steels are intended primarily for civilian and military infrastructure applications. Since 1991, the Lehigh University Center for Advanced Technology for Large Structural Systems (ATLSS) has been actively involved with the development of HPS, their proof-of-principle testing, and the structural testing of HPS prototypes.

In the development of new and improved HPS, ATLSS has investigated various alloy-steel systems with emphasis on improving the fracture toughness, weldability, and hardenability of structural plate steels with yield strengths in the range of 70 to 130 ksi for civilian and military infrastructure applications. The results of these investigations indicated that the Cu-Ni alloy system is significantly superior to the other systems studied. This occurs because the Cu-Ni steels are strengthened by copper-rich precipitates as well as by transformation to strong microconstituents such as martensite and bainite; whereas the other systems are strengthened only by the transformation mechanism. Consequently, the desired strength of the Cu-Ni steels is obtained at carbon contents less than 0.10 percent whereas the other systems require carbon contents in the range 0.10 to 0.20 percent. At the lower carbon content, the toughness and weldability of the Cu-Ni steels are significantly better than those of the other steel systems and with sufficient hardenability to obtain the desired strength in heavy sections.

To confirm the superiority of the Cu-Ni system, steels of two hardenability levels were evaluated. The results[1*] demonstrated that the a yield strength of 100 ksi could be attained through 2 inches and marginally at 4 inches by the higher hardenability steel, and that a yield strength of 100 ksi could be attained through 1/2 inch and and marginally at 2 inches and 80 ksi at 4 inches by the lower hardenability steel. The toughness was extraordinarily good (typical transistion temperatures lower than -120F) along with excellent weldability.

*See references

These results confirmed the superiority of the Cu-Ni alloy system for most civilian and military infrastructure applications.

Studies of Cu-Ni steels began in the early 50's when Armco proposed a normalized and aged 70 ksi yield-strength plate steel referred to as NES 70[2]. In the 70's INCO[3] promoted the IN 787 approach because nickel is added at a minimum of 50 percent of the copper content to avoid hot shortness in high copper steels. In the 80's the Navy developed HSLA 80 and 100 steels and various nonmilitary researchers[4-10] cooperated in the development of ASTM A 710 steel. However, there has been no definitive study relating the carbon and alloying elements of the Cu-Ni system to strength, toughness, weldability, and hardenability in a statistical program that would permit prediction of properties from the chemical composition. Consequently the extraordinary advantages of the Cu-Ni alloy-steel system are not being fully realized because the optimum composition for a particular application can not readily be selected. Therefore, ATLSS proposed the a full-factorial parametric statistical study involving the following Cu-Ni steel compositions:

1. Melt eight 300-pound heats with the following alloy compositions

Steel	Mn	Cu	Ni	Cr	Mo	V	Cb
A	1.00	1.00	0.75	0.50	0.25	0.06	0.015
B	1.00	"	0.75	"	0.50	"	"
C	1.00	"	2.50	"	0.25	"	"
D	1.00	"	2.50	"	0.50	"	"
E	1.50	"	0.75	"	0.25	"	"
F	1.50	"	0.75	"	0.50	"	"
G	1.50	"	2.50	"	0.25	"	"
H	1.50	"	2.50	"	0.50	"	"

2. Pour three 100-pound ingots for each of the above heats with respectively, 0.04, 0.06, and 0.08 % C contents and roll to 1-inch-thick plate.
3. Conduct appropriate hardenability, mechanical-property, and weldability tests.

EXPERIMENTAL PROCEDURE

`In accordance with Items 1 and 2 above, 300-pound heats of Steels A and H were melted, poured, and rolled. The chemical composition and related properties are listed in Table I. Six Jominy end-quench hardenability test specimens were machined from Steels H4, H6, and H8 and tested in accordance with ASTM A255. The austenitizing temperature was 1650F (899C). After each of the six specimens was hardness tested, one test specimen from each of the three steels was tempered at 950F (510 C), a second at 1050F (565 C), a third at 1150F (621C), and a fourth at 1250F (677C). Hardnesses along the length were taken at the same positions as for the quenched specimens but on the flat opposite to the flat that was hardness-tested as-quenched.

RESULTS and DISCUSSION

The hardness curves for the as-quenched Jominy end-quench-test specimens are plotted in Figure 1 for Steels H4, H6, and H8. The curves are based on the average values for the six as-quenched specimens for each steel. The effect of carbon with respect to the all martensite micro-structure at the quenched end was expected. However the impact of carbon on the overall hardenability was not fully anticipated. In addition, the relatively high level of hardness at the slow-cooled end (32 sixteenths;3.5F/sec.;2C/sec.) of 26, 32, and 35 HR_C, for H4, H6, and H8, respectively was not anticipated, and supports reports that the Cu-Ni steels precipitation-strengthen during cooling whereas precipitation strengthening is usually associated with aging after quenching to produce supersaturation. This phenomenon indicates that high strengths can be obtained in very heavy sections. It also indicates, however, that the carbon content must be carefully controlled to obtain specific strength levels.

The effect of tempering on the as-quenched Jominy curves for Steels H4, H6, and H8 is illustrated in Figures 2, 3 and 4, respectively. Figure 2 for Steel H4 (0.044%C) shows that tempering (aging) at 950F and 1050F (510C and 565C) increases hardness from Cu-rich precipitates more than the loss in hardness from carbide agglomeration in martensite/bainite transformation products. At 1150F (621C), carbide-agglomeration softening prevails up to 11 sixteenths (20F/sec.; 11C/sec.) beyond which precipitation-strengthening prevails. At 1250F (677C), carbide agglomeration is the controlling mechanism and precipitation-strengthening is small due to overaging. The results also clearly demonstrate that optimum precipitation-strengthening occurs in the range 950F to 1050F (510C to 565C). In applications involving post-weld heat treatment, commonly performed at or above 1100F (593C), optimum strengthening may not be appropriate.

Figure 3 illustrates the effect of tempering (aging) on Steel H6 (0.061%C). The effects are similar to those observed for Steel H4, except that the overall hardness levels are somewhat higher. In addition, precipitation-strengthening does not increase the hardness levels compared to the as-quenched hardnesses as much for Steel H6 as for Steel H4.

Figure 4 illustrates the effect of tempering (aging) on Steel H8 (0.080%C). At this higher carbon level, transformation to martensite and bainite results in significantly higher hardness at all distances from the quenched end (reduced cooling rates) and precipitation-strengthening is not sufficient to offset the carbide-agglomeration softening. Nevertheless, the final hardnesses are higher for Steel H8 at all cooling rates than for the lower carbon Steels H4 and H6.

As previously noted, the real advantage of the Cu-Ni steels is that the combined transformation- and precipitation-strengthening permit the attainment of high strengths at very low carbon contents, which greatly enhance fracture toughness and weldability. This advantage can be readily estimated with respect to strength for virtually all practical plate-steel applications from Jominy-test information for as-quenched and for quenched and tempered specimens. For example, Table I lists the hardnesses that were obtained from the Jominy curves in Figures 1 through 4 at distances from the quenched end of 6 sixteenths (1-inch-thick production-quenched plate - 50F/sec.),11 sixteenths (2-inch-thick production-quenched plate - 20F/sec.), 17 sixteeenths (4-inch-thick production-quenched plate - 9F/sec.), and 32 sixteenths (approximating air-cooled 1-inch-thick plate - 3.5F/sec.). When these hardness data are converted to tensile strengths, Table 4 indicates that the tensile strength of Steel H4 will probably be in the range 120 to 150 ksi (830 to 1035 MPa) for all practical plate thicknesses. The corresponding tensile strengths for Steel H6 are 130 to 160 ksi (900 to 1100 MPa) and for Steel H8 are 135 to 170 ksi (930 to 1170 MPa). Yield strengths can be very roughly estimated from the tensile strengths on the basis that the yield/tensile ratio will be about 0.7 for as-quenched plate, 0.8 for the 950F (510C) temper, 0.85 for the 1050F (565C) temper, 0.90 for the 1150 (621C), and 0.95 for the 1250F (677C) temper. Although tensile tests are required to obtain accurate strength values, the Jominy test permits the selection of potential steel compositions for plate applications with respect to strength and hardenability and related heat treatment.

CONCLUSIONS

1. The Jominy end-quench hardenability test is extremely useful in estimating the strength and hardenability for specific plate-steel compositions and heat treatments.
2. The Jominy-test characteristics of Cu-Ni Steel H indicate that it can meet tensile strengths from 120 to 170 ksi (830 to 1170 MPa) when conventionally quenched and tempered.The corresponding yield strengths would be expected to be in the range 100 to 150 ksi (690 to 1035 Mpa).
3. The strength and hardenability of Steel H was significantly influenced by the carbon content of the individual steels, Steel H4 @ 0.044%C, Steel H6 @ 0.061%C, and Steel H8 @ 0.080%C. This result indicates that in production the carbon content of these very low carbon steels must be controlled, probably to ± 0.01 %.
4. On the basis of previous studies, the fracture toughness and weldability of Steel H is expected to be considerably better than any other current steel at the same strength level.

FUTURE WORK

The data obtained in the present study will be a useful step in further optimizing HSLA steels. However, the mechanical-property, weldability, and metallographic information is necessary to characterize fully the three Steel H compositions. In addition, the balance of the parametric factorial study outlined in the INTRODUCTION must be undertaken if strength, hardenability, fracture toughness, and weldability are to be stated accurately from statistical-study coefficients based on chemical composition. Results of the completed study will represent an opportunity to specify chemical compositions for high-performance steels that are significantly better than any current plate steels, and that will be cost effective when fabrication, erection, and life-cycle costs are considered.

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	STEEL			STEEL		
	A4	A6	A8	H4	H6	H8
C	0.045	0.064	0.082	0.044	0.061	0.080
Mn	1.00	1.01	1.00	1.50	1.51	1.50
P	0.012	0.013	0.013	0.010	0.012	0.011
S	0.003	0.003	0.003	0.003	0.003	0.003
Si	0.23	0.23	0.24	0.24	0.24	0.24
Cu	1.02	1.02	1.02	1.03	1.04	1.03
Ni	0.75	0.74	0.75	2.50	2.50	2.53
Cr	0.50	0.50	0.50	0.49	0.49	0.49
Mo	0.24	0.24	0.24	0.49	0.49	0.49
V	0.057	0.056	0.056	0.056	0.056	0.056
Cb	0.015	0.015	0.015	0.016	0.016	0.016
Al(total)	0.022	0.020	0.019	0.023	0.023	0.022
		Calculated Metallurgical Characteristics				
D_I -ASTM	0.85	1.20	1.56	2.88	4.12	5.38
A_{e1}, F	1325	1325	1325	1270	1270	1270
A_{e3}.	1560	1540	1525	1495	1480	1465
B_S, F	1195	1185	1175	960	950	940
M_S, F	900	885	860	840	820	800

Table 1 - Chemical Composition of Steels A and H

STEEL H4

Jominy-Test Condition	1-Inch-Quenched Plate*	2-Inch-Quenched Plate*	4-Inch-Quenched Plate*	1-Inch-Air-Cooled Plate*
	Tensile Strength/(Hardness) Corresponding to Production Treatment Simulation Based on Equivalent Cooling Rates, ksi (HR_C)			
As-Quenched	150 (32)	142 (30)	134 (28)	127 (26)
Tempered @ 950F	154 (33)	154 (33)	150 (32)	146 (31)
" @ 1050F	150 (32)	150 (32)	146 (31)	146 (31)
" @ 1150F	146 (31)	142 (30)	138 (29)	131 (27)
" @ 1250F	124 (25)	124 (25)	124 (25)	121 (24)

STEEL H6

As-Quenched	163 (35)	159 (34)	154 (33)	150 (32)
Tempered @ 950F	163 (35)	163 (35)	163 (35)	154 (33)
" @ 1050F	159 (34)	159 (34)	159 (34)	150 (32)
" @ 1150F	154 (33)	150 (32)	150 (32)	150 (32)
" @ 1250F	131 (27)	131 (27)	131 (27)	127 (26)

STEEL H8

As-Quenched	172 (37)	168 (36)	168 (36)	163 (35)
Tempered @ 950F	163 (35)	163 (35)	163 (35)	159 (34)
" @ 1050F	163 (35)	163 (35)	163 (35)	159 (34)
" @ 1150F	159 (34)	159 (34)	159 (34)	150 (32)
" @ 1250F	134 (28)	134 (28)	134 (28)	134 (28)

*The reported hardnesses were obtained from Figures 2, 3, and 4 from the vertical lines located at the following distances from the quenched end of the Jominy-test specimen and corresponding to the cooling rates at the midthickness of plates cooled as follows: 6 sixteenths - production-quenched 1-inch-thick plate; 11 sixteenths - production-quenched 2-inch-thick plate; 17 sixteenths - production-quenched 4-inch-thick plate; 32 sixteenths - air-cooled 1-inch-thick plate. Note: the cooling rate at the center of a 1-inch-thick air-cooled plate is 1F/sec. at 1300F. The slowest cooling rate obtained in the Jominy test is 3.5 F/sec. at 1300F from 32 to 48 sixteenths. Therefore the distance of 32 sixteenths was used as a first approximation of an air-cooled 1-inch-thick plate.

Table II -Steel H Tensile Strengths Converted from Jominy - Test Hardnesses

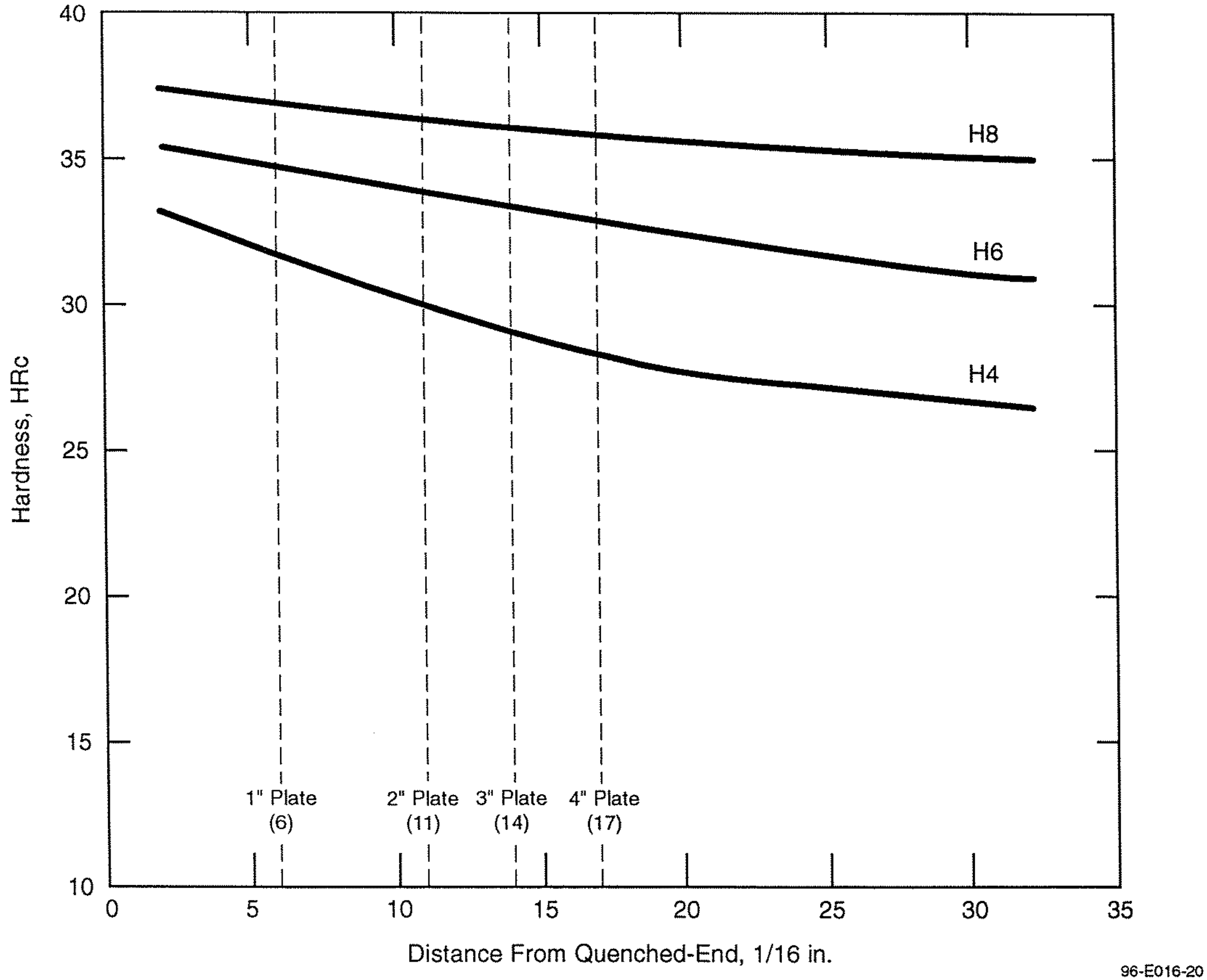

Figure 1 - Averaged Jominy End-Quench Hardenability Results for Steels H4, H6, and H8

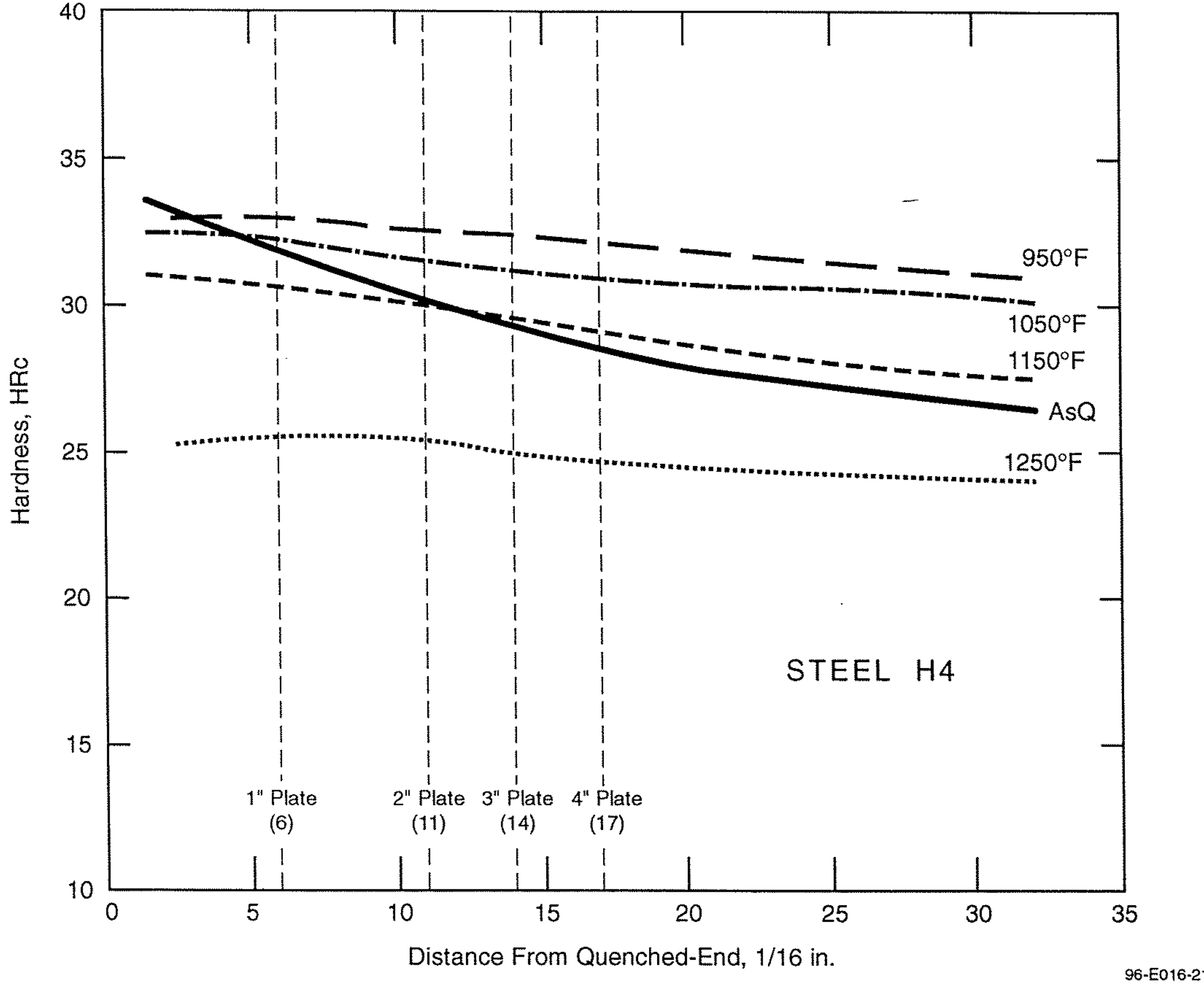

Figure 2 - Results for Tempered End-Quench Jominy Tests for Steel H4

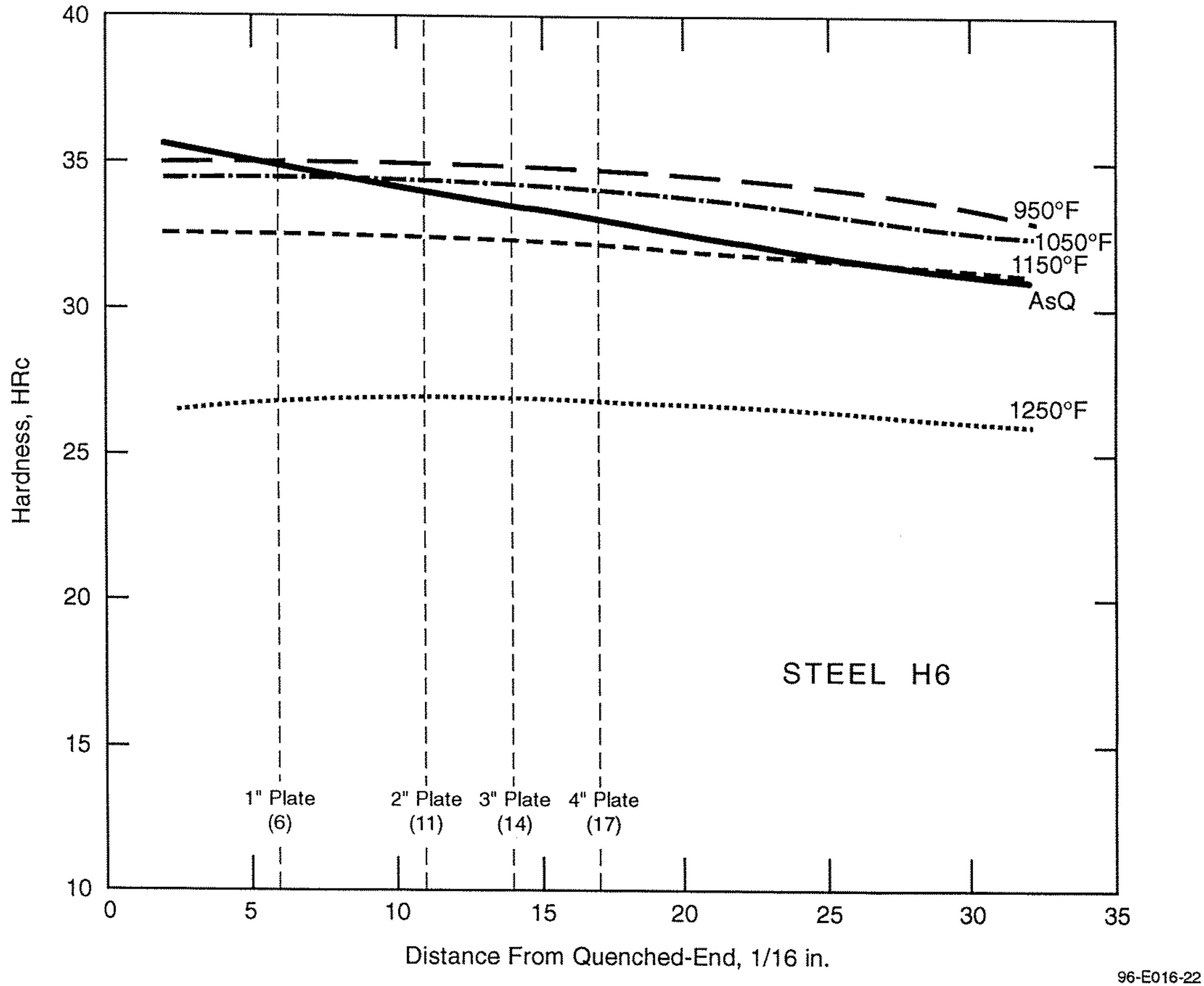

Figure 3 - Results for Tempered End-Quench Jominy Tests for Steel H6

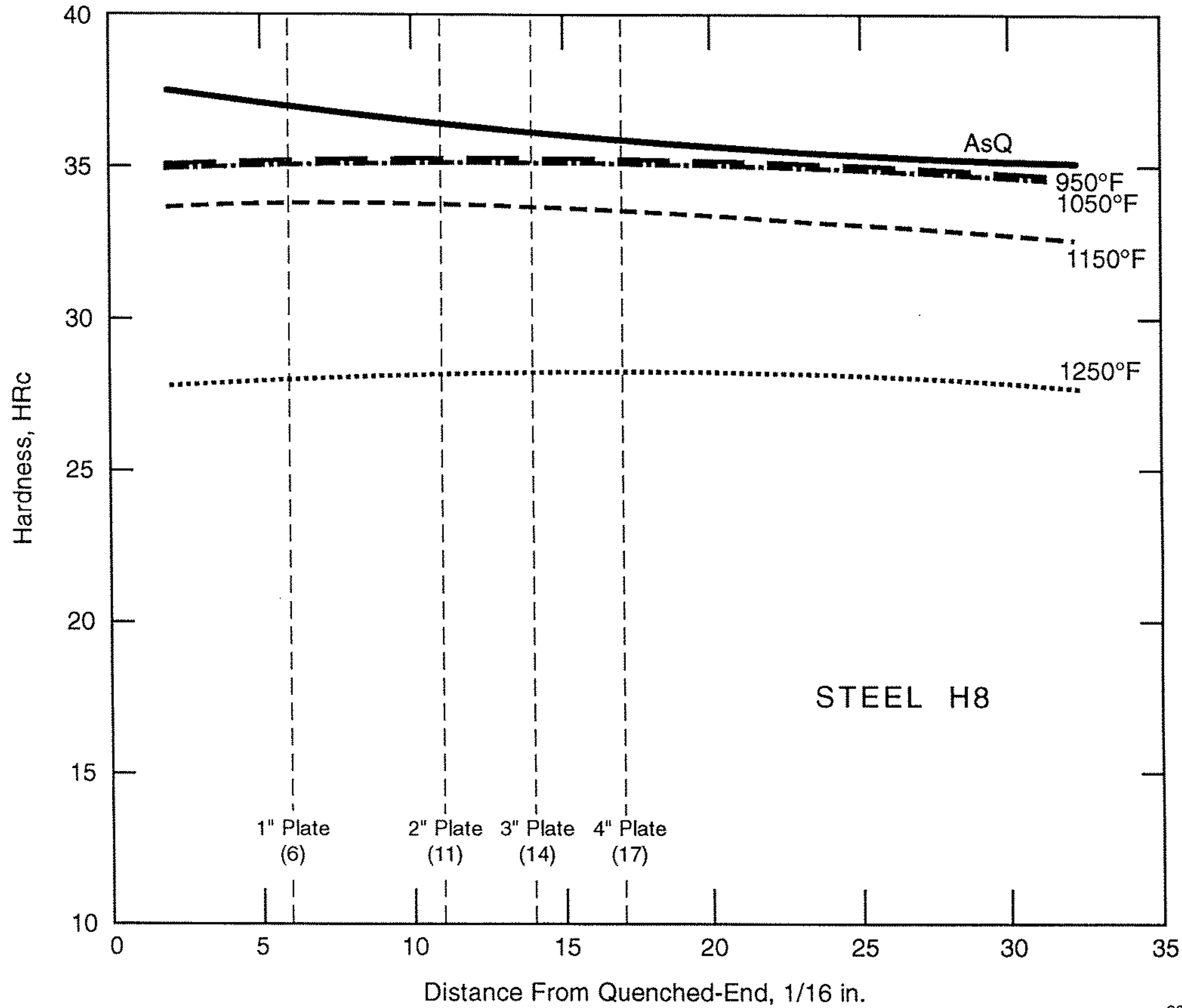

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Figure 4 - Results for Tempered End-Quench Jominy Tests for Steel H8