6-1-1996

Optimization of an 80/100 KSI Yield-Strength High-Performance Bridge Steel

A. B. Magee

John H. Gross

Robert D. Stout

ADVANCED TECHNOLOGY FOR
LARGE
STRUCTURAL SYSTEMS

Lehigh University

Optimization of an 80/100 ksi Yield-Strength High-Performance Bridge Steel

by

A. B. Magee
Graduate Research Assistant

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

ATLSS Report No. 96-08

June 1996

ATLSS Engineering Research Center
Lehigh University
117 ATLSS Dr., Imbt Laboratories
Bethlehem, PA 18015-4729
(610) 758-3525

An NSF Sponsored Engineering Research Center

OPTIMIZATION OF AN 80/100ksi YIELD-STRENGTH HIGH-PERFORMANCE BRIDGE STEEL

by A. B. Magee, J. H. Gross, and R. D. Stout

ABSTRACT

This project was intended to develop an 80/100-ksi yield-strength high-performance bridge steel with low susceptibiliy to weld heat-affected-zone cracking and therefore minimize the requirement for preheat and to increase its fracture toughness at service temperatures. Previous studies by the Lehigh University Center for Advanced Technology for Large Structural Systems have suggested that a Cu-Ni steel with the following composition was an excellent candidate for such a bridge steel.

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.070	1.50	0.009	0.005	0.25	1.00	0.75	0.50	0.50	0.06	0.010	0.030

To confirm that observation, 500-pound heats of the candidate steel were melted and processed to 1/2-, 1-, and 2-inch thick plate by various thermomechanical practices, and the weldability and mechanical properties determined. To evaluate the feasibility of reducing the alloy content, two 500-pound heats were melted with carbon at 0.06, Mn at 1.25, and Mo at 0.25 and similarly processed and tested.

The results indicate that the steels were not susceptible to hydrogen-induced weld-heat-affected-zone cracking when welded without preheat. Jominy end-quench tests of the higher-hardenability steel indicate that a minimum yield-strength of 100 ksi should be readily attainable in thicknesses through 2 inches and marginally at 4 inches . Mechanical-property tests of conventionally quenched and tempered plates confirmed these observations and showed that a transition temperature lower than -120F was typical for plates through 2 inches. In addition, a yield strength of 100 ksi can be obtained upon accelerated cooling after rolling. The toughness of the steel readily met AASHTO specifications for Zone 3 in all conditions and thicknesses, and may be sufficiently tough so that the critical crack size will minimize fatigue-crack-extension problems.

The results of the Jominy tests on the lower-alloy lower-hardenability steel indicate that a yield strength of 100 ksi could be achieved only through 1/2-inch-thick plate, marginally at 2 inches and a yield strength of 80 ksi through 4 inches. Mechanical-property tests confirmed these observations and showed that the toughness was excellent for 1/2-inch plate but diminished as the plate thickness increased.

Metallographic studies showed that the microconstituents of the higher-hardenability steel was martensite plus granular bainite through 4 inches whereas the lower hardenability steel contained increasing amounts of polygonal ferrite as the thickness increased above 1/2-inch.

A production heat of the candidate steel should be melted and tested in plates through 4 inches to confirm the excellent combination of strength and toughness that was obtained in laboratory heats. Additional studies of the interaction between carbon and various alloying additions is recommended to optimize the composition of a 70W steel.

INTRODUCTION

Commonly, dynamic infrastructure applications such as bridges specify ASTM A36 (36-ksi min.yield-strength), and A572 and A588 (50-ksi min.yield strength) steels. Previous analyses suggest that significant weight-saving and cost advantages could accrue to such structures if steels with yield strengths in the 70- to 100-ksi range were employed. However, currently available steels are not attractive because of the following limitations:

1. the fatigue strength does not scale-up with the yield strength.
2. most of the steels average about 0.15% carbon, have high coarse-grain heat-affected-zone (HAZ) hardness when welded, and therefore require costly preheat to avoid hydrogen-assisted HAZ cracking.

3. many of the steels do not have sufficient notch toughness to meet specifications for fracture-critical members.

4. the steels often have unacceptably high yield-strength to tensile-strength ratios.

5. the higher-strength thinner-section steels must exhibit better corrosion to provide acceptable life cycles.

Various investigators* are addressing the foregoing limitations. At the Lehigh University Center for Advanced Technology for Large Structural Systems (ATLSS), a solution to the fatigue problem is being studied through improved design. Limitations 2, 3, 4 and 5 are being addressed through the development of new high-performance steels (HPS). This approach involves studies of chemical composition and thermomechanical processing (TMCP).

`Previous ATLSS investigations of chemical composition have included a broad range of carbon contents, alloying elements, and atomic strengthening mechanisms. These have indicated that the carbon content should be less than 0.09% to minimize susceptibility to HAZ cracking and to optimize fracture toughness. In addition the Cu-Ni precipitation-hardening type steels showed the greatest promise for good strength and toughness in heavy sections. A proposed base composition was as follows:

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.070	1.50	0.009	0.005	0.25	1.00	0.75	0.50	0.50	0.06	0.010	0.030

To evaluate the potential of Cu-Ni steels, studies were undertaken at this composition and at a leaner lower hardenability composition to effect some cost reduction and to reproduce production variations.

Previous ATLSS investigations of thermomechanical controlled processing indicated the following:

1. controlled rolling followed by direct quenching (CRDQ) increased the yield strength by 10 to 20 ksi, resulted in significant anisotropy, but it reduced the toughness in the transverse direction, and increased the yield-tensile ratio.

2. cross-rolling produced a better balance of mechanical properties than straightaway rolling.

3. for certain compositions, controlled rolling followed by air cooling and off-line quenching and tempering (CRAQ) was observed to improve the strength-toughness relationship compared with conventional hot rolling followed by air-cooling and off-line quenching and tempering (HRAQ)

To evaluate these TMCP variables, the optimization study included comparisons of straightaway vs cross rolling and CRDQ vs CRAQ vs HRAQ processing. In addition, the applicability of interrupted-accelerated cooling (IAC) to this composition was evaluated.

EXPERIMENTAL PROCEDURE

MELTING OF STEELS

Two 500-pound heats were vacuum-melted by the U.S. Steel Technology Center for the higher-hardenability composition and two were melted for the lower-hardenability composition to provide enough material for the planned tests. The compositions of the steels were as follows:

Higher-Hardenability

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
U Steel											
0.075	1.50	0.012	0.0046	0.25	0.96	0.75	0.50	0.50	0.058	0.025	0.035
V Steel											
0.073	1.49	0.015	0.0050	0.23	0.95	0.75	0.50	0.50	0.059	0.022	0.034------

---

*See Wilson, A. D., et al, "Properties and Microstructures of Copper Precipitation Aged Plate Steels", Proceedings of Microalloying '88, ASM International, and associated references.

Lower- Hardenability

K Steel

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.057	1.20	0.014	0.005	0.25	0.99	0.74	0.50	0.25	0.059	0.010	0.027

L Steel

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.060	1.20	0.014	0.005	0.27	0.95	0.75	0.50	0.26	0.060	0.015	0.022

THERMOMECHANICAL PROCESSING

HOT-ROLLING PRACTICE

Steel U - The 7-inch-thick ingot was rolled to a 3.5-inch-thick slab (12"wide x 39" long), cut into three 13-inch long pieces, and cross-rolled to 1-inch-thick plate as follows:

1. Cut A - Heat slab to 2275F, roll in 6 passes and finish at 1900F, and-air cool (HRA).
2. Cut B - Heat slab to 2150F, roll in 3 passes to 2 inches, hold to 1750F, control-roll in 4 passes to 1 inch at 16 00F, and direct-quench at 50F/sec. (CRDQ)
3. Cut C - Heat slab to 2150F, roll in 3 passes to 2 inches, hold to 1750F, control-roll in 4 passes to 1 inch at 1600F, and air cool. (CRA)

Steel V - The 7-inch-thick ingot was rolled to a 5-inch-thick slab (12" wide x 30" long), cut into three 10-inch long pieces, and cross-rolled to 2-inch-thick plate as follows:

1. Cut A - Heat slab to 2275F, roll in 4 passes and finish at 1900F, and air-cool (HRA).
2. Cut B - Heat slab to 2150F, roll in 2 passes to 4 inches, hold to 1750F, control-roll in 4 passes to 2 inches at 1600F, and direct-quench at 15F/sec. (CRDQ)
3. Cut C - Heat slab to 2150F, roll in 2 passes to 4 inches, hold to 1750F, control-roll in 4 passes to 2 inches at 1600F, and air-cool (CRA).

Steel K - The 7-inch-thick ingot was rolled to a 3-inch-thick slab (12" wide x 45" long), cut into five 9-inch long pieces, and rolled to plate as follows:

1. Cut A - Heat slab to 2275F, conventionally straightaway roll in 6 passes to 1850F to 1/2-x13-x50-inch long plate, and air-cool (HRA).
2. Cut B - Heat slab to 2275F, conventionally straightaway roll in 4 passes to 1850F to 1-x12-x27-inch long plate, and air-cool (HRA).
3. Cut C - Heat slab to 2150F, straightaway roll in 3 passes to 2 inches, hold to 1800F, straightaway control-roll in 4 passes to 1600F to 1-x12-x27-inch long plate, quench at 20F/sec.to 1050F, and air-cool (IAC).
4. Cut D - Heat slab to 2150F, conventionally cross-roll in 4 passes to 1850F to 1-x9x27-inch long plate, and air-cool (HRA).
5. Cut E - Hold slab for future work

Steel L - The 7-inch-thick ingot was rolled to a 5-inch-thick slab (12" wide x 27" long), cut into three 9-inch long pieces and rolled to plate as follows:

1. Cut A - Heat slab to 2275F, conventionally straightaway roll in 5 passes to 1850F to a 2-x12-x21-inch long plate, and air-cool (HRA)
2. Cut B - Heat slab to 2150F, straightaway roll in 2 passes to 4 inches, hold to 1800F, straightaway control-roll in 5 passes to 1600F, quench at 9F/sec.to 1050F, and air-cool (IAC)
3. Cut C - Heat slab to 2275F, conventionally cross-roll in 5 passes to 1850F to 2-x10-x27-inch-long plate, and air-cool (CrRA)

HEAT TREATMENT

Austenitizing -The hot-rolled plates were cut into convenient test sections and heat-treated as outlined in Tables I and II for steels U&V and K&L, respectively. The cooling rates were chosen to simulate those that would be expected in production as illustrated in Figure 1. The curves shown are the best current information for production facilities. Additonal information, particularly for accelerated-cooling facilities is desired because of the limited number of such facilities in the U.S.The cooling rates reported in Tables I and II are based on the rate between 1472F and 932F (800C and 500C).

The "IQ Water" practice involved immersion quenching into mildly agitated water at 60F. The average typical cooling curves for immersion-quenched 1/2-, 1-, and 2-inch-thick plates are shown in Figure 2. The corresponding cooling rates are tabulated for plates cooled from 800 to 500C (1472 to 932F). For practical purposes, these rates are the same as the rates at 1300F (cooling from 1500 to 1100F), which are the rates published for the Jominy test. These rates are shown on Figure 1 for comparison with typical spray-quench production practices and on Figure 3 to illustrate their location with respect to distance from the quenched end of the Jominy test. As shown on Figure 1, this laboratory quenching practice agrees extremely well with that shown for typical production. Therefore, the cooling rates for 3- and 4-inch-thick plates were obtained by extrapolation of the production curves. The results for 1/2- through 4-inch-thick plates are tabulated on Figure 3 and are identified by plate thickness on subsequent Jominy curves.

"Spray Q" involved spray quenching using four solid cone nozzles, 5.5 inches apart vertically and horizontally, and eight inches from the mid-thickness on both sides of a vertically suspended plate, using 60F water at 95 psi. The rates were varied by using different nozzle sets.

All plates were treated in the thickness indicated except for the simulation of production quenching of 4-inch plate, which was done at three different cooling rates - air-cooling a 1/2-inch plate (2F/sec.) and spray quenching a 1-inch plate using different nozzle sets to produce cooling rates of 5F/sec. and 9F/sec. The different rates represent different opinions on the best simulation for production quenching of a 4-inch plate.

At the U. S. Steel Technical Center facility, the " USS Spray" involved direct cooling from the rolling mill into a spray-quench runout table. All plates were cooled continuously to room temperature using the same cooling medium, except for the "CR+IAC" interrupted-accelerated-cooling practice which involved quenching from 1600F to 1050F followed by air cooling to ambient temperature.

Tempering - After each test plate was austenitized, a test strip was cut into small pieces, which were tempered at a series of temperatures between 1000F and 1350 F, and the hardness was determined on each piece. The resulting tempering curves are shown in Figure 4 for the U and V steel treatments and in Figure 5 for K and L steels. The tempering curves were used to select appropriate tempering temperatures. The details of the heat treatment are summarized in Table I for U and V Steels and in Table II for K and L Steels.

JOMINY END-QUENCH-HARDENABILITY TESTING

For each of the four steels, three 1-inch-diameter by 3-inch-long cylinders were machined, austenitized at 1650F, end-quenched and hardness-tested in accordance with ASTM A255, and examined metallographically. The specimens were then tempered at 1050F, 1150F, or 1250F and hardness-tested.

MECHANICAL TESTING

TENSION TESTING - For each test condition, dupicate 0.252-inch-diameter or duplicate 0.505-inch-diameter tension-test specimens were machined from 1/2-inch-thick plate and from 1- and 2-inch-thick plate respectively, and tested in accordance with ASTM E8 and A370.

IMPACT TESTING - For each test condition, a series of sixteen Charpy V-notch impact-test specimens was machined and notched in the thickness direction. For 1-inch-thick plate, specimens were machined from both halves of the plate. For 2-inch-thick plate, four specimens were machined from the plate and identified as top, top-middle, bottom-middle, and bottom specimen Each series was tested over a range of temperatures chosen to ductile to brittle transition-temperature behavior. Testing was in accordance with ASTM A370.

METALLOGRAPHIC TESTING

JOMINY END-QUENCH-HARDENABILITY TEST - One hardness-test flat on the end-quench specimen for each steel was polished and etched and the microstructure at sixteenth-inch intervals for the first inch from the quenched end and at eighth-inch intervals for the second inch was photographed at 1000X. Selected scanning-electron micrographs were also obtained.

MECHANICAL TESTS - For each mechanical-test series, the microstructure at 1000X was obtained to characterize that test condition.

WELDABILITY TESTS

Implant-test specimens were machined from U and K steels, and after welding were tested at a range of stress levels selected to produce failure in 24 hours and at stress levels that did not produce failure in 24 hours. The shielded-metal-arc welding tests were made with an E11018 electrode and the gas-metal-arc tests were made with 100-s filler-wire and $98Ar/2O_2$ shielding gas The heat input was 35 kilojoules per inch.

RESULTS AND DISCUSSION

JOMINY END-QUENCH-HARDENABILITY RESULTS

Standard-Test Results - The results of the Jominy tests are shown in Figure 6. The curve marked U&V incorporates the hardness values for three U steel and three V steel specimens and the curve marked K&L incorporates those for each of the three specimens for K and L steels. The results demonstrate the profound effect of relatively small changes in chemical composition for these very low-carbon steels. The reduction in carbon content from an average of 0.074 to 0.058 percent, in manganese from 1.50 to 1.20 percent, and molybdenum from 0.50 to 0.25 percent reduced the calculated ideal critical diameter D_I by over 50 percent from 3.04 to 1.22, and this effect is clearly shown by the marked downward shift in the curves.

The microstructure and hardness at the various distances from the quenched end of the bar correspond to continuous-cooling rates (measured at 1300F) of about 500F/second at 1/16 inch from the quenched end to 3.5 F/second at two inches from the quenched end. These cooling rates encompass all the rates that occur at the midthickness of plates of any thickness through 4 inches when quenched in production facilities. Consequently, the curves are useful in estimating the microstructure and hardness and therefore the tensile strength to be expected. The cooling rates at 1300F at the center of 1-, 2-, 3-, and 4-inch thick plates quenched at an approximate severity of H=1.5 (Figures 1 and 3) are shown along the abscissa of the Jominy plots. These are the approximate cooling rates to be expected when plates are quenched in standard roller or platen production facilities, which are also the same for the Laboratory "IQ Water" quench employed in the present study. The plateau hardness of 25 HR_C for the higher hardenability Steels U and V suggests that 4-inch-thick and thicker plate can attain a tensile strength of about 123 ksi and therefore a yield strength above 100 ksi. The hardness of 19 HR_C (tensile strength of approximately 108 ksi) corresponding to 2-inch-thick plate for the lower hardenability Steels K and L indicates that 2-inch-thick plate is probably the maximum thickness for a yield strength of 100 ksi. For thicker plates, a yield-strength of 90 ksi is more likely.

Tempered-Jominy-Test Results - Tempering the Jominy specimens permits analysis of the effect of reheating on the full range of microstructures that result from end-quenching. In the case of these Cu-Ni steels, tempering results in competition between softening due to carbide agglomeration and strengthening due to copper-particle precipitation. The efffect of tempering the Jominy-test specimens for Steels U and V is shown in Figure 7. At 1050F, the previous plateau value of 25HR_C increases to 28/29 HR_C as a result of copper precipitation strengthening. At 1150 and 1250F, the original plateau hardness is retained as a result of a lesser but significant copper precipitation strengthening and some vanadium strengthening at 1150F. A similar phenomenon occurred for Steels K and L, Figure 8, which shows that copper-precipitation increased the hardness at all the tempering temperatures.

MECHANICAL-PROPERTY TESTING

The mechanical-property tests were conducted to characterize the four steels with respect to tensile and toughness behavior. Of particular importance was the ability of the steels to meet a minimum yield-strength of 100 ksi in a minimum plate thickness of 2 inches with an aim of 4 inches. The determination of yield strength in the present tests was done in accordance with Section 7.5.1

Offset Method of ASTM E8 using the usual offset of 0.2%. The choice of an offset other than 0.2% can significantly change the yield depending on the type of flow-stress curve as illustrated in Figure 9. In general, plates which were not tempered exhibited continuous yielding of the type shown in Figure 9A whereas those that were tempered exhibited well-defined discontinuous yielding as shown in Figure 9B. The determination of the onset of plastic flow that best relates to design and service performance is not known.

Tension- and Impact-Test Results - The results of tension and Charpy V impact tests are listed in Tables III and IV for Steels U and V The strength and toughness properties are depicted in Figures 10 and 11 for 1- and 2-inch-thick plates. As illustrated in Figure 10, 1-inch-thick high-side-hardenability Steel U readily meets the 100-ksi minimum yield strength for all rolling practices after appropriate tempering. When conventionally rolled and air-cooled (HRA) and off-line austenitized and quenched, tempering at 1250F produced the best combination of strength and toughness. This was also the case for specimens control-rolled to 1600F, air-cooled (CRA), and off-line austenitized and quenched and then tempered at 1250F. When the plate was control-rolled to 1600F and immediately direct-quenched (CRDQ) and tempered at 1250F, the yield strength and tensile strength were increased by more than 10 ksi compared with the other two practices. However, this practice resulted in extraordinarily high yield-to-tensile-strength ratios approaching 1.0.

As also shown in Figure 10, the toughness of Steel U is extraordinary, and is characterized by very high energy absorptions in the fully ductile condition and by extremely low transitiion temperatures as evidenced by meeting the fracture-critical energy absorption of 35 ft-lb at -120F, rather than the AASHTO temperature of -30F. This Cu-Ni type steel exhibits a better combination of strength and toughness than any existing structural steel.

As illustrated in Figure 11, the strength and toughness of the higher-hardenability 2-inch-thick Steel V was similar to that of the 1-inch-thick, except that the toughness was not quite as good as that for the 1-inch-thick plate. As discussed in detail later, the 2-inch-thick plate was cooled at a mid-thickness rate of about 20F/second compared with 50F/second for the 1-inch-thick plate, typical for production quenching facilities (Figure 1). Consequently, the 2-inch-thick plate transformed to lesser amounts of low-temperature transformation products. Nevertheless, the combination of strength and toughness is far better than that of any existing 100-ksi yield-strength commercial steel.

Figure 12 illustrates the strength and toughness for Steel U when 1/2- and 1-inch-thick plates were cooled at rates similar to those at the mid-thickness of production-quenched 4-inch-thick plates. As shown in Figure 1, 9F/second is more typical for production quenching of 4-inch-thick plate, than 2 or 5F/second. In fact, 2F/second, which resulted from air cooling a 1/2-inch-thick plate, is ultraconservative and corresponds to plate much thicker than 4 inches. The strength and toughness were quite good but depended on the actual cooling rate (2, 5, or 9F/sec.) At a cooling rate of 2F/second, the yield strength averaged 98 ksi and the energy absorbed was 55 ft-lb at -40F. At 5F/second, the corresponding values were 114 ksi and 55 ft-lb, and at 9F/second the longitudinal and transverse values were 108/112 ksi and 65/48 ft-lb at -40F when tempered at 1175F. These results confirm the Jominy data for the higher-hardenability steels, which indicated that they should be suitable for the most stringent bridge requirements in 4-inch-thick plate. It should be noted that as the thickness increased from 1- to 2- to 4-inch-thick plate, the yield-tensile ratio decreased significantly as a result of the decrease in low-temperature transformation products with decreased cooling rates. However, it should also be noted that the properties of 4-inch plate were simulated with 1/2- or 1- inch plate, and therefore, the effect of thickness reduction during hot rolling is not incorporated in the results.

Figure 12 also illustrates simulated interrupted accelerated cooling (IAC) of 1-inch-thick Steel U. The results suggest that IAC may be appropriate for producing an 80-ksi yield-strength steel after appropriate tempering. However, its use as-quenched is not recommended because its yielding characteristics were so erratic that reproducible yield-strength values could not be obtained.

The strength and toughness properties for the lower-hardenability Steels K and L are

compiled in Tables V and VI and the data are illustrated in Figures 13, 14, and 15. Figure 13 demonstrates that the hardenability of Steel K is sufficient to harden fully the 1/2-inch thick plate and readily meet a yield strength of 100 ksi and excellent toughness. However, the hardenability is marginal for a yield strength of 100 ksi for 1-inch-thick plate and also for 2-inch-thick plate as shown in Figure 14 for Steel L. This Figure also shows that the simulated quenching and tempering of 4-inch-thick lower-hardenability steel resulted in low yield strength and toughness.
These results clearly demonstrate that a hardenability D_I value of 3.0 will ensure a minimum yield strength of 100 ksi and excellent toughness through 2 inches and possibly through 4 inches. However, at the D_I of 1.22 for the lower-hardenability steel, a cooling rate of 50F/second or higher is required to produce transform austenite to microconstituents that have a yield strength of 100 ksi and good toughness. It is therefore recommended that a minimum D_I of 3.0 be established for Cu-Ni steels of the type under study to ensure excellent toughness in plates through 4 inches thick when conventionally rolled and heat-treated. This level of hardenability is also estimated to be necessary for interrupted-accelerated-cooling to a minimum yield strength of 80 ksi and good toughness in plates through 2 inches thick, as indicated by Figure 15.

Strength - Toughness Relationships - Of particular interest are the combination of yield strength and Charpy notch toughness that can be obtained in these heats of Cu-Ni steel as a function of composition, section thickness, and thermomechanical treatment. Since the steels were selected as candidates for bridge construction among numerous potential applications, it is appropriate to examine their performance at -40F, a temperature conservatively below the -30F AASHTO test temperature specified for 100-ksi yield-strength steels in Zone 3, the most severe environment . Figures 16, 17, 18, and 19 present the range of strength-toughness combinations in Steels U, V, K, and L.

From Figure 16A it is evident that Steel U exceeded the 35 ft-lb requirement for all conditions studied. Water quenching from 1650F readily produced yield strengths above 100 ksi. Treatment simulating the quenching and tempering of 4-inch-thick plate also met the 100-ksi minimum-yield-strength goal. However, simulation of interrupted-accelerated cooling (IAC) resulted in yield-strengths of 90 to 98 ksi. The general decrease in the yield-strength-toughness curves from 1- to 4-inch-thick quenched and tempered plate and to 1-inch-thick IAC plate resulted from the respective decreases in cooling rate and low-temperature transformation product. However, the microstructure produced at the reduced cooling rates is surprisingly strong and tough. Figure 16B shows that the same composition in 2-inch thickness, Steel V, likewise exceeds 30 ft-lb in all treatments utilizing water quenching and appropriate tempering. As to be expected, tests in the longitudinal direction to rolling were somewhat tougher than those in the transverse direction, even though the plates were cross-rolled.

By comparison, as shown in Figure 17A, the lower-hardenability Steel K is marginal at a minimum yield strength of 100 ksi and only through 1-inch-thick plate when water-quenched from 1650F and appropriately tempered. It does, however, readily meet the 90-ksi yield-strength range with excellent toughness at -40F, and, in addition, has similar properties when IAC processed. At the 2-inch thickness, as indicated by Figure 17B, Steel L falls into the 80/90 ksi yield-strength range with acceptable toughness. Interrupted acccelerated cooling and tempering is less effective than water quenching and tempering but adequate.

The extraordinary notch toughness of the U and V heats of the Cu-Ni steels is further illustrated in Figure 18. The water-quench and temper treatments can generate 35 ft-lb transition temperatures below 120F and as low as -200F in the 1-inch-thick plate. Figure 19 suggests that K steel can also reach below -120F transition temperatures but in the 90-ksi yield-strength range.
The transition-temperature for the 2-inch-thick lower hardenability L steel is limited to about -80F at the 90-ksi yield strength.

METALLOGRAPHIC ANALYSIS

A survey of the microstructural changes occuring along the length of the Jominy specimens, beginning at the quenched end, is illustrated in Figures 20A through D and Figures 21 A through D for the higher hardenability and lower hardenability steels, respectively. Figure 20 (Steel V) shows that at 1/16-inch the microstructure is fully martensitic. At 2/16-inch, a very small amount of granular bainite is present with the martensite. From 3/16-inch, the amount of granular bainite increases until it reaches 100 percent at 6/16-inch. Granular bainite is described as packets of ferrite laths with interlath second phase particles of primarily martensite with some small amounts of retained austenite that has been significantly enriched in carbon content by the prior transformation products. From 7/16-inch on, the acicularity of the transformation products decreases very gradually with decreased cooling rate until the second phase tends to break-down into smaller discrete particles in a ferrite matrix. The second-phase particles also increase in size with decreased cooling rate, so that by 18/16-inch they are large enough to reflect light and begin to appear light in color. Except for some increase in size and decrease in number of the second-phase particles, the microstructures remains generally similar from from 12/16- through 32/16-inch. This behavior is consistent with the relatively constant hardness over this Jominy distance range. These are very desirable types of microconstituents, which after tempering have an excellent combination of strength and toughness.

The microstructure along the length of the Jominy specimen for the lower-hardenability Steel L is markedly different from that of Steel V. Although it is fully martensitic at 1/16-inch, it contains large amounts of granular bainite at 2/16-inch and is completely bainitic by 3/16-inch. From 5-16- to 7/16-inch, proeutectoid ferrite begins to form. Up to 4/16-inch, matching 1/2-inch quenched and tempered plate, a yield strength over 100 ksi and excellent toughness are obtained. Up to 6/16-inch, equivalent to 1-inch quenched and tempered plate, a yield strength approaching 100 ksi and good toughness are obtained. However, beyond 7/16-inch, as the amount of proeutectoid ferrite increases, the strength falls to the 80- to 90-ksi range with reduced toughness. Thus the plateau of 18 to 15 HR_C for the lower hardenability is associated with a much less desirable microstructure, specifically the blocky ferrite, than that at 28 to 25 HR_C for the higher hardenability steel. The microstructures observed in the as-cooled Jominy specimens are generally consistent with the mechanical properties that were developed, even after heat treatment.

To relate the microstructures of the heat-treated plates to those of the Jominy specimens, micrographs of the quenched 1- and 2-inch-thick plates of the lower and higher hardenability steels were compared with those of the corresponding Jominy specimens at 6/16 and 11/16 inch, respectively. Comparison of the micrographs in Figure 22 with those of Figure 20(a&b) and Figure 21(a&b) shows that the microstructure of the quenched plate specimens are reasonably similar to the corresponding Jominy specimen microstructure.

WELDABILITY

On the basis of the Graville Diagram, the lower- and higher-hardenability Steels K, L, U, and V, are not susceptible to hydrogen-assisted heat-affected-zone (HAZ) cracking because the carbon contents are below the 0.08 % minimum associated with such cracking at total carbon equivalents of 0.6 to 0.7. However, the results of implant tests were erratic, with failures occuring at stresses from the yield stress to 75 percent of the yield stress. Most of the failures occurred at very short times, usually less than one hour. In addition, many of the failures did not initiate at or near the fusion line in the coarse-grained HAZ, and therefore, are not believed to be hydrogen-induced. Studies are underway to understand the mechanism of the implant failures, and larger scale weldability tests on production plate is recommended.

CONCLUSIONS

The following conclusions are drawn as the product of this investigation:

1. Low-carbon Cu-Ni steels relatively lean in other alloy additions offer combinatiuons of yield strength and fracture toughness superior to present commercial structural steels. Yield strengths exceeding 100-ksi with high Charpy notch toughness down to -120F and lower are readily obtained by control of the carbon level and alloy additions for adequate hardenability when conventionally rolled and off-line quenched and tempered.

2. Cross-rolled plates containing 0.07C, 1.0Cu, 0.75Ni, and sufficient Mn, Cr, and Mo to ensure a critical-bar-diameter (D_I) hardenability of 3.0 exhibitedthe following properties when conventionally rolled and off-line quenched and tempered:

   a. a minimum yield strength of 100 ksi through 2 inches and a minimum Charpy V-notch energy at -40F of 100 ft-lb and 60 ft-lb for 1- and 2-inch-thick plate, respectively,

   b. a minimum yield strength of 90 ksi at 4 inches and a Charpy V-notch energy at -40F of 90 ft-lb.

3. When the foregoing steel was in-line-interrupted-accelerated-cooled, it exhibited a minimum yield strength of 90 ksi and a Charpy V-notch energy at -40F of 90 ft-lb in 1-inch plate.

4. Straightaway-rolled plates containing 0.06C, 1.0Cu, 0.75Ni and alloy additions that resulted in a critical-bar-diameter (D_I) hardenability of 1.2 exhibited the following properties when conventionally rolled and off-line quenched and tempered:

   a. a minimum yield strength of 100 ksi and Charpy V-notch energy of 150 ft-lb for 1/2-inch plate,

   b. a minimum yield strength of 100 ksi and Charpy V-notch energy of 100 ft-lb for 1-inch plate,

   c. a minimum yield strength of 90 ksi and Charpy V-notch energy of 100 ft-lb for 2-inch plate.

5. When the foregoing steel was in-line-interrupted-accelerated-cooled, the following properties were observed:

   a. as cooled, the yield strength was 97 ksi and the Charpy energy was 75 ft-lb for 1-inch plate and 88 ksi and 45 ft-lb for 2-inch plate,

   b. as cooled and tempered, the yield strength was 94 ksi and the Charpy energy was 90 ft-lb for 1-inch plate and 83 ksi and 50 ft-lb for 2-inch plate.

RECOMMENDATIONS FOR FUTURE WORK ON Cu-Ni STEELS

The results of the present study indicate that the higher hardenability steel is close to the optimum composition for a 100W bridge steel and justify the production of a commercial heat. However, the investigation has not established an optimum composition for a heavy-section 70W/80W bridge steel. Therefore, the following future work is recommended:

1. Melt production heat of following composition:

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al
0.070	1.50	0.009	0.005	0.25	1.00	0.75	0.50	0.50	0.06	0.010	0.030

   a. conventionally roll plates through 4-inches thick and off-line heat-treat,

   b. control-roll and interrupted-accelerated-cool 1- and 2-inch-thick plates.

2. Conduct Jominy end-quench hardenability tests (as-quenched and as tempered) and analyze metallographically
3. Evaluate mechanical properties and weldability of production heat
4. Conduct limit-state analyses on structural members
5. Conduct studies on Cu-Ni steels to establish regression equations interrelating carbon and alloying additions to optimize the composition of a heavy section 70W/80W steel.

Table I Plate Heat Treatment of Steels U and V

Designation	Thickness inch	Rolling Practice	Simulation	Austenitizing Temp (F)	Cooling Medium	Cooling Rate (F/s)	Tempering Temp (F)
U-Steel (1-inch-thick cross rolled)							
Transverse Tests							
UAY	1	HRA	Production Q&T-1"	1650	IQ Water	50	1200
UAX	1	HRA	Production Q&T-1"	1650	IQ Water	50	1275
UAM	1	HRA	Production Q&T-4"	1650	Spray Q	9	1250
UAK	1	HRA	Production Q&T-4"	1650	Spray Q	9	1175
UBY	1	CRDQ	CR+Direct Quench-1"	CR-1600	USS Spray	50	1200
UBX	1	CRDQ	CR+Direct Quench-1"	CR-1600	USS Spray	50	1275
UCY	1	CRA	CR+Prod. Q&T-1"	1650	IQ Water	50	1200
UCX	1	CRA	CR+Prod. Q&T-1"	1650	IQ Water	50	1275
UCM	1	CRA	Production Q&T-4"	1650	Spray Q	5	1225
UCIT	1	CRA	CR + IAC-1"	1650	Spray-1050	15	None
UCIX	1	CRA	CR + IAC-1"	1650	Spray-1050	15	1250
Longitudinal Test							
UAW	1	HRA	Production Q&T-1"	1650	IQ Water	50	1250
UAP	1	HRA	Production Q&T-4"	1650	Spray Q	9	1250
UAN	1	HRA	Production Q&T-4"	1650	Spray Q	9	1175
UBW	1	CRDQ	CR+Direct Quench-1"	CR-1600	USS Spray	50	1250
UCW	1	CRA	CR+Prod. Q&T-1"	1650	IQ Water	50	1250
UCP	0.5	CRA	Production Q&T- 1/2"	1650	IQ Water	115	1250
UCN	0.5	CRA	Production Q&T-4"	1650	Air Cooled	2	1175
UCIL	1	CRA	CR+IAC-1"	1650	Spray-1050	15	None
UCIW	1	CRA	CR+IAC-1"	1650	Spray-1050	15	1250
V STEEL (2-inch-thick cross-rolled)							
Transverse Tests							
VAZ	2	HRA	Production Q&T-2"	1650	IQ Water	20	1175
VAY	2	HRA	Production Q&T-2"	1650	IQ Water	20	1200
VAX	2	HRA	Production Q&T-2"	1650	IQ Water	20	1275
VCZ	2	CRA	CR+Prod. Q&T-2"	1650	IQ Water	20	1175
VCY	2	CRA	CR+Prod. Q&T-2"	1650	IQ Water	20	1200
VCX	2	CRA	CR+Prod. Q&T-2"	1650	IQ Water	20	1275
VBZ	2	CRDQ	CR+Direct Quench-2"	CR-1600	USS Spray	20	1175
VBY	2	CRDQ	CR+Direct Quench-2"	CR-1600	USS Spray	20	1200
VBX	2	CRDQ	CR+Direct Quench-2"	CR-1600	USS Spray	20	1275
Longitudinal Tests							
VAW	2	HRA	Production Q&T-2"	1650	IQ Water	20	1250
VCW	2	CRA	CR+Prod. Q&T-2"	1650	IQ Water	20	1250
VBW	2	CRDQ	CR+Direct Quench-2"	1600	USS Spray	20	1250

Table II Plate Heat Treatment of Steels K and L

Designation	Thickness inch	Rolling Practice	Simulation	Austenitizing Temp (F)	Cooling Medium	Cooling Rate (F/s)	Tempering Temp (F)
K-Steel (1/2-inch-thick straightaway rolled)							
Transverse Tests							
KAT	0.5	HRA	Production Q&T-4"	As Rolled	Air-cooled	2	None
KAX	0.5	HRA	Production Q&T-4"	As Rolled	Air-cooled	2	1200
KAQX	0.5	HRA	Production Q&T- 1/2"	1650	IQ Water	90	1250
Longitudinal Test							
KAL	0.5	HRA	Production Q&T-4"	As Rolled	Air-cooled	2	None
KAW	0.5	HRA	Production Q&T-4"	As Rolled	Air-cooled	2	1200
KAQW	0.5	HRA	Production Q&T- 1/2"	1650	IQ Water	90	1250
K-Steel (1-inch-thick straightaway-rolled)							
Transverse Tests							
KBX	1	HRA	Production Q&T-1"	1650	IQ Water	50	1250
KCT	1	CRIAC	CR+IAC-1"	CR-1600	USS Spray/1050	20	None
KCX	1	CRIAC	CR+IAC-1"	CR-1600	USS Spray/1050	20	1250
Longitudinal Test							
KBW	1	HRA	Production Q&T-1"	1650	IQ Water	50	1250
KBP	1	HRA	Production Q&T-1"	1650	IQ Water	50	1175
KCL	1	CRIAC	CR+IAC-1"	CR-1600	USS Spray/1050	20	None
KCN	1	CRIAC	CR+IAC-1"	CR-1600	USS Spray/1050	20	1100
KCP	1	CRIAC	CR+IAC-1"	CR-1600	USS Spray/1050	20	1250
K-Steel (1-inch-thick cross-rolled)							
Transverse Tests							
KDX	1	HRA	Production Q&T-1"	1650	IQ Water	50	1200
KDY	1	HRA	Production Q&T-1"	1650	IQ Water	50	1150
Longitudinal Test							
KDW	1	HRA	Production Q&T-1"	1650	IQ Water	50	1200
KDN	1	HRA	Production Q&T-1"	1650	IQ Water	50	1150
L-Steel (2-inch-thick straightaway-rolled)							
Transverse Tests							
LAX	2	HRA	Production Q&T-2"	1650	IQ Water	20	1175
LCT	2	CRIAC	CR+IAC-2"	CR-1600	USS Spray/1050	9	None
LCY	2	CRIAC	CR+IAC-2"	CR-1600	USS Spray/1050	9	1275
Longitudinal Tests							
LAW	2	HRA	Production Q&T-2"	1650	IQ Water	20	1175
LCL	2	CRIAC	CR+IAC-2"	CR-1600	USS Spray/1050	9	None
LCN	2	CRIAC	CR+IAC-2"	CR-1600	USS Spray/1050	9	1275
L-Steel (2-inch-thick cross-rolled)							
Transverse Tests							
LDX	2	HRA	Production Q&T-2"	1650	IQ Water	20	1175
Longitudinal Tests							
LDW	2	HRA	Production Q&T-2"	1650	IQ Water	20	1175

Table III - Mechanical Properties of Steel U (1" Plate Gauge)

U-STEEL	*Codes*	*Tensile Properties*					*Charpy V-Notch* Transition Temperature, deg. F				*Charpy V-Notch Energy*				
Processing Condition Temperature, deg. F		Y.S. ksi	T.S. ksi	EL. %	R.A. %	Y.S./T.S.	20 ft-lb	35 ft-lb	60 ft-lb	15 mils	70 F	0 F	-40 F	-80 F	-120 F
TRANSVERSE TESTS															
HRA (1650)+IQ+T1275	UAX	99	106	25	71	0.93	<-200	-170	-120	-200	-	110	110	90	60
HRA (1650)+IQ+T1200	UAY	114	121	22	67	0.94	-160	-125	-55	-130	-	85	65	50	35
HRA-4" Simulation 1650F+SQ(9F/s)															
Tempered at 1250F	UAM	96	107	26	72.5	0.90	-130	-100	-80	-120	-	90	75	55	25
HRA-4" Simulation 1650F+SQ(9F/s)															
Tempered at 1175F	UAK	112	123	24	64	0.90	-100	-70	0	-90	70	60	48	30	10
CRDQ+1275T	UBX	127	130	20	60	0.98	-185	-120	-60	-160	-	70	68	50	35
CRDQ+1200T	UBY	146	146	19	60	1.00	-100	-40	80	-80	-	50	35	25	15
CRA (1650)+IQ+T1275	UCX	99	108	24	70	0.92	<-200	-170	-120	-200	-	110	110	90	75
CRA (1650)+IQ+T1200	UCY	122	127	22	66	0.96	-160	-125	-55	-130	-	85	65	50	35
CRA-4" Simulation 1650F+SQ(5F/s)															
Tempered at 1225F	UCM	104	118	22	64	0.88	-115	-75	-30	-100	80	70	55	40	10
CRA (1650) CR+IAC (SQ, 1050F) (15F/s)	UCIT	120	140	17	61	0.84	-65	-40	-	-60	50	40	35	8	-
CRA (1650) CR+IAC (SQ, 1050F) (15F/s)															
Tempered at 1250F	UCIX	89	110	24	62.5	0.81	-80	-65	-50	-75	-	90	90	20	10
LONGITUDINAL TESTS															
HRA (1650)+IQ+T1250 (IQ)	UAW	105	112	26	71	0.94	-190	-180	-160	-200	-	135	140	110	70
HRA-4" Simulation 1650F+SQ(9F/s)															
Tempered at 1250F	UAP	93	107	26	70	0.87	-170	-110	-100	-140	-	115	100	85	35
HRA-4" Simulation 1650F+SQ(9F/s)															
Tempered at 1175F	UAN	108	122	24	65	0.88	-120	-95	-50	-100	120	85	65	45	20
CRDQ+1250T	UBW	129	131	23	68	0.98	-160	-140	-90	-140	-	90	85	60	55
CRA (1650)+IQ+T1250	UCW	110	116	26	73	0.95	<-200	<-200	-180	<-200	-	135	140	130	75
CRA (1650)+IQ+T1250 (1/2")	UCP	122	128	22	72	0.95	<-200	-200	-140	-200	130	120	115	100	75
CRA (1650)+AC(2F/s)+T1175 (1/2")	UCN	98	122	26	71	0.80	-90	-60	-30	-80	120	80	55	20	-
CRA (1650) CR+IAC (SQ, 1050F) (15F/s)	UCIL	77	123	21	65	0.63	0	+5	+10	0	90	20	15	10	-
CRA (1650) CR+IAC (SQ, 1050F) (15F/s)															
Tempered at 1250F	UCIW	88	110	25	66	0.80	-85	-75	-70	-80	-	125	120	25	15

Table IV. Mechanical Properties of Steel V (2" Plate Gauge)

V-STEEL Processing Condition Temperature, deg. F	Codes	Tensile Properties					Charpy V-Notch Transition Temperature, deg. F				Charpy V-Notch Energy				
		Y.S. ksi	T.S. ksi	EL. %	R.A. %	Y.S./T.S.	20 ft-lb	35 ft-lb	60 ft-lb	15 mils	70 F	0 F	-40 F	-80 F	-120 F
TRANSVERSE TESTS															
HRA (1650)+IQ+T1275	VAX	91	101	26	70	0.9	-155	-150	-110	-150	-	110	108	80	45
HRA (1650)+IQ+T1200	VAY	100	110	25	70	0.9	-100	-80	-60	-85	-	100	80	35	10
HRA (1650)+IQ+T1175	VAZ	110	119	22	67	0.92	-90	-70	-40	-80	-	80	60	30	2
CRDQ+T1275	VBX	113	118	22	67	0.96	-120	-90	-60	-80	-	72	60	15	5
CRDQ+T1200	VBY	124	128	21	62	0.96	-75	-60	-35	-65	-	70	55	17	7
CRDQ+T1175	VBZ	134	137	20	61	0.97	-45	-20	-	-40	-	45	25	15	5
CRA (1650)+IQ+T1275	VCX	89	101	26	71	0.88	-140	-100	-70	-120	-	118	82	30	20
CRA (1650)+IQ+T1200	VCY	102	111	24	67	0.92	-100	-80	-50	-80	-	90	70	35	15
CRA (1650)+IQ+T1175	VCZ	111	120	22	67	0.92	-80	-55	0	-60	-	60	45	20	5
LONGITUDINAL TESTS															
HRA (1650)+IQ+T1250	VAW	114	122	24	69	0.94	-120	-115	-90	-110	-	85	80	60	20
CRDQ+T1250	VBW	128	133	23	67	0.96	-60	-20	35	-40	-	35	25	10	5
CRA (1650)+IQ+T1250	VCW	112	120	23	67	0.94	-75	-60	-45	-70	-	80	60	15	5

Table V. Mechanical Properties of Steel K (0.5 & 1" Plate Gauge)

K-STEEL	Codes	Tensile Properties					Charpy V-Notch				Charpy V-Notch Energy				
Processing Condition							Transition Temperature, deg. F								
Temperature, deg. F		Y.S. ksi	T.S. ksi	EL. %	R.A. %	Y.S./T.S.	20 ft-lb	35 ft-lb	60 ft-lb	15 mils	70 F	0 F	-40 F	-80 F	-120 F
LONGITUDINAL TESTS															
HRA (As Rolled) (1/2")	KAL	76	107	26	69	0.71	50	80	110	60	25	10	5	-	-
HRA (As Rolled)+T1200 (1/2")	KAW	90	109	26	74	0.83	-20	0	30	-15	100	35	10	-	-
HRA(1650)+IQ+T1250 (1/2")	KAQW	106	112	24	76	0.95	<-200	-195	-170	-200	160	160	160	135	95
HRA (1650)+IQ+T1250 (1")	KBW	94	102	28	77	0.92	-170	-160	-150	-170	190	190	190	170	125
HRA (1650)+IQ+T1175 (1")	KBP	100	111	26	75	0.90	-145	-140	-130	-140	150	135	125	100	80
CR1600+IAC (1050)+AC (1")	KCL	97	111	24	76	0.87	-105	-80	-55	-105	140	110	75	40	15
CR1600+IAC (1050)+AC+T1250 (1")	KCP	94	111	25	72	0.86	-110	-90	-75	-100	150	95	90	50	15
CR1600+IAC (1050)+AC+T1100 (1")	KCN	102	122	24	66	0.83	-50	-25	30	-40	70	45	25	10	-
HRA (Cr.R) (1650)+IQ+T1200 (1")	KDW	98	106	25	74	0.92	-120	-115	-100	-125	165	160	135	105	20
HRA (Cr.R) (1650)+IQ+T1150 (1")	KDN	100	110	25	72	0.91	-140	-120	-100	-130	125	115	105	90	40
TRANSVERSE TESTS															
HRA (As-Rolled) (1/2")	KAT	71	104	26	63	0.68	+60	+95	+135	+50	25	10	5	-	-
HRA (As-Rolled)+T1200 (1/2")	KAX	89	108	24	67	0.82	+10	+30	+65	+10	55	15	-	-	-
HRA(1650)+IQ+T1250 (1/2")	KAQX	103	110	24	71	0.94	-190	-140	-60	-160	-	90	65	50	40
HRA (1650)+IQ+T1250 (1")	KBX	92	103	24	67	0.90	-150	-130	-100	-150	125	110	90	75	55
CR1600+IAC (1050)+AC (1")	KCT	102	122	19	65	0.84	-110	-70	20	-100	65	55	45	30	15
HRA (Cr.R) (1650)+IQ+T1200 (1")	KDX	102	110	23	74	0.93	-120	-105	-100	-105	130	115	95	85	15
HRA (Cr.R) (1650)+IQ+T1150 (1")	KDY	101	111	24	72	0.91	-140	-100	-50	-115	125	100	65	45	15

Table VI. Mechanical Properties of Steel L (2" Plate Gauge)

L-STEEL Processing Condition Temperature, deg. F	Codes	Tensile Properties					Charpy V-Notch Transition Temperature, deg. F				Charpy V-Notch Energy				
		Y.S. ksi	T.S. ksi	EL. %	R.A. %	Y.S./T.S.	20 ft-lb	35 ft-lb	60 ft-lb	15 mils	70 F	0 F	-40 F	-80 F	-120 F
LONGITUDINAL TESTS															
HRA (1650)+IQ+T1175	LAW	99	106	24	73	0.94	-110	-105	-95	-105	120	115	105	80	10
CR1600+IAC (1050)+AC (2")	LCL	88	113	23	74	0.77	-100	-80	-40	-90	150	100	45	35	13
CR1600+IAC (1050)+AC+T1275 (2")	LCN	83	104	26	70	0.80	-70	-60	-40	-70	115	85	50	15	-
HRA (Cr.R) (1650)+IQ+T1175 (2")	LDW	94	104	27	74	0.91	-110	-105	-100	-110	170	170	120	85	5
TRANSVERSE TESTS															
HRA (1650)+IQ+T1175 (2")	LAX	99	107	25	71	0.92	-110	-90	-60	-105	135	125	75	40	10
CR1600+IAC (1050)+AC (2")	LCT	82	109	23	71	0.76	-80	-40	0	-40	100	55	35	25	8
CR1600+IAC (1050)+AC+T1275 (2")	LCY	90	104	26	66	0.87	-90	-80	-50	-90	70	65	50	35	7
HRA (Cr.R) (1650)+IQ+T1175 (2")	LDX	94	104	23	71	0.90	-90	-80	-70	-90	105	100	85	30	7

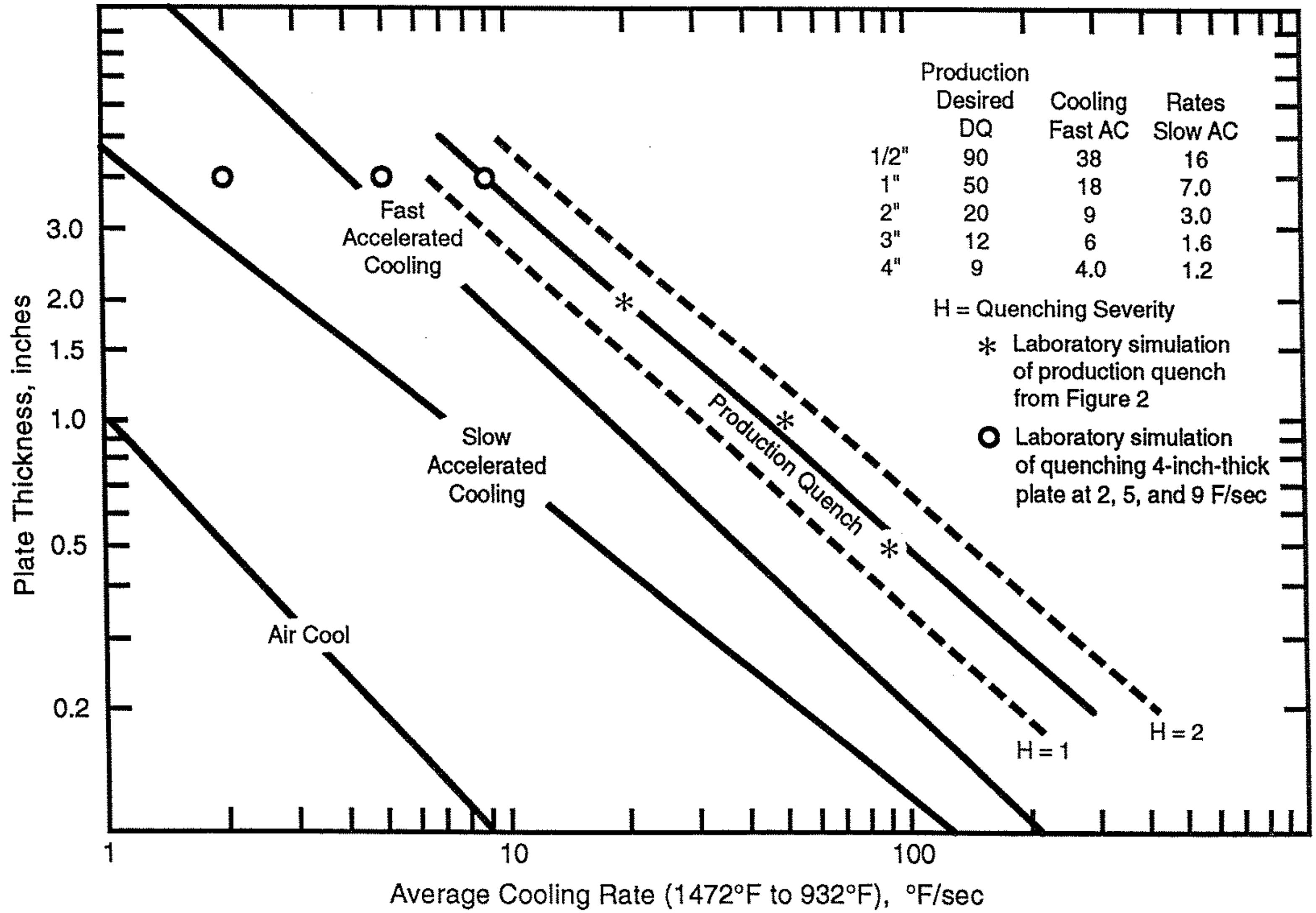


Figure 1 - Illustration of Various Cooling Practices

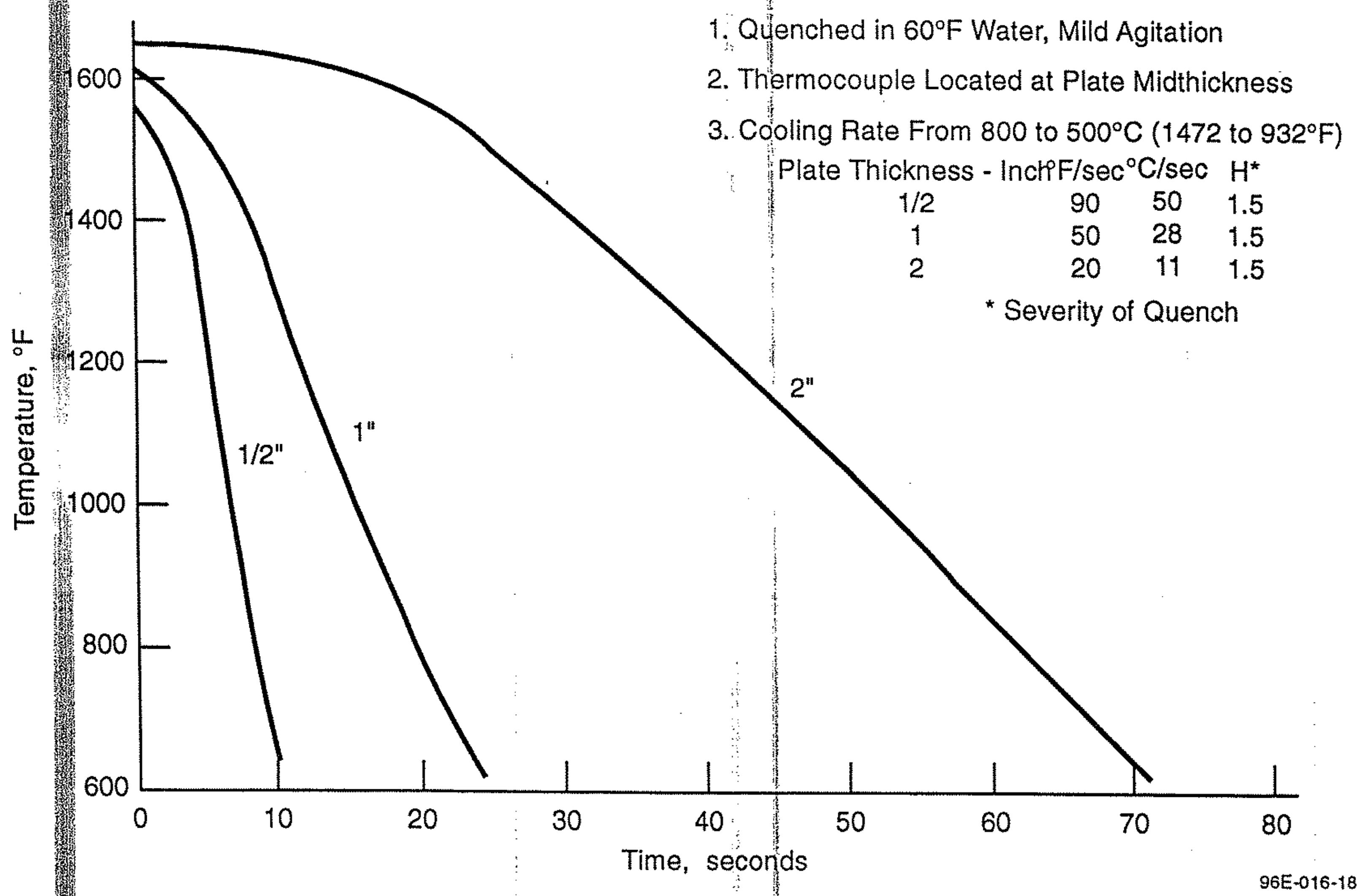


Figure 2 Cooling Curves for Laboratory Water-Quenched Plates

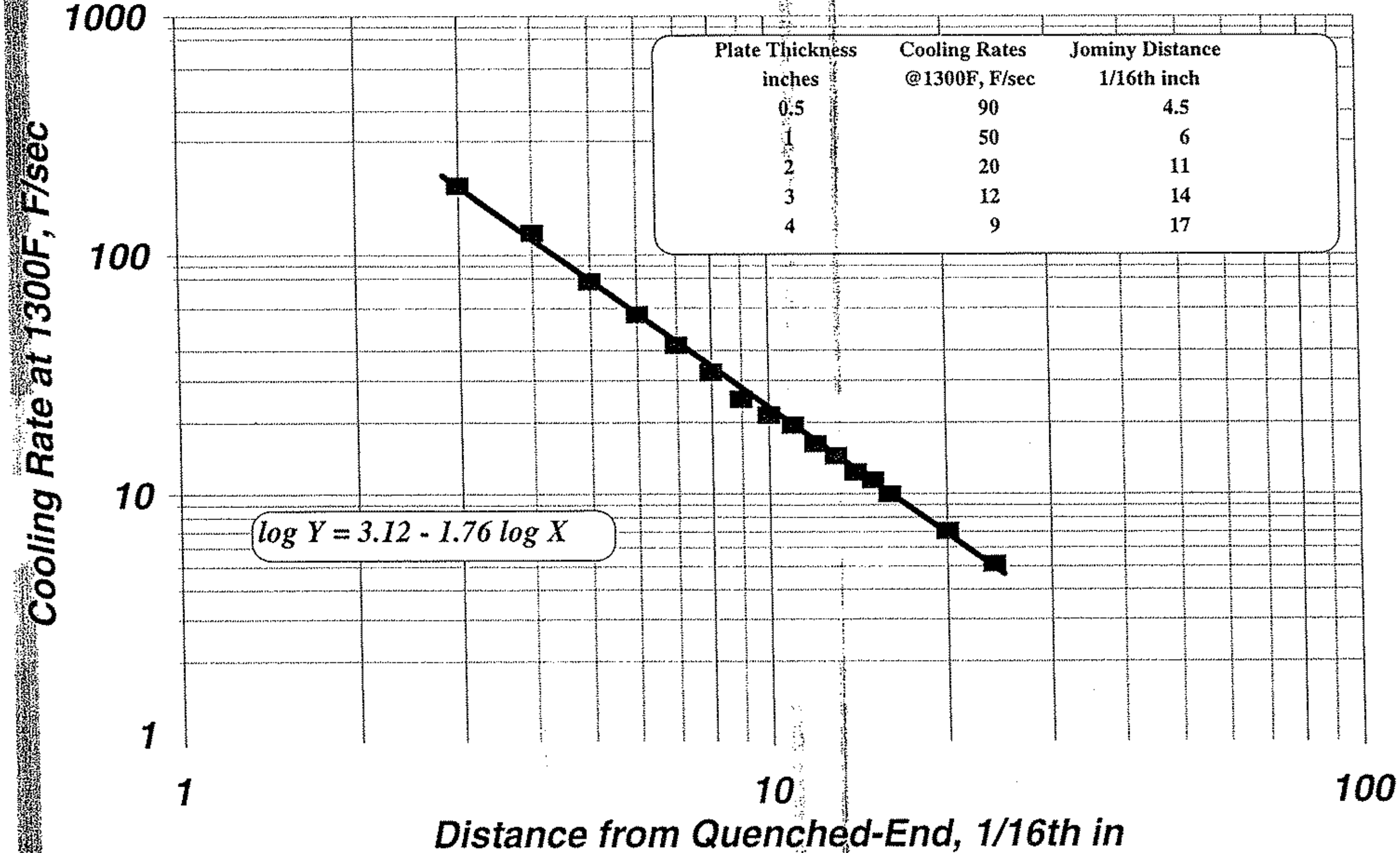


Figure 3 Jominy Test Cooling Rates and Corresponding Distances from Quenched End for Cooling Rates of Typical Production Spray Quenched and ATLSS Laboratory Immersion Quenched Steel Plates

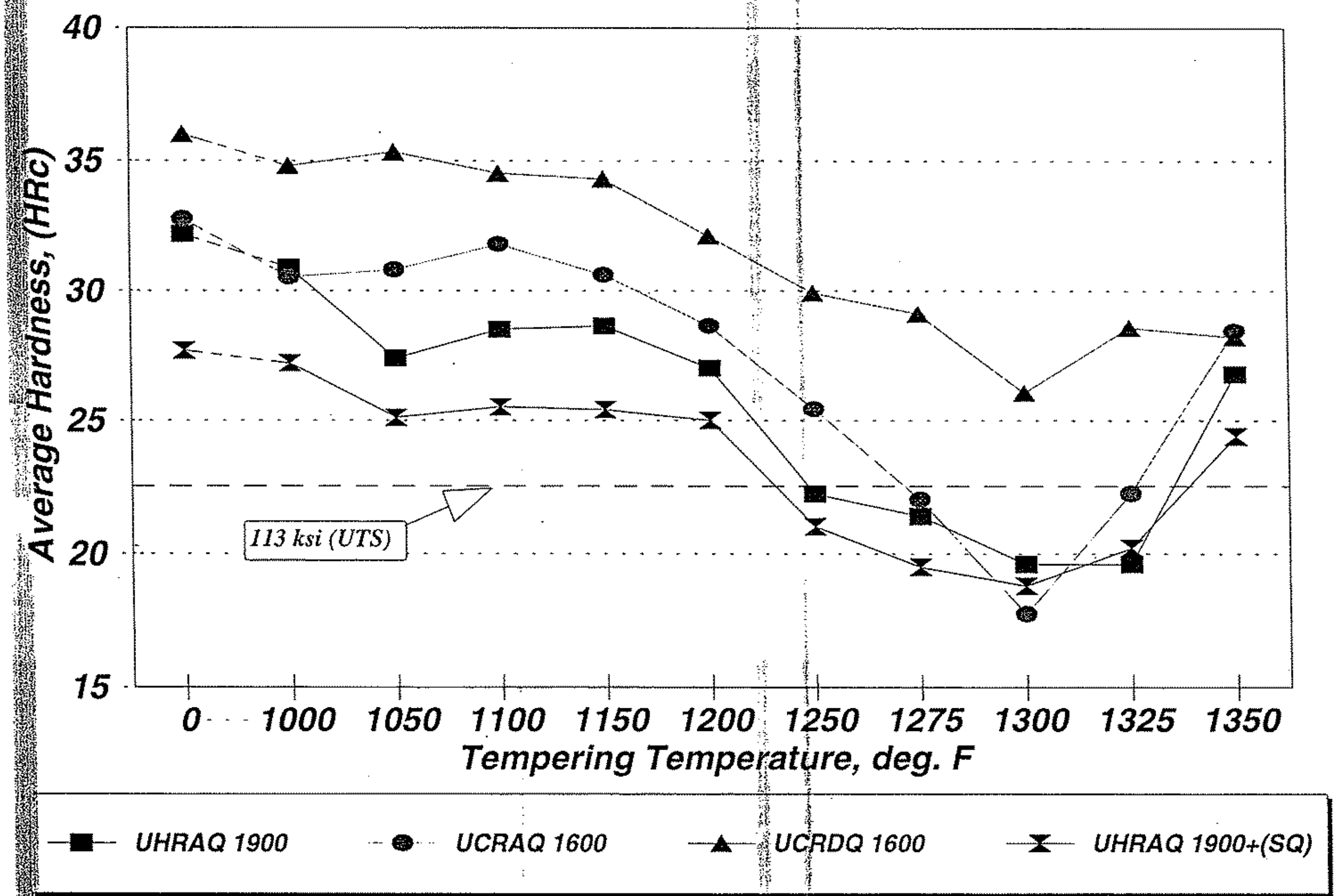


Figure 4a. Effect of Tempering on Hardness for Various Treatments of Steel U

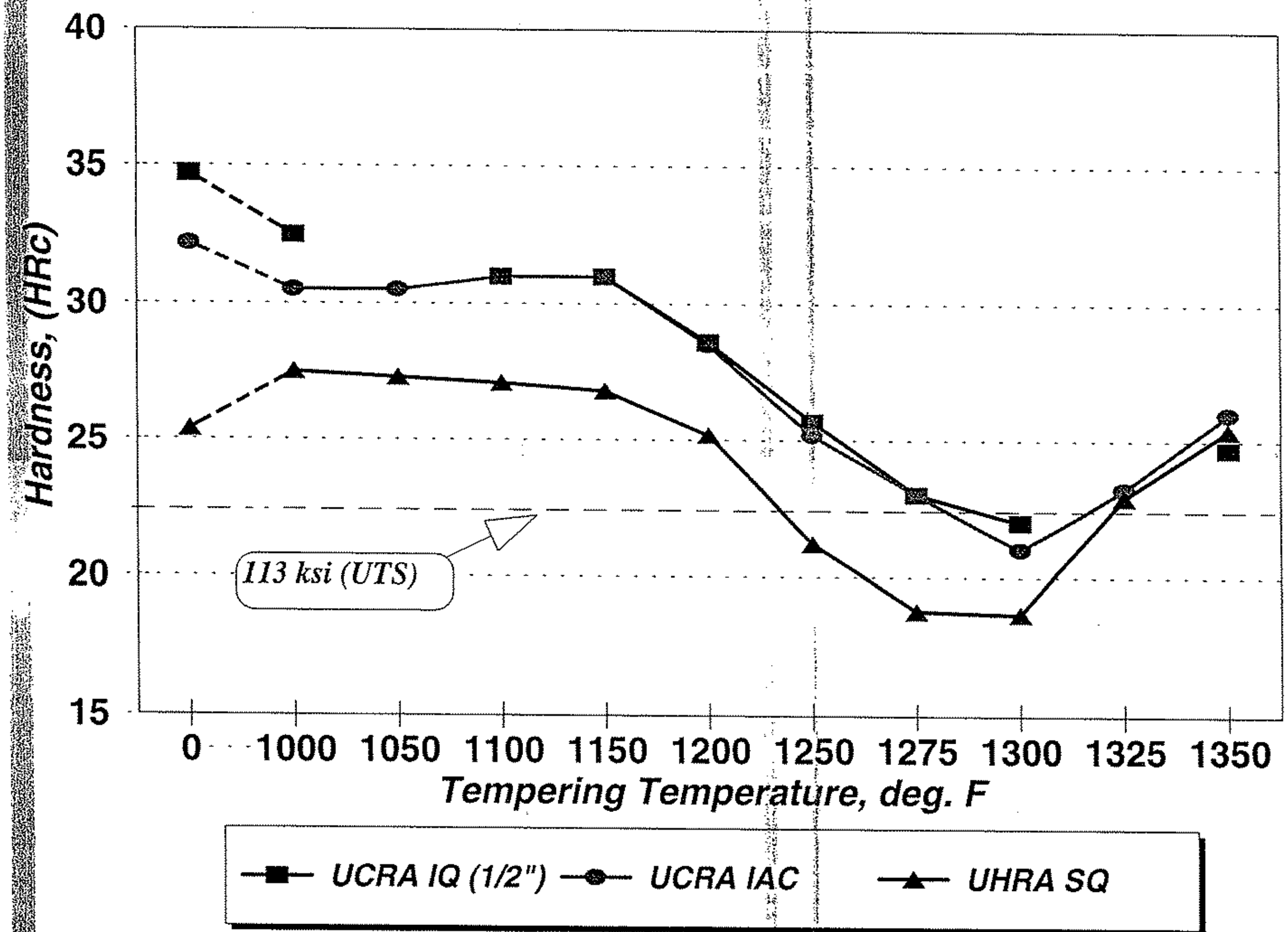


Figure 4b. Effect of Tempering on Hardness for Other Treatments of Steel U

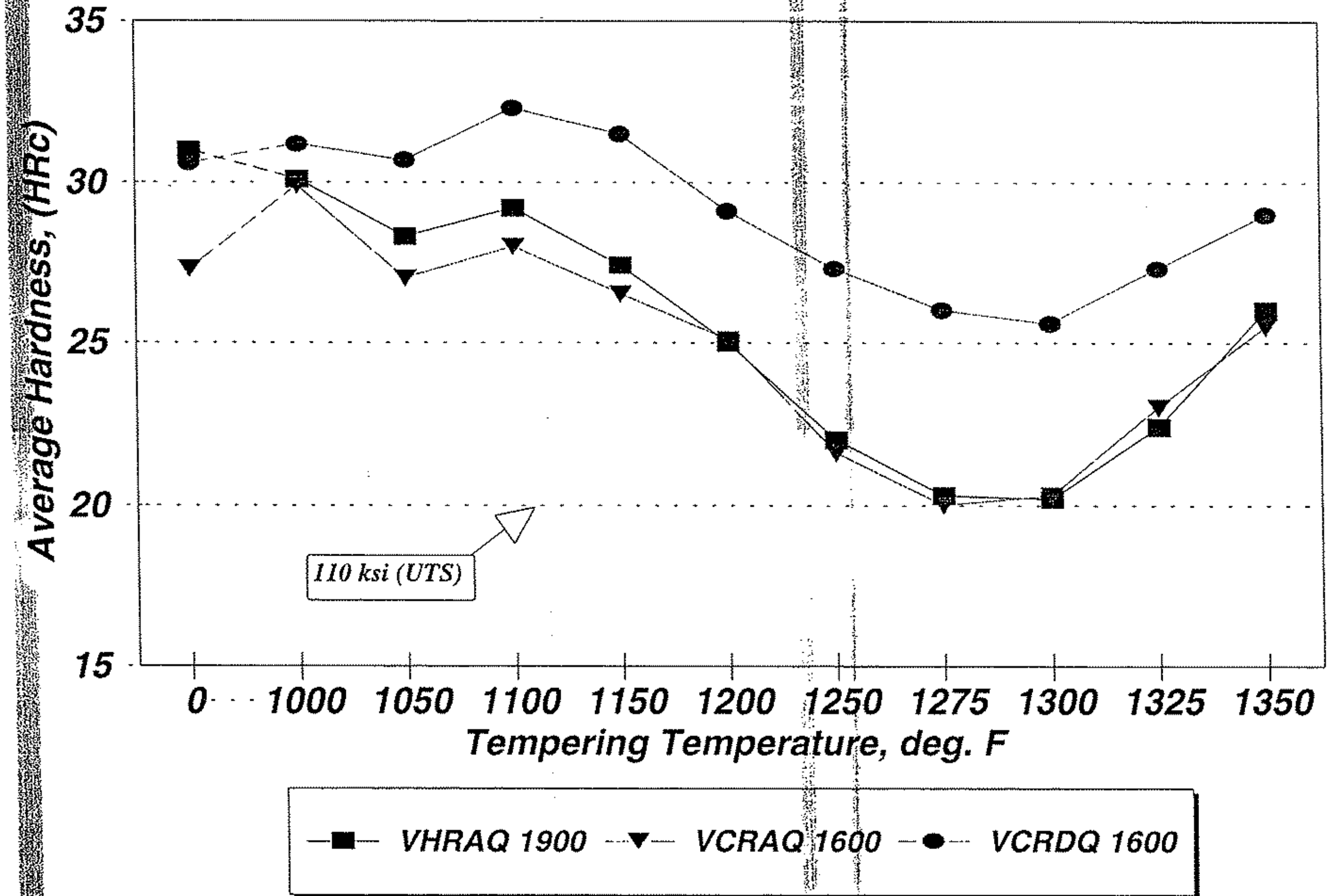


Figure 4c. Effect of Tempering on Hardness for Various Treatments of Steel V

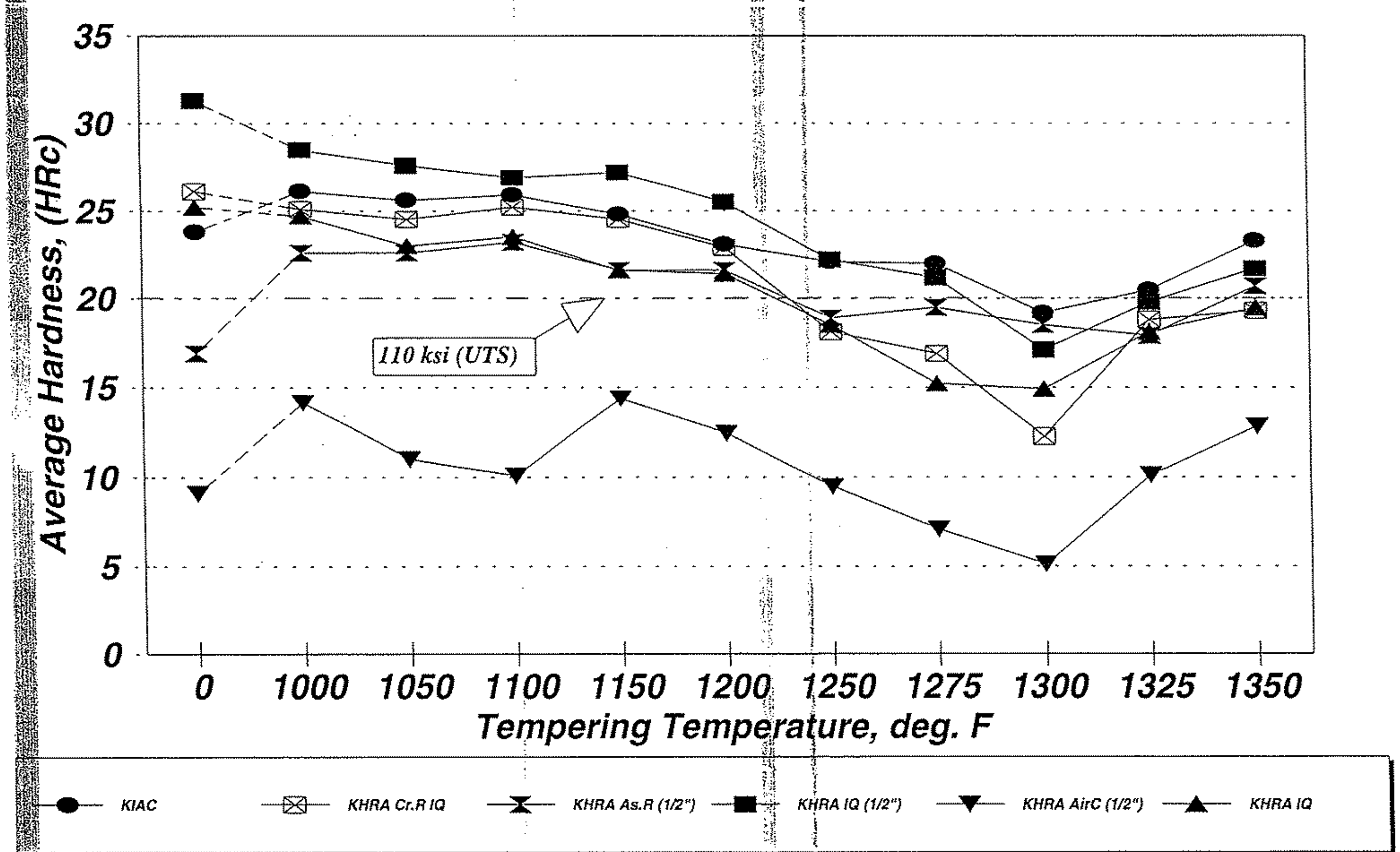


Figure 5a. Effect of Tempering on Hardness for Various Treatments of Steel K

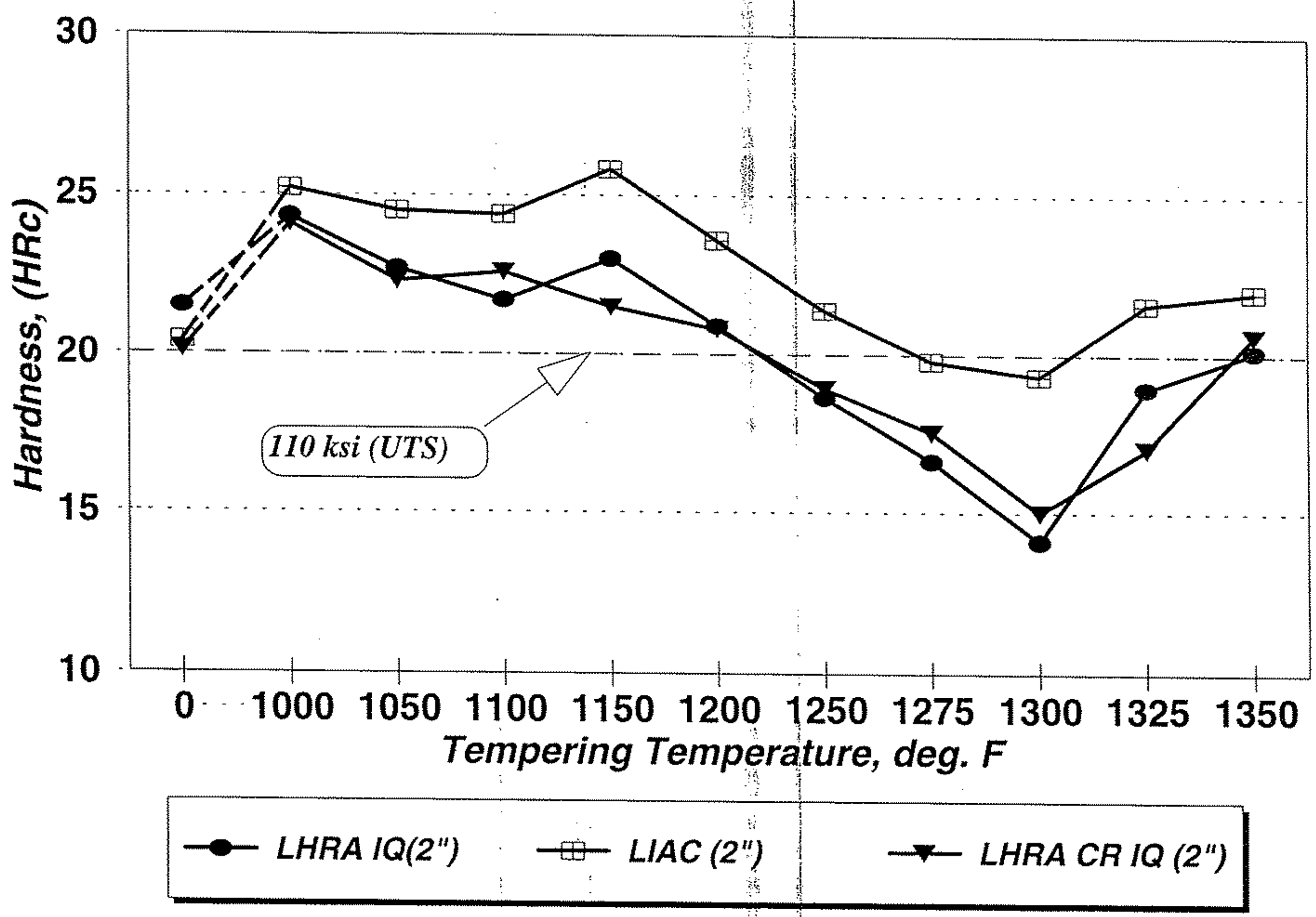


Figure 5b. Effect of Tempering on Hardness for Various Treatments of Steel L

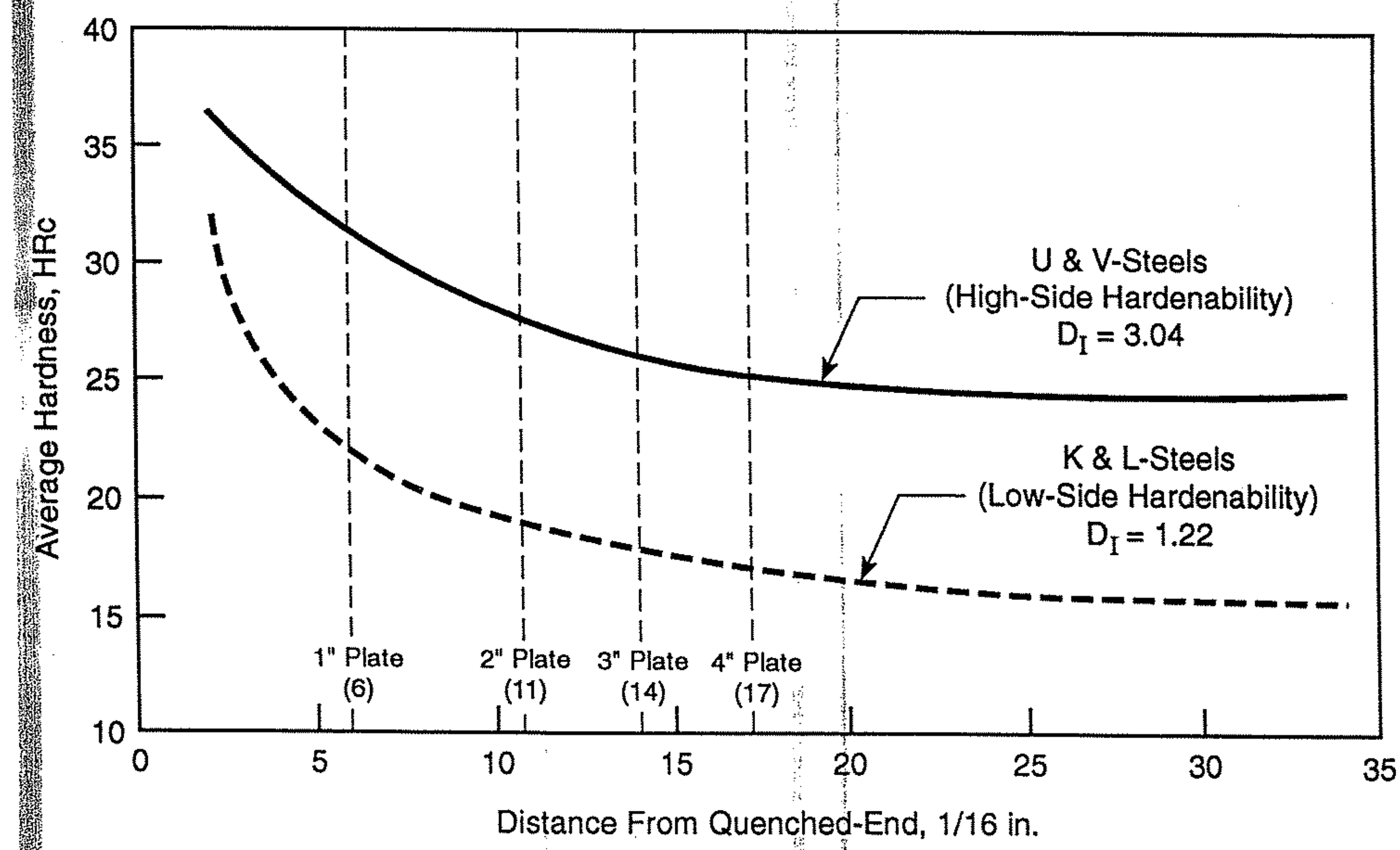


Figure 6 Averaged Jominy End-Quench Hardenability Results of U&V Steels and K&L Steels

96-E016-2

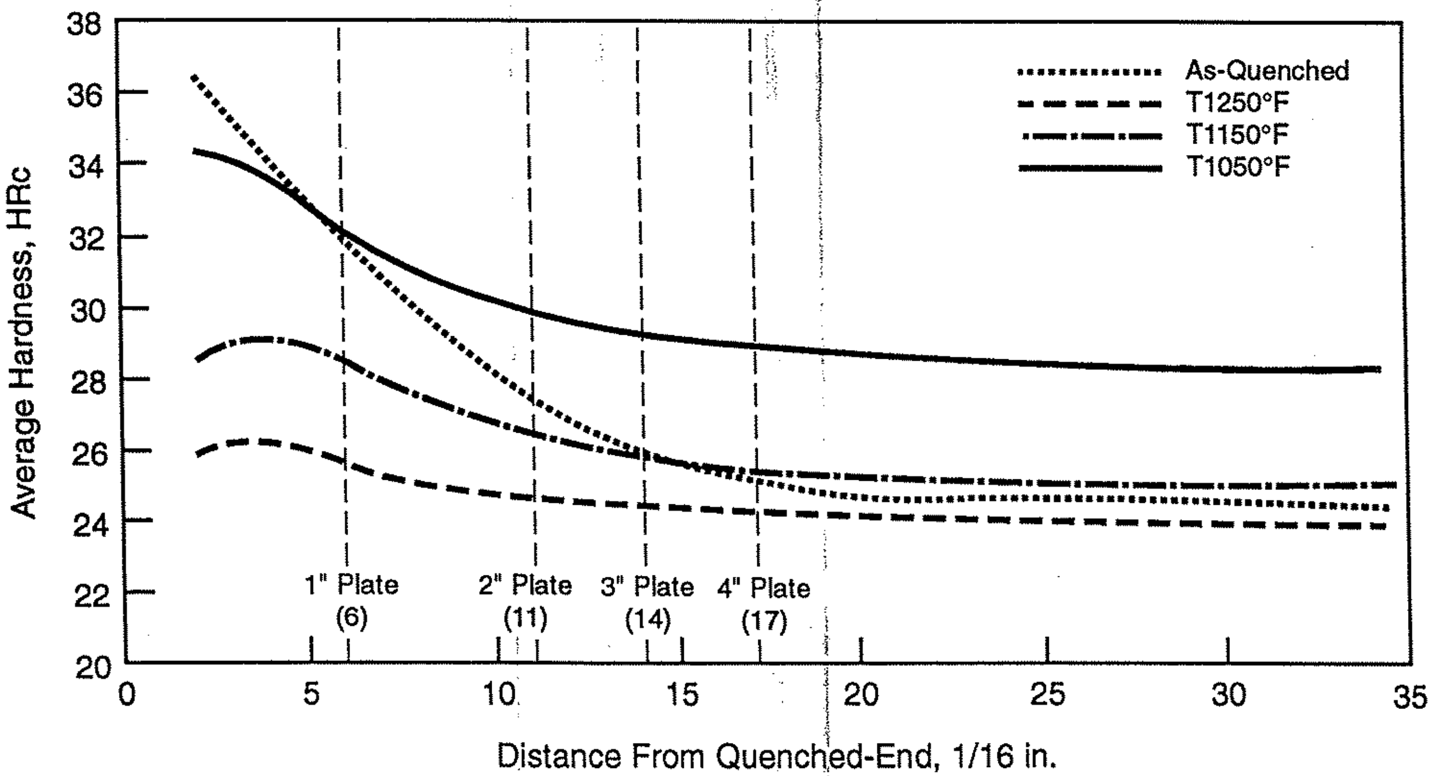


Figure 7 Jominy End-Quench High-Side Hardenability Results at Various Tempering Temperatures: U&V Steels

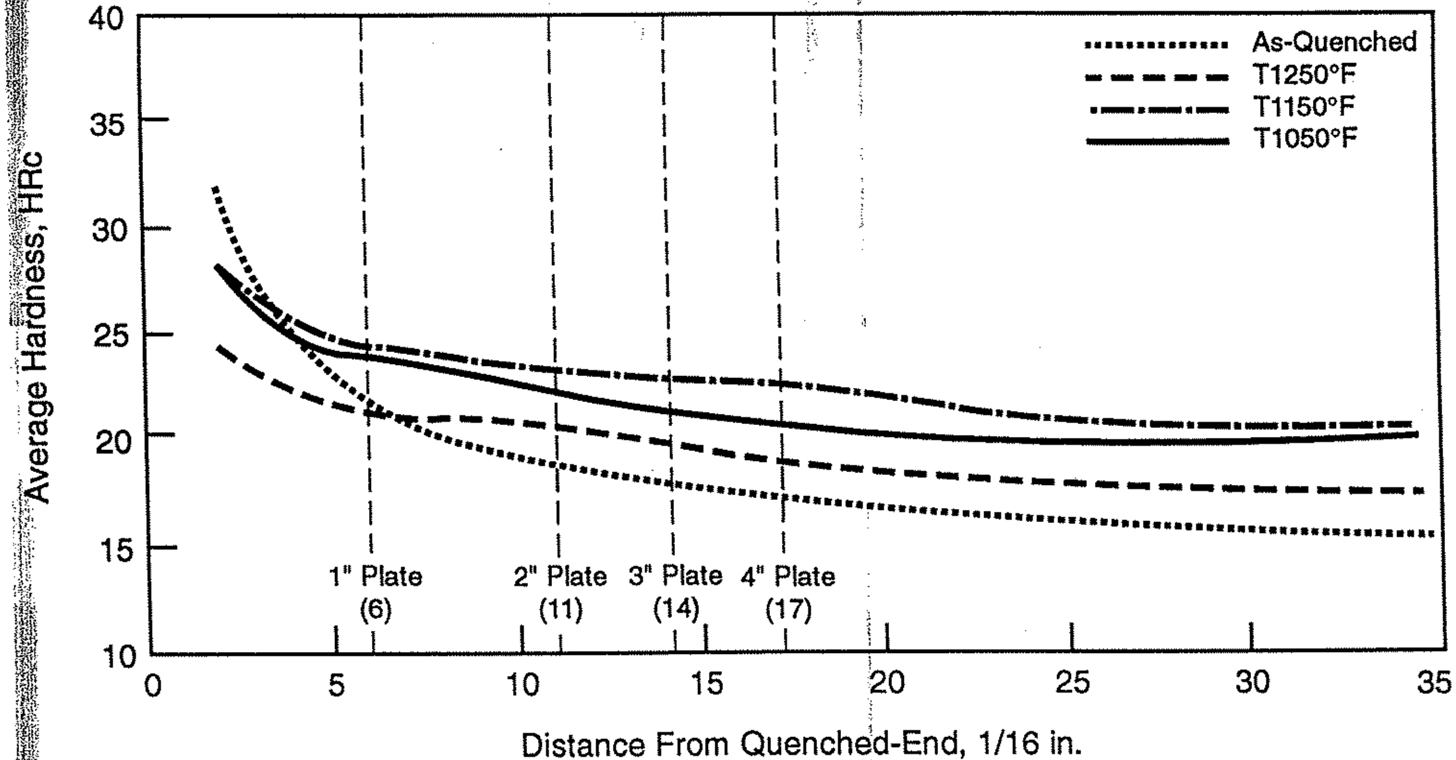


Figure 8 Jominy End-Quench Low-Side Hadenability Results at Various Tempering Temperatures: K and L Steels Averaged

96-E016-4

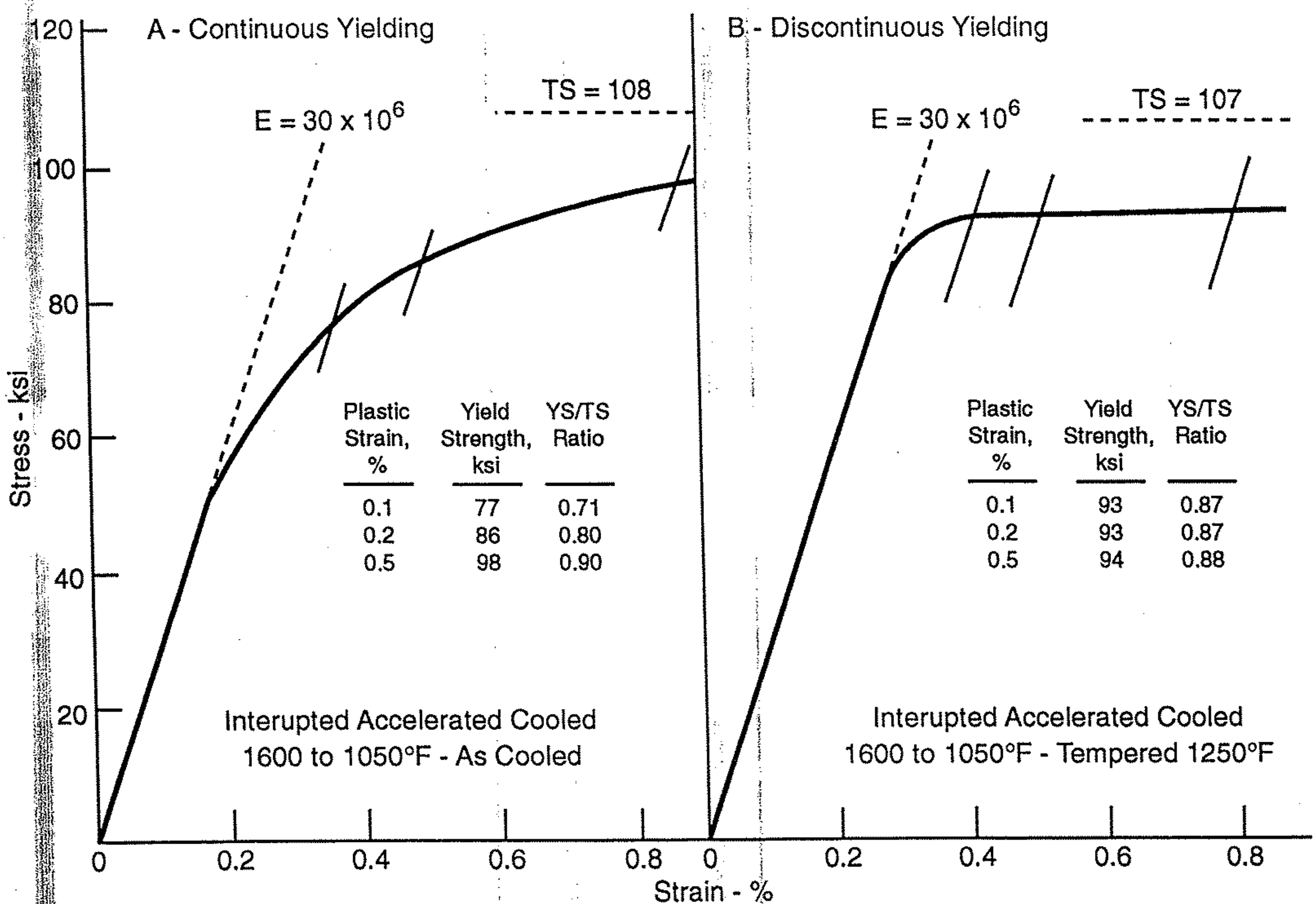


Figure 9 Comparison of Flow-Stress Curves for Quenched and as Tempered Interupted-Accelerated-Cooled 2-inch-thick L Steel (IAC Rate=9°F/sec)

96-E016-7

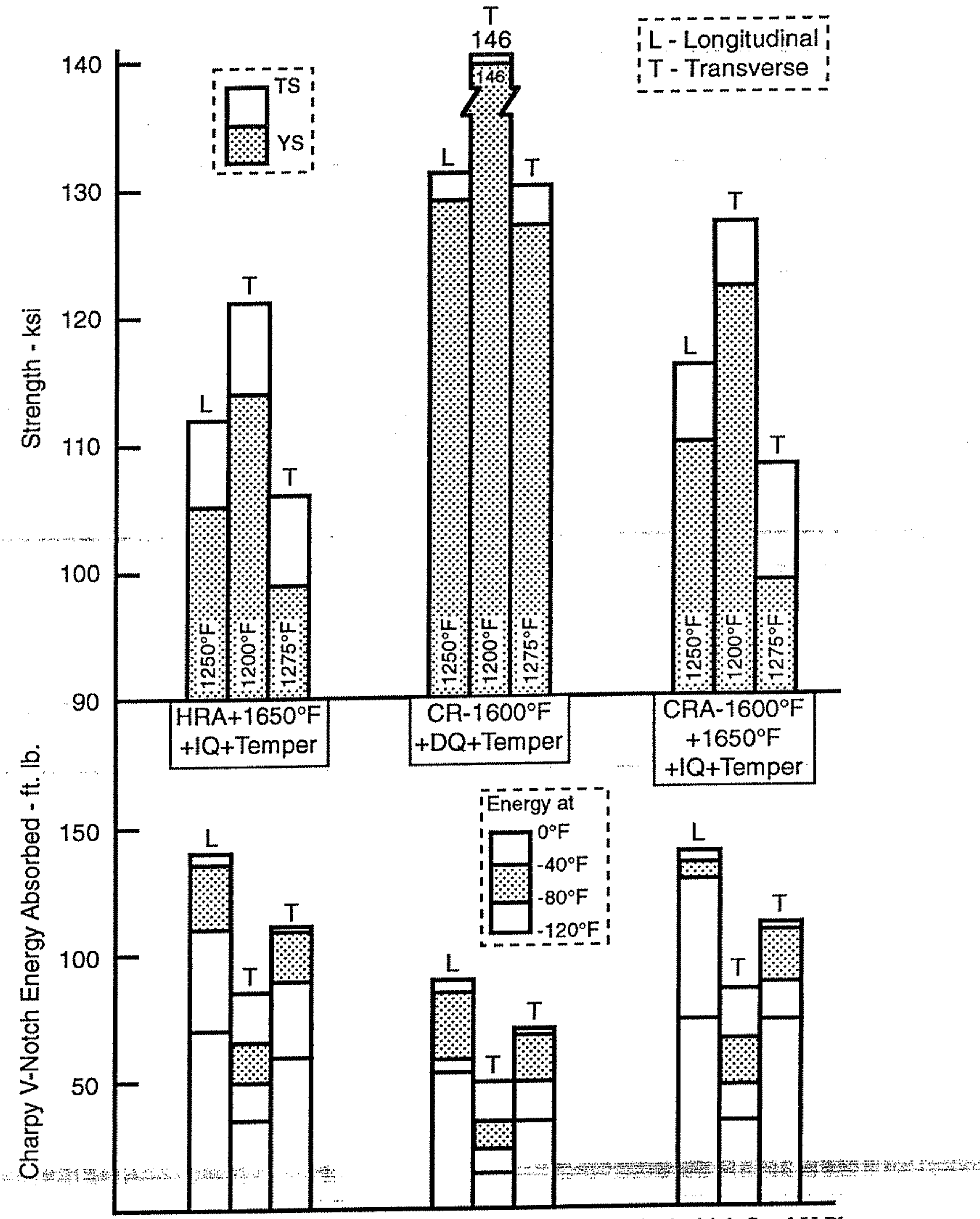


Figure 10 Strength and Toughness Properties of Cross-Rolled 1-inch-thick Steel U Plate

96-E016-12

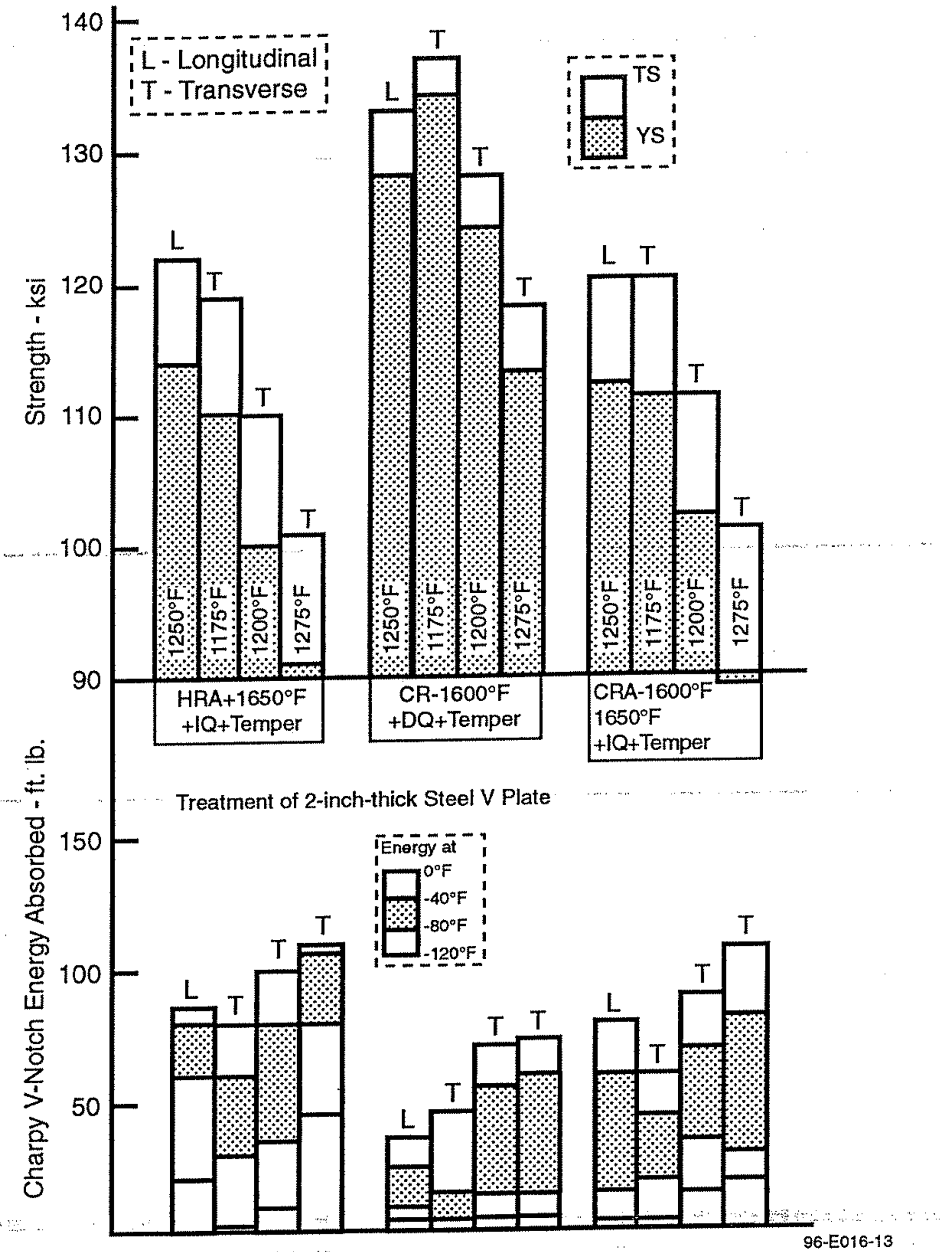


Figure 11 Strength and Toughness Properties of Cross-Rolled 2-inch-thick Steel V Plate

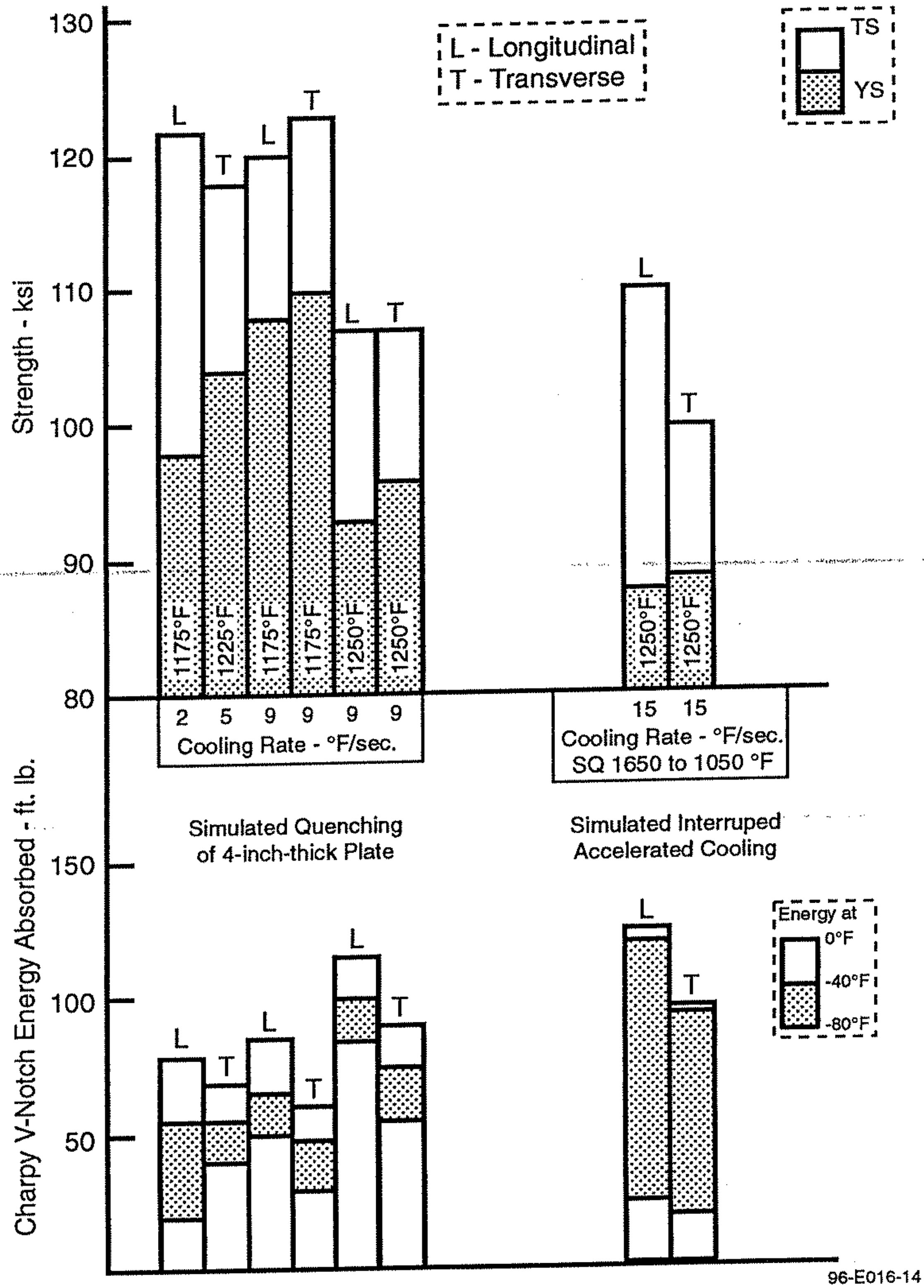


Figure 12 Strength and Toughness Properties for Special Processing Simulations of Steel U

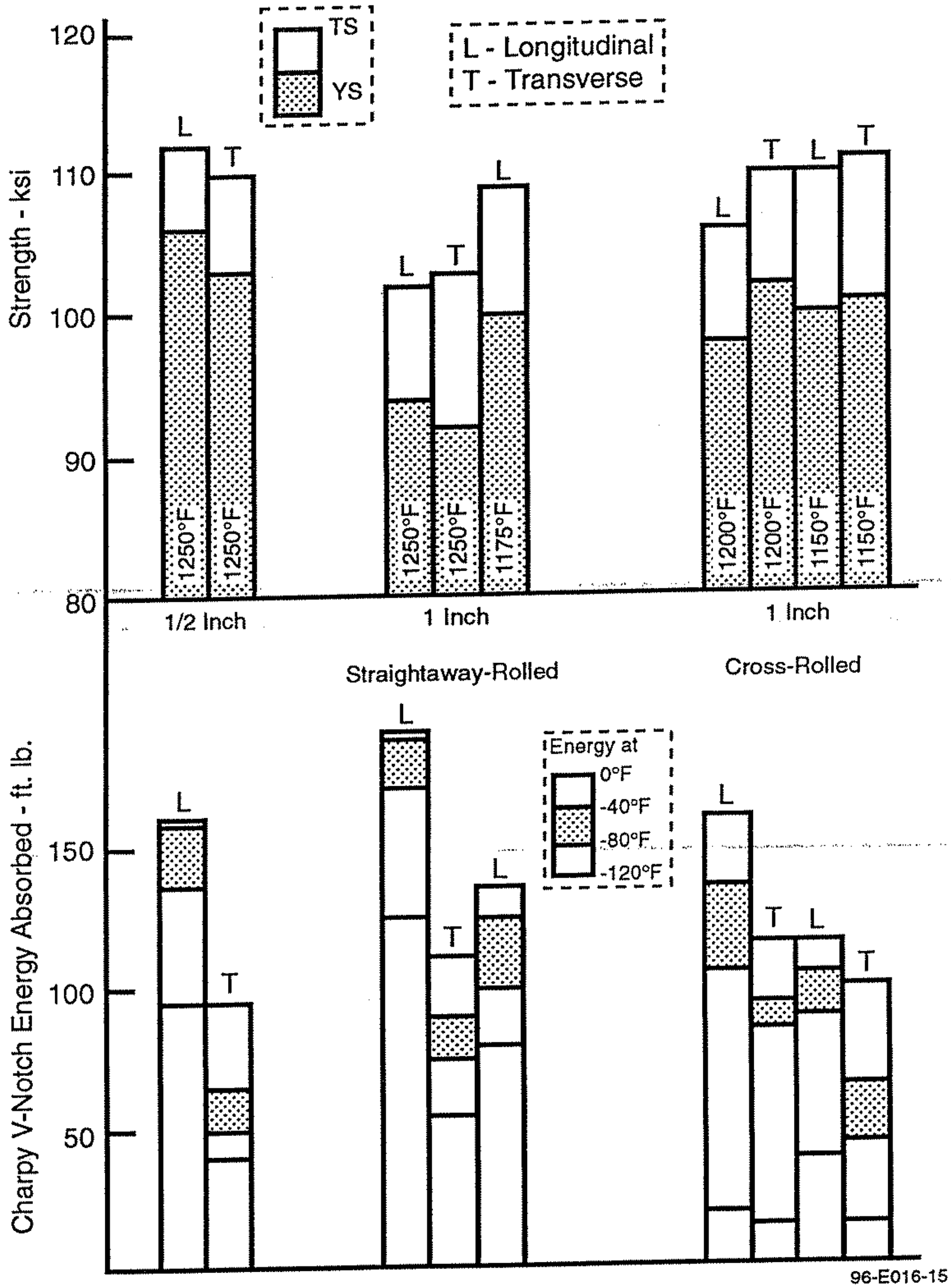


Figure 13 Strength and Toughness Properties for Conventionally Rolled and Off-Line Quenched and Tempered Steel K

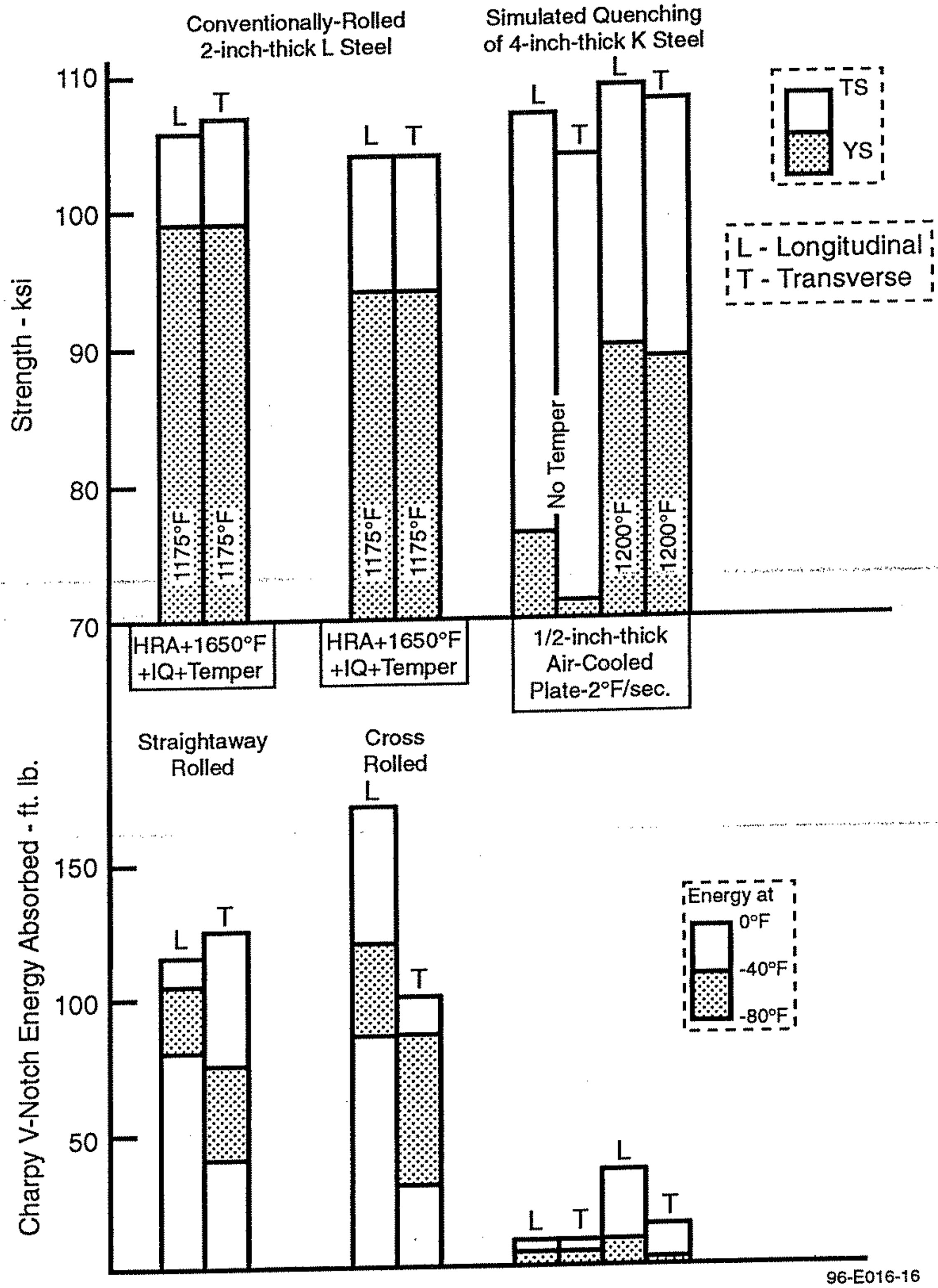


Figure 14 Strength and Toughness Properties for 2-inch-thick and 4-inch-thick Quenched and Tempered Steels K and L

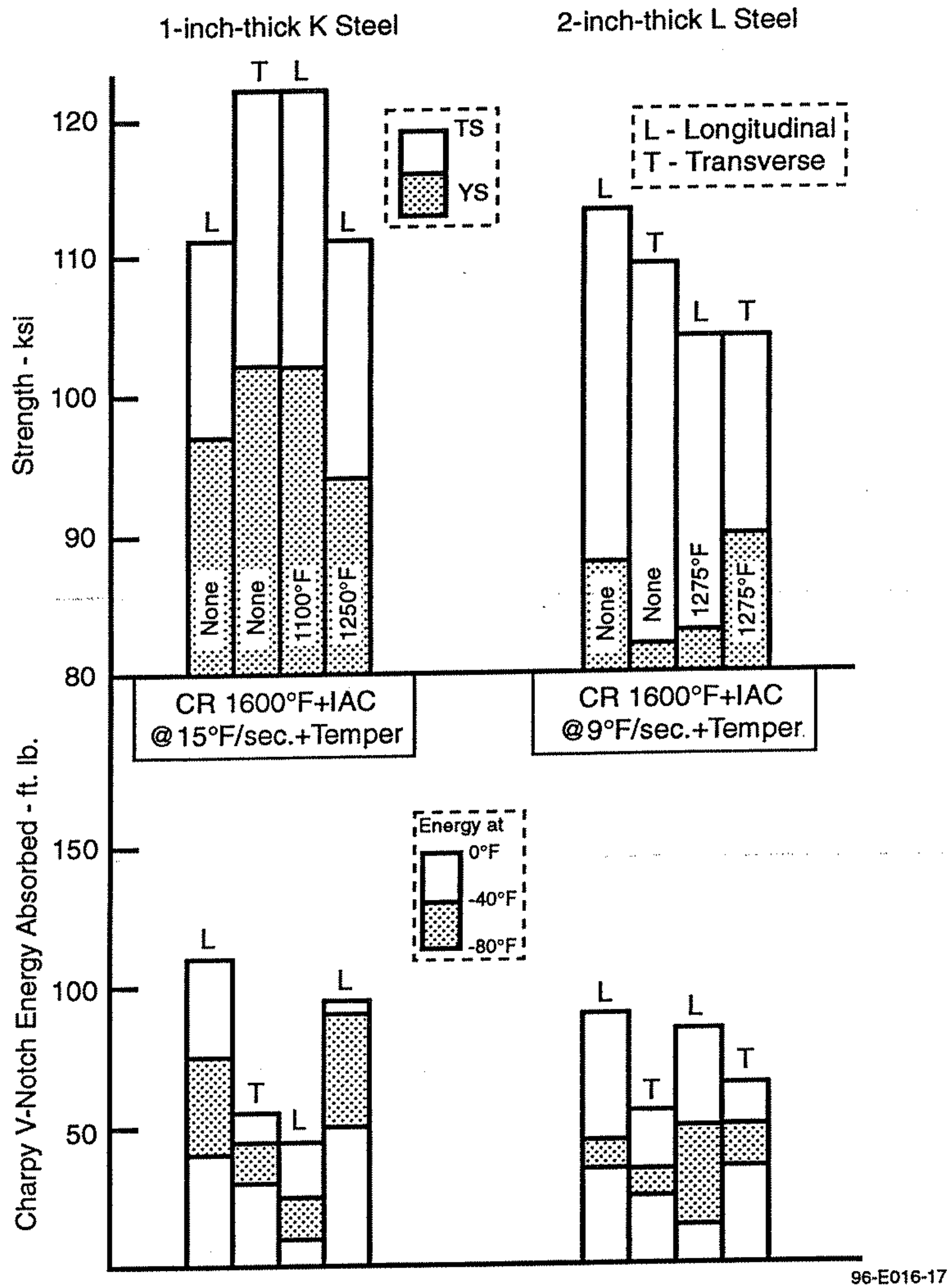


Figure 15 Strength and Toughness Properties for Interrupted Accelerated Cooling of 1-inch-thick Steel K and 2-inch-thick Steel L

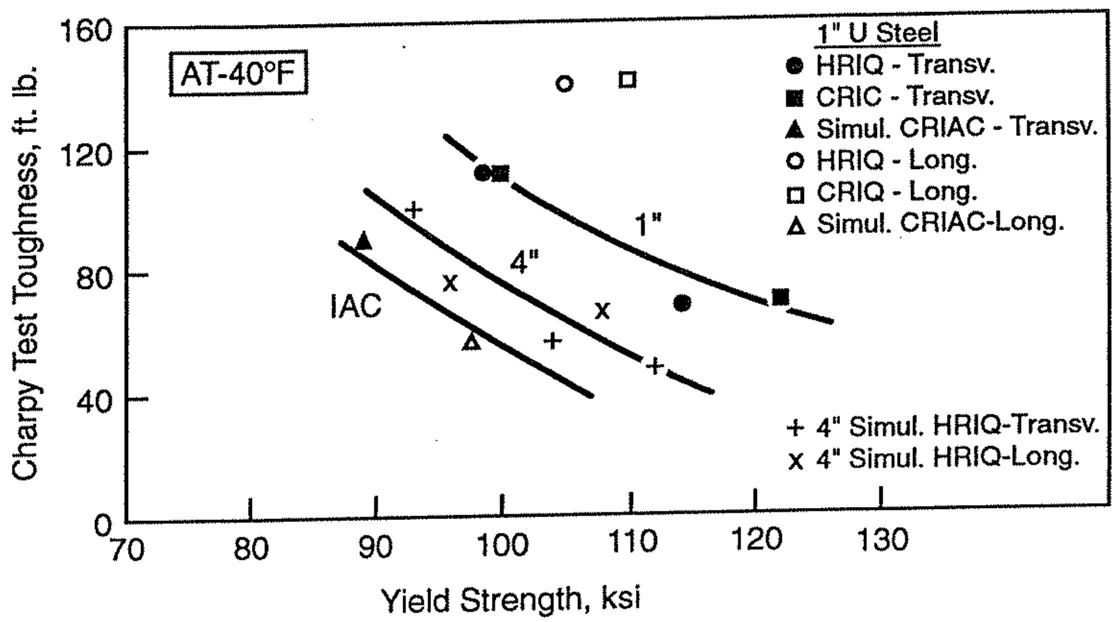


Figure 16a Yield Strength vs Notch Toughness of Steel U

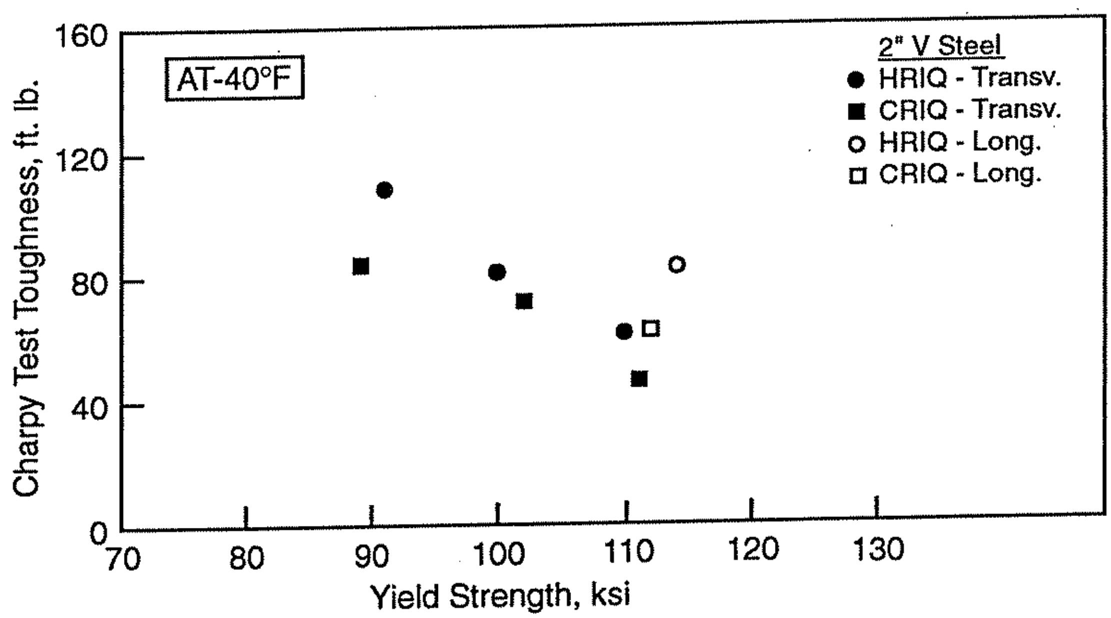


Figure 16b Yield Strength vs Notch Toughness of Steel V

96-E016-9

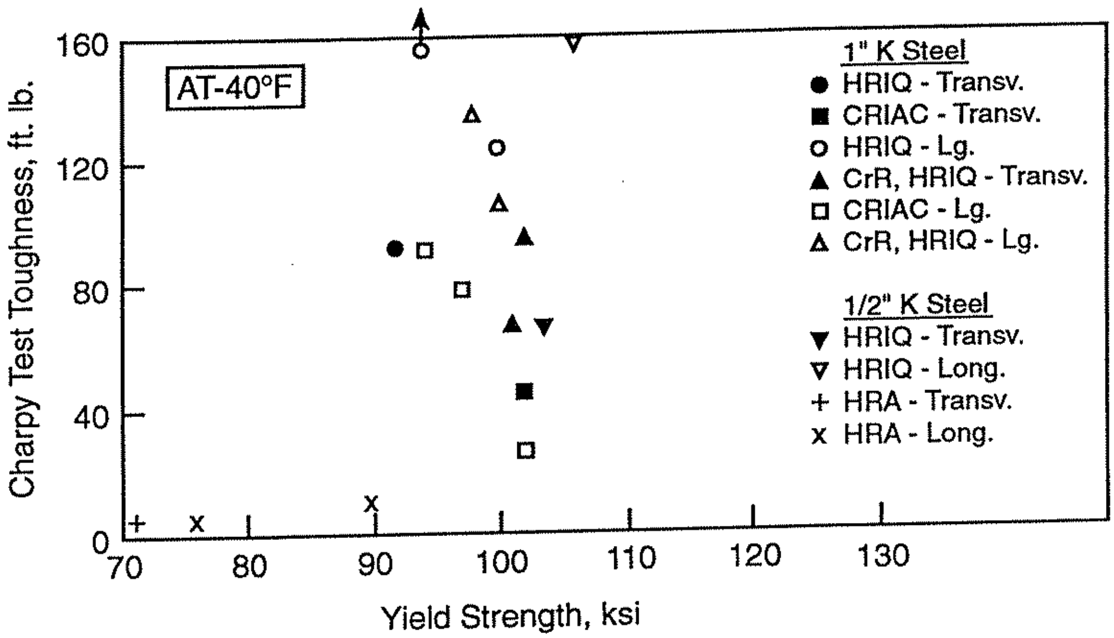


Figure 17A Yield Strength vs Notch Toughness of Steel K

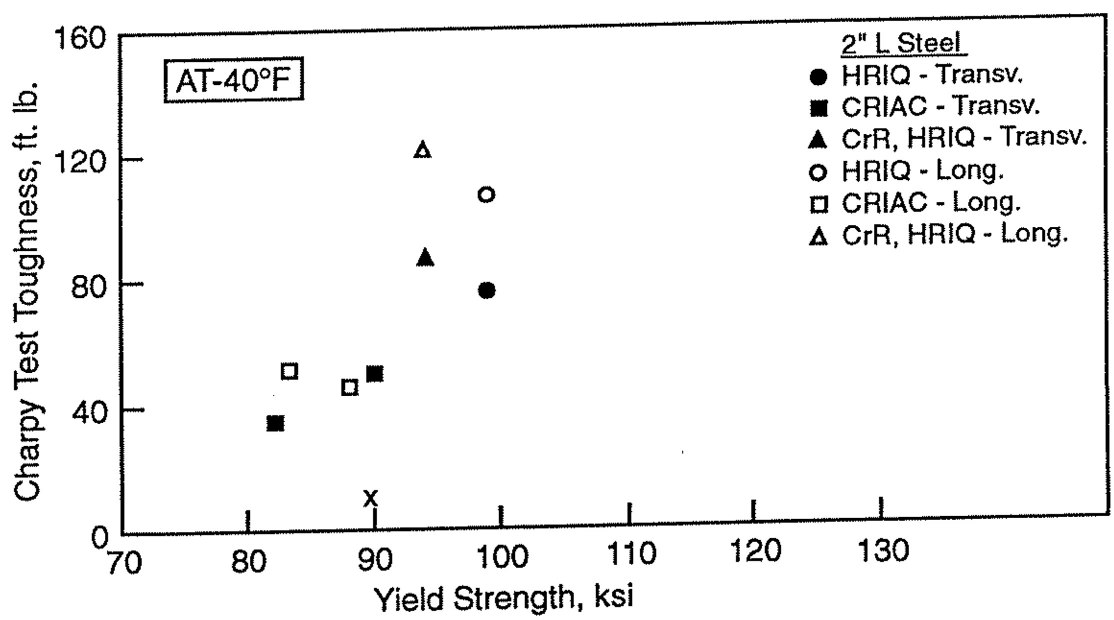


Figure 17B Yield Strength vs Toughness of Steel L

96-E016-8

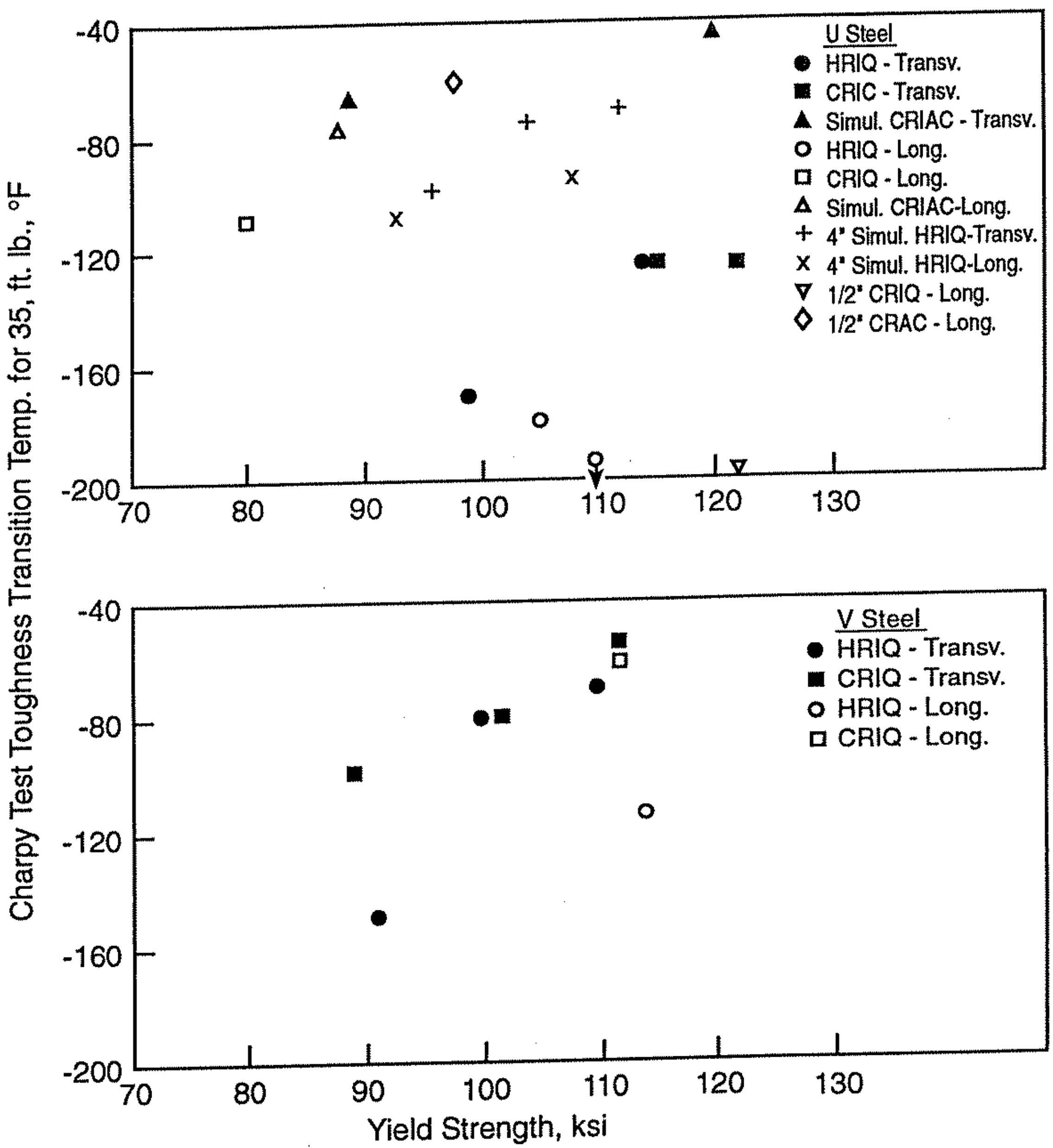


Figure 18 Charpy Transition (35ft.-lb.) Temperature for Various Treatments of U and V Steels

96-E016-10

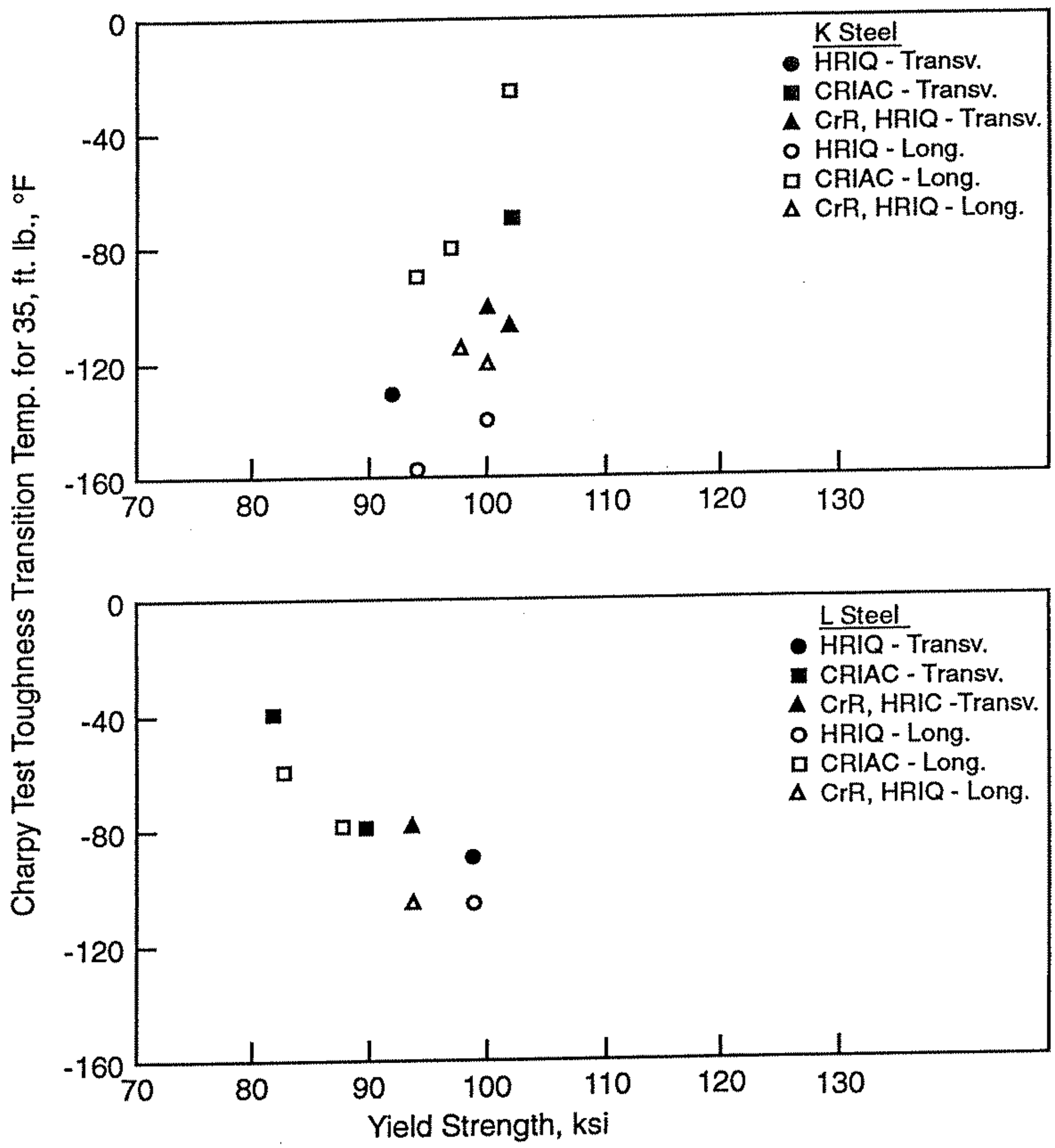


Figure 19 Charpy Test Transition Temperature for Various Treatments of K and L Steels

96-E016-11

Steel V

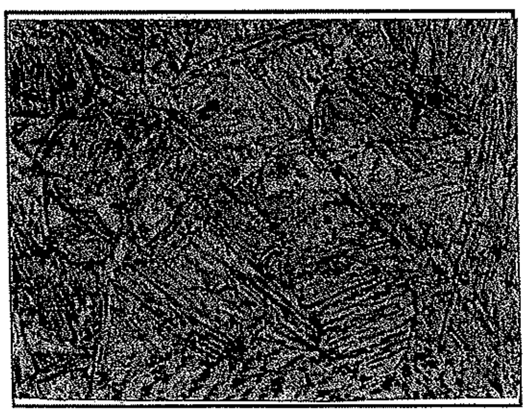
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al	N
0.073	1.49	0.015	0.005	0.23	0.95	0.75	0.50	0.50	0.059	0.022	0.034	0.0064

1/16" From Quenched-End

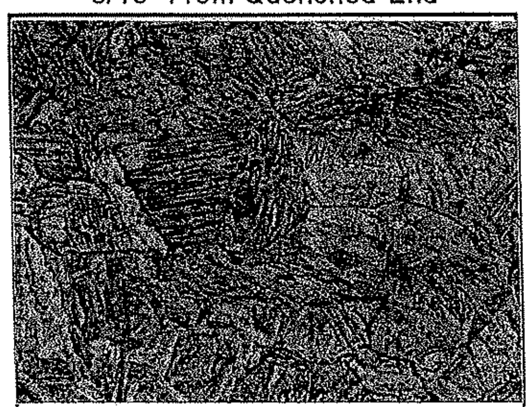
2/16" From Quenched-End

3/16" From Quenched-End

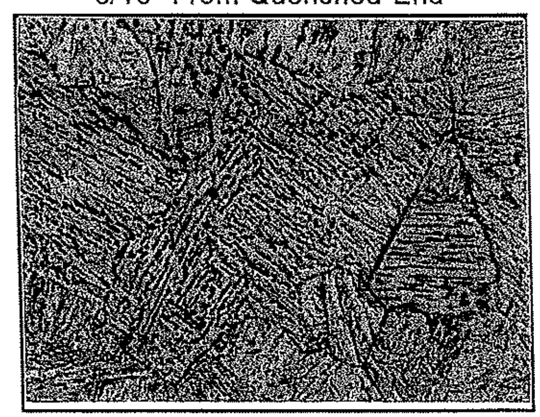
4/16" From Quenched-End



5/16" From Quenched-End



6/16" From Quenched-End



X1000 Nital-Picral

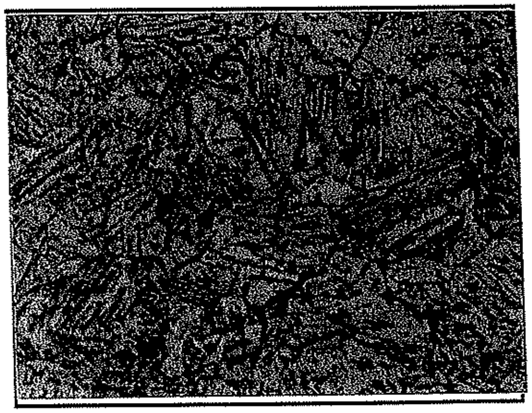
95-D057-1

Figure 20A Steel V Jominy End Quenched Hardenability Microstructures

Steel V

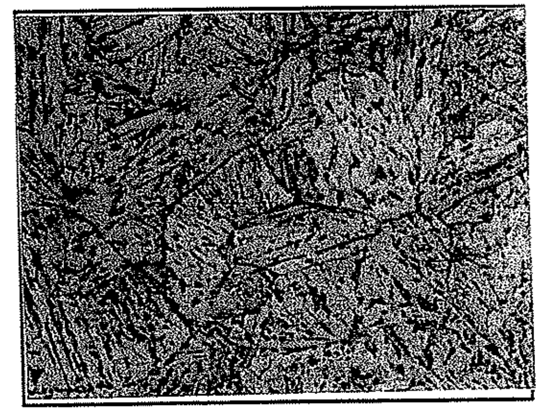
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al	N
0.073	1.49	0.015	0.005	0.23	0.95	0.75	0.50	0.50	0.059	0.022	0.034	0.0064

7/16" From Quenched-End

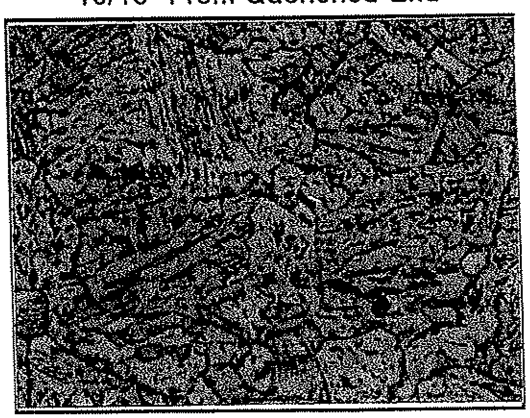


8/16" From Quenched-End

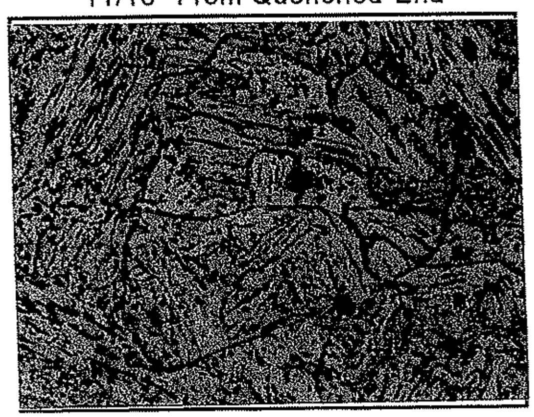
9/16" From Quenched-End



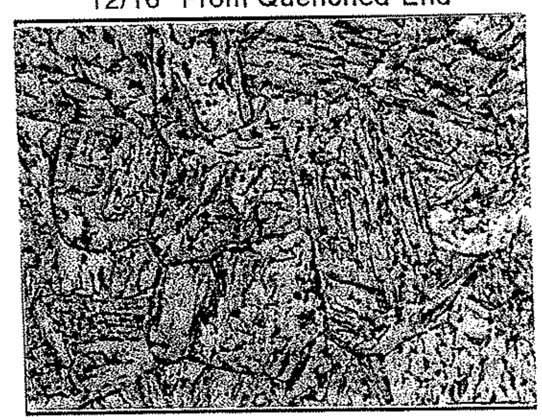
10/16" From Quenched-End



11/16" From Quenched-End



12/16" From Quenched-End



X1000 Nital-Picral

Figure 20B Steel V Jominy End Quenched Hardenability Microstructures

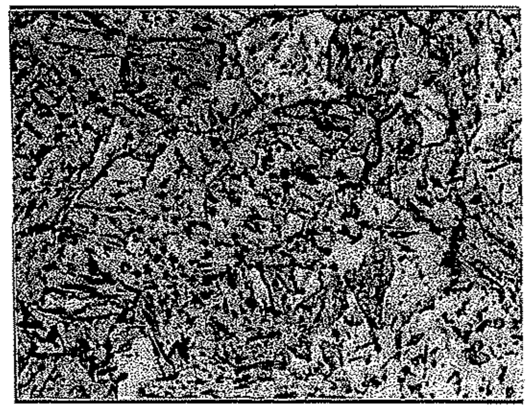
95-D057-2

Steel V

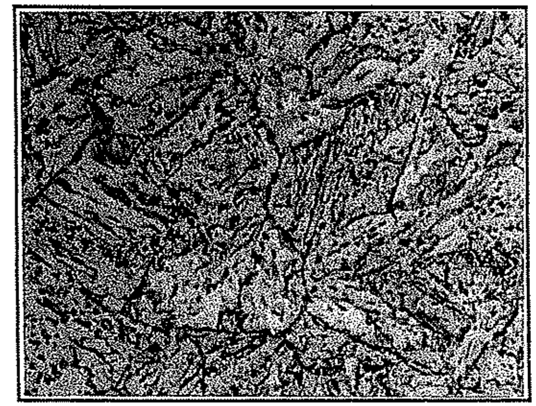
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al	N
0.073	1.49	0.015	0.005	0.23	0.95	0.75	0.50	0.50	0.059	0.022	0.034	0.0064

13/16" From Quenched-End

14/16" From Quenched-End



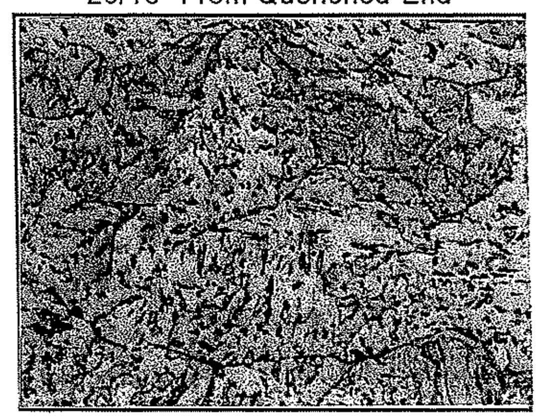
15/16" From Quenched-End



16/16" From Quenched-End

18/16" From Quenched-End

20/16" From Quenched-End



X1000 Nital-Picral

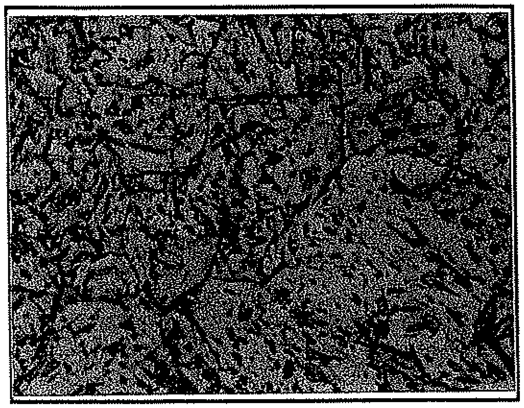
95-D057-3

Figure 20C Steel V Jominy End Quenched Hardenability Microstructures

Steel V

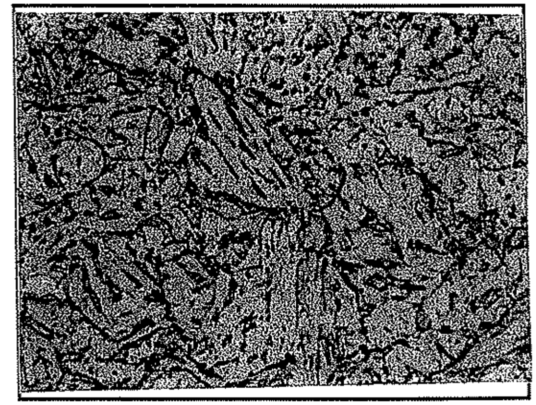
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al	N
0.073	1.49	0.015	0.005	0.23	0.95	0.75	0.50	0.50	0.059	0.022	0.034	0.0064

22/16" From Quenched-End



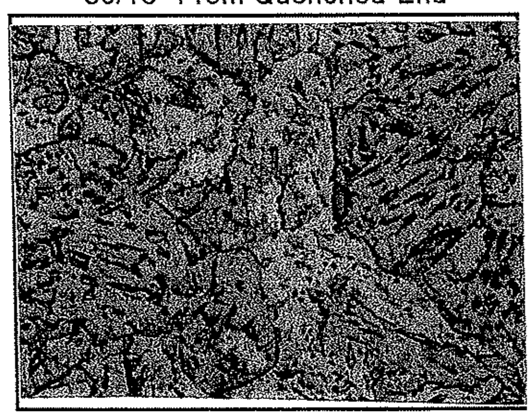
24/16" From Quenched-End

26/16" From Quenched-End



28/16" From Quenched-End

30/16" From Quenched-End



32/16" From Quenched-End

X1000 Nital-Picral

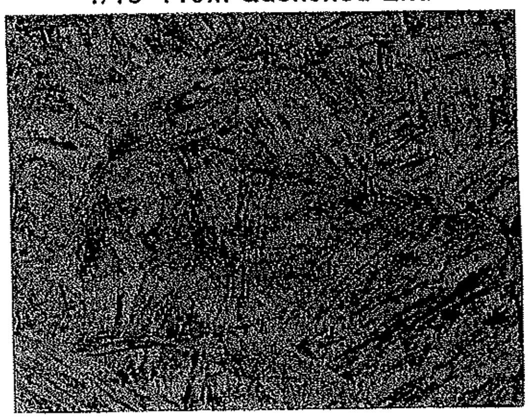
95-D057-4

Figure 20D Steel V Jominy End Quenched Hardenability Microstructures

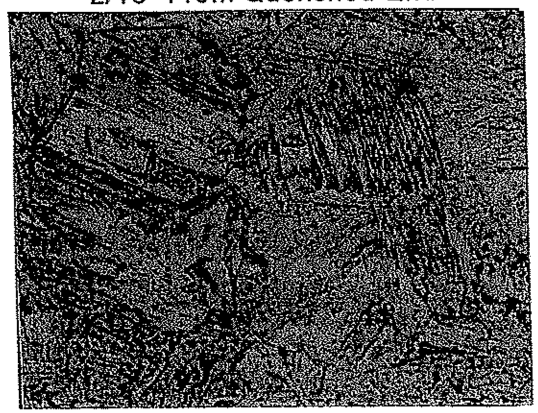
Steel L

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al	N
0.060	1.20	0.014	0.0054	0.25	0.995	0.75	0.50	0.26	0.060	0.015	0.022	0.0072

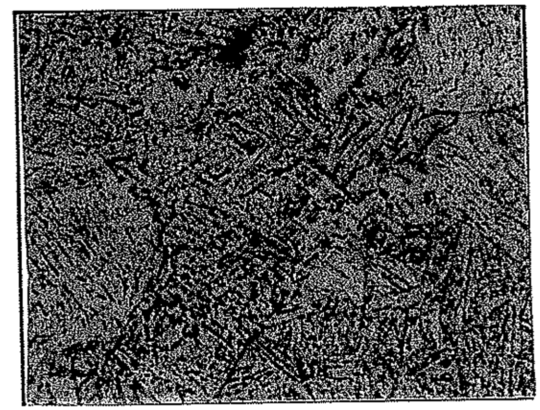
1/16" From Quenched-End



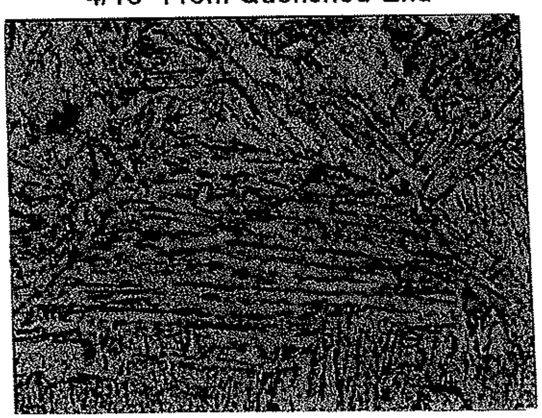
2/16" From Quenched-End



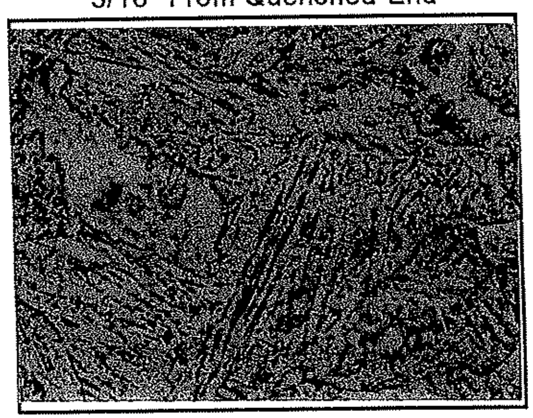
3/16" From Quenched-End



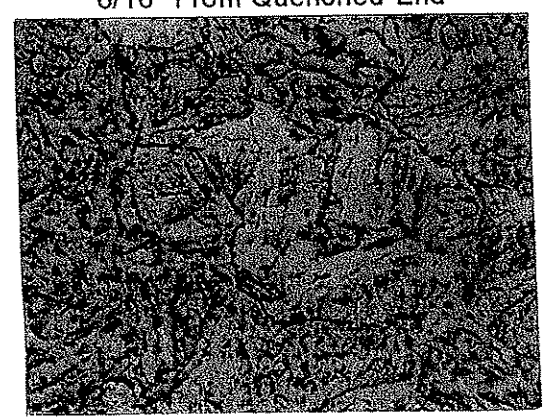
4/16" From Quenched-End



5/16" From Quenched-End



6/16" From Quenched-End



X1000 Nital-Picral

95-D057-25

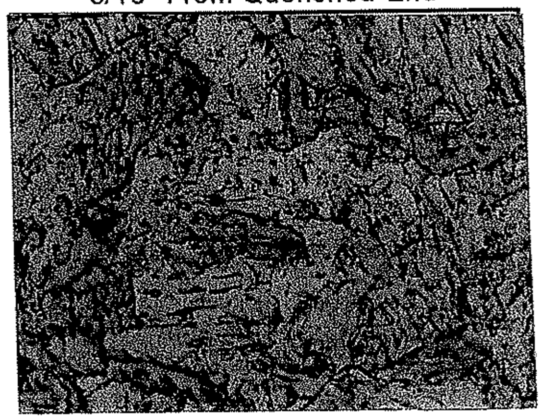
Figure 21A Steel L Jominy End Quenched Hardenability Microstructures

Steel L

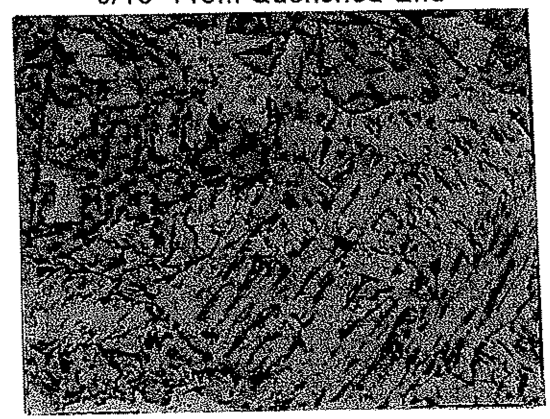
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al	N
0.060	1.20	0.014	0.0054	0.25	0.995	0.75	0.50	0.26	0.060	0.015	0.022	0.0072

7/16" From Quenched-End

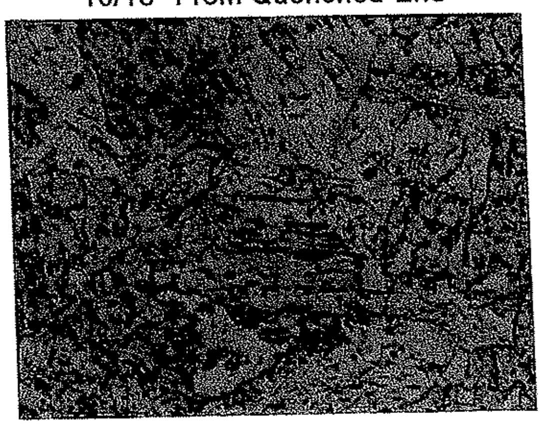
8/16" From Quenched-End



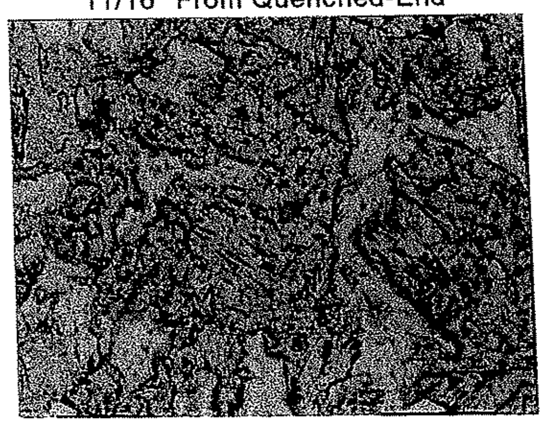
9/16" From Quenched-End



10/16" From Quenched-End



11/16" From Quenched-End



12/16" From Quenched-End

X1000 Nital-Picral

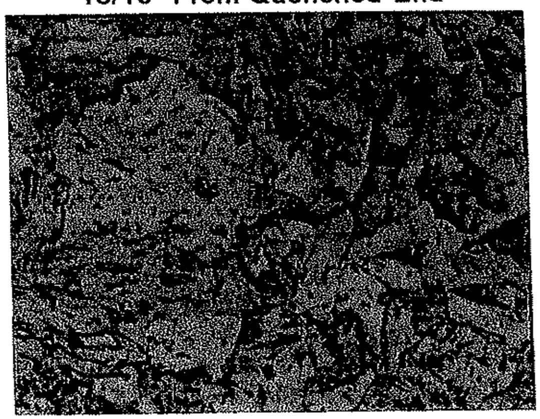
95-D057-26

Figure 21B Steel L Jominy End Quenched Hardenability Microstructures

Steel L

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al	N
0.060	1.20	0.014	0.0054	0.25	0.995	0.75	0.50	0.26	0.060	0.015	0.022	0.0072

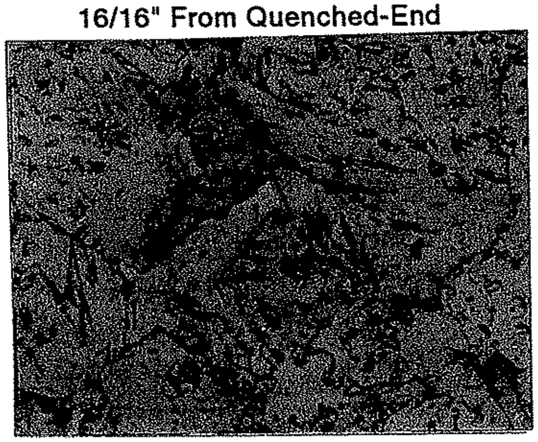
13/16" From Quenched-End



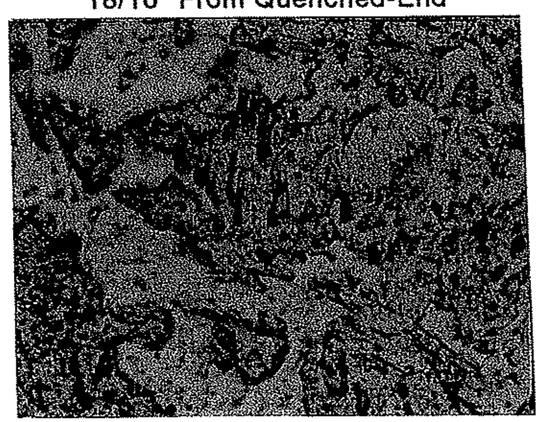
14/16" From Quenched-End

15/16" From Quenched-End

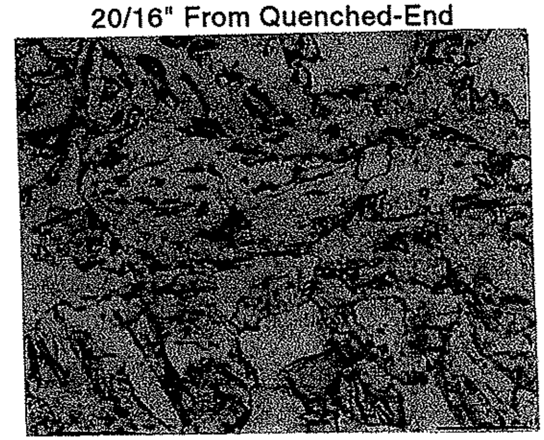
16/16" From Quenched-End



18/16" From Quenched-End



20/16" From Quenched-End



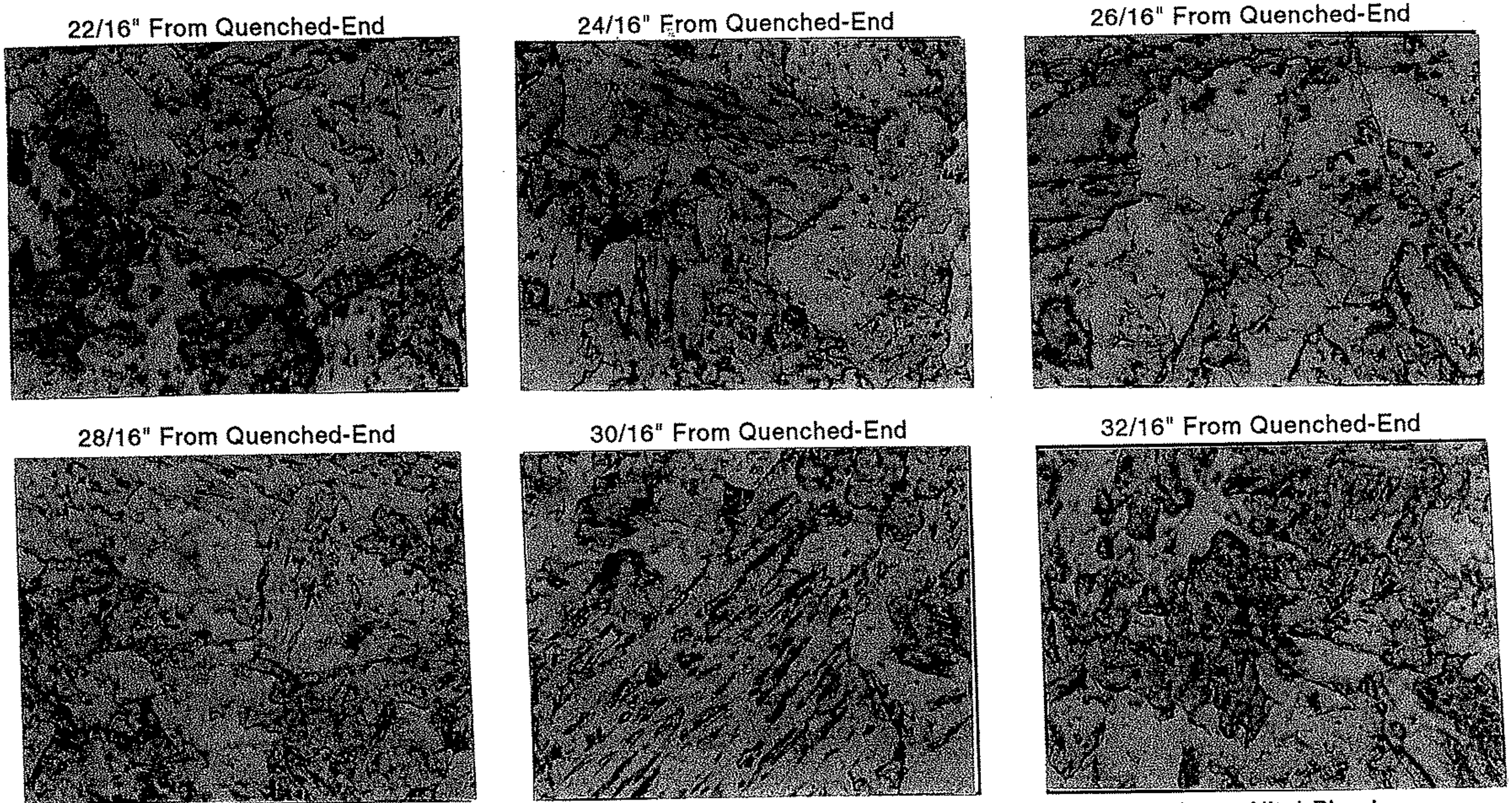
X1000 Nital-Picral

95-D057-27

Figure 21C Steel L Jominy End Quenched Hardenability Microstructures

Steel L

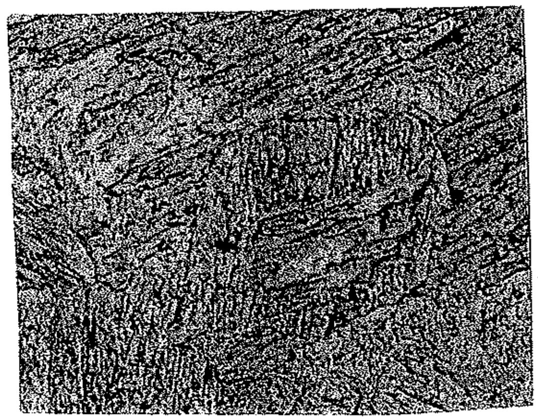
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Al	N
0.060	1.20	0.014	0.0054	0.25	0.995	0.75	0.50	0.26	0.060	0.015	0.022	0.0072



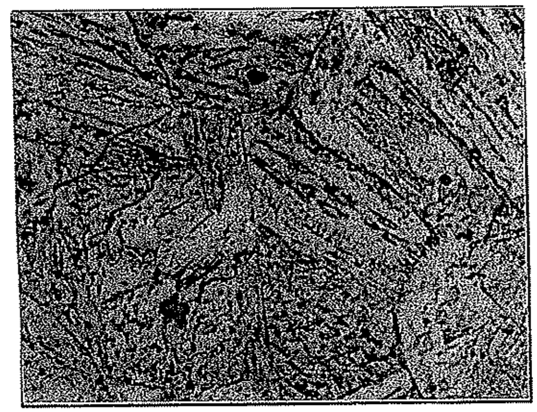
95-D057-28

Figure 21D Steel L Jominy End Quenched Hardenability Microstructures

Higher Hardenability



1" Plate (As Quenched)



2" Plate (As Quenched)

Lower Hardenability

1" Plate (As Quenched)

2" Plate (As Quenched)

Figure 22 Microstructures of Higher and Lower Hardenability 1-and2-inch Thick As-Quenched Steel Plates. (x1000 picral-nital)

95-D057-49