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Lehigh University

ATLSS Studies on Chemical Composition and Processing of High Performance Steels

Report to FHWA - AISI

Steering Committee - High Performance Steel

by

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ABSTRACT

The need for improved steels for the US infrastructure including bridges is well documented in the Civil Engineering Research Foundation (CERF) Report 94-5011, "Materials for Tomorrow's Infrastructure: A Ten-Year Plan for Deploying High-Performance Construction Materials and Systems." High Performance Steels (HPS) are defined as steels having a better combination of characteristics than existing steels with respect to one or more of the following: strength, yield-tensile ratio, fracture toughness, ductility, weldability, uniformity, corrosion resistance, and fatigue life. For bridges, increasing the yield strength from the established 50-ksi level to the 70-ksi and 100-ksi level has been the primary thrust for developing HPS. Currently, AASHTO does not recognize a 70-ksi yield-strength steel and the welding restrictions for A514 steels significantly increase fabrication costs. Therefore, the weight saving associated with increased strength has generated significant interest in 70-ksi and 100-ksi yield-strength bridge steels that can be welded without preheat and with adequate toughness for fracture-critical members.

One promising approach to improved weldability has been to lower the carbon content and offset the loss in strength by thermomechanical controlled processing (TMCP) of plate during the rolling from slab to plate. The ATLSS program to develop HPS for bridges has explored in some depth the benefits of various TMCP practices along with selection of appropriate chemical compositions.

The TMCP practices explored included controlled-rolling and direct quenching (CRDQ), conventional-rolling with air-cooling quenching and tempering (HRAQ), and controlled-rolling with air-cooling quenching and tempering (CRAQ). Steels included a low-carbon 5Ni-Cr-Mo-V steel with a minimum yield strength of 130 ksi, variants of both A514-F and A710 steels with yield strengths of about 100 ksi, and modified A852 steels with yield strengths of about 70 ksi. Evaluation criteria included weldability and hardenability test results, yield strength, yield-tensile ratio, and toughness relationships, metallographic exams, and anisotropy effects.

A number of conclusions and recommendations are presented. Among them, CRDQ processing raises yield strength at the cost of transverse notch toughness, produces coarse elongated grains, and results in yield-tensile ratios of at least 0.93. In contrast, CRAQ processing produces better notch toughness than CRDQ at the same yield strength levels. Overall, the studies indicate that controlled rolling with an off-line heat treatment should be considered an alternative viable means of producing high performance steels suitable for bridge applications.

INTRODUCTION

The need for improved steels for the US infrastructure including bridges is well documented in the Civil Engineering Research Foundation (CERF) Report 94-5011, "Materials for Tomorrow's Infrastructure: A Ten-Year Plan for Deploying High-Performance Construction Materials and Systems." High Performance Steels (HPS) are defined as steels having a better combination of characteristics than existing steels with respect to one or more of the following: strength, yield-tensile ratio, fracture toughness, ductility, weldability, uniformity, corrosion resistance, and fatigue life. For bridges, increasing the yield strength from the established 50-ksi level to the 70-ksi and 100-ksi level has been the primary thrust for developing HPS. Currently, AASHTO does not recognize a 70-ksi yield-strength steel and the welding restrictions for A514 steels significantly increase fabrication costs. Therefore, the weight saving associated with increased strength has generated significant interest in 70-ksi and 100-ksi yield-strength bridge steels that can be welded without preheat and with adequate toughness for fracture-critical members.

One promising approach to improved weldability has been to lower the carbon content and offset the loss in strength by thermomechanical controlled processing (TMCP) of plate during the rolling from slab to plate. The ATLSS program to develop HPS for bridges has explored in some depth the benefits of various TMCP practices along with selection of appropriate chemical compositions. The results of those studies are presented in this report.

BACKGROUND

Composition and Processing of 5Ni-Cr-Mo-V Steel

Although this first TMCP study was not directed at bridge steels, it was very instructive in identifying promising TMCP practices. The objective was to eliminate the need for welding preheat by reducing the carbon content from an average of 0.11 percent to values in the range of 0.04 to 0.07 percent (Table I) and still meet the minimum yield strength of 130 ksi by controlled-rolling and direct-quenching (CRDQ) the plates. After tempering, the yield strength of the CRDQ plates averaged 14 ksi higher for one-inch thick plate and 9 ksi higher for 2-inch thick plates than those that were conventionally rolled, air-cooled, and quenched and tempered (HRAQ). The strength-toughness relationships for CRDQ and HRAQ processing are compared in Figure 1 for Charpy V-notch energy absorptions at 30F and -120F. Unless otherwise noted, all tensile and Charpy specimens were machined from plates in the transverse direction. To determine whether the increased strength was the result of controlled rolling or direct quenching, plates were control-rolled, air-cooled, and then quenched and tempered (CRAQ). The results, also shown in Figure 1 by the individual points, indicate that, for this steel, the yield strength can be increased by CRAQ processing and that the strength-toughness relation for CRAQ processing is similar to that for CRDQ processing for Charpy tests run at 30F and may be somewhat better for Charpy tests run at -120F. As a result of these data, CRAQ processing was made a standard TMCP practice in subsequent bridge-steel studies, an approach that had received limited previous attention.

Weldability Tests

The weldability tests on the 5Ni-Cr-Mo-V steels were run to determine if the lowered carbon would permit welding without preheat and at low heat inputs, which in conventional 5Ni-Cr-Mo-V steels can cause heat-affected zone (HAZ) hydrogen-assisted cracking. The testing method employed was the implant test.

For the implant tests multiple specimens were prepared and welded into supporting plates with the GMA, SMA and GTA processes at a heat input of 35 kilojoules per inch. Filler metals of solid 0.045 inch diameter 140s were used for the GMA process, and 1/8-inch diameter E14018 covered electrodes were used for the SMA process. Because all failures occurred in the weld metal, GTA welds were produced without added filler metal in both 75%Ar-25%He and 90%Ar-4%H_2 to introduce low and high potentials of H in the arc atmosphere. The results are shown in Figure 2. It is evident that the cracking thresholds are controlled only by the welding filler metals and atmospheres. No HAZ hydrogen-assisted cracks were produced in these tests.

These tests indicate that 5Ni-Cr-Mo-V steel can be welded without preheat when the carbon content is reduced from a typical value of 0.11 percent to 0.04 to 0.07 percent.

INITIAL STUDIES ON 100 KSI YIELD-STRENGTH STEELS

Chemical Composition and Processing

The chemical composition of the steels melted for this study are listed in Table II. Steel C is a low-carbon boron-free modification of A514-F and Steels D,E and F are variants of A710 steel. Boron was omitted in Steel C because of its embrittling effect noted previously in very low carbon steels. The steels were melted as 500-pound heats, rolled to 3 1/2-inch thick slabs, cut into five pieces, and cross-rolled to 1-inch thick plate. For each steel, the five pieces were reheated and one slab was conventionally rolled to about 1900F and air-cooled (HRA), one was control-rolled to 1700F and direct-quenched (CRDQ-17), one was control-rolled to 1500F and direct-quenched (CRDQ-15), one was control-rolled to 1700F and air-cooled (CRA-17), and one was control-rolled to 1500F and air-cooled (CRA-15).

After the preceding processing, the HRA and CRA plates were austenitized at 1650F and quenched to simulate commercial spray quenching (HRAQ and CRAQ). Samples from the HRAQ, CRAQ and CRDQ plates were then tempered at one or more temperatures selected from hardness-tempering temperature data. Tempered samples were machined into transversely oriented tensile and Charpy specimens and then tested. Specimens for weldability tests were also prepared and tested.

Because the toughness of the CRDQ Charpy specimens was extremely poor, particularly for Steel C, additional CRDQ samples were austenitized, quenched and tempered to attempt to restore the toughness. So that the effect of this second heat treatment could be compared for all processing conditions, HRAQ and CRAQ plates were given a second quench and temper. Mechanical-property tests were then conducted as previously described.

Mechanical Property Tests

The mechanical properties (transverse) of the four steels are listed in Tables III through VI. From the tables representative tensile and Charpy values were selected and compared in Figure 3. As shown, CRDQ processing resulted in significantly increased strength compared with conventional processing (HRAQ) but dramatically reduced toughness, particularly for Steel C, and the effects were about the same for control-rolled finishing temperatures of 1500F and 1700F. On average, CRAQ processing increased the strength and improved the toughness compared to HRAQ processing. Note that the failure to show this strengthening for Steel F was the result of choosing the CRAQ results for 1300F tempering, which also resulted in very good toughness.

In general, CRDQ processing also resulted in very high yield-strength to tensile-strength ratios in the range 0.92 to 0.98. In some applications, ratios this high may be unacceptable. High ratios were also observed for HRAQ and CRAQ processing but not as high on average as for CRDQ processing. Note that when CRAQ specimens for Steel F were tempered at 1300F, the ratio fell to 0.84. Tempering close to the lower critical temperature and intercritical treatments are being investigated as a means to control the yield-tensile ratio.

The effect of CRDQ processing on toughness is apparently in the form of an increase in the transition temperature. For Steel C, which had the highest transition temperature for HRAQ processing, the CRDQ processing shifted the transition temperature so that brittle behavior occurred even at 0F. As hardenability increased from Steels C to D to E to F, the HRAQ transition temperatures were progressively lower. Therefore, the CRDQ transition-temperature shift did not result in low Charpy energy values until lower test temperatures were reached.

Effect of Second Heat Treatment

As previously noted, CRDQ plates were austenitized, quenched and tempered after controlled rolling and direct quenching in an effort to improve toughness. For comparison, HRAQ and CRAQ plates were also heat-treated a second time. The effect of the second heat treatment is shown in Figure 4. Generally, the second heat treatment resulted in a small loss in strength but a marked improvement in toughness, particularly for the CRDQ plates for Steel C. The toughness improvement is smaller for the other steels and conditions.

As previously noted, these effects are related to a shift in the transition temperature. For example, CRDQ processing of Steel C raised the transition temperature compared to the HRAQ base condition so that brittle behavior was observed at 0F. The second heat treatment reduced the deleterious effect of CRDQ processing and significantly improved toughness. This effect was less for the other three steels, which had increasing alloy content, increasing hardenability, and increasingly tougher transformation products in all conditions, taking into account, changes in strength.

Hardenability Results

The Jominy end-quench hardenability test results are shown in Figure 5. Also shown are the distances from the quenched end corresponding approximately to the cooling rates for commercial spray-quenching of 1-, 2-, 3-, and 4-inch-thick plates, and a horizontal line at HRc20 which corresponds to a tensile strength of 110 ksi and a yield strength of approximately 100ksi based on an assumed yield-tensile ratio of 0.91. These results suggest that on a strength basis HRAQ processing Steel C is suitable for 1-inch-thick plate, Steel D is suitable for 1-inch-thick plate and marginally for 2-inch-thick plate, whereas Steels E and F are suitable through 4-inch-thick plate. To increase the thickness suitability for Steel C, some form of controlled processing would be required. At a yield strength of 90 ksi, tensile strength of 99 ksi, which corresponds to HRc16, Steel D appears suitable through 4 inches.

Yield-Strength-Toughness Relationships

The relationship between the yield strength and Charpy V-notch energy absorbed at -40F for Steels C, D, E and F is illustrated in Figures 6 and 7. With some scatter, the points show a continuous downward trend in toughness with increased yield strength. As previously noted, the lowest toughness is associated with the CRDQ processed plates. Thus for Steels C and D, raising the yield strength by CRDQ processing to meet a yield-strength minimum of 100 ksi results in unacceptably low toughness. The same trend is observed for Steels E and F, except that the borderline toughness is for yield strengths far above 100ksi. For these steels, CRDQ processing is not required to meet a yield strength of 100 ksi, and both HRAQ and CRAQ processing resulted in yield strengths above 100 ksi and good toughness. These results again demonstrate that raising the yield strength by means of CRDQ processing is most effective for higher hardenability steels that transform upon quenching to low-temperature transformation products having inherent relatively high toughness such that CRDQ processing does not embrittle the steel at -40F.

Metallographic Evaluation

The micrographs for Steels C, D, E and F in the as-quenched condition are shown in Figures 8, 9, 10 and 11, respectively. These micrographs best illustrate the type of transformation products and grain size and shape that resulted from the various processing procedures. As shown, CRDQ processing resulted in highly elongated grains in the final rolling direction and a large grain size averaging about ASTM 5. The grain size was slightly finer for the plates finished at 1500F than for those finished at 1700F. This microstructure indicates that no recrystallization of the austenite occurred after controlled rolling and before direct quenching, which immediately followed rolling. This result is evident for both 1500F and 1700F finishing temperatures, and demonstrates that a significant time lapse between rolling and quenching is required to recrystallize austenite.

As a result of CRDQ processing, the elongated grains provided an easy failure path, which coupled with the large grain size, markedly reduced the toughness of transversely tested Charpy specimens. Consequently, transverse toughness tests should be chosen over longitudinal tests to provide a conservative estimate unless the application clearly obviates the need for transverse testing. Even poorer toughness in the through-thickness direction that could result in laminar tearing should be recognized for applications wherein attachments are welded to the plate face or in similar situations.

CRAQ processing also resulted in elongated grains after air cooling (CRA); however equiaxed grains were produced by the subsequent austenitizing and quenching. HRAQ processing also resulted in equiaxed grains. The grain size resulting from HRAQ and CRAQ processing averaged ASTM 7 to 8. As discussed later, elimination of elongated grains after controlled rolling may require an extended high-temperature hold after rolling or a subsequent austenitizing treatment.

The dominant microconstituent in Steel C was bainite. Steels D, E, and F contained essentially bainite and martensite with increasing amounts of martensite as the hardenability increased from Steels D to E to F.

Effect of Carbon Content on Modified A514-F Steel

Because the source of the poor properties of 0.07 percent carbon A514-F steel was not obvious, the low carbon content as a factor was examined by comparison with a heat of 0.11 percent C melted and processed by CRDQ and CRAQ practices. In addition to standard processing, plates were also given a second austenitizing, quenching and tempering treatment. Mechanical-property and weldability tests were conducted as previously described. The chemical composition of the steel, Steel G, is listed in Table II, which shows that Steels C and G are essentially identical except for the carbon content. Increasing the carbon content increased the hardenability of Steel G compared with Steel C, Figure 5.

The mechanical properties for Steel G are listed in Table VII, and representative values are compared in Figure 12 with corresponding values for Steel C from Table III. In general, the yield and tensile strength for Steel G were higher than those for Steel C but the energy values were lower after the standard first heat treatment, and CRDQ processing destroyed the toughness for Steel G as for Steel C and for the same reasons previously described for Steel C. As previously noted for Steel C, CRAQ processing resulted in the best balance of strength and toughness after the first treatment. When the CRDQ plates were austenitized and quenched and tempered (second heat treatment), the yield strength was reduced and the toughness greatly improved.

The relation of toughness to yield strength for Steels C and G is compared in Figure 13, which illustrates the general decrease in toughness with increasing yield strength. Although the yield strengths for Steel G are higher than those for Steel C, the relation between yield strength and toughness are essentially the same for both steels. Therefore, the increase in carbon from 0.07 percent to 0.11 percent does not appear to have significantly changed the strength-toughness relation.

Weldability Tests

Open-end slotted restraint specimens as shown in Figure 14 were conducted on one-inch thick plates of Steels C,D, E and F. Weld beads starting at the open end of the slot were deposited at 25 kilojoules per inch with a 75F preheat and two filler metals: 3/16-inch diameter E12018 and 0.045-inch diameter metal-core MC100. As shown in Table VIII cracking was confined to the centerline of the E12018 weld metal. No cracks were found in the tests with MC100 filler metal.

Implant tests were conducted with the same two filler metals also at 75 F preheat and 25KJ per inch heat input. The data from these tests are shown in Figures 15 and 16. The results for all four steels welded with E12018 were essentially the same with the threshold stress hovering around 100 ksi. The MC100 electrode displayed slightly higher thresholds than the E12018, but it is evident that the thresholds were weld metal-limited and virtually independent of the base metal compositions.

Interim Conclusions and Future Work

Thermomechanical controlled processing has significant potential for increasing strength but with potentially negative effects on toughness, particularly for low hardenability steels such as Steels C and G. Because of the interest in lower hardenability lower cost steels, additional heats of slightly modified Steels C and D were melted and thermomechanically processed to determine their suitability for 100-ksi yield-strength bridge steels.

ADDITIONAL TMCP STUDIES OF HIGH-PERFORMANCE STEELS

100-ksi Yield-Strength Bridge Steels

Two 500-pound heats of a 0.065C A514-F (containing boron) and a modified A710 steel were vacuum-melted and processed by HRA, CRDQ, and CRA practices to 1-inch-thick plate. Initially the CRDQ and CRA plates were finish-rolled at 1600F. Subsequently, CRDQ plates were finish-rolled at 1725F with the objective of improving toughness, and CRA plates were finish-rolled at 1500F with the objective of improving strength. The chemical composition of the two steels, identified as Steels N and P, are listed in Table IX. The HRA and CRA plates were austenitized and quenched and all plates were tempered at one or more tempering temperatures. The tempered plates were machined into transverse and a limited number of longitudinal tensile and Charpy V-notch specimens and then tested. In addition, weldability, implant-test, Jominy-test and metallographic specimens were prepared and tested.

Mechanical-Property-Test Results

The mechanical-property data for Steels N and P are listed in Tables X and XI. Selected values for Steels N and P are compared in Figure 17. The comparison shows that CRDQ processing resulted in poor toughness, at the finish rolling temperature of 1600F, particularly for Steel N. To improve toughness, CRDQ plates were finish-rolled at 1725F with the aim of promoting recrystallization. This increase in finish-rolling temperature did not significantly change either the strength or toughness. To increase the strength of the CRAQ plates finish-rolled at 1600F, plates were finish rolled at 1500F. Again, the decrease in finish-rolling temperature did not significantly change either the strength or toughness. These results suggest that CRDQ or CRAQ processing may not depend as much on finish rolling in the range 1500F to 1725F with respect to strength and toughness as previously thought.

The relation between yield strength and Charpy energy absorption is illustrated in Figure 18 for Steels N and P, and it conforms to the previously observed decreasing toughness with increasing strength. In general, the relation was slightly better for Steel P than for Steel N.

Anisotropy Effects

The mechanical properties previously discussed were for transversely oriented test specimens. Because CRDQ processing results in elongated grains, tensile and Charpy tests were also conducted on longitudinally oriented specimens to determine the effect of the grain orientation on isotropy. The results of these tests are also listed in Table X and XI. The effect of testing direction on the Charpy V-notch transition temperature is illustrated in Figure 19. The transition temperature for CRDQ processed Steel N plate is about 40 degrees higher for transverse specimens than for longitudinal specimens, but the difference is reduced to about 10 degrees by a second heat treatment. These results again demonstrate the need to consider anisotropy effects when determining the suitability of plates or fabricated members with respect to toughness requirements for specific applications. The selection of steel composition and/or processing practices can be significantly influenced by these effects.

Hardenability Results

The Jominy test results for Steels N and P are shown in Figure 20. The curve for Steel N shows much higher hardenability than that for Steel C. The difference is the result of adding boron to Steel N whereas Steel C did not contain boron because previous results indicated that boron may be deleterious to toughness in low-carbon (0.04 to 0.07%) steels. When boron-free Steel C also exhibited poor toughness, boron was added to Steel N to restore its hardenability. The curve for Steel P is not significantly different from Steel D, which is similar in composition.

On the previously described basis that HRc20 is a measure of suitability for a minimum yield strength of 100 ksi and HRc20 = HRa60, Steel N would appear potentially suitable in strength for 4-inch-thick plate whereas Steel P is again marginal at 2-inch-thick and could benefit from some form of processing that would increase strength.

Metallographic Evaluation of Steels N and P

The micrographs of Steels N and P were prepared from 1-inch-thick slices that were polished and etched on the longitudinal face parallel to the final rolling direction.

The HRA and CRA micrographs are compared in Figure 21. The prior austenite grains for Steels N and P in the HRA condition were equiaxed, whereas in the CRA condition, the grains were highly elongated in the final rolling direction. The grain size for both steels in both conditions was estimated to be about ASTM No. 5. The microstructure shown is typically bainite except that Steel P in the CRA condition also contained about 15 percent primary ferrite. These grain shapes indicate that finish-rolling at 1900F provides adequate time for austenite recrystallization whereas controlled-rolling down to 1600F does not.

The HRAQ, CRDQ and CRAQ micrographs are compared in Figure 22. Note that the HRA and CRA plates were off-line austenitized at 1650F and quenched, whereas the CRDQ plates were in-line quenched immediately after finish-rolling at 1600F. The prior austenite grains of the HRAQ and CRAQ samples were equiaxed and their size averaged about ASTM No. 7 to 8, indicating (1) that the austenite was refined from the prior grain size of 5 by reheating to 1650F and (2) that the prior elongated grains for the CRA plates were eliminated by the austenitizing treatment. Upon quenching from 1650F, the HRA and CRA plates transformed to bainite.

In contrast to the HRAQ and CRAQ microstructures, the prior austenite grams for the CRDQ plates were highly elongated when finish-rolled at 1600F and preserved to room temperature by quenching. The estimated grain sizes, about 5 for Steel N and 4 to 5 for Steel F, are similar to those for the HRA and CRA plates. The austenite of the CRDQ plates transformed to bainite and martensite when quenched from the 1600F finish-rolling temperature, a microstructure similar to that of the HRAQ and CRDQ plates.

The effect of finishing temperature is illustrated in Figure 23 for Steel N. The CRDQ finishing temperature was raised from 1600F to 1725F with the objective of improving toughness whereas the CRAQ finishing temperature was lowered from 1600F to 1500F with the objective of increasing strength. Neither change produced any significant change in strength or toughness, and the micrographs confirm that neither the grain size, grain shape nor transformation products were significantly affected by the changes in finishing temperature. The same results were observed for Steel P.

The effect of tempering on HRAQ, CRDQ and CRAQ plates is illustrated in Figure 24. The micrographs clearly show that the elongated grains resulting from CRDQ processing continue to exist after tempering at 1275F. The primary effect of tempering was to coalesce carbide particles.

STUDIES ON 70-KSI YIELD-STRENGTH BRIDGE STEELS

Chemical Composition and Processing

Three 500-pound heats of modified A852 steels were vacuum-melted and processed by HRA, CRDQ and CRA practices to 1-inch-thick plate. As for the 100-ksi plates, HRA plates were finish-rolled at 1900F, CRDQ plates were finish-rolled at 1600F and 1725F, and the CRA plates were finish-rolled at 1500F and 1600F. The chemical compositions of the three modified A852 steels are listed in Table IX. The HRA and CRA plates were austenitized and quenched and all plates were tempered at one or more temperatures. The tempered plates were machined into transverse and a limited number of longitudinal tensile and Charpy V-notch test specimens. In addition, weldability implant-test, Jominy-test and metallographic specimens were prepared and tested.

Mechanical-Property-Test Results

The mechanical properties for the three steels are listed in Tables XII, XIII and XIV for Steels R, S and T, respectively. Selected values for the three steels are compared in Figure 25. As illustrated, CRDQ processing significantly increased the strength of all three steels compared with that for HRAQ processing but with substantial loss in toughness. However, the increase in strength did not reduce the toughness to the same extent as for 100-ksi yield-strength steels and Steel R (0.066%C) retained more than 50 ft-lb down to -40F. Thus the yield strength could be raised well above the 70-ksi level while retaining acceptable toughness at a specification temperature of -30F. Even the lowest carbon steel, Steel R, met the 70-ksi minimum for HRAQ processing for 1-inch-thick plate. Thus CRDQ processing would be most beneficial for heavier gages, but CRDQ processing is less effective in raising strength as thickness increases and would not be expected to be effective beyond 2 inches in thickness. The increase in finishing temperature from 1600F to 1725F for CRDQ processing did not result in a major improvement in toughness. Likewise the decrease in finishing temperature from 1600F to 1500F for CRAQ processing did not markedly increase strength.

The relation between yield strength and Charpy V-notch energy absorbed at -40F is shown in Figure 26. A good correlation exists between yield strength and toughness, with no obvious advantage for Steel R (0.066%C), Steel S (0.10%C) or Steel T ().14%C). There is a small indication that CRAQ processing resulted in a better strength-toughness relation.

Hardenability Results

The Jominy curves for Steels R, S and T are illustrated in Figure 20. The hardenability was significantly influenced by the carbon content and was highest for Steel T. The horizontal line at HRa52.5 corresponds to a tensile strength of 80 ksi and a yield strength of 70 ksi for a yield-tensile ratio of 0.875, which was typical for the three steels. On that basis, Steel T should meet a minimum yield strength of 70 ksi in heavy sections whereas Steel R should meet it through 2 inches and Steel S through 2 1/2 inches, when properly quenched. The thickness capability of Steel R can be enhanced by CRDQ processing without reducing toughness below bridge specifications, but the extent to which CRDQ processing is effective beyond 2 inches is not known.

Metallographic Evaluation of Steels R, S and T

The micrographs of Steels R, S and T were prepared from 1-inch thick slices that were polished and etched on the face parallel to the final rolling direction.

The HRA and CRA micrographs are compared in Figure 27. The microstructures consisted of primary ferrite and fine pearlite. The pearlite colonies correspond to the carbon-enriched austenite that transformed after primary ferrite precipitation. The prior austenite grain size is estimated to have been about ASTM No. 4 for all conditions. HRA processing resulted in equiaxed prior austenite grains but CRA processing resulted in highly elongated prior austenite grains and pearlite colonies. Hot rolling to 1900F permitted austenite recrystallization whereas controlled-rolling down to 1600F did not. The decreasing amount of primary ferrite from Steel R to Steel S to Steel T is consistent with the increased carbon contents of 0.066, 0.10 and 0.14 percent, respectively.

The CRDQ and CRAQ micrographs are illustrated in Figure 28. CRDQ processing resulted in highly elongated prior austenite grains of about No. 4 size that transformed to primary ferrite in the grain boundaries and to bainite in the grain proper when in-line direct-quenched from 1600F. When the CRA plates, which had exhibited large elongated prior austenite grains, were austenitized at 1650F and quenched, the resulting microstructure was a fine-grained mixture of ferrite and bainite. The HRAQ microstructures (not shown) were similar to the CRAQ microstructures.

The effect of tempering on CRDQ and CRAQ plates is illustrated in Figure 29. The elongated grains that resulted from CRDQ processing were retained after tempering at 1275F. The primary effect of tempering was to coalesce carbide particles.

Weldability Tests

The weldability of the test steels was assessed by implant tests, which were produced at 35 K Joules/inch with E11018 electrodes and 75°F preheat. The results are presented in Table XV. The significant feature of these results is the dominant effect of carbon content on the threshold stress level. At 0.06% carbon the critical stress is close to the yield strength of the steel, whereas at 0.10, 0.11 or 0.14% C the threshold stress drops markedly. Thus for satisfactory resistance to hydrogen-assisted cracking at 75F preheat it appears that the carbon content must be kept well below 0.10%.

CONCLUSIONS

1. To enable welded fabrication with room temperature preheat and low-hydrogen covered or flux-cored electrodes, the carbon content of the steel must be held below 0.09%.

2. Controlled rolling with direct quenching (CRDQ) raises yield strength at the cost of transverse notch toughness. The loss of toughness takes the form of an upward shift in the transition temperature of 40F or more. The loss of toughness becomes acute if the hardenability of the steel is too low at the thickness processed to form martensite-bainite microstructures.

3. Controlled rolling produces coarse elongated grains which persist upon direct quenching but are eliminated by off-line reheating and quenching. Thus the transverse toughness is significantly lower than that in the longitudinal direction in CRDQ tests.

4. CRDQ processing results in extremely high yield-to-tensile strength ratios (0.93 to 0.98) for 100-ksi yield-strength steels. Tempering at or near the A_1 temperature reduces this ratio largely by lowering the yield strength. The yield-tensile ratio for 70-ksi yield strength steels is below 0.90.

5. Boron is detrimental to the notch toughness of steels containing less than 0.10% carbon.

6. A 0.065% carbon A852 type steel exhibits remarkable notch toughness when suitably quenched and tempered in thicknesses up to one-inch. The yield strength can attain 80 ksi in tests of CRDQ processed material without loss of notch toughness below the AASHTO requirements.

7. In the 100 ksi yield strength steels, CRAQ processing produces higher notch toughness than CRDQ processing at the same yield strength level.

RECOMMENDATIONS

1. At the 70 ksi yield strength level, a 0.065% carbon A852 is a promising candidate for 1-inch plate and up to 2-inch thickness if it is control-rolled, air cooled and then reaustenitized, quenched and properly tempered. For greater thicknesses the alloy content would need to be increased. A useful index for alloy requirements can be obtained from a hardenability test such as the Jominy end-quench test.

2. At the 100 ksi minimum yield strength level, a useful series of A710 type steels at 0.065% carbon is available for thicknesses ranging up to 4 inches by progressive additions in Ni and Cu to the base alloy steel. Again hardenability is a useful indicator of the alloy requirements.

3. Controlled rolling and direct quenching can be used to increase the yield strength of structural steels. However, their notch toughness when conventionally heat treated must be high enough to tolerate the loss due to direct quenching and still meet bridge steel specifications.

4. Controlled rolling and off-line heat treatment should be considered a viable alternative to the installation of in-line direct quenching facilities as a means of producing high performance steels.

5. The application of some of the trial steels to a 90-ksi minimum yield specification might be attractive in the family of structural steels for bridges, particularly in heavier gages.

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Table I - Chemical Composition of 5Ni-Cr-Mo-V Steel, %

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V
Typical	0.11	0.75	0.005	0.005	0.25	0.15	5.00	0.50	0.50	0.07
Reduced C	0.04/0.07	0.75	0.005	0.005	0.25	0.15	5.00	0.60	0.60	0.07

Table II - Chemical Composition of 100-ksi Yield-Strength Experimental Steels, Percent

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Al	N	Cb	CE*
C	0.074	1.000	0.009	0.003	0.250	0.007	0.750	0.500	0.490	0.071	0.021	0.006	0.030	0.54
D	0.068	1.520	0.009	0.004	0.260	0.730	0.750	0.500	0.250	NA	0.035	0.006	0.030	0.61
E	0.066	1.000	0.008	0.004	0.270	1.080	0.900	0.740	0.490	NA	0.027	0.005	0.032	0.66
F	0.067	1.250	0.008	0.004	0.280	1.230	1.250	0.740	0.490	0.070	0.029	0.005	0.032	0.76
G	0.110	0.990	0.011	0.003	0.250	NA	0.800	0.500	0.490	0.069	0.030	0.006	0.031	0.58

NA None Added

* Carbon Equivalent Based on IIW Formula

$CE = C+Mn/6+Si/6+(Cu+Ni)/15+(Cr+Mo)/5+V/5$

Table III - Mechanical Properties - Steel C
(0.074C - 1.00Mn - 0.75Ni - 0.50Cr - 0.49Mo - 0.071V)

Processing Condition Temperature, deg. F	Tensile Properties					Charpy V-Notch Energy Absorbed, ft. lb.			
	Y.S. ksi	T.S. ksi	Elong. %	R. A. %	Y.S./T.S.	0°F	-40°F	-80°F	-120°F
HRAQ - Tempered at 1200	98	107	23	68.0	0.92	80	40	20	4
HRAQ + QT (1650 + 1225)	99	106	23	71.2	0.93	116	70	60	30
(1650 + 1250)	98	107	23	73.0	0.92	141	48	26	22
CRDQ-15 - Tempered at 1200	114	123	22	69.6	0.93	12			4
at 1250	110	117	22	67.5	0.94	10	8		3
CRDQ-15 + QT (1650 + 1200)	106	112	22	72.0	0.95	128	70	50	26
(1650 + 1250)	102	108	23	73.8	0.94	147	121	95	68
CRAQ-15 + T (1650 + 1175)	106	115	22	72.3	0.92	193	95	108	19
(1650 + 1275)	98	104	25	75.0	0.94	184	124	122	95
CRAQ-15 + QT (1700 + 1625 + 1100)	98	110	24	74.8	0.89	149	120	113	38
(1700 + 1625 + 1175)	101	110	24	75.3	0.92	157	112	78	75
CRDQ-17 - Tempered at 1200	112	122	20	65.8	0.92	9	9	5	3
at 1250	109	117	22	67.5	0.93	10			3
CRDQ-17 + QT (1650 + 1200)	106	111	22	72.2	0.95	107	90	75	58
(1650 + 1250)	101	108	24	75.0	0.94	135	102	86	68
CRAQ-17 + T (1650 + 1175)	101	110	23	72.8	0.92	169	122	126	19
(1650 + 1275)	97	105	24	75.6	0.92	145	133	113	73
CRAQ-17 + QT (1700 + 1625 + 1100)	98	108	25	75.5	0.91	160	139	117	111
(1700 + 1625 + 1175)	99	108	24	75.2	0.92	155	150	122	110

Table IV - Mechanical Properties - Steel D
(0.068C - 1.52Mn - 0.73Cu - 0.75Ni - 0.50Cr - 0.49Mo)

Processing Condition Temperature, deg. F	Tensile Properties					Charpy V-Notch Energy Absorbed, ft. lb.			
	Y.S. ksi	T.S. ksi	Elong. %	R. A. %	Y.S./T.S.	0°F	-40°F	-80°F	-120°F
HRAQ - Tempered at 1100	100	109	24	76.0	0.92	108	90	70	46
HRAQ + QT (1650 + 1050)	97	107			0.91	209	190	155	135
CRDQ-15 - Tempered at 1150	113	122	20	64.5	0.93	42			17
at 1200	110	117	20	63.0	0.94	64	45	22	7
CRDQ-15 + QT (1650 + 1150)	99	106			0.93	118	95	60	31
(1650 + 1200)	95	102			0.93	121	114	82	48
CRAQ-15 +T (1650 + 1050)	100	112	22	71.6	0.89	119	96	99	82
(1650 + 1175)	98	106	22	69.8	0.92	135	115	104	94
CRAQ-15 + QT (1700 + 1625 + 1050)	96	108	23	71.8	0.89	148	113	118	93
(1700 + 1625 + 1150)	95	102	24	74.2	0.93	163	133	115	95
CRDQ-17 - Tempered at 1200	108	115	21	63.0	0.94	60	40	20	13
at 1225	106	113	20	62.5	0.94	41	32	19	13
CRDQ-17 + QT (1650 + 1150)	96	104			0.92	121	105	55	36
(1650 + 1200)	96	103			0.93	126	111	91	68
CRAQ-17 + T (1650 + 1050)	103	113	22	68.2	0.91	146	104	99	92
(1650 + 1175)	95	102			0.93	131	144	108	80
CRAQ-17 + QT (1700 + 1625 + 1050)	94	106	23	73.2	0.89	155	121	107	85
(1700 + 1625 + 1150)	94	102	25	74.8	0.92	170	138	130	113

Table V - Mechanical Properties - Steel E
(0.066C - 1.00Mn - 1.08Cu - 0.90Ni - 0.74Cr - 0.49Mo)

Processing Condition Temperature, deg. F	Tensile Properties					Charpy V-Notch Energy Absorbed, ft. lb.			
	Y.S. ksi	T.S. ksi	Elong. %	R. A. %	$\frac{Y.S.}{T.S.}$	0°F	-40°F	-80°F	-120°F
HRAQ - Tempered at 1150	103	111	21	71.0	0.93	122	105	70	52
HRAQ + QT (1650 + 1125)	113	120			0.94	117	86	55	46
(1650 + 1175)	108	115			0.94	122	118	92	65
CRDQ-15 - Tempered at 1100	127	141	20	59.0	0.90	40			9
at 1225	120	124	21	66.0	0.97	68	55	40	11
CRDQ-15 + QT (1650 + 1200)	108	114			0.95	121	115	92	80
(1650 + 1250)	100	107			0.93	137	128	128	130
CRAQ-15 + T (1650 + 1175)	106	114	22	71.5	0.93	144	112	70	45
(1650 + 1250)	102	109	23	66.7	0.94	132	157	122	109
CRAQ-15 + QT (1700 + 1625 + 1100)	112	122	22	70.8	0.92	116	101	78	62
(1700 + 1625 + 1200)	100	106	24	75.0	0.94	156	139	133	120
CRDQ-17 - Tempered at 1100	125	139	20	62.3	0.97	50			15
at 1200	123	127	20	65.5	0.97	59	55	40	29
CRDQ-17 (1650 + 1175)	108	114			0.95	117	119	95	68
(1650 + 1235)	104	108			0.96	128	128	122	126
CRAQ-17 + T (1650 + 1175)	109	117	21	68.0	0.93	161	133	77	86
(1650 + 1250)	100	108	23	71.0	0.93	162	148	115	60
CRAQ-17 + QT (1700 + 1625 + 1100)	109	120	23	71.5	0.91	125	113	85	62
(1700 + 1625 + 1200)	99	104	24	75.2	0.95	163	156	133	117

Table VI - Mechanical Properties - Steel F
(0.067C - 1.25Mn - 1.23Cu - 1.25Ni - 0.74Cr - 0.49Mo - 0.070V)

Processing Condition Temperature, deg. F	Tensile Properties					Charpy V-Notch Energy Absorbed, ft. lb.			
	Y.S. ksi	T.S. ksi	Elong. %	R. A. %	Y.S. / T.S.	0°F	-40°F	-80°F	-120°F
HRAQ - Tempered at 1200	126	130	20	65.8	0.97	85	75	60	52
at 1275	105	111	24	69.0	0.95	123	115	95	60
HRAQ + QT (1650 + 1250)	117	120			0.97	175	165	152	139
(1650 + 1300)	95	112			0.85	182	170	156	139
CRDQ-15 - Tempered at 1200	144	147	19	61.0	0.98	62	50	35	25
at 1250	134	137	18	59.0	0.98	67	55	40	29
CRDQ-15 + QT (1650 + 1250)	120	123			0.98	97	92	71	49
(1650 + 1300)	102	116			0.88	113	112	81	49
CRAQ-15 + T (1650 + 1200)	135	139	20	63.8	0.97	90	86	53	51
(1650 + 1300)	104	124	21	65.8	0.84	138	123	128	108
CRAQ-15 + QT (1700 + 1625 + 1200)	127	131	21	67.5	0.97	115	90	87	61
(1700 + 1625 + 1300)	94	116	23	70.2	0.81	139	132	127	106
CRDQ-17 - Tempered at 1200	143	147	17	59.1	0.97	52	40	35	31
at 1275	123	126	20	62.5	0.98	88	75	60	49
CRDQ-17 + QT (1650 + 1250)	119	122			0.98	102	93	67	49
(1650 + 1300)	97	116			0.84	113	109	96	87
CRAQ-17 + T (1650 + 1200)	139	142	19	63.2	0.98	91	81	65	58
(1650 + 1300)	104	121	22	64.8	0.86	126	134	124	98
CRAQ-17 + QT (1700 + 1625 + 1200)	134	136	18	66.8	0.98	109	86	65	65
(1700 + 1625 + 1300)	97	120	22	67.0	0.81	134	132	132	95

Table VII - Mechanical Properties - Steel G
(0.11C - 0.99Mn - 0.80Ni - 0.50Cr - 0.49Mo - 0.069V)

Processing Condition Temperature, deg. F	Tensile Properties					Charpy V-Notch Energy Absorbed, ft. lb.			
	Y.S. ksi	T.S. ksi	Elong. %	R. A. %	$\frac{\text{Y.S.}}{\text{T.S.}}$	0°F	-40°F	-80°F	-120°F
CRDQ-15 - Tempered at 1150	116	129	19	62.0	0.90	25	18	5	3
at 1225	117	124	19	63.0	0.94	32	17	4	2
CRDQ-15 + QT (1625 + 1150)	110	123	22	68.5	0.89	64	54	38	13
(1625 + 1250)	102	109	22	68.5	0.94	93	82	63	51
CRAQ-15 + T (1650 + 1150)	124	133	18	61.7	0.93				
(1650 + 1225)	116	123	19	64.7	0.94	74	60	47	41
CRAQ-15 + QT (1700 + 1625 + 1150)	117	128	19	66.5	0.91	66	56	47	40
(1700 + 1625 + 1250)	114	120	20	65.2	0.95	60	59	42	40
CRDQ-17 - Tempered at 1150	115	129	20	61.7	0.89	18	8	3	2
at 1225	114	124	19	65.1	0.92	11	8	4	3
CRDQ-17 + QT (1625 + 1150)	110	120	22	66.2	0.92	64	52	40	35
(1625 + 1250)	102	108	23	67.5	0.94	73	59	51	43
CRAQ-17 + T (1650 + 1150)	114	125	19	59.2	0.91	59	47	38	32
(1650 + 1225)	114	119	20	63.0	0.96				
CRAQ-17 + QT (1700 + 1625 + 1150)	116	127	20	63.0	0.91	50	44	36	33
(1700 + 1625 + 1250)	108	114	21	65.0	0.95	90	72	60	53

Table VIII - Restraint Test Weldability Results
1" Plate Grade 100

Steel	Welding Parameters		Crack Index *	
	Filler	Heat Input		
C	E12018	25kJ/in (1.0 kJ/mm)	0.120" (3.0mm)	all weld metal
	E12018	25kJ/in (1.0 kJ/mm)	0.030" (0.9mm)	
	E12018	25kJ/in (1.0 kJ/mm)	0.240" (6.0mm)	
D	E12018	25kJ/in (1.0 kJ/mm)	all weld metal complete cracking	
	E12018	25kJ/in (1.0 kJ/mm)		
	E12018	25kJ/in (1.0 kJ/mm)		
E	E12018	25kJ/in (1.0 kJ/mm)	all weld metal complete cracking	
	E12018	25kJ/in (1.0 kJ/mm)		
	E12018	25kJ/in (1.0 kJ/mm)		
	MC 100	25kJ/in (1.0 kJ/mm)	no cracking	
F	E12018	25kJ/in (1.0 kJ/mm)	all weld metal complete cracking	
	E12018	25kJ/in (1.0 kJ/mm)		
	E12018	25kJ/in (1.0 kJ/mm)		
	MC100	25kJ/in (1.0 kJ/mm)	no cracking	

* Cracking index is the projected height of crack in cross-section at 1 inch from weld stop at restrained end

Table IX - Chemical Composition of 70-ksi and 100-ksi Experimental Bridge Steels

Steel		C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Al	N	Cb	Ti	B
N	Aim	0.065	1.00	0.009	0.005	0.25	0.30	0.75	0.50	0.50	0.06	0.030	0.06	0.015	0.04	0.002
	Check	0.064	1.00	0.010	0.005	0.24	0.29	0.74	0.50	0.50	0.06	0.033	0.07	0.017	0.03	0.002
P	Aim	0.065	1.00	0.009	0.005	0.25	1.00	0.75	0.50	0.50	0.06	0.030	0.06	0.015		
	Check	0.062	1.01	0.008	0.005	0.25	1.02	0.75	0.48	0.50	0.07	0.033	0.07	0.015		
R	Aim	0.065	1.25	0.009	0.005	0.25	0.30	0.30	0.50	NA	0.06	0.030	0.06	0.015		
	Check	0.066	1.26	0.008	0.006	0.29	0.29	0.30	0.49	NA	0.07	0.031	0.07	0.014		
S	Aim	0.100	1.25	0.009	0.005	0.25	0.30	0.30	0.50	NA	0.06	0.030	0.06	0.015		
	Check	0.10	1.25	0.008	0.006	0.25	0.29	0.30	0.51	NA	0.06	0.038	0.07	0.015		
T	Aim	0.150	1.25	0.009	0.005	0.25	0.30	0.30	0.50	NA	0.06	0.030	0.06	0.015		
	Check	0.14	1.26	0.009	0.006	0.26	0.29	0.31	0.51	NA	0.06	0.030	0.07	0.015		

NA - None Added

N-STEEL	***Tensile Properties***					***Charpy V-Notch*** Transition Temperature, deg. F					***Charpy V-Notch Energy***					***Notes***
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	50% FAT	70 F	0 F	-40 F	-80 F	-120 F	
TRANSVERSE TESTS																
CRDQ 1600 As Q	95	132	19	67	0.72	+15	+25	+70	0	+85	60	16	12	-	-	B
CRDQ 1600+1200T	121	129	21	67	0.94	0	+45	+100	+40	>+100	45	16	15	5	-	B
CRDQ 1600+1275T	120	124	20.5	69	0.97	+30	+55	+90	+70	>+100		6	4	-	-	B
CRDQ 1600+1300T	115	119	21.5	69	0.97	+5	+25	+55	0	+70	72	27	4	-	-	B
CRDQ 1725+1275T 1hr	126	130	21.5	64	0.96	-20	+15	+60	+10	+55	-	30	15	5	-	H
CRDQ 1725+1275T 4hr	-	-	-	-	-	<-80	-15	+40	-80	+20	80	46	31	23	-	H
CRDQ 1725+1300T 4hr	115	118	21	66	0.97	-40	-10	+40	-55	+30	72	40	22	14	-	H
CRA 1500+1650 SQ+1275T 1hr	109	114	26	70	0.95	-90	-60	-20	-90	0	-	73	48	26	12	J
CRA 1500+1650 SQ+1175T 1hr	126	132	23	69	0.96	-35	-10	+20	-30	+40	80	45	15	-	-	J
CRA 1500+1650 SQ+1225T	120	130	23	69	0.93	-75	-60	-20	-70	+15	100	68	47	16	-	J
CRA 1600+1650 SQ+1275T	109	116	22.5	71	0.93	-85	-60	-35	-100	-25	109	56	52	22	-	C
HRA+1650 SQ+1275T	110	113	22.5	71	0.97	-90	-45	0	-60	+30	109	55	41	23	4	A
LONGITUDINAL TESTS																
CRDQ 1725+1275T 4hr	118	122	22	70	0.97	-75	-45	-15	-65	+30	116	77	40	17	-	H
CRDQ 1600+1200T	115	124	23	71	0.93	-30	+20	+60	-15	>+80	55	30	15	5	-	B
CRDQ 1600+1275T	116	122	23.5	73	0.95	-30	-15	+20	-30	+50	-	42	11	-	-	B
CRDQ 1600+1300T	112	118	23.5	71	0.94	-50	-30	+20	-45	+50	70	55	25	2	-	B
CRDQ 1725+1275T 4hr	118	122	22	70	0.97	-75	-45	-15	-65	+30	116	77	40	17	-	H
CRA 1500+1650 SQ+1275T	106	111	25	75	0.95	-105	-65	-45	-100	-20	-	97	53	24	9	J

Table X.   Mechanical Properties for Steel N

P-STEEL	***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	50% FAT	70 F	0 F	-40 F	-80 F	-120 F	***Notes***
TRANSVERSE TESTS																
CRDQ 1600 As Q	86	126	20	62	0.68	-90	-40	+5	-70	+30	58	71	29	24	15	B
CRDQ 1600+1200T	117	126	21	63	0.93	-65	-30	+25	-30	+60	78	20	33	13	-	B
CRDQ 1600+1275T	110	116	22.5	67	0.94	-75	-50	-20	-65	+25	95	74	43	15	-	B
CRDQ 1600+1300T	108	113	24	71	0.96	-95	-90	-60	-95	+25	97	83	67	50	4	B
CRDQ 1725+1275T 1hr	112	119	22.2	68	0.94	-50	-25	+30	-60	+50	70	50	20	10	2	H
CRDQ 1725+1300T 4hr	97	105	23.5	71	0.92	-80	-60	-45	-90	+10	123	118	72	20	15	H
CRA 1500+1650 SQ+1275T 1hr	94	104	26	73	0.91	<-120	-120	-100	<-120	-20	-	114	118	82	35	J
CRA 1500+1650 SQ+1175T 1hr	117	126	20	68	0.93	-110	-70	-20	-110	+25	105	70	50	30	15	J
CRA 1500+1650 SQ+1225T	109	116	28	73	0.94	-119	-117	-80	-117	-6	-	103	63	60	18	J
CRA 1600+1650 SQ+1225T	104	112	22.5	70	0.92	-110	-100	-80	-115	-15	-	109	95	56	4	C
HRA+1650 SQ+1225T	102	110	24.5	73	0.93	<-120	<-120	-115	<-120	-40	140	125	110	90	55	A
HRA+NORM@1650+1000T	80	113	26.2	65	0.79	-10	+20	+60	-15	+60	57	21	9	-	-	F
LONGITUDINAL TESTS																
CRDQ 1725+1275T 4hr	103	111	26	74	0.93	-90	-80	-70	-85	+25	140	116	111	46	4	H
CRA 1500+1650 SQ+1275T	94	103	24	77	0.92	<-120	<-120	<-120	<-120	-90	-	148	131	125	100	J

Table XI.   Mechanical Properties for Steel P

R-STEEL	***Tensile Properties***					***Charpy V-Notch*** Transition Temperature, deg. F					***Charpy V-Notch Energy***					***Notes***
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	50% FAT	70 F	0 F	-40 F	-80 F	-120 F	
TRANSVERSE TESTS																
CRDQ 1600 As Q	70	108	25	66	0.65	-35	0	+30	-45	+40	82	22	29	13	-	B
CRDQ 1600+1200T	88	100	25.5	70	0.88	-70	-65	-45	-55	+50	112	78	66	3	-	B
CRDQ 1600+1275T	84	94	25.2	73	0.89	-100	-85	-55	-100	-40	120	99	51	56	4	B
CRDQ 1600+1300T	79	90	28.5	73	0.88	-115	-100	-70	-115	0	152	112	102	39	-	B
CRDQ 1725+1275T 1hr	84	96	23.5	74	0.86	-80	-70	-60	-65	+5	150	115	85	20	-	H
CRDQ 1725+1275T 4hr	-	-	-	-	-	-78	-77	-70	-77	>+70	120	108	90	3	-	H
CRDQ 1725+1300T 4hr	75	86	28	77	0.87	-100	-90	-80	-90	-30	-	163	117	104	8	H
CRA 1500+1650 SQ+1275T 1hr	67	80	34	78	0.83	<-120	<-120	<-120	<-120	<-105	-	177	155	133	97	J
CRA 1500+1650 SQ+1175T 1hr	74	86	29	79	0.86	<-120	<-120	<-120	<-120	-35	-	170	115	95	85	J
CRA 1500+1650 SQ+1225T	70	82	35	79	0.85	<-120	<-120	<-120	<-120	-82	-	183	183	110	101	J
CRA 1600+1650 SQ+1275T	67	77	34.4	76	0.86	<-120	<-120	<-120	<-120	-100	-	240+	215	155	144	C
CRA 1600+1650 SQ+1150T	73	82	31.2	76	0.89	<-120	<-120	<-120	<-120	-60	168	162	148	110	103	C
HRA+1650 SQ+1150T	72	84	30.8	76	0.86	<-120	<-120	<-120	<-120	-30	175	145	130	125	115	A
HRA+1650 SQ+1250T	65	74	35.8	81	0.88	<-120	<-120	<-120	<-120	-90	240	240	240	230	160	A
HRA+NORM@1650	52	71	39.5	79	0.74	<-120	<-120	<-120	<-120	-115	200	240	240	176	146	F
LONGITUDINAL TESTS																
CRDQ 1725+1275T 4hr	81	91	23	74	0.89	-100	-80	-60	-100	-30	-	177	124	33	5	H
CRA 1500+1650 SQ+1275T	67	79	29	80	0.85	<-120	<-120	<-120	<-120	-120	-	240	224	197	132	J

Table XII. Mechanical Properties for Steel R

S-STEEL	***Tensile Properties***					***Charpy V-Notch*** Transition Temperature, deg. F					***Charpy V-Notch Energy***					***Notes***
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	50% FAT	70 F	0 F	-40 F	-80 F	-120 F	
TRANSVERSE TESTS																
CRDQ 1600 As Q	76	118	21.5	55	0.64	-30	+10	+80	-50	+70	55	35	21	14	-	B
CRDQ 1600+1200T	92	104	23.5	67	0.88	-60	-25	+30	-50	+60	82	47	30	6	-	B
CRDQ 1600+1275T	85	98	23.5	70	0.87	-60	-20	+10	-65	+40	110	53	40	15	-	B
CRDQ 1600+1300T	80	93	27.5	72	0.86	-70	-55	-35	-75	+40	106	79	61	4	-	B
CRDQ 1725+1275T 1hr	94	105	24	68	0.9	-90	-70	-40	-85	+70	100	95	60	30	3	H
CRDQ 1725+1275T 4hr	-	-	-	-	-	-78	-68	-48	-77	-	-	82	67	13	-	H
CRDQ 1725+1300T 4hr	80	91	26.5	73	0.88	-95	-85	-75	-85	+15	118	97	93	58	7	H
CRA 1500+1650 SQ+1275T 1hr	70	84	36	79	0.84	<-120	<-120	<-120	<-120	-55	-	164	142	98	83	J
CRA 1500+1650 SQ+1175T 1hr	78	92	26	74	0.85	<-120	<-120	<-120	<-120	-60	-	120	105	90	75	J
CRA 1500+1650 SQ+1225T	74	86	34	76	0.86	<-120	<-120	<-120	<-120	-48	-	156	130	103	82	J
CRA 1600+1650 SQ+1275T	72	82	26.5	73	0.88	<-120	<-120	<-120	<-120	-60	-	170	150	125	88	C
CRA 1600+1650 SQ+1150T	79	92	26.8	71	0.86	<-120	<-120	-90	<-120	-50	126	116	88	60	54	C
HRA+1650 SQ+1275T	75	87	31	77	0.86	<-120	<-120	<-120	<-120	-50	-	140	105	80	65	A
HRA+1650 SQ+1250T	68	79	34.8	78	0.86	<-120	<-120	<-120	<-120	-70	175	175	170	120	90	A
HRA+NORM@1650	58	76	35	75	0.76	<-120	<-120	<-120	<-120	-30	176	156	120	108	59	F
LONGITUDINAL TESTS																
CRDQ 1725+1275T 4hr	81	95	24.5	73	0.85	<-120	<-120	<-120	<-120	-10	-	118	106	100	22	H
CRA 1500+1650 SQ+1275T	69	83	30	83	83	<-120	<-120	<-120	<-120	-80	-	172	164	133	72	J

Table XIII. Mechanical Properties for Steel S

T-STEEL	***Tensile Properties***					***Charpy V-Notch*** Transition Temperature, deg. F					***Charpy V-Notch Energy***					***Notes***
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	50% FAT	70 F	0 F	-40 F	-80 F	-120 F	
TRANSVERSE TESTS																
CRDQ 1600 As Q	88	137	17	37	0.64	+20	+70	+100	+30	+90	31	21	10	-	-	B
CRDQ 1600+1200T	100	113	20	62	0.88	+10	+20	>+100	+35	+100	50	7	-	-	-	B
CRDQ 1600+1275T	94	107	21.5	65	0.88	-50	+10	+50	-75	+50	69	32	30	13	-	B
CRDQ 1600+1300T	86	100	24.5	65	0.86	-60	-30	0	-65	0	96	65	35	6	-	B
CRDQ 1725+1275T 1hr	96	109	22	62	0.88	-50	-30	-5	-40	+40	85	65	25	5	-	H
CRDQ 1725+1275T 4hr	-	-	-	-	-	-58	-43	-17	-60	-	93	60	45	16	-	H
CRDQ 1725+1300T 4hr	82	94	26	67	0.86	-90	-80	-40	-90	+40	102	87	54	34	7	H
CRA 1500+1650 SQ+1275T 1hr	78	92	29	75	0.85	<-120	<-120	-120	<-120	-60	-	118	115	64	66	J
CRA 1500+1650 SQ+1175T 1hr	88	102	24	70	0.86	<-120	<-120	-60	<-120	-50	-	95	75	50	40	J
CRA 1500+1650 SQ+1225T	85	97	26	72	0.88	<-120	<-120	-69	<-120	-25	-	116	88	52	38	J
CRA 1600+1650 SQ+1275T	76	90	26.5	71	0.85	<-120	<-120	-90	<-120	-60	-	111	92	60	47	C
CRA 1600+1650 SQ+1150T	88	101	25	66	0.87	<-120	-90	-45	<-120	-40	85	82	66	37	28	C
HRA+1650 SQ+1250T	74	85	29.2	75	0.87	<-120	<-120	-95	<-120	-45	-	115	95	70	55	A
HRA+NORM@1650	60	82	32.5	66	0.73	<-120	<-120	<-120	-70	-20	133	106	90	74	47	F
LONGITUDINAL TESTS																
CRDQ 1725+1275T 4hr	86	100	25.3	70	0.86	-90	-85	-70	-90	+45	110	100	78	53	13	H
CRA 1500+1650 SQ+1275T	77	90	29.5	78	0.85	<-120	<-120	<-120	<-120	-80	-	137	128	109	70	J

Table XIV. Mechanical Properties for Steel T

Table XV - Implant Test Results for Steels N, G, P, R, S and T SMA Welds with E 11018 Electrodes, 35 KJ/inch

Steel	% C	Yield Str. Min.	Threshold Stress
N (514)	0.065	100 ksi	96
G (514)	0.11	100	77
P (Cu-Ni)	0.064	100	92
R (852)	0.062	70	90
S (852)	0.10	70	75
T (852)	0.14	70	72

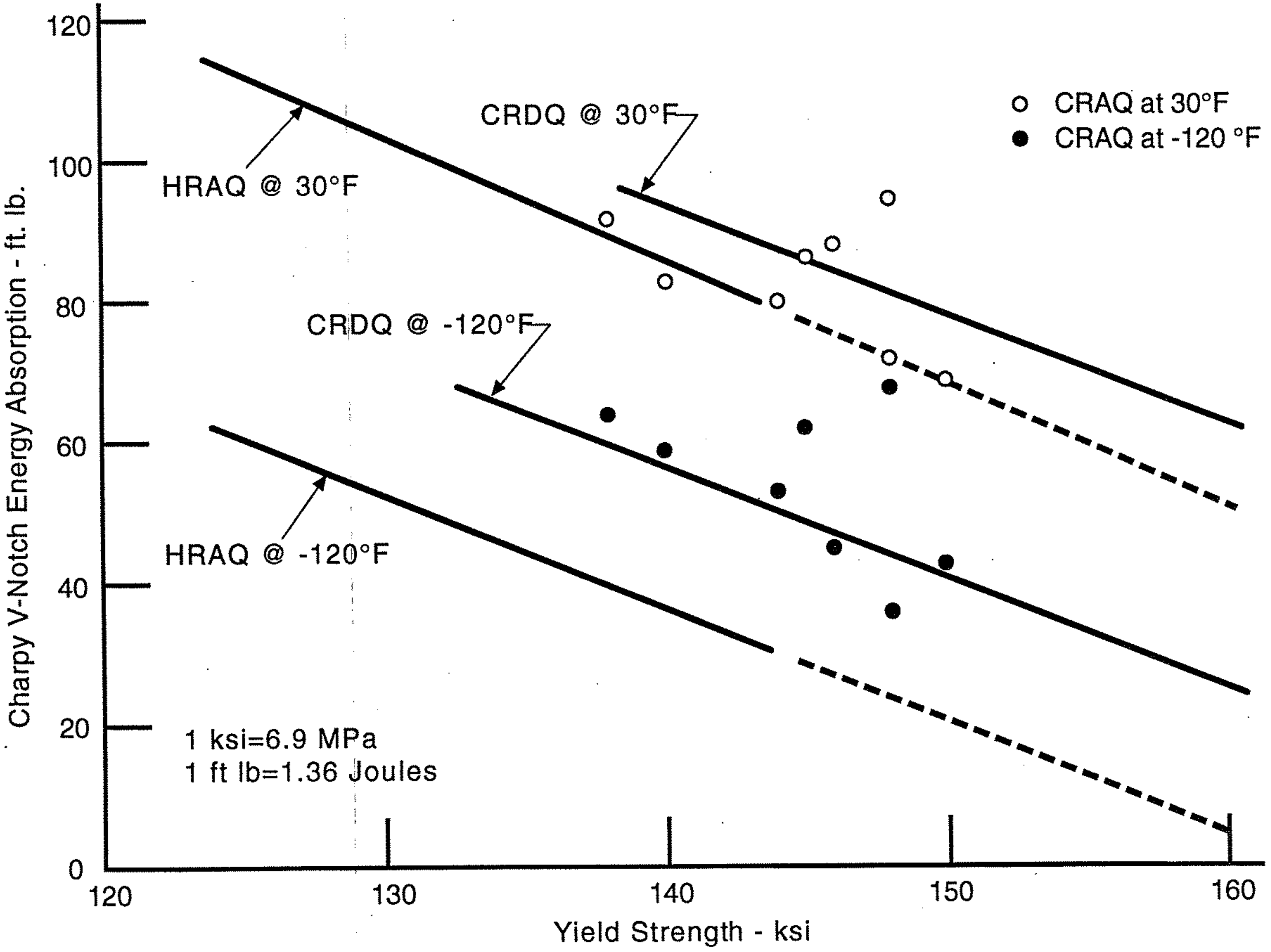

Figure 1 - Effect of CRAQ Processing on 5Ni-Cr-Mo-V Steel

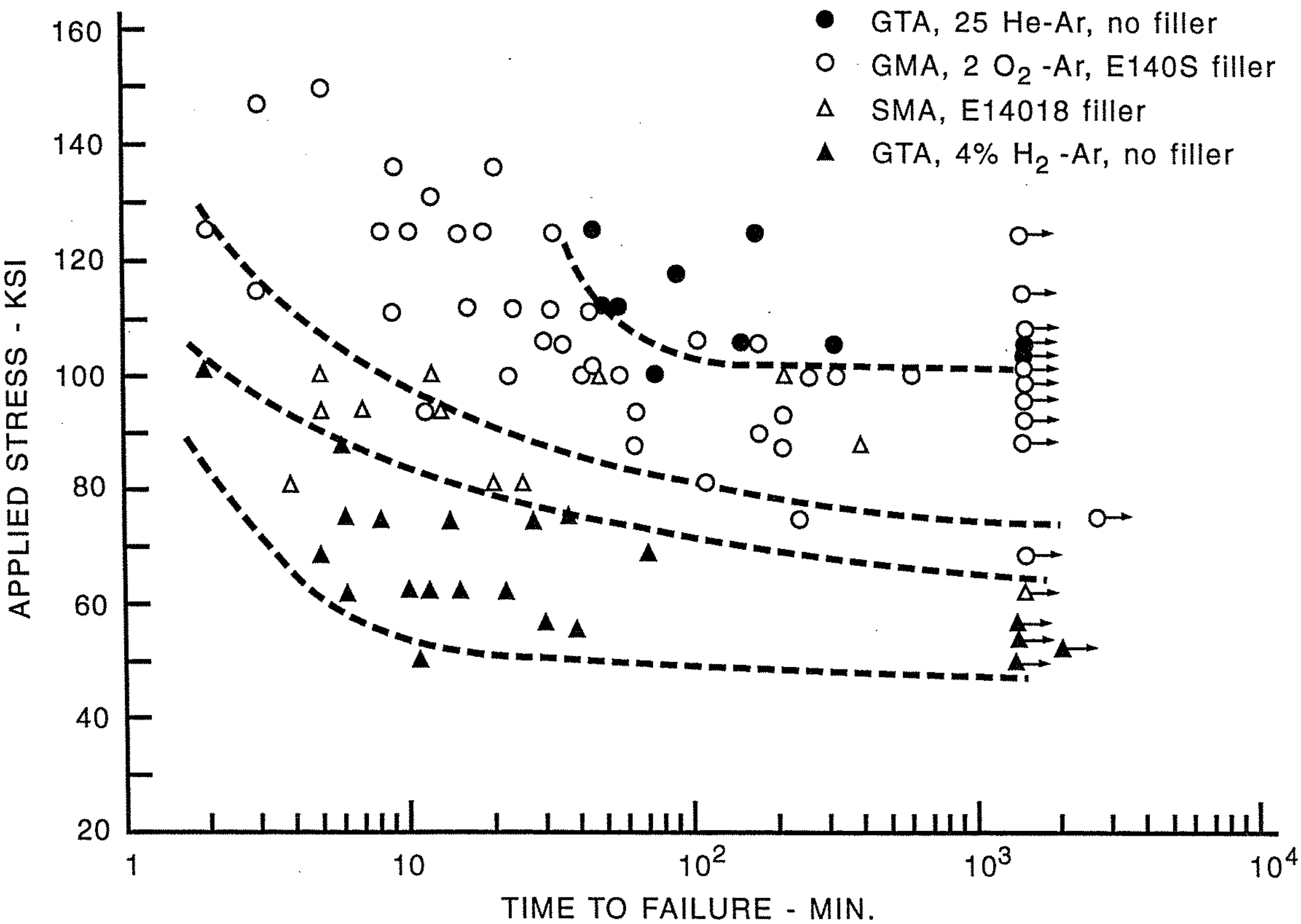

Figure 2 - Results of Implant Tests on 5Ni-Cr-Mo-V steel, Heat Input 35 KJ/inch.

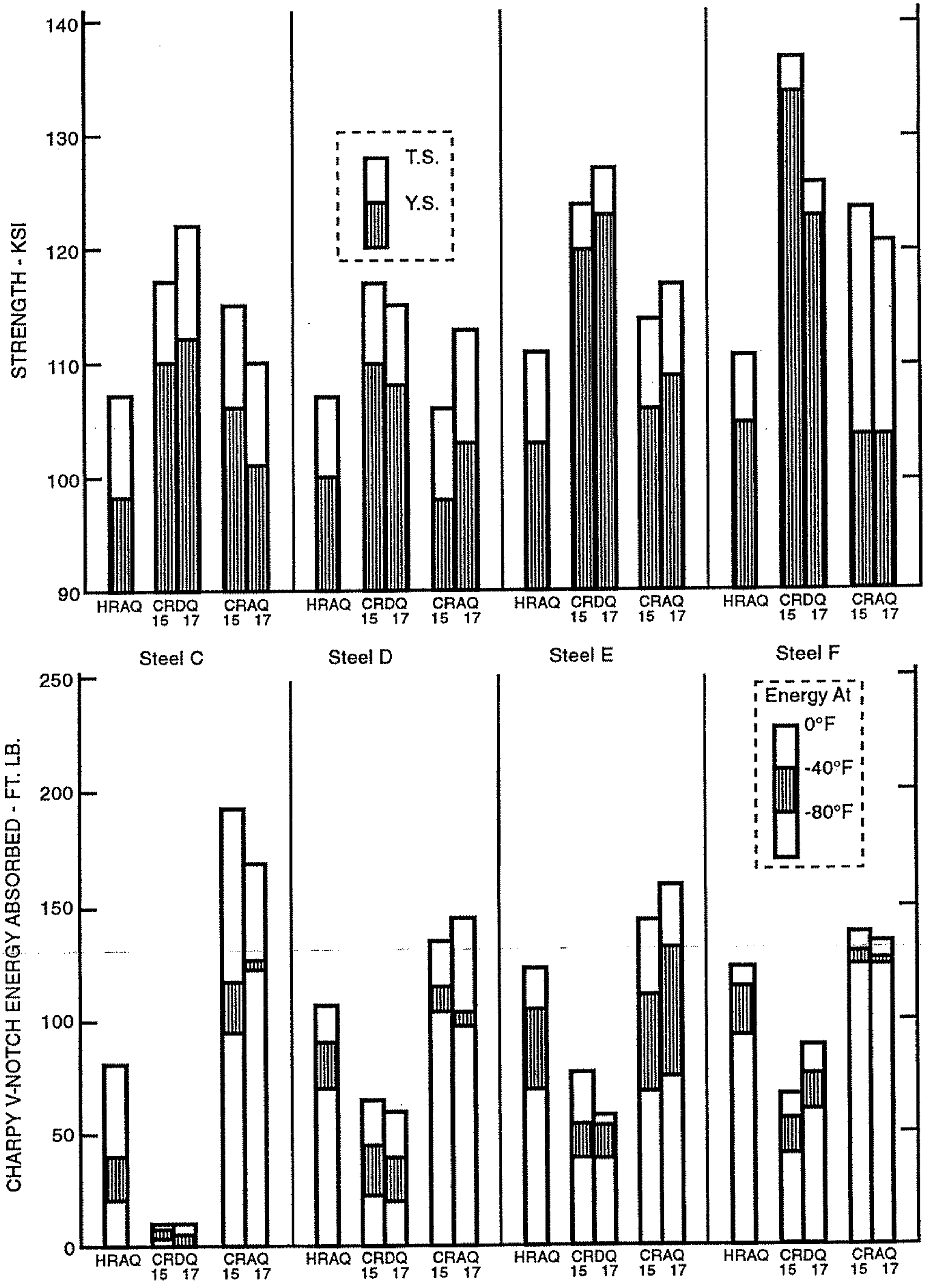

Figure 3 - Strength and Toughness Values for Steels C, D, E, and F

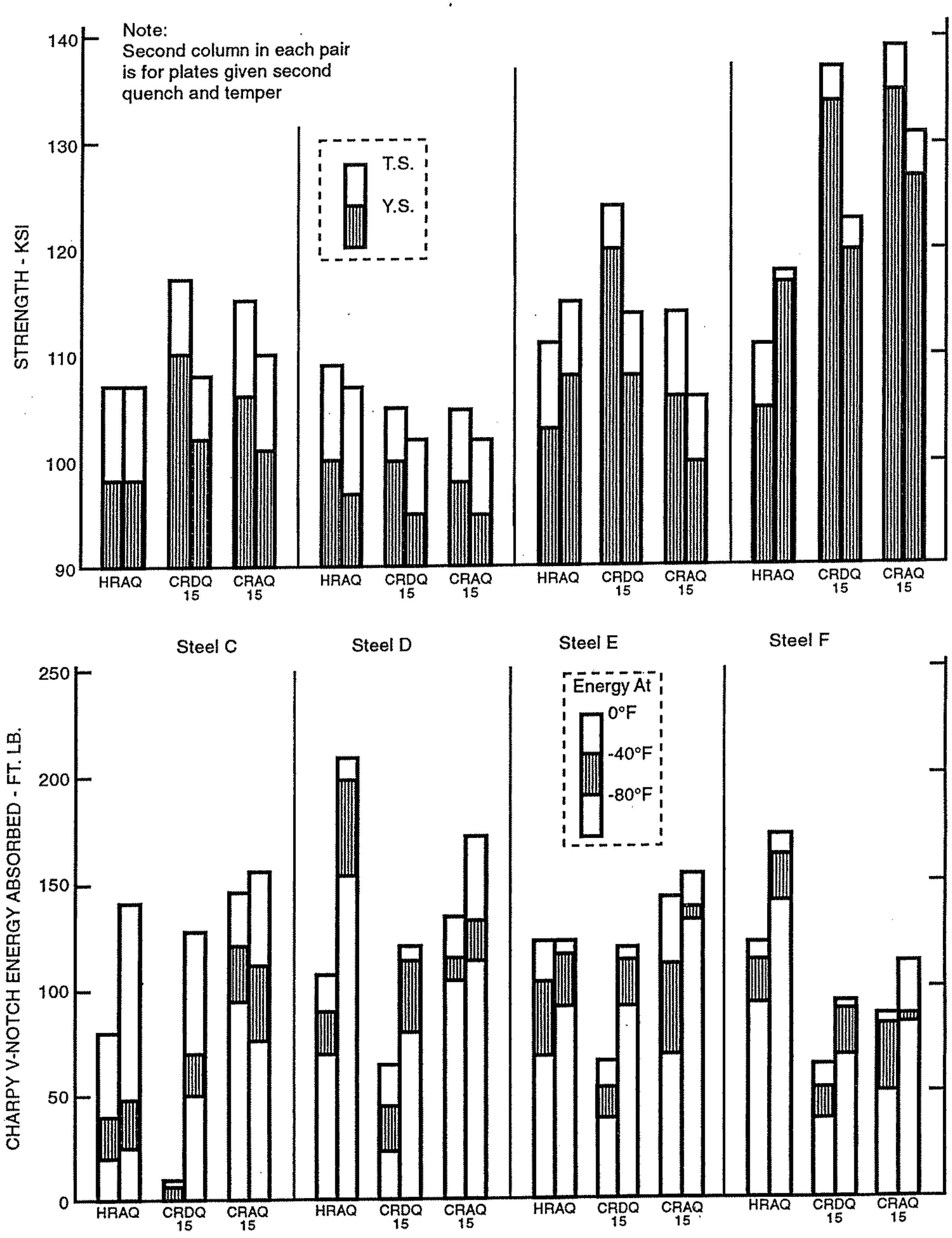

Figure 4 - Effect of Second Heat Treatment on Strength and Toughness

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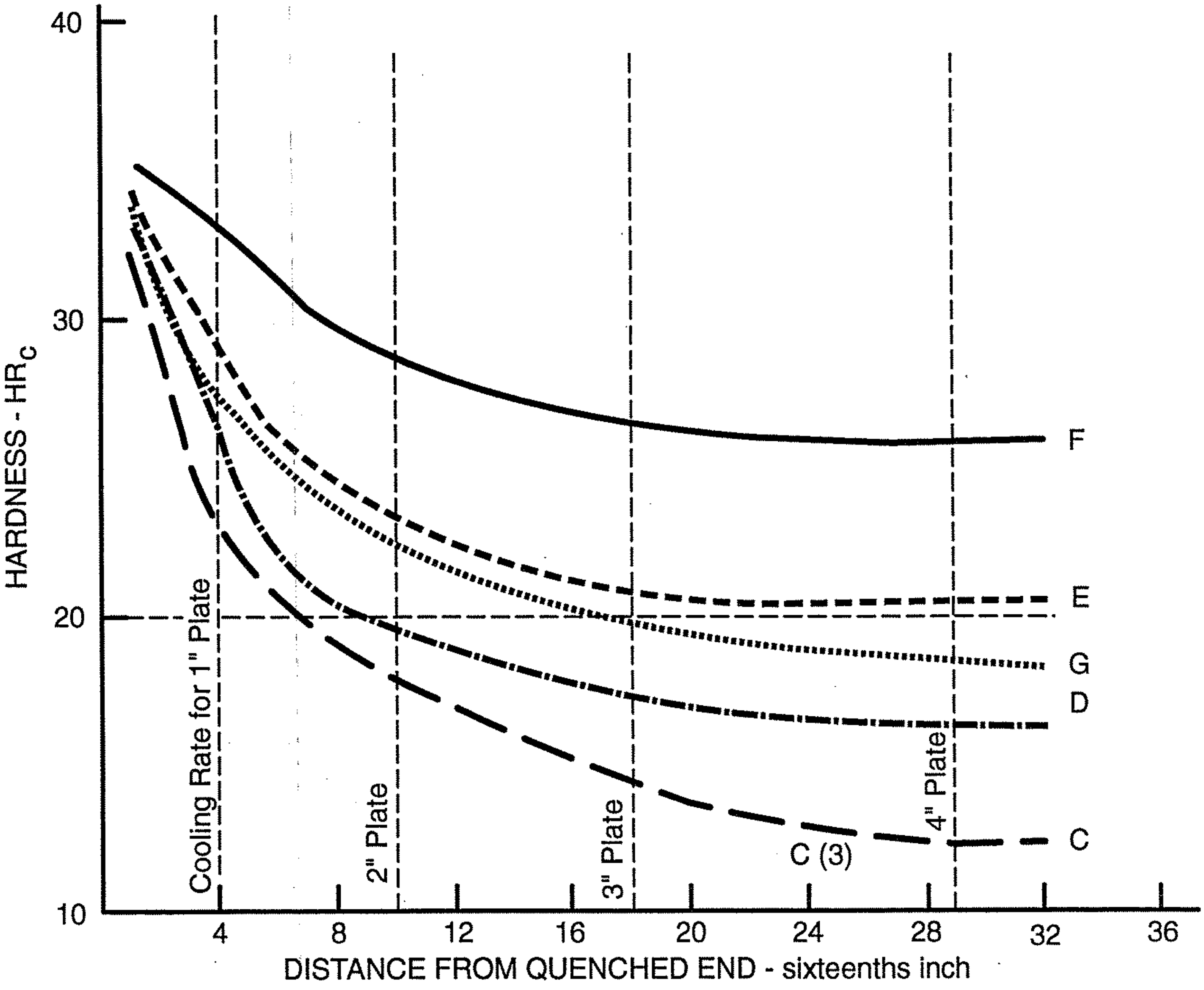


Figure 5 - Jominy Test Results for Steels C, D, E, F and G

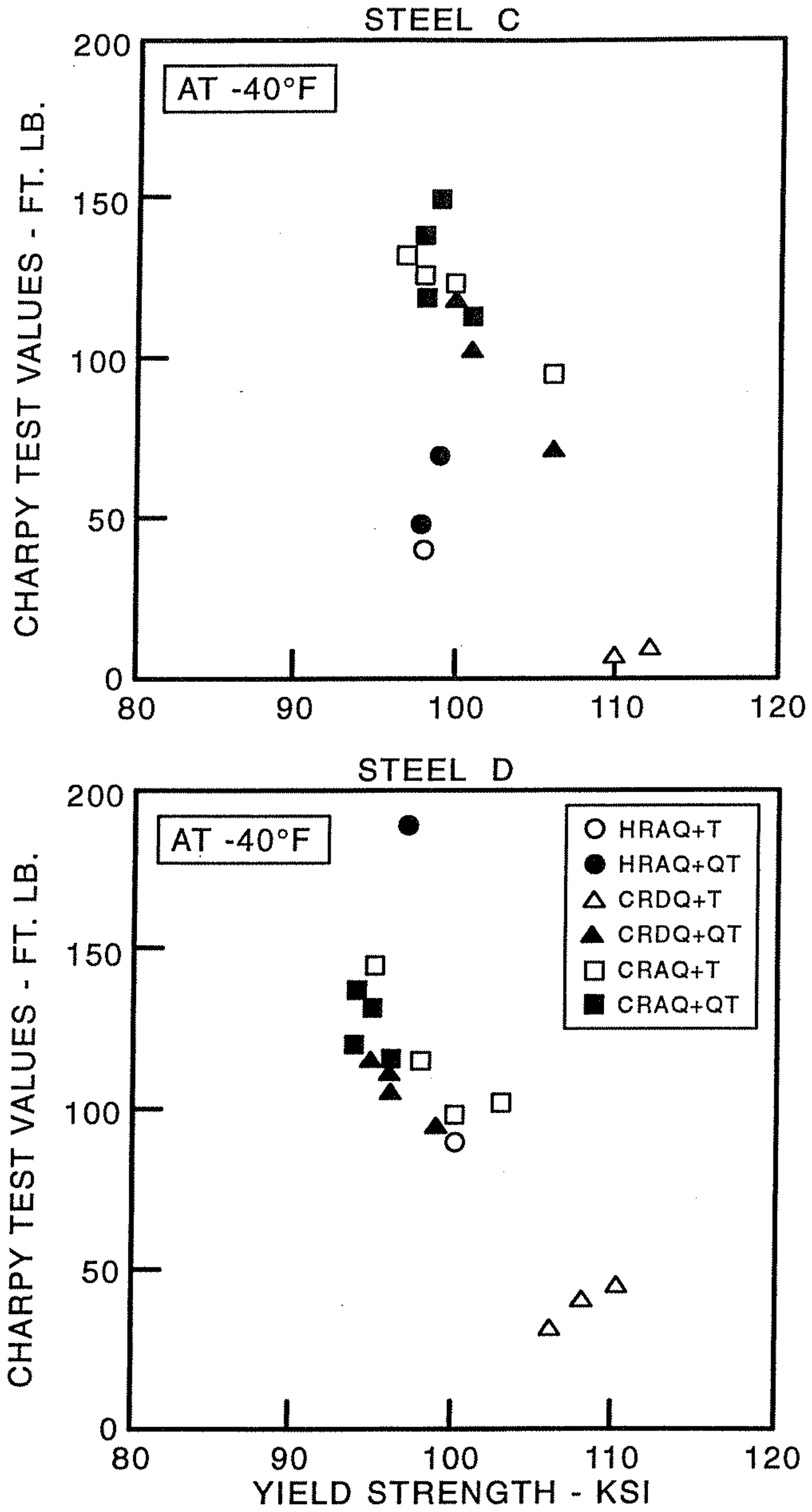


Figure 6- Relation of Charpy Notch-Toughness to Yield Strength

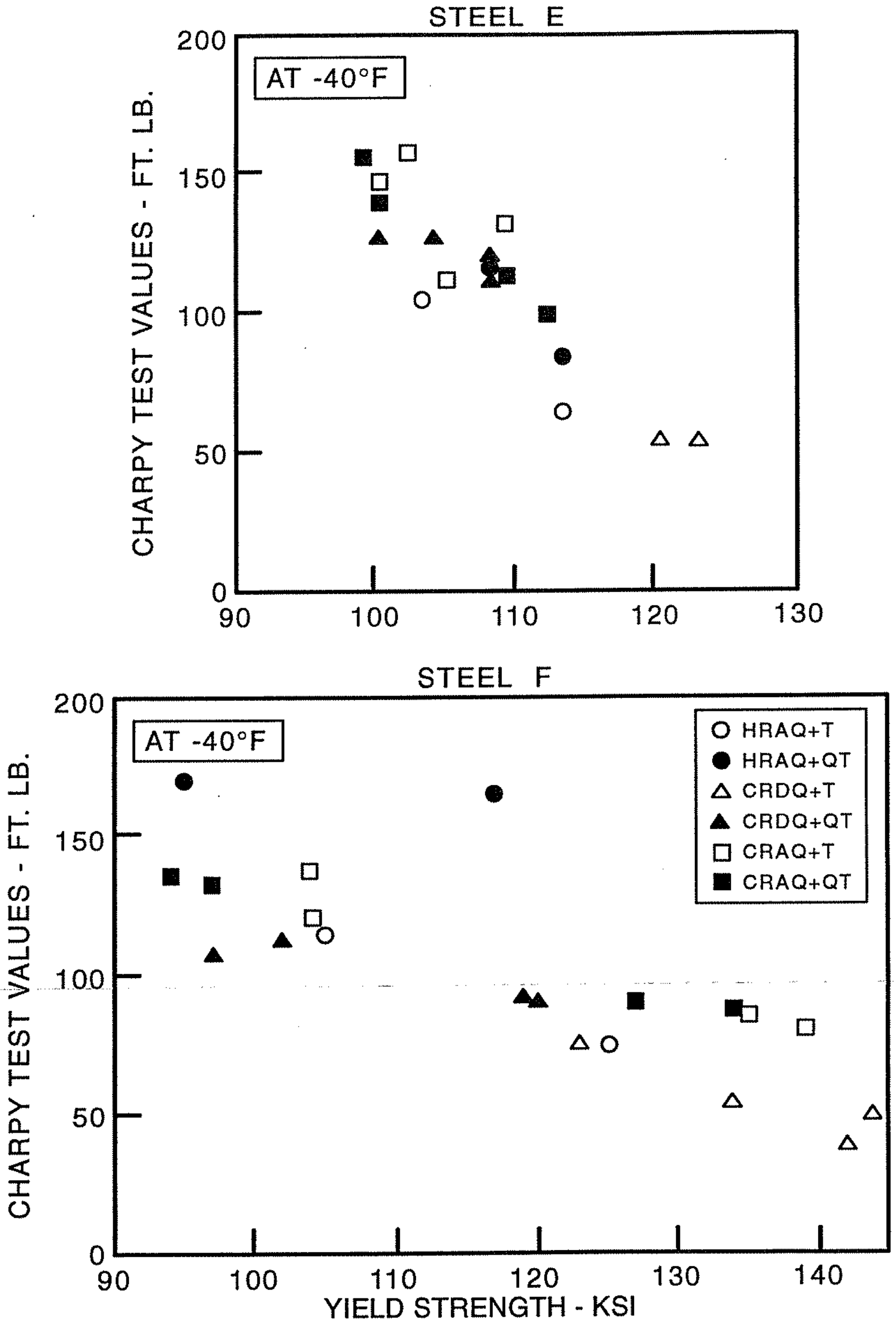
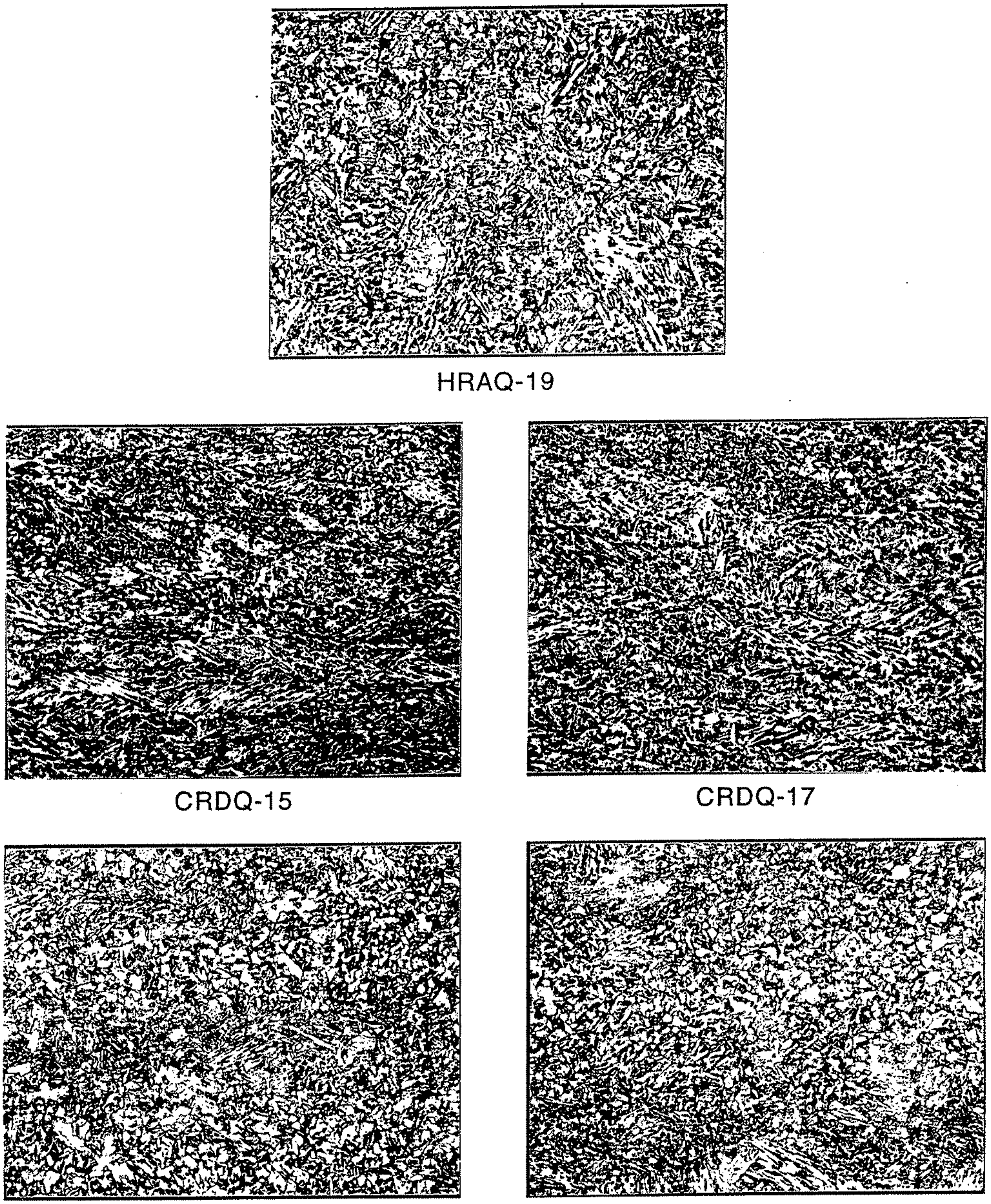


Figure 7- Relation of Charpy Notch-Toughness to Yield Strength



HRAQ-19

CRDQ-15

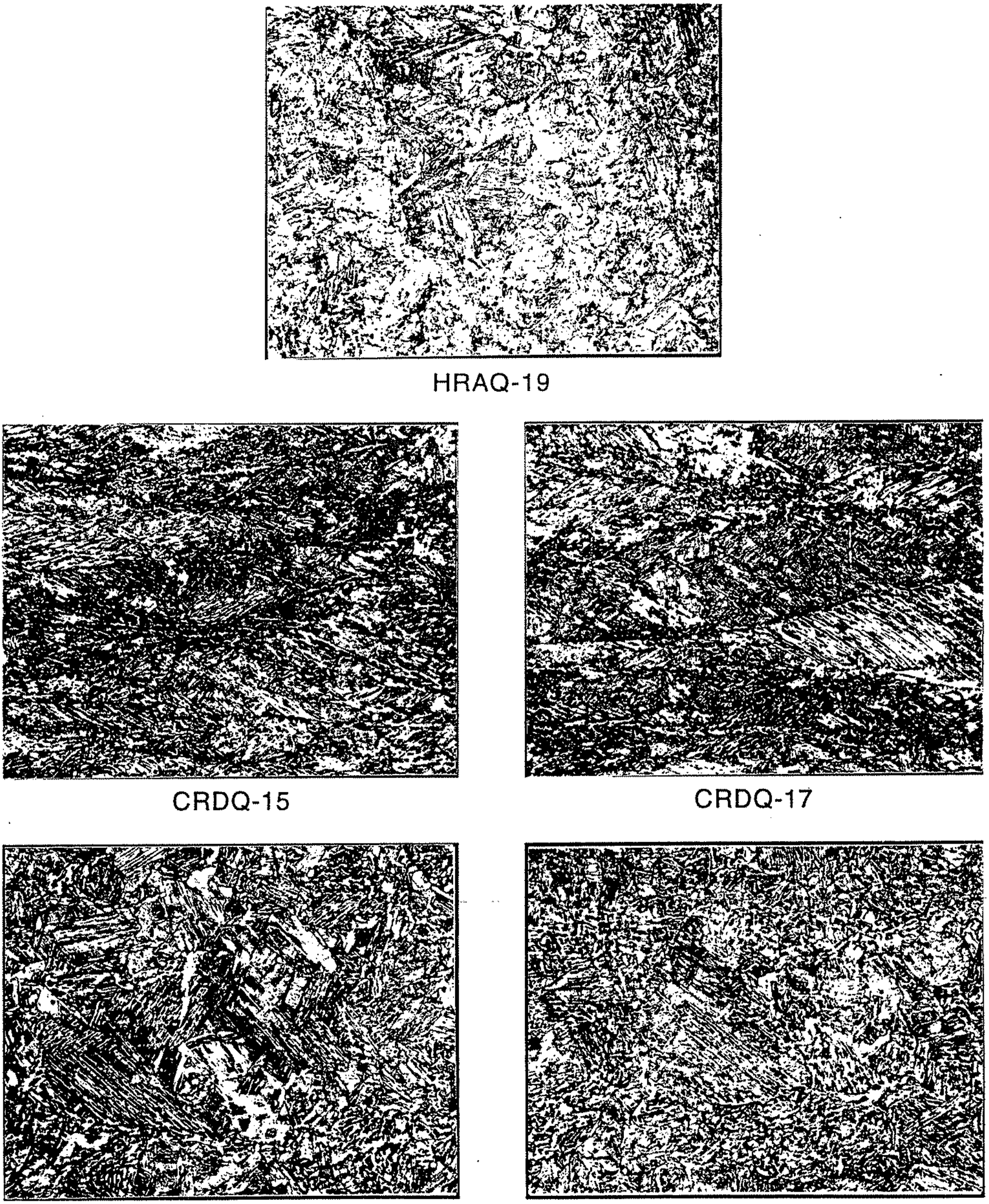
CRDQ-17

CRAQ-15

CRAQ-17

Nital-Picral x 400

Figure 8: Micrographs of Steel C, As-Quenched



HRAQ-19

CRDQ-15

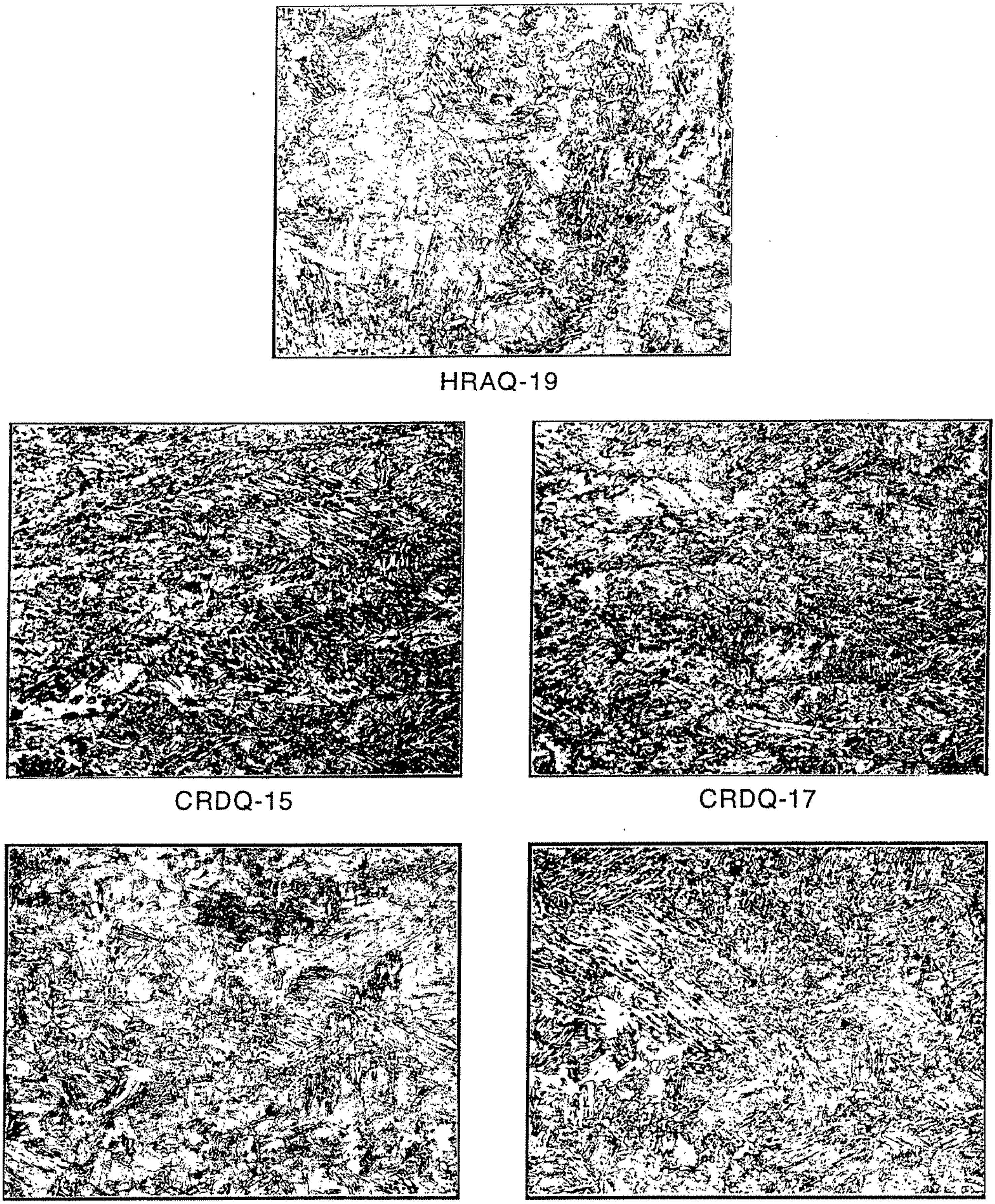
CRDQ-17

CRAQ-15

CRAQ-17

Nital-Picral x 400

Figure 9: Micrographs of Steel D, As-Quenched



HRAQ-19

CRDQ-15

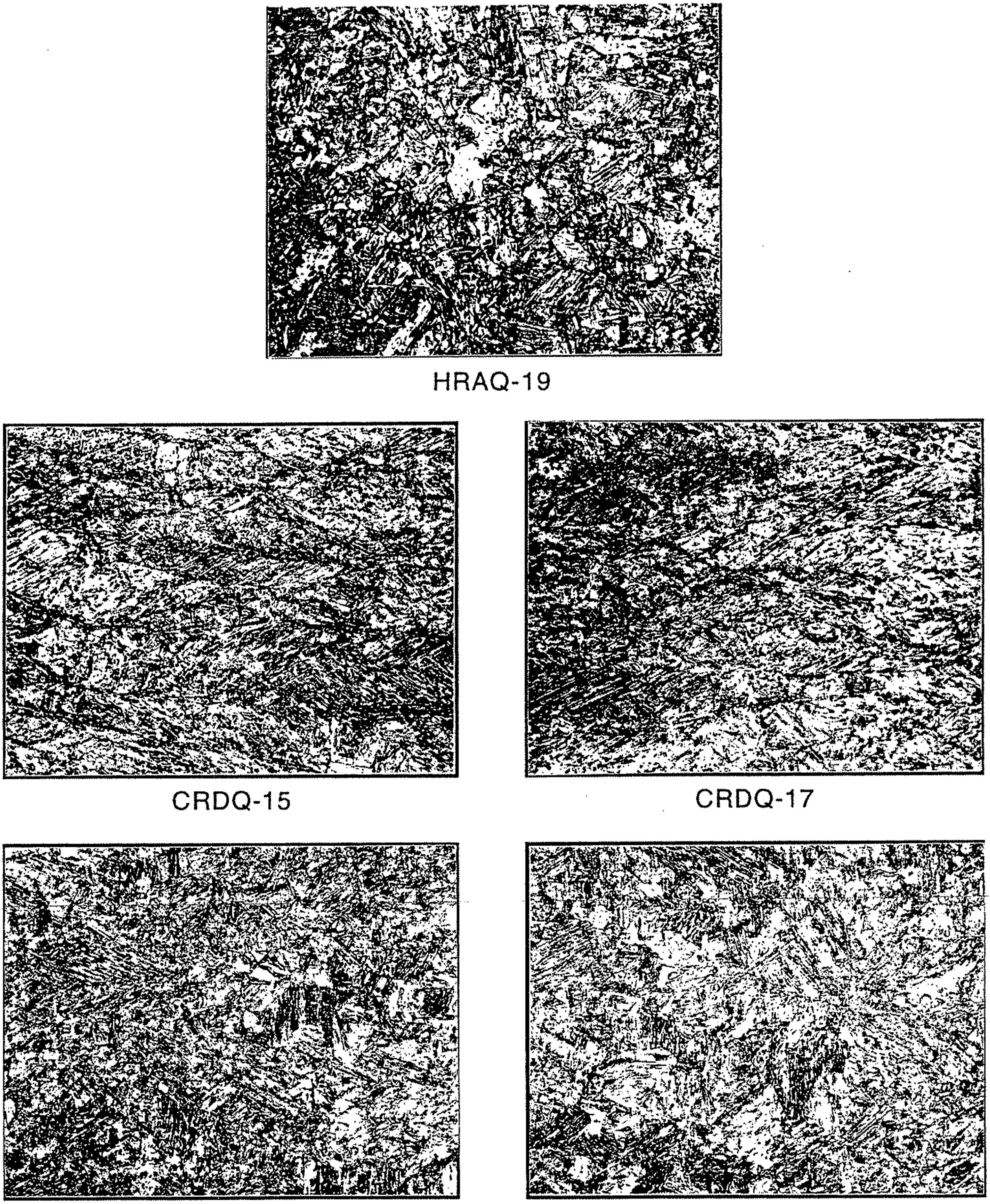
CRDQ-17

CRAQ-15

CRAQ-17

Nital-Picral x 400

Figure 10: Micrographs of Steel E, As-Quenched



HRAQ-19

CRDQ-15

CRDQ-17

CRAQ-15

CRAQ-17

Nital-Picral x 400

Figure 11: Micrographs of Steel F, As-Quenched

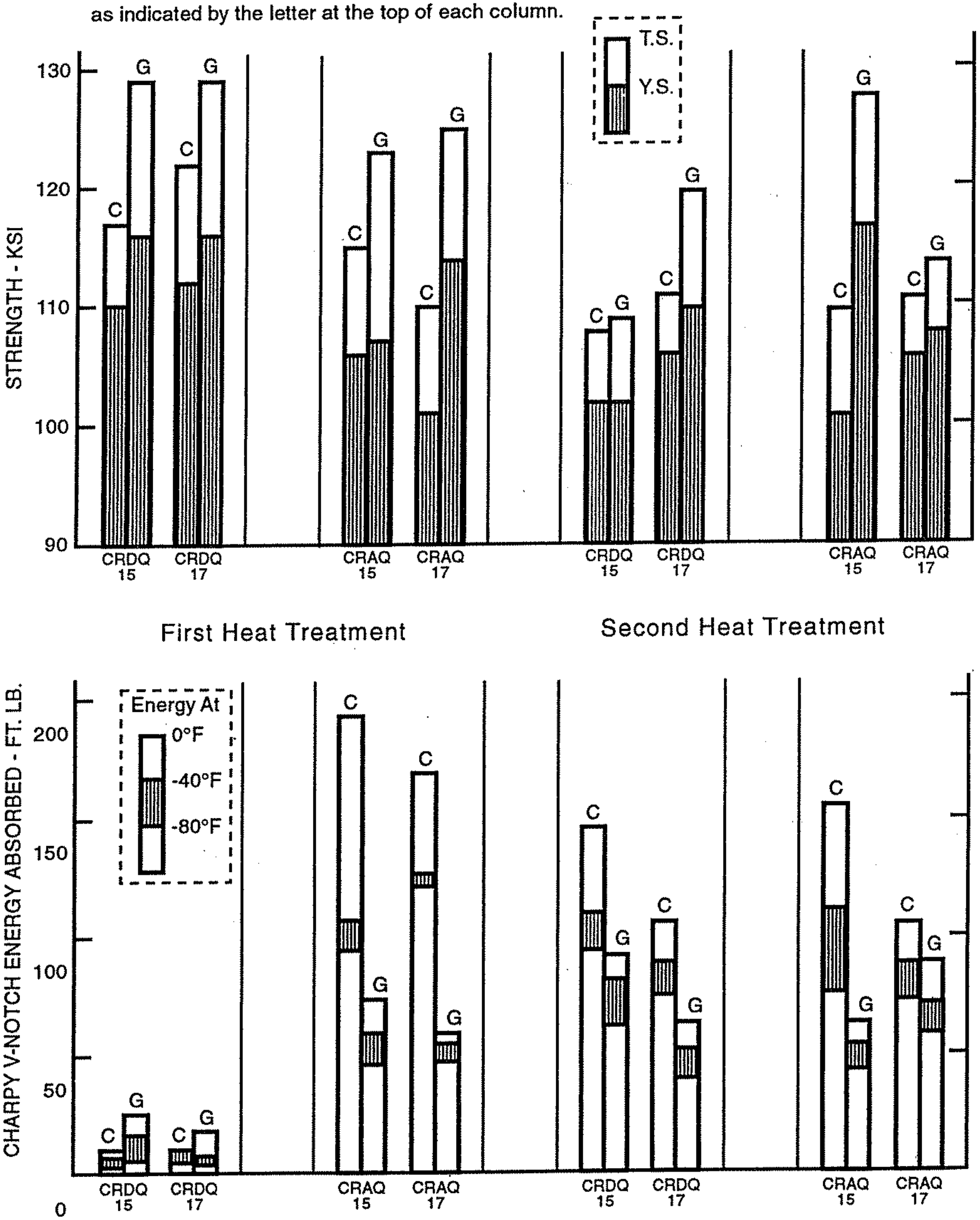

Note:
In each pair first column is for steel C (0.07C)
and second column is for steel G (0.11C)
as indicated by the letter at the top of each column.

Figure 12 - Comparison of Modified A514-F at 0.07 and 0.11 percent Carbon

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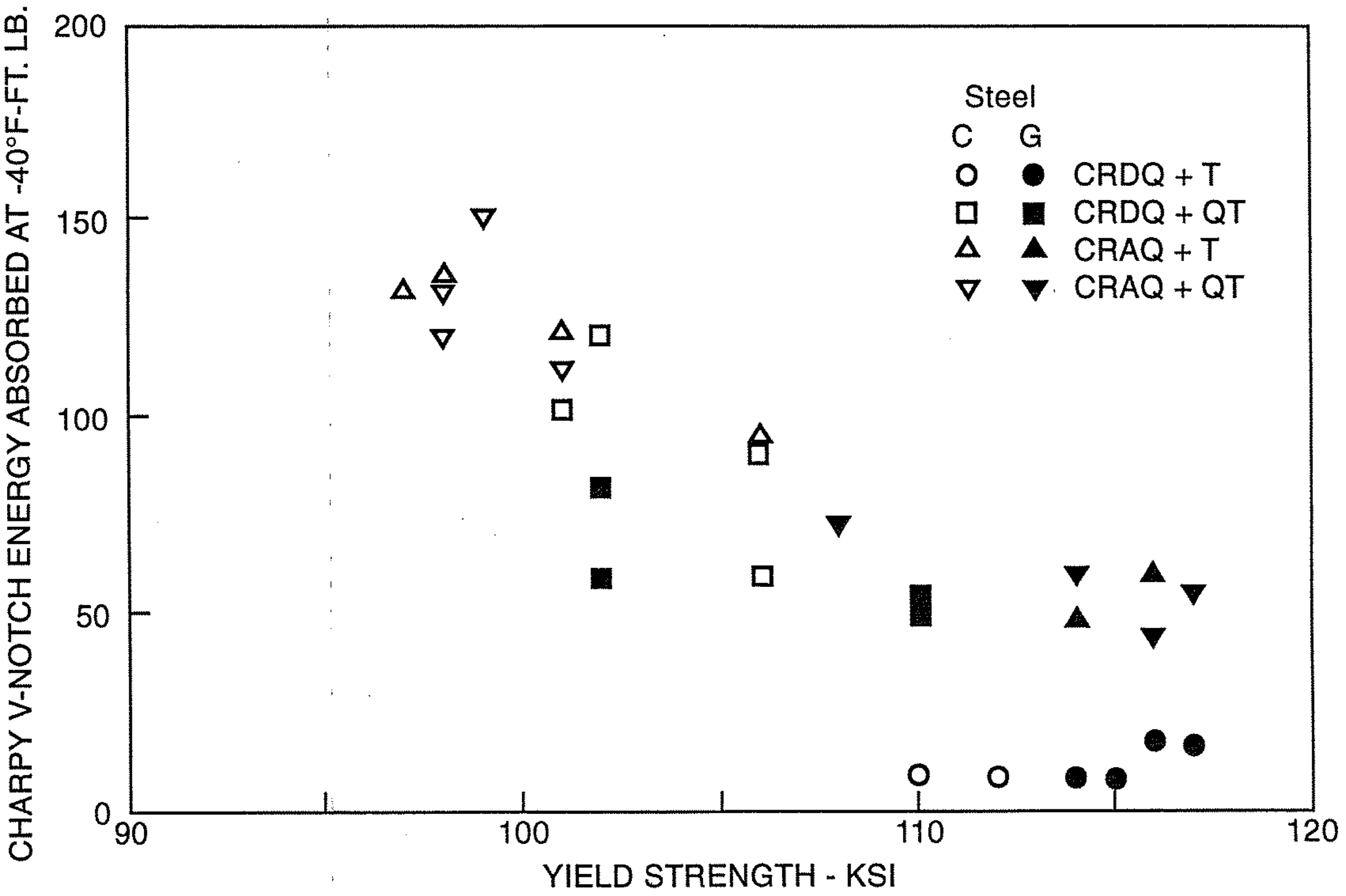


Figure 13 - Relation of Toughness to Yield Strength for Steels C and G

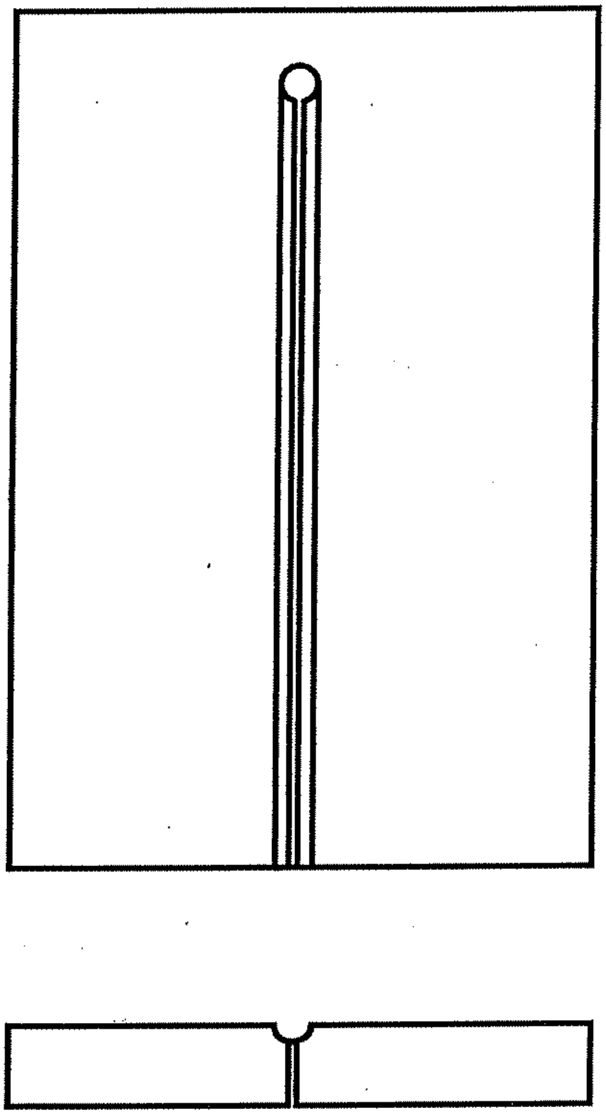


Figure 14 - Modified Restraint Test

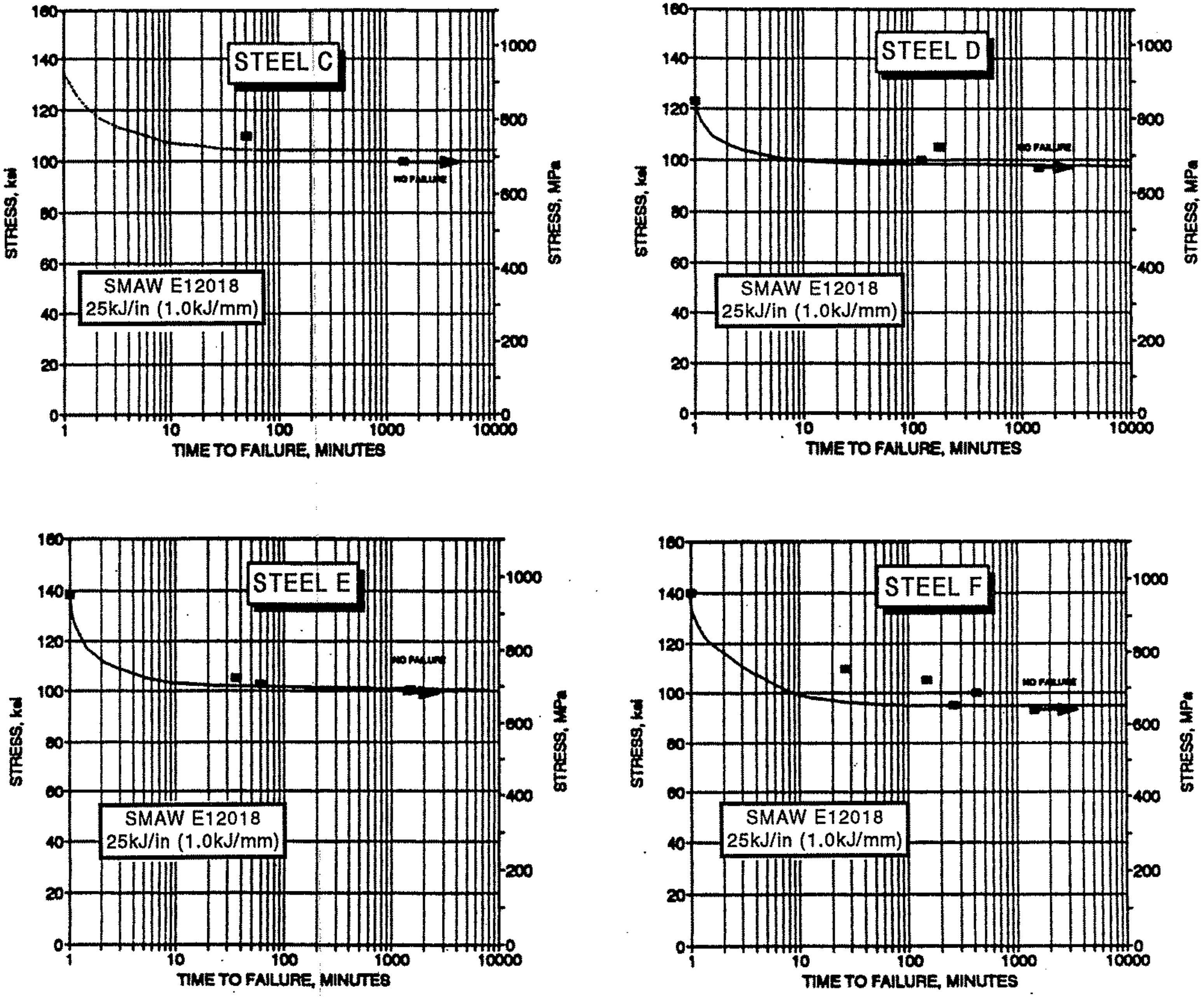


Figure 15 - Implant Results for 1-inch Steels C, D, E and F Welded with SMAW E12018

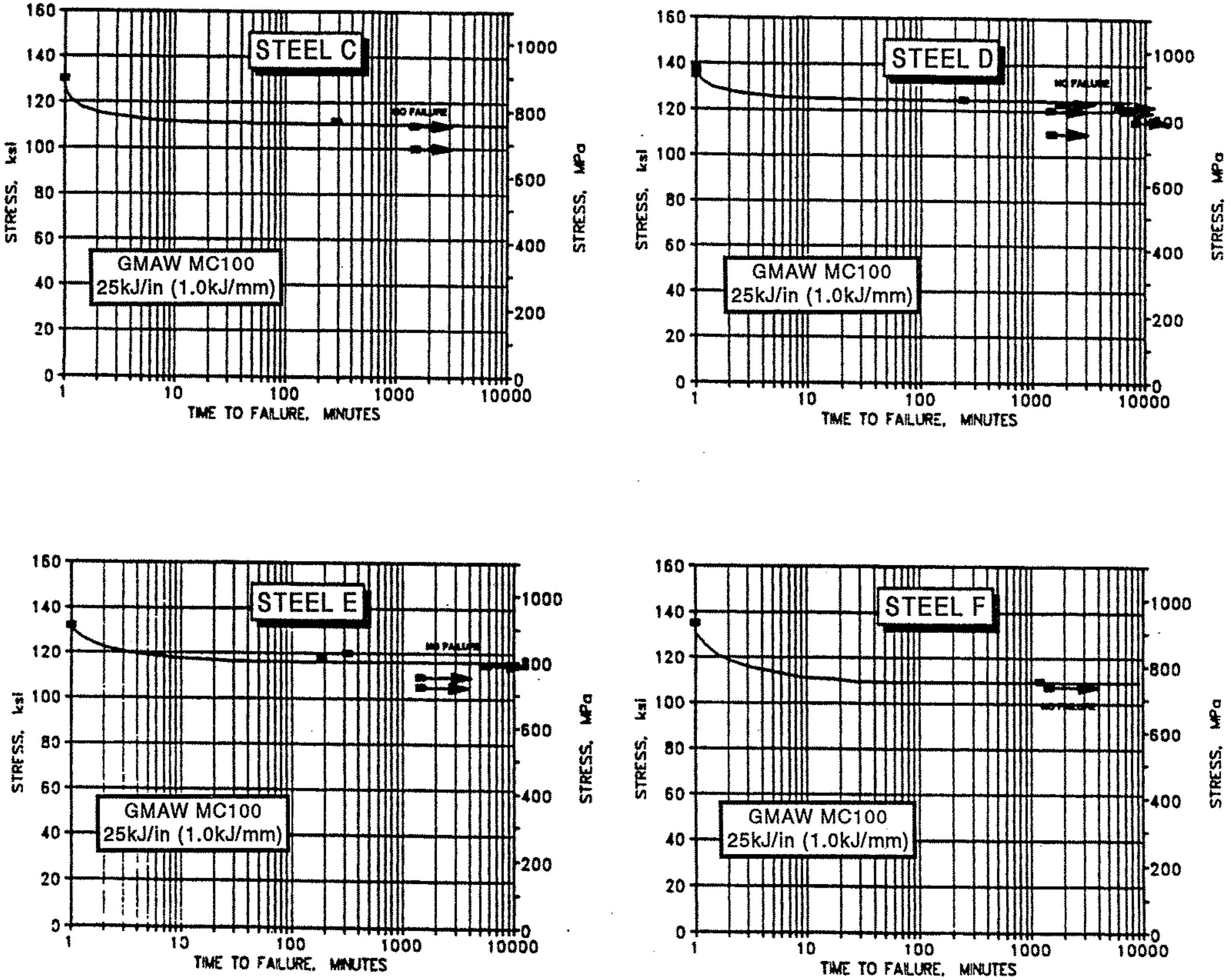


Figure 16 - Implant Results for 1-inch Steels C, D, E and F Welded with GMAW Using an MC100 Metal Cored Filler Wire

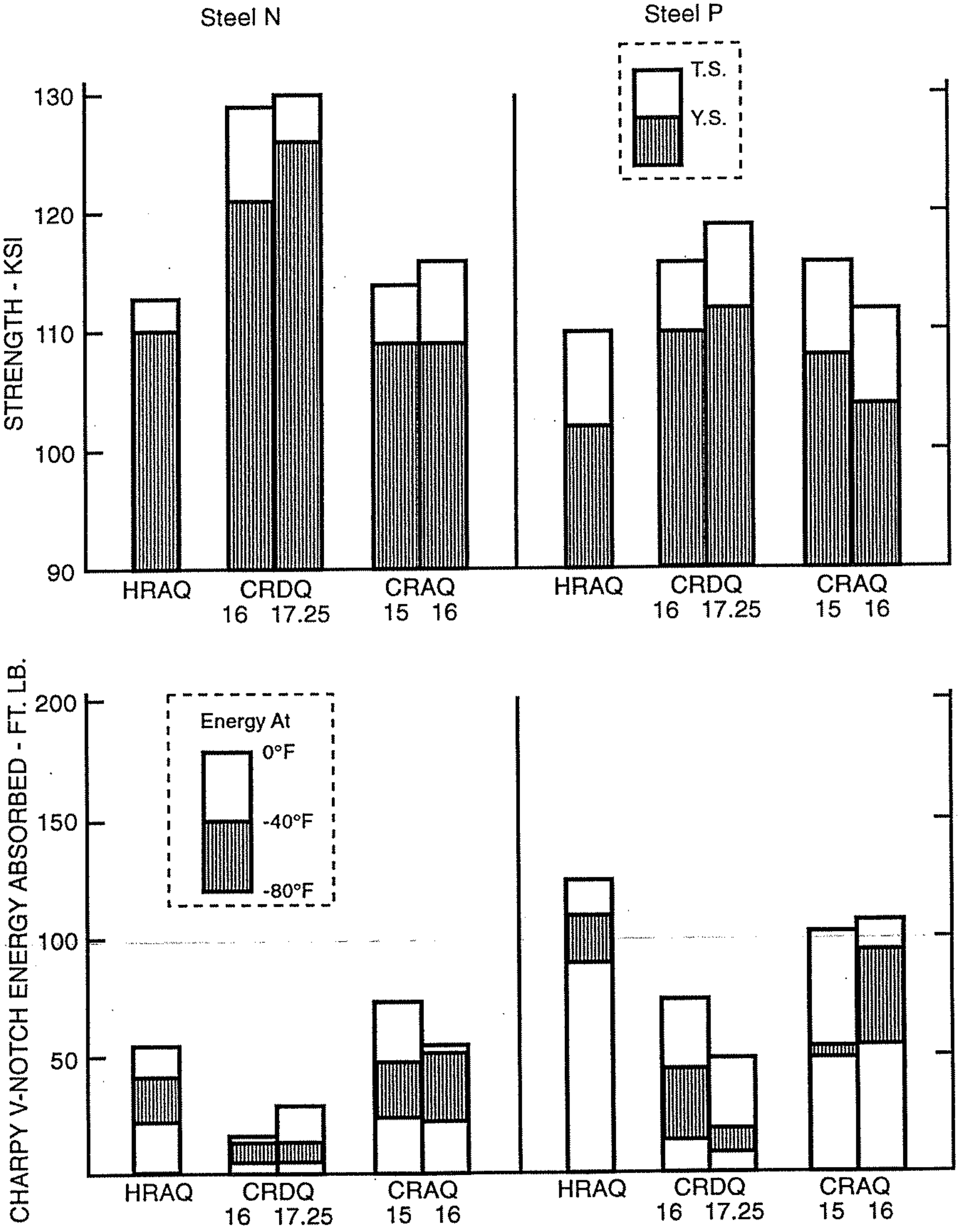


Figure 17 - Comparison of Strength and Toughness for Steels N and P

95-D010

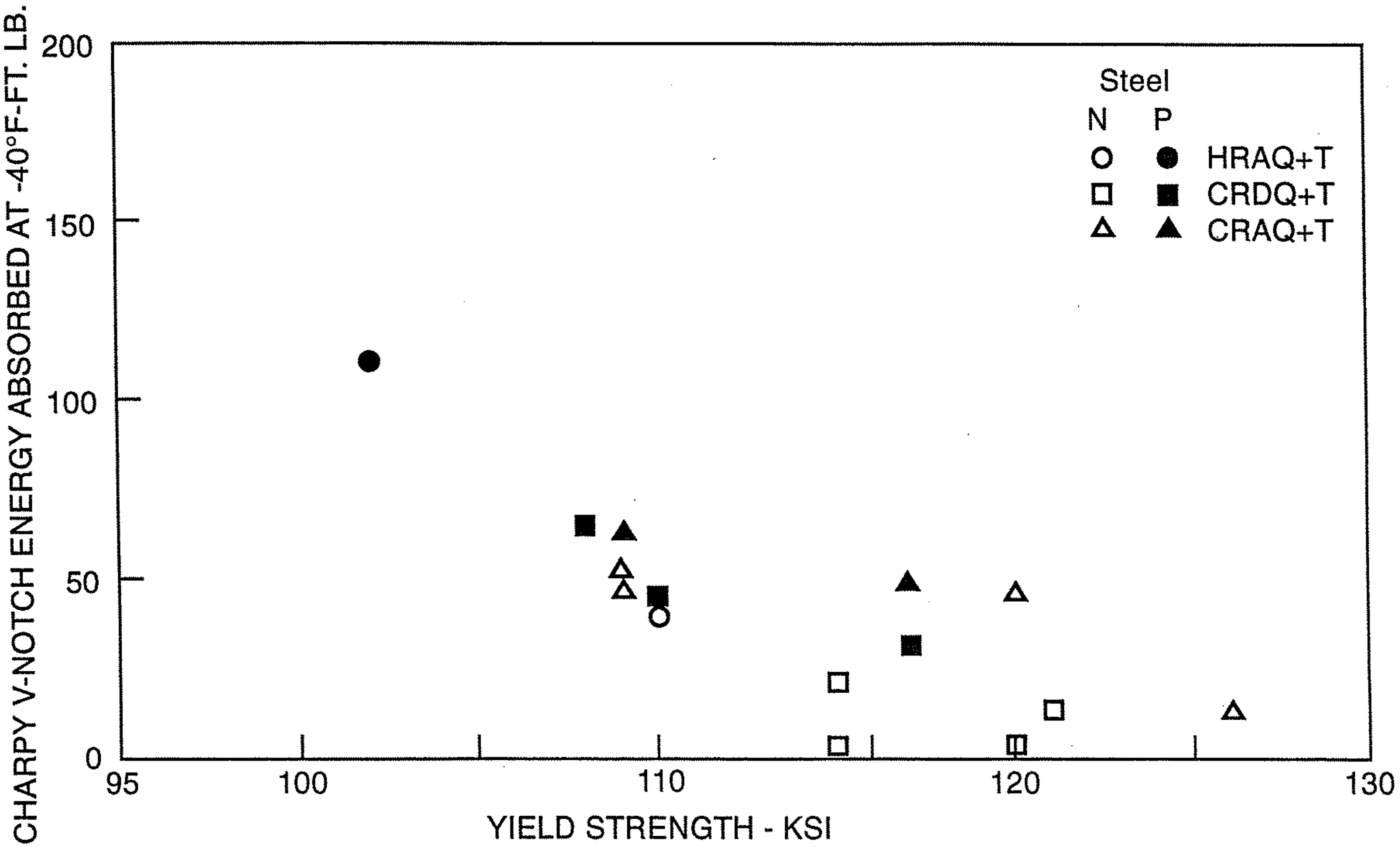


Figure 18 - Relation Between Yield Strength and Toughness for Steels N and P

95-D010

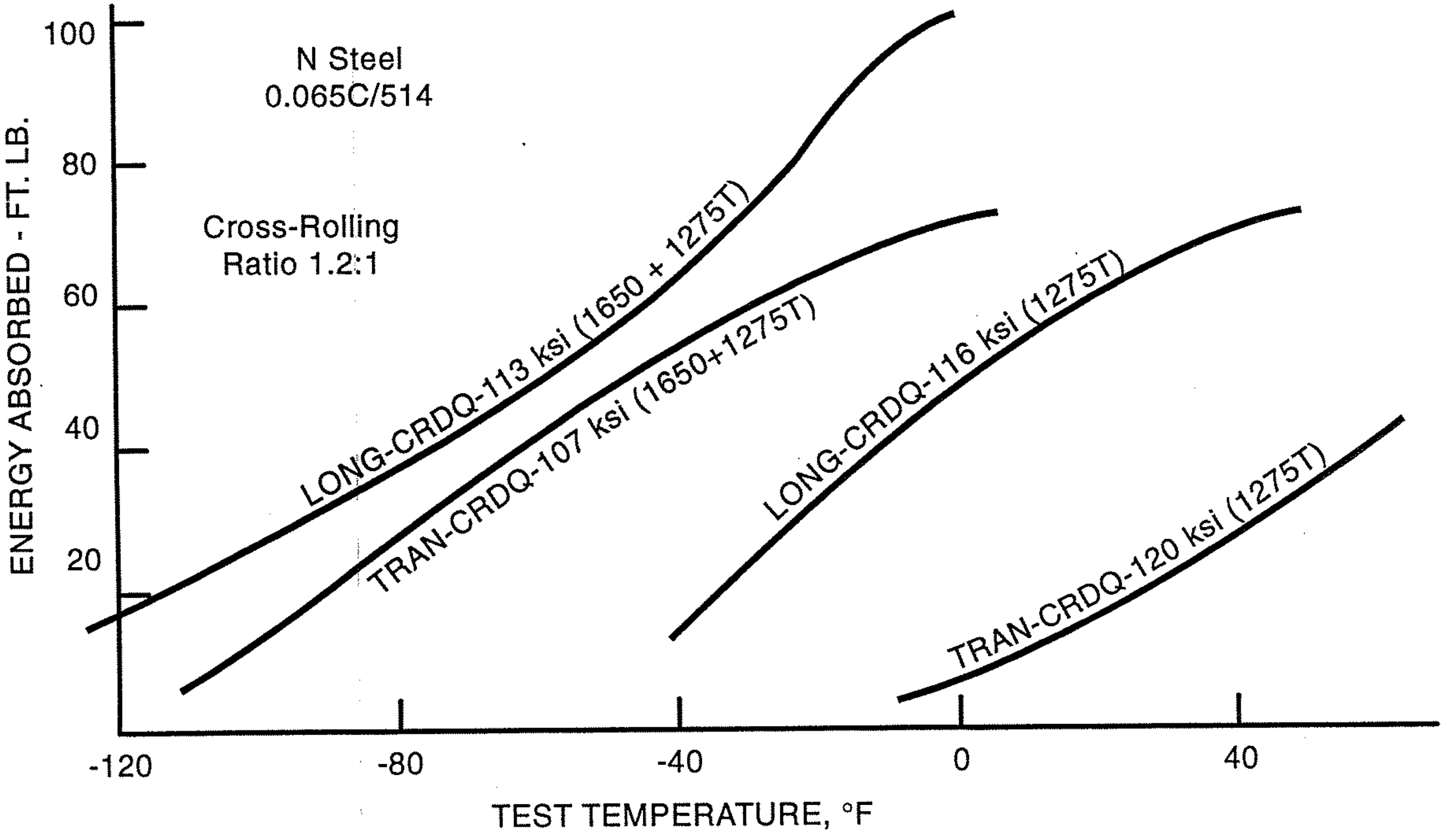


Figure 19 - Anisotropy Effects of Longitudinal vs Transverse Testing

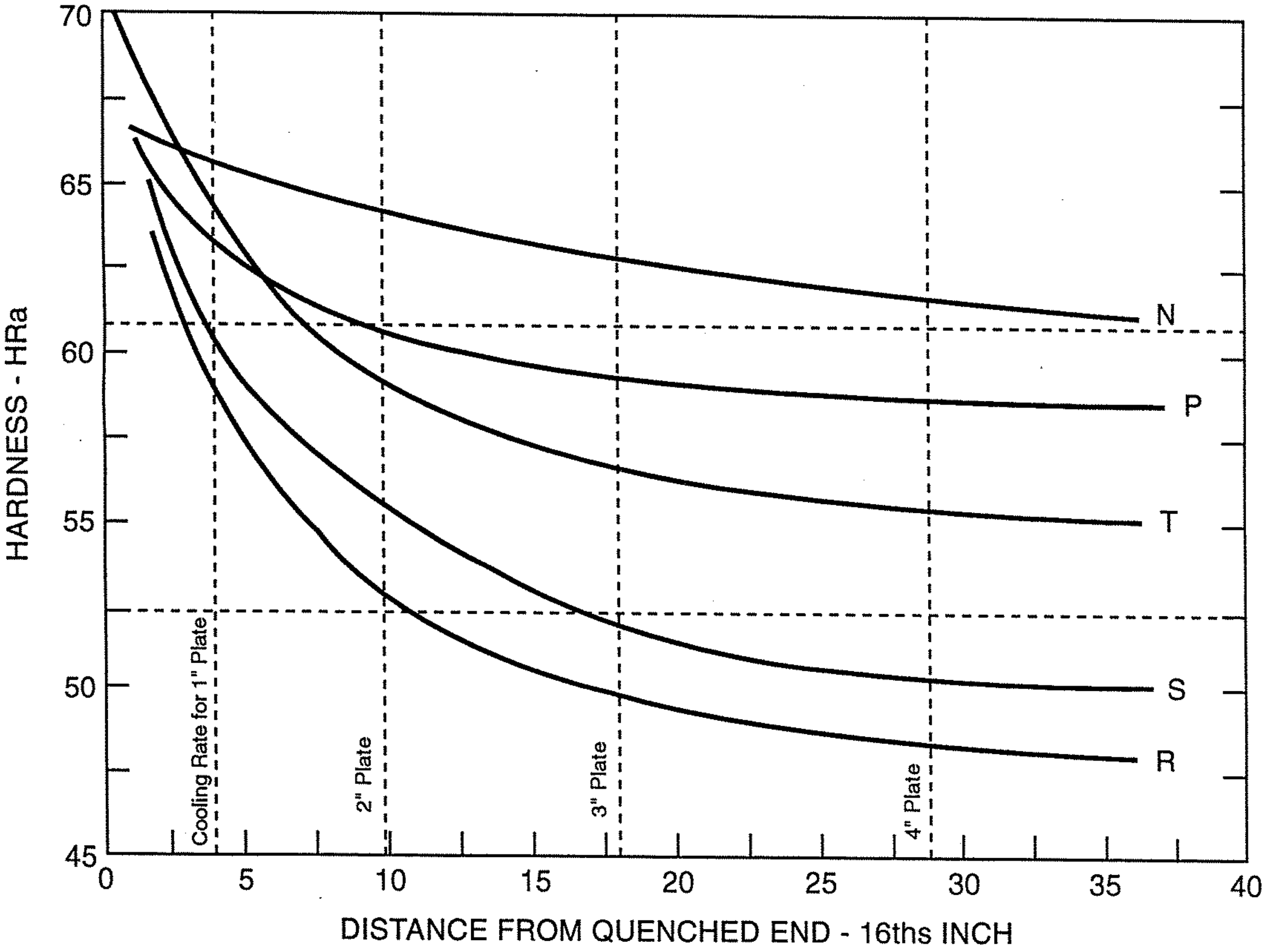
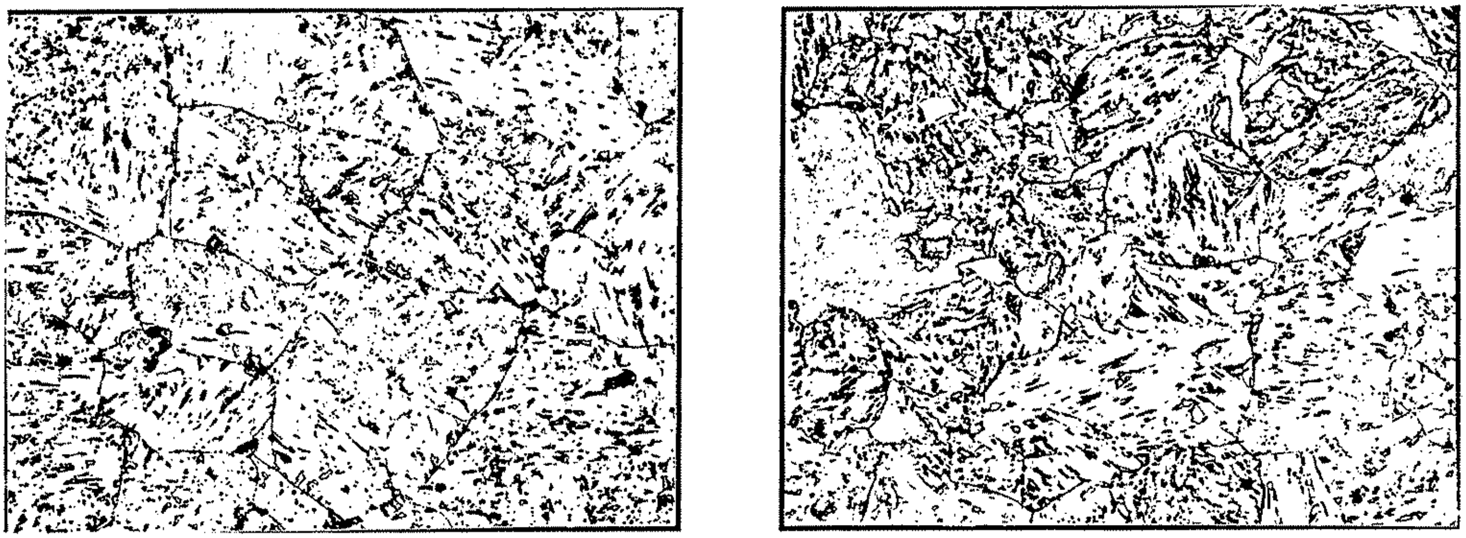


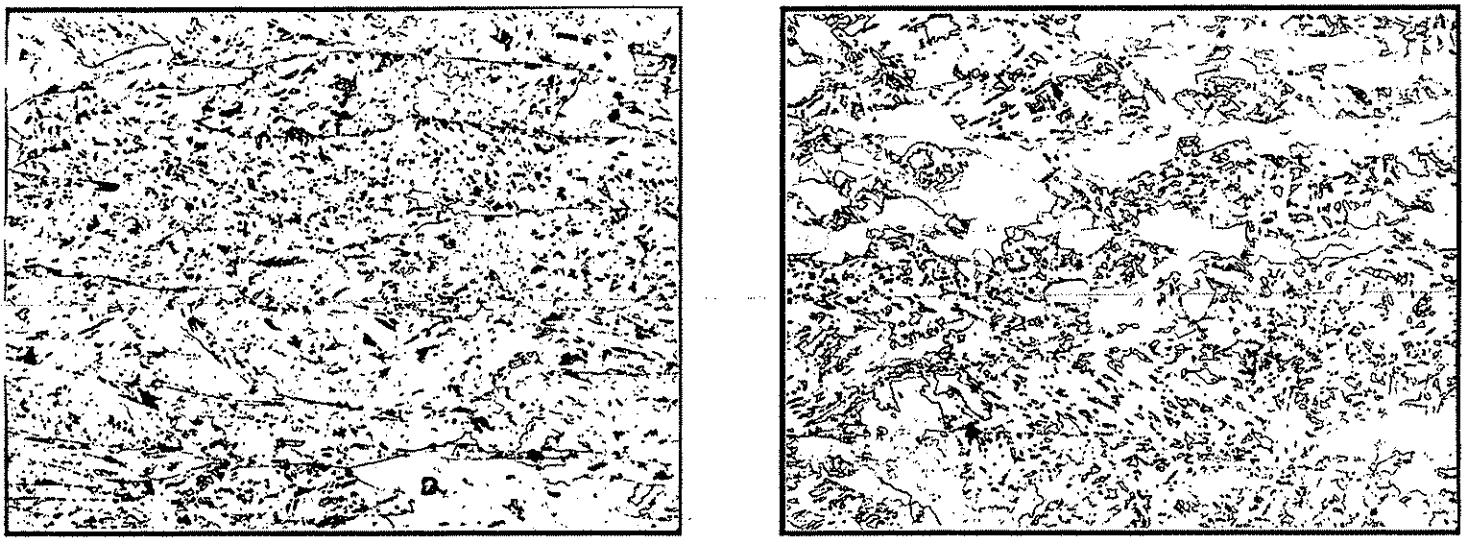
Figure 20 - Jominy Test Results for Steels N, P, R, S and T

95-D010



HRA-19 HRA-19

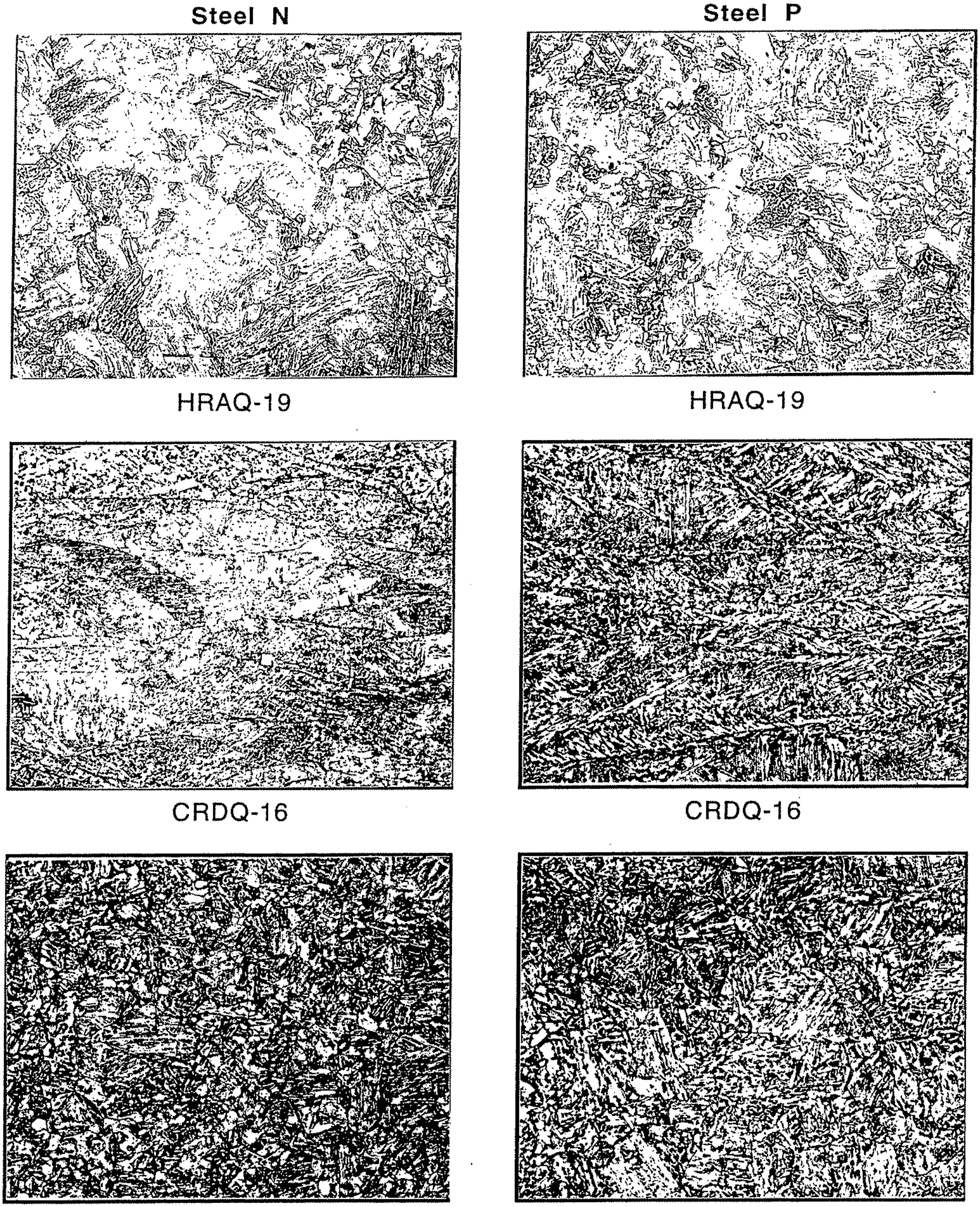
Steel N **Steel P**



CRA-16 CRA-16

Nital-Picral x 400

Figure 21: Micrographs of Steels N and P, Hot-Rolled or Control-Rolled and Air-Cooled



Steel N **Steel P**

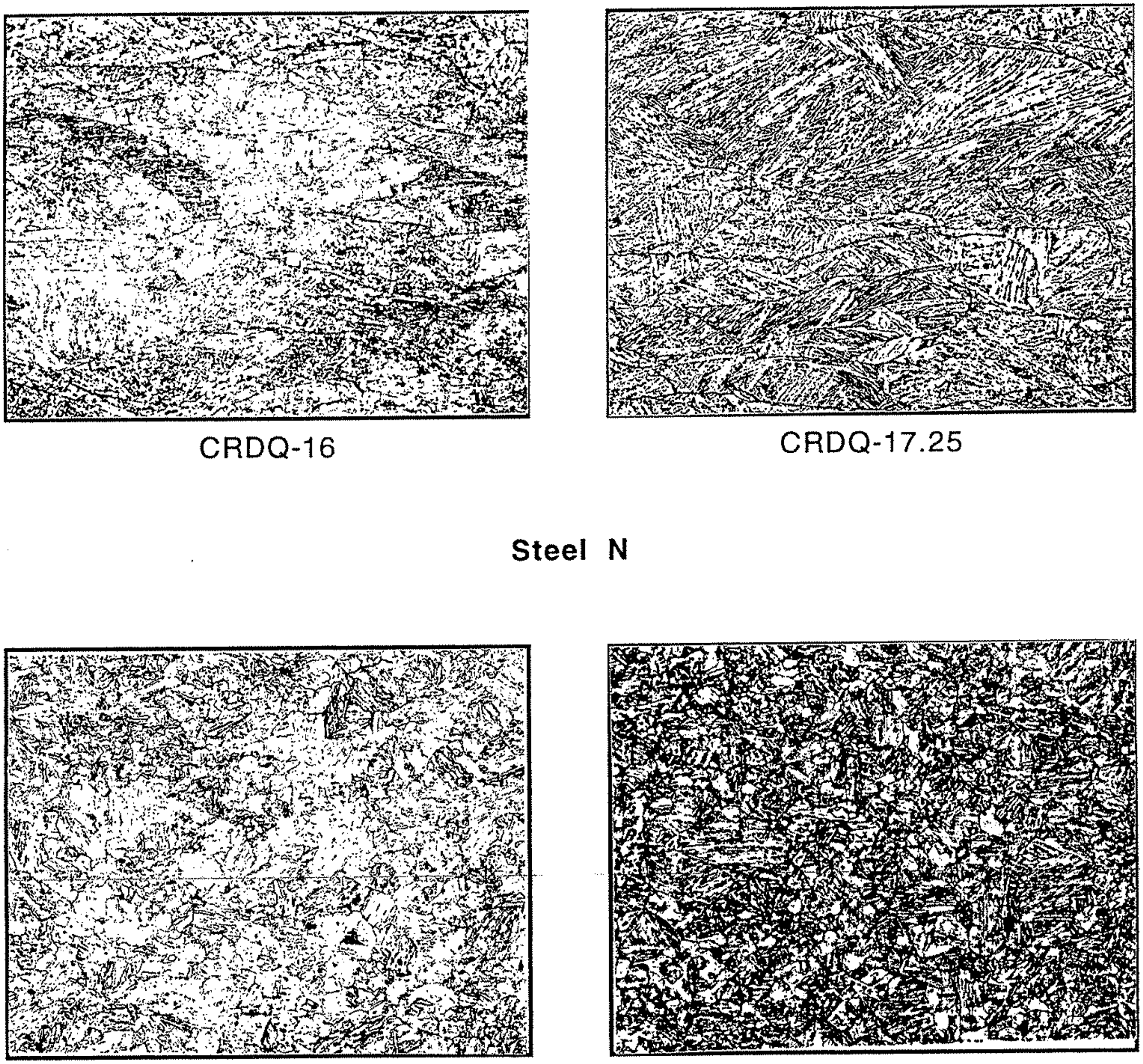
HRAQ-19 HRAQ-19

CRDQ-16 CRDQ-16

CRAQ-16 CRAQ-16

Nital-Picral x 400

Figure 22: Micrographs of Steels N and P, As-Quenched



CRDQ-16

CRDQ-17.25

Steel N

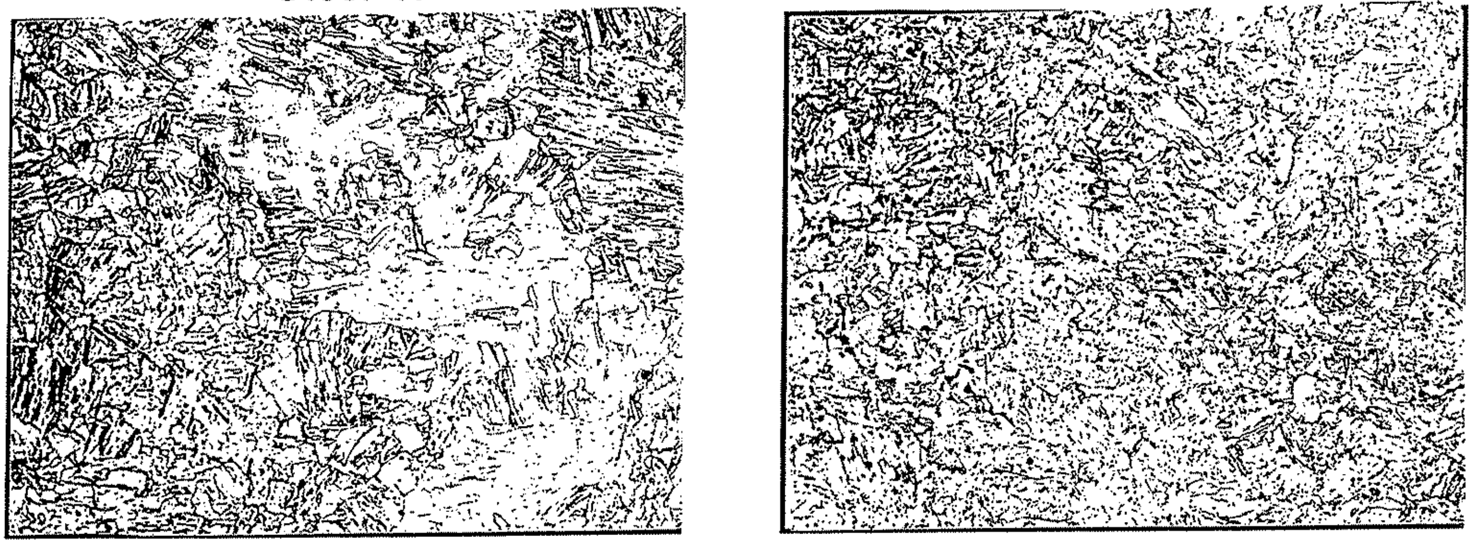
CRAQ-15

CRAQ-16

Nital-Picral x 400

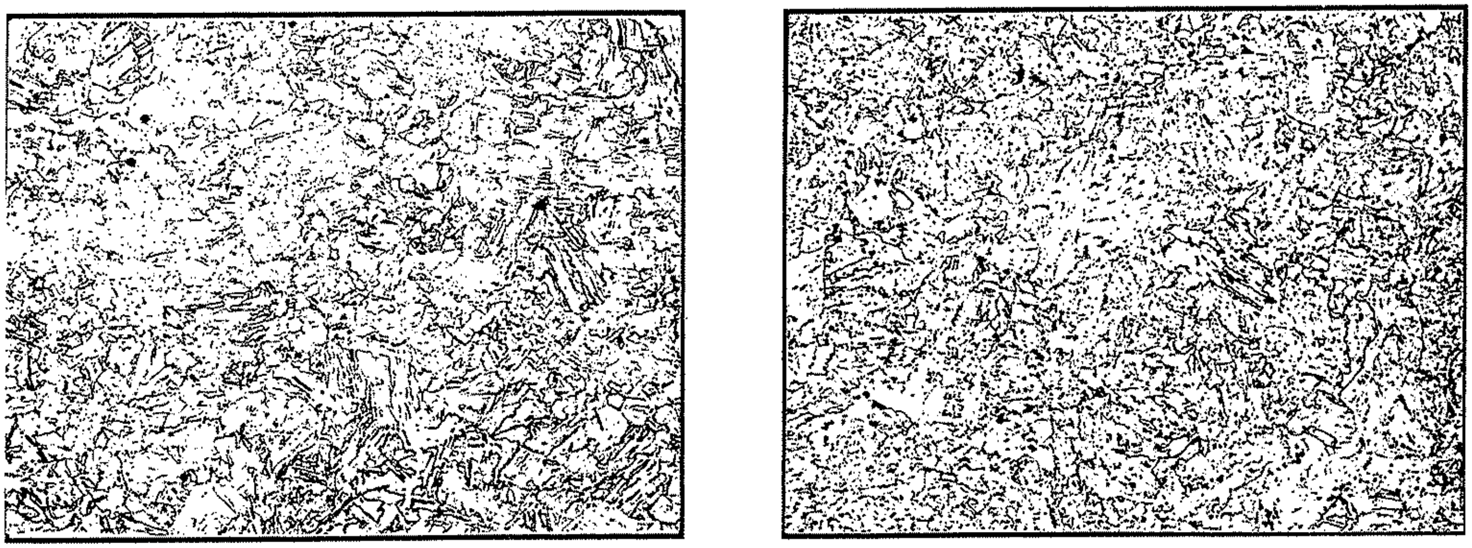
Figure 23: Effect of Controlled-Rolling Finishing Temperature on Microstructure of Steel N

Steel N **Steel P**



HRAQ-19+1275T HRAQ-19+1275T

CRDQ-16+1275T CRDQ-16+1275T



CRAQ-16+1275T CRAQ-16+1275T

Nital-Picral x 400

Figure 24: Effect of Tempering on Microstructure of Steels N and P

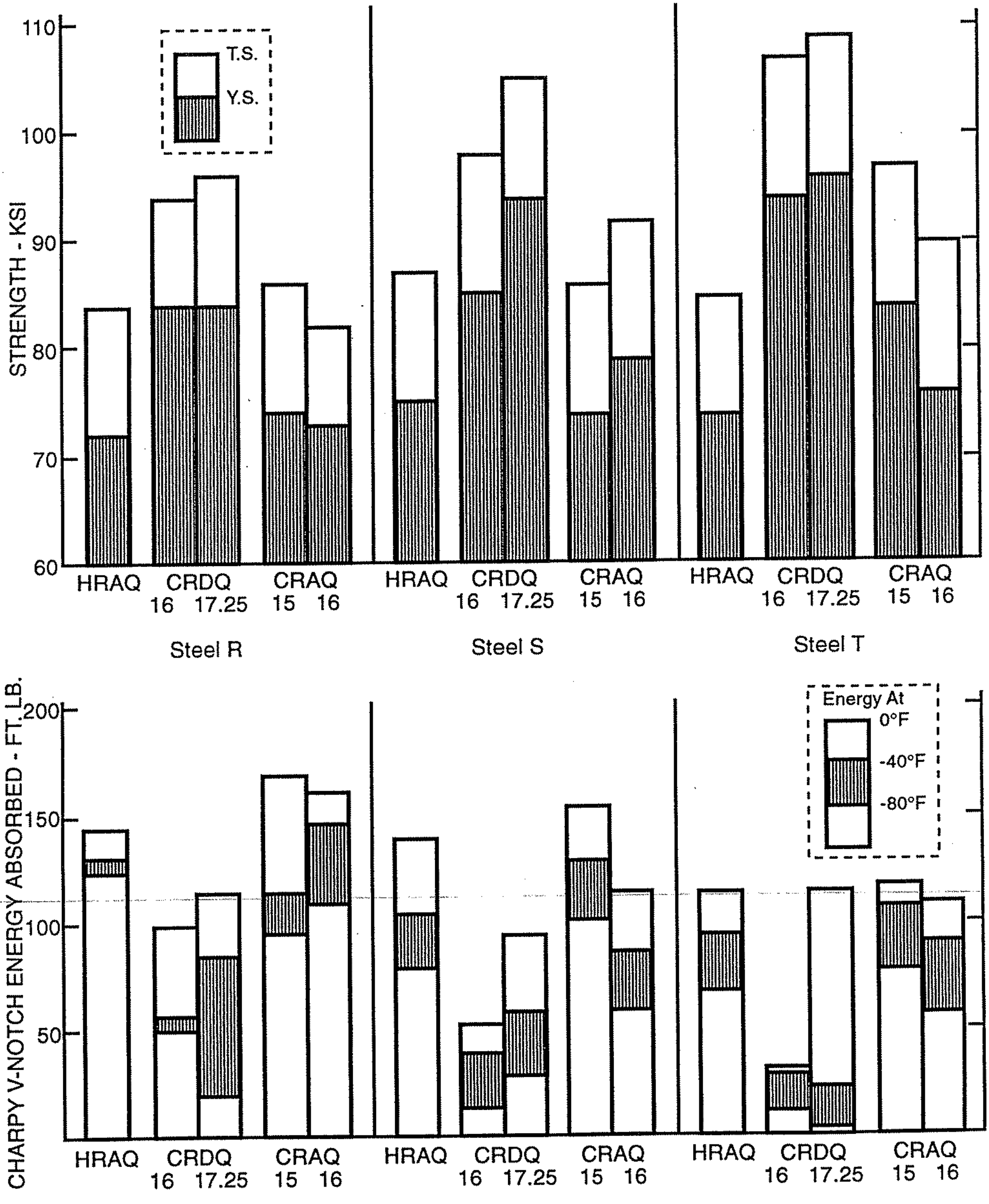


Figure 25 - Comparison of Strength and Toughness for Steels R, S and T

95-D010

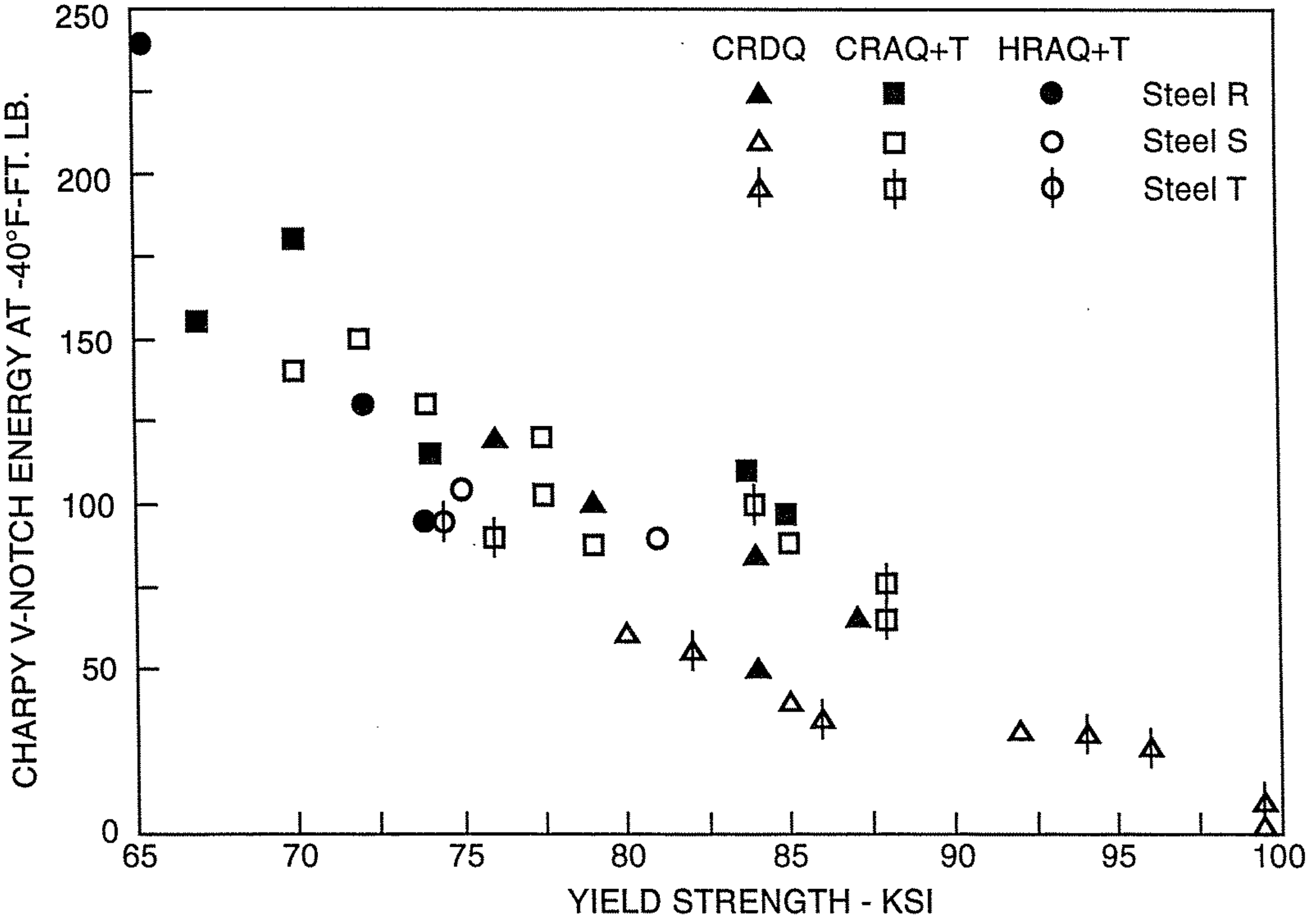
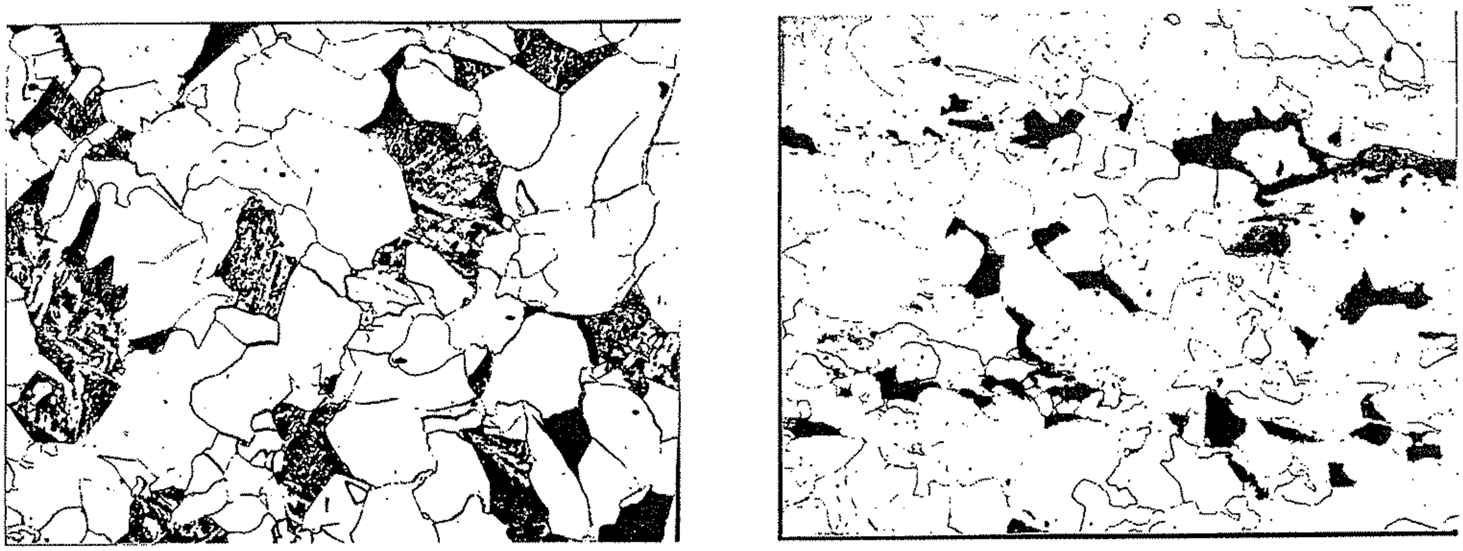
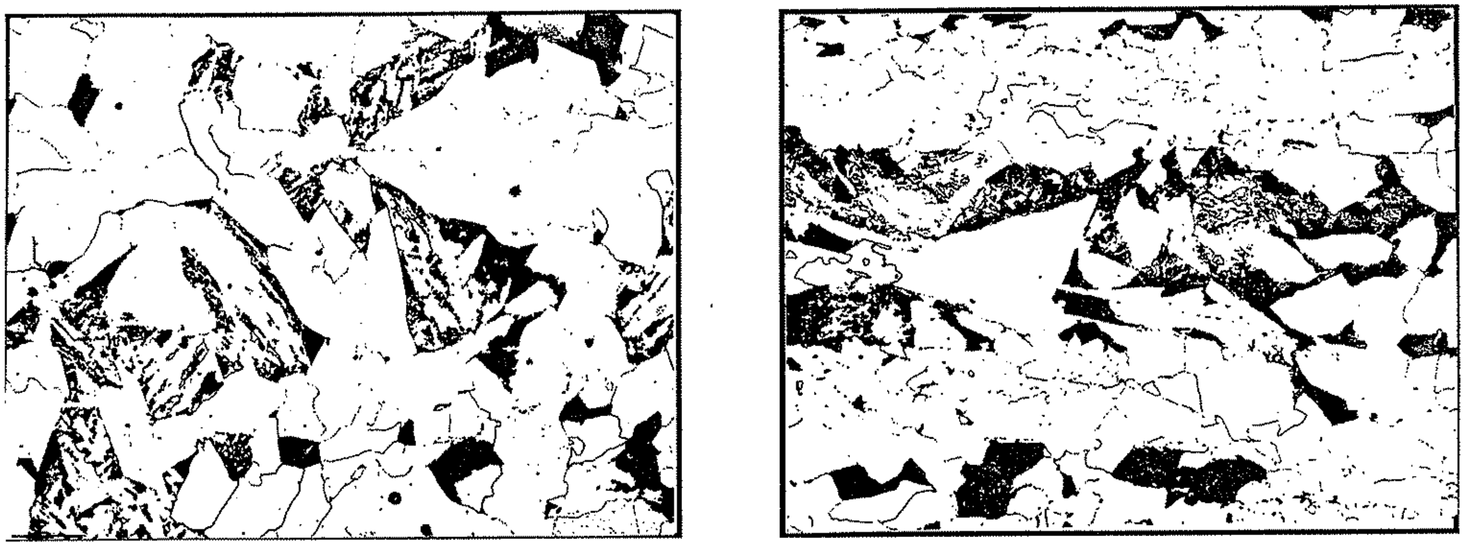


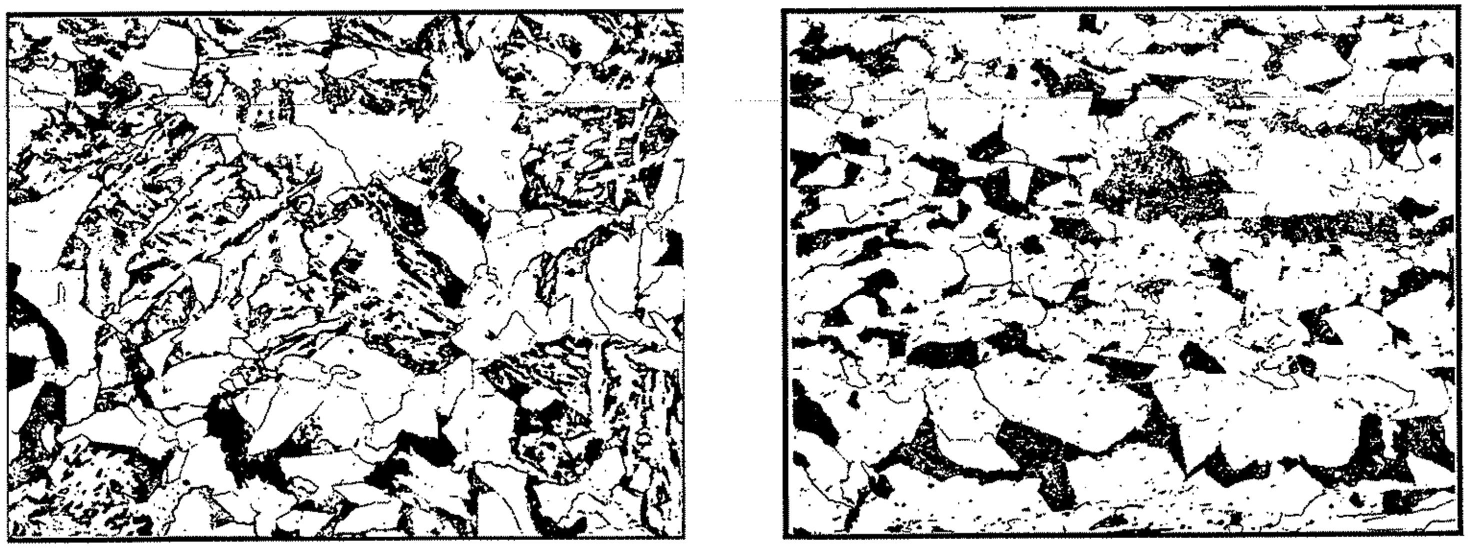
Figure 26 - Relation Between Yield Strength and Toughness for Steels R, S, and T



HRA-19 **Steel R** CRA-16



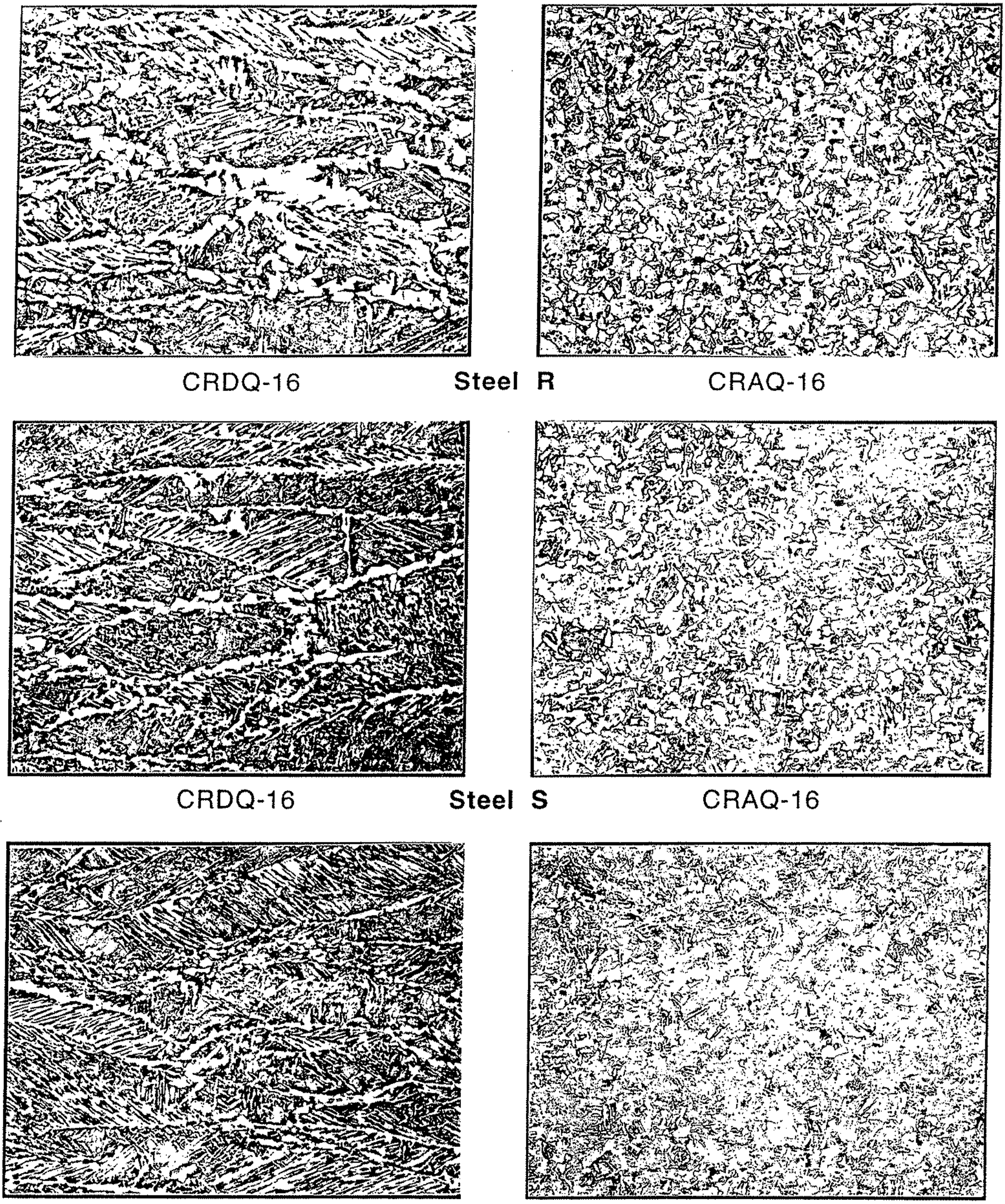
HRA-19 **Steel S** CRA-16



HRA-19 **Steel T** CRA-16

Nital-Picral x 400

Figure 27: Micrographs of Steels R, S and T, Hot-Rolled or Control-Rolled and Air Cooled



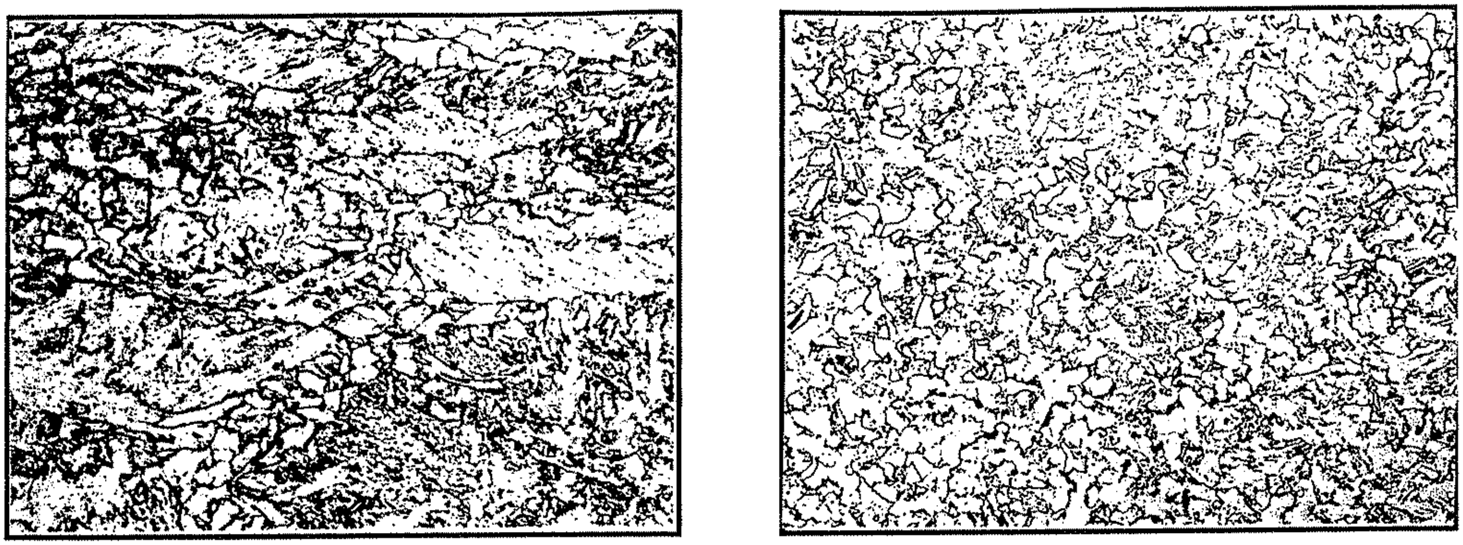
CRDQ-16 **Steel R** CRAQ-16

CRDQ-16 **Steel S** CRAQ-16

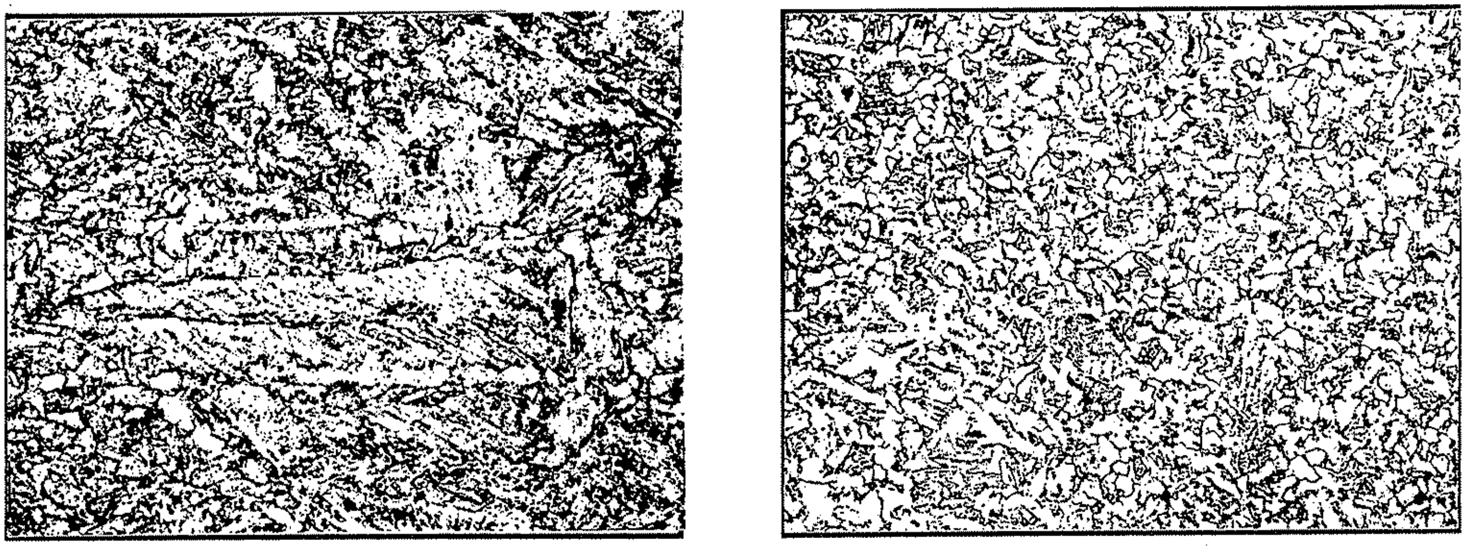
CRDQ-16 **Steel T** CRAQ-16

Nital-Picral x 400

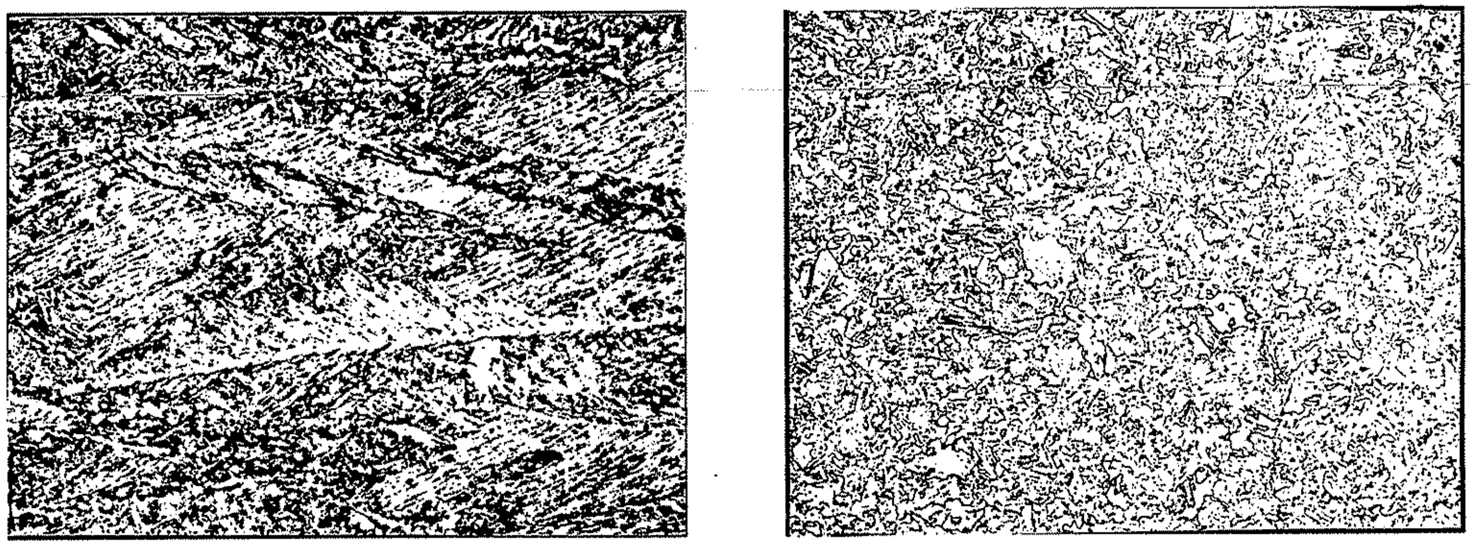
Figure 28: Micrographs of Steels R, S and T, As Quenched



CRDQ-16+1275T **Steel R** CRAQ-16+1275T



CRDQ-16+1275T **Steel S** CRAQ-16+1275T



CRDQ-16+1275T **Steel T** CRAQ-16+1275T

Nital-Picral x 400

Figure 29: Tempering on Microstructure of Steels R, S and T