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MODIFIED 43XX STEELS FOR HIGH TOUGHNESS

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N.J. Kar, V.F. Zackay and E.R. Parker
Department of Materials Science and Mineral Engineering
University of California
Berkeley, California 94720

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10 [redacted]J. KAR, V.F. ZACKAY [redacted] E.R. PARKER

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Isothermal transformations were carried out in the vicinity of M_s (subs) temperatures on Si, Al+Si modified AISI 4330, 4340 steels, which had been remelted by electroslag refining (ESR) techniques. The microstructures of the heat-treated variants were characterized by transmission electron microscopy. Mechanical property evaluations (Charpy impact energies, tensile strengths, plane-strain fracture toughness data) of the different microstructures were also carried out. Isothermal transformations in these steels resulted in bainite, → next page

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bainite + martensite microstructures, containing moderate amounts of retained austenite. The austenite was found to be in the form of thin films around the bainite, martensite laths. The strength-toughness combinations obtained in this investigation for Si-modified AISI 4330 steel appear to be superior to those for unmodified AISI 4340 and 300-M steels, whilst the strength-toughness combinations obtained for Al+Si modified AISI 4340 steel appear to be comparable to those for 18 NiCoMo maraging steel. The merits of ESR-processing these steels are also reflected in the uniform Charpy impact properties obtained for the different orientations investigated.

PREFACE

This final report describes work performed under contract DAAG46-78-C-0036 for the Army Materials and Mechanics Research Center. This report was prepared by Dr. Naresh J. Kar, Project Leader for the program through December 31, 1979, currently Senior Metallurgist, Anamet Laboratories Inc., Berkeley, CA 94710. Research for this program was performed under the direction of Professors V.F. Zackay and E.R. Parker at the Department of Materials Science and Mineral Engineering, University of California, Berkeley. The help of Dr. M.S. Bhat in administering the early stages of this program is acknowledged. The following personnel also assisted in the program:

Undergraduate Research Helpers: Philip Smith and John Chu.

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1. INTRODUCTION

The objective of this research program has been to develop high strength steels with maximum toughness and ductility, with a view to thereby enhancing their blast protection properties. Although the mechanical properties associated with adequate blast protection are not fully understood, the premise followed has been that a steel which manifests high strength concomitant with high toughness and ductility is likely to exhibit favorable blast protection properties.

In this investigation, the merits of combining two metallurgical principles: (i) the incorporation of a Transformation Induced Plasticity (TRIP) phenomenon and (ii) the improvements associated with utilizing a secondary refining process - the Electroslag refining process, have been investigated. These will now be elaborated upon.

Early research has shown that a class of steels termed TRIP,[1,2,3] (Transformation Induced Plasticity) steels were found to achieve high degrees of plasticity, associated with the strain-induced transformation of a microstructural phase, austenite, to martensite, thereby enhancing the effective ductility of these steels. Research conducted at Berkeley over the years has shown that it has been possible to incorporate this "trip" phenomenon in commercial grade steels such as AISI 4330[4] and 4340[5,6] steels. By suitable composition and heat treatment modifications,

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[1] V.F. Zackay, E.R. Parker, D. Fahr, R. Busch, Trans. ASM 60, pp 252-259 (1967).

[2] M.D. Bhandarkar, V.F. Zackay, E.R. Parker, Met. Trans. 3, p 2619 (1972).

[3] W.W. Gerberich, P.L. Hemming, V.F. Zackay, E.R. Parker, Fracture 1969, P.L. Pratt (editor) Chapman and Hall Ltd. London p 288 (1969).

[4] G. Kohn, Ph.D. Thesis, University of California, Berkeley (Nov. 1976).

[5] M.S. Bhat, Ph.D. Thesis, University of California, Berkeley (Feb. 1977).

[6] N.J. Kar, Ph.D. Thesis, University of California, Berkeley (June 1979).

these steels have been shown to exhibit excellent combinations of strength and toughness, associated with the presence of retained austenite and its subsequent transformation under stress/strain. It has been demonstrated that through the control of microstructural and metallurgical variables, an increase in the fracture toughness of these steels has been possible without a significant decrease in strength levels. The use of transmission electron microscopy has identified microstructural features such as martensite substructure (dislocated versus twinned), films of interlath retained austenite ("conditioned" to exhibit suitable stability), and a fine grain size as being beneficial to the improved strength-toughness combinations that can be obtained in this class steels.

The presence of clean steels has also been suggested[7,8] to improve the mechanical properties of steels. The demand for enhanced performance of steels has led to the investigations of melting and casting processes which result in clean steels. The electroslag refining process (ESR) has stimulated much interest among metal producers, both in the United States and abroad. A recent study at Berkeley[9] has shown that superior mechanical properties were obtained in ESR melted 300-M steel as compared to conventional vacuum arc remelted 300-M steel.

The ESR process is a secondary refining process in which a consumable electrode is melted so that droplets of molten metal pass through a refining slag layer (usually CaF_2-CaO mixtures), as illustrated in Figure 1. The ingot continuously solidifies in a water-cooled mold such that vertical dendritic growth is promoted. Casting defects such as shrinkage, segregation of elements and axial porosity are minimized. By proper slag control, the ESR technique has been found to reduce

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[7]R.H. Nafziger, R.L. Lincoln et. al., in Bulletin 669, United States Department of the Interior, Bureau of Mines.

[8]A. Boucher, A. Mercier, Re. Metallurgie 69, 1972, pp 13-22.

[9]T. Lechtenberg, M.S. Thesis, University of California, Berkeley (Feb. 1977).

sulphur contents to trace levels.[10,11] It has thus generally been recognized[12,13] that secondary remelting by the ESR process has resulted in improved ingot cleanliness, superior chemical homogeneity and structural uniformity throughout the ingots, compared with conventional melting practice.

The literature[14,15] cites examples of improved reductions in anisotropy of impact strengths in ESR-refined structural steels with increase in their absolute values. Other mechanical properties such as tensile strength, ductility and fatigue resistance have also been found to be more favorable in ESR processed steels as compared to conventional air-melted material. These improvements in mechanical properties have been attributed to a decrease in inclusion contents and their more favorable distribution arising as a result of ESR processing.[16,17]

Thus, in the present program ESR processing of modified AISI 4340 and 4330 steels was evaluated, with a view to enhancing strength-toughness combinations that could be obtained, incorporating: i) the merits of a TRIP phenomenon and ii) the improvements associated with ESR processed ingots.

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[10] A. Mitchell, M. Etieene, Trans. Met. Soc. AIME 242, p 1462 (1968).

[11] R. Schlatter, Met. Eng. Quart. 12, pp 48-60 (1972).

[12] Nafziger, see footnote p 2.

[13] Schlatter, see above.

[14] Nafziger, see above.

[15] L. Antoine et. al., Proc. 1st Internat. Symp. on Electrolag Consumable Electrode Remelting and Casting Tech., Pittsburgh PA, Aug. 1967, G.K. Bhat (editor) Carnegie Mellon-University.

[16] Nafziger, see above.

[17] Lechtenberg, see footnote p 2.

The heat treatment schedules used in this investigation were: a) Isothermal transformations above the M_s temperature to give mixtures of primarily lower bainite + retained austenite, b) Isothermal transformations below the M_s temperature to give mixtures of tempered martensite + lower bainite + retained austenite. These structures were subsequently tempered over a range of temperatures.

The emphasis in the use of isothermal transformations will now be discussed. Whether or not isothermal transformations are relevant to thick sections, or whether or not continuous cooling results in mixed microstructures is intimately related to the steel's hardenability. From a practical standpoint, interest in these isothermal transformation results stems from the fact that the microstructures obtained are equivalent to what might be obtained in the continuous cooling of thick plate. Experimentally, however, it is easier to control the final microstructures by isothermal transformation. Isothermal transformations also result in substantial amounts of the microconstituent -- austenite, being retained in the modified 43XX steels. The mechanisms of austenite retention have been related to 1) Mechanical stabilization[18] - the shear component of the bainite transformation constraining the austenite, preventing its further decomposition; 2) Chemical enrichment[19] - partitioning of C atoms from ferrite to austenite, lowering local M_s temperatures and 3) Thermal stabilization[20] - C atoms forming atmospheres in the substructures preventing interface motion, thereby preventing the bainite reaction from saturating, resulting in austenite retention.

Thus, in this investigation, by the proper choice of heat treatment schedules, the austenite has been "conditioned" to impart a maximum stability to stress/strain, thereby enhancing the toughness of these steels.

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[18] P.M. Kelly, J. Nutting, JISI 197, p 199 (1961).

[19] G.R. Speich, W.C. Leslie, Met. Trans 3, p 1043 (1972).

[20] G.S. Ansell, S.J. Donachie, R.W. Messler, Met. Trans. 2, p 2443 (1971).

2. EXPERIMENTAL PROCEDURE

2.1 Material Preparation

The alloy steel plates being used in this program are AISI 4330 + 2%Si and AISI 4340 + 1.5%Al + 1.5%Si. Ingots of the two alloys were air-induction melted at Army Materials and Mechanics Research Center, Watertown, MA. These ingots were then electroslag remelted (ESR) to produce 8" x 8" round cornered square ingots. The ingots were then forged from a temperature of 2200°F to one-inch thick plate. The axis of each ESR ingot lay in the plane of the plate, pointing towards the cut ends.

A chemical analysis was carried out on each ingot and is presented in Table 1. Chemical analysis revealed that an initial AISI 4340 modified ingot was of a lower carbon content than the required 0.4 wt-pct. Consequently, a new ingot was cast and ESR processed. The chemistry of this ingot (ESR-77) is also presented in Table 1.

The plates were homogenized in vacuum (4340 + 1.5Al + 1.5Si)/ argon-atmosphere (4330 + 2Si) at 2200°F for 48 hours to ensure uniformity of composition. These were then furnace-cooled to room temperature.

2.2 Heat Treatments

Oversized specimen blanks were heat-treated in vertical tube furnaces using an argon atmosphere (Fig. 2). Specimens were either quenched into oil, or an oversized salt pot placed beneath the tube furnace. The salt pot temperature was closely monitored, with a maximum change of $\pm$ 2°C. Tempering of all specimens was carried out in small neutral salt baths, followed by a water quench.

2.3 Mechanical Testing

2.3.1 Charpy Impact Testing: Room-temperature Charpy tests were carried out as per ASTM E-23-72. Oversized heat-treated blanks, were machined down to the final dimensions using flood-cooling (Fig. 3). An average of two and, in some cases, three Charpy energies are reported for each heat-treated condition. The Charpy orientations are shown in Fig. 3.

2.3.2 Fracture Toughness Testing: Compact tension specimens (Fig. 4) were used to carry out additional fracture toughness tests in part of the investigation. Specimens were tested in the L-T orientation. Prior to heat treatment, compact tension specimens were machined to final dimensions plus 0.05 in. per side for decarburization. These were ground to final dimensions after heat treatment, using flood-cooling. An 0.008-in. slot was ground into the specimen and fatigue cracking was carried out on a high-cycle MTS machine. The specimens were pulled on a 300-KIP capacity MTS machine at a ram speed of 0.005 in./sec. A crack opening displacement gage was used to monitor the crack length. From the load-displacement curves, the fracture toughness was calculated as per ASTM E399-72.

2.3.3 Hardness Testing: Two parallel cuts were made on each broken Charpy bar, using a flood-cooled wafer saw. An average of five hardness readings were taken on these flat specimens, using the R_c scale of a Wilson Rockwell Hardness tester.

2.3.4 Tensile Testing: Tensile properties were determined using 1 in. gage length, 1/4 in. diameter round tensile specimens, as shown in Fig. 3. Oversized specimens were heat-treated and then ground to final dimensions, using flood-cooling. Tests were conducted at room temperature using a 300-KIP MTS testing machine, at a cross-head speed of 0.04 in/min. From the load displacement curves, yield strengths were determined by the 0.2 percent offset method. The elongation to fracture was obtained by monitoring distance between fixed points, before and after testing, using a Vernier travelling microscope.

2.4 Microstructural Characterization

2.4.1 Optical Metallography: Optical Metallography was used to characterize prior austenite grain size and the presence of undissolved carbides. Since the low resolution of optical microscopy makes it virtually impossible to distinguish between martensitic and bainitic microstructures, limited metallography of isothermal transformation products by this means was carried out. For grain-size measurements, heat-treated specimen cubes were mounted in bakelite, abraded using SiC paper down to 600 grit and polished on 1μ diamond abrasive wheel. A Picral etchant was used to reveal prior austenite grain boundaries.

2.4.2 Transmission Electron Microscopy: Thin foils for transmission electron microscopy were obtained from broken Charpy bars. Using a wafer saw, slices 20 mil thick were obtained; these were ground down using an abrasive wheel to 12-14 mil and then chemically thinned in a solution of $HF-H_2O_2$ to 5 mil. Discs 3.0mm in diameter were spark cut from these slices. These discs were then mechanically sanded down to 1 mil thick foils. Finally, electropolishing was carried out in a Chromic-acetic acid solution (75 gm CrO_3, 400ml CH_3COOH, and 21ml distilled water) using an ice-water cooling bath, with an operating voltage of 40-45 volts.

The electropolished thin foils were stored in alcohol and subsequently examined in a JEM 7A and Philips EM301 microscope, at an operating voltage of 100KV.

2.4.3 X-Ray Analysis: A Picker X-ray diffractometer, using CuKα radiation was used to estimate retained austenite in the heat-treated specimens. Broken Charpy bars were mechanically polished and etched in a solution of $HF-H_2O_2$. The specimens were scanned from 72° to 96° to include the (311)γ, (211)α and (220)γ peaks. Quantitative estimates of the amount of retained austenite were made by using a computer program which scanned the peaks, and gave a numerical estimate of the integrated intensities after suppressing the background noise. The program was checked using a National Bureau of Standards specimen of 3.9% retained austenite and reflected an accuracy of ± 0.2% austenite in the quantitative measurements. To eliminate preferred orientations, specimens were rotated through 90° and quantitatively re-checked.

2.5 Scanning Electron Microscopy and Energy Dispersive Analysis of X-Rays: The fracture surfaces of broken Charpy bars were examined on an AMR-1000 scanning electron microscope at an operating voltage of 20KV. Inclusions on the fracture surfaces were analyzed using an Energy Dispersive Analysis of X-rays (EDAX) unit appended to the microscope.

3. RESULTS AND DISCUSSION

3.1 This research program was conducted in two phases:

Phase I: Mechanical Property Evaluations

(a) The toughness of the steels in the different heat treated variants was evaluated. The main test for toughness evaluations was the Room-Temperature Charpy V-notch test. With a view to studying the effect of anisotropy on the toughness of ESR steels, Charpy impact data was evaluated in longitudinal and transverse orientations (See Fig. 3). A limited amount of plane strain fracture toughness tests were also carried out in the longitudinal direction on some of the heat-treated steels that appeared to show promising strength-toughness combinations.

(b) The uniaxial tensile properties of the steels were determined in the different heat treated conditions. These included evaluations of the yield strengths, ultimate tensile strengths and the percent elongations obtained in the tensile tests.

Phase II: Microstructure Characterization

Microstructural characterization of the as-transformed steels was carried out essentially using transmission electron microscopy. Because of the limitations in resolving bainitic and austenite microconstituents by conventional optical microscopy, only a limited amount of metallography of the isothermal microstructures was carried out. The presence of phases such as retained austenite and carbides in the microstructures was established by using dark-field imaging techniques in transmission electron microscopy, coupled with selected area diffraction techniques. The presence of retained austenite in the microstructures was also confirmed by X-Ray diffraction techniques, as described in Chapter 2. The amount of retained austenite as a function of tempering temperature was also monitored by X-Ray diffraction techniques.

3.1.1 The two steels investigated in this program were AISI 4340 + 1.5Al + 1.5Si and AISI 4330 + 2Si. The philosophy behind the choice of these compositions can be found in Refs. 4, 5 and 6. In this program, the intent was to obtain high strength-toughness combinations in steels that had showed promise in previous research efforts, and to further enhance these properties as a result of ESR processing. For the benefit of comparisons, data obtained in conventional vacuum arc remelt ingots (VAR) from previous investigations,[21,22] will also be discussed. For the purposes of clarity, the two steels will be discussed separately.

3.2 AISI 4340 + 1.5Al + 1.5Si

3.2.1 The heat treatment schedules used in this steel involved:
a) isothermal transformations above the M_s temperature - to give mixtures of lower bainite + retained austenite and,
b) isothermal transformations below the M_s temperature - to give mixtures of tempered martensite + lower bainite + retained austenite. The M_s temperature of the steel was determined to be 300°C by high speed quenching dilatometry. Thus the isothermal transformation temperatures chosen for heat treatments were (a) 350°C - for treatments above the M_s temperature and (b) 250°C - for treatments below the M_s temperature. A transformation time of 1 hour at isothermal temperatures was determined by dilatometry to be sufficient for the reactions to saturate.

The data obtained employing these heat treatments will now be presented and discussed.

3.2.2 Isothermal Transformations above M_s

3.2.2.1 Mechanical Properties: The longitudinal and transverse Charpy impact energies obtained for the 4340 + 1.5Al + 1.5Si steel isothermally transformed at 350°C are shown in Table III and are plotted as a function of tempering temperature in Figure 5. A comparison between ESR-processed

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[21] Kohn, see footnote p 1.

[22] Kar, see footnote p 1.

steel and vacuum arc remelted (VAR) steel is also presented in Table IV and Fig. 6.

The yield strength, ultimate tensile strength, % elongation, and hardness in the longitudinal orientations are shown as a function of tempering temperature in Table V and Fig. 7.

3.2.2.2 Correlations Between Mechanical Properties and Microstructure

The microstructure obtained after isothermal transformation at 350°C was essentially lower bainite with interlath films of retained austenite as shown in the transmission electron micrographs of Fig. 8. Note the reversal of contrast obtained when the aperture was placed on a carbide spot, as shown in (b). Interlath films of retained austenite are clearly delineated by the arrows in (c), obtained by dark-field imaging of the (200) austenite spot.

The volume percentage retained austenite is plotted as a function of tempering temperature in Fig. 7.

The results show that when ESR processed AISI 4340 + 1.5Al + 1.5Si steel was isothermally transformed above the M_s temperature, the microstructure was a mixture of bainite + retained austenite exhibiting high Charpy impact energies (50 ft-lbs) concomitant with yield strengths of 170 ksi and ultimate tensile strengths of 200 ksi. The microstructure was associated with approximately 12% retained austenite. The austenite was fairly stable to tempering up to 400°C beyond which it destabilized. The results of the Charpy impact energy data for the longitudinal and transverse orientations showed that at the higher Charpy energy levels, there did not appear to be a significant difference in the data for these orientations. On the other hand, tempering at 500°C resulted in a decrease in the Charpy impact energies, the embrittlement being slightly more pronounced for the transverse orientations.

On comparing the ESR-processed steel data with the data for VAR steel (Ref. 6), at the relatively high Charpy impact energy levels, the ESR steel appeared to exhibit equivalent Charpy properties to the VAR steel (See Table IV).

On evaluating the Charpy impact energy and tensile strength data, the results showed than an isothermal heat treatment above the

M_s resulted in a bainite + retained austenite microstructure that exhibited $C_V \approx 50$ ft-lbs, 200 ksi tensile strength combinations. The mechanical properties of the duplex microstructures appeared to be fairly stable to tempering, exhibiting virtually no change in strength-toughness combinations up to a tempering temperature of 300°C. At a tempering temperature of 400°C, there appeared to be a partial transformation of retained austenite, manifested by an increase in yield strength (Fig. 7). Previous work[23] has suggested that the increase in yield may be partly explained by a mechanical destabilization of the austenite under stress/strain. The retained austenite content decreased from 12% to 10%; however partial transformation of the austenite appeared to have mechanically stabilized the remaining austenite, there being little change in the Charpy impact energy at 400°C. On tempering to 500°C, the Charpy impact energy dropped to approximately 20 ft-lbs. This was also associated with a decrease in the retained austenite content of the microstructure to approximately 3%. The drop in Charpy impact energies is suggested to be associated with a tempered martensite embrittlement, caused by the transformation of retained austenite. Tempered martensite embrittlement is generally encountered around 250°C in unmodified 4330, 4340 steels.[23,24] However several investigations[25,26,27] have shown that in Si, Al + Si modified 4330, 4340 steels, this embrittlement is found to occur at higher tempering temperature. It should also be noted that the effects of segregation of S, P, resulting in a temper embrittlement phenomenon at these temperatures cannot be ruled out. This, however, falls beyond the scope of this investigation.

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[23] E.B. Kohn, A. Anctil, J. of Mats. 4, p 817 (1969)

[24] B.R. Banerjee, JISI 203, p 166 (1965).

[25] Kohn, see footnote p 1.

[26] Kar, see footnote p 1.

[27] R.M. Horn, Ph.D. Thesis, University of California, Berkeley (Dec. 1976).

Fractography of the broken Charpy bars showed that the single overload fracture mode up to 400°C was typically dimpled rupture, characteristic of high energy fractures. On tempering at 500°C, the fracture mode was quasicleavage as typically shown in the fractographs of Fig. 9.

3.2.3 Isothermal Transformation Below M_S

3.2.3.1 Mechanical Properties: Mechanical properties of the steel isothermally transformed at 250°C (i.e. below M_S) were evaluated over the same tempering range. The Charpy impact energy data for the longitudinal and transverse orientations are presented in Table III and Figure 10. As a basis for comparison, the longitudinal Charpy impact properties are also plotted with similar data for vacuum arc remelted (VAR) steel data, obtained from Ref. 6, in Fig. 11.

3.2.3.2 Correlations between Microstructure and Mechanical Properties

Isothermal transformations below the M_S resulted in a mixture of tempered martensite + lower bainite, shown typically in the transmission electron micrographs of Figs. 12 and 13. This multiphase microstructure was associated with approximately 12% retained austenite, as determined by X-Ray measurements (Fig. 14).

The results in Table VI and Figs. 10 and 14 show that on tempering the martensite-bainite microstructure, approximately 3 - 4% of the retained austenite destabilized at 300°C. The volume expansion associated with the $\gamma \rightarrow M$ transformation appeared to have stabilized the remaining austenite, since tempering at 400°C did not significantly alter the austenite content. Beyond this temperature, because of the higher thermodynamic driving forces available, additional transformation of retained austenite and the appearance of interlath carbides seemed to have decreased the toughness. There did not appear to be a major difference in the Charpy impact properties with respect to orientation, as shown in the comparison between longitudinal and transverse Charpy impact energies of Fig. 10. In Fig. 14, the tensile strength, hardness and % retained austenite are plotted as a function of tempering temperature. The data indicate that the yield strength increased as the percentage of retained austenite in the microstructures decreased. Similar results have been obtained by Kohn in modified AISI 4330[28] steels. Kohn suggests that when these steels are isothermally transformed below their M_s temperatures, the austenite retained is lower in C, and consequently does not transform to brittle martensite on loading. The highest toughness in his investigation were obtained after partial transformation of austenite, mechanically stabilizing the remaining austenite, thereby enhancing energy absorption in a Charpy test.

The results obtained here are consistent with this observation, where the highest strength-toughness combinations have been obtained after partial stabilization of retained austenite. Typical values obtained after this isothermal heat treatment and 300°C tempering temperature are $C_v \approx 30$ ft-lbs, 193 ksi yield, 230 ksi ultimate tensile strengths. Additional K_{1C} data used to evaluate the toughness of this steel is shown in Fig. 15 and Table VII. A typical value of 123 ksi - $in^{1/2}$ at this temperature was obtained, indicating the merits of this heat-treatment.

On comparing the toughnesses of the ESR-processed steel with data obtained in VAR steel, (Figs. 6 and 11) the merits of ESR processing become apparent. The Charpy energy data of Fig. 11 suggests that the ESR steel has a slightly higher toughness than conventional VAR steel. This becomes more apparent in the K_{1C} data comparing the two steels (Fig. 15). The ESR processed steel appears to exhibit a 10% increase in K_{1C} value over the VAR steel, at a tempering temperature of 300°C. Another interesting observation is that the VAR steel appears to embrittle at a tempering temperature of 400°C, whereas at this temperature the ESR steel manifests a high fracture toughness value. Although the K_{1C} data were not evaluated at 500°C tempering, the Charpy data seems to suggest a drop in toughness at 500°C in the ESR steel. Whether this can be attributed to a temper embrittlement phenomena (as dictated by the lower S contents of the ESR steel) falls beyond the scope of this investigation.

[28] Kohn, see footnote, p 1.

3.3 AISI 4330 + 2%Si

The previous results on AISI 4340 + 1.5Al +1.5Si showed that when isothermal transformations were carried out above the M_s temperature, bainitic microstructures exhibiting high toughness, but relatively lower strength, were obtained. The strength of the multiphase microstructures was increased by introducing a martensitic phase, i.e., by isothermally transforming below the M_s temperature. In this ESR-steel optimum strength-toughness combinations were obtained below the M_s temperature (M_s=270°C). Earlier work[29] on VAR melted 4330 + 2Si also showed that optimum strength-toughness combinations were obtained in this steel also when isothermally transformed below the M_s temperature. Thus, in this part of the investigation, the two isothermal transformation temperatures chosen for study were both below the M_s temperature, namely 250°C and 200°C. It was envisaged that based on prior data, these temperatures were likely to give optimum strength-toughness combinations.

3.3.1 Isothermal Transformations at 250°C

3.3.1.1 Mechanical Properties: The Charpy impact energy data for the steel isothermally transformed at 250°C are shown in Table VIII and Figure 16. The data for the longitudinal and transverse orientations fall fairly close to each other, indicating that there does not appear to be an effect of anisotropy in this ESR-processed steel. The tensile properties of the steel are shown in Table IX and Figure 17 for the longitudinal orientation.

3.3.1.2 Correlation between Microstructure and Mechanical Properties: Isothermal transformation of the ESR-modified AISI 4330 + 2Si steel at 250°C resulted in a mixture of martensite and lower bainite, shown typically in Figure 18, containing approximately 18% retained austenite. (X-ray data plotted in Figure 17). The austenite was stable to tempering up to 300°C where some decomposition of the austenite occurred. An embrittlement in the Charpy impact energy (Figure 16) at this temperature

[29] Kohn, see footnote p 1.

is likely to be associated with the decomposition of austenite, which in most steels occurs nearer ?0°C.

The stability of austenite as a function of tempering is suggested to be governed by two factors:

i) in the isothermally transformed but untempered specimens, there are suggested to be unrelieved stresses resulting from quenching. These coupled with the loading stresses can result in the as-quenched specimens, exhibiting a lower Charpy energy than the 250°C tempered specimens, although the as-quenched specimens contain equivalent or greater amounts of retained austenite. Also, in the specimens quenched from the isothermal temperature, some of the austenite present before quenching could have transformed to martensite during quenching.

ii) The alloy composition and isothermal transformation temperature. This aspect of austenite decomposition will be discussed subsequently.

The data in Figure 17 show that with increasing tempering temperatures, the ultimate tensile strengths of the multiphase microstructures decreased. The effect of retained austenite on the yield strength of the alloy is evident from Figure 17 which shows that with increasing tempering temperatures, the amount of retained austenite decreased, accompanied by an increased yield strength.

The plane strain fracture toughness data for this heat treatment is shown in Table X and Figure 19. It should be noted that the 250°C tempering gives a value of K_q = 110 ksi-in$^{1/2}$. This would not satisfy the thickness criterion $b \geq 2.5\left(\frac{K_{1C}}{\sigma_y}\right)^2$ criterion for a valid K_{1C} measurement. The K_{1C}/K_q data profile tends to follow the Charpy data, showing a peak at 250°C tempering followed by a drop in the toughness at a 300°C tempering temperature.

3.3.2 Isothermal Transformations at 200°C

3.3.2.1 Mechanical Properties: Isothermal transformations at 200°C resulted in multiphase microstructures that exhibited higher strength and higher hardness levels than the 250°C isothermal microstructures, as shown by the data in Table XI and Figure 20. The Charpy impact data shown in Table VIII and Figure 21 also show that the Charpy impact energies were slightly increased over the entire tempering range. There does not appear to be a significant difference in the Charpy impact energies in the longitudinal and transverse orientations, indicating the merits of ESR-processing. Evaluation of the tensile strength data in Figure 20 showed that with increasing tempering temperature, there was a decrease in ultimate tensile strength and an increase in yield strength. There did not appear to be any decomposition of austenite between the as-quenched and 300°C tempering temperatures; thus the effect of increasing yield strength with increasing tempering temperature is likely to be associated with the precipitation reactions that occur during the tempering of martensite.

3.3.2.2 Correlation between Microstructure and Mechanical Properties: Isothermal transformations at 200°C resulted in microstructures that were essentially martensitic (Figure 22), with approximately 11% retained austenite. The austenite was stable to tempering, and no embrittlement occurred on tempering to 300°C. The fractographs of as-quenched and 300°C tempering temperatures Charpy bars are shown in Figure 23, exhibiting dimpled ruptures.

The stability of retained austenite appears to be a complex phenomenon related to several parameters: i) isothermal transformation temperature, and ii) alloy composition, particularly carbon content and silicon content. These parameters will now be discussed.

In evaluating the data for the 4330 + 2 Si steel, the austenite associated with the 250°C isothermal transformation decomposed at 300°C tempering whereas the austenite associated with the 200°C isothermal temperature did not destabilize on tempering. This appears to suggest that at the higher isothermal temperature, there was sufficient enthalpy for the diffusion of carbon to austenite, enriching the latter sufficiently to form high carbon martensite on impact loading, thereby giving lower impact properties. On the other hand, the finer lath size and slower diffusion rates for the lower isothermal temperature, seem to give austenite less enriched in carbon, thereby improving the strength-toughness combinations that can be obtained. A detailed analysis would be necessary involving high resolution lattice imaging or scanning transmission electron microscopy (STEM) where the enrichment of austenite in carbon (by lattice imaging) or silicon (lattice imaging, STEM techniques) could be studied. This, however, does not fall within the realm of this investigation.

Optimum strength toughness combinations were obtained at isothermal transformations of 200°C. Typical values obtained are 28 ft-lbs with tensile strengths of 235 ksi. The corresponding fracture toughness value obtained is 97 ksi-in$^{1/2}$. (Table XI)

3.4 Stability of Retained Austenite

The stability of retained austenite to tempering and its subsequent influence on impact properties appears to be a complex phenomenon related to chemical composition and isothermal transformation temperatures. The role of Si[30,31,32,33,34,35] content seems significant. In the 4330 + 2 Si steels, the austenite associated with higher isothermal transformation temperatures appears to be enriched in carbon, because of the relatively higher diffusion rates. In the presence of a larger amount of Si (2%), the precipitation of carbides from austenite is retarded during tempering. Thus the high carbon austenite is suggested to form brittle twinned martensite[36] on impact loading, thereby lowering

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[30]Kohn, see footnote p 1.

[31]Bhat, see footnote p 1.

[32]Kar, see footnote p 1.

[33]J. Vajda, J. Hauser, C. Wells, Trans. ASM 49, p 517 (1957).

[34]C.H. Shih, B.L. Averbach, M. Cohen, Trans ASM 48, p 86 (1956).

[35]C.J. Alstetter, M. Cohen, B.L. Averbach, Trans ASM 55, p 287 (1962).

[36]Kohn, see above.

Charpy impact properties. At lower isothermal transformation temperatures, diffusion of carbon to austenite occurs to a lesser extent. Thus the austenite does not appear to be significantly enriched in carbon to form twinned martensite on impact loading. Also the amount of austenite retained in the as-quenched microstructures decreases from 18% for the higher isothermal transformation temperature to 11% for the lower isothermal transformation temperature. The finer lath sizes associated with the lower transformation temperatures enhance attainable strength-toughness combinations in this steel.

The modified 4340 steel with small amounts of Si (1.5%) does not show an embrittlement associated with the decomposition of retained austenite, at lower tempering temperatures. It is suggested that the Si content controls the precipitation of carbides and, therefore, the consequent carbon enrichment of austenite. In addition, in the 4340 steel, the bainite/martensite shear transformations appear to mechanically stabilize the austenite, thereby preventing its decomposition at low tempering temperatures.

A full-scale electron microscopy program involving lattice imaging (to identify C enrichment of austenite) and localized micro-analysis techniques such as STEM to study Si enrichment[37] would be necessary to prove or disprove the above hypothesis. These comments are included here as suggestions for future work that could be carried out.

3.5 Overall Assessment of Strength-Toughness Combinations Obtained in the ESR Steels

The results show that the 4330 + 2Si steels exhibit relatively high toughness levels, but the attainable strength levels are relatively low. Typical values of K_{1C} = 97 ksi-in$^{1/2}$ at 235 ksi strength levels have been obtained. The results are plotted in a scatter band shown in Figure 24. The results suggest that the strength-toughness combinations obtained in this steel may be superior to unmodified 4340 and

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[37] W.M. Garrison, Jr., Private communication, University of California, Berkeley, CA 94720 (1980).

300M steels.

The results for isothermally transformed 4340 + 1.5Al + 1.5Si steel are also plotted here. These fall in the scatter band of the 18 Ni Co Mo maraging steels. The results suggest that by suitable composition modification of commercial grade 4340 steel, ESR processing and controlled heat-treatments, it is possible to obtain strength-toughness combinations equivalent to more expensive maraging steels. Typical values obtained for the steel(isothermally transformed below the M_s temperature)are K_{IC}-122 ksi-in$^{1/2}$ at 233 ksi strength levels, indicating the merits of this heat treated steel.

4. CONCLUSIONS

1. In all of the heat-treated steels, the longitudinal and transverse orientations showed similar Charpy impact energy data. Thus there does not appear to be a significant effect of anisotropy on the Charpy impact energies of these particular ESR-processed steels.

2. Isothermal transformations of AISI 4340+1.5Al+1.5Si steel above the M_s temperature resulted in bainitic microstructures associated with significant amounts of retained austenite. These microstructures exhibited Charpy energies of 40 ft-lbs with 200 ksi tensile strengths. The duplex microstructures were stable to tempering, the austenite appearing to be mechanically stabilized.

3. Isothermal transformations of the AISI 4340+1.5Al+1.5Si steel below the M_s temperature, resulted in higher strength because of the presence of martensite in the microstructures. Typical strength-toughness combinations obtained were C_V 30 ft lbs, 230 ksi tensile strengths, with plane strain fracture toughness of 123 ksi-in$^{1/2}$.

4. On comparing the data obtained in ESR-processed modified 4340 with vacuum arc remelted (VAR) steels (from previous investigations) it appeared that at high toughness levels, the ESR-steel exhibited Charpy impact energies equivalent to the VAR steel. At lower toughness levels the ESR-steel exhibited impact properties slightly superior to the VAR steel.

5. Previous investigations have established that the isothermally transformed VAR modified 4340 steel exhibits an embrittlement beyond a tempering temperature of 400°C, associated with the decomposition of austenite. The ESR modified steel does not appear to embrittle at 400°C, a decrease in impact properties appearing only at 500°C. However, the possibility of temper embrittlement occurring at this temperature in both steels cannot be ruled out.

6. Isothermal transformations in AISI 4330+2Si steels established that this steel exhibited mixtures of martensite and bainite with varying amounts of austenite retained in the microstructure. At the higher

isothermal transformation temperature, larger amounts of austenite were retained, but the steel was susceptible to a tempered martensite embrittlement. This is suggested to be related to the carbon enrichment of the austenite in the presence of 2%Si at the high isothermal temperature. Typical strength-toughness combinations obtained were K/q= 109 ksi-in$^{1/2}$. at 216 ksi tensile strength levels.

7. Isothermal transformations in the 4330+2Si steel at lower temperatures resulted in higher strength levels. Typical strength-toughness combinations were K_{1C} = 97 ksi-in$^{1/2}$ at 235 ksi strength levels.

8. The overall results suggest that the most promising strength-toughness combinations were obtained in ESR-processed 4340+1.5Al+1.5Si steel. When this steel was isothermally transformed below the M_s, strength-toughness combinations comparable to 18 Ni Co Mo maraging steel band were obtained. The merits of this ESR-processed steel with controlled microstructures to give optimum strength-toughness combinations are evident.

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TABLE 1: CHEMICAL ANALYSIS OF STEEL PLATES

Plate No.	Nominal Alloy Composition	Composition (%) C	Mn	Si	Ni	Cr	Mo	Al	P	S
ESR-70	4330+2Si	.29	.89	2.13	1.85	.83	.24	.067	.012	.003
ESR-71	4340+1.5Al +1.5Si	.32	.84	1.57	1.78	.82	.25	1.41	.011	.002
ESR-77	4340+1.5Al +1.5Si	.40	.97	1.74	1.73	.79	.26	1.33	.012	.004

TABLE 2. TRANSFORMATION TEMPERATURES USED FOR THE STEELS IN THIS INVESTIGATION.

Alloy	Austenitization Temp. (°C)	Isothermal Transformation Temperature (°C)
4340+1.5Al +1.5Si	1000	350
4340+1.5Al +1.5Si	1000	250
4330+2Si	900	200
4330+2Si	900	250

All alloys austenitized for 1 hour, isothermally transformed 1 hour, oil quenched

TABLE 3. CHARPY IMPACT TOUGHNESS OBTAINED IN ESR-PROCESSED 4340 + 1.5Al + 1.5Si STEEL.

Austenitized 1000°C (1 hour) → 350°C (1 hour) → Oil Quench + Temper (1 hour)

Tempering Temp. (°C)	Hardness (R_C)	Longitudinal C_V (ft-lb)	Transverse C_V (ft-lb)
As-quenched	43.4	49.1	43.6
200	42.8	48.2	51
300	43.3	49.3	45.5
400	42.8	45.5	45.5
500	42.3	19.9	15.0

Austenitized 1000°C (1 hour) → 250°C (1 hour) → Oil Quench + Temper (1 hour)

Tempering Temp. (°C)	Hardness (R_C)	Longitudinal C_V (ft-lb)	Transverse C_V (ft-lb)
As-quenched	53.3	22.5	17.75
200	53.2	26.0	23.75
300	51.8	30.0	27.0
400	51.1	25.0	23.5
500	48.3	12.0	-

TABLE 4. COMPARISON OF LONGITUDINAL CHARPY IMPACT TOUGHNESS OBTAINED IN ESR-PROCESSED 4340+1.5Al+1.5Si STEEL VS. VAR PROCESSED 4340+1.5Al+1.5Si.

Austenitized (1 hr) 1000°C → 350°C (1 hr)→Oil Quench + Temper (1 hr)

Tempering Temp. (°C)	ESR Steel	VAR Steel
As quenched	49.1	49.0
200	48.2	50.0
300	49.3	50.0
400	45.5	42.0
500	19.9	12.5

Austenitized (1 hr) 1000°C →250°C (1 hr)→Oil Quench + Temper (1 hr)

Tempering Temp. (°C)	ESR Steel	VAR Steel
As Quenched	22.5	20.0
200	26.0	26.8
300	30.0	25.0
400	25.0	20.0
500	12.0	9.0

TABLE 5. MECHANICAL PROPERTIES AND RETAINED AUSTENITE CONTENTS OF AISI 4340 + 1.5Al + 1.5Si STEEL, ISOTHERMALLY TRANSFORMED AT 350°.

Austenitized 1000°C (1 hr) → 350°C (1 hr) → Oil Quench + Temper (1 hr)

Tempering Temp (°C)	Ultimate Tensile Strength σ_u(ksi)	Yield Strength σ_u (ksi)	% Elongation	Hardness (Rc)	% Retained Austenite (by X-ray Techniques
AQ	200.7	168.04	14.1	43.6	12
200	196.4	167.0	12	44.1	12
300	194.7	168.2	14.6	45.2	12
400	202.2	181.1	14.2	43.6	10
500	209.4	141.7	10.0	43.7	3

TABLE 6. MECHANICAL PROPERTIES AND RETAINED AUSTENITE CONTENTS OF AISI 4340 + 1.5Al + 1.5Si STEEL, ISOTHERMALLY TRANSFORMED AT 250°.

Austenitized 1000°C (1 hr) → 250°C (1 hr) → Oil Quench + Temper (1 hr)

Tempering Temp (°C)	Ultimate Tensile Strength σ_u(ksi)	Yield Strength σ_u(ksi)	% Elongation	Hardness (Rc)	% Retained Austenite (by X-ray Techniques)
AQ	260.7	150.0	7.5	53.3	12
200	258.7	161.9	6.7	53.2	10
300	232.2	193.9	6	51.8	9
400	220.8	198.0	8	51.1	9
500	216.1	165.1	4	48.3	4

TABLE 7. PLANE STRAIN FRACTURE TOUGHNESS DATA FOR AISI 4340 + 1.5Al + Si.

Austenitized 1000°C (1 hr) → 250°C (1 hr) → Oil Quench + Temper (1 hr)

Tempering Temp (°C)	K_{IC} Ksi-in$^{1/2}$
AQ	88.055
200	128.170*
300	122.683
400	123.020

(* K_q)

TABLE 8. CHARPY IMPACT TOUGHNESSES OBTAINED IN ESR-PROCESSED 4330+2Si STEEL.

Austenitized 900°C (1 hour)→250°C (1 hour)→Oil Quench + Temper (1 hour)

Tempering Temp (°C)	Hardness (R_c)	Longitudinal C_v (ft-lbs)	Transverse C_v (ft-lbs)
As quenched	46.5	16.8	16.1
250	47.3	27.8	27.2
300	46.7	18.4	15.4
350	47.2	21.3	24.2
400	46.2	20.5	17.6

Austenitized 900°C (1 hour)→200°C (1 hour)→Oil Quench + Temper (1 hour)

Tempering Temp (°C)	Hardness (R_c)	Longitudinal C_v (ft-lbs)	Transverse C_v (ft-lbs)
As quenched	48	27.8	22.8
250	48.2	34.0	30.0
300	47.8	32.0	27.8
350	47.6	36.9	31.0
400	46.3	30.5	27.0

TABLE 9. MECHANICAL PROPERTIES AND RETAINED AUSTENITE CONTENTS OF AISI 4330 + 2Si STEEL, ISOTHERMALLY TRANSFORMED AT 250°C.

Austenitized 900°C (1 hr) → 250°C (1 hr) → Oil Quench + Temper (1 hr)

Tempering Temp (°C)	Ultimate Tensile Strength σ_u(ksi)	Yield Strength σ_y (ksi)	% Elongation	Hardness (Rc)	% Retained Austenite (by X-ray Techniques)
AQ	225.1	139.0	14.0	46.5	18
250	216.3	143.0	15.1	47.3	16.5
300	215.1	175.5	9.0	46.7	12
350	206.6	175.4	10.1	47.2	10
400	206.2	176.2	10.0	46.2	10

TABLE 10. PLANE STRAIN FRACTURE TOUGHNESS DATA FOR AISI 4330 + 2Si

Austenitized 900 °C (1 hr) → 250°C (1 hr) → Oil Quench + Temper (1 hr)

Tempering Temp (°C)	K_{IC} (Ksi-in$^{1/2}$)
AQ	88.717
250	109.473*
300	74.146
350	63.718
400	-

(* K_q)

TABLE 11. MECHANICAL PROPERTIES AND RETAINED AUSTENITE CONTENT OF AISI 4330 + 2Si STEEL, ISOTHERMALLY TRANSFORMED AT 200°C.

Austenitized 900°C (1 hr) → 200°C (1 hr) → Oil Quench + Temper (1 hr)

Tempering Temp °C	Ultimate Tensile Strength σ_u (ksi)	Yield Strength σ_y (ksi)	% Elongation	Hardness (Rc)	% Retained Austenite (by X-ray Techniques)	K_{1C} Ksi -in$^{\frac{1}{2}}$
AQ	234.5	149.1	10.5	48.1	11	97.030
250	224.5	168.0	13.0	48.2	10	92.482
300	216.4	185.6	13.5	47.8	10	-
350	213.8	181.7	12.0	47.6	8	-
400	202.6	179.3	12.0	46.3	8	-

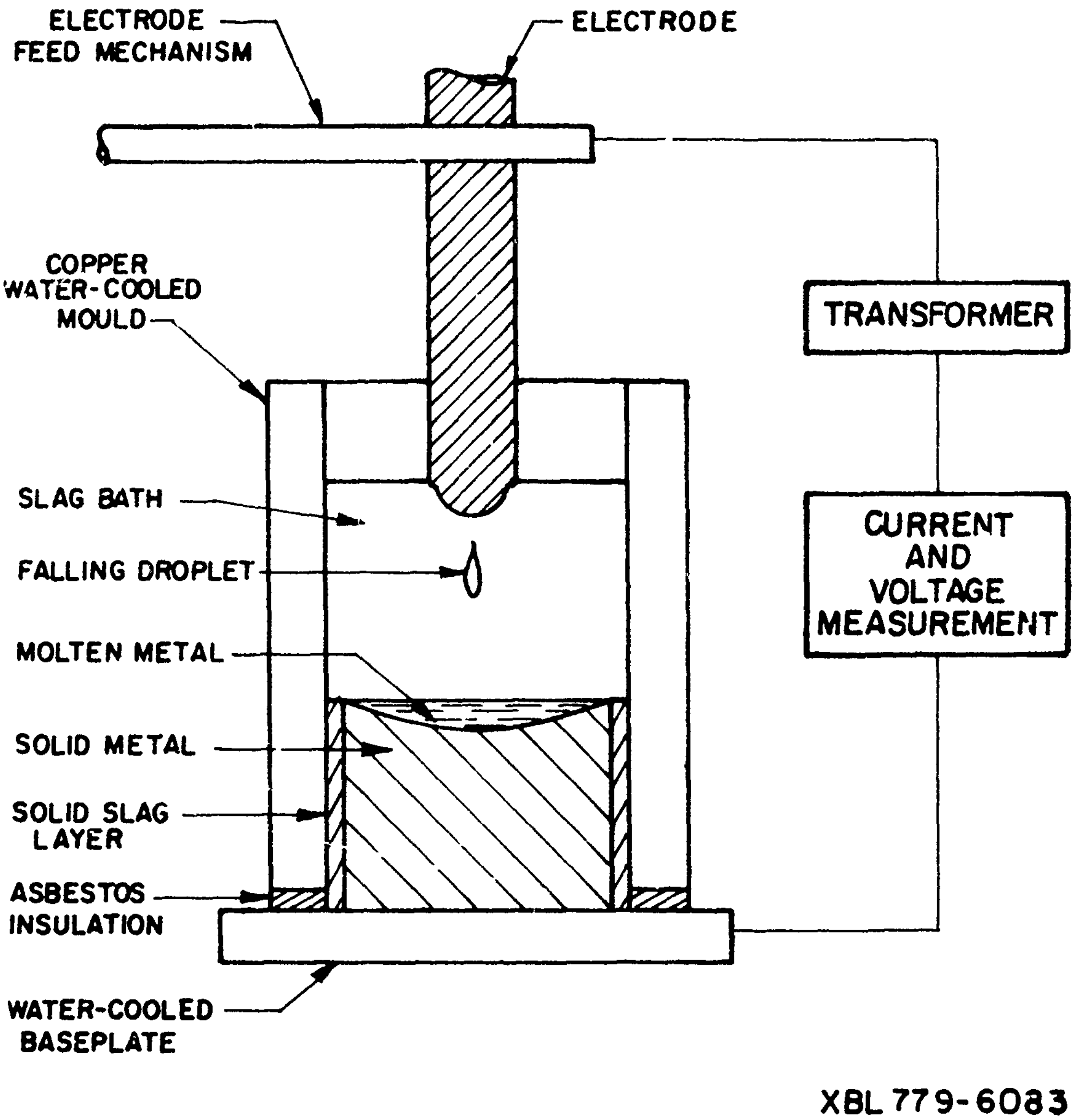

Figure 1. The electroslag refining process.

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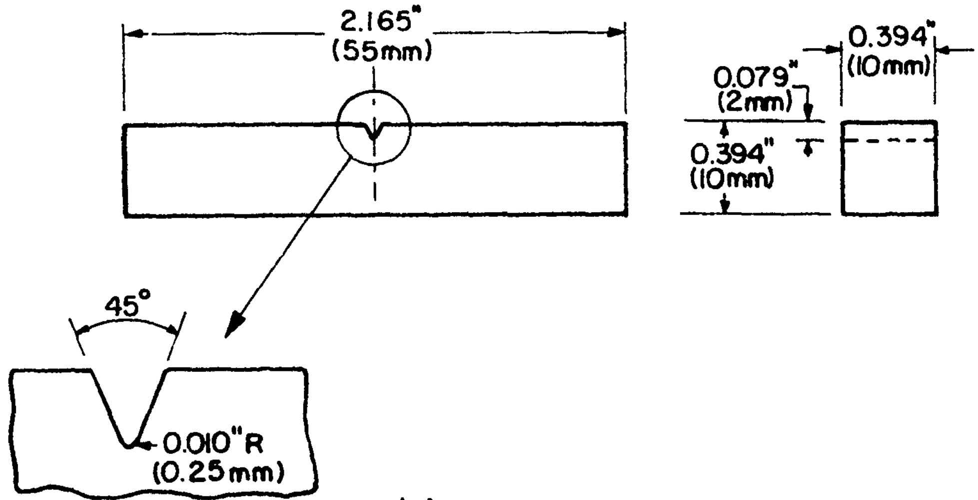
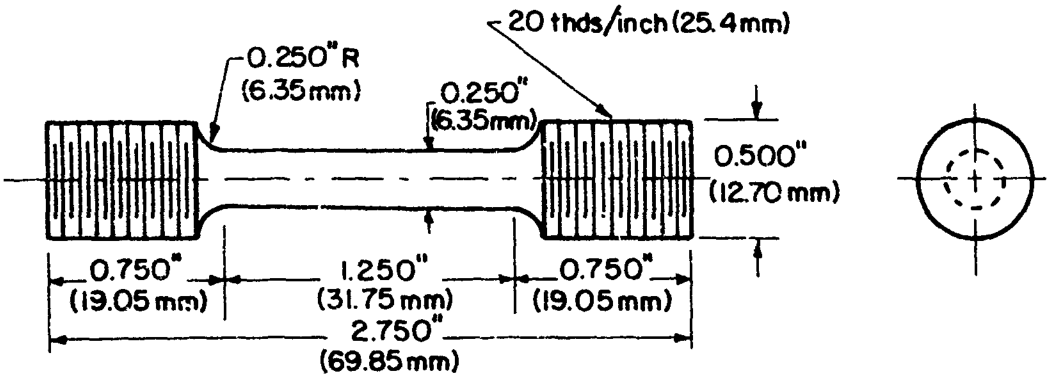
Figure 2. Tube furnaces employed for heat treatments. An argon atmosphere was used during heat treatment.



(a)



(b)

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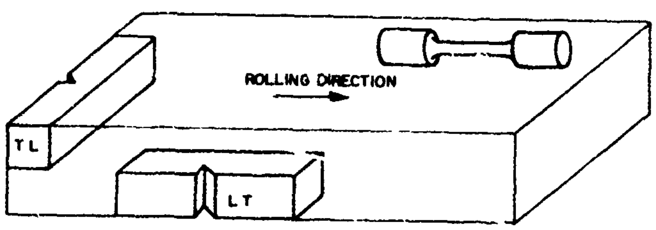

Figure 3. Charpy V-notch specimens and round tensile specimens tested as per the orientation shown.

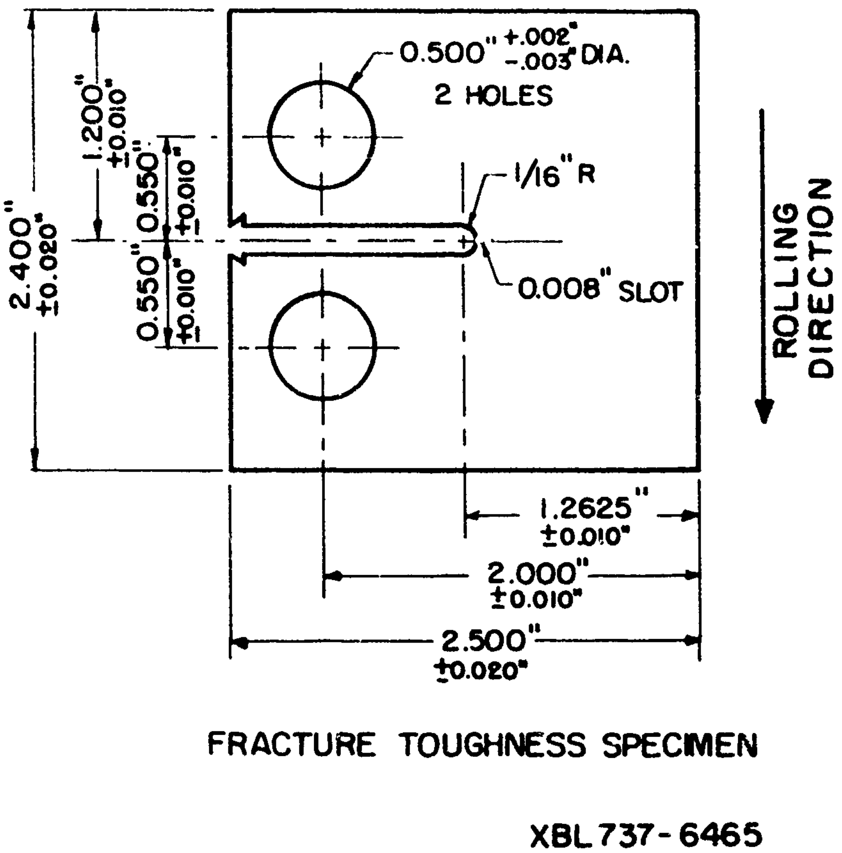

Figure 4. Compact tension test specimen used to evaluate plane strain fracture toughness (K_{IC}) in the L-T orientation.

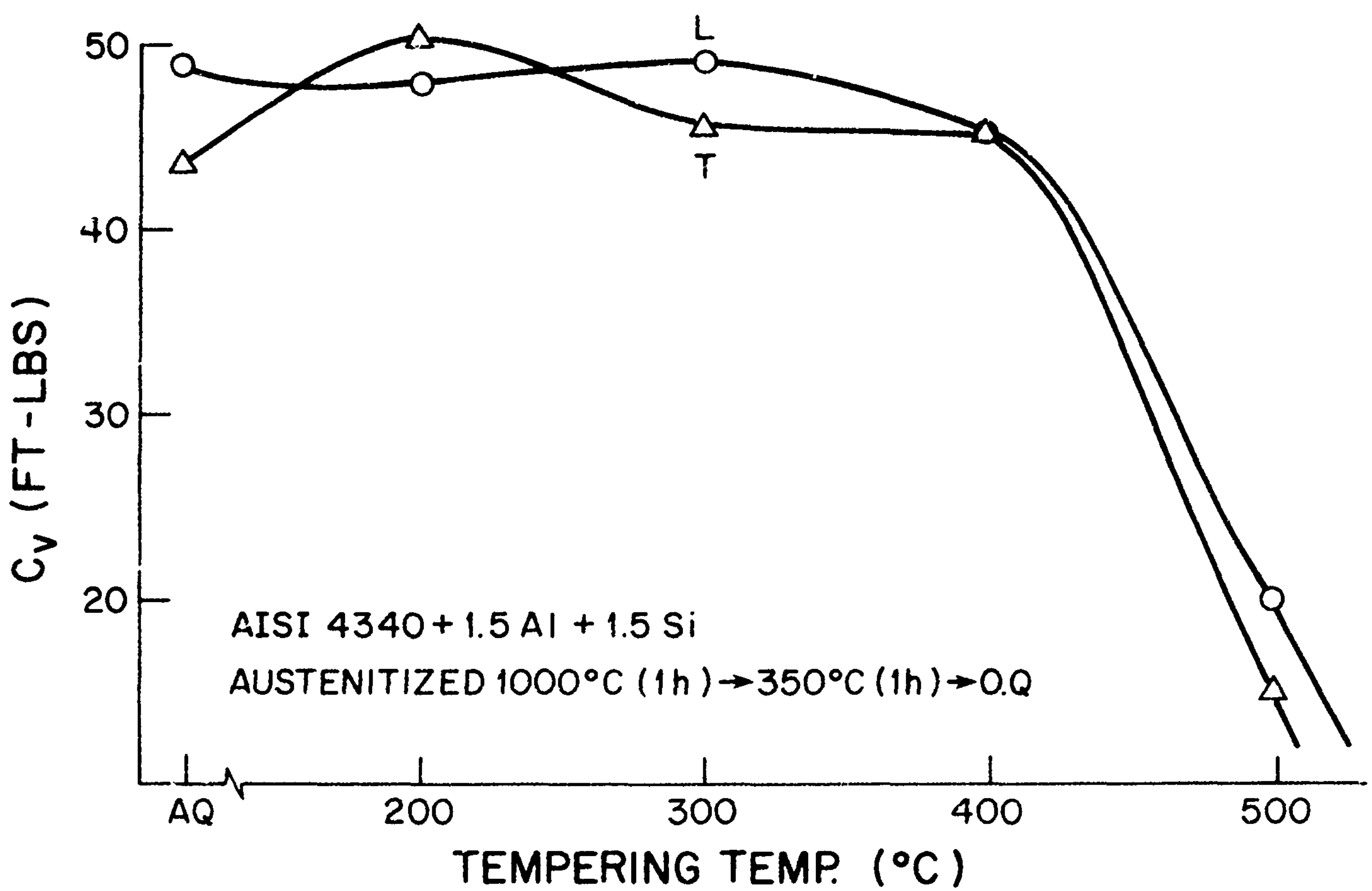

Figure 5. Room temperature Charpy impact energies as a function of tempering temperature for AISI 4340 + 1.5Al + 1.5SI steel heat treated: Austenitized at 1000°C (1h) + isothermal at 350°C (1h) + oil quench + tempered (1h). L and T refer to the longitudinal and transverse orientations.

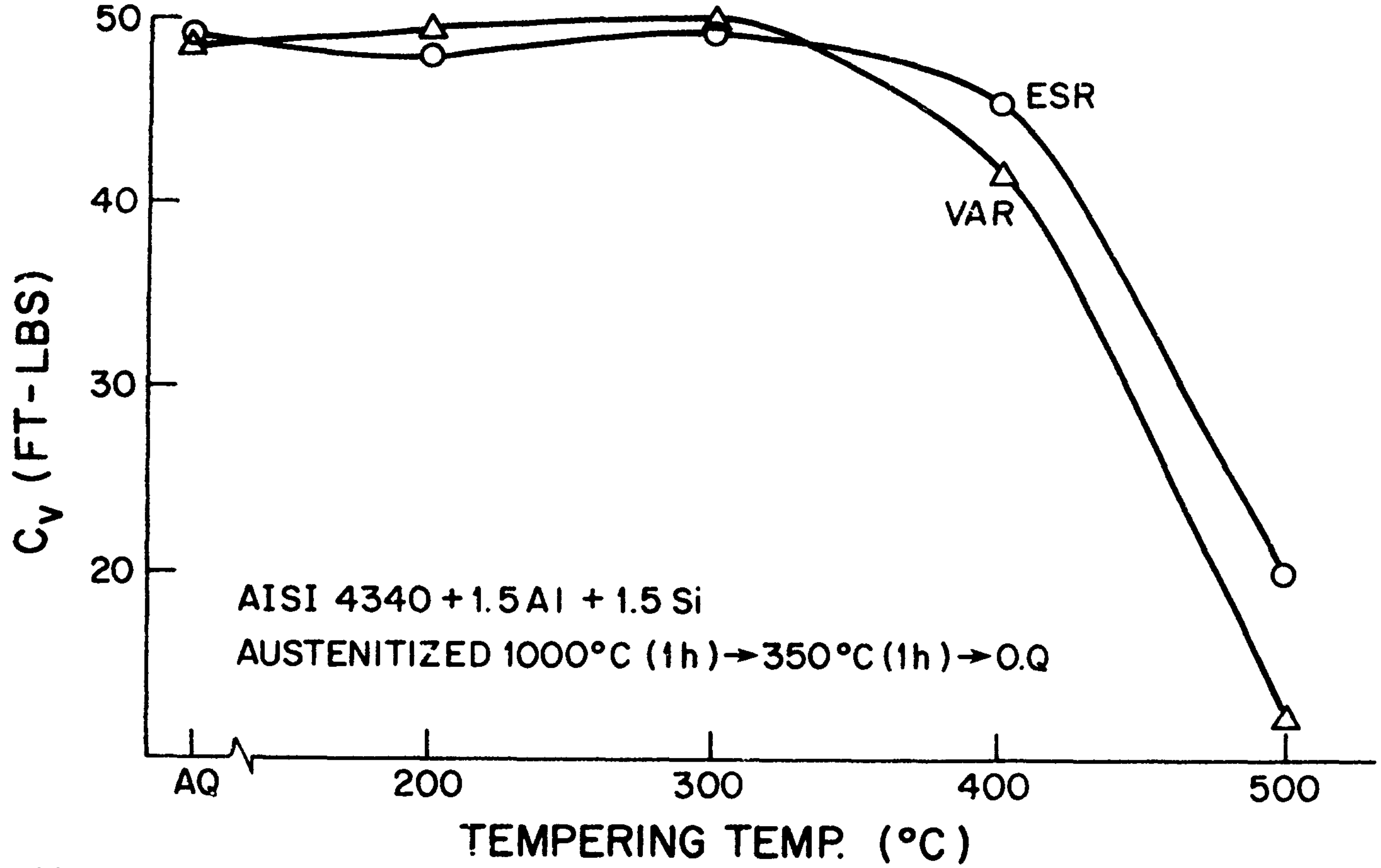

Figure 6. A comparison between Charpy data obtained for ESR processed and VAR processed AISI 4340 + 1.5Al + 1.5Si steel, isothermally transformed at 350°C.

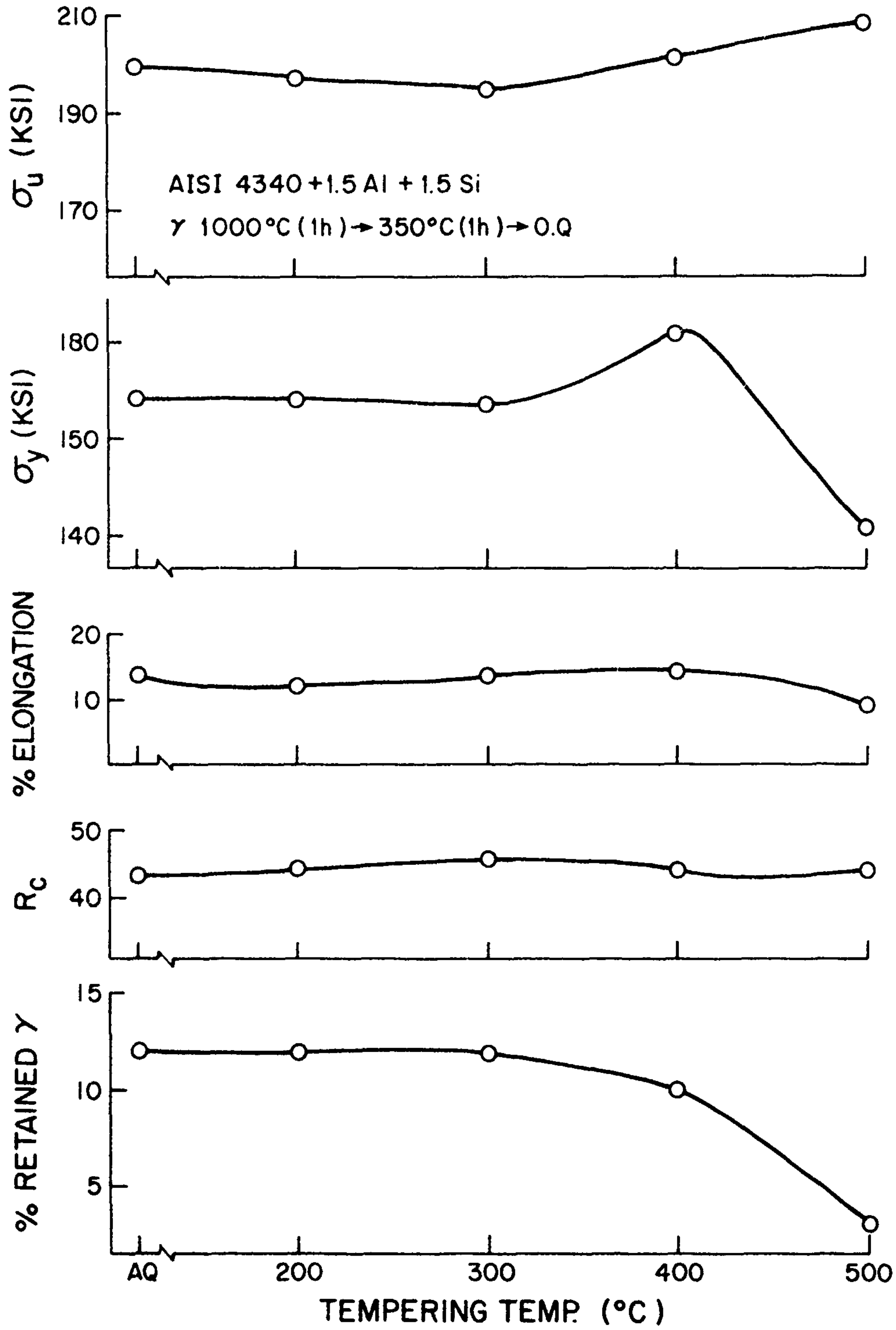

Figure 7. Plots of ultimate tensile strength, yield strength, % elongation, (all longitudinal orientation), hardness and % retained austenite as a function of tempering temperature for AISI 4340 + 1.5Al + 1.5Si steel isothermally transformed at 350°C.

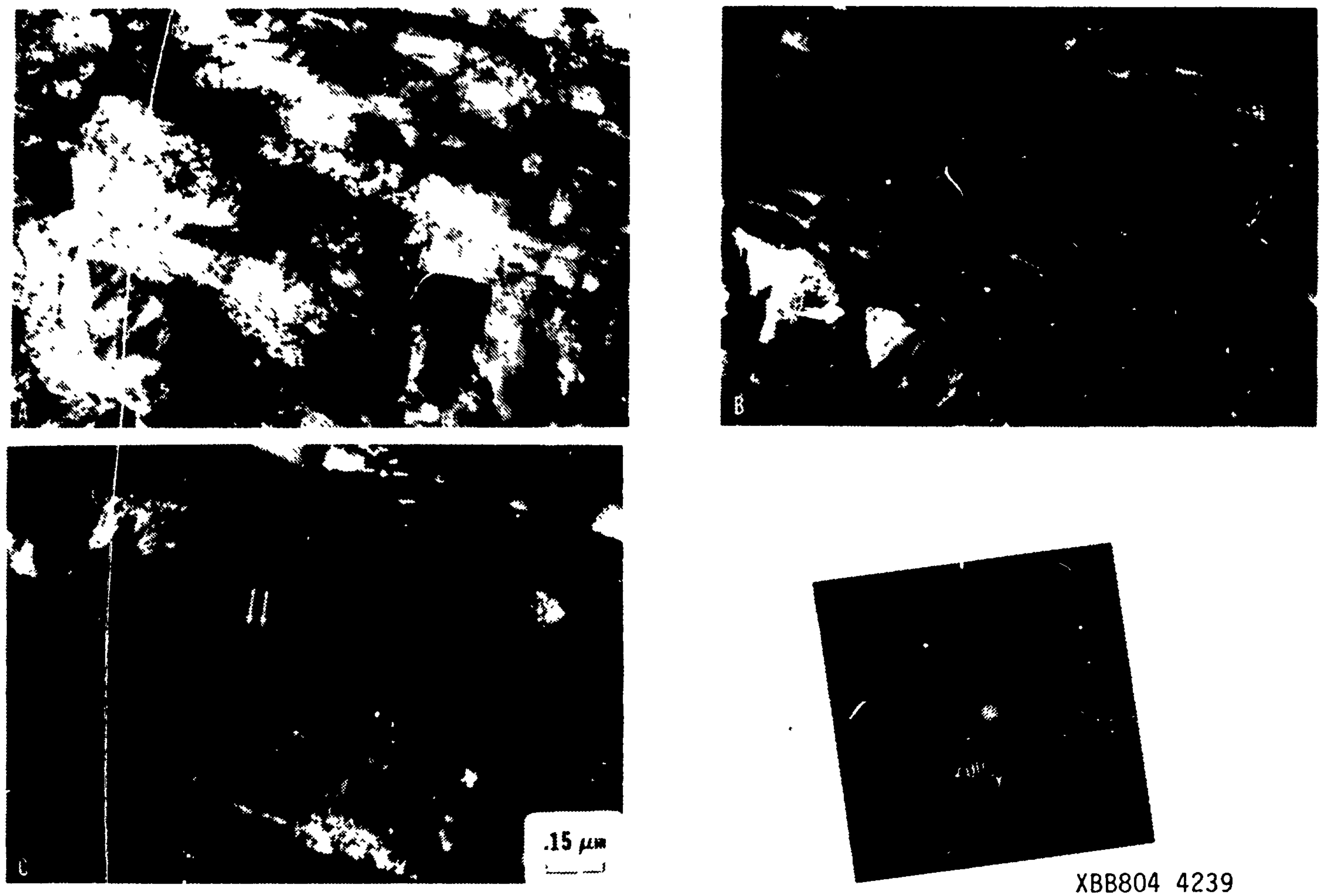

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Figure 8. Transmission electron micrographs of AISI 4340 + 1.5Al + 1.5Si steel isothermally transformed at 350°C, showing lower bainite with interlath films of retained austenite
(a) Bright field shows lower bainite microstructure
(b) Dark field image showing intralath bainitic carbides
(c) Dark field image showing interlath films of retained austenite
(d) Diffraction pattern showing the $(200)_\gamma$ spot used to image the austenite.

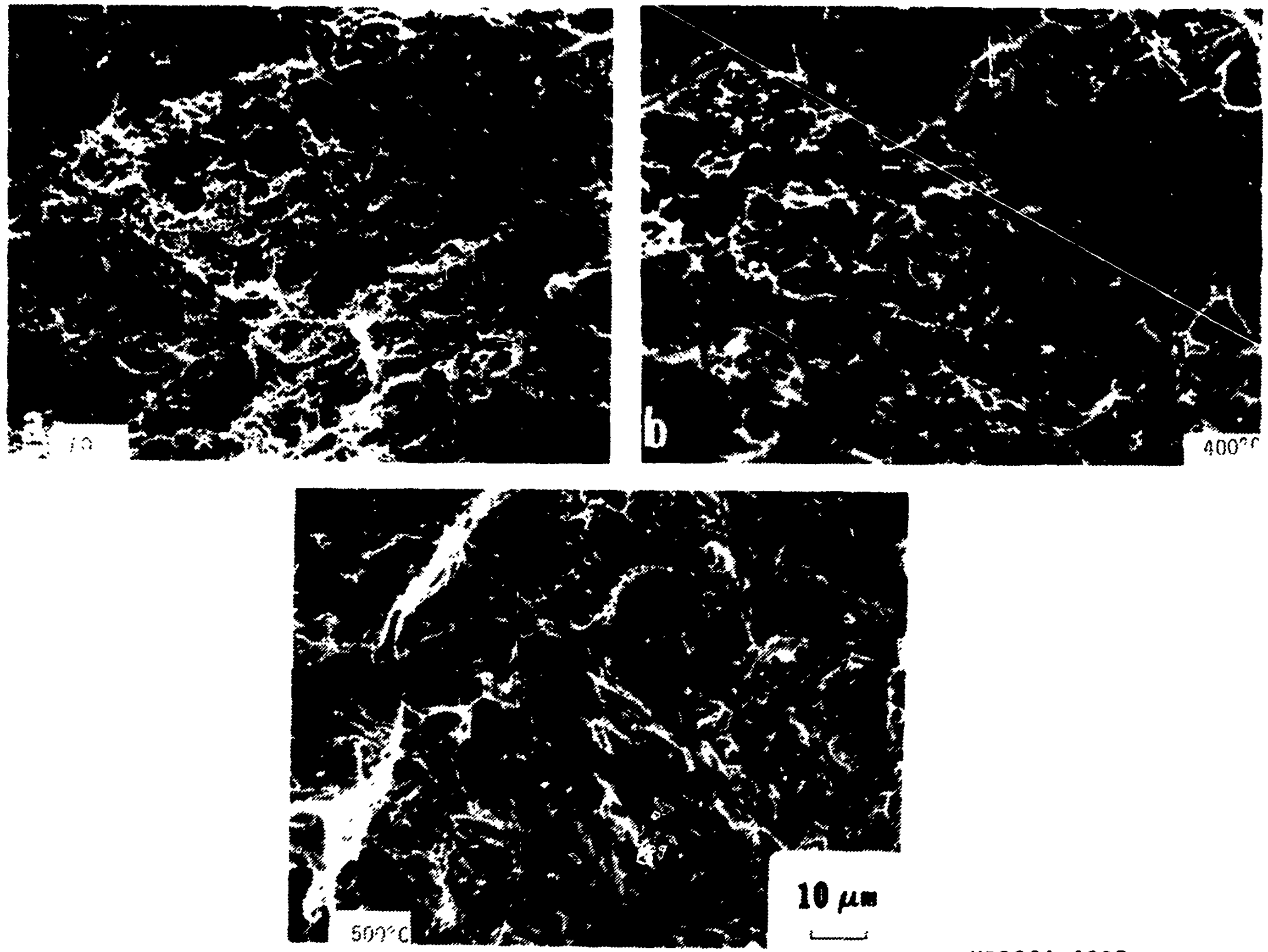

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Figure 9. Scanning electron photomicrographs of 350°C isothermally transformed AISI 4340 + 1.5Al + 1.5Si steel, showing the overload fracture mode
(a) As-quenched (i.e. untempered).
(b) 400°C tempering
(c) 500°C tempering

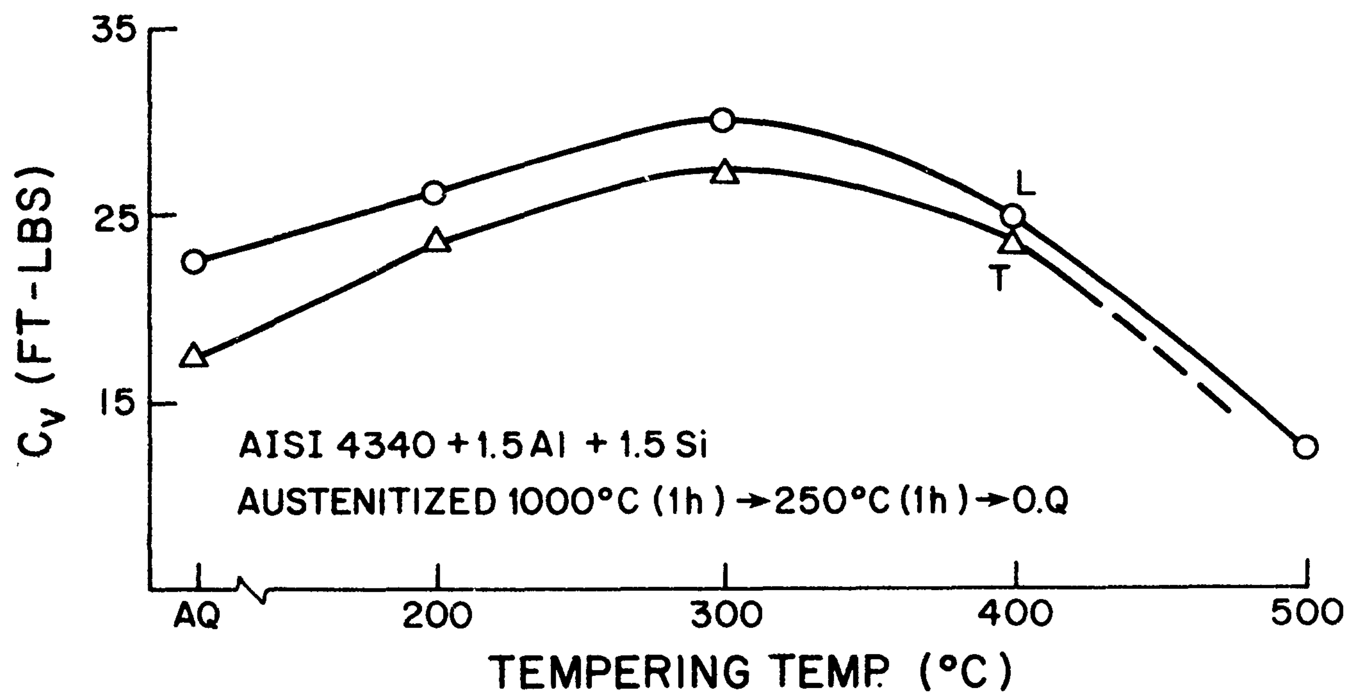

Figure 10. Room temperature Charpy impact energies as a funtion of tempering temperature for AISI 4340 + 1.5Al + 1.5Si steel heat treated: Austenitized at 1000°C (1h) + isothermal at 250°C (1h) + oil quench + tempered (1h).
(L and T refer to the longitudinal and transverse orientations.)

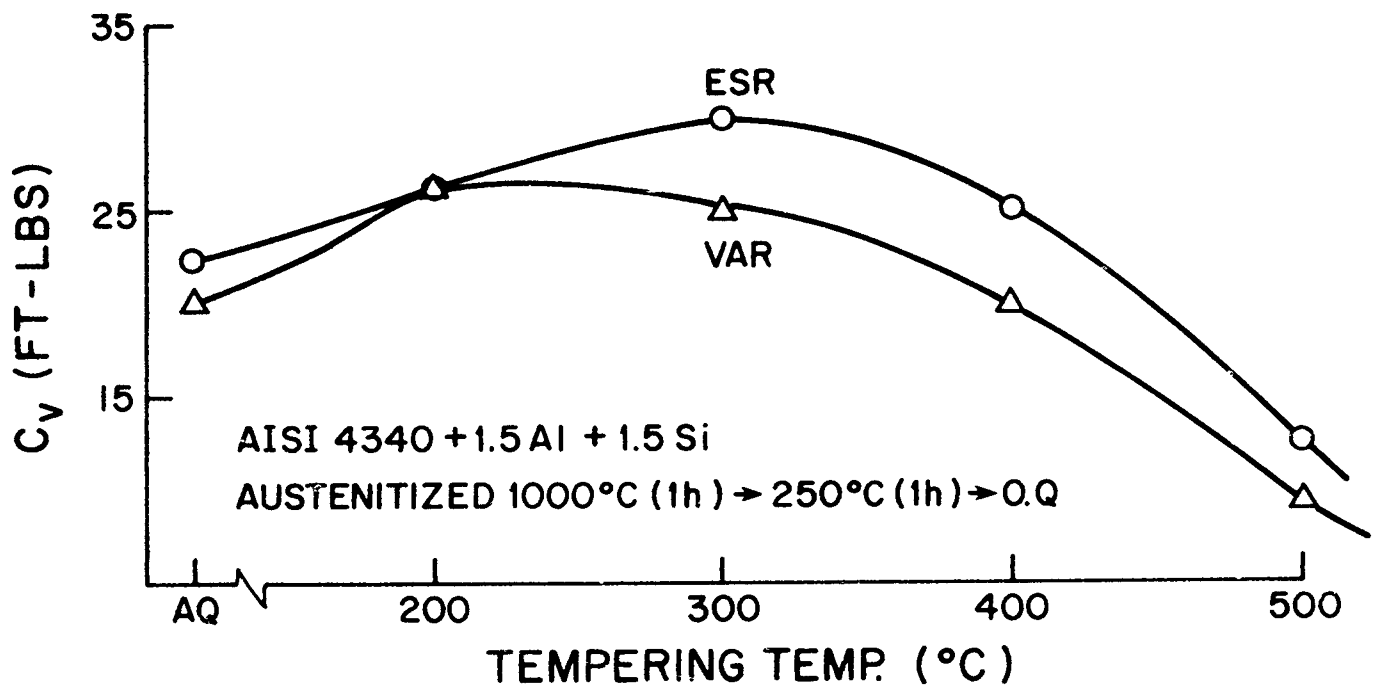

Figure 11. A comparison between Charpy data obtained for ESR processed and VAR processed AISI 4340 + 1.5Al + 1.5Si steel, isothermally transformed at 250°C.

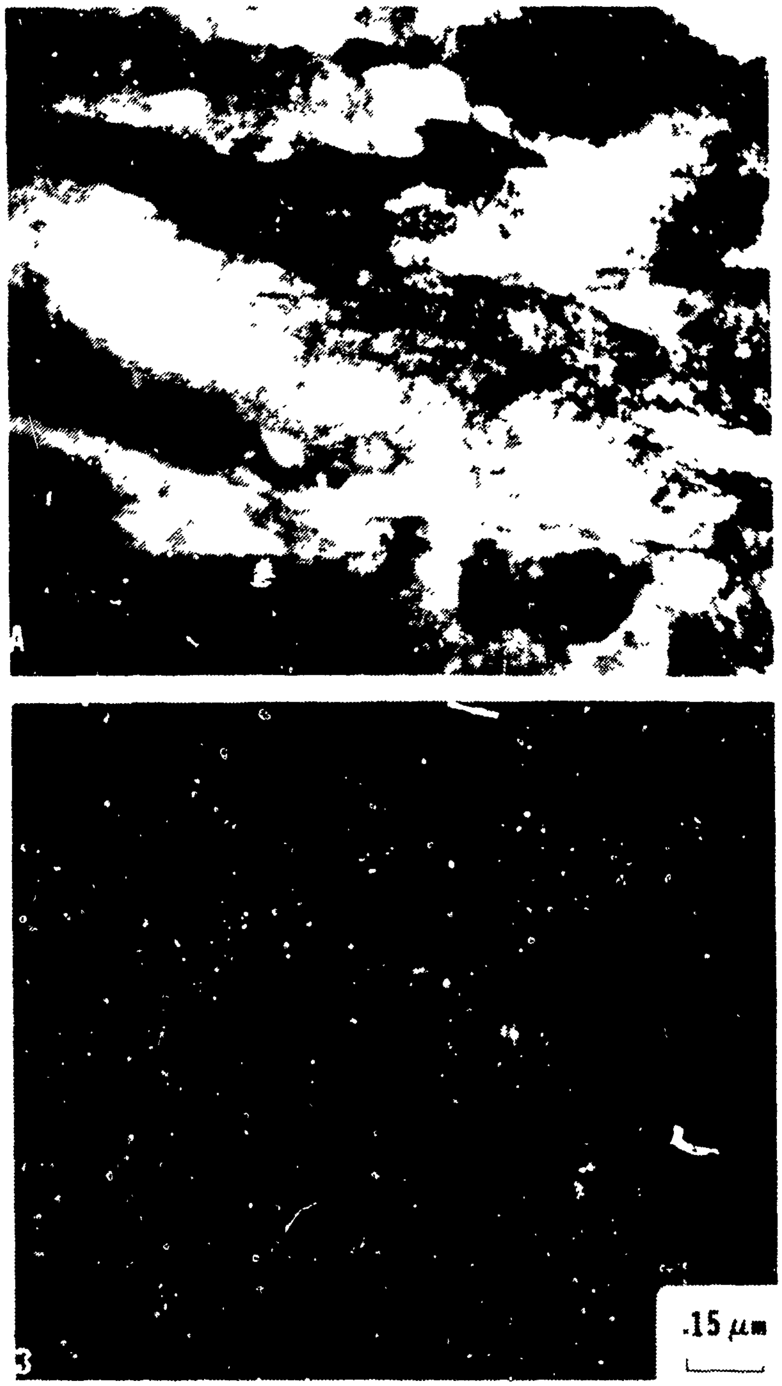

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Figure 12. Transmission electron micrographs showing the lower bainite associated with the 250°C isothermal microstructure.
(a) Bright field micrograph
(b) Dark field showing bainitic carbides.

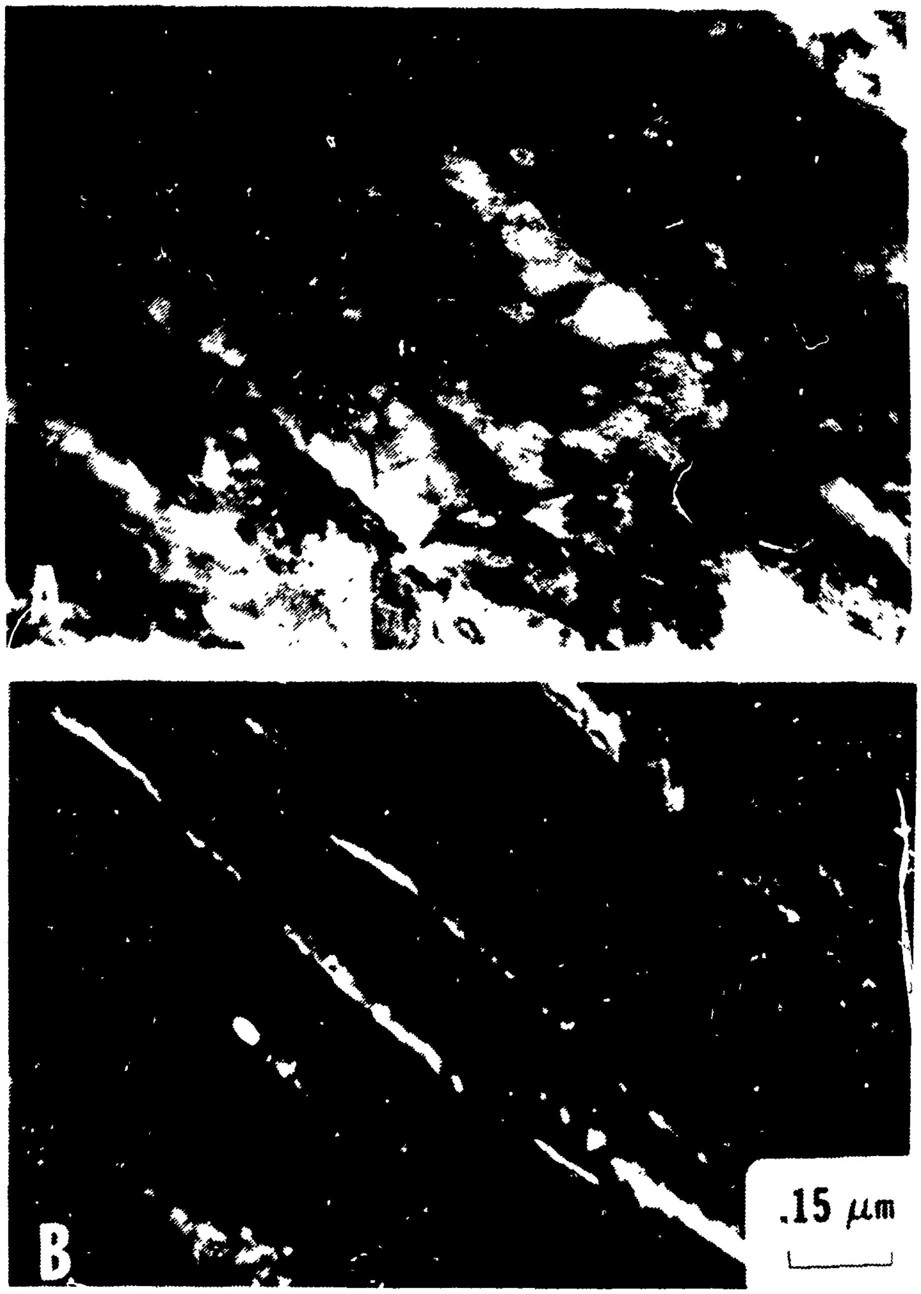

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Figure 13. Transmission electron micrographs showing the retained austenite associated with the 250°C isothermal microstructure.
(a) Bright field micrograph
(b) Dark field showing interlath films of retained austenite.

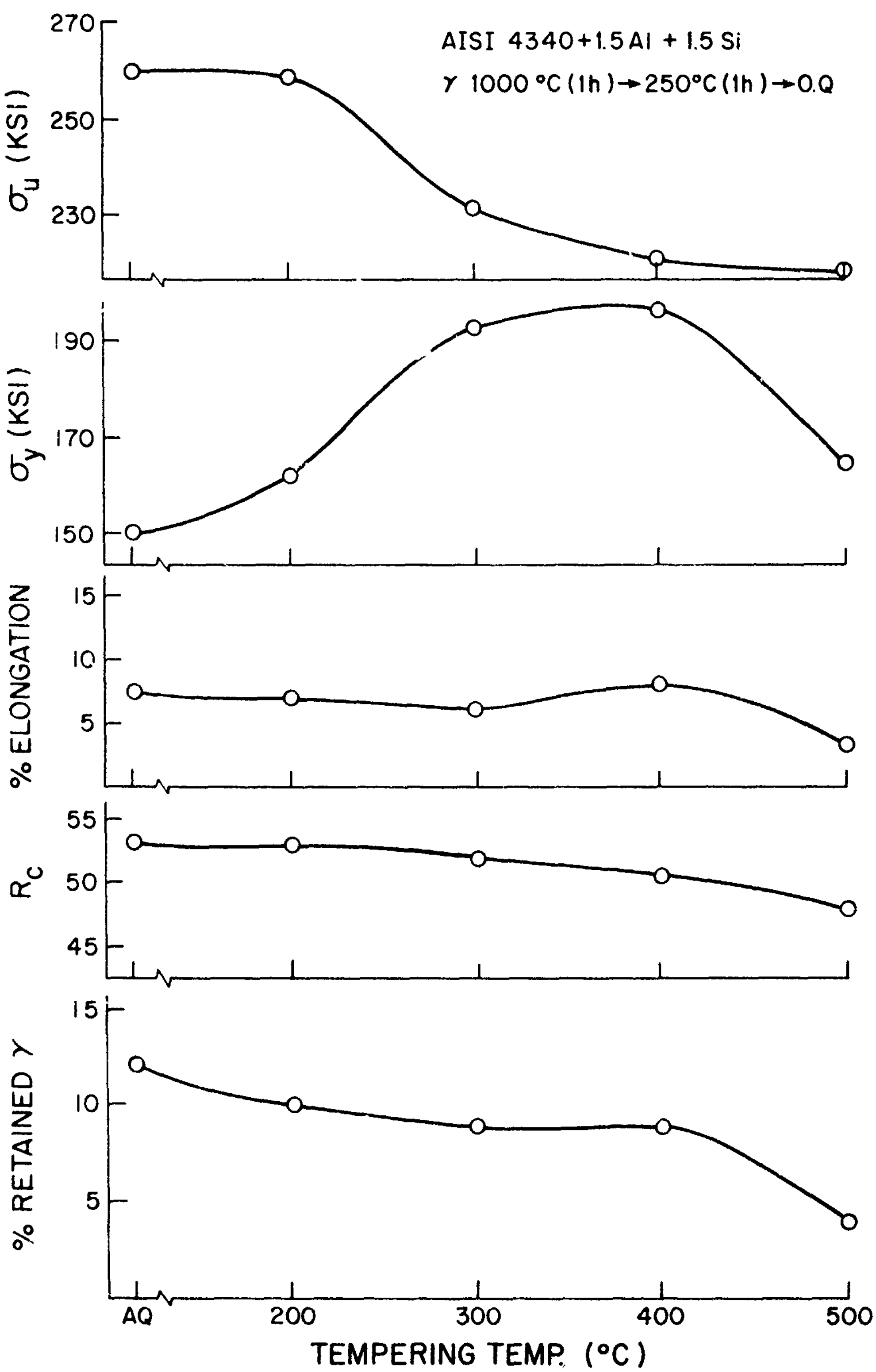


Figure 14. Plots of ultimate tensile strength, yield strength, % elongation (all longitudinal orientation), hardness and % retained austenite as a function of tempering temperature for AISI 4340 + 1.5Al + 1.5Si steel isothermally transformed at 250°C.

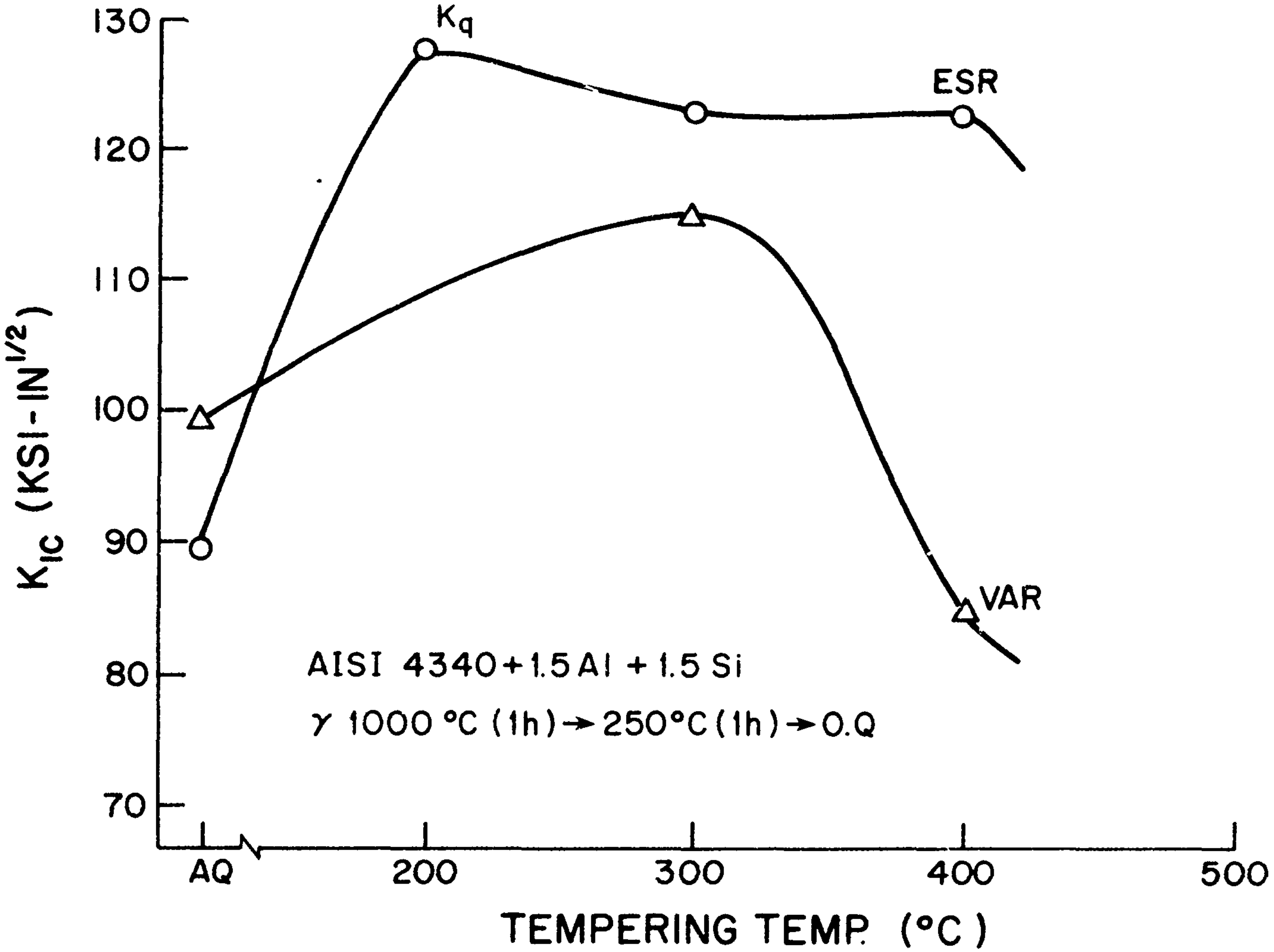


Figure 15. A comparison between plane-strain fracture toughness data (K_{IC} values in the L-T orientation) of ESR processed and VAR processed AISI 4340 + 1.5Al + 1.5Si steel isothermally transformed at 250°C.

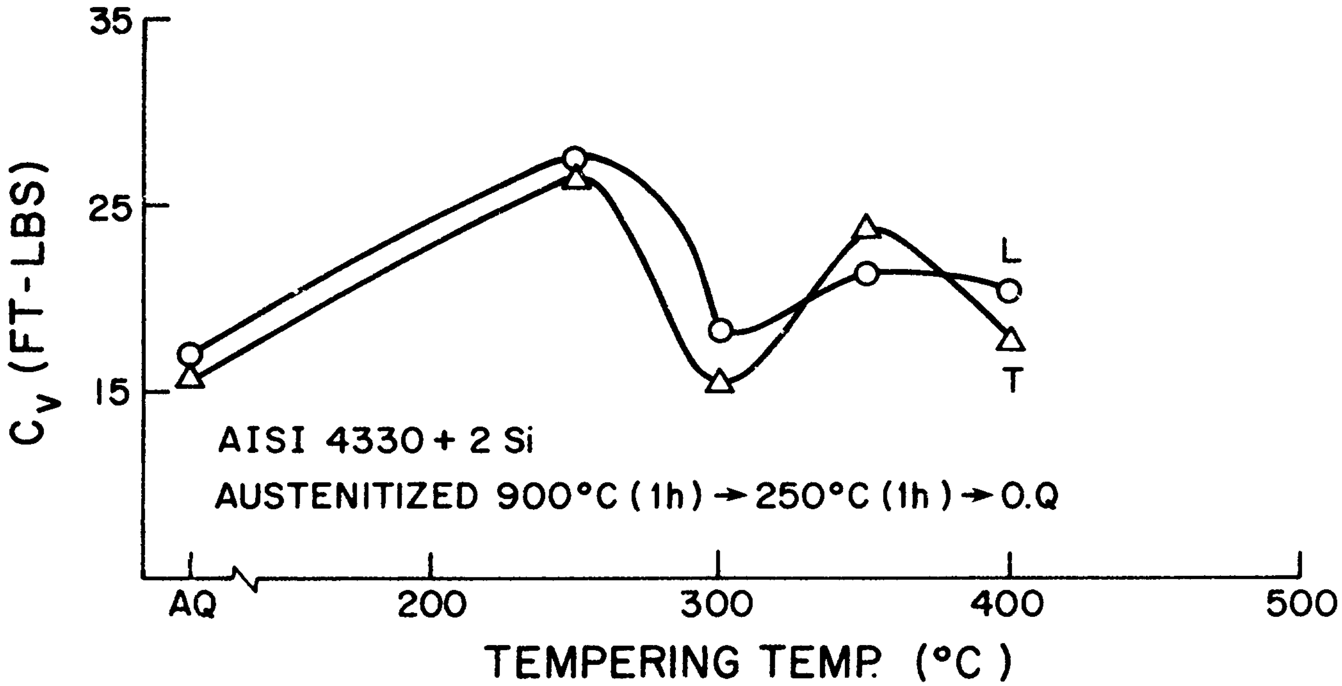


Figure 16. Room temperature Charpy impact energies as a function of tempering temperature for AISI 4330 + 2Si steel heat treated:
Austenitized at 900°C (1h) + isothermal at 250°C (1h) + oil quench + tempered (1h).
(L and T refer to the longitudinal and transverse orientations.)

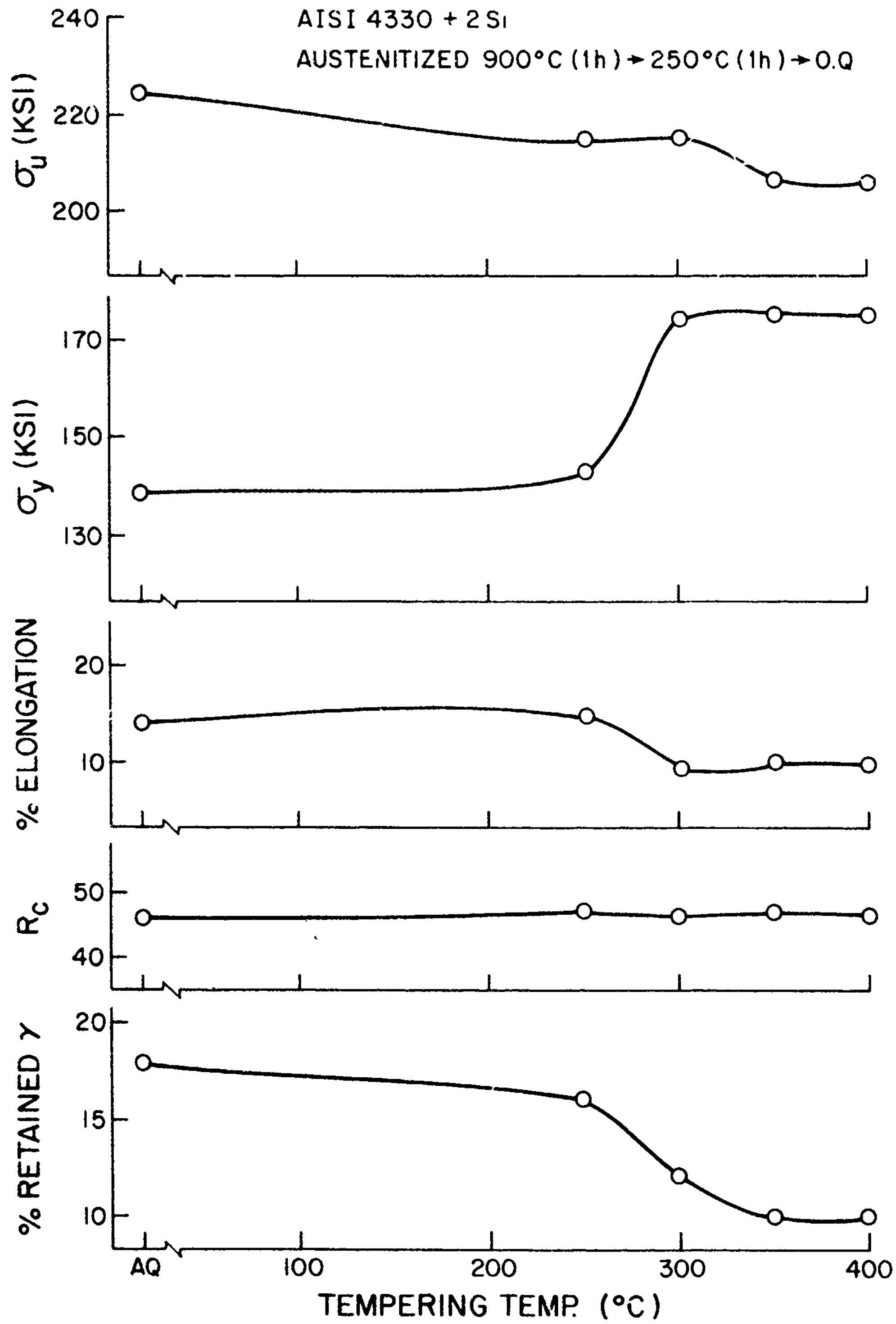
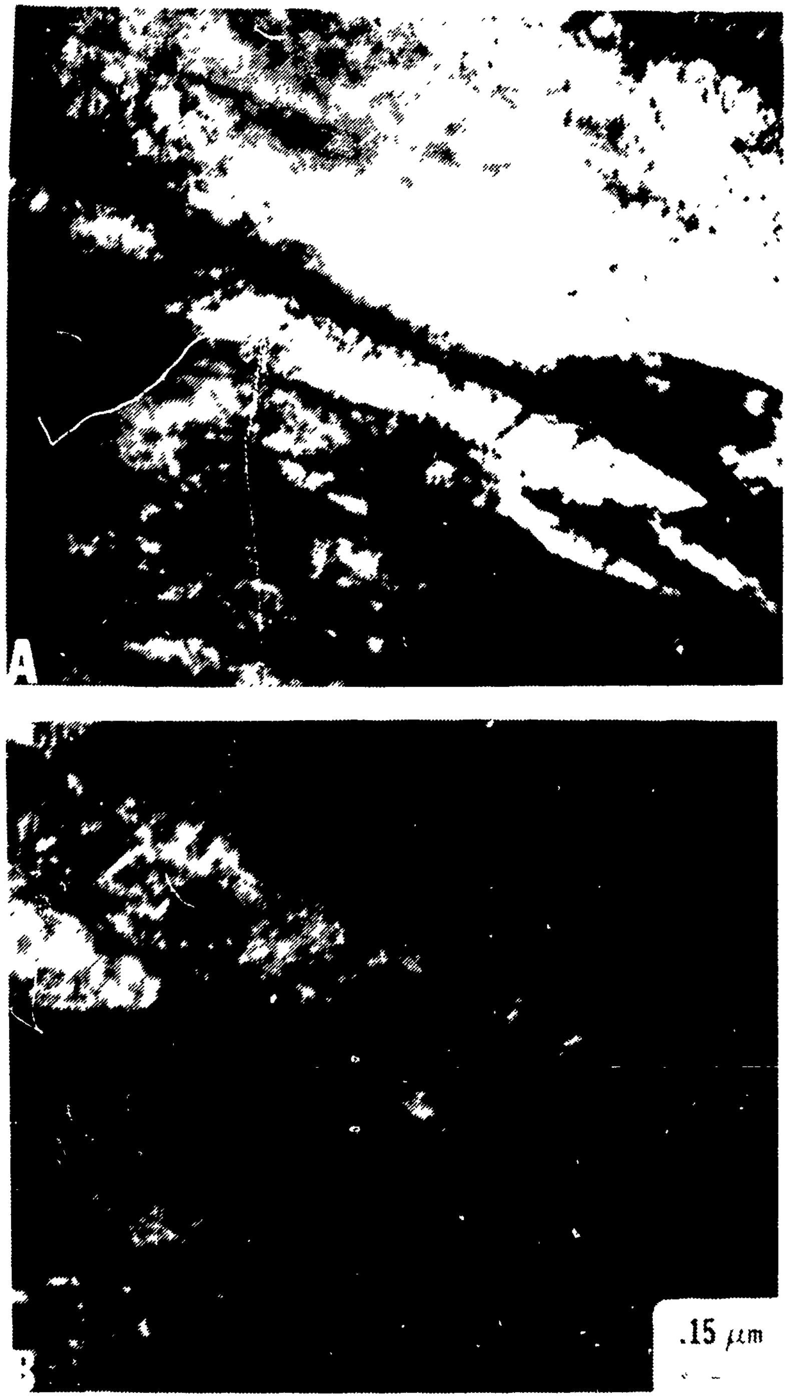


Figure 17. Plots of ultimate tensile strength, yield strength, % elongation (all longitudinal orientation), hardness and % retained austenite as a function of tempering temperature for AISI 4330 + 2Si steel isothermally transformed at 250°C.



XBB804 4238

Figure 18. Transmission of electron micrographs of AISI 4330 + 2Si steel isothermally transformed at 250°C, showing tempered martensite and lower bainite microstructure.

(a) Bright field micrograph

(b) Dark field, showing reversal of contrast of the bainite carbides.

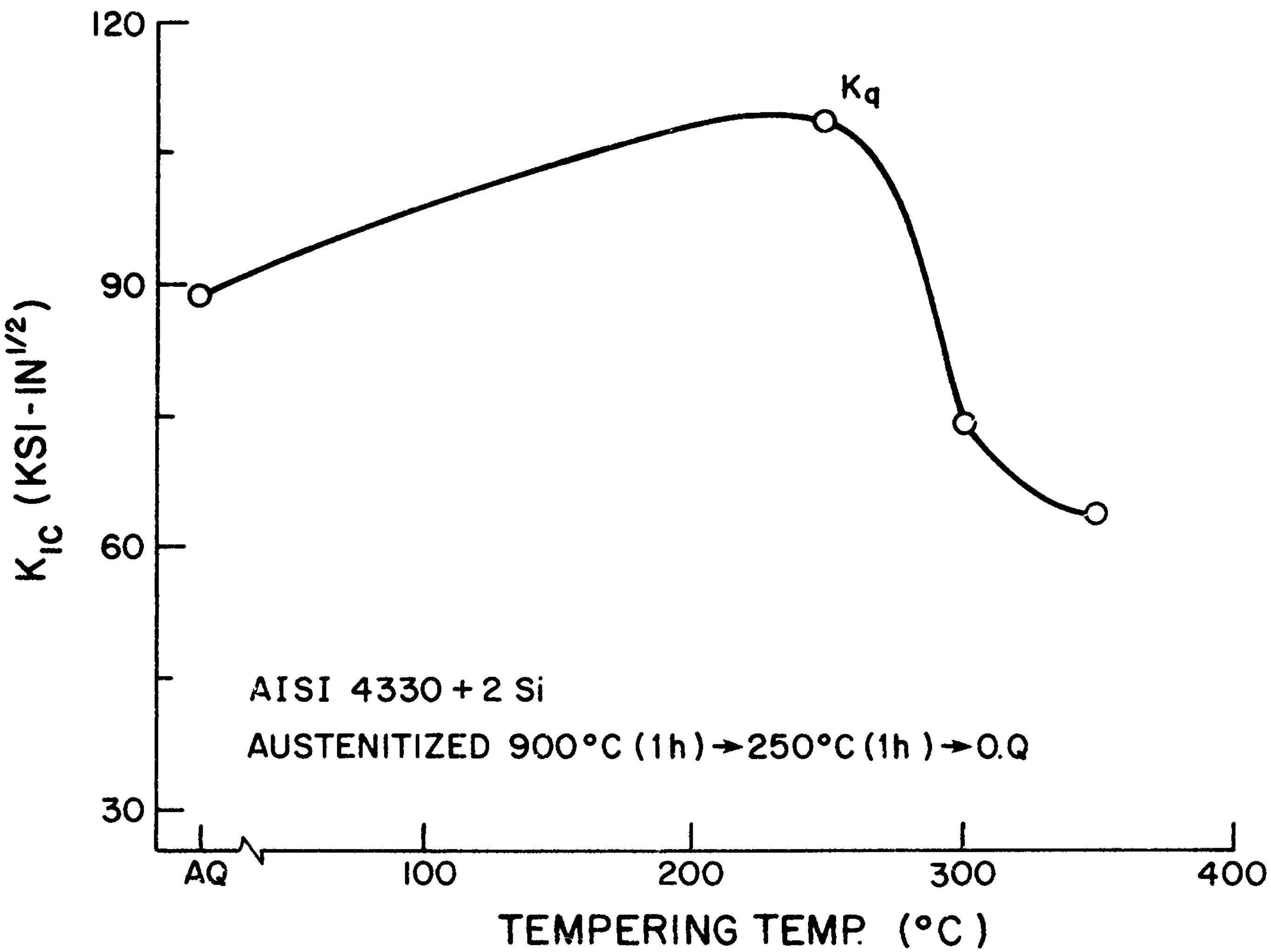


Figure 19. Plot of plane strain fracture toughness (K_{IC} data in the L-T orientation) as a function of tempering temperature for AISI 4330 + 2Si steel, isothermally transformed at 250°C.

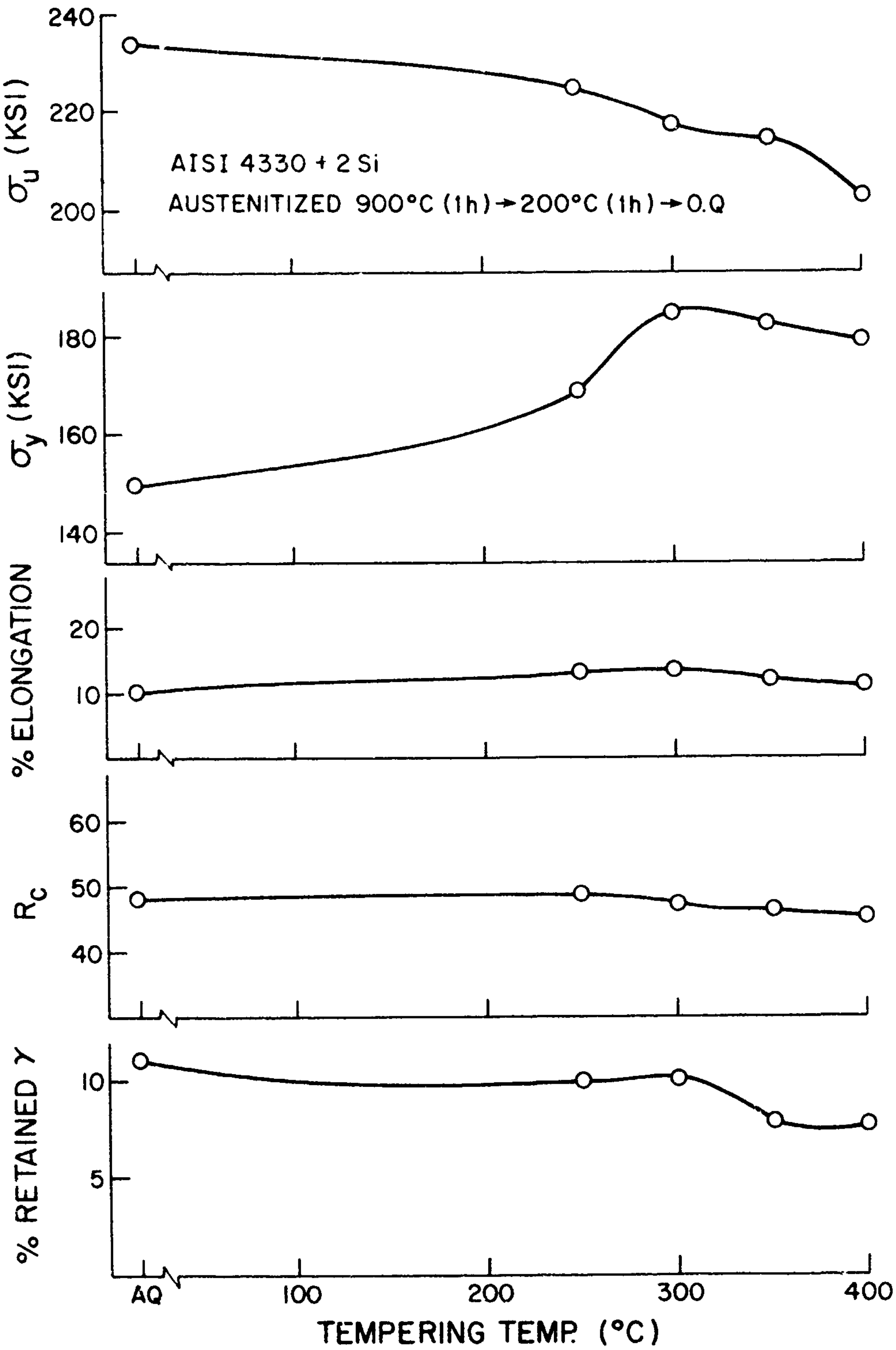


Figure 20. Plots of ultimate tensile strength, yield strength, % elongation (all longitudinal orientation), hardness and % retained austenite as a function of tempering temperature for AISI 4330 + 2Si steel, isothermally transformed at 200°C.

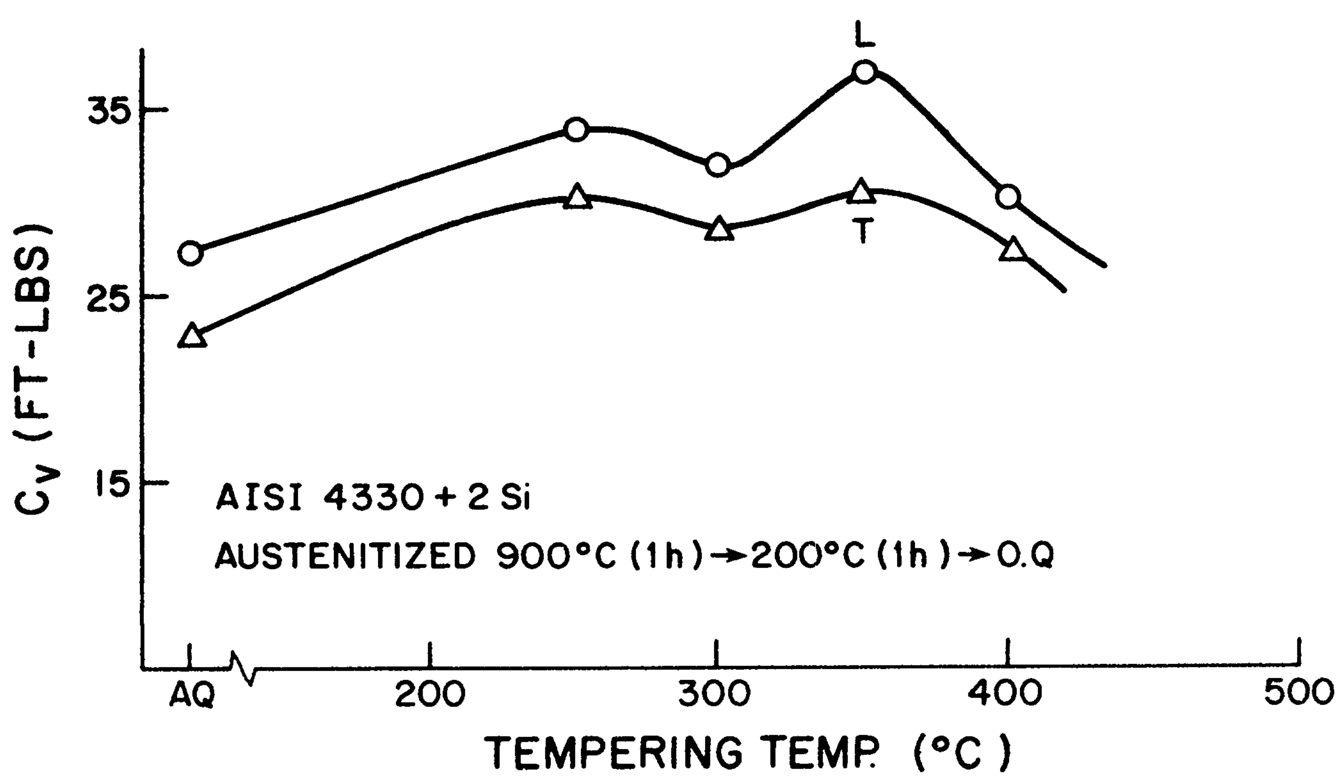


Figure 21. Room-temperature Charpy impact energies as a function of tempering temperature for AISI 4330 + 2Si steel heat treated:
Austenitized at 900°C (1h) + isothermal at 200°C (1h) + oil quench + tempered (1h)
L and T refer to the longitudinal and transverse orientations.

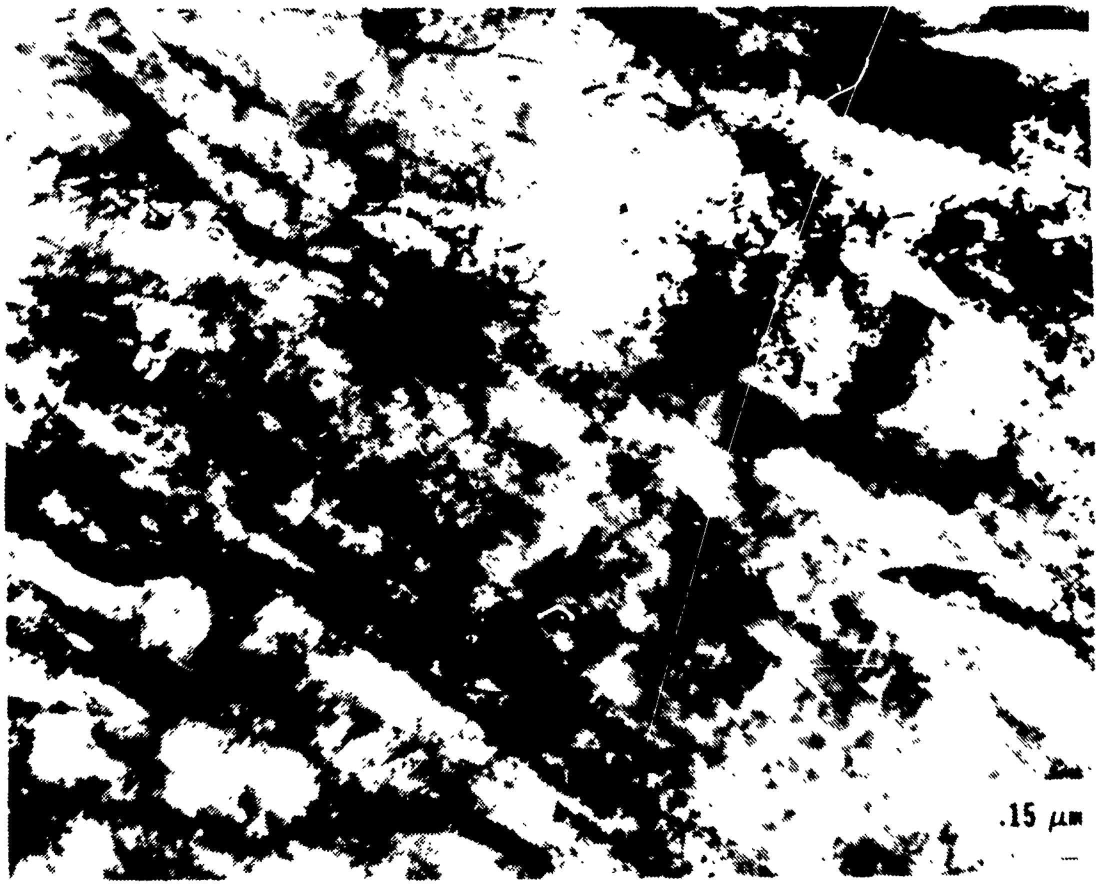


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Figure 22. Transmission electron micrograph showing the tempered martensitic microstructure obtained when AISI 4330 + 2Si steel was isothermally transformed at 200°C.

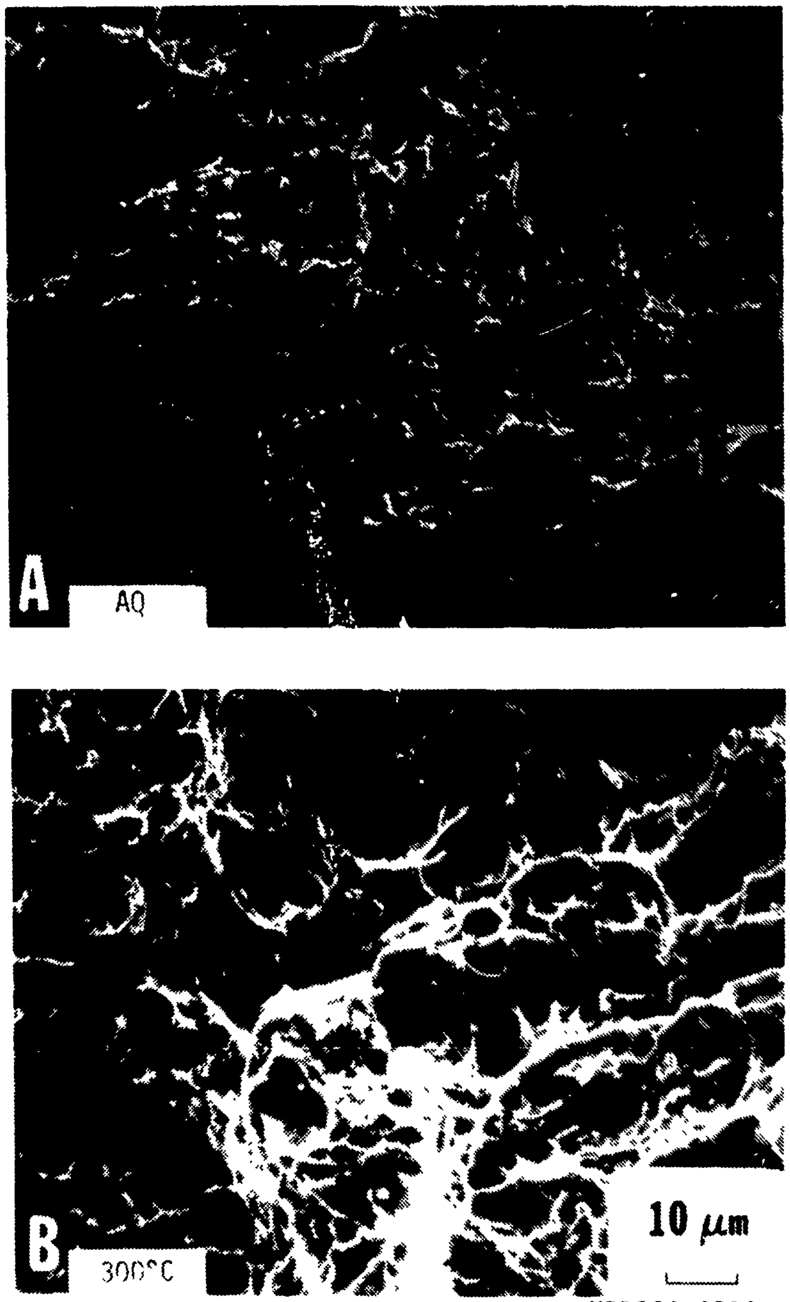

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Figure 23. Scanning electron photomicrographs of AISI 4330 + 2Si steel isothermally transformed at 200°C.
(a) As-quenched (i.e. untempered).
(b) 300°C tempering.

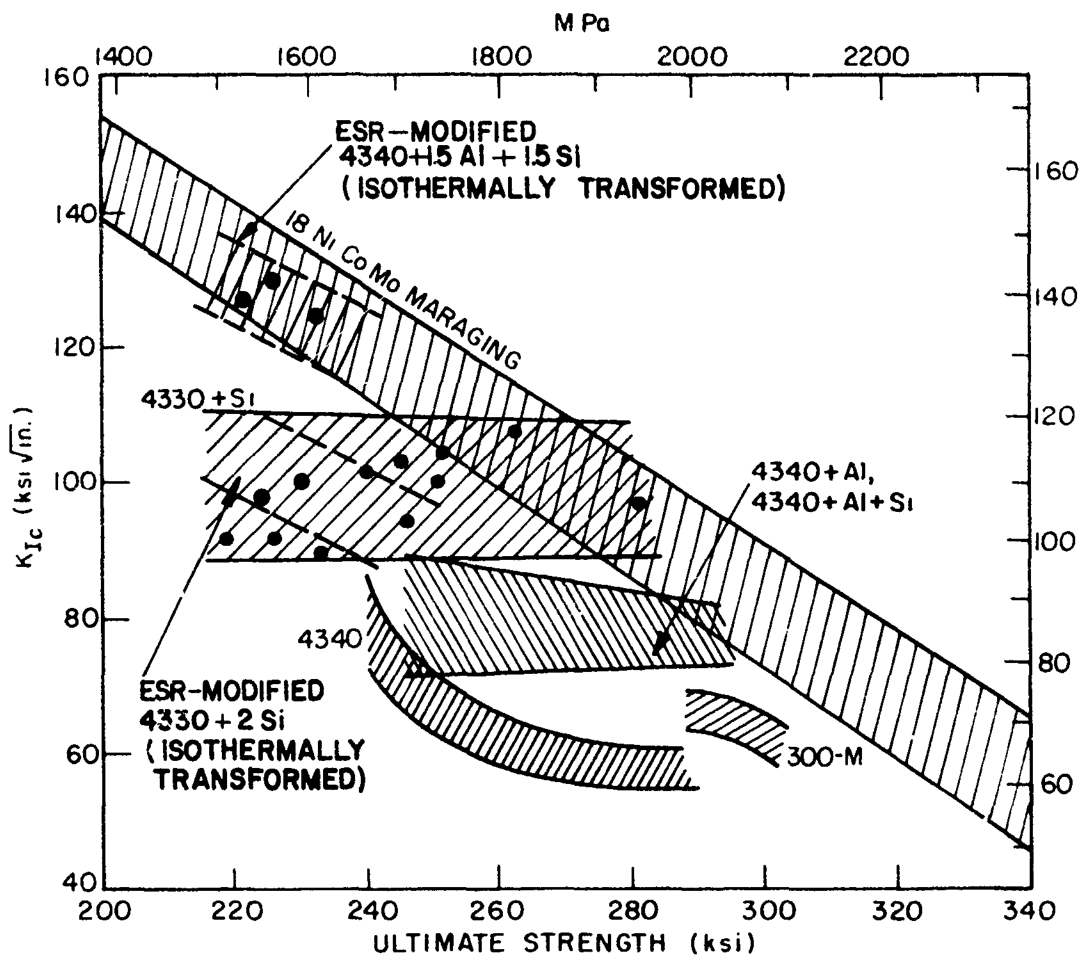

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Figure 24. Schematic plot of K_{IC} data as a function of ultimate tensile strength for commercial steels and the strength-toughness combinations obtained for the modified 43XX steels in the present investigation.

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MODIFIED 43XX STEELS FOR HIGH TOUGHNESS
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Technical Report AMMRC TR 80-20, April 1980
70 pp. illus-tables, CONTRACT DAA G46-78-C-0036
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Isothermal treatment	Hot quenching
Microstructure	Austenite
Bainite Martensite	Electroslag remelting

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