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ADA039488

FA-TR-76073

Study of Improved Aluminum Materials for Vehicular Armor

April 7, 1977

Final Report on Contract Number DAAA25-73-C-0657

Approved for Public Release; Distribution Unlimited

FRANKFORD ARSENAL • U.S. ARMY ARMAMENT COMMAND • PHILADELPHIA, PENNSYLVANIA 19137

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (18) (19) FFA Report No FA-TR-76073	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) Study of Improved Aluminum Materials for Vehicular Armor		5. TYPE OF REPORT & PERIOD COVERED (9) Final Report, June[redacted]973 - June[redacted]975
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) J. E. Vruggink		8. CONTRACT OR GRANT NUMBER(s) (15) DAAA25-73-C-0657 New
9. PERFORMING ORGANIZATION NAME AND ADDRESS Aluminum Company of America, Alcoa Technical Center, Alcoa Center, PA 15069 (12) 179 p.		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (16) DA Project 1X663620DG20
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Tank Automative Research and Development Command ATTN: DRDTA-RKA, Warren, MI 48090 (11)		12. REPORT DATE 7 Apr[redacted]77
		13. NUMBER OF PAGES 183
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Frankford Arsenal ATTN: SARFA-PDM-P Philadelphia, PA 19137		15. SECURITY CLASS (of this report) U
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

aluminum alloys
plate
intermediate thermal mechanical treatment
final thermal mechanical treatment
tensile properties
fracture toughness
microstructure

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An Intermediate Thermal Mechanical Treatment (ITMT), consisting of warm rolling at 500°F followed by a recrystallization treatment, produced a fine-grained, relatively equiaxed, recrystallized structure in 7475 plate. Alloy 7475-T6 plate having this recrystallized structure (AR) had slightly lower strengths and fracture toughness and higher ductility (tensile reduction in area) than laboratory or commercial hot rolled 7475-T6 plate having an unrecrystallized structure.

Alloy 7475-T6, similarly processed to a fine-grained, recrystallized structure, → over

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20. then hot rolled 25% at 750°F (AR+HR) had (1) strengths similar to laboratory and commercial hot rolled 7475-T6 plate, (2) fracture toughness similar to commercial hot rolled 7475-T6 plate but slightly lower than laboratory hot rolled 7475-T6 plate, and (3) ductility higher than laboratory or commercial hot rolled 7475-T6 plate. The fracture toughness of both the recrystallized (AR) and the recrystallized plus hot rolled (AR+HR) 7475-T6 plate was significantly higher than the fracture toughness of conventionally processed commercial 7075-T651 plate.

Application of Final Thermal Mechanical Treatment (FTMT) practices to 7475 plate produced strength/toughness relationships generally superior to that of 7075-T651 plate.

FOREWORD

The Aluminum Company of America, Alcoa Technical Center, Alcoa Center, PA 15069, prepared this report to satisfy the requirements of U.S. Army Contract DAAA25-73-C-0657. The Alcoa personnel responsible for this program were Mr. J. E. Vruggink, principal investigator; Dr. B. K. Park, technical assistance in the area of microstructural interpretation; and Dr. R. E. Frishmuth, technical assistance in the area of notch sensitivity. The investigation was supervised by Messrs J. T. Staley and H. Y. Hunsicker. The Frankford Arsenal contract technical supervisor was Dr. Jeffrey Waldman and the Tank Automotive Research and Development Command Project Engineer was Mr. Harry Spiro.

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INTRODUCTION

Medium strength, high toughness aluminum alloys have been widely used in armor plate applications due to their good resistance to kinetic energy impact rounds. Indications are that resistance to penetration is increased with increases in strength, but that the reduced toughness levels accompanying significant increases in strengths achieved by conventional alloying and fabrication are not sufficient to prevent plate cracking and shattering. To take advantage of the greater potential penetration resistance resulting from higher strengths, increases in the toughness level of the high-strength aluminum alloys are required.

The aluminum industry has made significant advances in increasing fracture toughness at high strength levels in 2XXX and 7XXX aircraft structure alloys, i.e., 2419, 2124, 2048, 7149, 7050, 7175, and 7475, by refining alloy chemistry and introducing special processing. The increase in fracture toughness by reduction or elimination of both soluble and insoluble constituents (second-phase particles) present in the alloy structure has been broadly successful, but further substantial improvements derived solely by changes in alloy chemistry for the basic alloy systems are not considered as offering a high probability of achievement at the present time. Moreover, ballistic evaluations of alloys of these types have shown no consistently significant improvement in ballistic performance over that afforded by the aluminum alloys presently used for armor plate. Consequently, a new approach is needed.

Modifications in the grain structure of high-strength alloys have shown promise as a way to develop improved combinations of strength and ductility.

Plate commercially available today of both standard and high toughness varieties of the 7XXX alloys, hot rolled to final gauge, has typically an unrecrystallized, highly elongated lamellar grain structure and has fracture toughness in the short-transverse direction which is lower than the fracture toughness in the longitudinal and long-transverse directions. Recently, DiRusso, et al,[1] and Waldman, et al,[2] developed novel processes specifically designed to produce a much finer controlled grain morphology in 7XXX alloy plate than is obtained with conventional processing. These processes, referred to as Intermediate Thermal Mechanical Treatments (ITMT), involve establishing preliminary structures amenable to recrystallization by applying appropriate thermal treatments prior to working at lower than conventional hot working temperatures (warm working).* These treatments introduce a relatively high degree of strain hardening which promotes recrystallization to fine, relatively equiaxed grain structures during subsequent thermal treatment. The ITMT products can be utilized either in this as-recrystallized condition (AR) or after subsequent hot rolling to elongate the grains (AR+HR).

Properties reported by these investigators have been very promising. DiRusso, et al,[1] reported that 0.4-in. thick super

*The processes employed by DiRusso (ISML-ITMT) and by Waldman (FA-ITMT) differ in the thermal practices prior to warm rolling.

purity (0.0013% Fe and 0.004% Si) 7075-T6 plate fabricated using ISML-ITMT processes exhibited higher longitudinal and long-transverse ductility and toughness and short-transverse stress-corrosion properties than were exhibited in conventionally produced super purity 7075-T6 plate of the same gauge. Waldman, et al,[2] using super purity (0.01% Fe and 0.01% Si) 7075 ingots fabricated 0.4 and 0.7-in. thick plate using FA-ITMT and conventional processes. The specially processed plate developed higher ductility as measured by reduction in area of long-transverse tensile specimens, and the reduction in area increased as the mean grain thickness decreased. Waldman, et al,[3] also disclosed that 1.0-in. thick super purity (0.02% Fe and 0.02% Si) 7075 plate fabricated using FA-ITMT processes, both (AR) and (AR+HR), had higher fracture toughness in the longitudinal and long-transverse directions in the T6, T76, and T73 tempers than did commercially produced 7075 plate in similar tempers.

Another method for improving the strength-fracture toughness relationship of 7XXX alloys is the use of a combination of special thermal and mechanical treatments following solution heat treatment and quenching called Final Thermal Mechanical Treatment (FTMT). The FTMT procedures, which have been extensively investigated,[1,4-8] involve generally a preage at an artificial aging temperature prior to mechanical working and a second artificial aging treatment following the mechanical working step.

The goals of this contract were to explore and develop industrially viable schedules for producing aluminum alloy plate with significantly improved plane strain fracture toughness at two target yield strength levels, (a) 60 to 70 ksi, (b) 70 to 80 ksi. The approach was to use ITMT processes to develop two types of grain structure in 1.25-in. to 2.50-in. plate of high purity Al-Zn-Mg-Cr alloys with and without a Cu addition. One target structure was fine recrystallized grains (AR), the other was a hot worked, fine-grain structure that had recrystallized at an intermediate step (AR+HR). Unrecrystallized (HR) 7475 plate was produced for comparison with ITMT processed plate from the same ingot, and results are also compared with data on commercial 7475 and 7075 plate.

MATERIAL AND PROCEDURE

Alloy and Composition Selection

Alloy 7475 and an experimental Cu-free Al-Zn-Mg-Cr alloy were selected for the program. Alloy 7475 is a modification of 7075 that has the Fe, Si, and other impurity elements restricted to the lowest values that are considered to be commercially practical. The Cu-free Al-Zn-Mg-Cr alloy contained slightly more Zn and Mg than nominal 7475 so that it would develop strength comparable to that of 7475. It was included because Cu-free Al-Zn-Mg-Cr alloys are weldable. The Fe and Si contents of the experimental alloy were controlled to the same limits as those of the alloy 7475.

Ingot

Direct chill (D.C.) ingots, 12-in. x 38-in. x 100-in., were used for this program. The ingots were stress relieved at 575°F, cropped, scalped to a thickness of either 9.25 or 10-in., and sawed into rolling sections (Figure 1). The compositions of the ingots were determined on analytical samples cast with the ingots:

Alloy	S. Number	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
7475	418967	0.06	0.12	1.65	0.00	2.35	0.23	5.79	0.01
7475	421675	0.04	0.07	1.64	0.01	2.23	0.17	5.62	0.01
7475	422622A,B,C	0.07	0.05	1.70	0.02	2.40	0.18	5.80	0.00
Al-Zn-Mg-Cr	422014	0.04	0.06	0.00	0.00	2.51	0.22	6.47	0.00

Fabrication and Thermal Practices

In the previous ITMT investigations,[1,2,3] thermal treatment temperatures conventional for 7075 and up to about 900°F were employed. Prior Alcoa investigations[9] had demonstrated beneficial effects of higher temperature and 960°F was employed extensively in the present investigation for ingot preheat, intermediate recrystallization, and final solution treatments.* Salt baths were employed in the prior investigations; in the present case, all thermal treatments were performed in circulating air furnaces. Work reported in Appendix A showed that the warm rolled 7475 plate recrystallized at 960°F for up to 20 hours developed the same grain size as comparable samples recrystallized for one hour at 860°F, regardless of heating rate or furnace type. In various parts of the program, thermal treatments at 860°F were used to provide direct comparison of results at the two temperatures. The treatment variants that included 860°F heating corresponded to ISML-ITMT and FA-ITMT practices.

For comparison and control at various stages of the ITMT process development, sections of the same ingot used for special

*The use of 960°F thermal treatments on nonhomogeneous material requires a presoak at lower temperatures to eliminate eutectic-forming phases.

processing were fabricated by a completely hot rolling practice which produces an unrecrystallized structure (HR).

ITMT

The ITMT process development and evaluation proceeded in four phases, the principal variants of which were warm rolling temperature and reduction. These factors strongly affect roll pressures, susceptibility to cracking or alligatoring, and the recrystallized grain size, which should be as fine as possible. Since workability and grain size are favorably affected in opposite directions by these warm working variables, there is a trade-off relationship between commercial viability and the metallurgical structure objectives.

Phase I. Rolling schedules for 7475 and the experimental Cu-free alloy to produce final gauges of 1.25 and 2.50-inches involving combinations of hot (750°F) and warm (600°F) rolling were followed as detailed in Tables 1 and 2. Warm (600°F) rolling reductions of up to 75% were applied directly to ingot rolling sections and to previously hot rolled material. Recrystallization treatments (960°F) were applied either at final gauge (AR) or at an intermediate gauge followed by 50% hot rolling reduction (AR+HR). Grain count data for these materials are tabulated in the tables.

Phase II. In an effort to achieve finer grain structures, warm rolling temperatures from 500 to 575°F were used in the second phase (Tables 3 and 4). Difficulties with alligatoring were encountered in applying large warm rolling reductions directly to non-beveled 7475 ingots at 500 and 550°F. Grain count data obtained with 7475 warm rolled at 575°F were not greatly different than those observed in the Phase I material.

Phase III. Practices employed are described in Table 5. To obtain reductions >65% by warm rolling at 500°F, the entry end of ingot rolling sections or of previously hot rolled slab were beveled by sawing (Figure 2) prior to warm rolling to prevent alligatoring. Using the beveled rolling pieces, reductions of 81 to 88% were successfully applied at 500°F to ingot sections and 75% (higher reductions not attempted because of final thickness requirements) to previously hot rolled material. Accordingly, items were rolled to final 1.25-inch gauge entirely at 500°F by Alcoa Laboratories (S. No. 422622E1) and by Frankford Arsenal (S. Nos. 427506 and 427507), the latter employing recrystallization and solution heat treating temperatures lower than 960°F in salt baths. Other sections were fabricated employing preliminary hot rolling followed by 75% warm (500°F) reductions and final recrystallization (HR-WR-AR) or intermediate recrystallization followed by 28% final hot rolling reduction (HR-WR-AR-HR).

Grain count data included in Table 5 show that much finer grain sizes were produced by application of the lower temperature (500°F) warm rolling operations preceding recrystallization treatment.

To assist in selection of the fabricating practices employed in the final phase to produce material for more complete evaluation, tensile, notched-tensile and fracture toughness data were obtained from material produced in all three phases. This also served to extend the range of fabricating variables covered by the mechanical property evaluations.

Phase IV. The final phase was designed to provide more complete three direction mechanical property evaluation and unequivocal correlation of these properties with the different grain morphologies unconfounded with differences in composition or particle morphologies derived from thermal practice variations. Using three rolling sections cut from a single ingot, three rolling schedules were employed to produce hot rolled, unrecrystallized (HR); fine-grain recrystallized (AR); and fine-grain recrystallized plus hot rolled (AR+HR) plate. A final gauge of 1.5-inches was selected to provide for maximum warm rolling reduction consistent with use of reasonable ingot breakdown reduction by hot rolling with further allowance for final hot rolling. This gauge was the minimum that permits satisfactory short-transverse direction mechanical property evaluation.

Use of the same thermal treatments (960°F) throughout was intended to eliminate any differences in morphology of second-phase insoluble constituent particles and high temperature solid-state precipitate ($Al_{12}Mg_2Cr$ dispersoid). Fabricating practice details are summarized in Table 6. The ITMT practices produced fine grains.

Details of all the ITMT fabricating practices employed in the four phases are illustrated by flow charts in Figures B1 through B16 in Appendix B.

FTMT

After a review was made of the various FTMT practices described in the literature, an FTMT practice developed for 7475 sheet at Frankford Arsenal[8] was selected for evaluation because it could be readily applied to 1.25-in. thick 7475 plate. The Frankford practice consisted of solution heat treatment, quenching, preaging 6 hrs at 220°F, cold rolling, and final artificial aging at 250°F. In the work reported here, 8-in. x 12-in. pieces of 1.25-in. thick 7475 plate having either a recrystallized plus hot rolled structure (S-422622A) or an unrecrystallized structure (S-422622C2) were used. The FTMT practice used consisted of solution heat treating at 960°F, cold water quenching, preaging 6 hrs at 220°F, cold rolling 10, 15, or 20%, and final artificial aging at 250°F for 8, 16, or 24 hrs. The fabricating details are given in Figure B17 in Appendix B.

Grain Size Determinations

The grain size was determined at the midplane of 1.00-in. to 2.50-in. thick plate from grain count measurements made microscopically using the linear intercept method. Materials produced in Phases I and II were examined only in the longitudinal/short-transverse plane, while measurements were made in this and in the long-transverse/short-transverse plane for most of the items produced in Phases III and IV.

Mechanical Property Determination

The location, number, and type of specimens used to determine the properties and grain size of the 7475 and Al-Zn-Mg-Cr alloy plate are described in Figures 3 and 4. The notched tensile and compact tension fracture toughness specimen configurations are shown in Figures C1, C2, and C3 of Appendix C. Notched tensile and fracture toughness tests could not be made in the short-transverse direction on samples of 1.00-in. to 1.25-in. thick plate because of specimen size limitations.

None of the candidate plane strain stress intensity fracture toughness test measurements, K_Q, were valid K_{Ic} values because one or more of the criteria specified by ASTM E-399 were not met, i.e., specimens not thick enough, fatigue crack too short, or curvature of fatigue crack exceeded allowable variation. The criteria which were not met, however, were not far beyond the specified limits. Consequently, the K_Q values obtained are considered to be meaningful for comparing relative fracture toughness of the various samples of plate.

RESULTS AND DISCUSSION

The experimental alloy Al-Zn-Mg-Cr plate developed a duplex grain structure which was attributed to the presence of twin columnar grains in the ingot. When this structure was detected, additional fabrication of the experimental alloy plate was stopped, and efforts concentrated on developing the target recrystallized grain size in 7475 plate.

Grain counts and complete mechanical property data for both alloys are presented in Tables 7 through 18. All of the mechanical property values reported are the arithmetic means of values determined in duplicate tests. In the following paragraphs the effects of ITMT fabrication practice on grain dimensions are discussed first, then the effects of grain structure on mechanical properties. The relationships between the grain dimensions and the ductility and toughness of recrystallized plate are examined next, followed by structure analysis of plate fabricated from pieces of a single ingot with no differences in thermal history during fabrication other than rolling temperature.

ITMT of 7475 Plate

Grain Dimensions vs Fabrication Variables. The ITMT fabricating practices used in this program were designed to evaluate more thoroughly than had been possible in previous investigations the merits of the nonconventional processing and to explore the possibility of developing a commercially viable ITMT process. They were not designed to optimize or survey completely the effects of individual fabricating variables in the ITMT process. Thus, the warm rolling temperatures, reductions during warm rolling, and reductions during the initial hot rolling of the ingot (ingot breakdown) at 750°F were not changed in a systematic fashion, so the individual effect of each fabricating variable on grain dimensions of the plate is difficult to determine.

The grain counts, average grain dimensions calculated from the grain counts, and the corresponding fabricating variables for the 7475-T6 plate are given in Table 19. Three dimensional photomicrographs at 100X of the various plates in T6 temper are included as Figures 5 through 16. Figures 5 through 9 show the ITMT (AR+HR) recrystallized plus hot rolled structures, Figures 10 through 13 show the ITMT (AR) recrystallized structures, and Figures 14 through 16 show the structures of the (HR) unrecrystallized 7475-T6 plate fabricated by hot rolling only. The grain thickness, grain length, and aspect ratio (average grain dimension in the longitudinal direction divided by average grain dimension in the short-transverse direction) of the grains (Table 19) are plotted as functions of the reduction achieved during warm rolling in Figures 17 and 18. No exact relationship between the grain dimensions and the different fabricating variables could be established but the following indications with respect to the 1.25 and 1.50-in. plate were noted:

1. Increasing the reduction during warm rolling prior to the recrystallization treatment decreased the thickness of the recrystallized grains and had no consistent effect on their length.

2. The reduction by warm rolling required to obtain the desired small grain thickness and length was lower when the warm rolling was preceded by hot rolling at 750°F (ingot breakdown) than when the ingot was warm rolled immediately.

Hot rolling the ingot at 750°F followed by warm rolling 75% at 500°F produced the desired fine grain, recrystallized structure. Due to limitations on the thickness of the rolling sections, the desired degree of grain refinement was not obtained in the 2.50 in. thick plate.

Grain Structure vs Mechanical Properties. The tensile properties, notched tensile strength/yield strength ratios, and K_Q values obtained on the samples of 7475-T6 plate are presented in detail for the 1.25-in. thickness in Tables 7 through 9 and for the 2.50-in. thickness in Tables 11 through 13.

Elongation, reduction in area, notched tensile strength/yield strength ratio, and K_Q values are plotted as functions of yield strength for each of the three test directions, longitudinal, long-transverse, and short-transverse, in Figures 19 through 21, respectively. Data for both plate gauges are included in Figures 19 and 20; only the thicker material can be used for the Figure 21 comparisons. Coded symbols distinguish between data for the two gauges, for the three major process variants, (AR+HR), (AR), and (HR), and for the two temperature variants (960°F), (860-900°F). Included in these figures are lines representing the upper and lower bounds of the previously determined relationships between the toughness- and ductility-related properties and the yield strength for commercially hot rolled plate of alloys 7475 and 7075 in T651, T7651, and T7351 tempers (gauge range 1.30 to 2.62-in.).

The data reveal several significant points:

1. The longitudinal and long-transverse yield strengths of the recrystallized (AR) 7475-T6 plate were slightly lower than those of either the unrecrystallized (HR) or the recrystallized plus hot rolled (AR+HR) material, while the short-transverse yield strength variations showed no systematic relation to the process variables.

2. The longitudinal and long-transverse ductilities (elongation and reduction in area values) of the recrystallized (AR) and the recrystallized plus hot rolled (AR+HR) material were generally higher than those of the unrecrystallized (HR) material.

3. The longitudinal and long-transverse NTS/YS ratios of the recrystallized plus hot rolled (AR+HR) and

the unrecrystallized (HR) plate lie within the band established for commercial hot rolled 7475 plate in the T651, T7651, and T7351 tempers, the K_Q values for the recrystallized plus hot rolled (AR+HR) plate are in the lower half of the band for commercial hot rolled 7475 plate, and the K_Q values for the unrecrystallized (HR) plate are in the upper half or above the band for commercial hot rolled 7475 plate.

4. The longitudinal and long-transverse fracture toughness (NTS/YS and K_Q values) of the recrystallized (AR) plate were generally below the band for commercial hot rolled 7475 plate in the T651, T7651, and T7351 tempers and above the band for commercial conventionally hot rolled 7075 plate in the T651, T7651, and T7351 tempers.

Mechanical Properties vs Grain Dimensions. The effect of grain dimensions on the properties of the samples of laboratory-fabricated 7475-T6 plate cannot be even speculatively determined from Figures 19 through 21. Because of the wide range of yield strengths and indications that the other mechanical properties were influenced by yield strength and plate thickness, an estimate of the effects of these variables, yield strength and plate thickness, on the longitudinal, long-transverse, and short-transverse elongation, reduction in area, notched tensile strength/yield strength ratio, and K_Q values was attempted using multiple regression analyses so that ductility and toughness could be compared on the basis of equivalent yield strength levels. Yield strength, plate thickness, Fe content, plate structure (AR, AR+HR, and HR), and grain dimensions were used as independent variables, and the coefficients determined by the regression analyses were used as estimates of the effect of each independent variable on a given property. The large change in the coefficient for yield strength, plate thickness, and Fe content, in some cases from a negative to a positive value, with the selection of the independent variables representing plate structure and grain dimensions was unfortunate. This large change in coefficients is shown by the listing of the individual coefficients for the longitudinal properties in Table D1, Appendix D.

Because of the large variation in coefficients indicating the effect of yield strength, plate thickness, and Fe content on the ductility and toughness of the plate, the properties were not normalized. Thus, the elongation, reduction in area, notched tensile strength/yield strength ratios and K_Q values (Tables 7, 8, 11, and 12) are plotted as functions of grain thickness in Figures 22 through 24, of grain length in Figures 25 through 27, and of grain aspect ratio in Figures 28 through 30. The parameter of grain thickness used in Figures 22 through 24 was the same parameter used by Waldman[2] in plotting the data from 0.4-in. and 0.7-in. thick plate.

The plots in Figures 22 through 30 show no significant change in the longitudinal, long-transverse, or short-transverse elongation, notched tensile strength/yield strength ratio, or K_Q values for the plates having a recrystallized (AR) or a recrystallized plus hot rolled (AR+HR) structure with decreasing grain thickness, decreasing grain length or increasing grain aspect ratio. There is some indication that the reduction in area increases with decreasing grain size.

Ductility and Toughness vs Microstructure. The mechanical properties (Table 10) of the 1.50-in. thick 7475-T6 plate fabricated to develop a recrystallized structure (AR), a recrystallized plus hot rolled structure (AR+HR), and an unrecrystallized structure (HR) are plotted as functions of yield strength for each testing direction in Figure 31. Also plotted in Figure 31 are bands (upper and lower bounds) showing the relationship between yield strength and notched tensile strength/yield strength ratio and K_{Ic} values previously determined for commercially hot rolled 7475 plate. Comparison of these plots with Figures 19 through 21 show that the higher Fe content in the 1.50-in. thick plate in comparison to those in the 1.25-in. and 2.50-in. thick plate, i.e., 0.12% Fe in the former vs 0.05 to 0.07% Fe in the latter, produced lower notched tensile strength/yield strength ratios and K_Q values. The relationship between the notched tensile strength/yield strength ratios and K_Q values for the three different plate structures (AR, AR+HR, and HR) remained the same as noted in the other comparisons. In an effort to explain these results, analyses were made of smooth and notched tensile data (Appendix E) and a detailed microstructural examination was made on samples of the plate (Appendix F). The results of the analyses described in Appendix E indicated that the recrystallized structure was more notch sensitive than either the recrystallized plus hot rolled or the unrecrystallized structures. The results of the microstructural examinations showed that the fracture toughness increased as the proportion of intergranular fracture decreased. The relative proportion of the intergranular fracture was related to the population and size of large particles at the grain boundaries in addition to those effects attributable simply to grain boundary morphology, in particular, the relative orientation/grain boundary area relationships normal to the direction of tension. Some of the particles present at the grain boundaries were identified as having originated by precipitation during quenching.

To reduce the amount of such precipitate at the grain boundaries, 0.6-in. dia. cylindrical blanks were machined from the three types of plate. The blanks were heat treated, quenched in cold water, aged to the T6 temper and machined to 0.357-in diameter smooth specimens and 0.500-in. diameter notched tensile specimens. Analysis of the smooth and notched tensile data from the more rapidly quenched reheat treated specimens showed that the notch tensile strengths of all three structures increased but that the recrystallized structure was still the most notch sensitive structure. Microscopic (TEM) examination of the rapidly quenched material showed a reduced number of precipitate particles at the grain boundaries in the recrystallized and the recrystallized plus hot rolled material, but particles identified as Al_7Cu_2Fe constituents were unaffected by the reheat treatment.

Analysis of the results of the microstructural examinations of samples from the plate heat treated at full thickness (Appendix F) indicated that differences in the dislocation substructures strongly affected the ductility and the fracture toughness. The recrystallized grain structure, which developed high ductility, was essentially free of dislocations in contrast with the unrecrystallized structure, which contained dislocations within subgrains and along cell walls. Dislocations generated during deformation of the recrystallized structure interacted with the grain boundaries, however, and provided low resistance to coalescence of voids nucleated by fracture or decohesion of particles at the grain boundaries. The resultant low toughness, intergranular fracture was significantly different from the high toughness, transgranular dimpled rupture mechanism initiated by $Al_{12}Mg_2Cr$ dispersoids predominantly within the grains of the unrecrystallized material.

Summary - ITMT Processing of 7475 Plate

Rolling temperature and the amount of reduction were the main variable factors in the present investigation which were used to control the grain structure and resultant mechanical properties. For the 7475 plate, reductions of at least 75% at a temperature near 500°F produced a fine, relatively equiaxed grain structure (AR) containing few dislocations and a relatively large number of particles along the grain boundaries. Plate having this structure developed slightly lower strength, higher ductility (reduction of area in smooth tensile specimens), and lower fracture toughness (NTS/YS ratios and K_Q values) than unrecrystallized (HR) 7475 plate containing dislocations within subgrains and along cell walls. Hot rolling the recrystallized structure at 750°F produced a structure after solution heat treatment that consisted of elongated recrystallized grains containing polygonized cells. This structure developed strength comparable to that of the unrecrystallized material with better ductility, equal notch toughness, and somewhat lower fracture toughness (K_Q).

FTMT of 7475 Plate

The results of long-transverse tensile and notched tensile tests made of the samples of 1.00-in. to 1.16-in. thick 7475 plate given the various FTMT practices are summarized in Table XX. The thickness of the plate samples dictated use of only 0.5-in. diameter notched tensile specimens as a measure of toughness. Comparison of the notched tensile strength/yield strength ratios determined on the FTMT plates with ratios obtained on thicker 7475 plate tested using 1-1/16-in. diameter notched specimens required that the ratios obtained using 0.5-in. diameter notched specimens be converted to ratios expected from 1-1/16-in. diameter specimens. The ratios were converted using correlations established at Alcoa Laboratories.

In order to compare toughness over a range of yield strengths and provide for any differences in response to final artificial aging arising from possible prior strain effects on aging rate at 250°F, three aging times at this temperature were used, i.e., 8, 16, and 24 hours. There was no consistent change in yield strengths or notched tensile strength/yield strength ratios with increasing aging time at 250°F for the various amounts of cold rolling. Therefore, the yield strengths, reduction in area values, and notched tensile strength/yield strength ratios obtained for the three aging times were averaged for each amount of cold rolling.

The average, maximum and minimum yield strengths, reduction in area values, and notched tensile strength/yield strength ratios for the various samples of plates are plotted as functions of percent reduction applied during cold rolling in Figure 32 and as functions of the yield strengths in Figure 33. Also included in Figure 33 are two bands, one representing the notched tensile strength/yield strength ratio versus yield strength relationship for commercially-hot rolled 7475 plate and the other for conventionally-processed commercial 7075 plate. The plots in Figure 32 show that the yield strength increases and the reduction in area and notched tensile strength/yield strength ratios decrease with increasing amount of cold work for plate having either an initially recrystallized plus hot rolled structure (AR+HR) or an unrecrystallized structure (HR). The yield strengths increased at a slightly higher initial rate and the notched tensile strength/yield strength ratios decreased at a slightly lower rate with increasing amounts of cold rolling for the unrecrystallized (HR) plate than for the recrystallized plus hot rolled (AR+HR) plate. The reduction in area values for the recrystallized plus hot rolled plate (AR+HR) were consistently higher than those for the unrecrystallized plate (HR).

The data in Figure 33 show that the use of FTMT practices produced yield strengths exceeding the expected range for either 7475 or 7075 in the T6 temper. The notched tensile strength/yield strength ratios of the FTMT material fall at and below a linear extrapolation of the lower edge of the band for commercially-hot rolled 7475-T6. The notch toughness of the FTMT-processed recrystallized plus hot rolled (AR+HR) material was somewhat lower than that of the FTMT-processed unrecrystallized (HR) material for a given yield strength.

The greater the amounts of cold rolling used, the closer the notch toughness approached that of 7075. The data indicated, however, that the use of FTMT practices on 7475 plate will produce an improvement in the strength-fracture toughness relationship over that which would be expected with similarly processed 7075 plate. Moreover, the data clearly indicate that recrystallized plus hot rolled (AR+HR) 7475 plate develops higher ductility than unrecrystallized (HR) 7475 plate when given a FTMT-type practice.

ITMT of Al-Zn-Mg-Cr Plate

Results of the mechanical property tests made on the samples of 1.25-in. and 2.50-in. thick Al-Zn-Mg-Cr alloy plate in the T6 temper (Tables 14 through 18) show that the Al-Zn-Mg- Cr alloy plate developed strengths that were comparable to those of the 7475-T6 plates and notched tensile strength/yield strength ratios that were substantially lower than those of 7475-T6.

Fabrication of 7475 Plate for Ballistic Evaluation

The results of the mechanical property tests and optical microscopic examinations made on the samples of 1.25-in. and 2.50-in. thick 7475-T6 and Al-Zn-Mg-Cr alloy T6 plate fabricated using ITMT practices and on 1.00-in. to 1.16-in. thick 7475 plate fabricated using FTMT practices were reviewed and discussed with personnel at Frankford Arsenal. As a result of these discussions, two practices were selected to be used in the fabrication of 1.00-in. thick 7475 plate for ballistic evaluation. These two practices are described in Table 21 and the details of the practices are given in Figure B18 in Appendix B of this report.

The first practice was designed to produce 1.00-in. thick plate having a fine grain, recrystallized plus hot rolled (AR+HR) structure and a long-transverse yield strength in the range of 60 to 70 ksi. The structure and strength were to be obtained by the use of an ITMT practice and overaging to a T7X temper. The second practice was designed to produce plate of the same thickness having a fine grain, recrystallized plus hot rolled (AR+HR) structure and a long-transverse yield strength in the range of 70 to 80 ksi. The structure and strength were to be obtained by combining an ITMT practice with an FTMT practice.

Thirty pieces 1.0-in. x 9-in. x 18-in. of 7475 plate were fabricated at Alcoa Laboratories using the first practice and thirty-eight pieces of the same dimensions using the second practice. These were supplied to Frankford Arsenal for ballistic evaluation.

Microstructures and tensile properties obtained on a sample of the plate fabricated by each practice are included as Figures 34 and 35. Fine grain, recrystallized structures were obtained in both plates and the long-transverse yield strengths were in the desired range.

CONCLUSIONS

The results of the work carried out under this contract showed the following:

1. An ITMT practice consisting of warm rolling at 500°F for a reduction of at least 75%, followed by a recrystallization treatment at 960°F, produced fine-grained, relatively equiaxed recrystallized structure (AR) in 7475 plate.

2. Alloy 7475-T6 plate having this recrystallized (AR) structure had slightly lower strengths and fracture toughness and higher ductility than laboratory or commercial 7475-T6 plate having an unrecrystallized (HR) structure.

3. Alloy 7475-T6 plate that was recrystallized to a fine-grain size, then hot rolled 25% at 750°F had strengths similar to, and ductility higher than either laboratory or commercial hot rolled unrecrystallized 7475-T6 plate and had fracture toughness similar to commercial hot rolled 7475-T6 plate but slightly lower than laboratory hot rolled 7475-T6 plate.

4. The lower toughness of the 7475-T6 plate having a recrystallized (AR) structure is attributed to a higher proportion of intergranular fracture.

5. Al-Zn-Mg-Cr (Cu-free) alloy plate in the T6 temper having either a recrystallized (AR) or a recrystallized plus hot rolled (AR+HR) structure had comparable strengths and lower toughness than 7475-T6 plate with the same structures.

6. FTMT practices applied to 7475 plate developed strength-toughness relationships generally superior to that of 7075-T6 plate.

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TABLE 1

FABRICATION OF 1.25" AND 2.50" THICK 7475-T6 PLATE IN PHASE I

Plate			10"x9"x20" Rolling Sections				Rolled Slab				Recrystallization		Rolling at 750°F	
	Grain Count, g/mm				Rolling				Rolling					
S. Number	Y	Z	Sect. Fab.	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment, Hrs/°F	Reduction, %	Sol.HT Hrs/°F
							1.25" Thick Plate							
421675A1	14	33	421675A	A	750	75	2.50	A	600	50	1.25	10/960	None	2/960
421675B1			421675B	Hot Rolled										
421675C1	12	50	421675C	A	750	50	5.00	A	600	75	1.25	10/960	None	2/960
421675D1	N.D.		421675D	B	600	75					2.50	10/960	50	2/960
421675E1	8	20	421675E	A	750	50	5.00	A	600	50	2.50	10/960	50	2/960
							2.50" Thick Plate							
421675B3			421675B	Hot Rolled										
421675C3	8	12	421675C	A	750	50	5.00	A	600	50	2.50	10/960	None	2/960
421675D3	14	20	421675D	B	600	75					2.50	10/960	None	2/960
421675F3[1]	5	24	421675F	B	600	50	5.00	B	600	50	2.50	10/960	None	2/960
421675F1	N.D.		421675F	B	600	50					5.00	10/960	50	2/960

Ingot Thermal Treatments "A" - Heated 6 hrs at 860°F plus 20 hrs at 960°F.

"B" - Heated 6 hrs at 860°F plus 20 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr and soaked at least 4 hrs at 650° or 500°F.

Slab Thermal Treatments "A" - Heated 2 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr and soaked at least 4 hrs at 650° or 500°F.

"B" - Heated 10 hrs at 960°F, cooled to room temperature, heated 2 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr and soaked at least 4 hrs at 650° or 500°F.

All thermal treatments carried out in circulating air furnaces.

Plates cold water quenched after solution heat treatment and aged 24 hrs at 250°F at least 4 days after quenching.

Note: 1. Double recrystallization treatment.

TABLE 2

FABRICATION OF 1.25" AND 2.50" THICK Al-Zn-Mg ALLOY-T6 PLATE IN PHASE I

Plate			10"x9"x20" Rolling Sections				Rolled Slab				Recrystallization		Rolling at 750°F	
	Grain Count, g/mm				Rolling				Rolling					
S. Number	Y	Z	Sect. Fab.	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment, Hrs/°F	Reduction, %	Sol.HT Hrs/°F
							1.25" Thick Plate							
422014A1	1	14	422014A	A	750	75	2.50	A	600	50	1.25	10/960	None	2/960
422014B1			422014B	Hot Rolled										
422014C1	10	33	422014C	A	750	50	5.00	A	600	75	1.25	10/960	None	2/960
422014D1	N.D.		422014D	B	600	75					2.50	10/960	50	2/960
422014E3	2	50	422014E	A	750	50	5.00	A	600	50	2.50	10/960	50	2/960
							2.50" Thick Plate							
422014B3			422014B	Hot Rolled										
422014C3	2	5	422014C	A	750	50	5.00	A	600	50	2.50	10/960	None	2/960
422014D3	5 1	14[1] 3	422014D	B	600	75					2.50	10/960	None	2/960
422014F3[2]	N.D.		422014F	B	600	50	5.00	B	600	50	2.50	10/960	None	2/960
422014F1	N.D.		422014F	B	600	50					5.00	10/960	50	2/960

Ingot Thermal Treatments "A" - Heated 6 hrs at 860°F plus 20 hrs at 960°F.
"B" - Heated 6 hrs at 860°F plus 20 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr, and soaked at least 4 hrs at 650° or 500°F.

Slab Thermal Treatments "A" - Heated 2 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr, and soaked at least 4 hrs at 650° or 500°F.
"B" - Heated 10 hrs at 960°F, cooled to room temperature, heated 2 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr, and soaked at least 4 hrs at 650°F or 500°F.

All thermal treatments carried out in circulating air furnaces. Plates cold water quenched after solution heat treatment and aged 24 hrs at 250°F at least 4 days after quenching.

Notes: 1. Duplex grain structure.
2. Double recrystallization treatment.

TABLE 3

FABRICATION OF 2.50" THICK 7475-T6 PLATE IN PHASE II

Plate			10"x9"x20" Rolling Sections				Rolled Slab				Recrystallization		Rolling at 750°F	
	Grain Count, g/mm				Rolling				Rolling					
No. Number	Y	Z	Sect. Fab.	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment, Hrs/°F	Reduction, %	Sol.HT, Hrs/°F
421675H	6	16	421675H	A	750°F	20	8.00	A	575	69	2.50	10/960	None	2/960
			421675I[1]	C	550	Alligatored at 4.3" (57% Reduction)								
421675J1	12	33	421675J	A	750	30	7.00	A	575	64	2.50	10/960	None	2/960
421675G1	6	12	421675G	B	575	65					3.50	10/960	28	2/960
421675J2	7	26	421675J	A	750	30	7.00	A	575	50	3.50	10/960	28	2/960
			421675K[2]	D	500	Alligatored at 3.6" (64% Reduction)								
421675L1	5	20	421675L[2]	D	500°F	65	Alligatored on Front End				3.50	10/860	28	2/860

Ingot Thermal Treatments "A" - Heated 6 hrs at 860°F plus 20 hrs at 960°F.

"B" - Heated 6 hrs at 860°F plus 20 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at775°F, cooled to 650° or 500°F at 50°F/hr, and soaked at least 4 hrs at 650° or 500°F.

"C" - Heated 18 hrs at 750°F, cooled to 575°F at 50°F/hr, and soaked at least 4 hrs at 575°F.

"D" - Heated 20 hrs at 860°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr, and soaked at least 4 hrs at 650° or 500°F.

Slab Thermal Treatments "A" - Heated 2 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr, and soaked at least 4 hrs at 650° or 500°F.

All thermal treatments carried out in circulating air furnaces.

Notes:
1. ISML-ITMT-type practice.
2. FA-ITMT-type practice.

TABLE 4

FABRICATION OF 2.50" THICK Al-Zn-Mg ALLOY-T6 PLATE IN PHASE II

Plate			10"x9"x20" Rolling Sections				Rolled Slab				Recrystallization		Rolling at 750°F	
	Grain Count, g/mm				Rolling				Rolling					
S. Number	Y	Z	Sect. Fab.	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment, Hrs/°F	Reduction, %	Sol.HT Hrs/°F
422014H	7 2	10 5	422014H	A	750	20	8.00	A	575	69	2.50	10/960	None	2/960
422014J1	N.D.		422014J	A	750	30	7.00	A	575	64	2.50	10/960	None	2/960
422014L1	5	33	422014L[1]	D	500	75					2.50	10/860	None	2/860
422014G1	1	33	422014G	B	575	65					3.50	10/960	28	2/960
422014I	N.D.		422014I[2]	C	575	57					4.30	10/860	42	2/860
422014J2	N.D.		422014J	A	750	30	7.00	A	575	50	3.50	10/960	28	2/960
422014K	5	14	422014K[1]	D	500	65					3.50	10/860	28	2/860

Ingot Thermal Treatments "A" - Heated 6 hrs at 860°F plus 20 hrs at 960°F.
"B" - Heated 6 hrs at 860°F plus 20 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr, and soaked at least 4 hrs at 650° or 500°F.
"C" - Heated 18 hrs at 750°F, cooled to 575°F at 50°F/hr and soaked at least 4 hrs at 575°F.
"D" - Heated 20 hrs at 860°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr, and soaked at least 4 hrs at 650° or 500°F.

Slab Thermal Treatment "A" - Heated 2 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650°F at 50°F/hr, and soaked at least 4 hrs at 650°F.

All thermal treatments carried out in circulating air furnaces.

Notes: 1. FA-ITMT-type practice.
2. ISML-ITMT-type practice.

TABLE 5

FABRICATION OF 1.25" AND 2.50" THICK 7475-T6 PLATE IN PHASE III

Plate	Grain Count, g/mm		10"x9"x20" Rolling Sections		Rolling		Rolled Slab		Rolling		Recrystallization		Rolling at 750°F	
S. Number	Y	Z	Sect. Fab.	Thermal Treat-ment	Temp, °F	Reduc-tion, %	Thick, in.	Thermal Treat-ment	Temp, °F	Reduc-tion, %	Thick, in.	Thermal Treat-ment, Hrs/°F	Reduc-tion, %	Sol.HT Hrs/°F
							1.25" Thick Plate							
421675E61	23	48	421675E	A	750	50	5.00	A	500	75	1.25	10/960	None	2/960
422622E1	8	40	422622E	B	500	88					1.25	10/960	None	2/960
427506[2]	12	61	422622	E	500	88					1.25	48/860[1]	None	2/900[1]
421675E51	10	38	421675E	A	750	50	5.00	A	500	67	1.75	10/960	28	2/960
422622A	14	63	422622A	A	750	30	7.00	A	500	75	1.75	10/960	28	2/960
422622B1	14	60	422622B	A	750	30	7.00	A	500	75	1.75	10/960	28	2/960
422622B2	10	51	422622B	A	750	30	7.00	C	500	75	1.75	10/960	28	2/960
422622C2			422622C	Hot Rolled							1.75	10/960	28	2/960
422622E2	9	61	422622E	B	500	83								
427507[2]	8	52	422622	E	500	81					1.90	48/860[1]	35	2/900[1]
							2.50" Thick Plate							
422622C1			422622C	Hot Rolled										
422622G1	8	42	422622G	B	500	65					3.50	10/960	28	2/960

Ingot Thermal Treatments "A" - Heated 6 hrs at 860°F plus 20 hrs at 960°F.

"B" - Heated 6 hrs at 860°F plus 20 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr, and soaked at least 4 hrs at 650° or 500°F.

"E" - Heated 48 hrs at 860°F, cooled to 775°F, soaked 5 hrs at 775°F, cooled to 500°F, soaked 4 hrs at 500°F. Treatments carreid out in salt baths.

Slab Thermal Treatments "A" - Heated 2 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr, and soaked at least 4 hrs at 650° or 500°F.

"C" - Heated 2 hrs at 960°F, furnace cooled to 500°F, and soaked at least 4 hrs at 500°F.

Unless otherwise noted, all thermal treatments carried out in circulating air furnaces. Plates cold water quenched after solution heat treatment and aged 24 hrs at 250°F at least 4 days after quenching.

Notes. 1. Thermal treatments carried out in salt baths.
2. FA-ITMT process.

TABLE 6

FABRICATION OF 1.50" THICK 7475-T6 PLATE IN PHASE IV

Plate			9.25"x6"x22" Rolling Sections				Rolled Slab				Recrystallization		Rolling at 750°F	
	Grain Count, g/mm				Rolling				Rolling					
S. Number	Y	Z	Sect. Fab.	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment, Hrs/°F	Reduction, %	Sol. HT Hrs/°F
418967-30			418967	Hot Rolled										
418967-40	11	62	418967	A	750	35	6.0	A	500	75	1.50	18/960	None	2/960
418967-50	20	54	418967	A	750	14	8.0	A	500	75	2.00	18/960	25	2/960

Ingot Thermal Treatment "A" - Heated 6 hrs at 860°F plus 20 hrs at 960°F.

Slab Thermal Treatment "A" - Heated 2 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 650° or 500°F at 50°F/hr and soaked at least 4 hrs at 650° or 500°F.

All thermal treatments carried out in circulating air furnaces. Plates cold water quenched after solution heat treatment and aged 24 hrs at 250°F at least 4 days after quenching.

TABLE 7

PROPERTIES OF 1.25" THICK RECRYSTALLIZED PLUS HOT ROLLED 7475-T6 PLATE

(AR+HR)

S. Number	SHT Temp, °F	Test Dir.	Tensile T.S., ksi	Tensile Y.S., ksi	Tensile El., %	Tensile R.A., %	Toughness N.T.S.,[1] ksi	Toughness NTS/TS	Toughness NTS/YS	Toughness K_Q,[2] ksi$\sqrt{in.}$	Grain Count g/mm X	Grain Count g/mm Y	Grain Count g/mm Z	Grain Count g/mm^3 XYZ
421675D1	960	L	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		T	77.4	64.6	16.8	28	97.3	1.26	1.51	N.D.				
		N	71.8	62.2	12.0	N.D.	N.D.	N.D.	N.D.	N.D.				
421675E1	960	L	77.6	68.7	17.1	32	101.9	1.31	1.48	41.5	N.D.	8	20	N.D.
		T	77.8	68.9	16.4	26	96.3	1.24	1.40	37.8				
		N	71.8	62.2	12.0	N.D.	N.D.	N.D.	N.D.	N.D.				
421675ES1	960	L	77.8	67.7	17.8	33	101.9	1.31	1.51	45.7	16	10	38	6080
		T	77.5	67.2	17.1	30	94.4	1.22	1.40	38.4				
		N	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.				
422622A	960	L	83.2	73.6	16.7	37	100.8	1.21	1.37	33.2	21	14	63	18522
		T	80.1	70.0	17.1	31	91.0	1.14	1.30	30.6				
		N	80.5	70.0	14.0	N.D.	N.D.	N.D.	N.D.	N.D.				
422622B1	960	L	83.8	73.4	16.4	21	98.9	1.18	[illegible]	42.6	22	14	60	18480
		T	82.4	72.0	13.6	27	98.2	1.19	1.36	32.4				
		N	79.5	67.9	13.0	N.D.	N.D.	N.D.	N.D.	N.D.				
422622B2	960	L	82.6	73.0	16.0	24	101.2	1.23	1.39	N.D.	17	10	51	8670
		T	80.7	70.7	14.3	28	97.0	1.20	1.37	N.D.				
		N	79.5	67.9	13.0	N.D.	N.D.	N.D.	N.D.	N.D.				
422622E2	960	L	82.0	72.3	17.5	28	96.9	1.18	1.34	N.D.	18	9	61	9882
		T	80.1	69.7	16.0	33	88.8	1.11	1.27	N.D.				
		N	78.4	68.1	13.0	N.D.	N.D.	N.D.	N.D.	N.D.				
427507[3]	900	L	80.4	70.4	16.1	24	96.2	1.20	1.37	38.6	13	8	52	5408
		T	78.9	68.7	14.6	24	81.5	1.03	1.19	30.1				
		N	78.8	69.6	8.0	N.D.	N.D.	N.D.	N.D.	N.D.				

TABLE 8

PROPERTIES OF 1.25" THICK RECRYSTALLIZED 7475-T6 PLATE
(AR)

S. Number	SHT Temp, °F	Test Dir.	Tensile: T.S., ksi	Tensile: Y.S., ksi	Tensile: El., %	Tensile: R.A., %	Toughness: N.T.S.,[1] ksi	Toughness: NTS/TS	Toughness: NTS/YS	Toughness: K_Q,[2] ksi$\sqrt{in.}$	Grain Count g/mm: X	Grain Count g/mm: Y	Grain Count g/mm: Z	Grain Count g/mm³: XYZ
421675A1	960	L	74.5	65.0	19.0	35	97.0	1.30	1.49	35.7	N.D.	14	33	N.D.
		T	76.7	66.4	17.1	24	89.3	1.16	1.34	32.4				
		N	73.1	62.9	12.0	N.D.	N.D.	N.D.	N.D.	N.D.				
421675C1	960	L	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	12	50	N.D.
		T	76.4	64.4	17.1	30	89.1	1.17	1.38	N.D.				
		N	73.2	62.6	11.0	N.D.	N.D.	N.D.	N.D.	N.D.				
421675E61	960	L	75.2	64.8	19.6	40	95.7	1.27	1.48	40.2	30	23	48	33120
		T	77.1	66.3	17.1	30	84.7	1.10	1.28	32.2				
		N	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.				
422622E1	960	L	78.2	67.9	17.5	33	90.6	1.16	1.33	N.D.	12	8	48	3840
		T	78.9	67.7	16.7	27	86.8	1.10	1.28	N.D.				
		N	78.3	67.9	12.0	N.D.	N.D.	N.D.	N.D.	N.D.				
427506[3]	900	L	78.5	68.6	19.3	40	95.0	1.21	1.38	33.6	18	12	61	13176
		T	78.7	67.8	17.1	32	84.0	1.07	1.24	29.3				
		N	80.9	71.1	14.0	N.D.	N.D.	N.D.	N.D.	N.D.				

TABLE 9

PROPERTIES OF 1.25" THICK HOT ROLLED 7475-T6 PLATE

(HR)

S. Number	SHT Temp, °F	Test Dir.	Tensile T.S., ksi	Tensile Y.S., ksi	Tensile El., %	Tensile R.A., %	Toughness N.T.S.,[1] ksi	Toughness NTS/TS	Toughness NTS/YS	Toughness K_Q[2] ksi$\sqrt{in.}$	Grain Count g/mm X	Grain Count g/mm Y	Grain Count g/mm Z	Grain Count g/mm³ XYZ
421675B1	960	L	76.4	67.8	17.9	32	100.2	1.31	1.48	49.0				
		T	77.2	67.5	15.7	24	92.0	1.19	1.36	39.7				
		N	72.8	63.8	8.0	N.D.	N.D.	N.D.	N.D.	N.D.				
422622C2	960	L	83.7	74.0	13.2	17	99.3	1.19	1.34	49.9				
		T	80.4	70.7	10.7	12	92.8	1.15	1.31	43.1				
		N	76.1	65.9	9.0	N.D.	N.D.	N.D.	N.D.	N.D.				

TABLE 10

PROPERTIES OF 1.50" THICK 7475-T6 PLATE

S. Number	SHT Temp, °F	Test Dir.	Tensile T.S., ksi	Tensile Y.S., ksi	Tensile El., %	Tensile R.A., %	Toughness N.T.S.,[1] ksi	Toughness NTS/TS	Toughness NTS/YS	Toughness K_Q,[2] ksi$\sqrt{in.}$	g/mm X	g/mm Y	g/mm Z	g/mm³ XYZ
Recrystallized Plus Hot Rolled (AR+HR)														
418967-50	960	L	82.1	70.6	17.1	28	97.1	1.18	1.38	29.9	24	11	62	16368
		T	80.5	69.0	15.0	25	84.7	1.05	1.23	29.2				
		N	79.3	66.3	12.0	N.D.	79.2	1.00	1.19	29.0				
Recrystallized (AR)														
418967-40	960	L	79.3	67.7	17.9	32	90.1	1.14	1.33	32.4	22	20	54	23760
		T	80.2	68.5	15.7	22	82.1	1.02	1.20	27.5				
		N	79.3	67.4	8.0	N.D.	85.0	1.07	1.26	23.6				
Hot Rolled (HR)														
418967-30	960	L	83.8	73.0	15.0	19	99.8	1.19	1.37	40.9				
		T	81.3	70.3	15.7	21	90.0	1.11	1.28	32.6				
		N	81.4	67.1	10.0	N.D.	85.3	1.05	1.28	31.0				

TABLE 11

PROPERTIES OF 2.50" THICK RECRYSTALLIZED PLUS HOT ROLLED 7475-T6 PLATE
(AR+HR)

			Tensile				Toughness				Grain Count			
	SHT										g/mm			g/mm³
S. Number	Temp, °F	Test Dir.	T.S., ksi	Y.S., ksi	El., %	R.A., %	N.T.S.,[1] ksi	NTS/TS	NTS/YS	K_Q,[2] ksi in.	X	Y	Z	XYZ
421675F1	960	L	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	44.8	N.D.	N.D.	N.D.	N.D.
		T	77.3	66.7	14.3	23	82.3	1.06	1.23	N.D.				
		N	77.0	65.6	10.0	18	92.5	1.20	1.41	58.0				
421675J2	960	L	76.2	66.2	17.5	26	95.5	1.25	1.44	N.D.	8	7	26	1456
		T	75.5	64.8	16.4	24	85.6	1.13	1.32	N.D.				
		N	75.4	62.6	8.0	N.D.	91.2	1.21	1.46	N.D.				
421675G1	960	L	77.2	67.4	18.2	29	93.3	1.21	1.38	N.D.	N.D.	6	12	N.D.
		T	76.2	65.2	16.4	24	83.4	1.09	1.28	N.D.				
		N	69.6	61.6	4.0	N.D.	83.2	1.20	1.35	N.D.				
421675L1	860	L	76.7	67.0	15.4	26	93.4	1.22	1.39	N.D.	N.D.	5	20	N.D.
		T	74.7	64.8	12.2	14	74.2	0.99	1.15	N.D.				
		N	68.4	57.6	7.0	N.D.	75.6	1.11	1.31	N.D.				
422622G1	960	L	79.2	68.6	20.7	27	92.0	1.16	1.34	N.D.	14	8	42	4704
		T	78.6	67.4	14.3	28	84.8	1.08	1.26	N.D.				
		N	77.7	65.2	13.0	N.D.	92.7	1.19	1.42	N.D.				

TABLE 12

PROPERTIES OF 2.50" THICK RECRYSTALLIZED 7475-T6 PLATE
(AR)

			Tensile				Toughness				Grain Count			
											g/mm			g/mm[3]
S. Number	SHT Temp, °F	Test Dir.	T.S., ksi	Y.S., ksi	El., %	R.A., %	N.T.S.,[1] ksi	NTS/TS	NTS/YS	K_Q,[2] ksi$\sqrt{in.}$	X	Y	Z	XYZ
421675C3	960	L	74.4	63.8	16.4	32	87.6	1.18	1.37	39.1	N.D.	8	12	N.D.
		T	75.0	64.6	16.4	22	76.4	1.05	1.21	N.D.				
		N	77.4	65.7	9.0	20	88.9	1.15	1.35	46.4				
421675D3	960	L	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	14	20	N.D.
		T	74.5	63.0	15.7	24	79.0	1.06	1.25	N.D.				
		N	76.4	66.0	8.0	12	86.6	1.13	1.31	N.D.				
421675F3	960	L	75.9	65.2	17.1	28	84.3	1.11	1.29	N.D.	9	5	24	1080
		T	75.4	64.8	16.4	24	79.0	1.05	1.22	N.D.				
		N	76.2	63.3	12.0	N.D.	91.2	1.20	1.44	N.D.				
421675J1	960	L	73.5	63.6	19.0	34	86.0	1.17	1.35	N.D.	N.D.	12	33	N.D.
		T	75.0	64.2	15.4	20	75.6	1.01	1.18	N.D.				
		N	69.8	56.6	10.0	N.D.	83.2	1.19	1.47	N.D.				
421675H	960	L	74.2	64.0	18.6	32	84.6	1.14	1.32	N.D.	N.D.	6	16	N.D.
		T	75.3	64.3	13.6	19	80.1	1.06	1.25	N.D.				
		N	76.7	63.0	12.0	N.D.	89.6	1.17	1.42	N.D.				

TABLE 13

PROPERTIES OF 2.50" THICK HOT ROLLED 7475-T6 PLATE
(HR)

S. Number	SHT Temp, °F	Test Dir.	Tensile T.S., ksi	Tensile Y.S., ksi	Tensile El., %	Tensile R.A., %	Toughness N.T.S.,[1] ksi	Toughness NTS/TS	Toughness NTS/YS	Toughness K_Q,[2] ksi$\sqrt{in.}$	Grain Count g/mm X	Grain Count g/mm Y	Grain Count g/mm Z	Grain Count g/mm³ XYZ
421675B3	960	L	81.8	71.7	13.6	18	101.2	1.24	1.43	56.6				
		T	78.4	66.7	11.4	14	87.4	1.11	1.31	N.D.				
		N	77.2	65.8	8.0	15	93.0	1.20	1.41	56.5				
422622C1	960	L	83.9	74.4	11.0	12	98.6	1.18	1.33	N.D.				
		T	76.5	67.8	5.7	8	94.0	1.23	1.39	N.D.				
		N	73.0	60.2	10.0	N.D.	94.2	1.29	1.56	N.D.				

NOTES FOR TABLES 7 THROUGH 13

S. Number	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
	Composition							
421675	0.04	0.07	1.64	0.01	2.23	0.17	5.62	0.01
422622, 427506, 427507	0.07	0.05	1.70	0.02	2.40	0.18	5.80	0.00
418967	0.06	0.12	1.65	0.00	2.35	0.23	5.79	0.01

Unless otherwise noted, all thermal treatments carried out using circulating air furnaces.

Plate cold water quenched after solution heat treatment and aged 24 hrs at 250°F four days after quenching.

0.375" dia. tapered seat tensile specimens used for longitudinal and long-transverse tests, 0.125" dia. and 0.250" dia. tapered seat tensile specimens used for short-transverse tests.

Duplicate tests carried out on all plate samples with exception of 1.50" thick plates, S-418967-30, 40 and 50, where only single tests made.

Yield Strength = 0.2% offset.

M.T. No. C90573-D

1. 1-1/16" dia. threaded end notched tensile specimens used for longitudinal and long-transverse tests, 0.500" dia. tapered seat notch tensile specimens used for short-transverse tests.
2. K_Q values used because the values were not valid K_{IC} values, but the K_Q values are meaningful. 1.00" thick compact tension fracture toughness specimens used for longitudinal and long-transverse tests, 0.50" thick compact tension fracture toughness specimens used for short-transverse tests.
3. Plate fabricated by Frankford Arsenal using 7475 ingot sections provided by Alcoa. All thermal treatments carried out in salt baths.

TABLE 14

PROPERTIES OF 1.25" THICK RECRYSTALLIZED PLUS HOT ROLLED Al-Zn-Mg ALLOY T6 PLATE

(AR+HR)

			Tensile				Toughness				Grain Count			
											g/mm			g/mm^3
S. Number	Temp, °F	Test Dir.	T.S., ksi	Y.S., ksi	El., %	R.A., %	N.T.S.,[1] ksi	NTS/TS	NTS/YS	K_Q,[2] ksi$\sqrt{in.}$	X	Y	Z	XYZ
422014D1	960	L	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		T	77.4	71.6	12.9	31	79.0	1.02	1.10	N.D.				
		N	73.7	66.4	10.0	N.D.	N.D.	N.D.	N.D.	N.D.				
422014E3	960	L	79.5	74.9	11.4	21	85.2	1.07	1.15	43.7	N.D.	2	50	N.D.
		T	77.3	71.9	11.4	27	68.6	0.89	0.95	28.0				
		N	74.0	67.1	12.0	N.D.	N.D.	N.D.	N.D.	N.D.				

TABLE 15

PROPERTIES OF 1.25" THICK RECRYSTALLIZED Al-Zn-Mg ALLOY T6 PLATE
(AR)

			Tensile				Toughness				Grain Count			
	SHT										g/mm			g/mm³
S. Number	Temp, °F	Test Dir.	T.S., ksi	Y.S., ksi	El., %	R.A., %	N.T.S.,[1] ksi	NTS/TS	NTS/YS	K_Q,[2] ksi$\sqrt{in.}$	X	Y	Z	XYZ
422014A1	960	T	74.9	69.0	8.6	13	52.9	0.71	0.77	N.D.	N.D.	1	14	N.D.
		N	71.6	64.4	5.0	N.D.	N.D.	N.D.	N.D.	N.D.				
422014C1	960	T	75.0	68.9	13.2	23	56.5	0.75	0.82	N.D.	N.D.	10	33	N.D.
		N	73.4	66.6	8.0	N.D.	N.D.	N.D.	N.D.	N.D.				

TABLE 16

PROPERTIES OF 2.50" THICK RECRYSTALLIZED PLUS HOT ROLLED Al-Zn-Mg ALLOY T6 PLATE
(AR+HR)

S. Number	SHT Temp, °F	Test Dir.	Tensile				Toughness				Grain Count			
			T.S., ksi	Y.S., ksi	El., %	R.A., %	N.T.S.,[1] ksi	NTS/TS	NTS/YS	K_Q,[2] ksi$\sqrt{in.}$	g/mm X	g/mm Y	g/mm Z	g/mm³ XYZ
422014F1	960	L	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		T	76.5	70.4	7.1	9	64.3	0.84	0.91	N.D.				
		N	74.6	68.4	5.0	9	84.8	1.14	1.24	N.D.				
422014G1	960	L	76.9	71.7	11.8	17	77.4	1.01	1.08	N.D.	N.D.	1	33	N.D.
		T	76.2	69.6	11.8	18	60.6	0.80	0.87	N.D.				
		N	75.9	67.6	9.0	N.D.	61.3	0.81	0.91	N.D.				
422014I1	860	L	80.3	75.8	10.0	11	90.5	1.13	1.19	N.D.	N.D.	N.D.	N.D.	N.D.
		T	75.3	71.4	4.0	6	69.4	0.92	0.97	N.D.				
		N	66.8	63.0	2.0	N.D.	69.7	1.04	1.11	N.D.				
422014J2	960	L	75,5	70.6	14.0	24	80.8	1.07	1.14	N.D.	N.D.	N.D.	N.D.	N.D.
		T	75.4	69.8	7.9	17	67.4	0.89	0.97	N.D.				
		N	77.2	68.0	11.0	N.D.	82.2	1.06	1.21	N.D.				
422014K1	860	L	78.4	73.0	12.5	16	86.2	1.10	1.18	N.D.	N.D.	5	14	N.D.
		T	76.8	70.5	8.9	15	68.0	0.89	0.96	N.D.				
		N	75.8	67.9	10.0	N.D.	83.8	1.11	1.23	N.D.				

TABLE 17

PROPERTIES OF 2.50" THICK RECRYSTALLIZED Al-Zn-Mg ALLOY T6 PLATE
(AR)

S. Number	SHT Temp, °F	Test Dir.	Tensile T.S., ksi	Tensile Y.S., ksi	Tensile El., %	Tensile R.A., %	Toughness N.T.S.,[1] ksi	Toughness NTS/TS	Toughness NTS/YS	Toughness K_Q,[2] ksi$\sqrt{in.}$	Grain Count g/mm X	Grain Count g/mm Y	Grain Count g/mm Z	Grain Count g/mm³ XYZ
422014C3	960	L	73.4	67.4	15.0	28	59.8	0.81	0.89	35.0	N.D.	2	5	N.D.
		T	74.4	67.4	10.0	16	59.3	0.80	0.88	N.D.				
		N	76.5	69.7	5.5	10	64.1	0.84	0.92	33.0				
422014D3	960	L	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	5	14[3]	N.D.
		T	74.9	67.7	9.7	12	52.5	0.70	0.78	N.D.		1	3[3]	
		N	76.9	70.4	4.0	6	61.5	0.80	0.87	N.D.				
422014F3	960	L	72.6	67.6	13.6	24	65.1	0.90	0.96	N.D.	N.D.	N.D.	N.D.	N.D.
		T	73.6	67.5	10.7	24	53.2	0.72	0.79	N.D.				
		N	76.8	68.4	9.0	N.D.	58.0	0.76	0.85	N.D.				
422014H	960	L	73.0	67.8	13.9	24	62.8	0.88	0.93	N.D.	N.D.	7	10[3]	N.D.
		T	74.9	69.0	7.5	14	53.9	0.72	0.78	N.D.		2	5[3]	
		N	78.2	69.2	6.0	N.D.	68.9	0.88	1.00	N.D.				
422014J1	960	L	72.6	67.7	15.0	28	63.8	0.88	0.94	N.D.	N.D.	N.D.	N.D.	N.D.
		T	75.4	70.2	6.4	10	59.0	0.78	0.84	N.D.				
		N	65.9	62.5	2.0	N.D.	57.[illegible]	0.87	0.92	N.D.				
422014L1	860	L	73.9	67.9	15.4	28	68.1	0.92	1.00	N.D.	N.D.	5	33[3]	N.D.
		T	74.9	68.2	12.5	22	57.5	0.77	0.84	N.D.		5	14[3]	
		N	76.3	69.6	10.0	N.D.	78.1	1.02	1.12	N.D.				

TABLE 18

PROPERTIES OF Al-Zn-Mg ALLOY T6 PLATE PRODUCED BY HOT ROLLING
(HR)

S. Number	SHT Temp, °F	Test Dir.	Tensile T.S., ksi	Tensile Y.S., ksi	Tensile El., %	Tensile R.A., %	Toughness N.T.S.,[1] ksi	Toughness NTS/TS	Toughness NTS/YS	Toughness K_Q,[2] ksi$\sqrt{in.}$	Grain Count g/mm X	Grain Count g/mm Y	Grain Count g/mm Z	Grain Count g/mm^3 XYZ
2.50" Thick Plate														
422014B3	960	T	73.0	70.0	3.6	6	71.3	0.98	1.02	N.D.				
		N	75.0	68.9	4.0	4	76.6	1.02	1.11	N.D.				
1.25" Thick Plate														
422014B1	960	T	78.3	74.4	6.5	10	71.9	0.92	0.97	N.D.				
		N	73.4	65.2	5.0	N.D.	N.D.	N.D.	N.D.	N.D.				

NOTES FOR TABLES 14 THROUGH 18

S. Number	Composition							
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
422014	0.04	0.06	0.00	0.00	2.51	0.22	6.47	0.00

All thermal treatments carried out using circulating air furnaces.

Plate cold water quenched after solution heat treatment and aged 24 hrs at 250°F four days after quenching.

0.357" dia. tapered seat tensile specimens used for longitudinal and long-transverse tests, 0.125" dia. and 0.250" dia. tapered seat tensile specimens used for short-transverse tests.

Duplicate tests carried out on all plate samples.

Yield Strength = 0.2% offset.

M.T. No. 090573-D

1. 1-1/16" dia. threaded end notched tensile specimens used for longitudinal and long-transverse tests, 0.500" dia. tapered seat notch tensile specimens used for short-transverse tests.

2. K_Q values used because the values were not valid K_{IC} values, but the K_Q values are meaningful. 1.00" thick compact tension fracture toughness specimens used for longitudinal and long-transverse tests, 0.50" thick compact tension fracture toughness specimens used for short-transverse tests.

3. Duplex grain structure.

TABLE 19

GRAIN COUNT, GRAIN DIMENSIONS, AND FABRICATING VARIABLES FOR ITMT PROCESSED 7475-T6 PLATE
(AR+HR)

Warm Rolling Reduction, %	Warm Rolling Temp, °F	Rolling at 750°F After Recrystallization Reduction, %	Ingot Breakdown at 750°F Reduction, %	Recrystallization Temp, °F	Grain Count g/mm Z	Grain Count g/mm Y	Grain Count g/mm X	Grain Count g/mm³ XYZ	Grain Dimensions Thick, mm 1/Z	Grain Dimensions Length, mm 1/Y	Grain Dimensions Aspect Ratio, Z/Y	S. Number
1.25" thick Plate Having Recrystallized plus Hot Rolled Structure												
83	500	28	None	960	61	9	18	9882	0.016	0.111	6.778	422622E2
81	500	35	None	860	52	8	13	5408	0.019	0.125	6.500	427507
75	500	28	30	960	63	14	21	18522	0.016	0.071	4.500	422622A
75	500	28	30	960	60	14	22	18480	0.017	0.071	4.286	422622B1
75	500	28	30	960	51	10	17	8670	0.020	0.100	5.100	422622B2
67	500	28	50	960	38	10	16	6080	0.026	0.100	3.80	421675E51
50	600	50	50	960	20	8	ND	---	0.050	0.125	2.500	421675E1
1.50" thick Plate Having Recrystallized plus Hot Rolled Structure												
75	500	25	14	960	62	11	24	16,368	0.016	0.090	5.636	418967-50
2.50" thick Plate Having Recrystallized plus Hot Rolled Structure												
65	500	28	None	960	42	8	14	4704	0.024	0.125	5.250	422622G1
65	500	28	None	860	20	5	ND	---	0.050	0.200	4.000	421675L1
65	575	28	None	960	12	6	ND	---	0.083	0.167	2.00	421675G1
50	575	28	30	960	26	7	8	1456	0.038	0.143	3.714	421675J2

TABLE 19 (CONTINUED)

GRAIN COUNT, GRAIN DIMENSIONS, AND FABRICATING VARIABLES FOR ITMT PROCESSED 7475-T6 PLATE
(AR)

Warm Rolling Reduction, %	Warm Rolling Temp, °F	Rolling at 750°F After Recrystallization Reduction, %	Ingot Breakdown at 750°F Reduction, %	Recrystallization Temp, °F	Grain Count g/mm Z	Grain Count g/mm Y	Grain Count g/mm X	Grain Count g/mm XYZ	Grain Dimensions Thick, mm 1/Z	Grain Dimensions Length, mm 1/Y	Grain Dimensions Aspect Ratio, Z/Y	S. Number
1.25" thick Plate Having Recrystallized Structure												
88	500	None	None	860	61	12	18	13176	0.016	0.083	5.083	427506
88	500	None	None	960	48	8	12	3840	0.021	0.125	6.000	422622E1
75	500	None	50	960	48	23	30	33120	0.021	0.043	2.087	421675E61
75	600	None	50	960	50	12	ND	---	0.020	0.083	4.167	421675C1
50	600	None	75	960	33	14	ND	---	0.030	0.071	2.357	421675A1
1.50" thick Plate Having Recrystallized Structure												
75	500	None	35	960	54	20	22	23760	0.019	0.050	2.700	418967-40
2.50" thick Plate Having Recrystallized Structure												
69	575	None	20	960	16	6	ND	---	0.062	0.167	2.667	421675H
64	575	None	30	960	33	12	ND	---	0.030	0.083	2.750	421675J1
75	600	None	None	960	20	14	ND	---	0.050	0.071	1.429	421675D3
50	600	None	50	960	12	8	ND	---	0.083	0.125	1.500	421675C3
50	600[1]	None	None	960	24	5	9	1080	0.042	0.200	4.800	421675F3

Note: 1. Double recrystallization treatment.

TABLE 20

LONG-TRANSVERSE PROPERTIES OF 7475 PLATE FABRICATED USING FTMT TREATMENTS

Percent Cold Work	Aging After Cold Work, hrs/°F	T.S., ksi	Y.S., ksi	El., %	R.A., %	0.50"Ø Specimen[2] N.T.S., ksi	0.50"Ø Specimen[2] NTS/YS	1-1/16"Ø Specimen[1] N.T.S., ksi	1-1/16"Ø Specimen[1] NTS/YS
S-422622A - 7475 Plate Having a Recrystallized plus Hot Rolled Structure[3] (AR+HR)									
0	24/250	80.1	70.0	17.1	31			91.0	1.30
10.5	8/250	85.9	77.4	12.0	28	105.7	1.37		1.11
	16/250	86.1	77.4	12.5	23	101.1	1.31		1.02
	24/250	86.8	78.5	12.0	25	110.3	1.41		1.18
			77.8		25				1.10
16.4	8/250	88.0	80.1	11.5	25	104.7	1.31		1.02
	16/250	88.5	80.6	10.5	26	103.7	1.29		1.00
	24/250	87.7	80.3	11.5	24	102.1	1.27		0.97
			80.3		25				1.00
22.6	8/250	89.9	82.6	11.0	23	96.5	1.17		0.81
	16/250	89.3	82.8	10.0	24	97.5	1.18		0.82
	24/250	88.8	82.6	9.5	26	94.5	1.14		0.79
			82.7		24				0.81
S-422622C2 - Hot Rolled 7475 Plate[2] (HR)									
0	24/250	80.4	70.7	10.7	12			92.8	1.31
9.5	8/250	87.2	78.4	7.5	11				
	16/250	87.6	79.9	5.5	6	110.8	1.39		1.15
	24/250	88.1	79.4	9.0	11	112.4	1.42		1.20
			79.6		9				1.18
14.7	8/250	89.6	81.3	8.0	9	109.3	1.34		1.07
	16/250	89.4	82.0	8.0	10	111.8	1.36		1.10
	24/250	89.0	81.5	8.0	11	112.4	1.38		1.13
			81.6		10				1.10
20.0	8/250	89.4	81.3	6.0	9	107.3	1.32		1.02
	16/250	89.4	82.1	8.5	9	106.7	1.30		1.01
	24/250	88.9	81.5	7.5	10	108.8	1.33		1.05
			81.6		9				1.03

NOTES FOR TABLE 20

1. 1-1/16" diameter threaded end notched tensile specimens from 1.30" or 1.26" thick plate.

2. 0.50" diameter tapered seat notched tensile specimens from 1.163" to 1.004" thick plate. The NTS/YS ratio obtained using 0.50" diameter notched tensile specimens converted to NTS/YS ratio for 1-1/16" diameter specimens using correlation developed at Alcoa Laboratories.

3. Initial plate thickness - 1.30".

4. Initial plate thickness - 1.26".

0.357" diameter tapered seat tensile specimens tested for properties.

Plate solution heat treated 2 hrs at 960°F, cold water quenched, aged 6 hrs at 220°F 4 days after quenching, cold rolled indicated amount, and second-step aged as indicated.

Yield strength = 0.2% offset.
MT No. 090573-D

Composition

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.07	0.05	1.70	0.02	2.40	0.18	5.80	0.00

TABLE 21

FABRICATION OF 1.00" THICK 7475 PLATE FOR BALLISTIC EVALUATION BY FRANKFORD ARSENAL

	10"x9"x20" Rolling Sections				Rolled Slab (Entry Ends Beveled)				Recrystallization		Rolling at 750°F		
			Rolling				Rolling						
Plate S. No.	Sections Fabricated	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment	Temp, °F	Reduction, %	Thick, in.	Thermal Treatment, Hrs/°F	Reduction, %	Sol.HT Hrs/°F	Aging Pract.
422622-1	422622A,B,C	A	750	30	7.00	A	500	82	1.25	10/960	20	2/960	A
422622-2	422622A,B,C	A	750	30	7.00	A	500	79	1.45	10/960	22	2/960	B

Ingot Thermal Practice "A" - Heated 6 hrs at 860°F plus 20 hrs at 960°F.

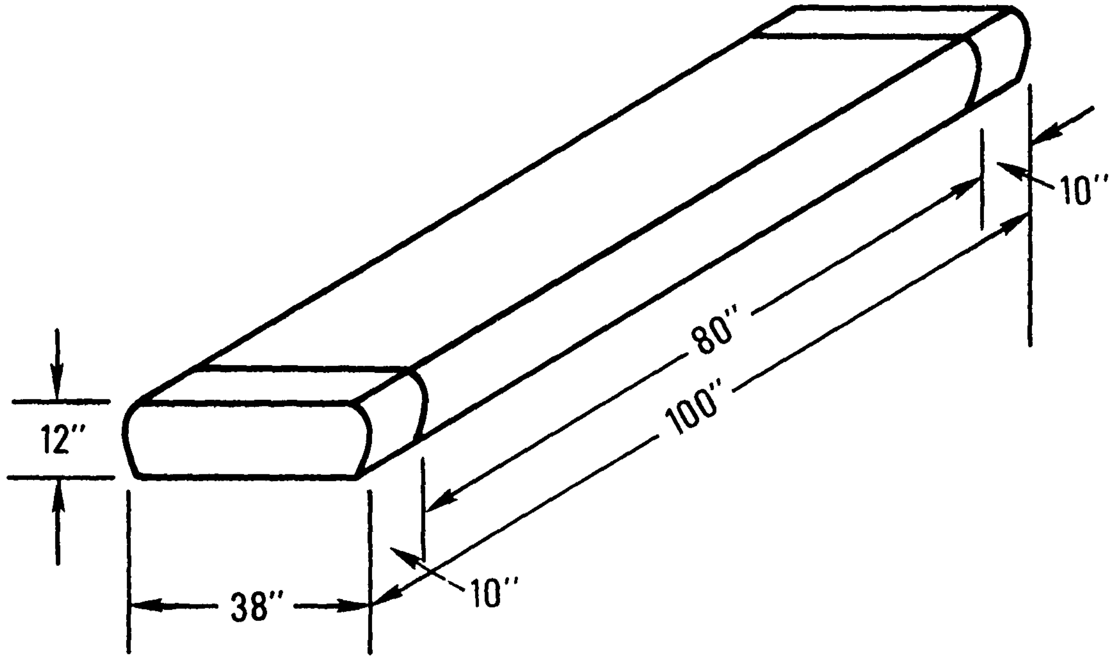
Slab Thermal Practice "A" - Heated 2 hrs at 960°F, cooled to 775°F at 50°F/hr, soaked 2 hrs at 775°F, cooled to 500°F at 50°F/hr, and soaked at least 4 hrs at 500°F.

Aging Practice "A" - 1.00" thick plate aged 24 hrs at 250°F plus 4 hrs at 350°F 4 days after quenching.

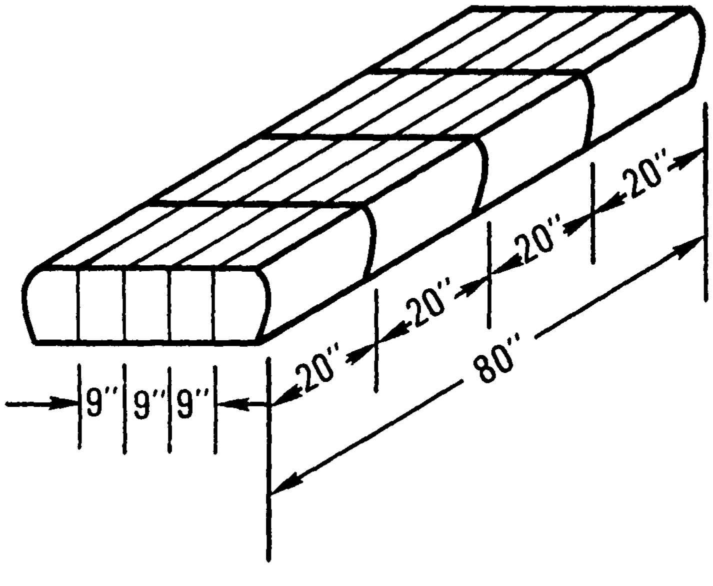
Aging Practice "B" (FTMT) - 1.13" thick plate aged 6 hrs at 220°F 4 days after quenching, cold rolled 12%, and aged 8 hrs at 250°F.

Composition

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.07	0.05	1.70	0.02	2.40	0.18	5.80	0.00

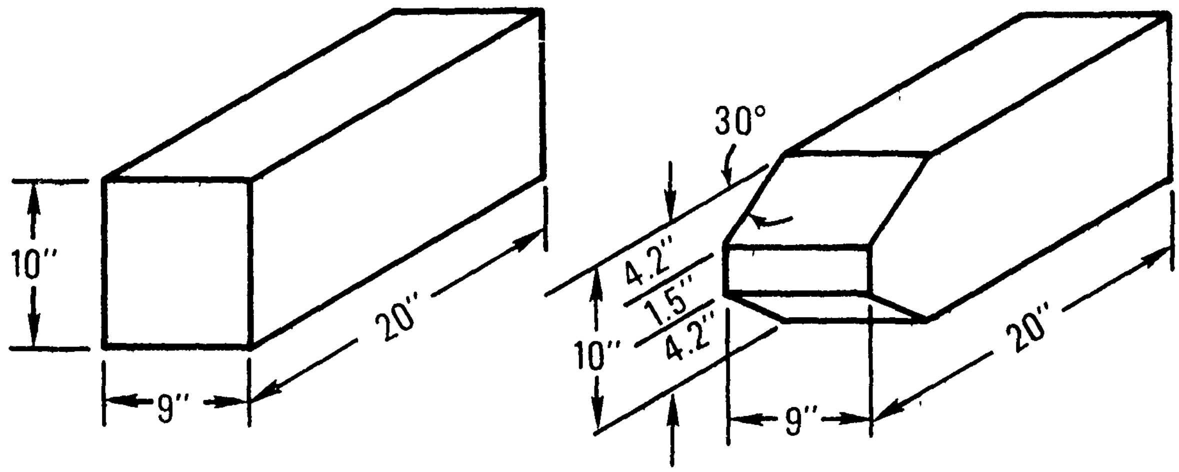


CROPPING OF 12"×38"×100" DC INGOTS



SECTIONING OF 12"×38"×80" CROPPED D.C. INGOTS TO OBTAIN 12 12"×9"×20" SECTIONS FROM EACH INGOT

Figure 1

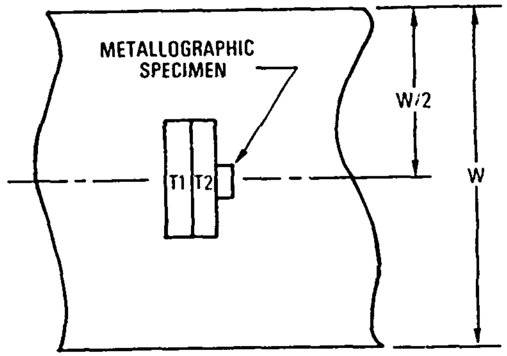


NORMAL ROLLING SECTION BEVELED ROLLING SECTION

10" × 9" × 20" ROLLING SECTIONS USED IN I.T.M.T. EVALUATION

Figure 2

1.00" – 1.15" THICK PLATE



TENSILE PROPERTIES

LONG-TRANSVERSE T1

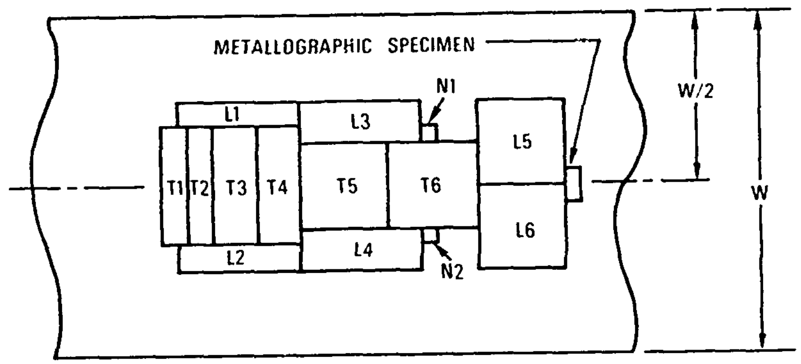
0.357" Φ TAPERED SEAT TENSILE SPECIMEN

NOTCHED TENSILE STRENGTH

LONG-TRANSVERSE T2

0.500" Φ TAPERED SEAT NOTCHED TENSILE SPECIMEN

1.25" THICK PLATE



TENSILE PROPERTIES

LONGITUDINAL (L1, L2), LONG-TRANSVERSE (T1, T2)

0.357" Φ TAPERED SEAT TENSILE SPECIMEN

SHORT-TRANSVERSE (N1, N2) 0.125" Φ TAPERED SEAT TENSILE SPECIMEN

NOTCHED TENSILE STRENGTH

LONGITUDINAL (L3, L4), LONG-TRANSVERSE (T3, T4)

1 1/16" Φ THREADED END NOTCHED TENSILE SPECIMENS

FRACTURE TOUGHNESS (K_{Ic})

LONGITUDINAL (L5, L6), LONG-TRANSVERSE (T5, T6)

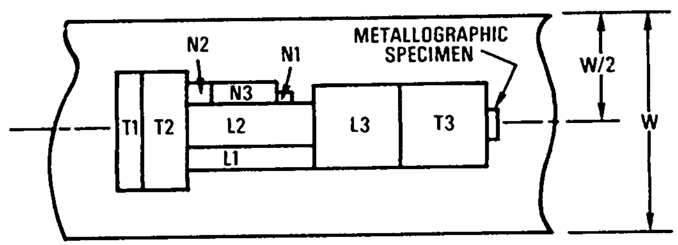
1.00" THICK COMPACT TENSION FRACTURE TOUGHNESS SPECIMEN

ALL SPECIMENS FROM T/2 LOCATION

LOCATION AND TYPE OF SPECIMENS USED IN EVALUATING PROPERTIES OF 1.00" TO 1.25" THICK 7475 AND Al-Zn-Mg ALLOY PLATE

Figure 3

1.50" THICK PLATE



TENSILE PROPERTIES

LONGITUDINAL (L1), LONG-TRANSVERSE (T1) 0.357" ⌀ TAPERED SEAT TENSILE SPECIMEN

SHORT-TRANSVERSE (N1) 0.125" ⌀ TAPERED SEAT TENSILE SPECIMEN

NOTCHED TENSILE STRENGTH

LONGITUDINAL (L2), LONG-TRANSVERSE (T2) 1 1/16" ⌀ THREADED END NOTCHED TENSILE SPECIMEN

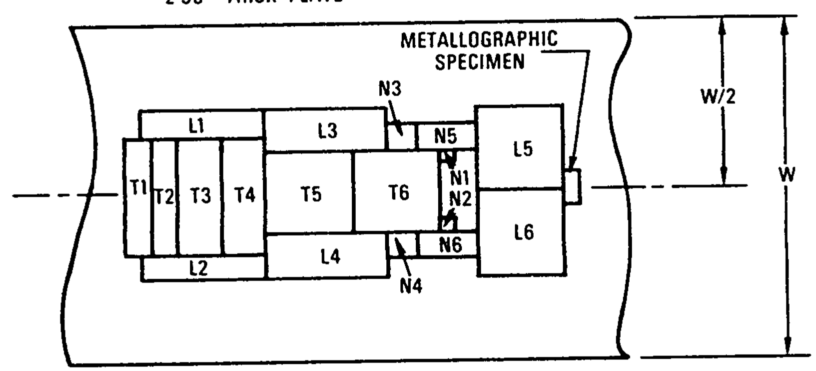
SHORT-TRANSVERSE (N2) 0.500" ⌀ TAPERED SEAT NOTCHED TENSILE SPECIMEN

FRACTURE TOUGHNESS (K_{Ic})

LONGITUDINAL (L3), LONG-TRANSVERSE (T3) 1.00" THICK COMPACT TENSION FRACTURE TOUGHNESS SPECIMEN

SHORT-TRANSVERSE (N3) 0.50" THICK COMPACT TENSION FRACTURE TOUGHNESS SPECIMEN

2.50" THICK PLATE



TENSILE PROPERTIES

LONGITUDINAL (L1, L2), LONG-TRANSVERSE (T1, T2) 0.357" ⌀ TAPERED SEAT TENSILE SPECIMEN

SHORT-TRANSVERSE (N1, N2) 0.125" ⌀ OR 0.250" ⌀ TAPERED SEAT TENSILE SPECIMEN

NOTCHED TENSILE STRENGTH

LONGITUDINAL (L3, L4), LONG-TRANSVERSE (T3, T4) 1 1/16" ⌀ THREADED END NOTCHED TENSILE SPECIMEN

SHORT-TRANSVERSE (N3, N4) 0.500" ⌀ TAPERED SEAT NOTCHED TENSILE SPECIMEN

FRACTURE TOUGHNESS (K_{Ic})

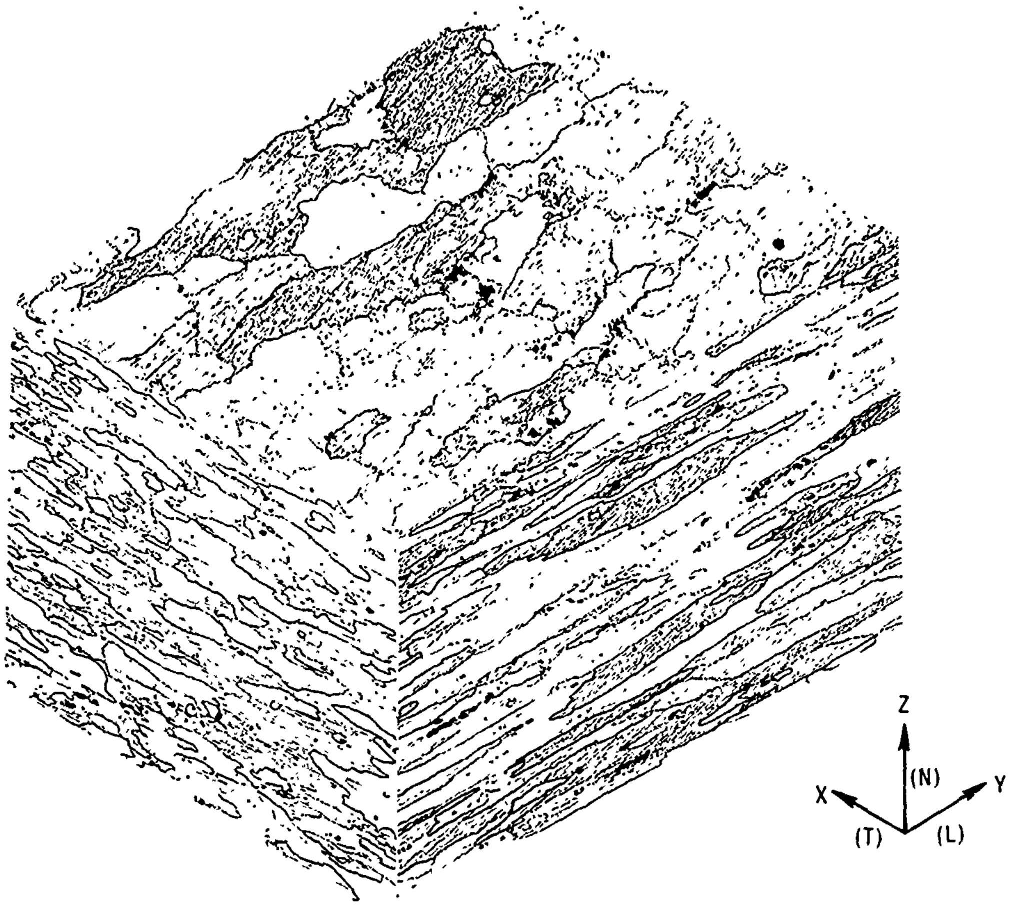
LONGITUDINAL (L5, L6), LONG-TRANSVERSE (T5, T6) 1.00" THICK COMPACT TENSION FRACTURE TOUGHNESS SPECIMEN

SHORT-TRANSVERSE (N5, N6) 0.50" THICK COMPACT TENSION FRACTURE TOUGHNESS SPECIMEN

ALL SPECIMENS FROM T/2 LOCATION

LOCATION AND TYPE OF SPECIMENS USED IN EVALUATING PROPERTIES OF 1.50" AND 2.50" THICK 7475 AND Al-Zn-Mg ALLOY PLATE

Figure 4



MAG: 100X

ETCH:KELLERS

1.25" THICK 7475-T6 PLATE S-427507

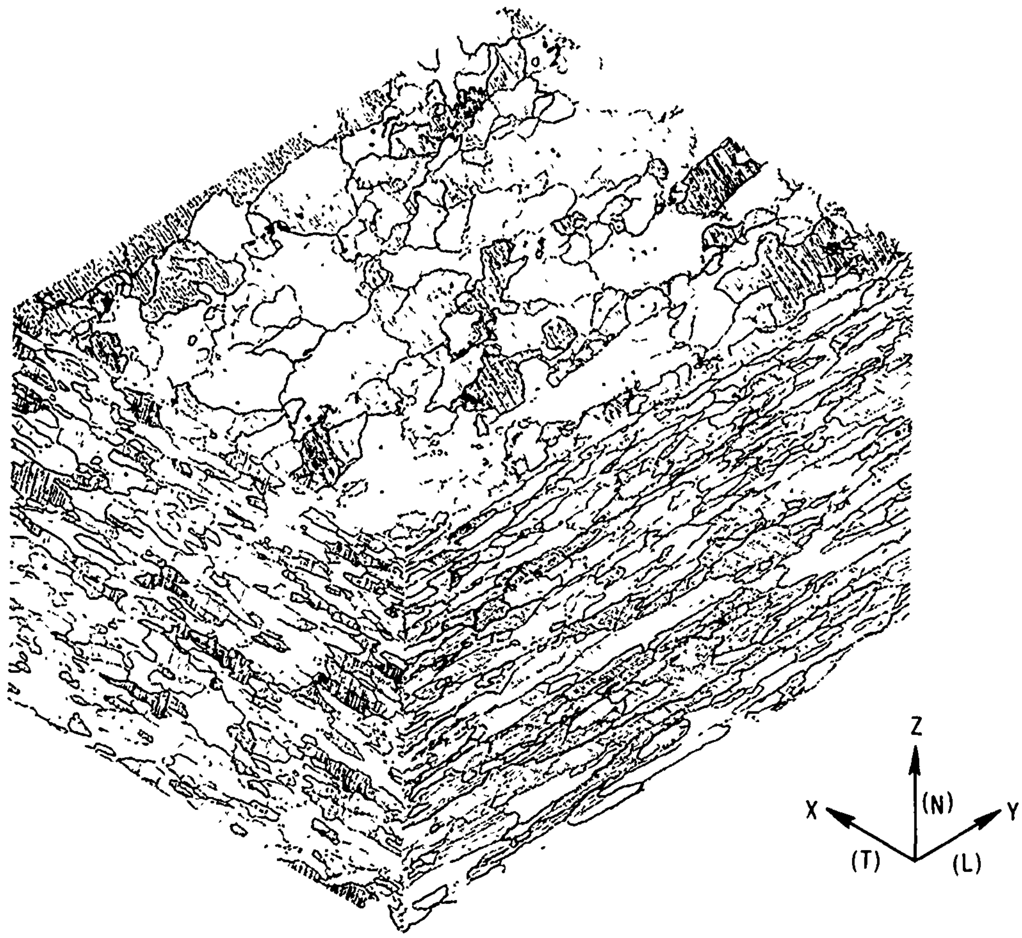
INGCT				SLAB			RECRYSTALLIZATION			PLATE				
									ROLLING		GRAIN COUNT			
THERMAL(1)	ROLLING			THERMAL(1)	ROLLING			THERMAL(1)	AT 750°F	SOLUTION(1)	g/mm			g/mm³
TREATMENT	TEMP	RGD	THICK	TREATMENT	TEMP	RGD	THICK	TREATMENT	RGD	HEAT-TREAT	X	Y	Z	XYZ
48hr/860°F 5hr/775°F	500°F	81%		NONE			1 90"	10hr/860°F	35%	3hr/900°F	13	8	52	5 408

(1) THERMAL TREATMENTS CARRIED OUT IN A SALT BATH

PROPERTIES							
DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi$\sqrt{in.}$
L	80.4	70.4	16.1	24	96.2	1.37	38 6
T	78.9	68 7	14.6	24	81.5	1.19	30.1
N	78.8	69.6	8.0	N.D.	N.D.	N.D.	N.D.

MICROSTRUCTURE AND PROPERTIES OF 1.25" THICK RECRYSTALLIZED PLUS HOT ROLLED (AR + HR) 7475-T6 PLATE S-427507

Figure 5



MAG: 100X

ETCH: KELLERS

1.25" THICK 7475-T6 PLATE S-422622-A

INGOT				SLAB				RECRYSTALLIZATION		PLATE				
									ROLLING		GRAIN COUNT			
THERMAL(1)	ROLLING			THERMAL(1)	ROLLING			THERMAL(1)	AT 750°F	SOLUTION(1)	g/mm			g/mm³
TREATMENT	TEMP	RGD	THICK	TREATMENT	TEMP	RGD	THICK	TREATMENT	RGD	HEAT-TREAT	X	Y	Z	XYZ
6hr/860°F 20hr/960°F	750°F	30%	7 0"	2hr/960°F 2hr/775°F 4hr/500°F	500°F	75%	1 75"	10hr/960°F	28%	2hr/960°F	21	14	63	18.522

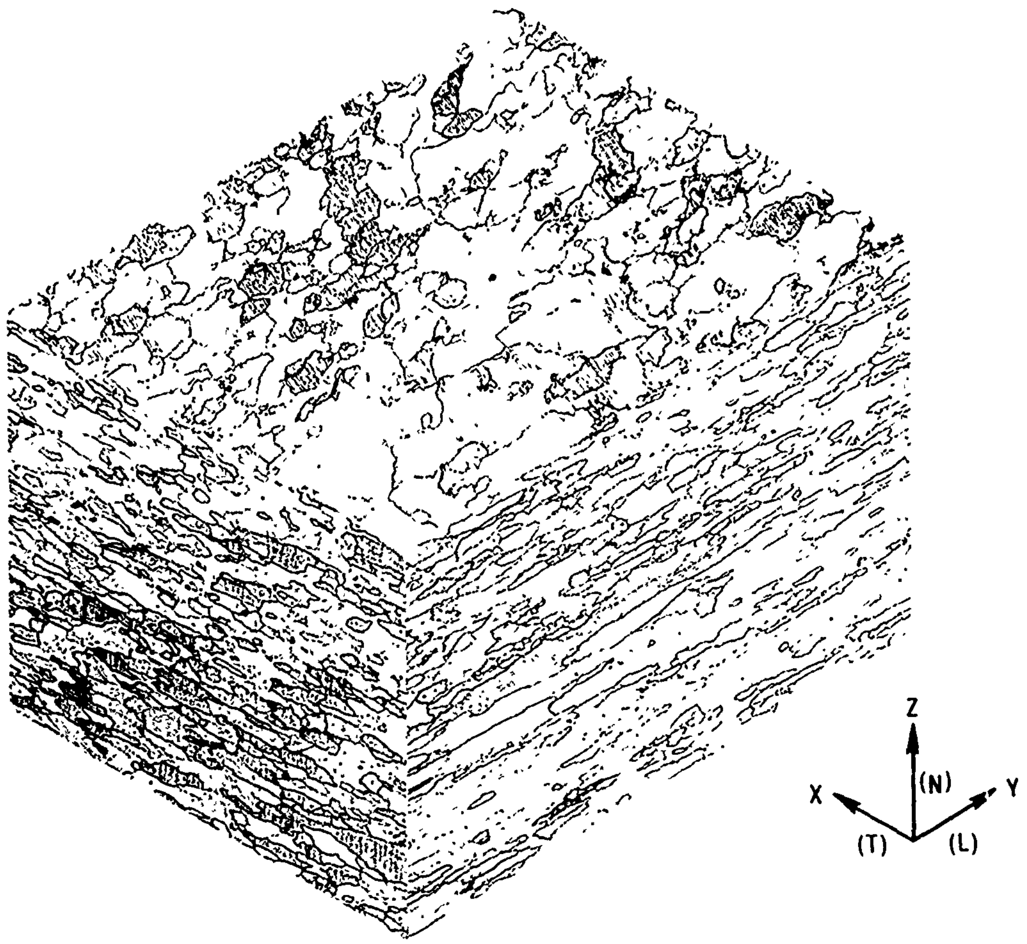
(1) THERMAL TREATMENTS CARRIED OUT IN A CIRCULATING AIR FURNACE

PROPERTIES

DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi$\sqrt{in.}$
I	83 2	73.6	16.7	37	100.8	1.37	33.2
I	80.1	70.0	17.1	31	91.0	1.30	30.6
N	80 5	70.0	14.0	N.D.	N.D.	N.D.	N.D.

MICROSTRUCTURE AND PROPERTIES OF 1.25" THICK RECRYSTALLIZED PLUS HOT ROLLED (AR + HR) 7475-T6 PLATE S-422622-A

Figure 6



MAG: 100X

ETCH: KELLERS

1.25" THICK 7475-T6 PLATE S-422622-B1

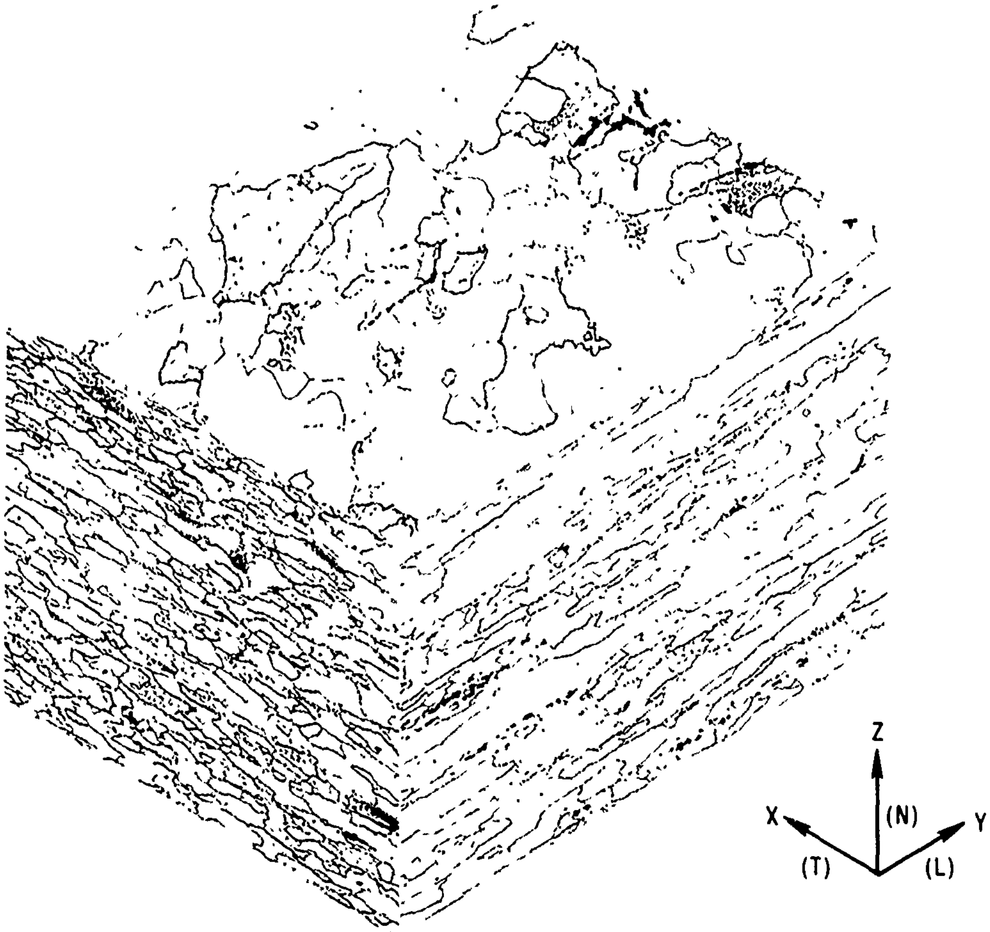
INGOT				SLAB				RECRYSTALLIZATION		PLATE				
									ROLLING		GRAIN COUNT			
THERMAL(1)	ROLLING			THERMAL(1)	ROLLING			THERMAL(1)	AT 750°F	SOLUTION(1)	g/mm			g/mm³
TREATMENT	TEMP	RGD	THICK	TREATMENT	TEMP	RGD	THICK	TREATMENT	RGD	HEAT-TREAT	X	Y	Z	XYZ
6hr/860°F 20hr/960°F	750°F	30%	7.0"	2hr/960°F 2hr/775°F 4hr/500°F	500°F	75%	1.75"	10hr/960°F	28%	2hr/960°F	22	14	60	18 480

(1) THERMAL TREATMENTS CARRIED OUT IN A CIRCULATING AIR FURNACE

	PROPERTIES						
DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi$\sqrt{in.}$
L	83.8	73.4	16.4	21	98.9	1.35	42.6
T	82.4	72.0	13.6	27	98.2	1.36	32.4
N	79.9	67.5	13.0	N.D.	N.D.	N.D.	N.D.

MICROSTRUCTURE AND PROPERTIES OF 1.25" THICK RECRYSTALLIZED PLUS HOT ROLLED (AR + HR) 7475-T6 PLATE S-422622 B1

Figure 7



MAG: 100X

ETCH: KELLERS

1.50" THICK 7475-T6 PLATE S-418967-50

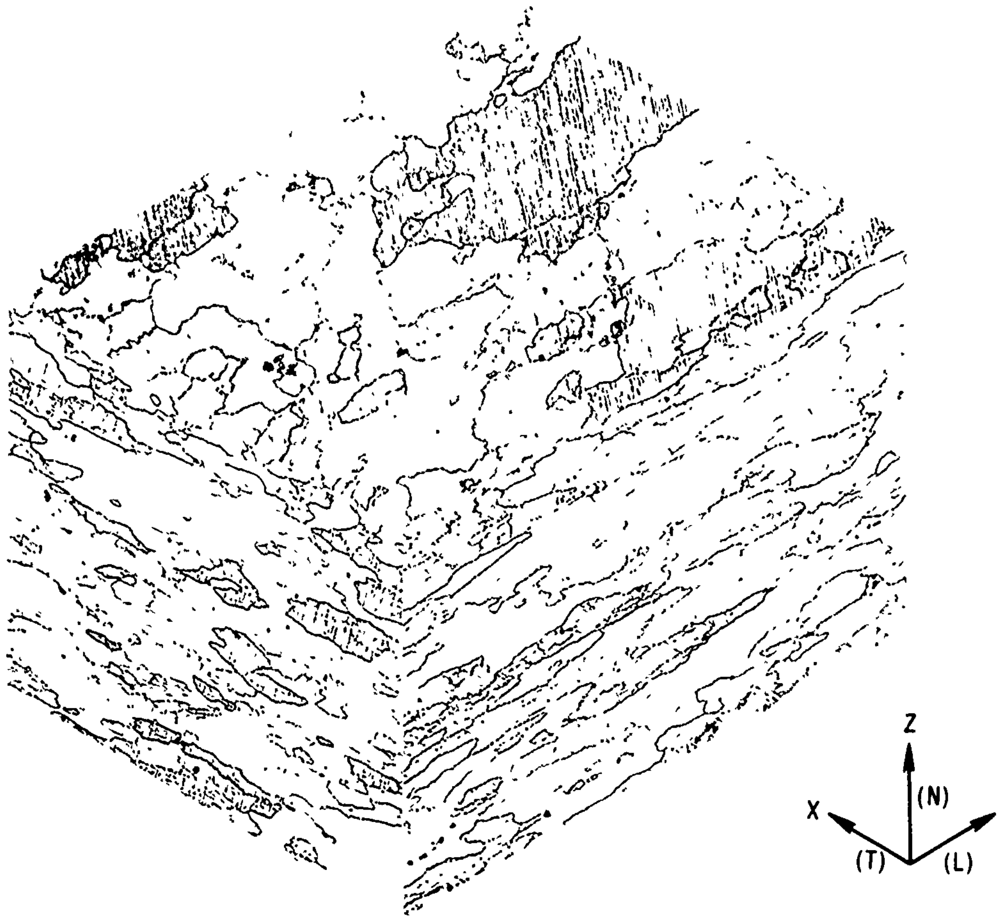
INGOT				SLAB				RECRYSTALLIZATION		PLATE				
THERMAL(1) TREATMENT	ROLLING TEMP	ROLLING RGD	THICK	THERMAL(1) TREATMENT	ROLLING TEMP	ROLLING RGD	THICK	THERMAL(1) TREATMENT	ROLLING AT 750°F RGD	SOLUTION(1) HEAT-TREAT	GRAIN COUNT g/mm X	GRAIN COUNT g/mm Y	GRAIN COUNT g/mm Z	GRAIN COUNT g/mm³ XYZ
6hr/860°F 20hr/960°F	750°F	14%	8.0"	2hr/960°F 2hr/775°F 4hr/500°F	500°F	75%	2.0"	8hr/960°F	25%	2 hr/960°F	24	11	62	16,368

(1) THERMAL TREATMENTS CARRIED OUT IN A CIRCULATING AIR FURNACE

PROPERTIES							
DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi$\sqrt{in.}$
L	82.1	70.6	17.1	28	97.1	1.37	29.9
T	80.5	69.0	15.0	25	84.7	1.23	29.2
N	79.3	66.3	12.0	N.D.	79.2	1.20	29.0

MICROSTRUCTURE AND PROPERTIES OF 1.50" THICK RECRYSTALLIZED AND HOT ROLLED (AR+HR) 7475-T6 PLATE S-418967-50

Figure 8



MAG: 100X ETCH: KELLERS

2.50" THICK 7475-T6 PLATE S-422622-G1

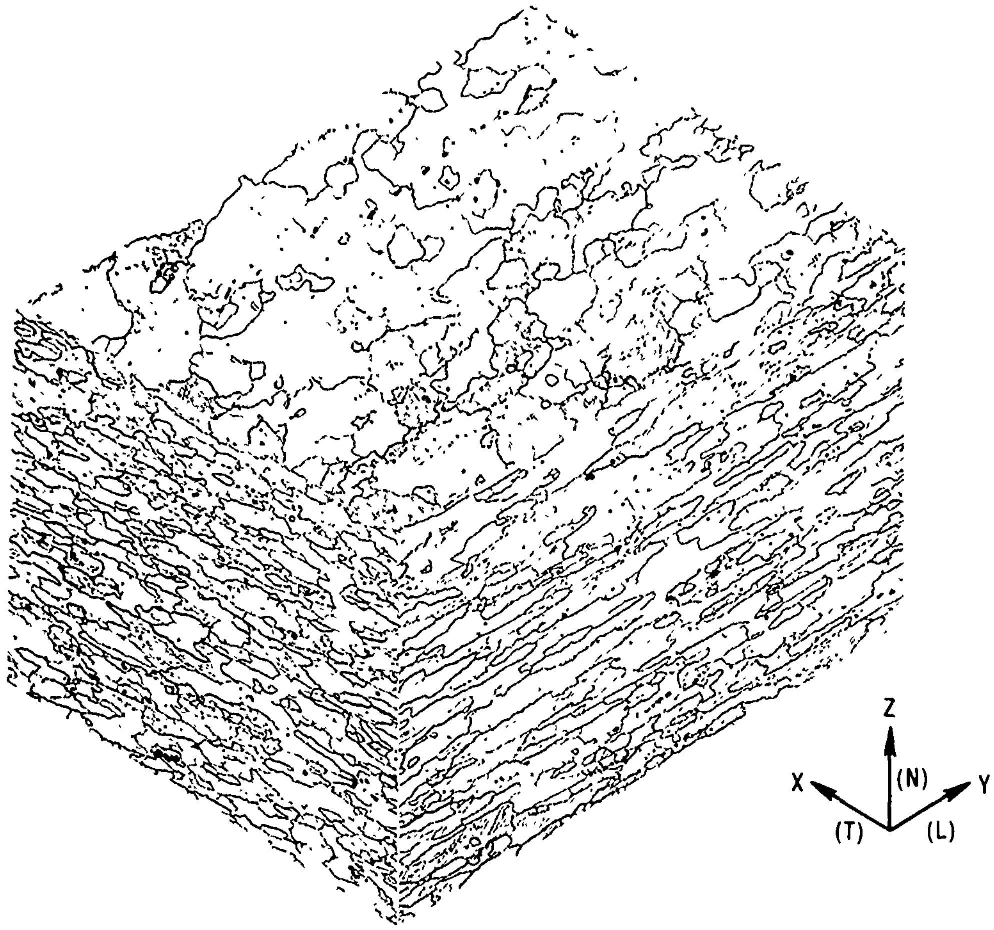
INGOT			SLAB				RECRYSTALLIZATION			PLATE				
									ROLLING AT 750 F		GRAIN COUNT			
THERMAL(1) TREATMENT	ROLLING TEMP	ROLLING RGD	THICK	THERMAL(1) TREATMENT	ROLLING TEMP	ROLLING RGD	THICK	THERMAL(1) TREATMENT	RGD	SOLUTION(1) HEAT-TREAT	g/mm X	g/mm Y	g/mm Z	g/mm^3 XYZ
6hr/860°F 20hr/960°F 2hr/775°F 4hr/500°F	500°F	65%	—	NONE	—	—	3.50"	10hr/960°F	28%	2hr/960°F	14	8	42	4704

(1) THERMAL TREATMENTS CARRIED OUT IN A CIRCULATING AIR FURNACE

PROPERTIES							
DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi$\sqrt{in.}$
L	79.2	68.6	20.7	27	92.0	1.34	N.D.
T	78.6	67.4	14.3	28	84.8	1.26	N.D.
N	77.7	65.2	13.0	N.D.	92.7	1.42	N.D.

MICROSTRUCTURE AND PROPERTIES OF 2.50" THICK RECRYSTALLIZED PLUS HOT ROLLED (AR + HR) 7475-T6 PLATE S-422622-G1

Figure 9



MAG: 100X

ETCH: KELLERS

1.25" THICK 7475-T6 PLATE S-427506

INGOT				SLAB				RECRYSTALLIZATION		PLATE				
	ROLLING				ROLLING				ROLLING AT 750°F		GRAIN COUNT g/mm			g/mm³
THERMAL[1] TREATMENT	TEMP	RGD	THICK	THERMAL[1] TREATMENT	TEMP	RGD	THICK	THERMAL[1] TREATMENT	RGD	SOLUTION[1] HEAT-TREAT	X	Y	Z	XYZ
48hr/860°F 5hr/775°F 4hr/500°F	500°F	88%	———	———	NONE	———	1.25"	48hr/860°F	NONE	3hr/900°F	18	12	61	13,176

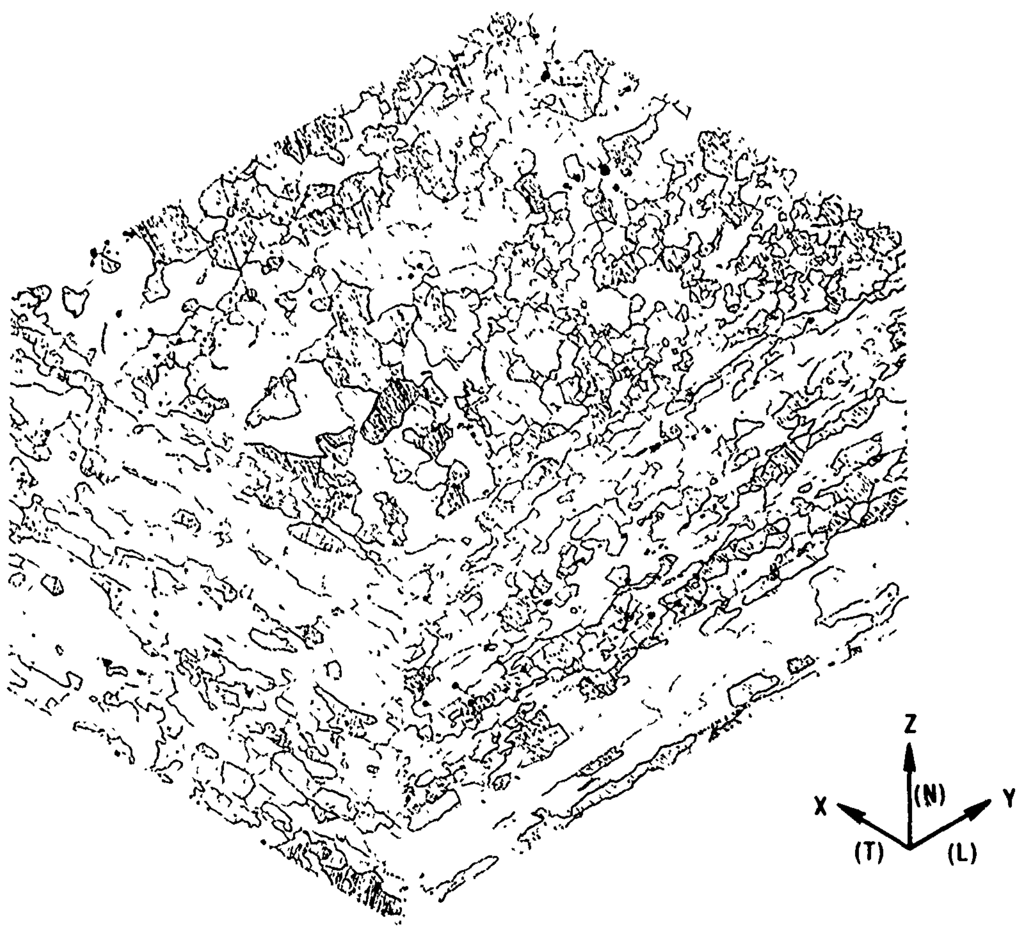
(1) THERMAL TREATMENTS CARRIED OUT IN A SALT BATH

PROPERTIES

DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi$\sqrt{in.}$
L	78.5	68.6	19.3	40.5	95.0	1.38	33.6
T	78.7	67.8	17.1	32.0	84.0	1.24	29.3
N	80.9	71.1	14.0	N.D.	N.D.	N.D.	N.D.

MICROSTRUCTURE AND PROPERTIES OF 1.25" THICK RECRYSTALLIZED (AR) 7475-T6 PLATE S-427506

Figure 10



MAG: 100X

ETCH: KELLERS

1.25" THICK 7475-T6 PLATE S-421675-E61

INGOT				SLAB				RECRYSTALLIZATION		PLATE				
THERMAL(1) TREATMENT	ROLLING TEMP	ROLLING RGD	THICK	THERMAL(1) TREATMENT	ROLLING TEMP	ROLLING RGD	THICK	THERMAL(1) TREATMENT	ROLLING AT 750 F RGD	SOLUTION(1) HEAT-TREAT	GRAIN COUNT g mm X	GRAIN COUNT g mm Y	GRAIN COUNT g mm Z	GRAIN COUNT g mm· XYZ
6hr/860°F 20hr/960°F	750°F	50%	5 0"	2hr/960°F 2hr/775°F 4hr/650°F	500°F	75%	1 25"	10hr/960°F	NONE	2hr/960 F	30	23	48	33 120

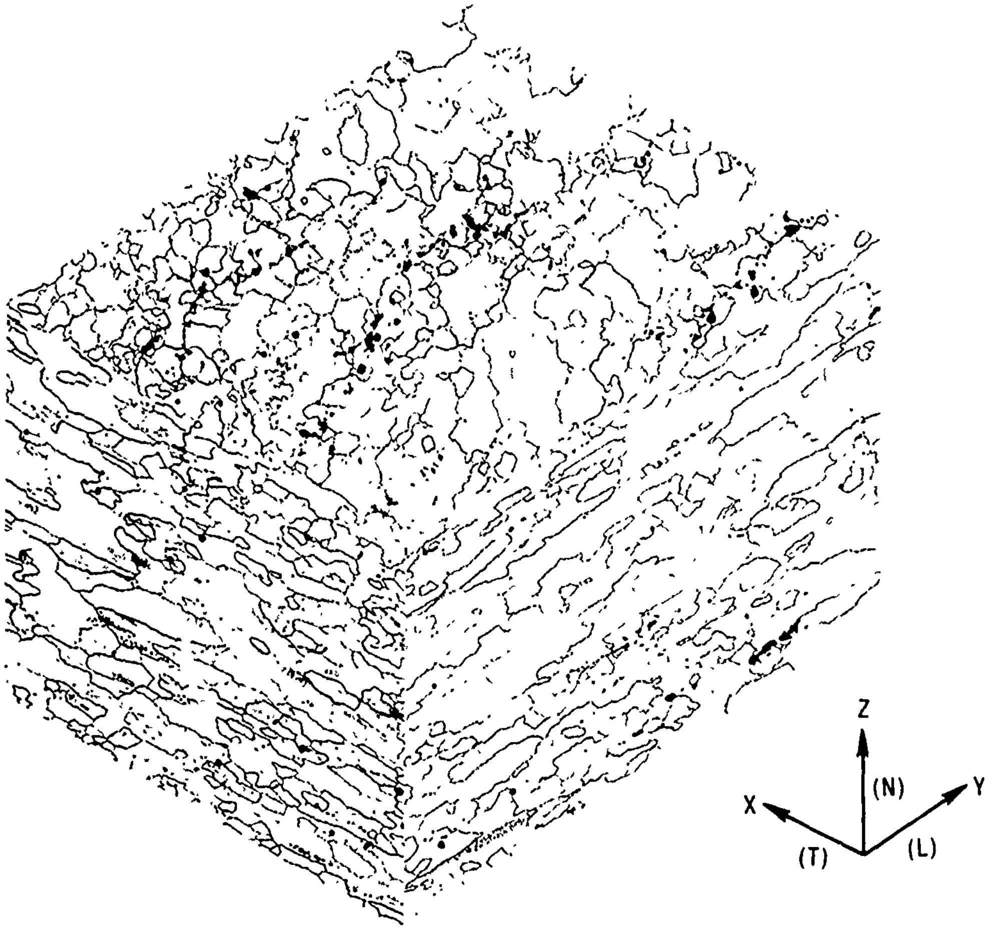
(1) THERMAL TREATMENTS CARRIED OUT IN A CIRCULATING AIR FURNACE

PROPERTIES

DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. / Y.S.	K_Q ksi$\sqrt{in.}$
L	75.2	64.8	19.6	40	95 7	1.49	40.2
T	77.1	66 3	17.1	30	84.7	1.32	32.2
N	N.D.	N.D	N.D.	N.D.	N.D.	N.D.	N.D..

MICROSTRUCTURE AND PROPERTIES OF 1.25" THICK RECRYSTALLIZED (AR) 7475-T6 PLATE S-421675-E61

Figure 11



MAG: 100X

ETCH: KELLERS

1.50" THICK 7475-T6 PLATE S-418967-40

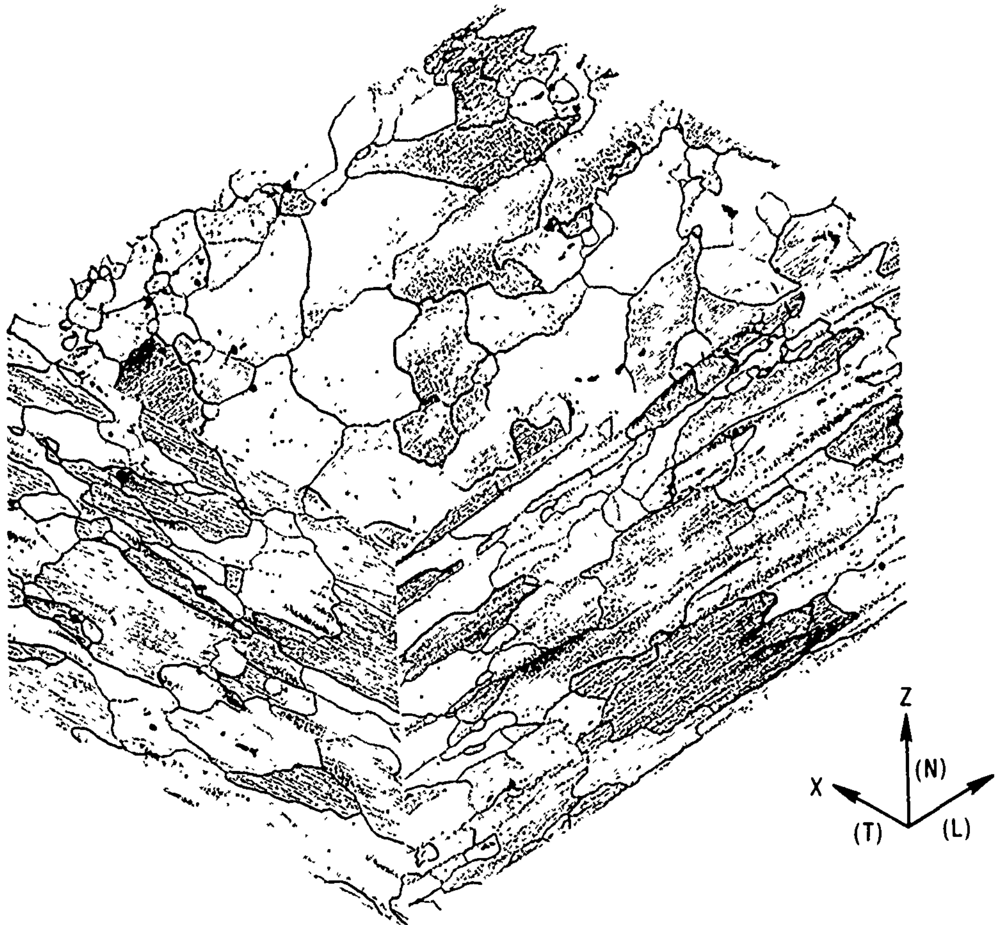
INGOT				SLAB				RECRYSTALLIZATION	PLATE					
									ROLLING		GRAIN COUNT			
THERMAL(1)	ROLLING			THERMAL(1)	ROLLING			THERMAL(1)	AT 750 F	SOLUTION(1)	g/mm			g/mm³
TREATMENT	TEMP	RGD	THICK	TREATMENT	TEMP	RGD	THICK	TREATMENT	RGD	HEAT-TREAT	X	Y	Z	XYZ
6hr/860 F 20hr/960 F	750 F	35%	6 0"	2hr/960°F 2hr/775°F 4hr/500°F	500°F	75%	1 50"	18hr/960°F	NONE	2hr/960 F	22	20	54	23 760

(1) THERMAL TREATMENTS CARRIED OUT IN A CIRCULATING AIR FURNACE

	PROPERTIES						
DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi$\sqrt{in.}$
L	79.3	67.7	17.9	32	90.1	1.33	32 4
T	80.2	68.5	15.7	22	82.1	1.20	27.5
N	79.3	67.4	8 0	N.D.	85 0	1 27	23.6

MICROSTRUCTURE AND PROPERTIES OF 1.50" THICK RECRYSTALLIZED (AR) 7475-T6 PLATE S-418967-40

Figure 12



MAG: 100X

ETCH: KELLERS

2.50" THICK 7475-T6 PLATE S-421675-F3

INGOT				SLAB			RECRYSTALLIZATION		PLATE					
	ROLLING				ROLLING				ROLLING		GRAIN COUNT			
											g mm			g/mm³
THERMAL(1) TREATMENT	TEMP	RGD	THICK	THERMAL(1) TREATMENT	TEMP	RGD	THICK	THERMAL(1) TREATMENT	AT 750 F RGD	SOLUTION(1) HEAT-TREAT	X	Y	Z	XYZ
6hr/860 F 20hr 960 F 2hr 775 F 4hr 650 F	600 F	50%	5.0"	10hr/960 F 2hr/960 F 2hr/775 F 4hr/650 F	600 F	50%	2.50"	10hr/960 F	NONE	2hr/960 F	9	5	24	1080

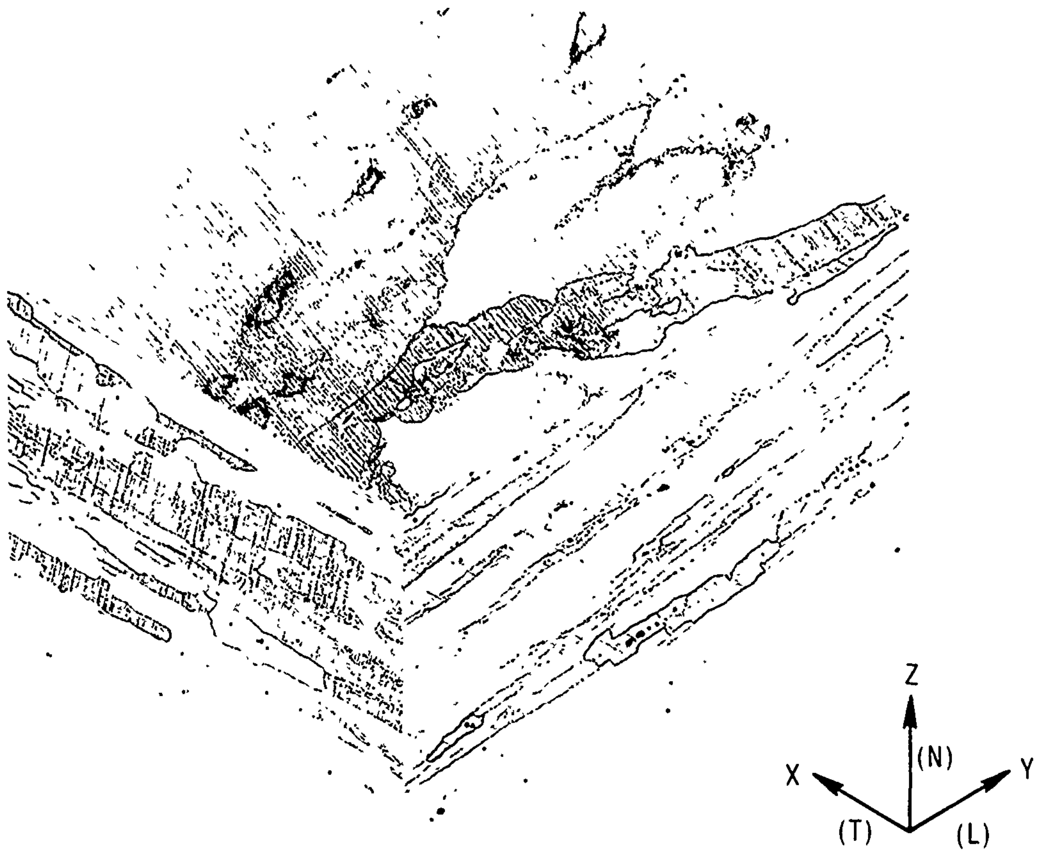
(1) THERMAL TREATMENTS CARRIED OUT IN A CIRCULATING AIR FURNACE

PROPERTIES

DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. / Y.S.	K_Q ksi$\sqrt{in.}$
L	75.9	65.2	17 1	28	84.3	1 29	N.D.
T	75 4	64.8	16 4	24	79.0	1.22	N.D.
N	76 2	63.3	12.0	N.D.	91 2	1.44	N.D.

MICROSTRUCTURE AND PROPERTIES OF 2.50" THICK RECRYSTALLIZED (AR) 7475-T6 PLATE S-421675-F3

Figure 13



MAG: 100X

ETCH: KELLERS

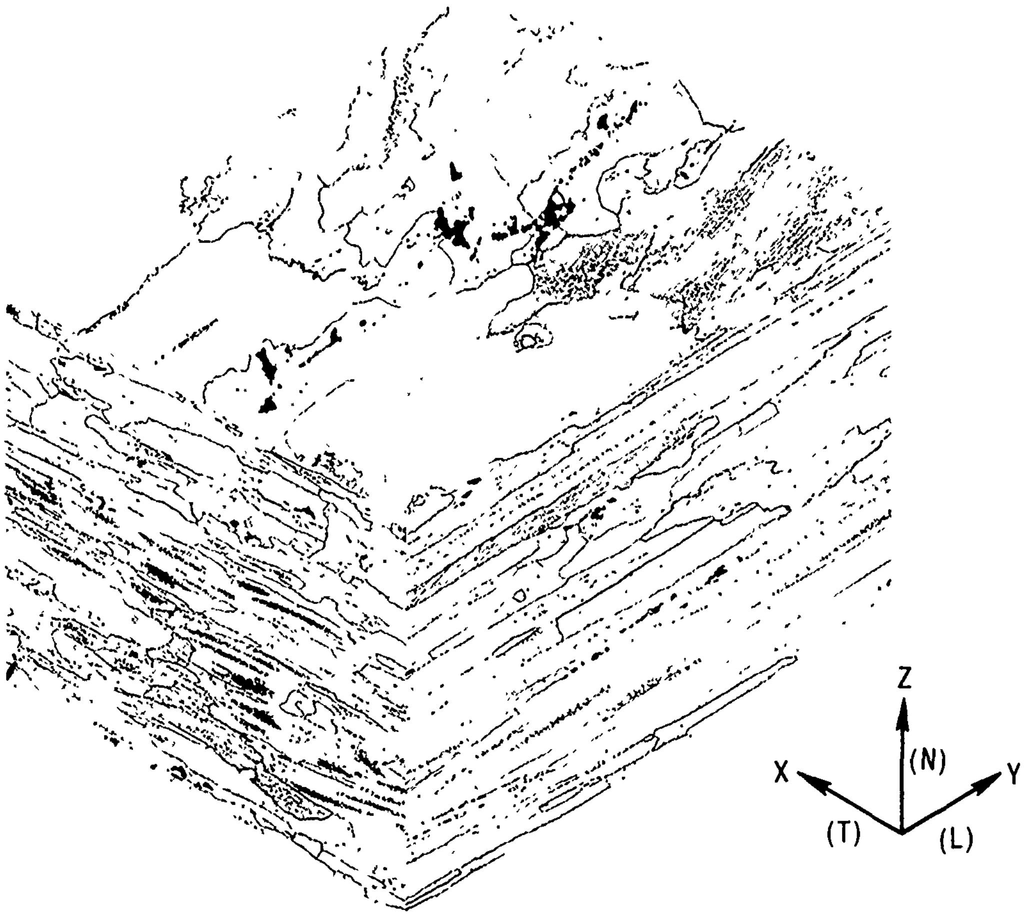
1.25" THICK HOT ROLLED (HR) 7475-T6 PLATE S-422622-C2

PROPERTIES

DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi$\sqrt{in.}$
L	83.7	74.0	13.2	17	99.3	1.34	49.9
T	80.4	70.7	10 7	12	92.8	1.31	43.1
N	76 1	65.9	9.0	N.D.	N.D.	N.D.	N.D.

MICROSTRUCTURE AND PROPERTIES OF 1.25" THICK HOT ROLLED (HR) 7475-T6 PLATE S-422622-C2

Figure 14



MAG: 100X

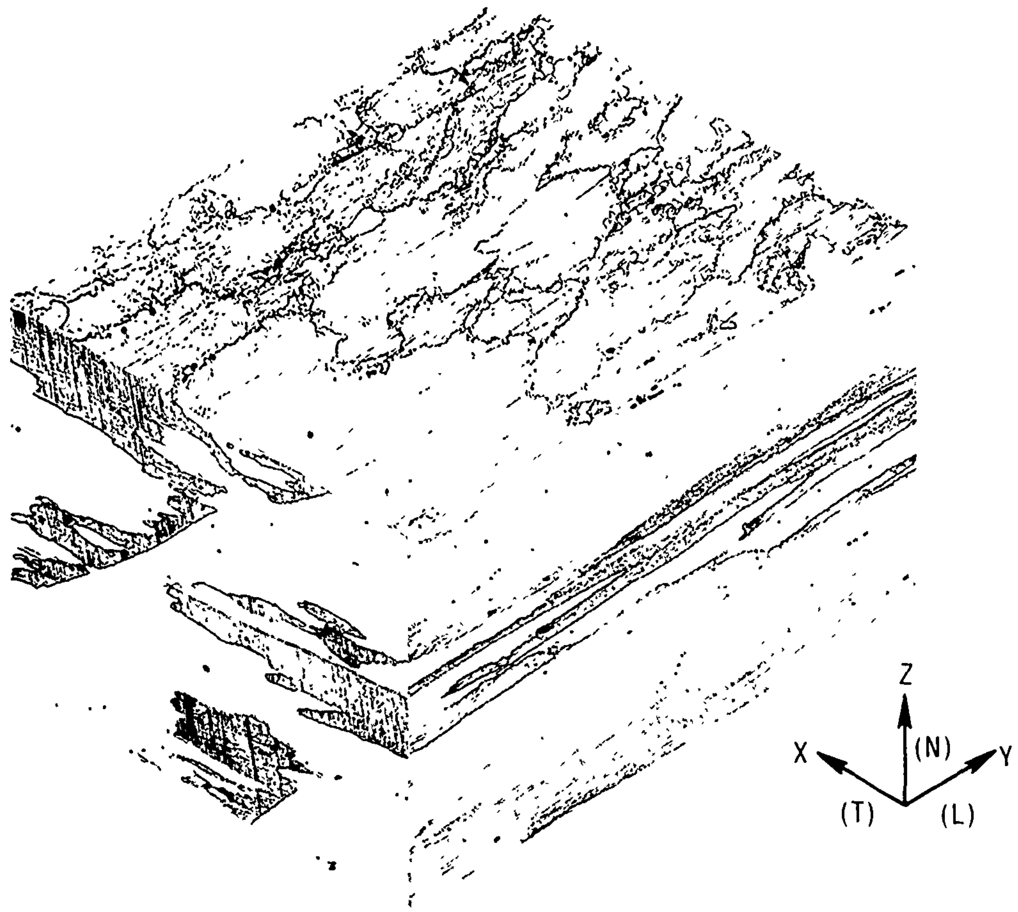
ETCH: KELLERS

1.50" THICK HOT ROLLED (HR) 7475-T6 PLATE S-418967-30

PROPERTIES							
DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi $\sqrt{in.}$
L	83.8	73.0	15.0	19	99.8	1.37	40.9
T	81.3	70.3	15.7	21	90.0	1.28	32.6
N	81.4	67.1	10.0	N.D.	85.3	1.28	31.0

MICROSTRUCTURE AND PROPERTIES OF 1.50" THICK HOT ROLLED (HR) 7475-T6 PLATE S-418967-30

Figure 15



MAG. 100X

ETCH: KELLERS

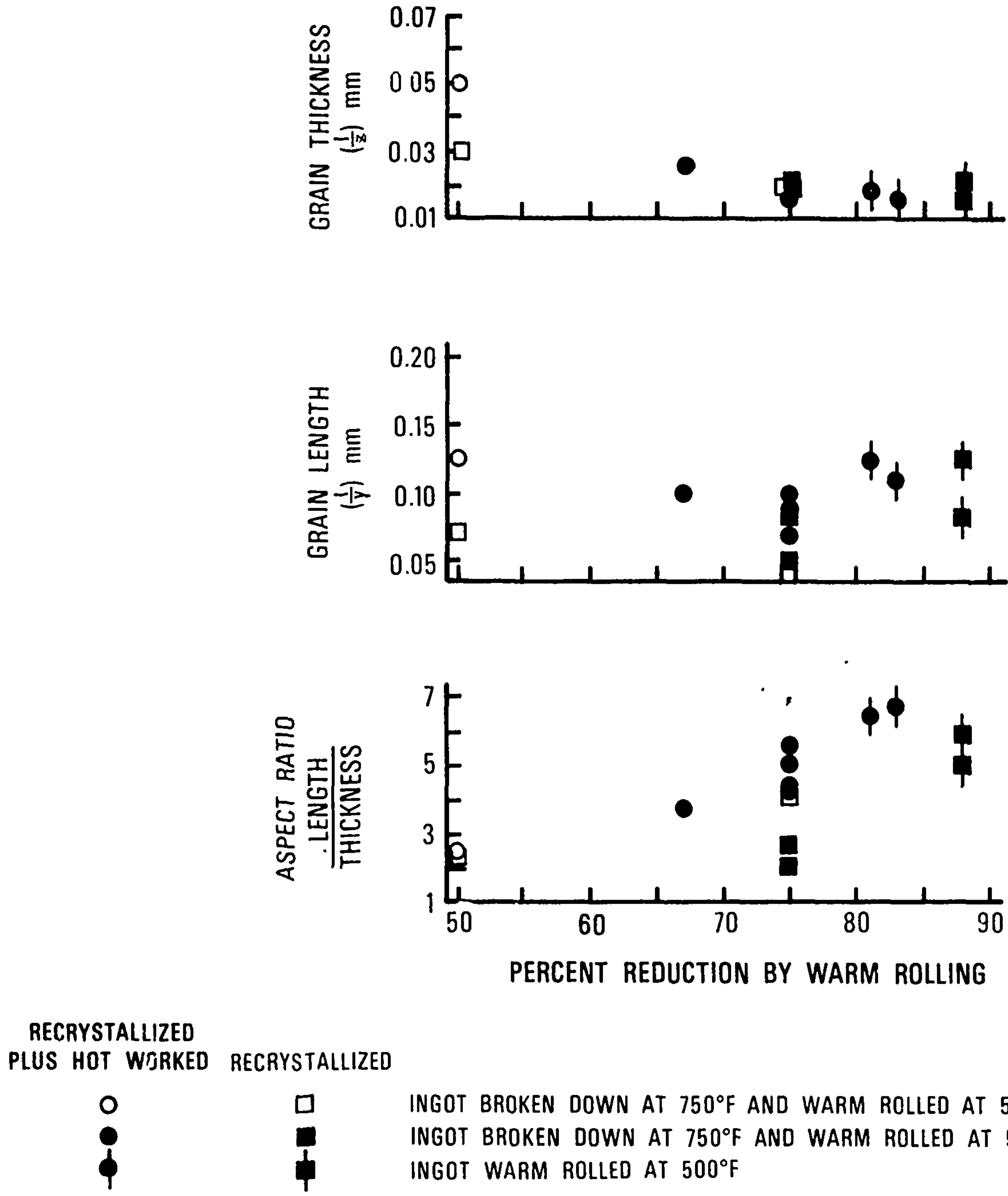
2.50"THICK HOT ROLLED (HR) 7475-T6 PLATE S-422622-C1

PROPERTIES

DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi$\sqrt{in.}$
L	83.9	74.4	11.0	12	98.6	1.33	N.D.
T	76.5	67.8	5.7	8	94.0	1.39	N.D.
N	73.0	60.2	10.0	N.D.	94.2	1.56	N.D.

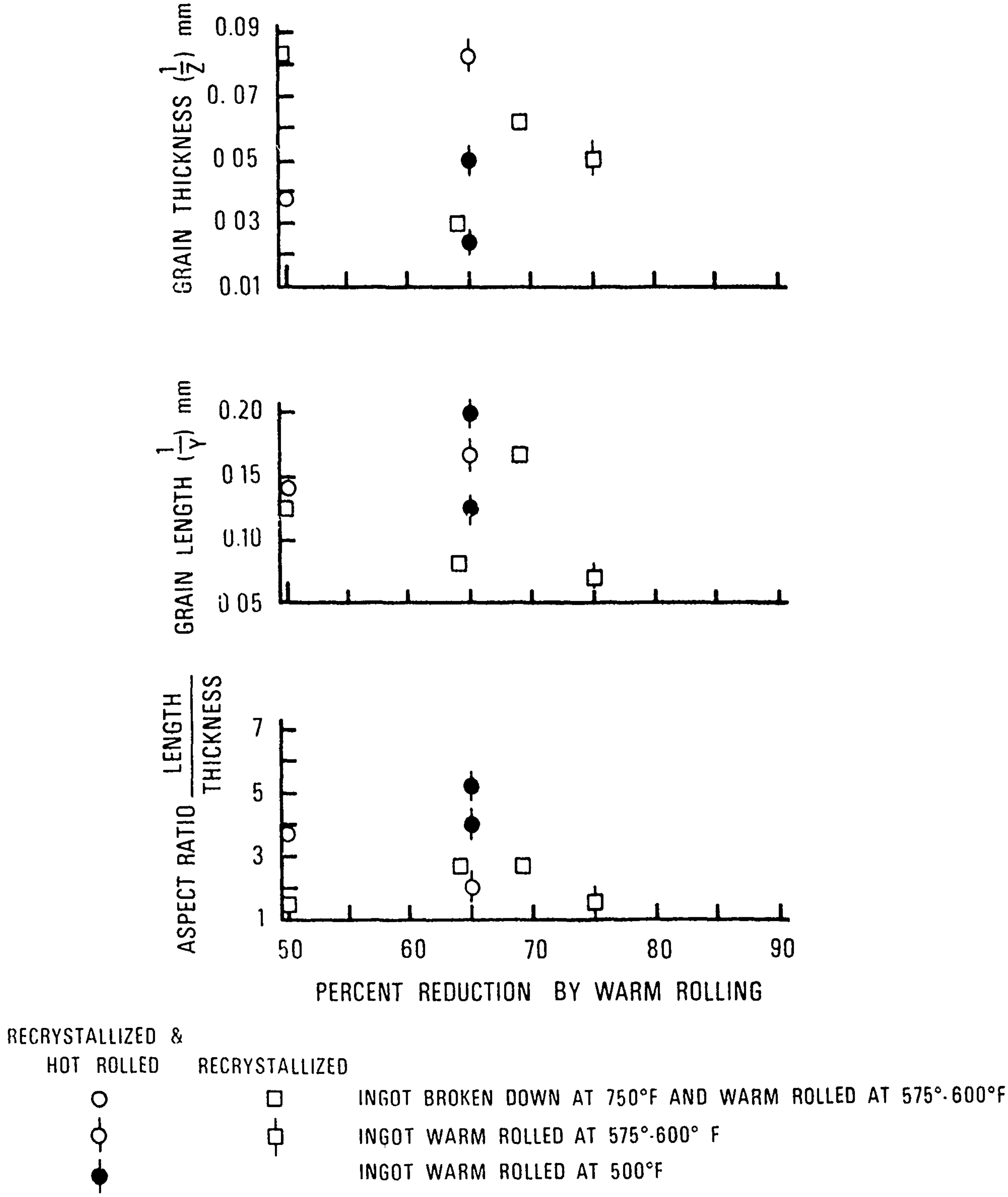
MICROSTRUCTURE AND PROPERTIES OF 2.50" THICK HOT ROLLED (HR) 7475-T6 PLATE S-422622-C1

Figure 16



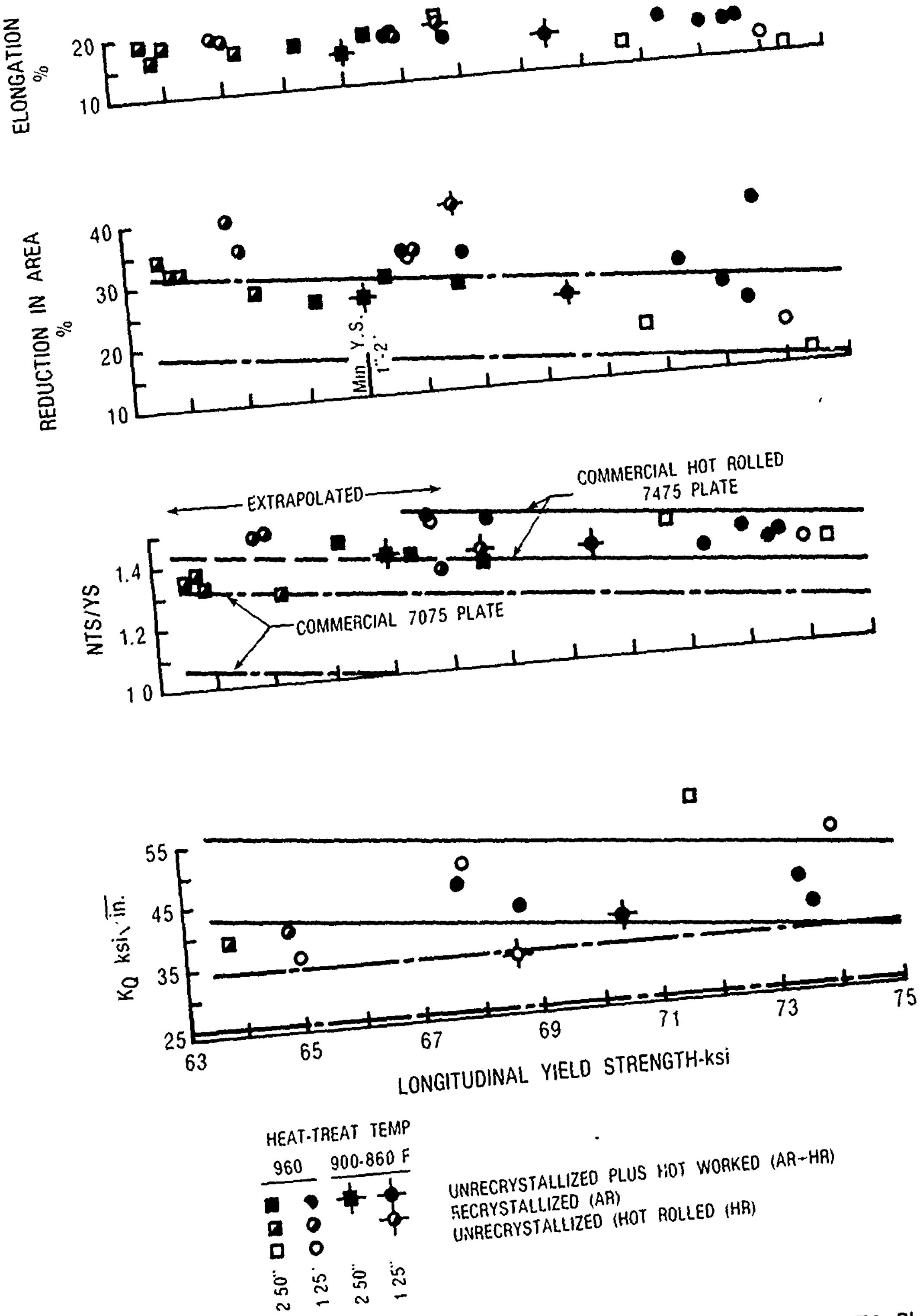
EFFECT OF WARM ROLLING REDUCTIONS ON GRAIN DIMENSIONS OF 1.25" - 1.50" THICK RECRYSTALLIZED AND RECRYSTALLIZED PLUS HOT WORKED 7475-T6 PLATE FABRICATED USING ITMT PRACTICES

Figure 17



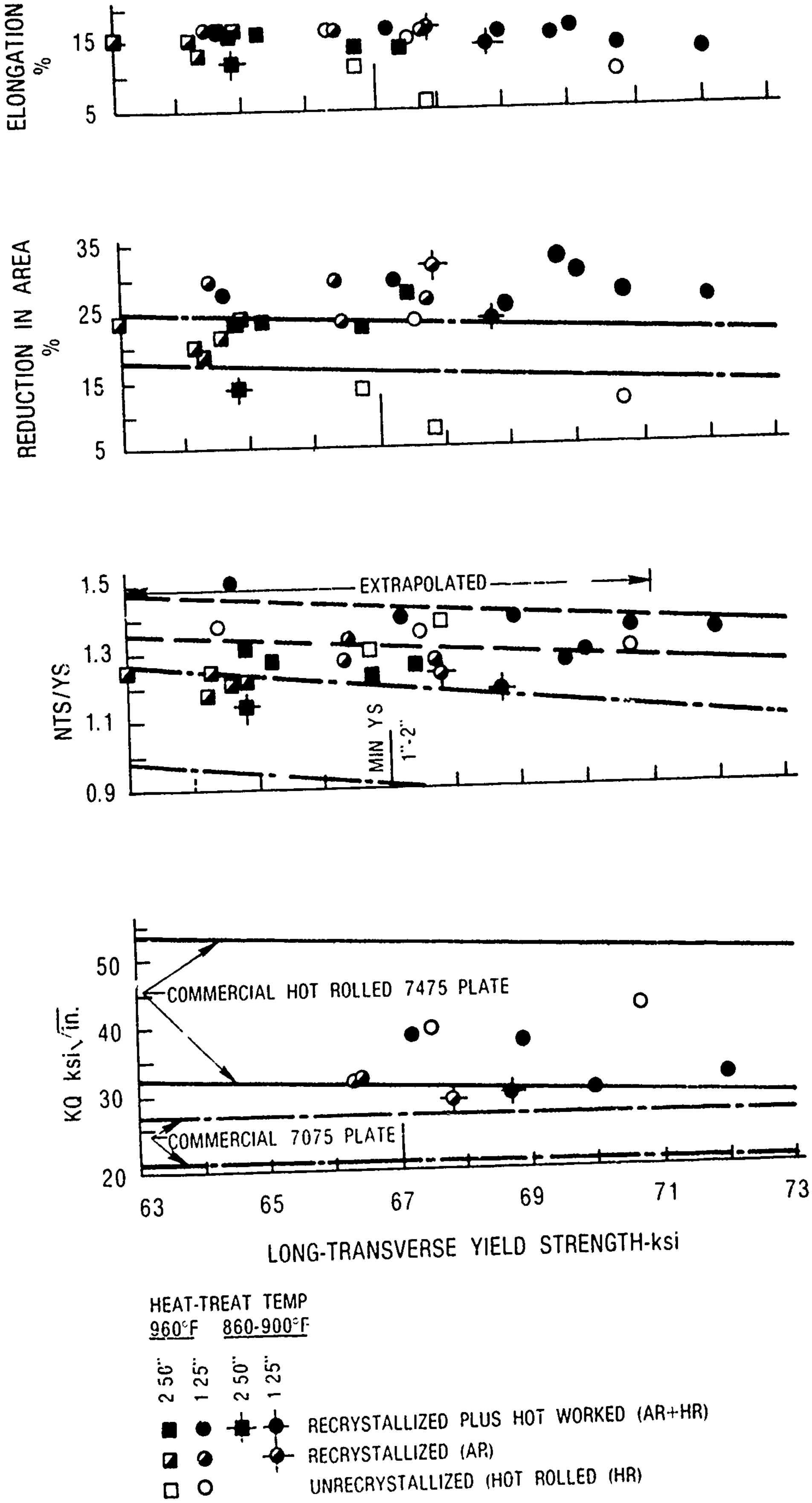
EFFECT OF WARM ROLLING REDUCTIONS ON GRAIN DIMENSIONS OF 2.50" THICK RECRYSTALLIZED AND RECRYSTALLIZED PLUS HOT WORKED 7475-T6 PLATE FABRICATED USING ITMT PRACTICES

Figure 18



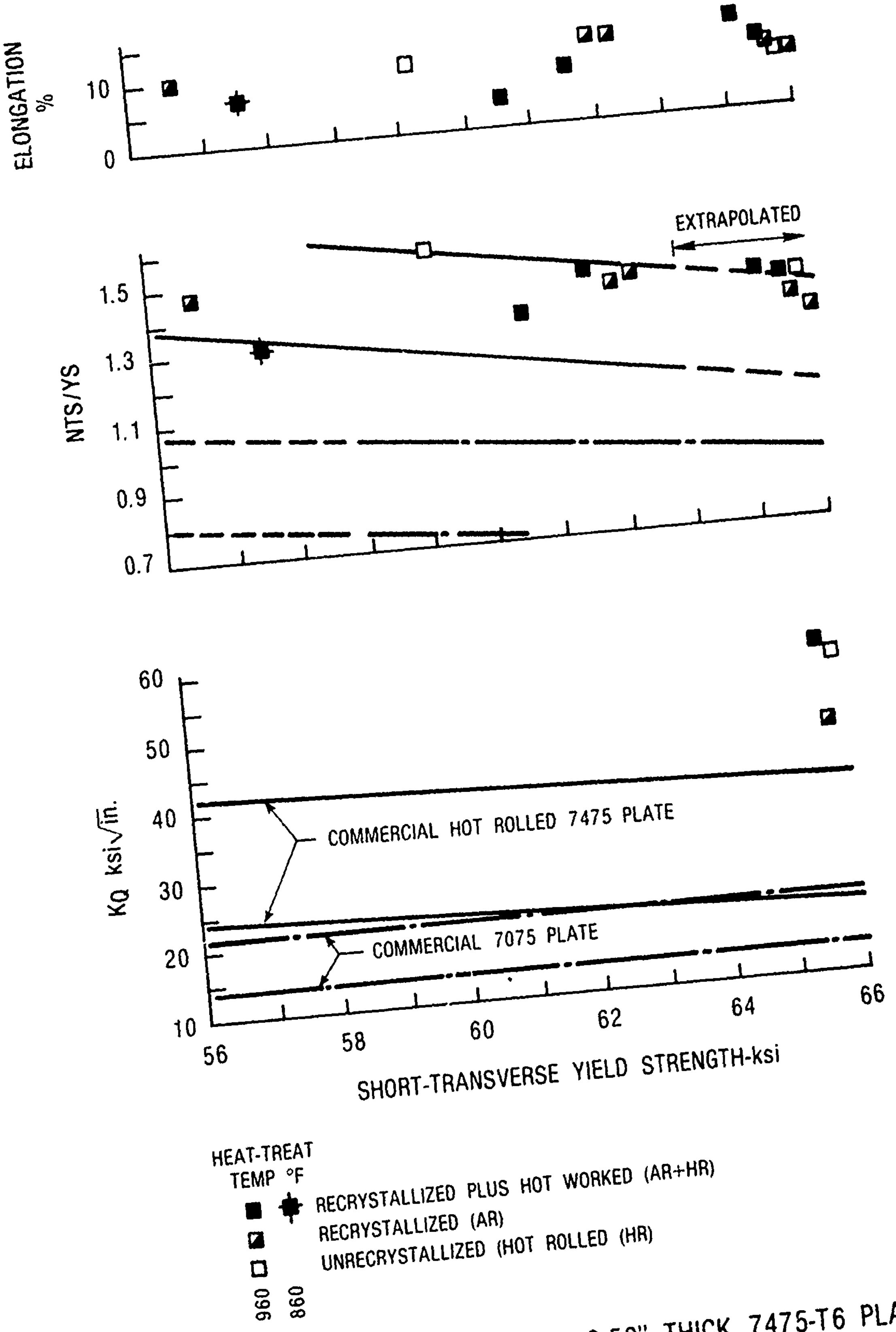
LONGITUDINAL PROPERTIES OF 1.25" AND 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF YIELD STRENGTH

Figure 19



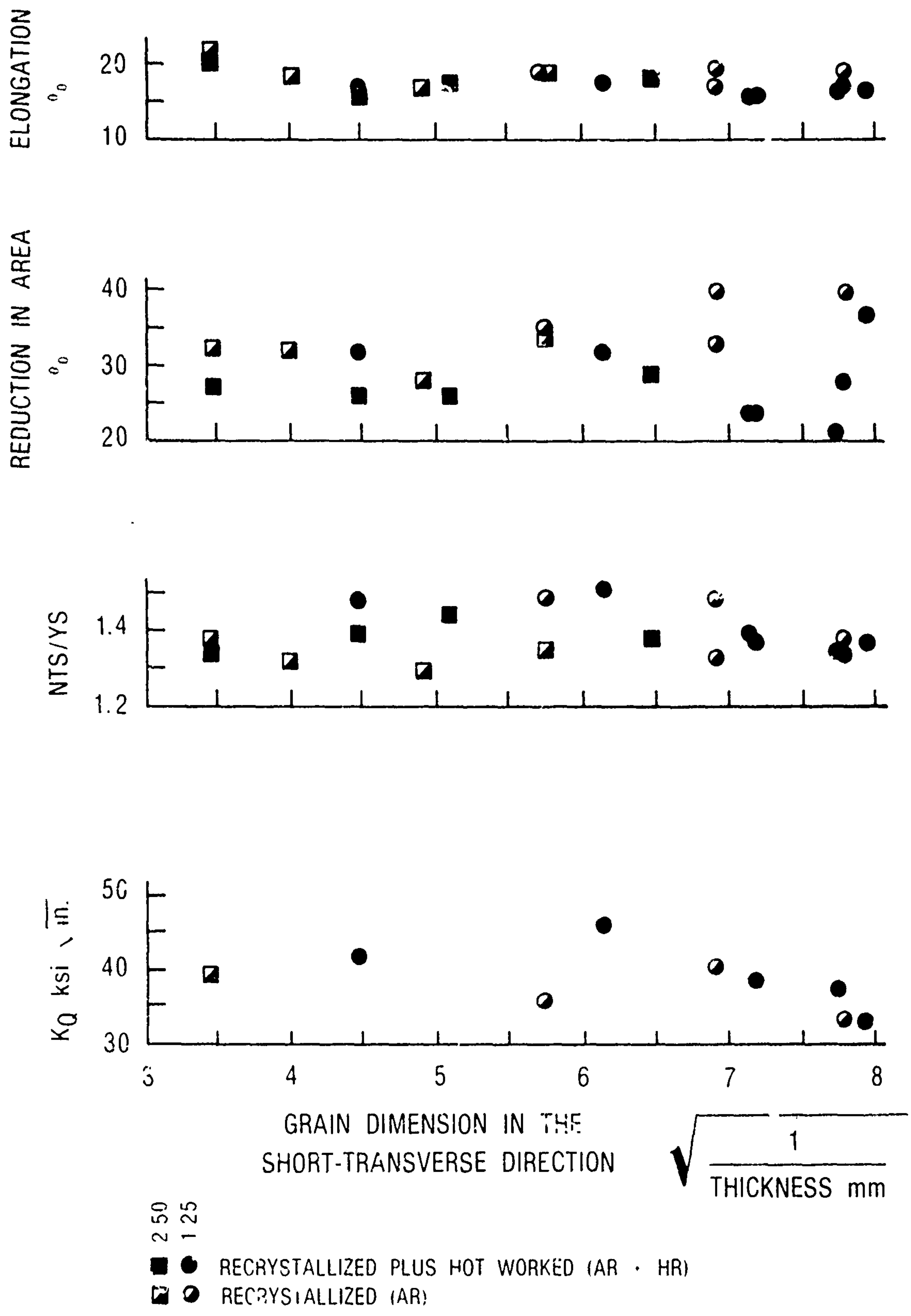
LONG TRANSVERSE PROPERTIES OF 1.25" AND 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF YIELD STRENGTH

Figure 20



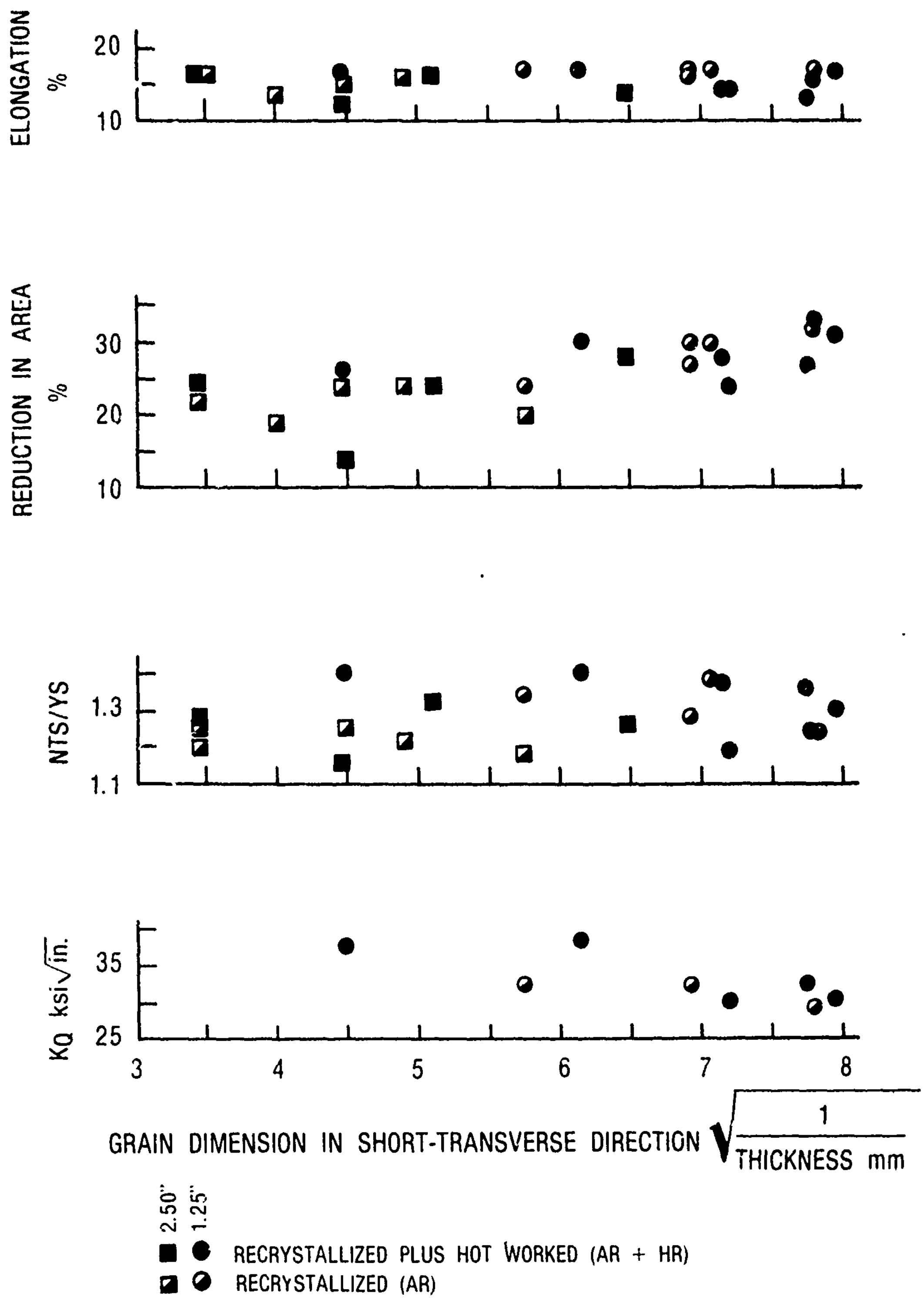
SHORT-TRANSVERSE PROPERTIES OF 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF YIELD STRENGTH

Figure 21



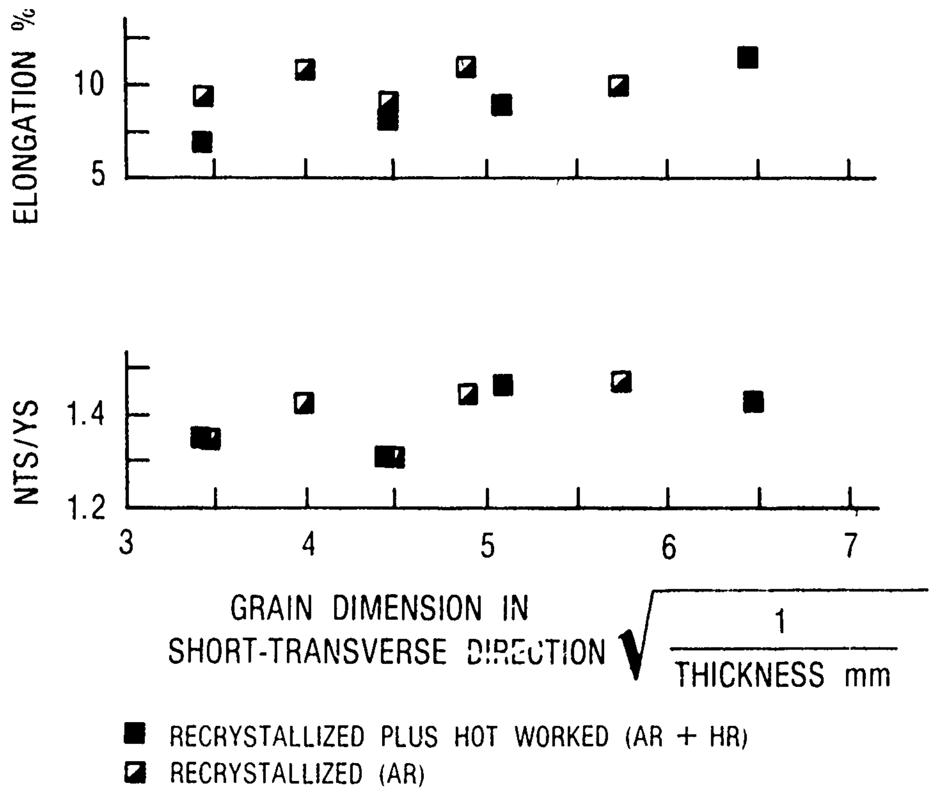
LONGITUDINAL PROPERTIES OF 1.25" AND 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF GRAIN DIMENSION IN THE SHORT-TRANSVERSE DIRECTION

Figure 22



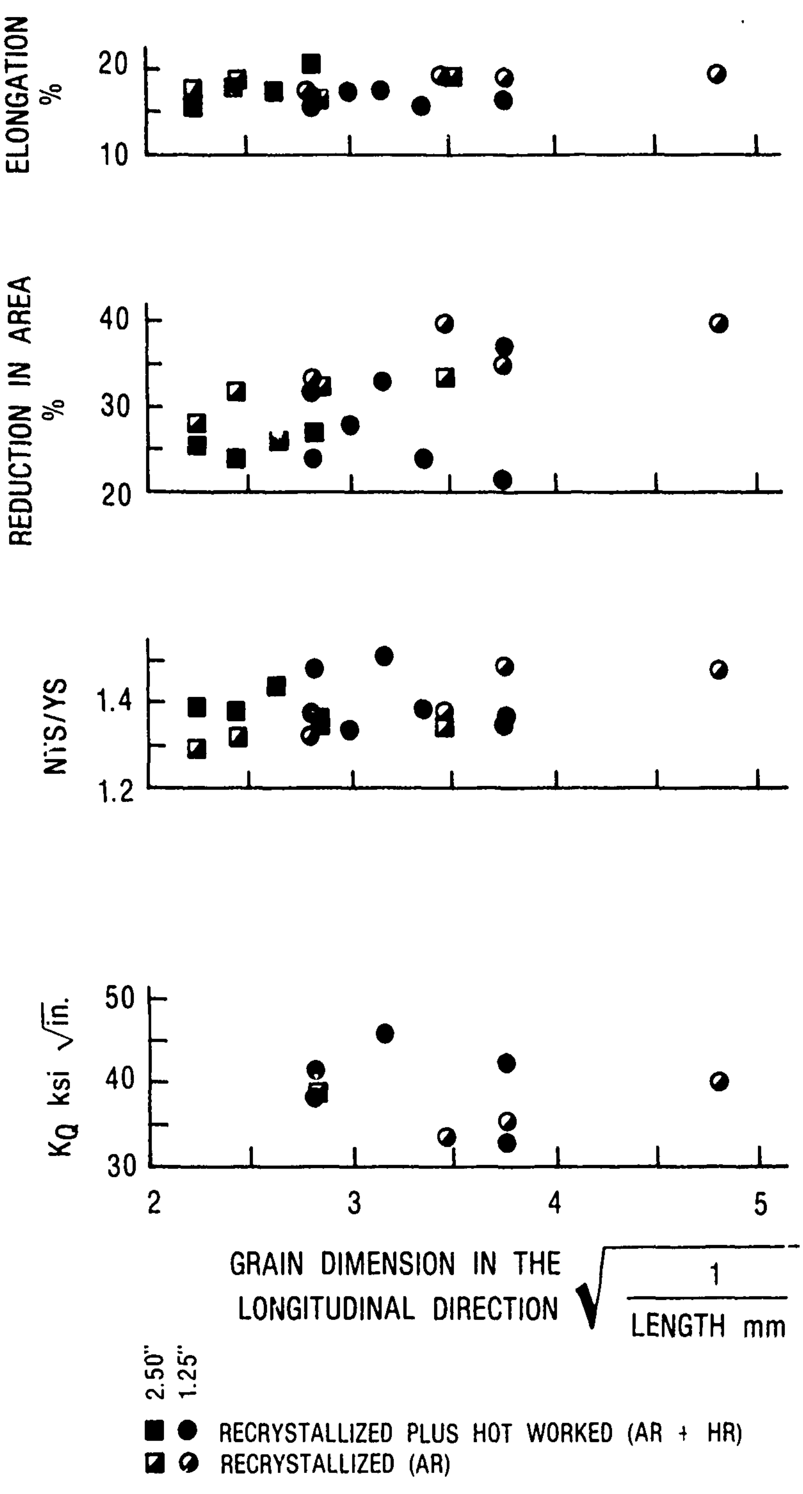
LONG TRANSVERSE PROPERTIES OF 1.25" AND 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF THE GRAIN DIMENSION IN THE SHORT TRANSVERSE DIRECTION

Figure 23



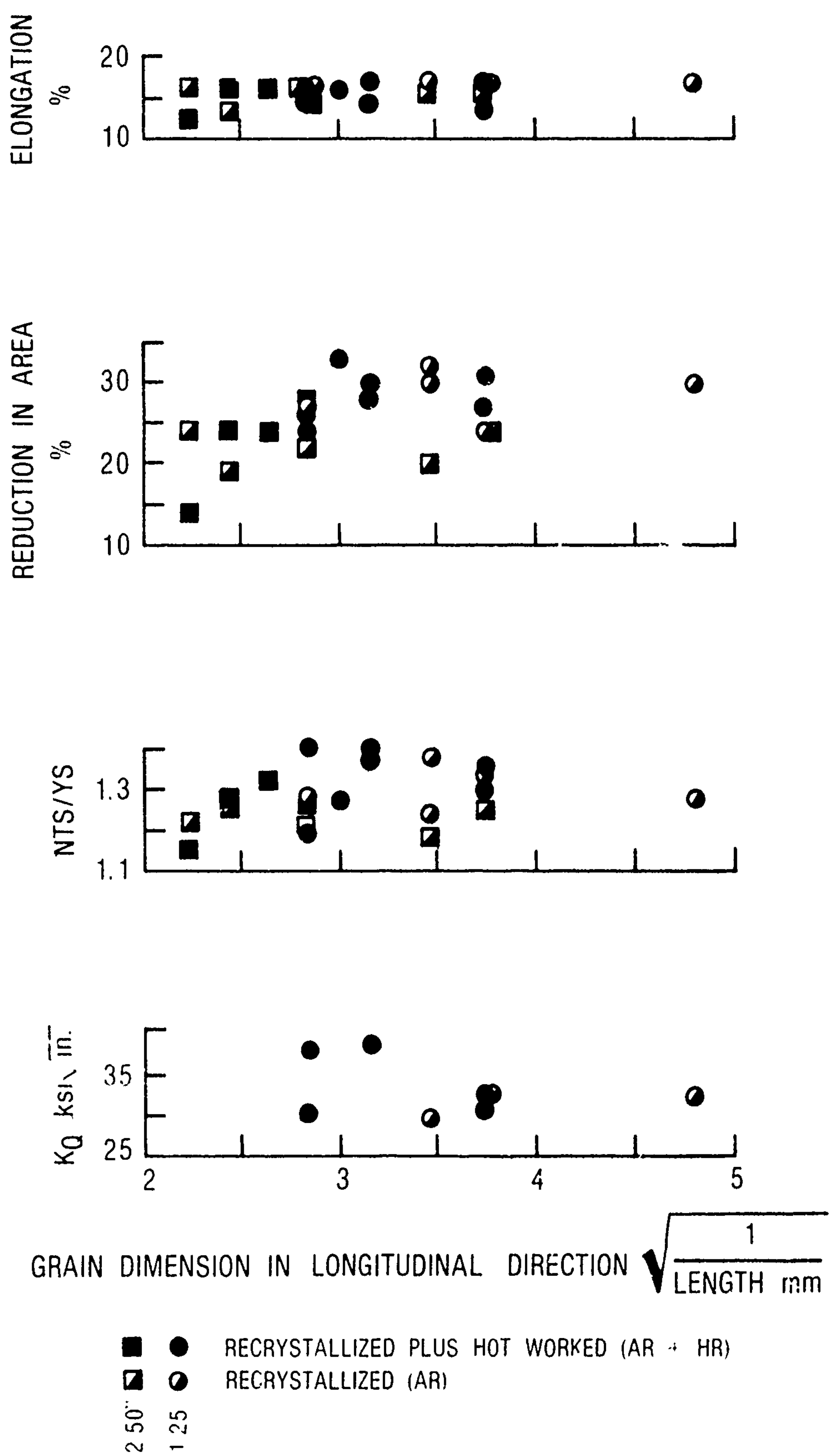
SHORT-TRANSVERSE PROPERTIES OF 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF THE GRAIN DIMENSION IN THE SHORT-TRANSVERSE DIRECTION

Figure 24



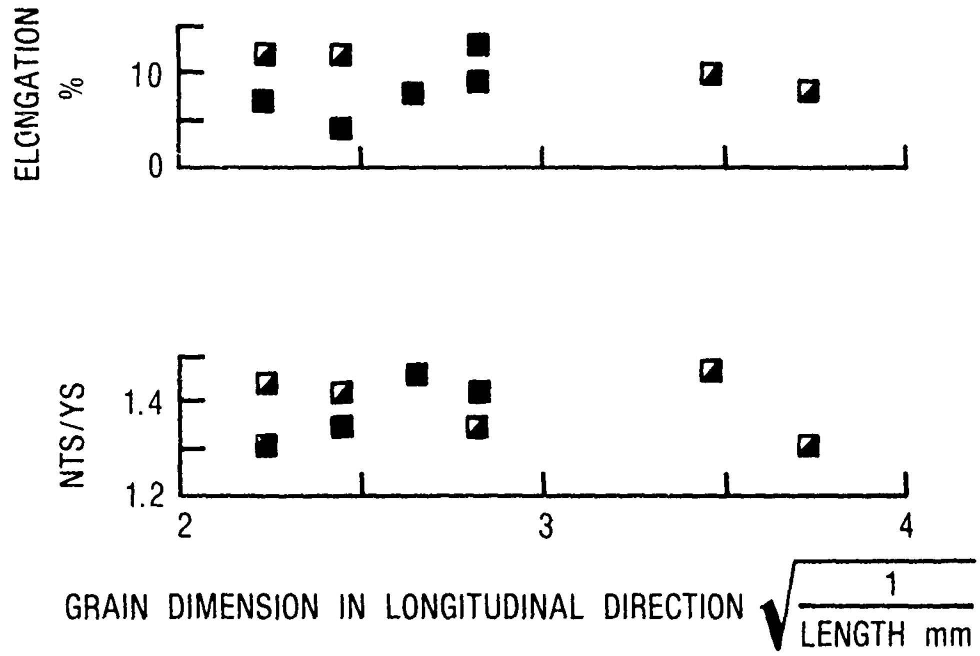
LONGITUDINAL PROPERTIES OF 1.25" AND 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF THE GRAIN DIMENSION IN THE LONGITUDINAL DIRECTION

Figure 25



LONG-TRANSVERSE PROPERTIES OF 1.25" AND 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF THE GRAIN DIMENSION IN THE LONGITUDINAL DIRECTION

Figure 26

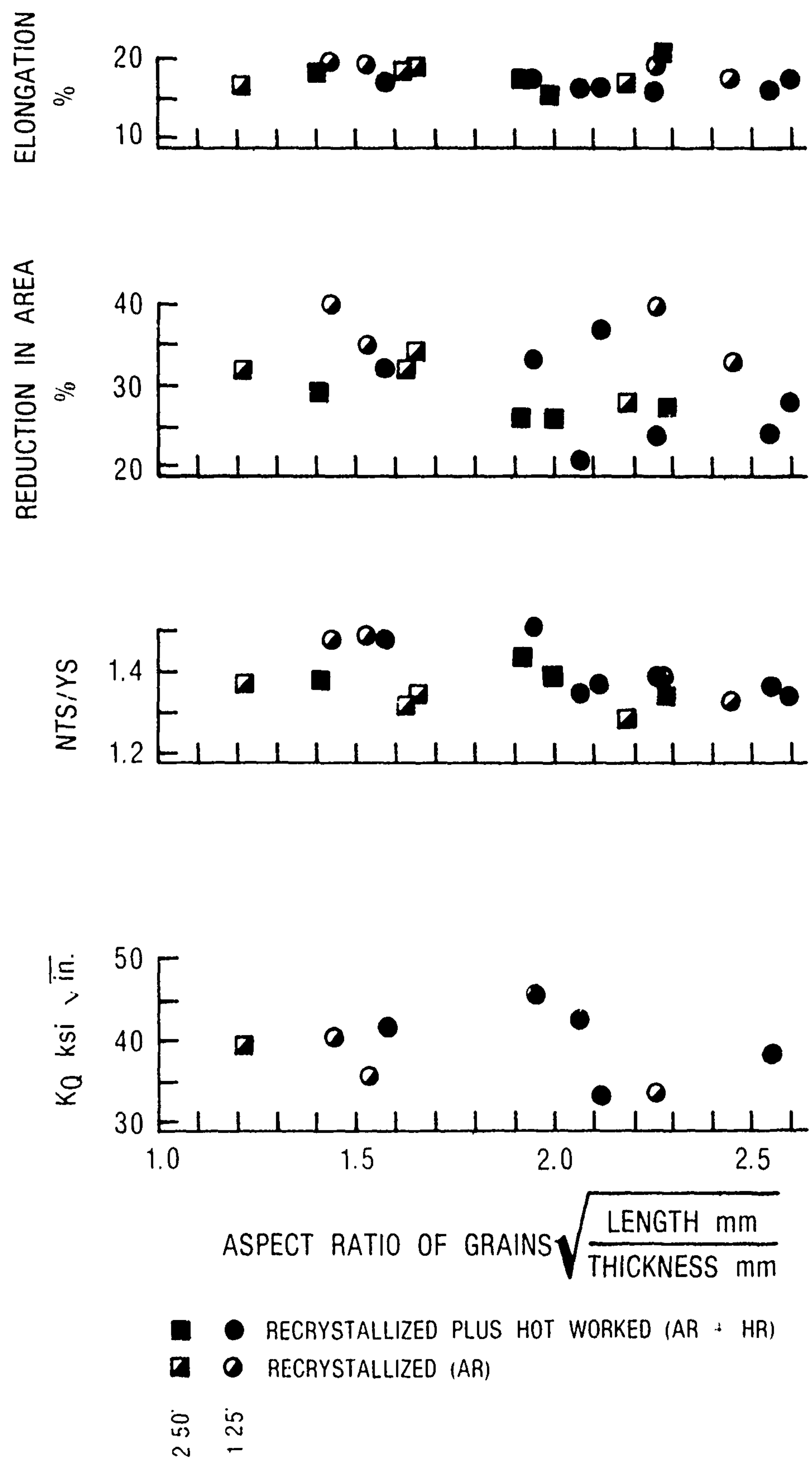


■ RECRYSTALLIZED PLUS HOT WORKED (AR + HR)

◪ RECRYSTALLIZED (AR)

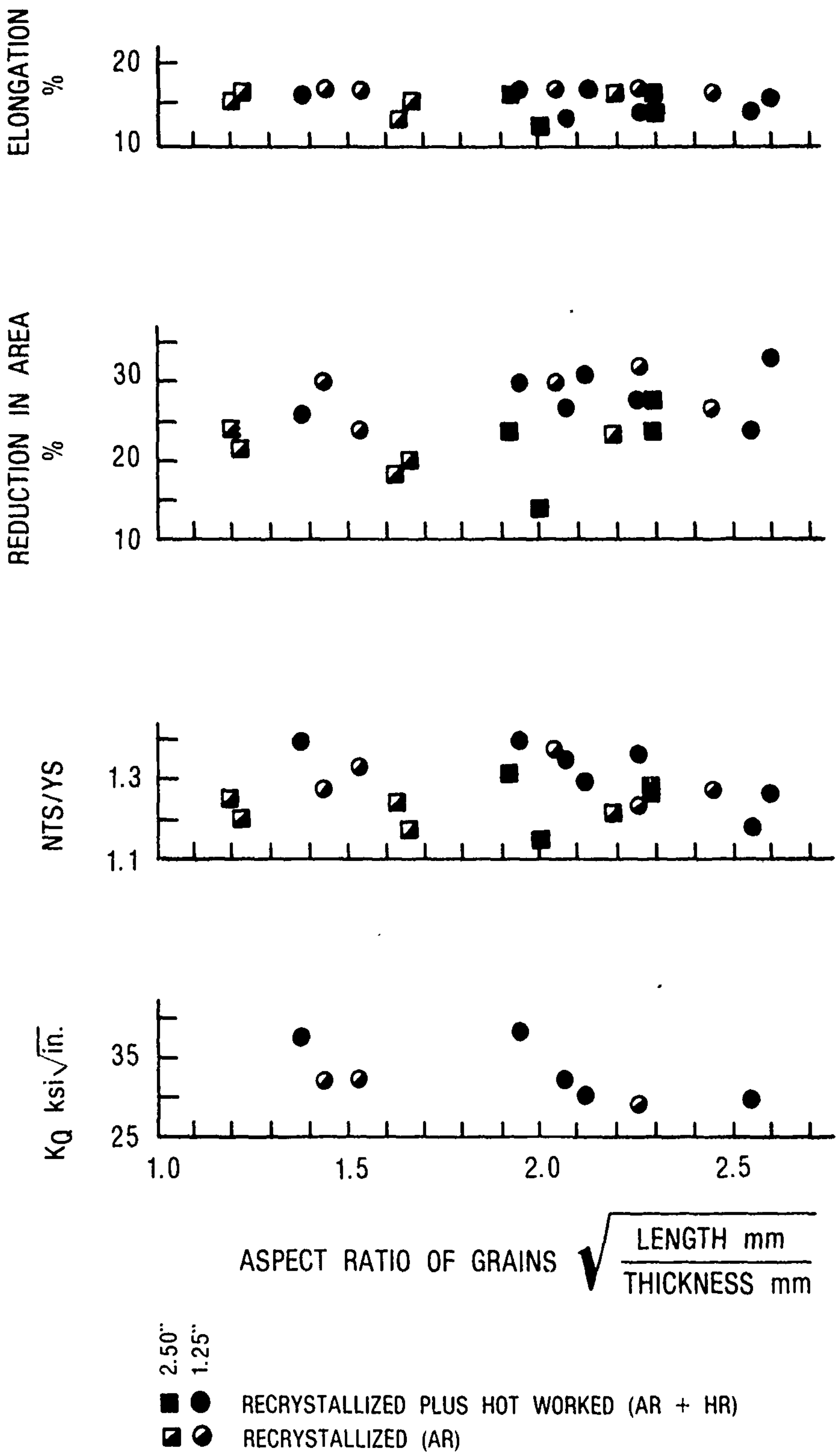
SHORT-TRANSVERSE PROPERTIES OF 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF THE GRAIN DIMENSION IN THE LONGITUDINAL DIRECTION

Figure 27



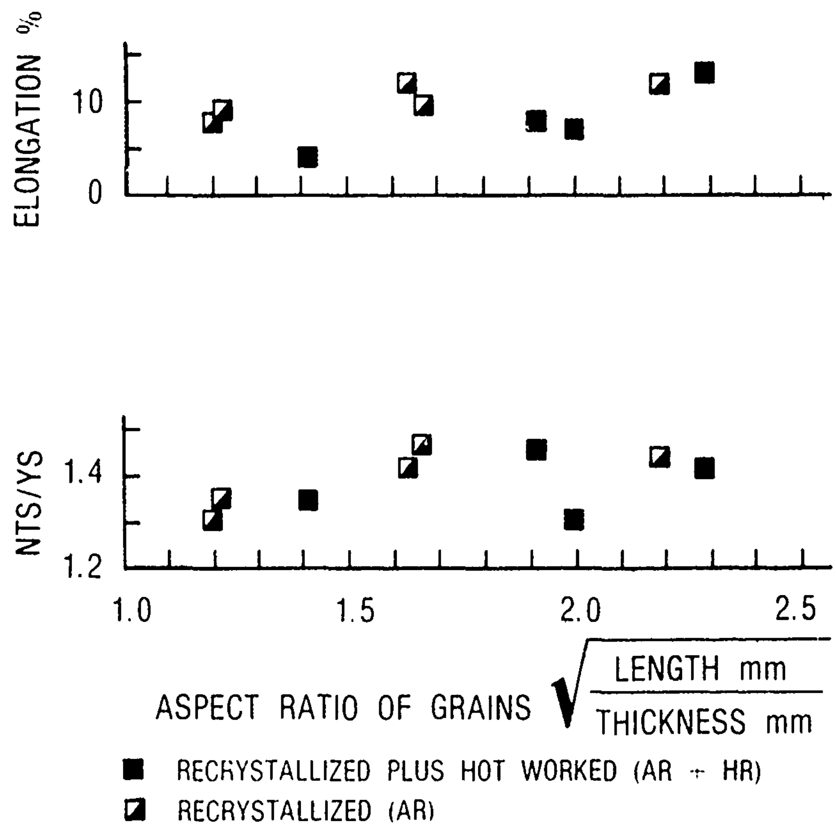
LONGITUDINAL PROPERTIES OF 1.25" AND 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF THE ASPECT RATIO OF THE GRAINS

Figure 28



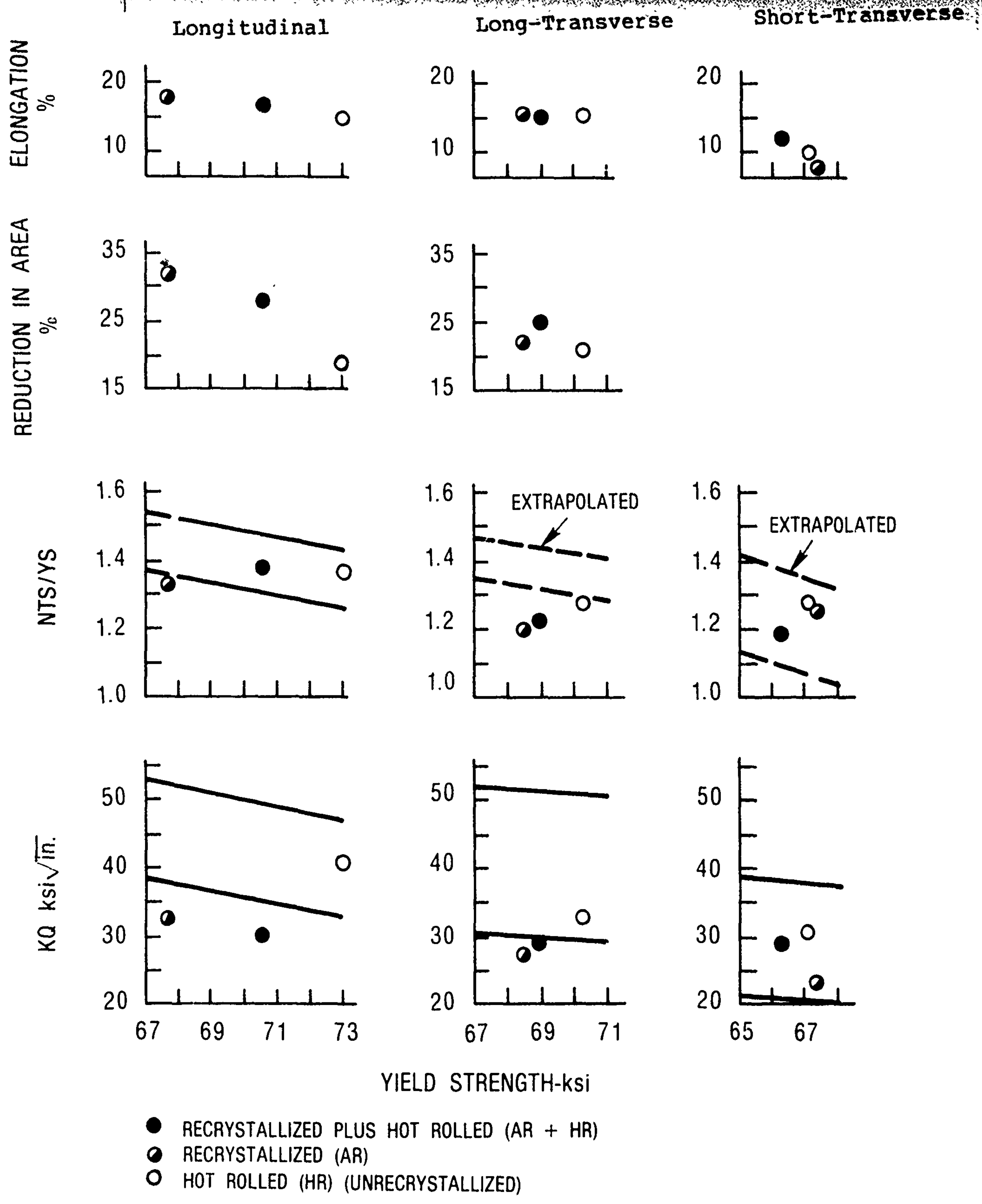
LONG-TRANSVERSE PROPERTIES OF 1.25" AND 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF THE ASPECT RATIO OF THE GRAINS

Figure 29



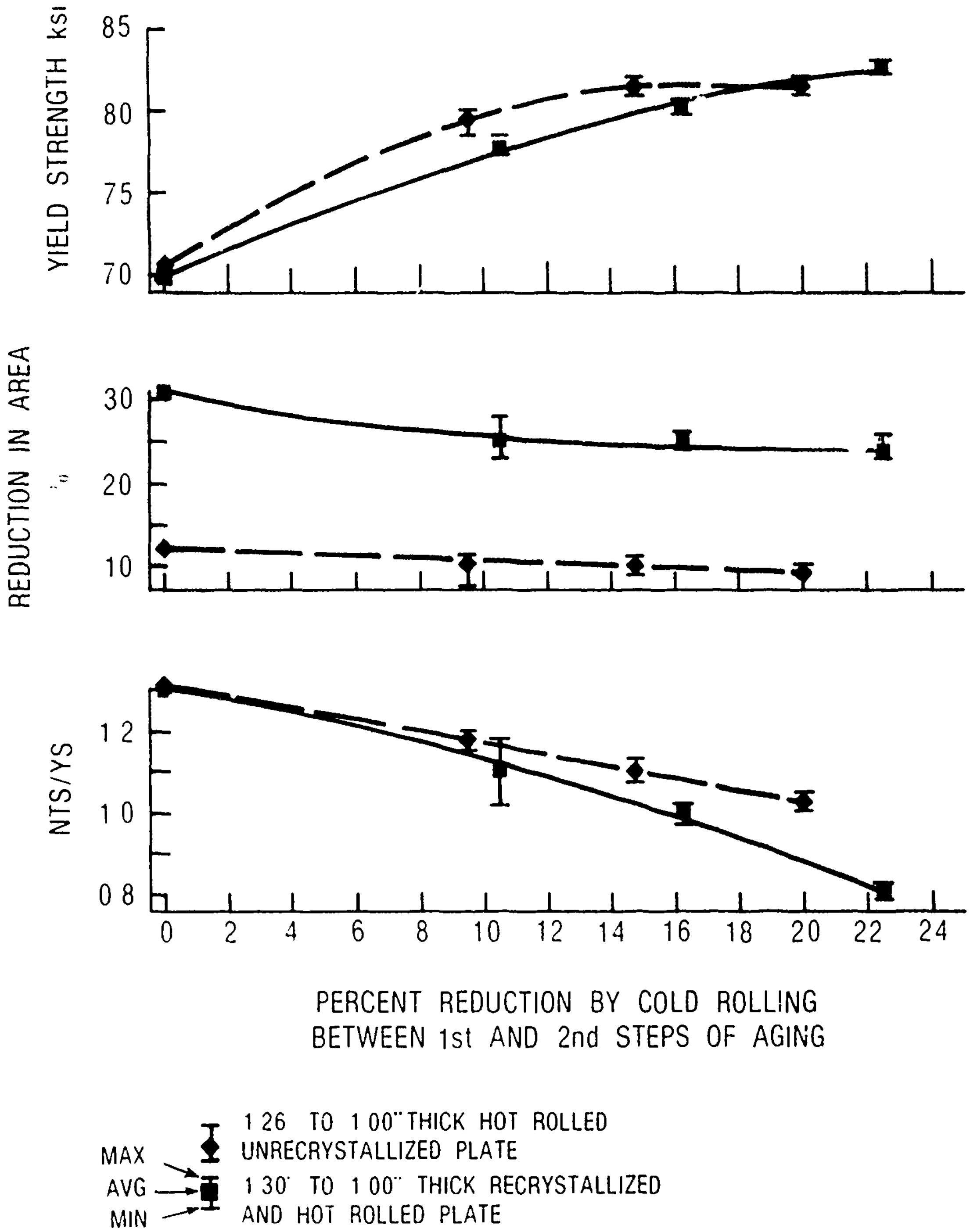
SHORT-TRANSVERSE PROPERTIES OF 2.50" THICK 7475-T6 PLATE AS A FUNCTION OF THE ASPECT RATIO OF THE GRAINS

Figure 30



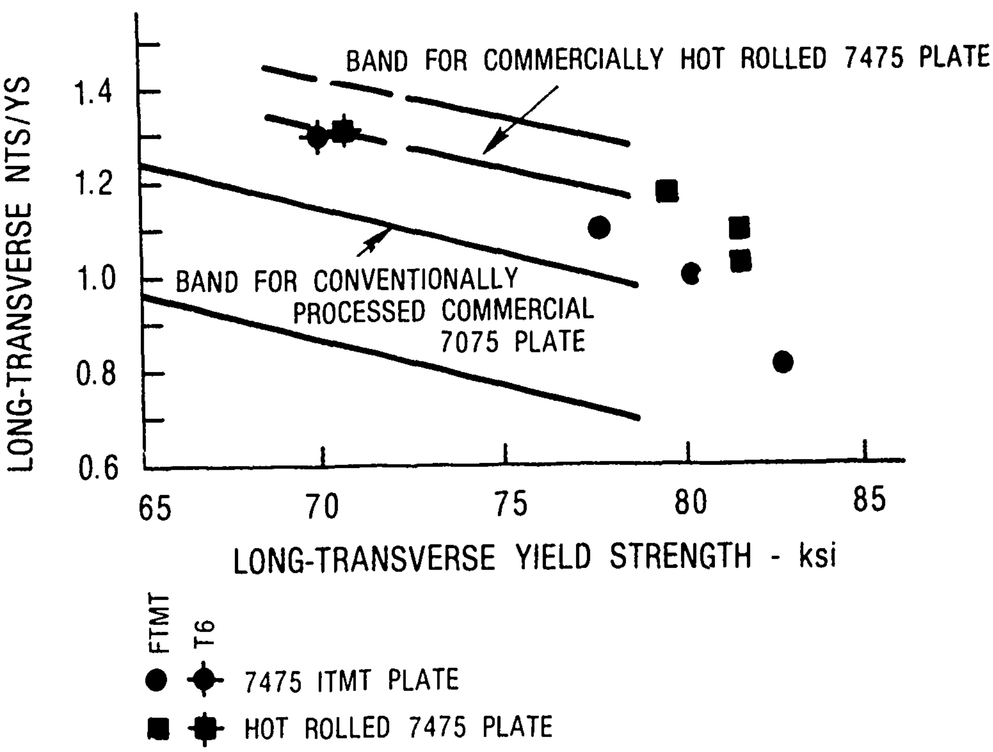
PROPERTIES OF 1.50" THICK 7475-T6 PLATE
AS A FUNCTION OF YIELD STRENGTH

Figure 31



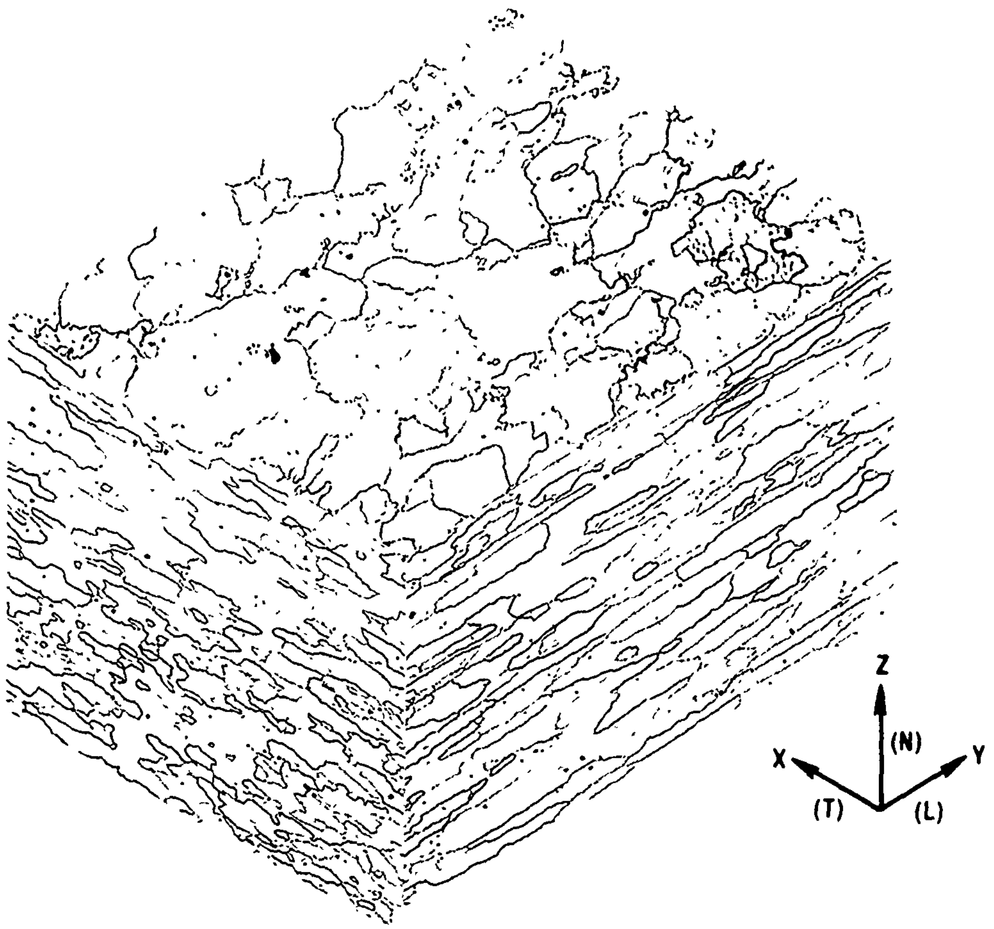
EFFECT OF AMOUNT OF COLD ROLLING ON THE LONG-TRANSVERSE PROPERTIES OF 1.00" TO 1 30" THICK 7475-TX PLATE FABRICATED USING FTMT PRACTICES

Figure 32



NTS/YS RATIO - YIELD STRENGTH RELATIONSHIP FOR 1.00" TO 1.30" THICK 7475 PLATE PROCESSED USING FTMT PRACTICES

Figure 33



MAG: 100X

ETCH: KELLERS

1.00" THICK 7475-T7X PLATE S-422622-1

INGOT			SLAB				RECRYSTALLIZATION		PLATE[2]					
									ROLLING		GRAIN COUNT			
THERMAL[1]	ROLLING			THERMAL[1]	ROLLING			THERMAL[1]	AT 750°F	SOLUTION[1]	g/mm			g/mm³
TREATMENT	TEMP	RGD	THICK	TREATMENT	TEMP	RGD	THICK	TREATMENT	RGD	HEAT-TREAT	X	Y	Z	XYZ
6hr/860°F 20hr/960°F	750°F	30%	7.0"	2hr/960°F 2hr/775°F 4hr/500°F	500 F	82%	1.25"	10hr/960°F	20%	2hr/960°F	22	12	50	13 200

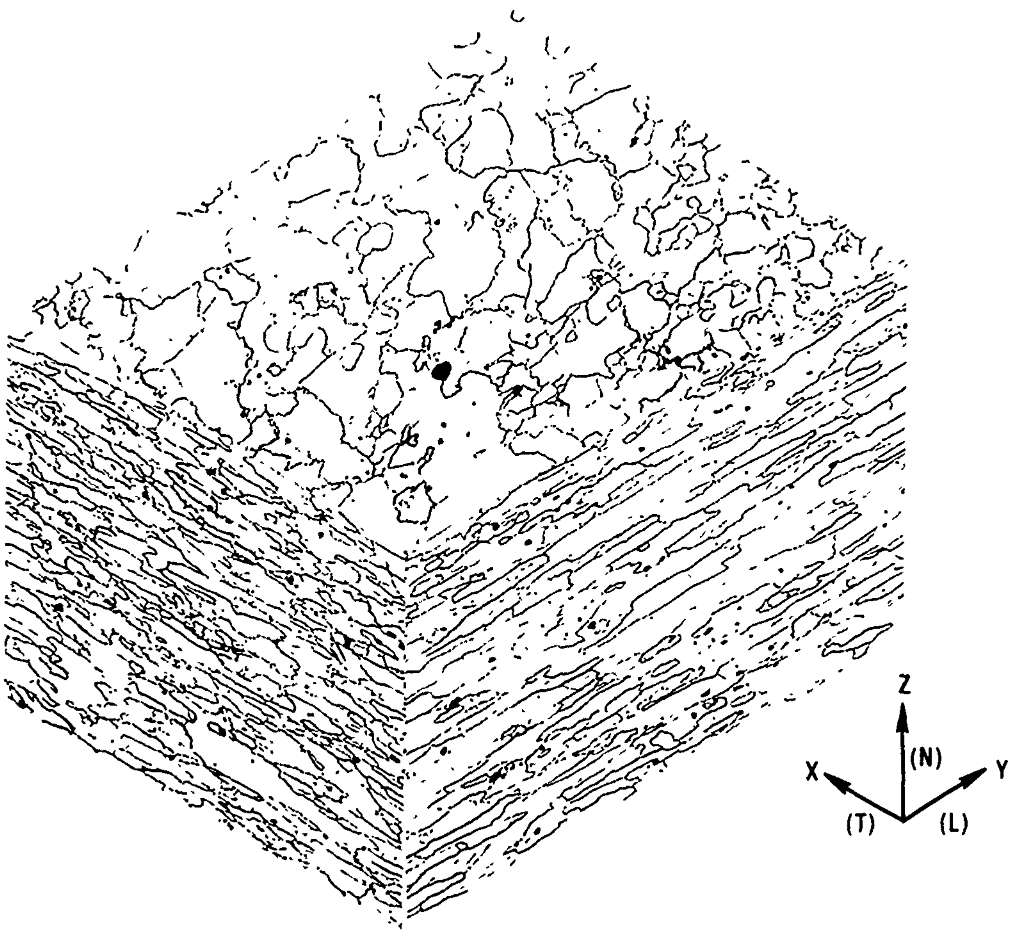
(1) THERMAL TREATMENTS CARRIED OUT IN A CIRCULATING AIR FURNACE

(2) PLATES ARTIFICIALLY AGED 24hr/25 + 4hr/350°F

PROPERTIES			
DIR	T.S. ksi	Y.S. ksi	EL %
T	75.4	63.7	15.0

MICROSTRUCTURE AND PROPERTIES OF 1.00" THICK RECRYSTALLIZED PLUS HOT ROLLED (AR + HR) 7475-T7X PLATE FABRICATED FOR BALLISTIC EVALUATION S-422622-1

Figure 34



MAG: 100X

ETCH: KELLERS

1.00" THICK 7475-T6X PLATE S-422622-2

INGOT				SLAB				RECRYSTALLIZATION		PLATE[2]				
									ROLLING		GRAIN COUNT			
THERMAL[1]	ROLLING			THERMAL[1]	ROLLING			THERMAL[1]	AT 750°F	SOLUTION[1]	g/mm			g/mm^3
TREATMENT	TEMP	RGD	THICK	TREATMENT	TEMP	RGD	THICK	TREATMENT	RGD	HEAT-TREAT	X	Y	Z	XYZ
6hr/860°F 20hr/960°F	750°F	30%	7.0"	2hr/960°F 2hr/775°F 4hr/500°F	500°F	79%	1.45"	10hr/960°F	22%	2hr/960°F	24	16	68	26112

(1) THERMAL TREATMENTS CARRIED OUT IN A CIRCULATING AIR FURNACE

(2) PLATE SOLUTION HEAT-TREATED AND QUENCHED AT 1.13". ARTIFICIALLY AGED 6hr/220°F. COLD ROLLED 12% AND AGED 8hr/250°F

DIR	T.S. ksi	Y.S. ksi	El %
T	86.8	76.8	12.0

MICROSTRUCTURE AND PROPERTIES OF 1.00" THICK RECRYSTALLIZED PLUS HOT ROLLED (AR+HR) 7475-FTMT PLATE FABRICATED FOR BALLISTIC EVALUATION S-422622-2

Figure 35

APPENDIX A

Recrystallization Procedure

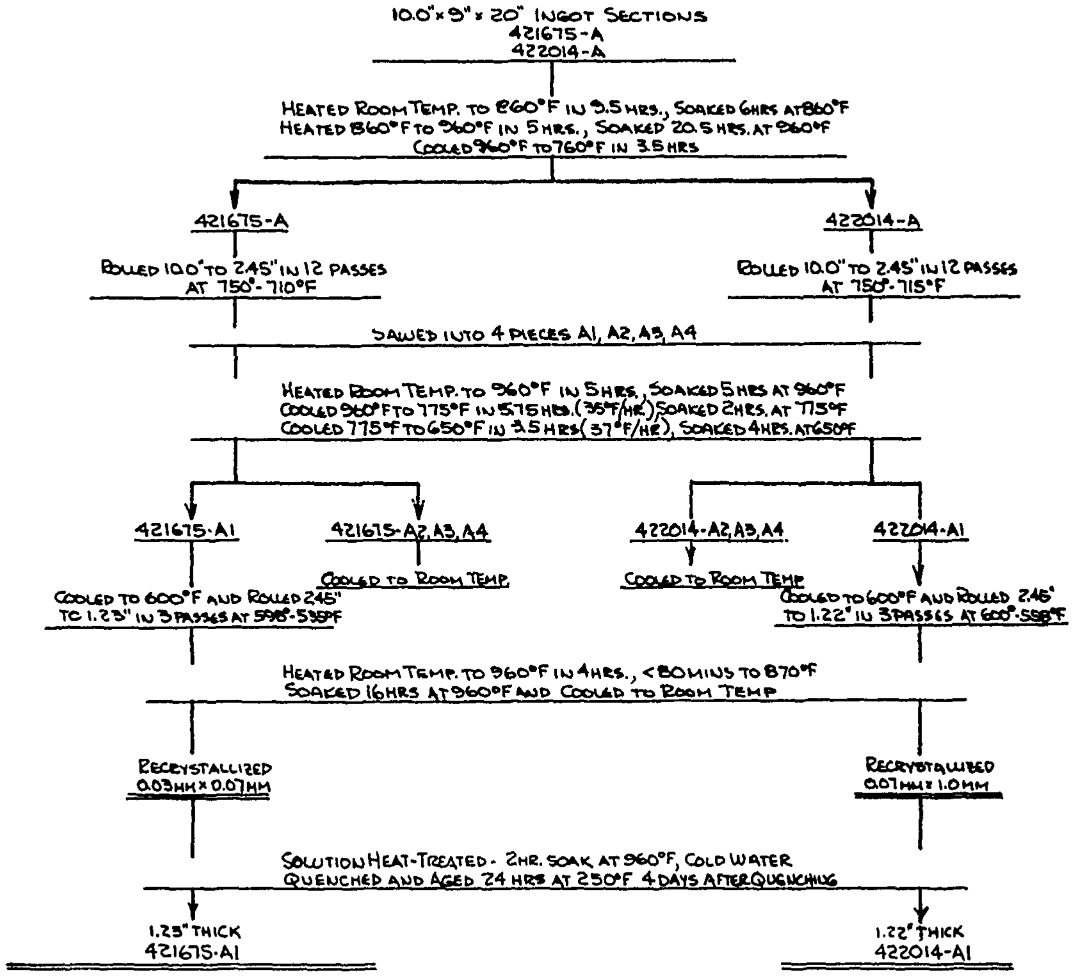
The use of a 10-hour at 960°F recrystallization treatment for the ITMT processed 7475 and Al-Zn-Mg alloy plate fabricated at Alcoa Laboratories raised questions as to the effect of time at the recrystallization temperature, the temperature at which recrystallization is achieved and the time required to reach the recrystallization temperature on the grain size of the recrystallized plate. Answers to these questions were not available and a limited investigation was carried out at Alcoa Laboratories to obtain the desired answers. In this work, 1" x 1" x full thickness samples were sawed from plate samples after the warm rolling operation and subjected to various thermal treatment.

Samples of warm rolled plate fabricated using rolling sections 421675A, C, D, E, and F and 422014A, C, D, E, and F were heated 4 hours at 860°F and 10 hours at 960°F using a circulating air furnace. Microscopic examination of the samples showed that for each alloy and fabrication practice the recrystallization procedure of 10 hours at 960°F produced grain lengths and thicknesses that were the same or less than the grain dimensions produced by the heating procedure of 4 hours at 860°F. Further work using samples of warm rolled plate fabricated using rolling sections 421675G, H, J, L, and I and 422014G, H, J, L, and I in which the samples were heated to 960°F in 1 minute (salt bath), 30 minutes (circulating air furnace) and 3 hours (programmed heatup in a circulating air furnace) showed that increasing the time required to reach the recrystallization temperature of 960°F did not increase the grain length or grain thickness of the recrystallized grains in the plate samples.

Samples of 1.25" thick 7475 plate, S-421675E6, warm rolled at 500°F were recrystallized by soaking 1, 4.5, 10, and 20 hours at 860°F or 960°F. Microscopic examination of the samples showed no significant difference in the grain length or thickness that could be attributed to either the soak time at the recrystallization temperature and/or the recrystallization temperatures of 860 or 960° F.

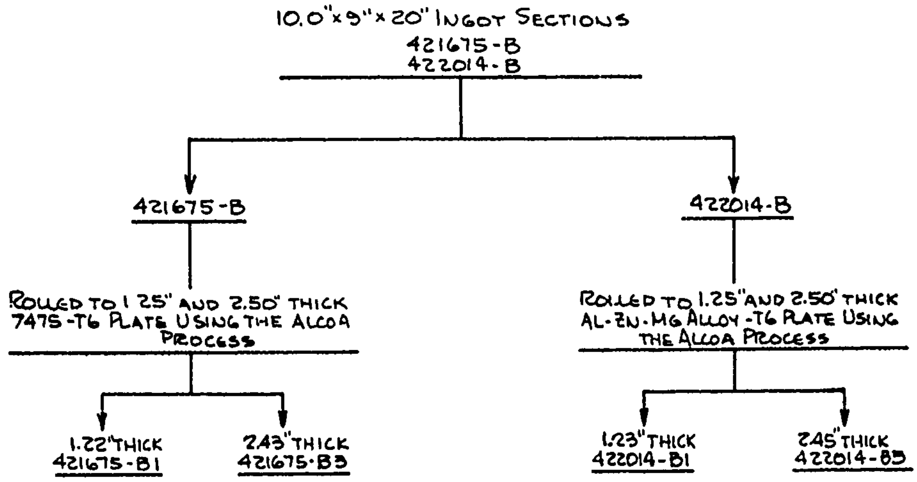
Thus, it was shown that the use of a 10-hour at 960°F recrystallization treatment and the use of circulating air furnaces to carry out the recrystallization treatments in the ITMT work carried out at the Alcoa Laboratories would not be expected to have a detrimental effect on the size of the grains obtained in the recrystallized 7475 and Al-Zn-Mg alloy plate.

APPENDIX B



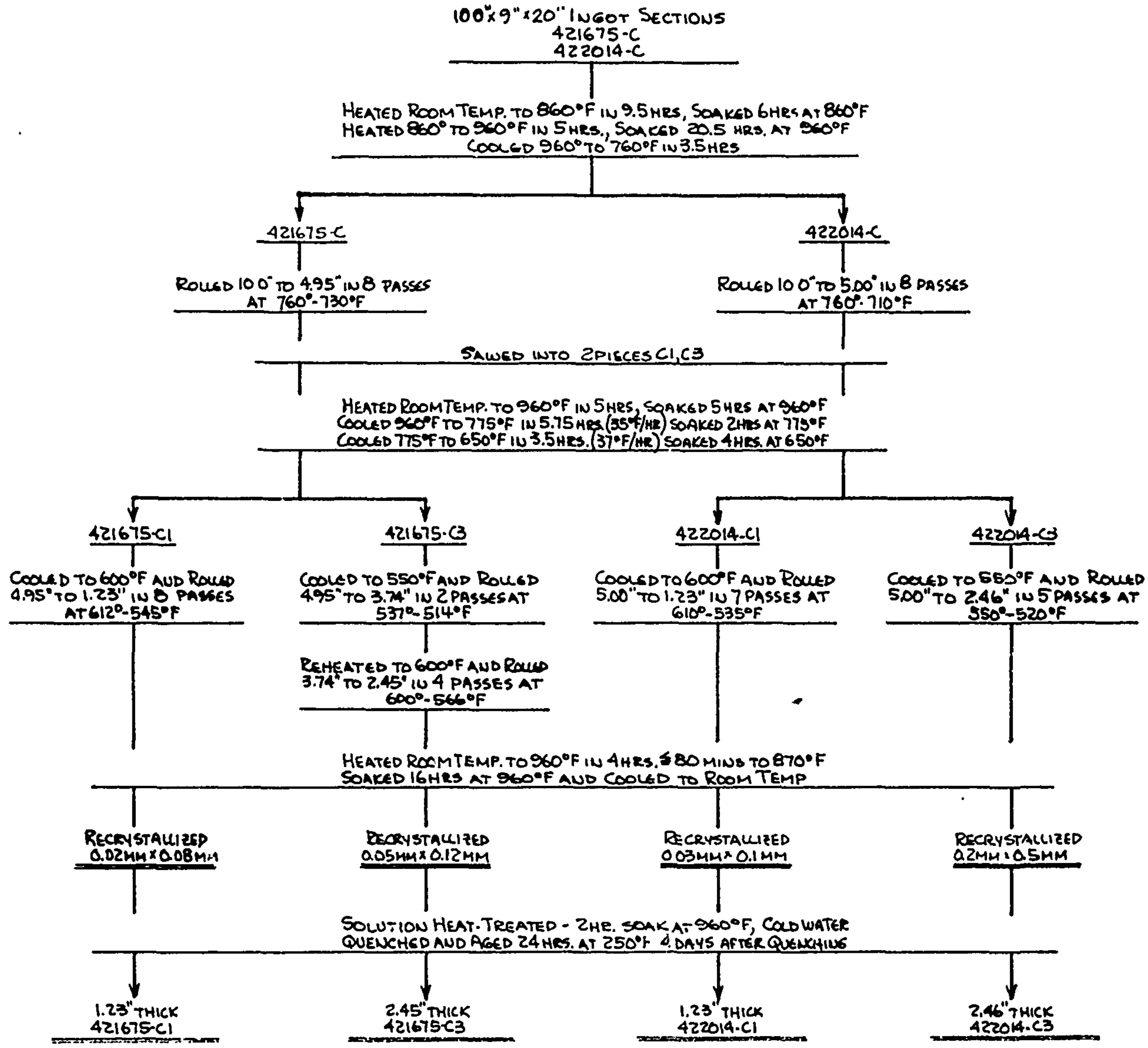
FABRICATION DETAILS FOR INGOT SECTIONS 421675A AND 422014A

Figure B1



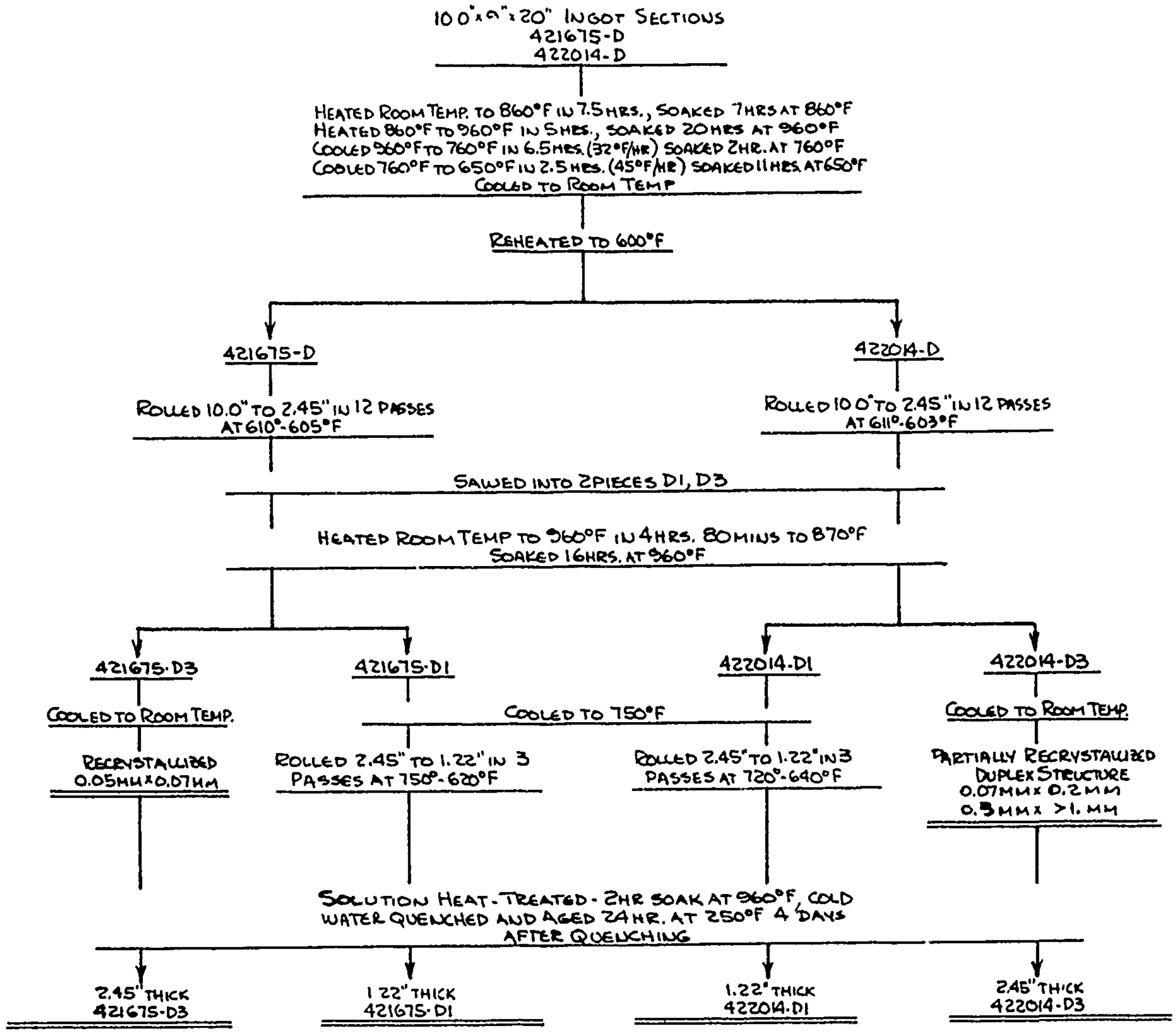
FABRICATION DETAILS FOR INGOT SECTIONS 421675-B AND 422014-B

Figure B2



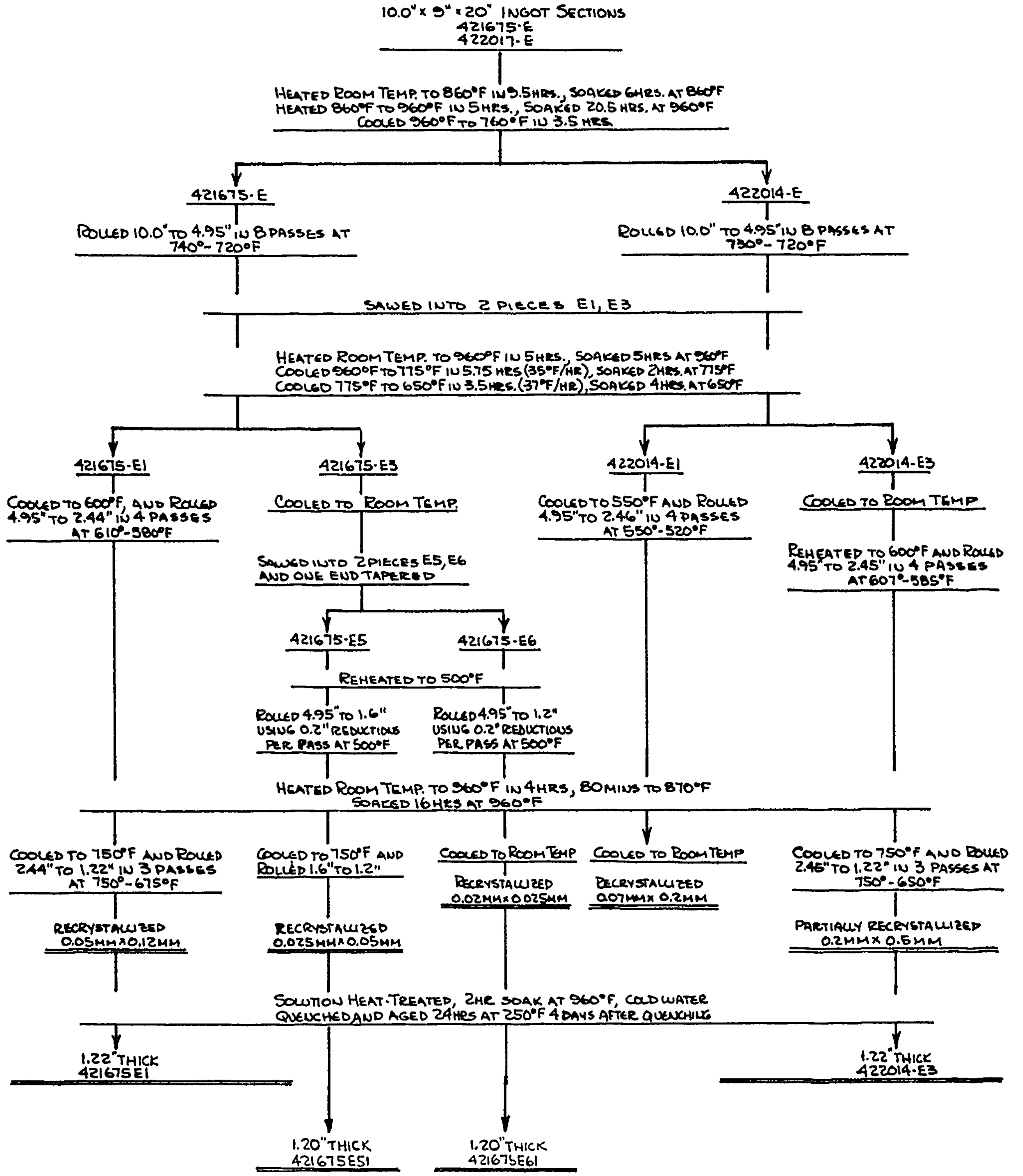
FABRICATION DETAILS FOR INGOT SECTIONS 421675-C AND 422014-C

Figure B3



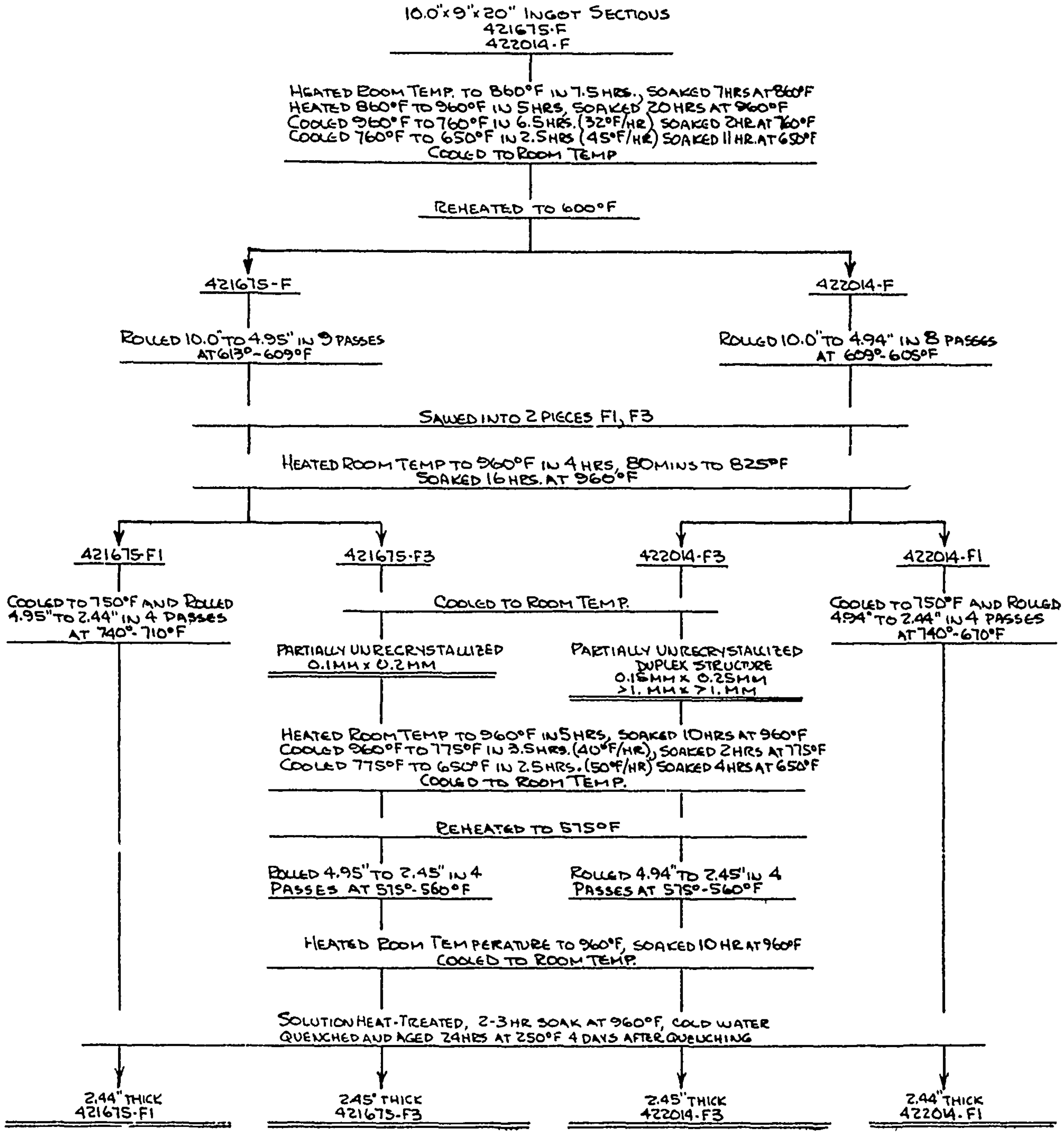
FABRICATION DETAILS FOR INGOT SECTIONS 421675-D AND 422014-D

Figure B4



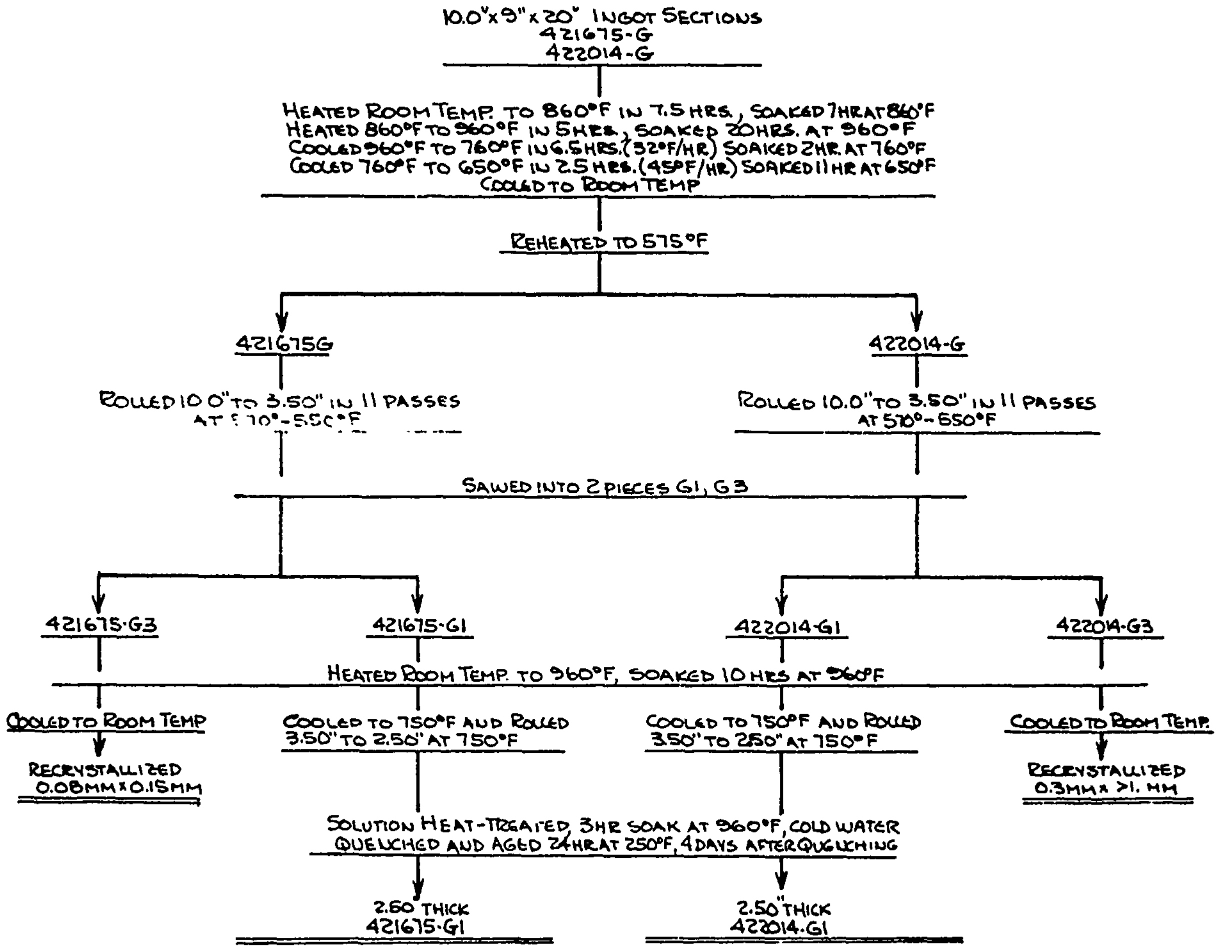
FABRICATION DETAILS FOR INGOT SECTIONS 421675-E AND 422014-E

Figure B5



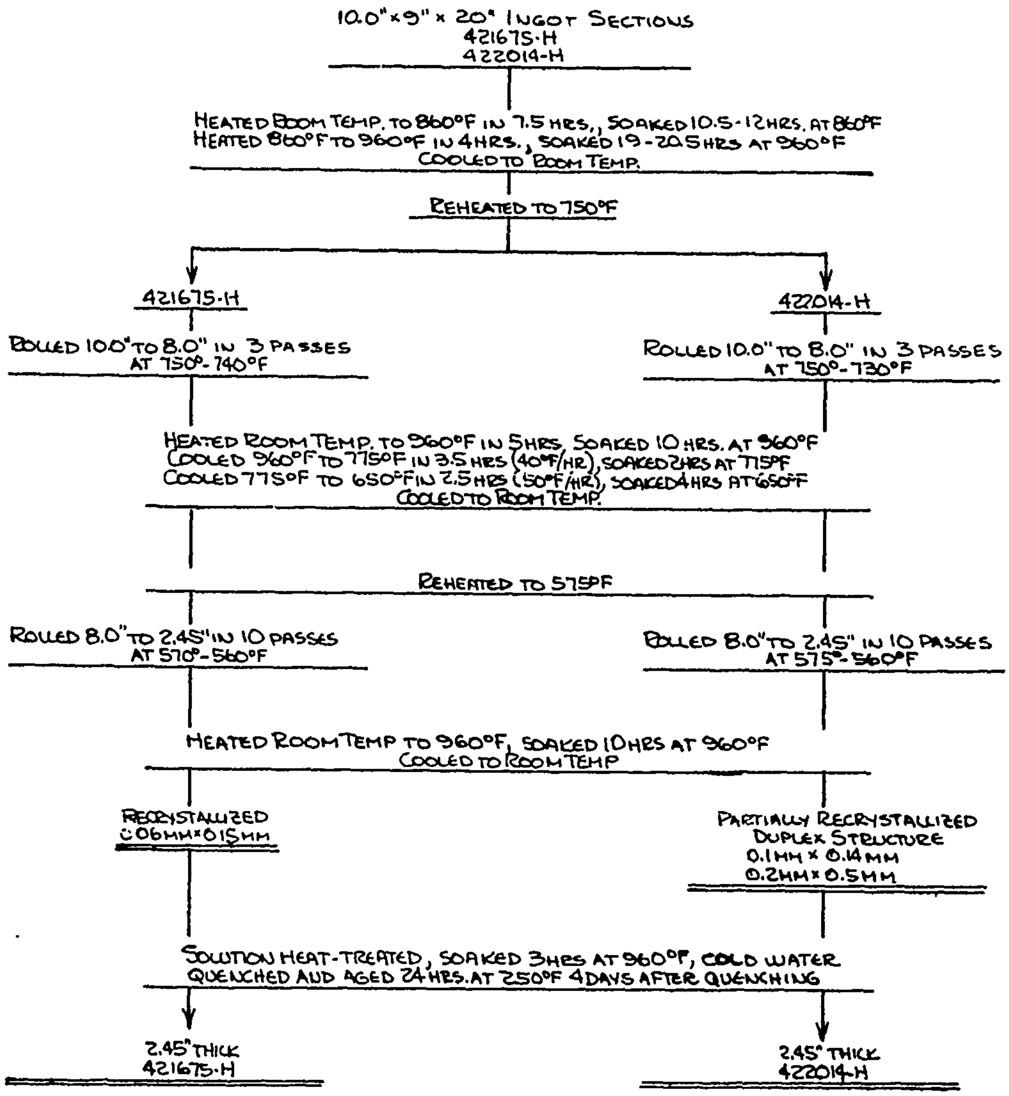
FABRICATION DETAILS FOR INGOT SECTIONS 421675-F AND 422014-F

Figure B6



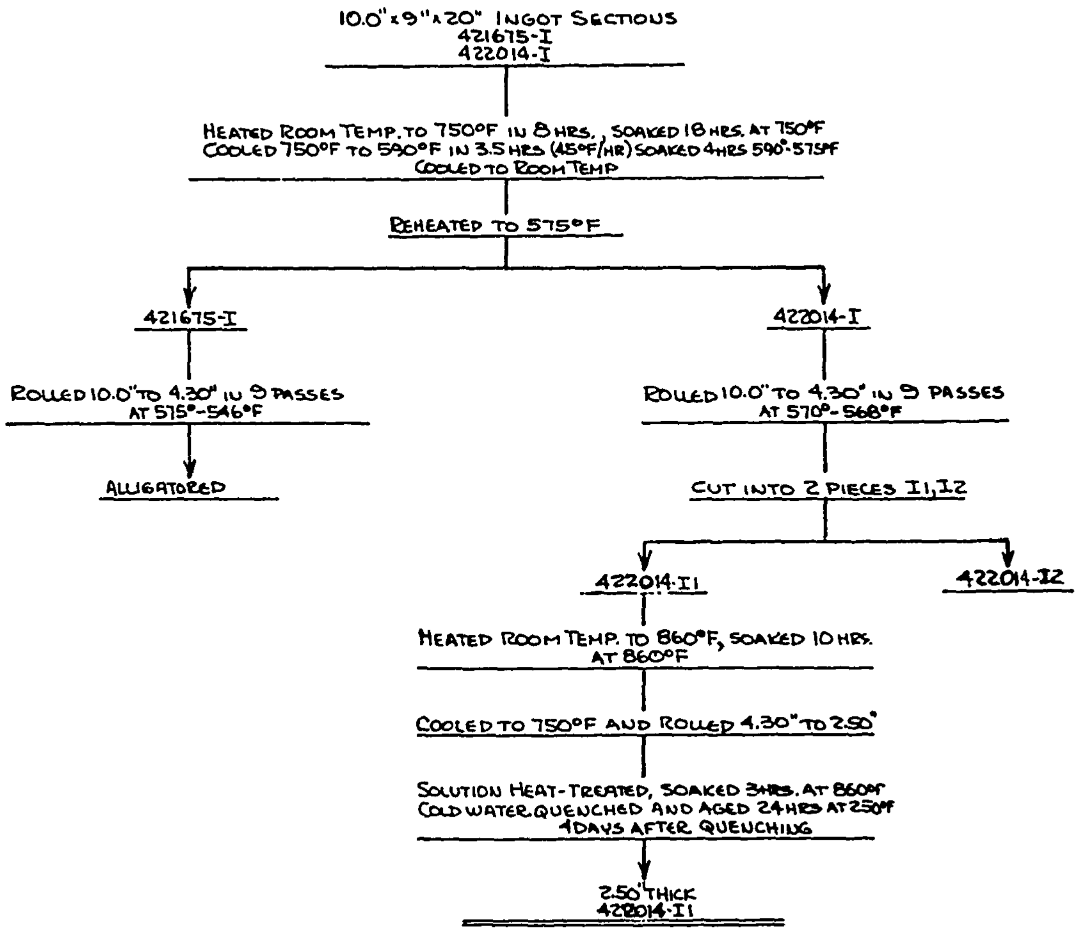
FABRICATION DETAILS FOR INGOT SECTIONS 421675 G AND 422014-G

Figure B7



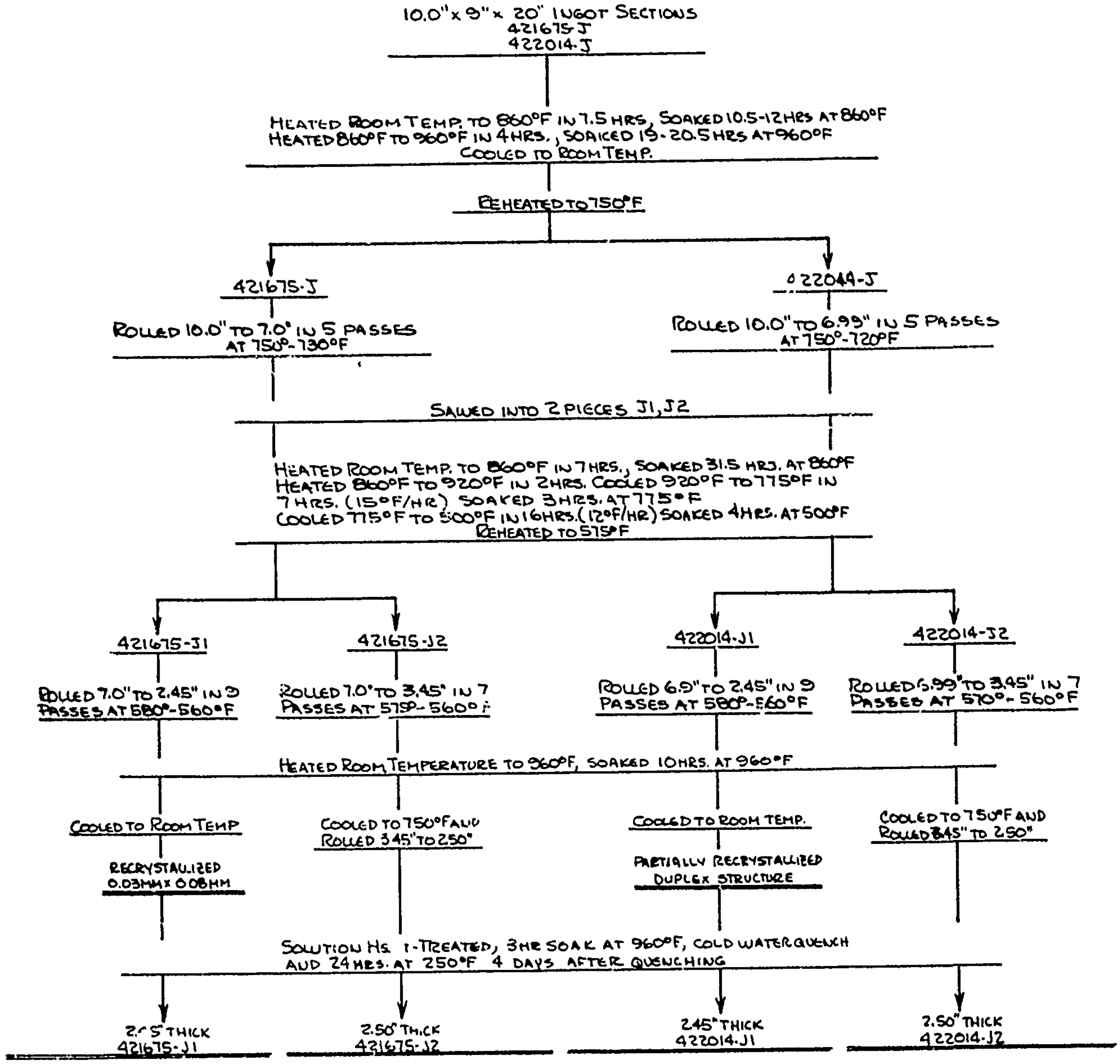
FABRICATION DETAILS FOR INGOT SECTIONS 421675H AND 422014-H

Figure B8



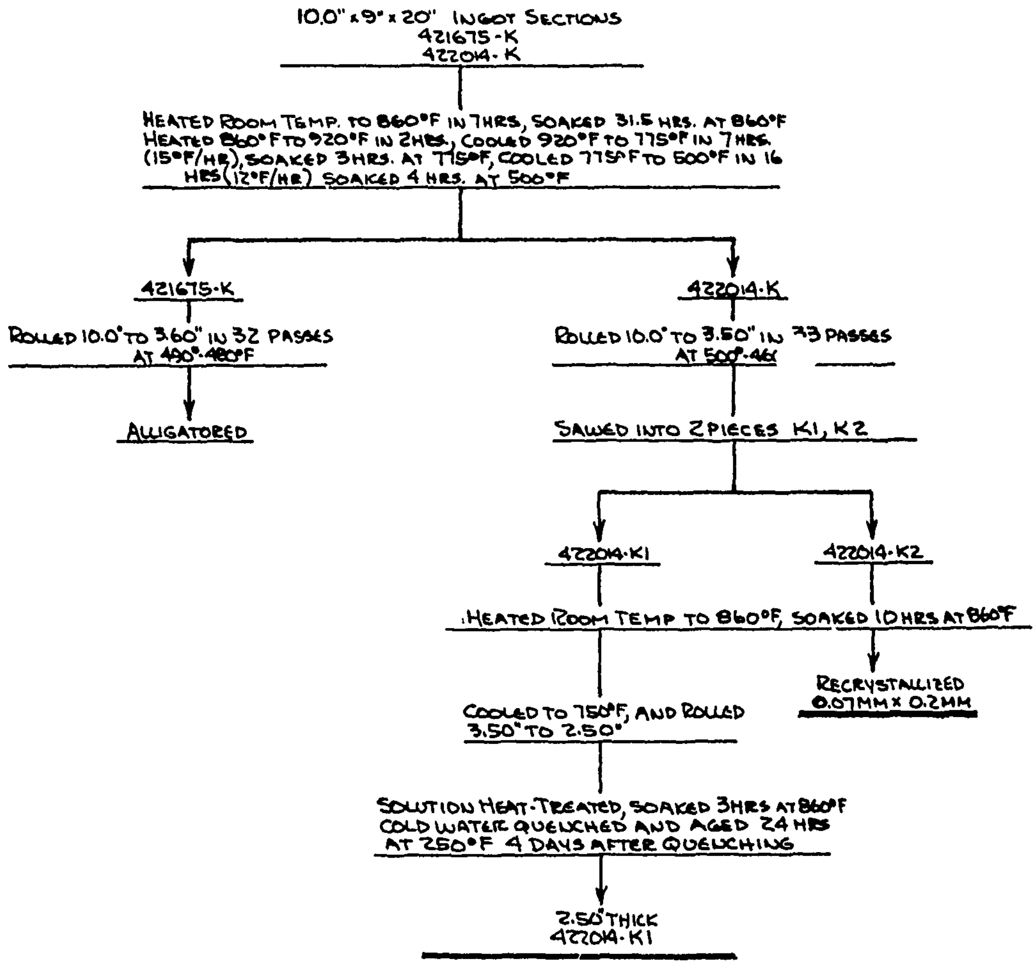
FABRICATION DETAILS FOR INGOT SECTIONS 421675-I AND 422014-I

Figure B9



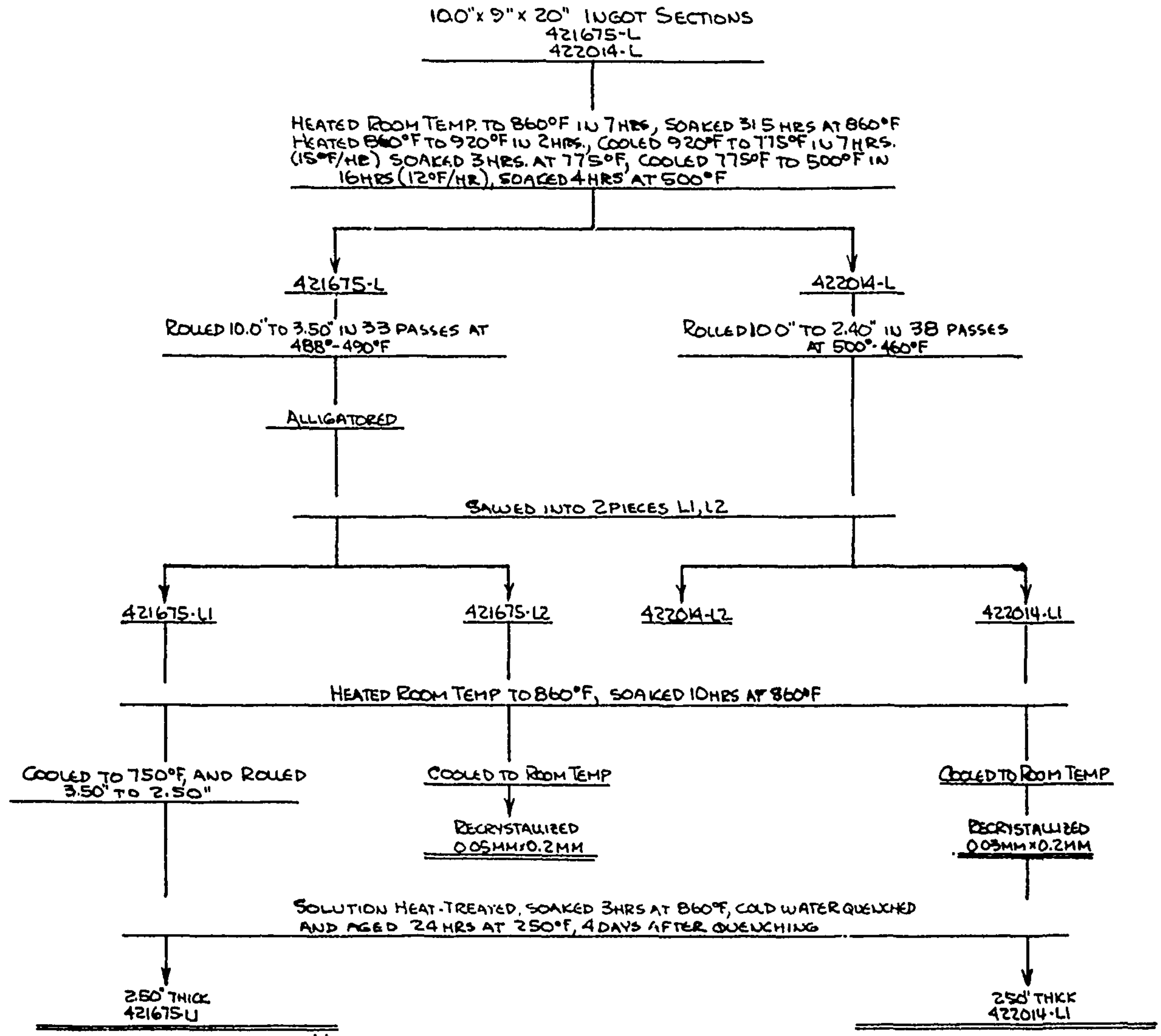
FABRICATION DETAILS FOR INGOT SECTIONS 421675-J AND 422014-J

Figure B10



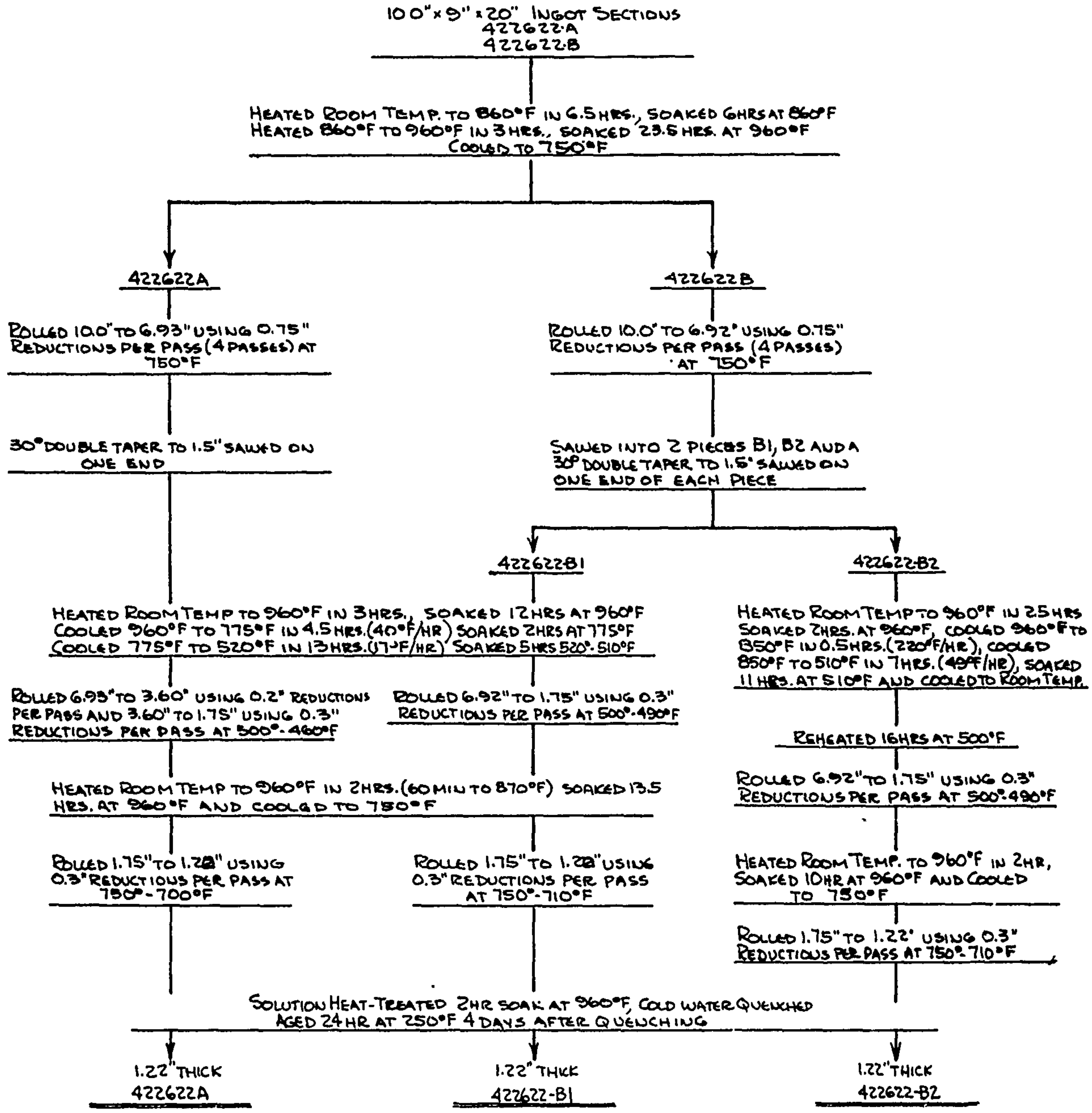
FABRICATION DETAILS FOR INGOT SECTIONS 421675-K AND 422014-K

Figure B11



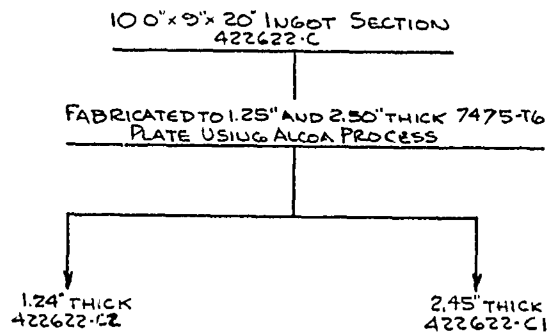
FABRICATION DETAILS FOR INGOT SECTIONS 421675-L AND 422014-L

Figure B12



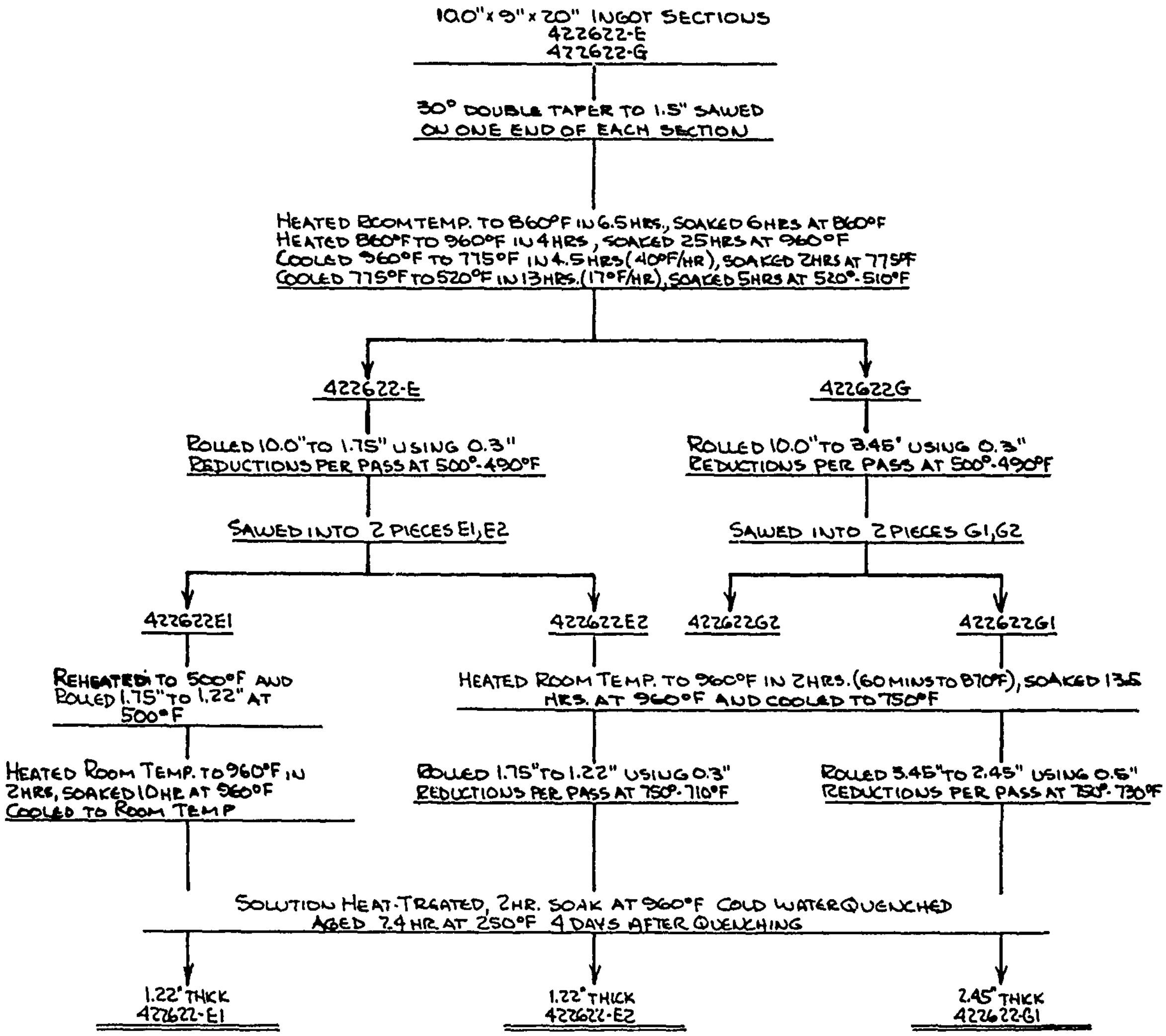
FABRICATION DETAILS FOR INGOT SECTIONS 422622-A AND-B

Figure B13



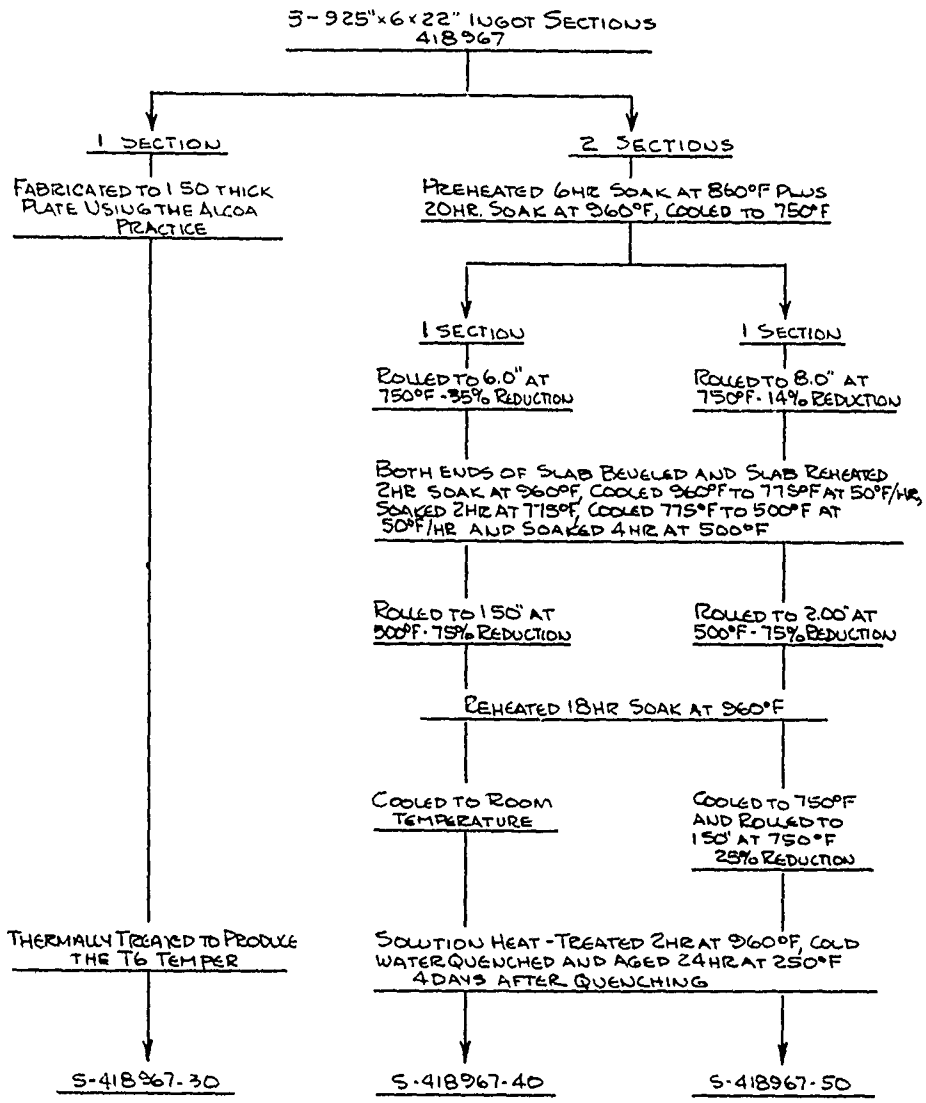
FABRICATION DETAILS FOR INGOT SECTION 422622-C

Figure B14



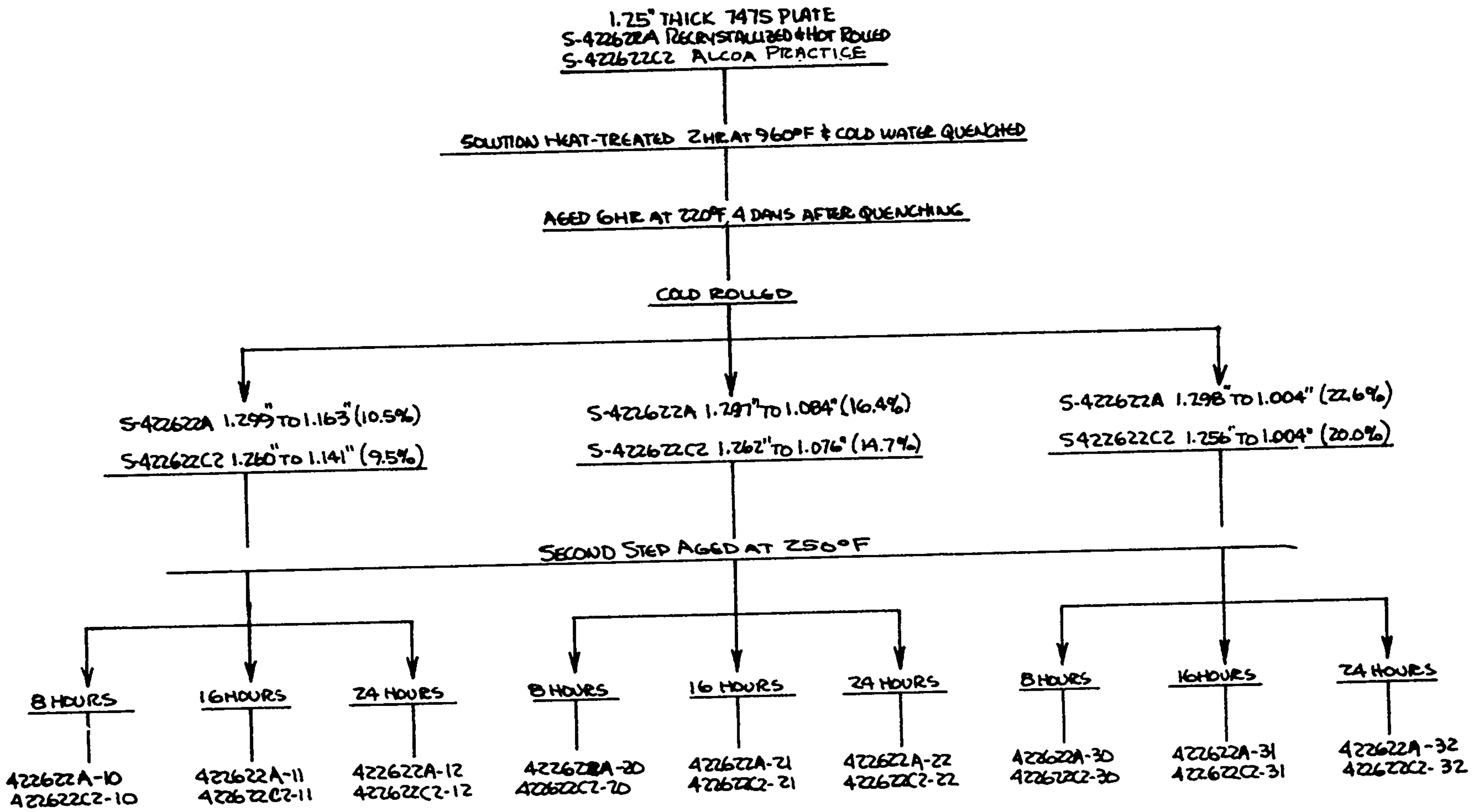
FABRICATION DETAILS FOR INGOT SECTIONS 422622-E AND -G

Figure B15



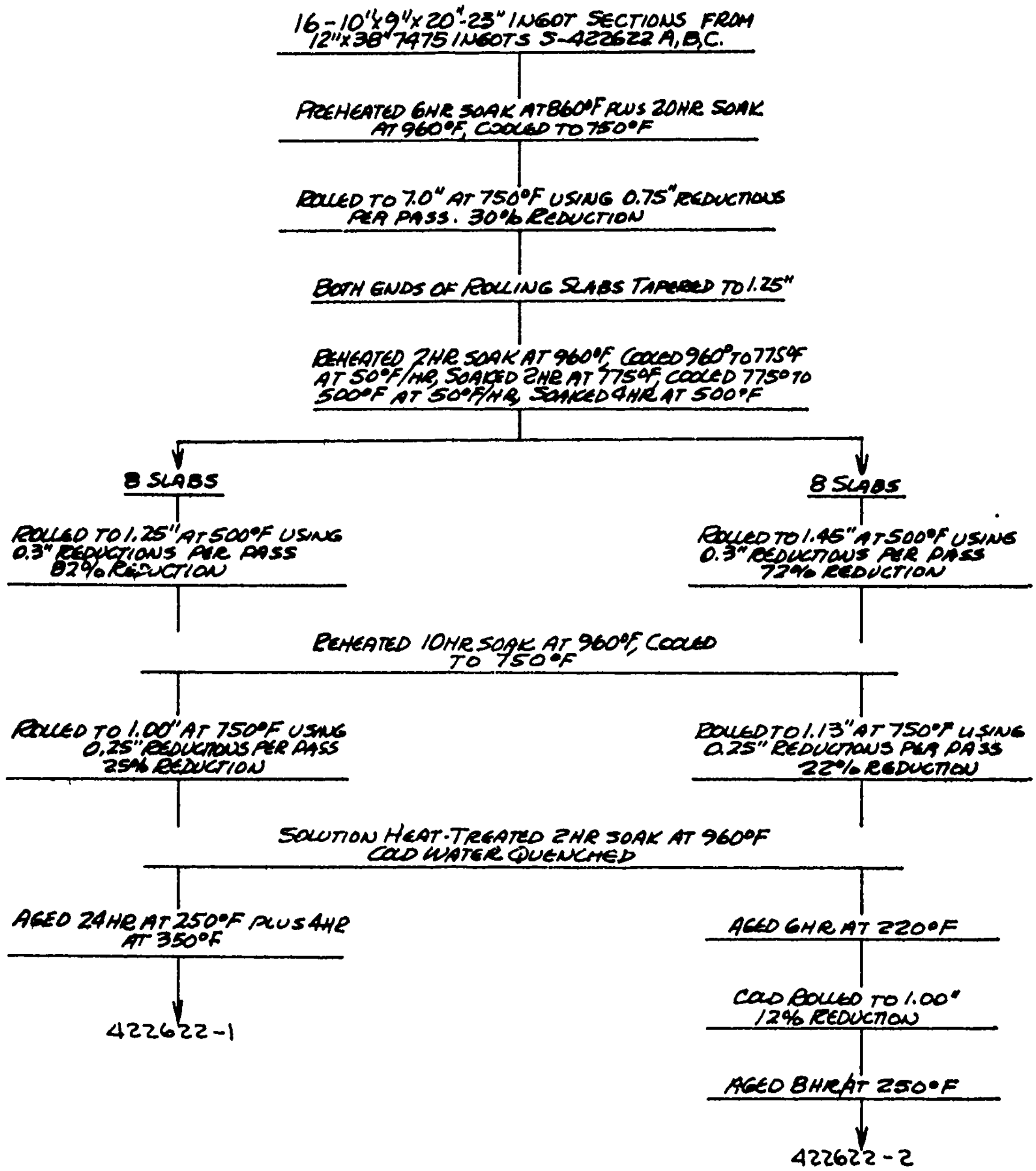
PROCEDURES USED TO FABRICATE 1.50" THICK 7475-T6 PLATE

Figure B16



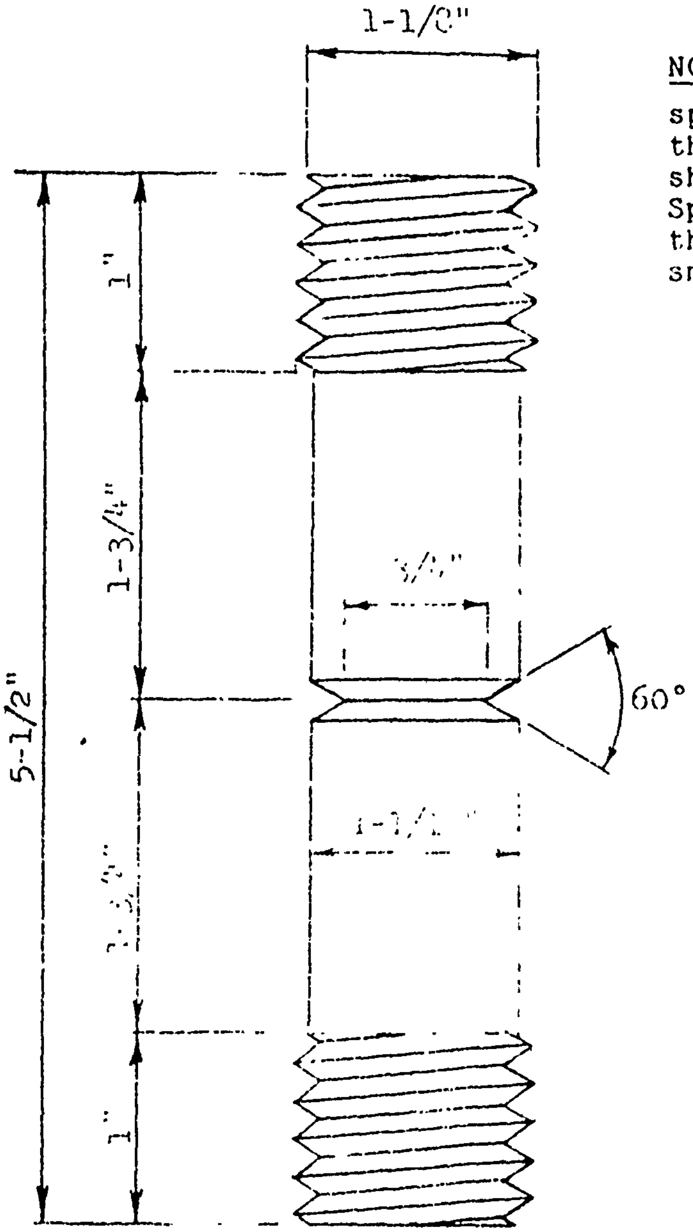
Procedures Used to Evaluate FTMT Practices on 1.25" Thick 7475 Plate

Figure B17



PROCEDURES USED TO FABRICATE 1.00" THICK PLATE FOR BALLISTIC EVALUATION

Figure B18



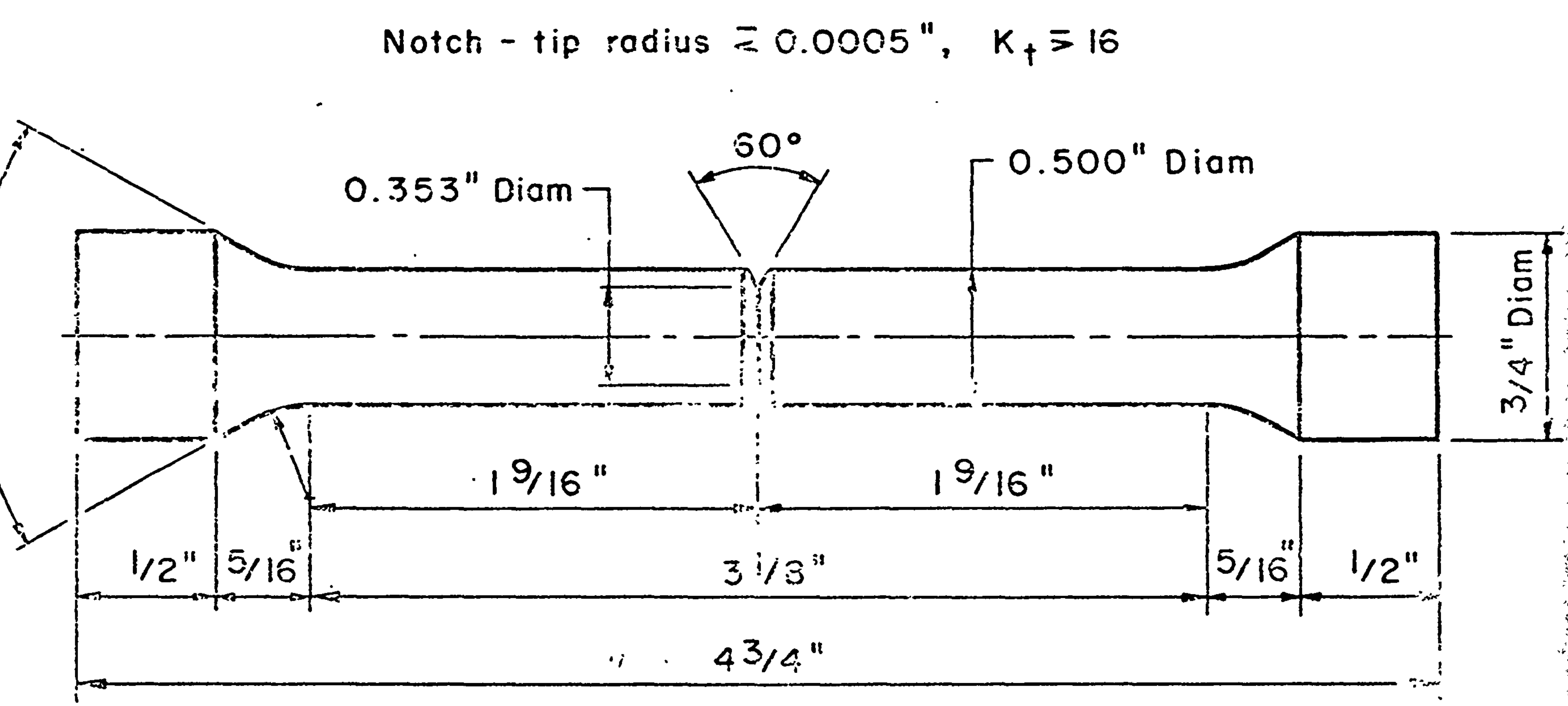
NOTE: Short-transverse specimens from plate thinner than 5-1/2 in. have shortened reduced sections. Specimens from plate thinner than 1-1/8 in. have small flats on threads.

Notch-Tip Radius ≈ 0.0005 in.

Sharply Notched Round Tensile Specimens (1-1/16-in. dia.).

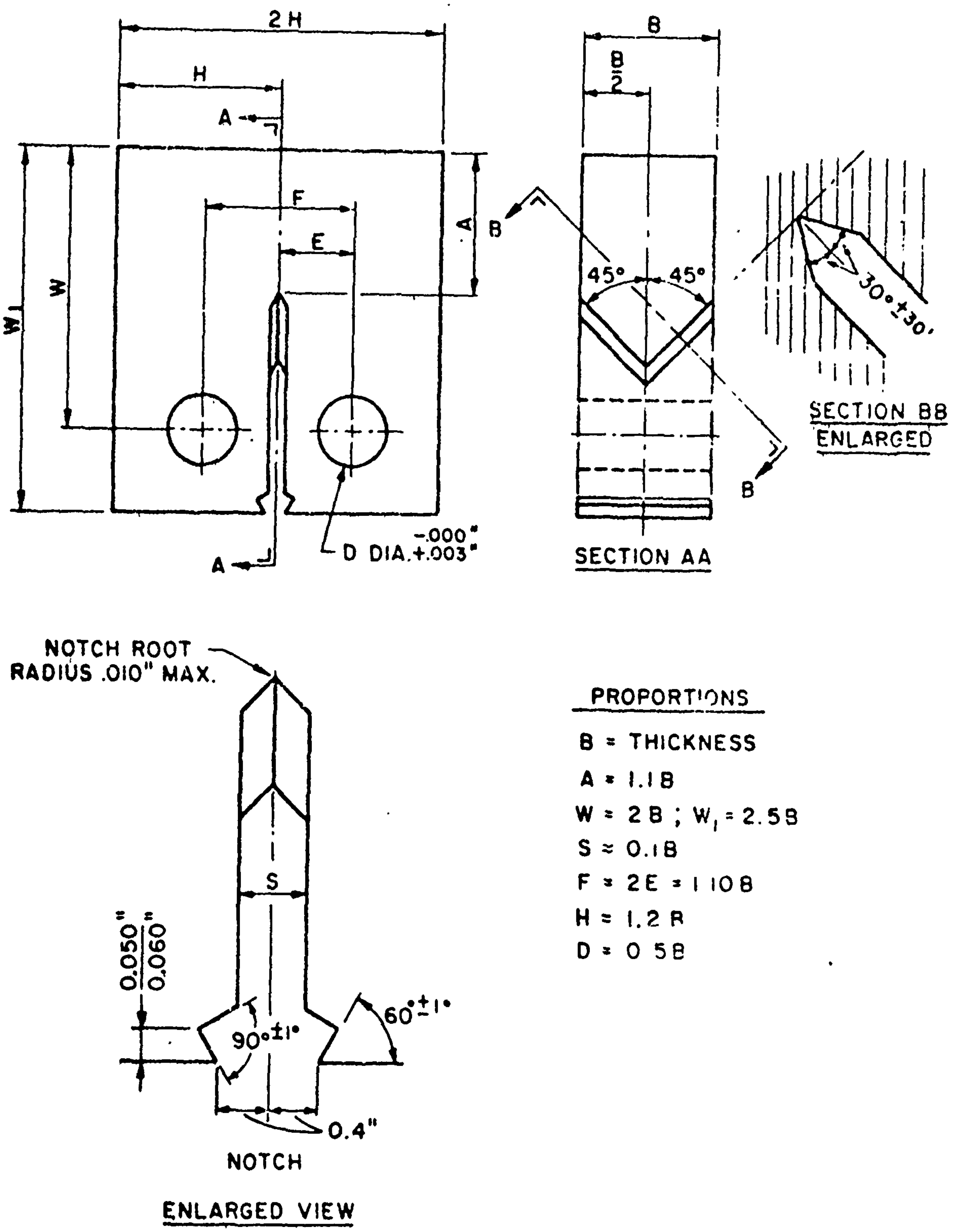
Figure C1

XFE30



Sharply Notched 1/2-in. Diameter Notch-Tensile Specimen (Tapered Seat).

Figure C2



COMPACT TENSION FRACTURE TOUGHNESS SPECIMEN

Figure C3

TABLE D1

RESULTS OF MULTIPLE LINEAR REGRESSION ANALYSES OF LONGITUDINAL DATA FOR 7475-T6 PLATE

Type Data	Coefficients in Multiple Linear Regression Equation								Intercept	Multiple Correlation
	Y.S., ksi	T, in.	Fe, wt.%	Structure[1]		Grain Dimensions, $\frac{1}{T,mm}$	$\frac{1}{L,mm}$	$\frac{L,mm}{T,mm}$		
				Longitudinal Elongation, %						
1	-0.41	-1.16	-0.08	+1.49	+2.01	N.U.	N.U.	N.U.	45.72	0.66
1	-0.63	-0.53	-2.81	-4.15	-2.93	+0.71	N.U.	N.U.	60.71	0.74
1	-0.44	-0.85	-4.08	-0.85	-0.05	N.U.	+0.66	N.U.	47.95	0.68
1	-0.46	-1.13	+2.18	-0.41	+0.10	N.U.	N.U.	+0.86	49.49	0.68
2	-0.47	+0.26	-13.75	+0.56	N.U.	+0.73	N.U.	N.U.	45.14	0.41
2	-0.20	+0.46	-18.77	+0.17	N.U.	N.U.	+1.14	N.U.	28.19	0.37
2	-0.19	-0.31	-7.21	-0.38	N.U.	N.U.	N.U.	+0.18	31.67	0.22
				Longitudinal Reduction in Area, %						
1	-1.26	-5.70	-14.50	+6.30	+4.69	N.U.	N.U.	N.U.	122.01	0.75
1	-1.57	-4.84	-18.50	-1.52	-2.16	+0.98	N.U.	N.U.	142.83	0.77
1	-1.37	-4.75	-27.36	-1.32	-1.67	N.U.	+2.05	N.U.	128.90	0.77
1	-1.19	-5.74	-17.34	+8.86	+7.28	N.U.	N.U.	-1.16	116.91	0.76
2	-0.98	-4.21	-18.53	-2.63	N.U.	+0.43	N.U.	N.U.	104.54	0.51
2	-0.86	-3.03	-37.26	-2.25	N.U.	N.U.	+2.31	N.U.	90.79	0.55
2	-0.50	-4.27	-24.16	-3.81	N.U.	N.U.	N.U.	-2.95	81.61	0.54
				Longitudinal N.T.S./Y.S.						
1	-0.02	-0.07	-0.13	-0.16	-0.05	N.U.	N.U.	N.U.	3.07	0.63
1	-0.02	-0.07	-0.14	-0.16	-0.06	+0.001	N.U.	N.U.	3.09	0.63
1	-0.02	-0.05	-0.39	-0.31	-0.18	N.U.	+0.04	N.U.	3.20	0.72
1	-0.02	-0.07	-0.27	-0.03	+0.08	N.U.	N.U.	-0.06	2.81	0.70
2	-0.03	-0.12	-0.14	+1.32	N.U.	-0.003	N.U.	N.U.	3.53	0.82
2	-0.03	-0.10	-0.42	+0.15	N.U.	N.U.	+0.03	N.U.	3.53	0.85
2	-0.03	-0.11	-0.32	+0.13	N.U.	N.U.	N.U.	-0.05	3.34	0.87
				Longitudinal K_Q, ksi$\sqrt{in.}$						
1	-0.93	+3.57	-119.66	-18.08	-11.25	N.U.	N.U.	N.U.	119.40	0.81
1	-0.93	+3.58	-119.70	-18.12	-11.29	+0.006	N.U.	N.U.	119.52	0.81
1	-1.20	+5.41	-138.20	-34.53	-23.81	N.U.	+3.90	N.U.	136.79	0.85
1	-0.66	+2.93	-120.35	-8.99	-1.33	N.U.	N.U.	-4.70	101.06	0.83
2	-1.20	-1.79	-92.82	+7.21	N.U.	-0.48	N.U.	N.U.	128.04	0.61
2	-1.71	+2.06	-127.92	+12.13	N.U.	N.U.	+3.49	N.U.	142.19	0.69
2	-1.00	-1.96	-97.71	+8.38	N.U.	N.U.	N.U.	-5.15	120.69	0.69

NOTES FOR TABLE D1

Note 1. To obtain a quantitative representation of a qualitative variable in regression analysis: when three structures available, unrecrystallized represented by 0:0, recrystallized represented by 1:0, and recrystallized plus hot worked represented by 0:1. When two structures available, recrystallized represented by 1, recrystallized plus hot worked represented by 0.

Type Data: 1 - regression determined using data for unrecrystallized, recrystallized, and recrystallized plus hot worked plate; 2 - regression determined using data for recrystallized and recrystallized plus hot worked plate.

T = thickness, L = length.

N.U. = not used.

APPENDIX E

Analysis of Smooth Versus Notch-Tensile Data

Supplementary smooth and notch-tensile tests were conducted on samples of 1.50" thick 7475-T6 plate having a recrystallized, a recrystallized plus hot rolled, and an unrecrystallized structure to help explain the relation between the ductility and K_Q values for the recrystallized, recrystallized plus hot rolled, and unrecrystallized materials. The tests included one tensile and one notched specimen from each sample of plate. The smooth specimens were 0.357" dia. with no tapered section, while the notched specimens were 0.505" gross section diameter and 0.353" net section diameter. The results of tests are given in Table E1.

Table E2 shows the ratio of the notch-tensile stress to the smooth tensile stress at fracture using both engineering stress (original cross-sectional area) and true stress (final cross-sectional area). This ratio is called the notch sensitivity index and is a measure of a material's resistance to triaxial stress fields induced by notches. In general, for a fixed specimen size the lower this ratio, the more sensitive the material is to notches and the lower will be the fracture toughness. As shown in Table E2, if engineering stress is used, the recrystallized material is most sensitive to notches while the recrystallized plus hot rolled material is least. If true stress is used, the recrystallized material is still most sensitive to notches, but the unrecrystallized material is least. True stress is probably a better comparison since it takes account of area changes beyond instability (necking). Based on these true stress NTS/TS ratios, one could infer that the fracture toughness, K_{Ic}, of the recrystallized material would be lower than that of either the recrystallized plus hot rolled or unrecrystallized materials and that the unrecrystallized material should give the highest K_{Ic} values of the three.

A word of caution is in order here. The fracture toughness, K_{Ic}, is supposed to be a measure of a material's resistance to crack propagation. A means of insuring this is to fatigue precrack the specimen prior to testing to insure a crack-like defect for measuring propagation with no initiation phase. The notch-tensile test, on the other hand, is not fatigue precracked, and hence measures both <u>initiation</u> <u>and</u> <u>propagation</u> of a crack. What is being implied in the prediction of K_{Ic} trends from NTS/TS ratio trends is that the distinction between initiation and propagation is relatively unimportant in this particular instance and what really matters is how the material reacts to any triaxial stress field at a notch, regardless of whether the notch is sharp or blunt.

Additional smooth and notch-tensile tests were made on samples of 1.50" thick 7475-T6 plate which were quenched as 0.600" dia. blanks, The results of the tensile tests are given in Table E3. The tensile and yield strengths and the load at fracture for the notched specimens were higher for the specimens from the material quenched as 0.600" dia. blanks than for the specimens from the material quenched as 1.50" thick plate.

The notched tensile stress/tensile stress ratio (notch sensitivity index) was calculated for the rapidly quenched material using true stress and is given in Table E4 along with the results of the calculations made for the material quenched as 1.50-in. thick plate. The test data show that even though increasing the quench rate has increased the yield, ultimate, and notch-tensile strengths, the notch sensitivities of the materials have remained unchanged. The unrecrystallized material is still the least notch sensitive and should give higher toughness than either the recrystallized or the recrystallized plus hot rolled material.

In reaching the conclusions discussed here, it is assumed that the constraint conditions at the notch in the notched round bar tests for all materials are roughly the same; that is, the differences in yield strengths of the materials is assumed small and hence the constraint conditions at the notch are similar in all cases. With this assumption, one is then able to say that for the same constraint, one material behaves differently than another under triaxial stress conditions.

TABLE E1

RESULTS OF TENSILE AND NOTCHED TENSILE TESTS ON 1.50" THICK 7475-T6 PLATE, S-418967-30, 40, 50 - MATERIAL QUENCHED AS 1.50" THICK PLATE

Structure	Y.S., ksi	Elongation at Fracture, %	Load at Fracture, lb	Change in Dia. at Fracture,[1] %	Area at Fracture, in.^{2}	True Stress at Fracture, ksi
			Smooth Specimens			
Unrecrystallized	73.0	17.1[2]	7840	13.08	0.0756	103.70
Recrystallized	67.7	19.3[2]	7720	13.84	0.0743	103.90
Recrystallized plus hot rolled	70.6	20.0[2]	7600	16.30	0.0701	108.42
			Notched Specimens			
Unrecrystallized	--	6.9[3]	9990	3.2	0.0917	108.94
Recrystallized	--	8.2[3]	9180	1.9	0.0942	97.45
Recrystallized plus hot rolled	--	6.4[3]	9700	1.9	0.0941	103.08

Notes:
1. Average of three diameter measurements taken from fractured specimen used to calculate area.
2. Gauge length = 1.4 in.
3. Cauge length = notch mouth at specimen surface - 0.854 in.

TABLE E2

NOTCHED TENSILE/TENSILE STRENGTH AND K_Q RESULTS, 1.50" THICK 7475-T6 PLATE, S-418967-30, 40,50 - MATERIAL QUENCHED AS 1.50" THICK PLATE

Structure	Notched Tensile Strength/Tensile Strength: Engineering Stress	Notched Tensile Strength/Tensile Strength: True Stress[1]	K_Q ksi$\sqrt{in.}$
Unrecrystallized	1.303	1.050(100%)	40.9[2]
Recrystallized	1.243	0.938(89.3%)	27.8[3]
Recrystallized plus hot rolled	1.305	0.951(90.6%)	26.8[3]

Notes:
1. Based on final area only. No correction for necking has been applied due to difficulty in measuring large radii of necked regions.
2. Based on 5% secant line on load displacement curve.
3. Based on initial stepwise departure from a smooth line.

TABLE E3

RESULTS OF TENSILE AND NOTCHED TENSILE TESTS ON 1.50" THICK 7475-T6 PLATE - S-418967-30, 40, 50 - MATERIAL QUENCHED AS 0.600"Ø BLANKS

Structure	Yield Strength, ksi	Ultimate Strength, ksi	Load at Failure, lb	Reduction of area, %	Total Elongation, %
		Smooth Specimens			
Unrecrystallized	75.0	84.2	8300	23	17.1
Recrystallized	70.1	79.8	7070	38	20.7
Recrystallized plus hot rolled	75.7	84.7	7480	36	19.3
		Notched Specimens			
Unrecrystallized	--	110.8	10850	--	--
Recrystallized	--	108.3	10600	--	--
Recrystallized plus hot rolled	--	111.1	10870	--	--

TABLE E4

NOTCHED TENSILE/TENSILE STRENGTH RATIO BASED ON TRUE STRESSES
1.50" THICK 7475-T6 PLATE - S-418967-30, 40, 50

Structure	Notched Tensile Strength/Tensile Strength Material Quenched as 1.50" Thick Plate	Notched Tensile Strength/Tensile Strength Material Quenched as 0.6"Ø Blanks
Unrecrystallized	1.050	1.033
Recrystallized	0.938	0.957
Recrystallized plus hot rolled	0.951	0.947

APPENDIX F

MICROSTRUCTURE VS. DUCTILITY AND TOUGHNESS

INTRODUCTION

The investigation reported in the main body of this report indicated that 7475 plate thermomechanically processed to produce recrystallized grains comparable in size to those reported by DiRusso et al and Waldman et al developed the anticipated high ductility (tensile reduction in area) relative to that of unrecrystallized 7475 plate. Toughness, however, measured using either compact tension fracture toughness specimens or circumferentially notched tension specimens was lower than that of the unrecrystallized plate. Examination of undeformed samples and of fracture specimens of the plates that were produced in the initial phases were difficult to interpret because the different thermomechanical histories produced differences in second phase particle morphologies along with differences in grain structure so that the relative effects of particles and of grain structure could not be separated. Consequently, additional plate samples from a new 7475 ingot were fabricated in Phase IV using identical procedures with the exception of rolling practices. Three structure variants were produced: (1) unrecrystallized, (2) recrystallized to a fine, relatively equiaxed grain structure, (3) a structure which was recrystallized, then hot rolled to elongate the recrystallized grains. Test results reported in the body of this report indicated that the toughness of these plates were generally lower than the toughness of the 7475 plates produced during the initial phases. This difference was anticipated because of the higher impurity content of the ingot fabricated for the microstructural studies (Phase IV). The relative toughness and ductility differences between these unrecrystallized, recrystallized, and recrystallized plus hot worked structures were comparable, however, to the differences originally observed.

The object of this work was to establish in greater detail the nature of the microstructural differences and to relate them more closely with respect to deformation and fracture mechanisms to the observed differences in fracture toughness and ductility. Transmission electron microscopy (TEM), scanning electron microscopy (SEM), optical microscop_ x-ray, and electron microprobe techniques were used.

EXPERIMENTAL

All the samples used for microstructural studies were the ones tested in the longitudinal direction. Samples for slip line studies were 0.065" thick, 3/8" wide and 2" long (gauge length). They were mechanically polished and then electropolished before subjecting them to deformation to fracture. Thin foils for TEM were electropolished using a solution consisting of 25 vol. % nitric acid and 75 vol. % methanol. A Philips EM301G microscope equipped with eucentric goniometer stage was used for the examination. The operating voltage of the microscope was 100 KV. Fractographs were prepared representing the fracture locations at the initial region of unstable crack propagation, and also in the vicinity of the stretched zone. In order to show the relation between second phase particles and the grains at fairly high magnification in the SEM, an etchant (10% bromine in methanol) was used which was known to put the particles in relief without altering their appearance.

RESULTS

Undeformed Structure

The distributions of coarse constituent particles and dispersoid particles (E phase) are shown in the 500X and 2000X scanning electron micrographs in Fig. F1a-1c. Because of low Fe and Si contents, the volume fraction of large constituent particles (up to ∿10μm) was low in all three structures. The largest insoluble constituents (a few microns to ∿10μm) were identified as Al-Fe-Cu particles by energy dispersive x-ray (Kevex) and also by Guinier x-ray diffraction analyses. There were also some M (η) and very few S($CuMgAl_2$) phase particles present in the alloy. The smallest particles shown in the figures are dispersoids (E phase particles).

In the unrecrystallized sample, the constituent particles were not preferentially located at the grain boundaries (Fig. F1a). However, in the recrystallized sample constituent particles were preferentially located along grain boundaries (Fig. F1b). Constituent particles also tended to lie along the elongated grain boundaries in the sample which was recrystallized and subsequently hot rolled (Fig. F1c). Three-dimensional light micrographs and the mechanical properties of these samples are shown in Figure F2a-F2c.

A typical electron microstructure representing the unrecrystallized material is shown in Fig. F3a and F3b. The dispersoids are the E phase described as $Al_{12}Mg_2Cr$ by Hunter and McMillan[1] and $Al_{18}Cr_3Mg_2$ by others[2]. Since all thermal treatments were the same for the three samples, there was no appreciable variation between samples in the size and distribution of the E phase particles. Different rolling temperatures, however, gave rise to different substructures among the samples: cell structures in the unrecrystallized sample (Fig. F3a and F3b), relatively dislocation-free recrystallized grains in the recrystallized sample (Fig. F4a and F4b) and polygonized cells in the recrystallized plus hot rolled sample (Fig. F5). Even though there was no appreciable fluctuation in the distribution of Cr according to electron microprobe analysis (on a light microscope scale) the distribution of E phase was inhomogeneous (on an electron microscope scale).

Deformed Structure

In order to understand the mechanical properties in a precipitation hardened alloy, it is necessary to examine the interaction between the hardening particles and moving dislocations. If the particles are coherent, the moving dislocations can either shear them or by-pass them depending on the size, distribution and also volume fraction of the particles. The advantage of changing the deformation mechanism from a cutting to a by-pass mechanism (better ductility) was shown by Lütjering and Hornbogen[3] and Lütjering and Weissmann[4].

In this study the microstructural observations were made in a uniformly deformed region of each of the structures generated by the different thermomechanical histories. As will be discussed later, the mode of fracture seemed to be very important in controlling the toughness of the alloy. Therefore, the interaction between dislocations and precipitates along grain boundaries was also examined in addition to the interaction between dislocations and matrix precipitates.

Typical transmission electron micrographs showing the unrecrystallized sample after deformation are shown in Fig. F6a and F6b. The distribution of dislocations was relatively homogeneous and there was no preferential deformation along the grain boundaries. Also, in most regions dislocation bands piled against the grain boundary were not observed (Fig. F6a). The moving dislocations by-passed the large constituent particles (intermetallic phase) and concentration of slip was observed. Due to the deformation, some of the rod-shaped particles thought to be Al_7Cu_2Fe were fractured (Fig. F6b). However, there was no evidence of shearing of η' particles by the moving dislocations.

In contrast to the unrecrystallized sample, the recrystallized sample showed a quite different deformed microstructure (Fig. F7a and F7b). As shown in Fig. F7b, the grain boundary was much more heavily deformed compared to the grain-interior. Grain boundary dislocations (GBD) were proposed by Gleiter and his co-workers[5,6] and Price and Hirth[7]. According to the former[5,6] grain boundaries function as sources of dislocations, and two generation mechanisms are operative. In mobile grain boundaries GBD's move along the boundary. Also GBD's showed interactions similar to those of lattice dislocations such as networks, pile ups, etc. Dislocation bands, presumably generated by these grain boundary dislocations in the recrystallized material, are apparent in Fig. F7a and F7b.

In the recrystallized and hot rolled sample strong interaction between dislocation bands and grain boundaries was also observed (Fig. F8a and F8b). As in the recrystallized sample, heavier deformation resulted along the high angle grain boundaries.

Slip Line Study

When the unrecrystallized sample was deformed and the originally polished surface was examined in a light microscope, slip lines more or less uniformly distributed throughout the grains were observed along with a slight grain boundary sliding along high angle grain boundaries (Fig. F9a). Fracture, as shown in Fig. F9b and F9c usually followed slip bands and was predominantly transgranular.

In contrast to the unrecrystallized sample, the recrystallized sample showed much more grain boundary sliding and the fracture path usually followed grain boundaries rather than slip bands (Fig. F10a,b,c). In the recrystallized plus hot rolled sample, the slip line structure showed that cracking occurred along grain boundaries as well as at slip bands (Fig. F11a-F11c).

Fractography

To further determine differences in fracture mechanisms of the fracture toughness specimens, the fractured surfaces were examined in the scanning electron microscope. Observed fracture modes were consistent with the results from the slip line studies, and were closely related to the respective fracture toughness values determined in this investigation. The higher the proportion of intergranular fracture, the lower was the fracture toughness (Figs. F12, F13 and F14). The unrecrystallized sample had the highest toughness and fractured almost entirely by a transgranular mode (Figs. F9 and F12). The fracture surface exhibited large and small dimples (Fig. F12). The spacing of the small dimples was consistent with and apparently controlled by the average interparticle distance of the dispersoids (E phase). The recrystallized sample, which showed the lowest toughness, had predominantly intergranular fracture and the fracture surface was almost free of small dimples (Fig. F13). On the other hand, the recrystallized plus hot rolled sample showed a transgranular-intergranular mixed mode fracture (Fig. F13) and generally had an intermediate level of toughness.

When fractures of the notched tensile specimens were compared to those of the corresponding fracture toughness specimens, the same mode of fracture was observed (compare Figs. F12, F13, and F14 with Figs. F15, F16, and F17).

According to other investigators[8,9] other fracture features such as stretched zones and vertical cliffs can be related to fracture toughness and yield stress. Consequently, these features were also examined to determine whether any evidence could be found of a relationship between fracture toughness and stretched zones and cliff heights in the fracture toughness specimens of the three materials having relatively large differences in grain structure.

The stretched zone lay between the fatigue striations of the fatigue precrack and the dimpled region of typical tensile overload. It represented the first plastic deformation at the tip of the fatigue crack. When fracture occurred, it tended to leave a cliff representing a displacement between the tensile fracture plane and the fatigue fracture plane.

In the unrecrystallized sample the cliffs were not continuous and some small dimples were present on the cliff surface (Fig. F18a). In the recrystallized sample (Fig. F18b) also the cliffs were not continuous, and, in most regions, were almost featureless and free of dimples. This probably reflected the tendency for cracks to follow grain boundaries in this material. Similar discontinuous cliffs were observed in the unrecrystallized plus hot rolled sample (Fig. F18c). Except for the recrystallized sample (Fig. F18b), the stretched zones could not be clearly identified.

Microstructure of Rapidly-Quenched Samples

As will be discussed later, the mode of fracture seemed to be partly related to the grain boundary particles (constituent particles and precipitate particles). To eliminate some of the precipitate particles, a faster quenching rate was obtained by using smaller specimens (0.6"ϕ). As shown in Fig. F19, the amount of grain boundary precipitate was to some extent reduced by the more rapid quench. Notch toughness data indicated that toughness of all three materials was increased by the rapid quench, but the ranking was the same as for the bulk-quenched samples. The same kinds of fracture modes were observed regardless of quenching rate.

DISCUSSION

One of the most important findings in this study was that fracture toughness increased as the proportion of intergranular fracture decreased. The unrecrystallized sample showed the highest fracture toughness and fractured almost entirely by the transgranular mode. On the other hand, the recrystallized sample showed lower fracture toughness which corresponded with a fracture that was almost entirely intergranular. The recrystallized plus hot rolled sample had a mixed transgranular-intergranular mode of fracture.

Several investigators[8,9] have pointed out a relationship between fracture toughness and stretched zone width (and cliff heights). In this study, stereo pairs of fractographs revealed that the cliff height appeared to increase with increasing level of fracture toughness. Peel et al[9] reported that higher fracture toughness was associated with the larger cliff height and that over considerable portions of the crack fronts, stretched zones were not observed. In the present investigation because of discontinuous cliff heights and irregular stretched zones, no clear relationship was obtained. Rather it was found that fracture toughness was closely related to the percentage of intergranular fracture. Therefore, observed differences in cliff height were not sufficient to give information on the fracture toughness, and the mode of fracture was the most important factor controlling the fracture toughness. A similar conclusion was made on Al-Zn-Mg-Cu-Zr alloys by DiRusso, et al[10].

Intergranular fracture ensues when the matrix is stronger than the grain boundary and depends upon the grain boundary morphology and mutual orientation relationships with respect to the tension axis. The effect of precipitate-free zones (PFZ) on ductility or toughness has been studied by many investigators. Varley et al[11] postulated that preferential deformation within a PFZ might improve ductility due to a reduction in stress concentration at the grain boundary. Unwin and Smith[13] found that the PFZ width had little effect on ductility and fracture toughness of Al-6%Zn-3%Mg alloy. However, they pointed out that deformation might be concentrated in certain favorably oriented PFZ. As shown in Fig. F7a, the PFZ in the present materials was minimal even in the recrystallized sample which showed predominantly intergranular fracture. Such a narrow PFZ is not expected to control the intergranular fracture. Therefore, in this study, the fracture toughness and ductility were not believed to be appreciably affected by PFZ width. Similar results were obtained by Kirman[14] who concluded that the fracture of 7075 was not primarily affected by PFZ width.

Preferential deformation along grain boundaries in the recrystallized and recrystallized plus hot rolled samples is shown in Figs. F7b and F8b. The sources of the dislocations observed along the grain boundaries are a special type termed grain boundary dislocations[5,6], and they move along the boundary when the boundaries are mobile. Preferential deformation along grain boundaries might lead to an intergranular fracture and low toughness as was actually observed in these materials. In the case of the unrecrystallized sample, which showed a transgranular fracture mode and the highest toughness, no preferential deformation was observed along the grain boundary (Fig. F6a). The dislocation pile-ups shown in the recrystallized and recrystallized plus hot rolled materials (Figs. F7b and F8b) would also favor the intergranular fracture.

Another significant difference in the microstructures among the three treatments was the grain boundary particles (Fig. F1a-F1c). The recrystallized sample with low fracture toughness had preferential distribution of large particles (insoluble constituents and η particles) along the grain boundary. This evidence suggests that the large Al_7Cu_2Fe constituent particles, which formed prior to the recrystallization treatments, in addition to the smaller E-phase dispersoids acted as obstacles to the growth of new grains during recrystallization and for this reason could be found at the recrystallized grain boundaries. The small η particles probably formed along these boundaries during quenching and/or aging following the solution heat treatment.

The fractographic, microstructural and slip line study evidence suggests that the mechanism of intergranular fracture in the recrystallized material is the nucleation of voids by fracture of the large grain boundary precipitates and the Al_7Cu_2Fe constituents followed by void coalescence associated with grain boundary dislocations and by matrix dislocation pile-ups affecting a force normal to the grain boundaries. Kirman[14] also suggested that the intergranular fracture in 7075 occurs by the ductile void-coalescence mechanism.

The unrecrystallized sample which showed predominantly transgranular fracture did not have coarse particles located preferentially along the grain boundaries (Fig. F1a). Cracks were initiated mostly at slip bands (Fig. F9b). Also shown in the figure is the concentration of slip around large particles. When the size of the small dimples was compared to the average interparticle distance of the E phase, it was concluded that the small dimples were formed by the formation of voids at dispersoids (E phase) during straining with eventual void coalescence.

The Cr-bearing E phase particles were inhomogeneously distributed. This was especially apparent in the recrystallized samples. Actually there is no reason to anticipate that the distribution should be different among the different structures investigated, since the Cr does not diffuse from its initial dendritic segregation pattern but precipitates essentially in situ[15]. The distribution of Cr, Mg, Cu and Zn in 7475 was studied by Flemings and his co-workers[16]. They reported significant segregation of Cu and Cr in a cast ingot (high Cr at the dendritic center and high Cu in the interdendritic region) and Cr segregation was very difficult to reduce with thermomechanical treatments. Our electron microprobe examination on light microscope scale showed that after thermomechanical treatments the concentration of Cr did not significantly vary across the grains even though the distribution of dispersoids changed from grain to grain or even inside the grain as shown in the transmission electron micrographs (Figs.F3a, F3b, F4a, F4b, and F5). inhomogeneous distribution of E phase did not seem to affect the mechanical properties appreciably.

CONCLUSIONS

1. The fracture toughness of 7475 plate processed to have different grain structure was most significantly affected by the fracture mode. The unrecrystallized plate showed a predominantly transgranular fracture mode and had a higher fracture toughness than the recrystallized plate which showed an almost entirely

intergranular mode. The toughness of the recrystallized plus hot rolled plate was intermediate, and fracture mode was mixed transgranular-intergranular.

2. The intergranular fractures were attributed to nucleation of voids at grain boundaries by large constituent and precipitate particles and by coalescence of these voids through an interaction of dislocations with the grain boundaries.

3. Fractographic features such as stretched zones and cliff heights were not prominent as indicators of relative fracture toughness of 7475.

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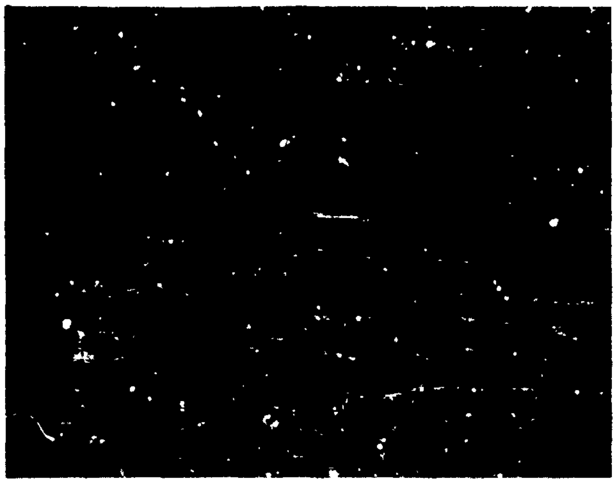
500X

2000X

Fig. Fla - Micrographs (SEM) showing the distribution of particles in the unrecrystallized sample.



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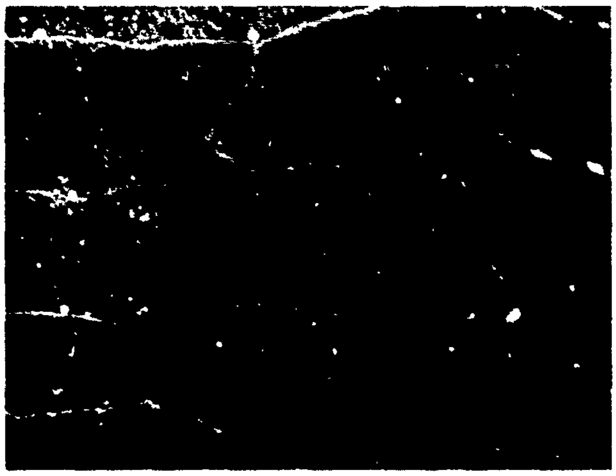
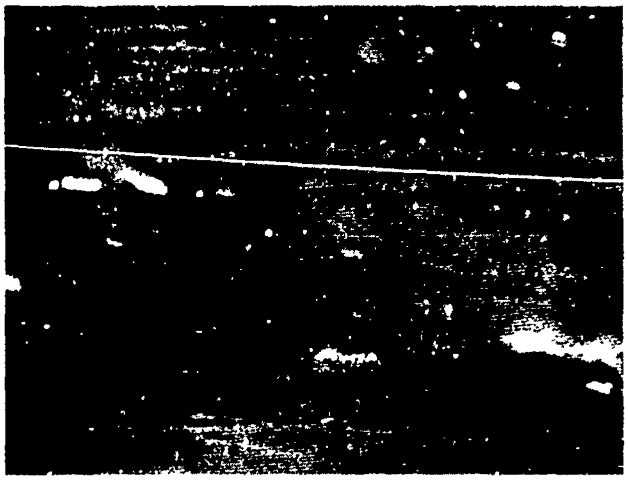


2000X

Fig. Flb - Micrographs (SEM) showing the distribution of particles in the recrystallized sample.



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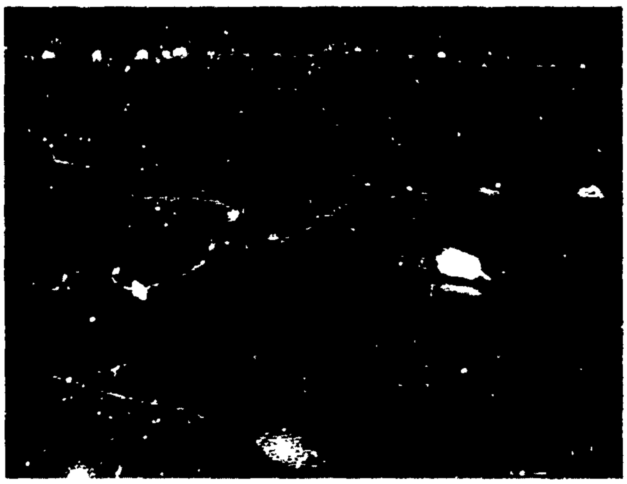
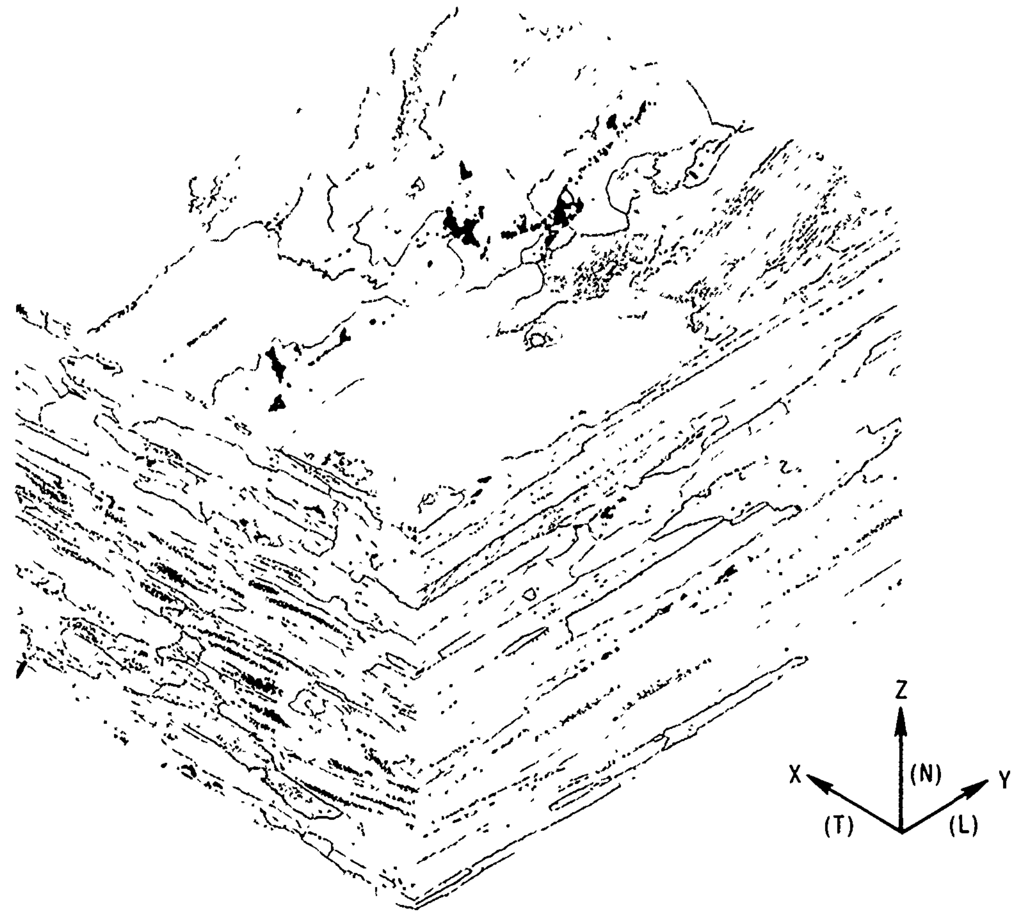


2000X

Fig. Flc - Micrographs (SEM) showing the distribution of particles in the recrystallized plus hot rolled sample.



MAG: 100X

ETCH: KELLERS

1.50" THICK 7475-T6 PLATE S-418967-50

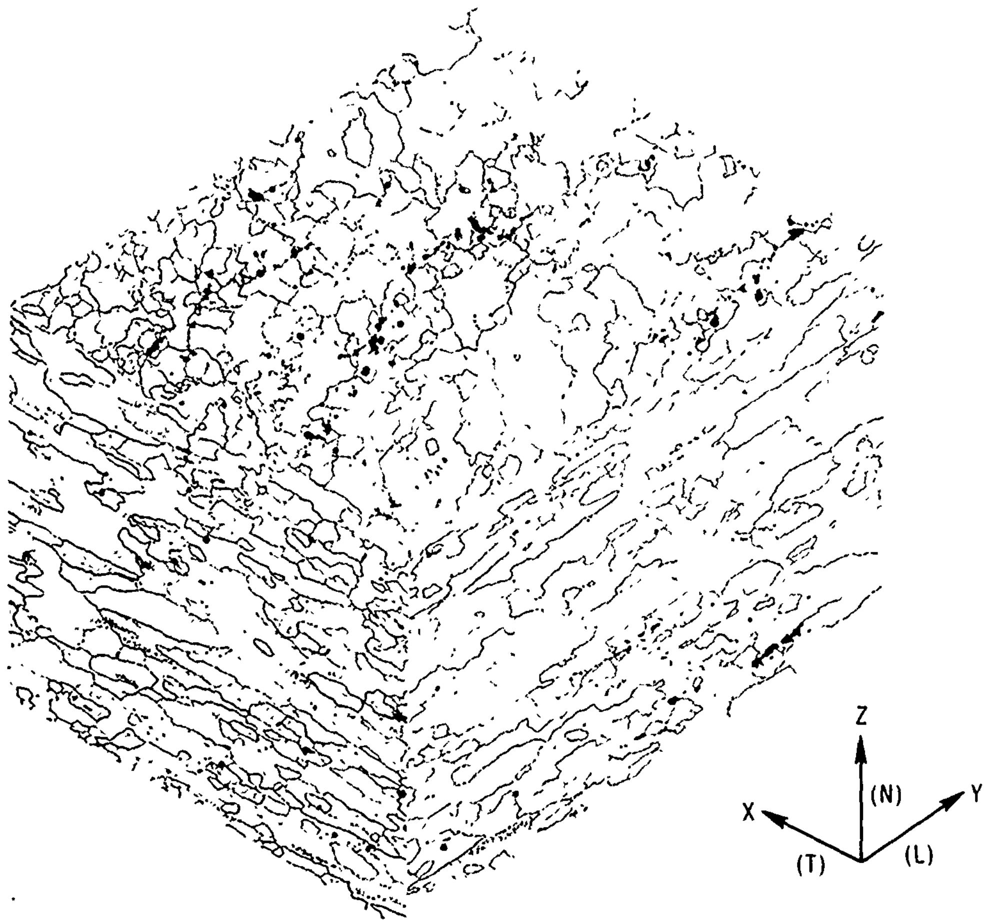
INGOT				SLAB				RECRYSTALLIZATION		PLATE				
									ROLLING		GRAIN COUNT			
THERMAL[1]	ROLLING			THERMAL[1]	ROLLING			THERMAL[1]	AT 750°F	SOLUTION[1]	g/mm			g/mm³
TREATMENT	TEMP	RGD	THICK	TREATMENT	TEMP	RGD	THICK	TREATMENT	RGD	HEAT-TREAT	X	Y	Z	XYZ
6hr/860°F 20hr/960°F	750°F	14%	8 0"	2hr/960°F 2hr/775°F 4hr/500°F	500°F	75%	2 0"	8hr/960°F	25%	2 hr/960°F	24	11	62	16 368

(1) THERMAL TREATMENTS CARRIED OUT IN A CIRCULATING AIR FURNACE

	PROPERTIES						
DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi$\sqrt{in.}$
L	82.1	70.6	17.1	28	97.1	1.37	29.9
T	80.5	69.0	15.0	25	84 7	1.23	29.2
N	79.3	66.3	12.0	N.D.	79.2	1.20	29.0

MICROSTRUCTURE AND PROPERTIES OF 1.50" THICK RECRYSTALLIZED AND HOT ROLLED (AR+HR) 7475-T6 PLATE S-418967-50

Figure F2a



MAG: 100X ETCH: KELLERS

1 50" THICK 7475-T6 PLATE S-418967-40

INGOT				SLAB				RECRYSTALLIZATION		PLATE				
THERMAL (1) TREATMENT	ROLLING TEMP	ROLLING RGD	THICK	THERMAL (1) TREATMENT	ROLLING TEMP	ROLLING RGD	THICK	THERMAL (1) TREATMENT	ROLLING AT 750 F RGD	SOLUTION (1) HEAT TREAT	GRAIN COUNT g mm X	GRAIN COUNT g mm Y	GRAIN COUNT g mm Z	GRAIN COUNT g mm XYZ
6hr 860 F 20hr/960 F	750 F	35%	6 0"	2hr/960 F 2hr/775 F 4hr/500 F	500 F	75%	1 50"	18hr/960 F	NONE	2hr 960 F	22	20	54	23 760

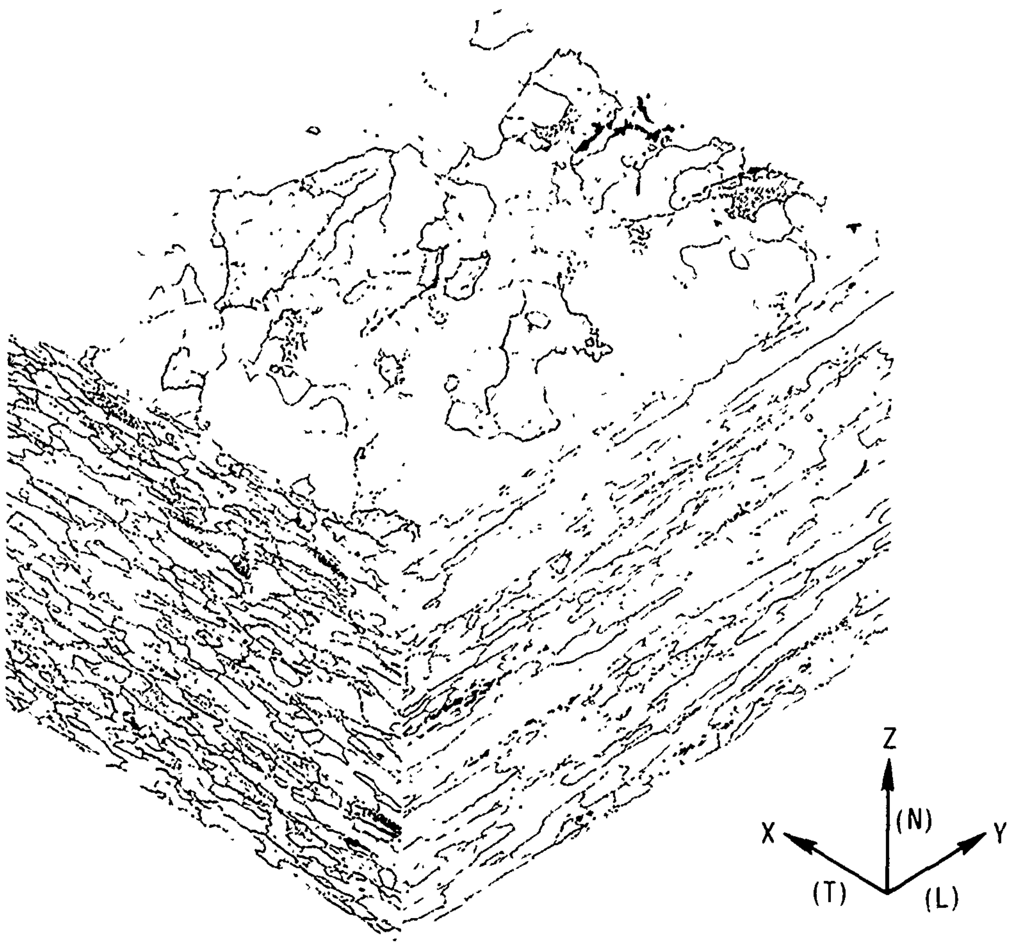
(1) THERMAL TREATMENTS CARRIED OUT IN A CIRCULATING AIR FURNACE

PROPERTIES

DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. Y.S.	K_Q ksi$\sqrt{in.}$
L	79.3	67.7	17.9	32	90 1	1 33	32 4
T	80 2	68.5	15.7	22	82.1	1 20	27 5
N	79.3	67 4	8.0	N.D.	85.0	1 27	23 6

MICROSTRUCTURE AND PROPERTIES OF 1.50" THICK RECRYSTALLIZED (AR) 7475-T6 PLATE S-418967-40

Figure F2b



MAG: 100X

ETCH: KELLERS

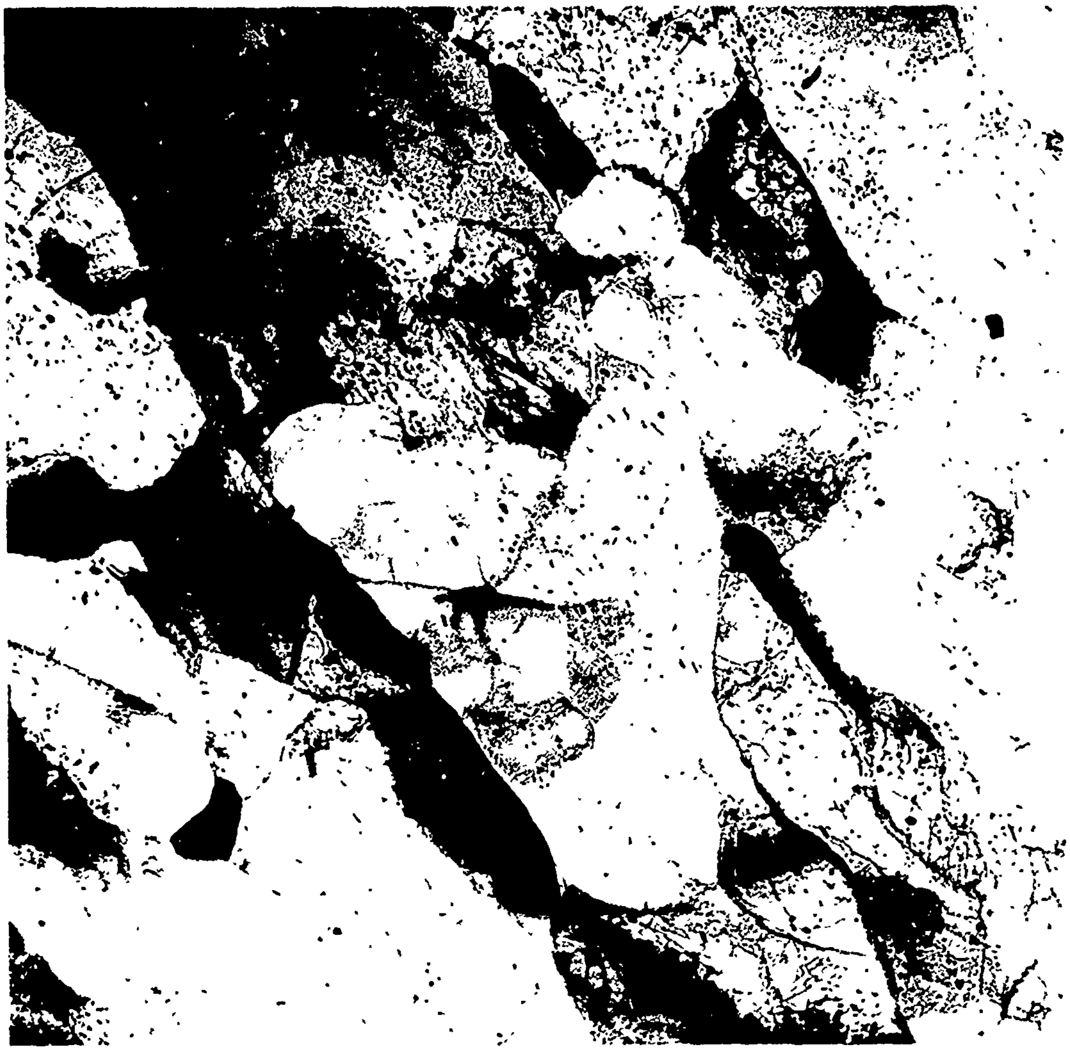
1.50" THICK HOT ROLLED (HR) 7475-T6 PLATE S-418967-30

PROPERTIES

DIR	T.S. ksi	Y.S. ksi	EL %	R.A. %	N.T.S. ksi	N.T.S. / Y.S.	K_Q ksi$\sqrt{in.}$
L	83.8	73.0	15.0	19	99.8	1.37	40.9
T	81.3	70.3	15.7	21	90.0	1.28	32.6
N	81.4	67.1	10.0	N.D.	85.3	1.28	31.0

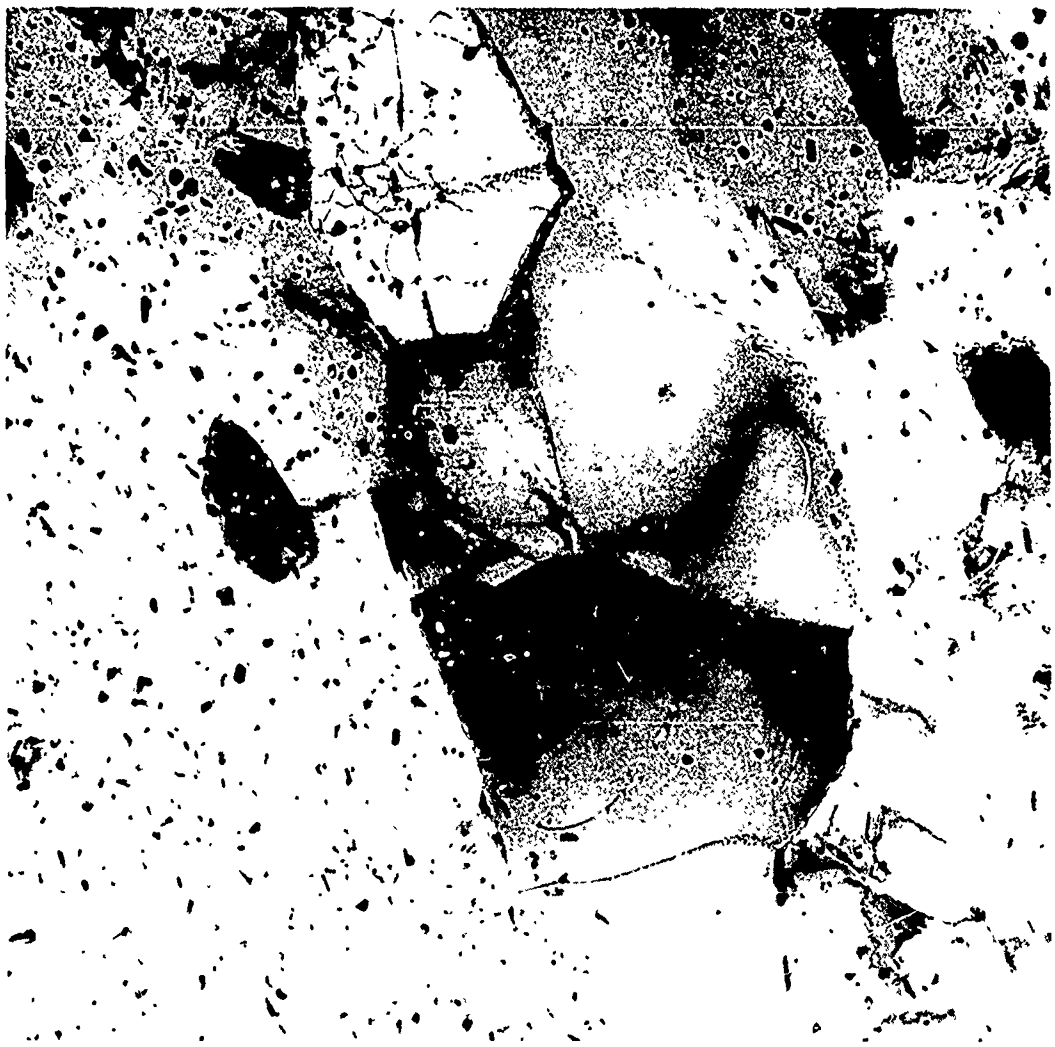
MICROSTRUCTURE AND PROPERTIES OF 1.50" THICK HOT ROLLED (HR) 7475-T6 PLATE S-418967-30

Figure F2c



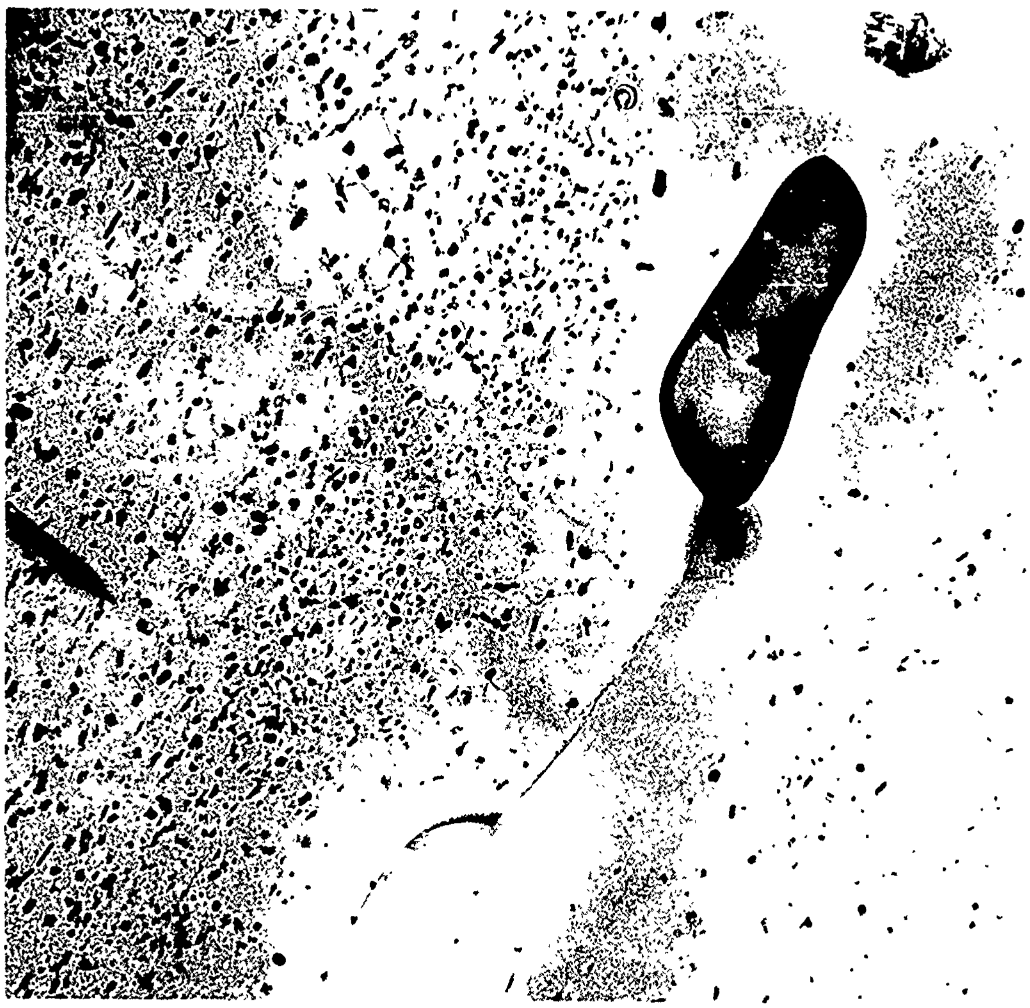
8600X

Fig. F3a - Micrograph (TEM) of undeformed unrecrystallized material. Note the cells and dislocations inside the subgrains. The small particles (~0.05μm to ~0.15μm) are mostly the E phase.



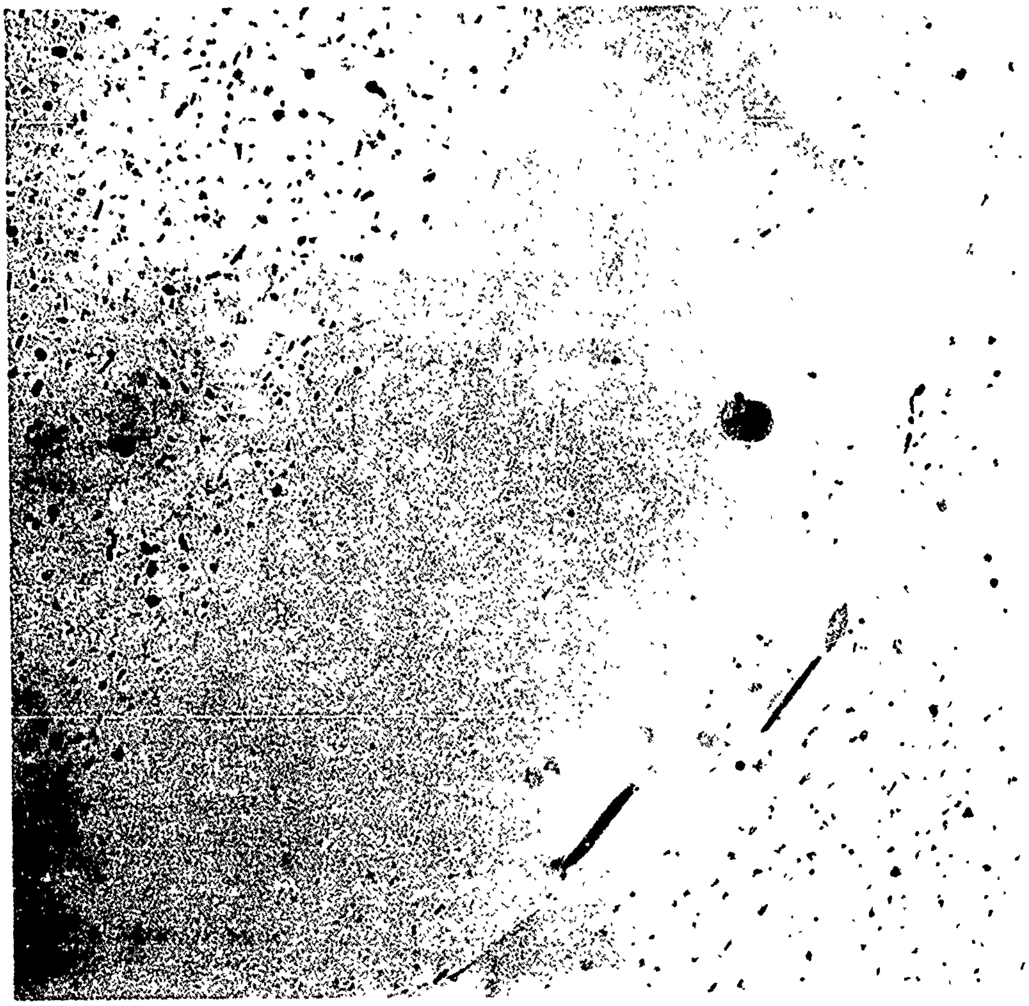
15,000X

Fig. F3b - Micrograph (TEM) of undeformed unrecrystallized material. Note the small M' or M particles along the subgrain.



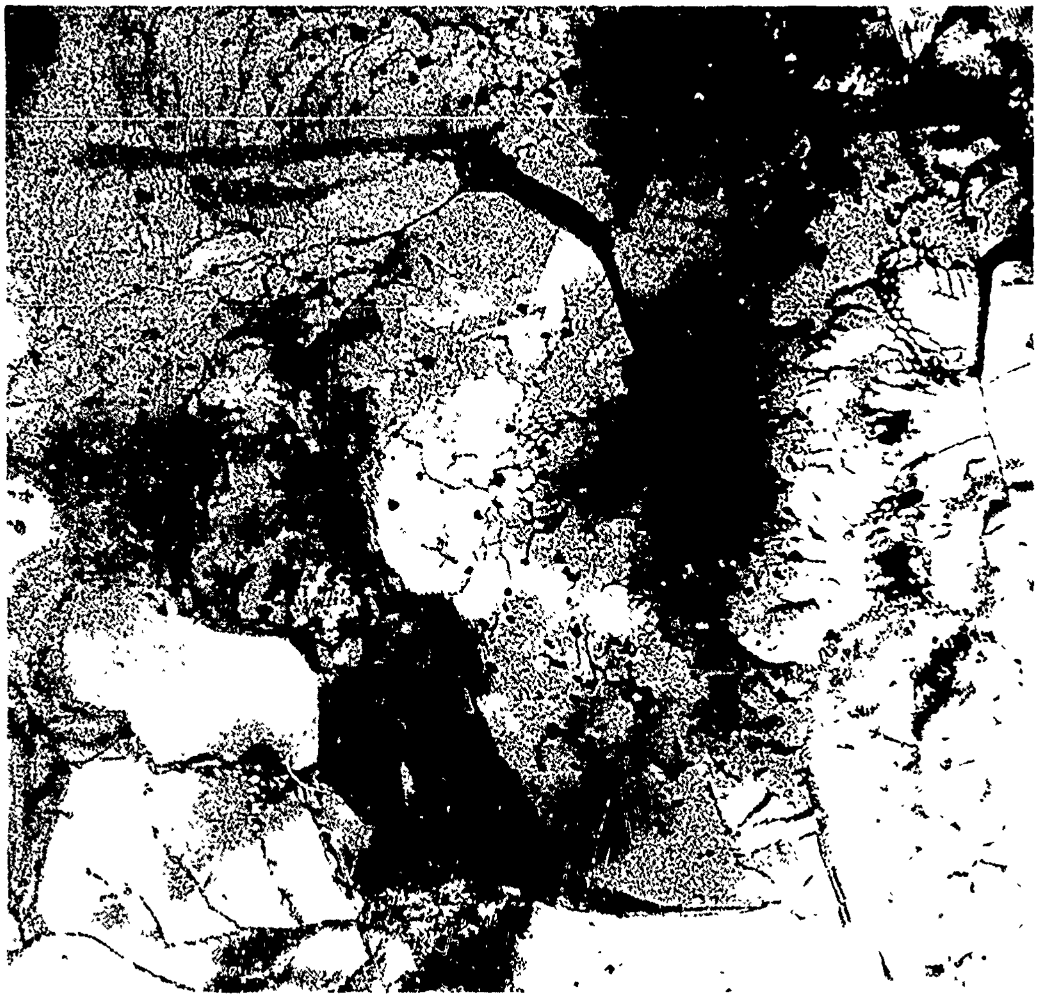
11,800X

Fig. F4a - Micrograph (TEM) of undeformed recrystallized material. Note the large constituent particles along grain boundary.



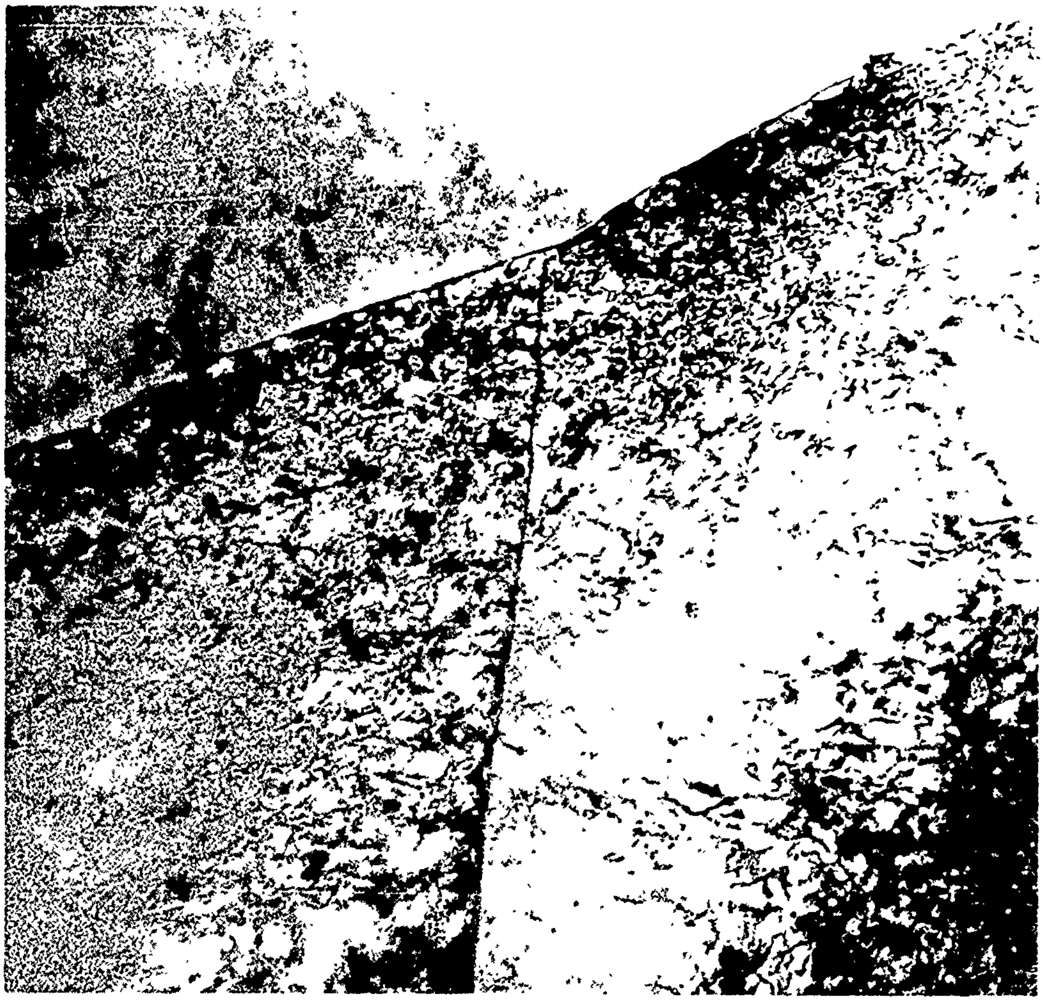
11,800X

Fig. F4b - Micrograph (TEM) of undeformed recrystallized material. Note the inhomogeneous distribution of the E phase.



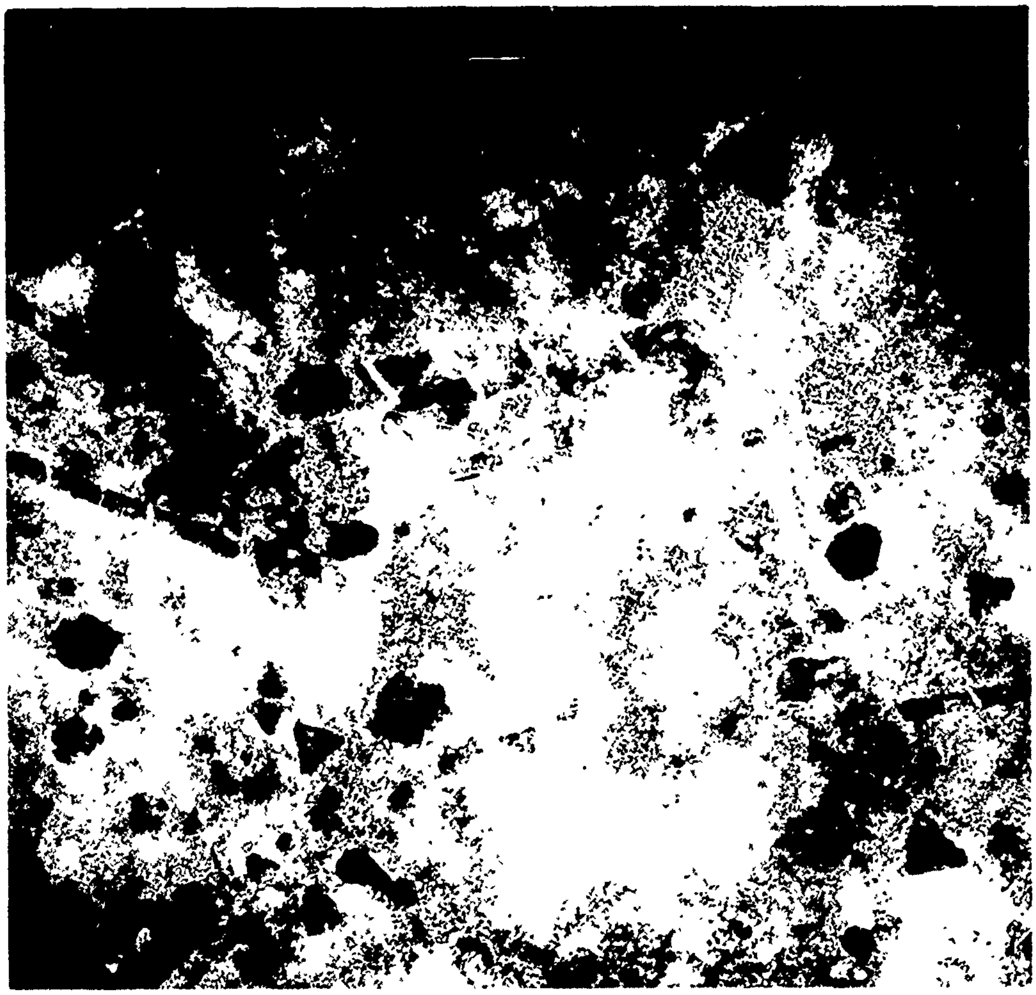
15,000X

Fig. F5 - Micrograph (TEM) of undeformed recrystallized plus hot rolled material. Note the polygonized structure due to hot rolling following recrystallization.



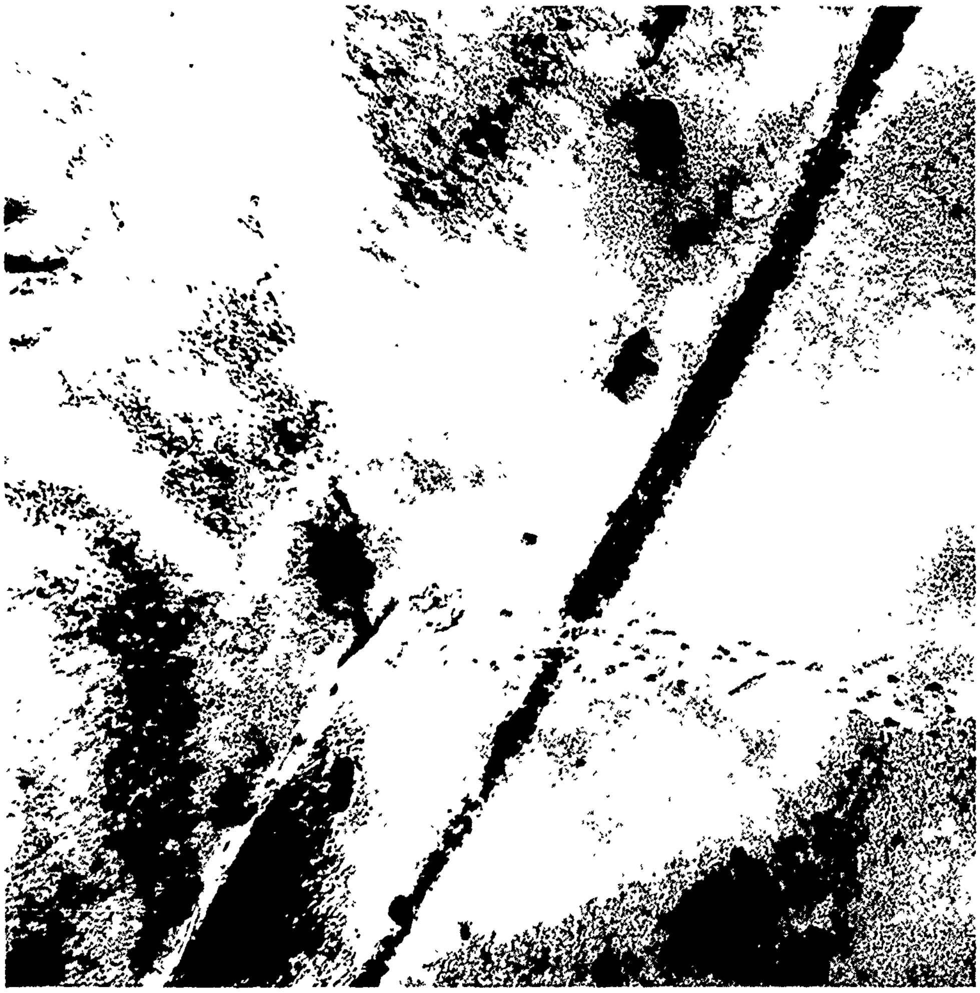
72,000X

Fig. F6a - Micrograph (TEM) representing the uniformly deformed regions of unrecrystallized material. Note the relatively homogeneous distribution of dislocations.



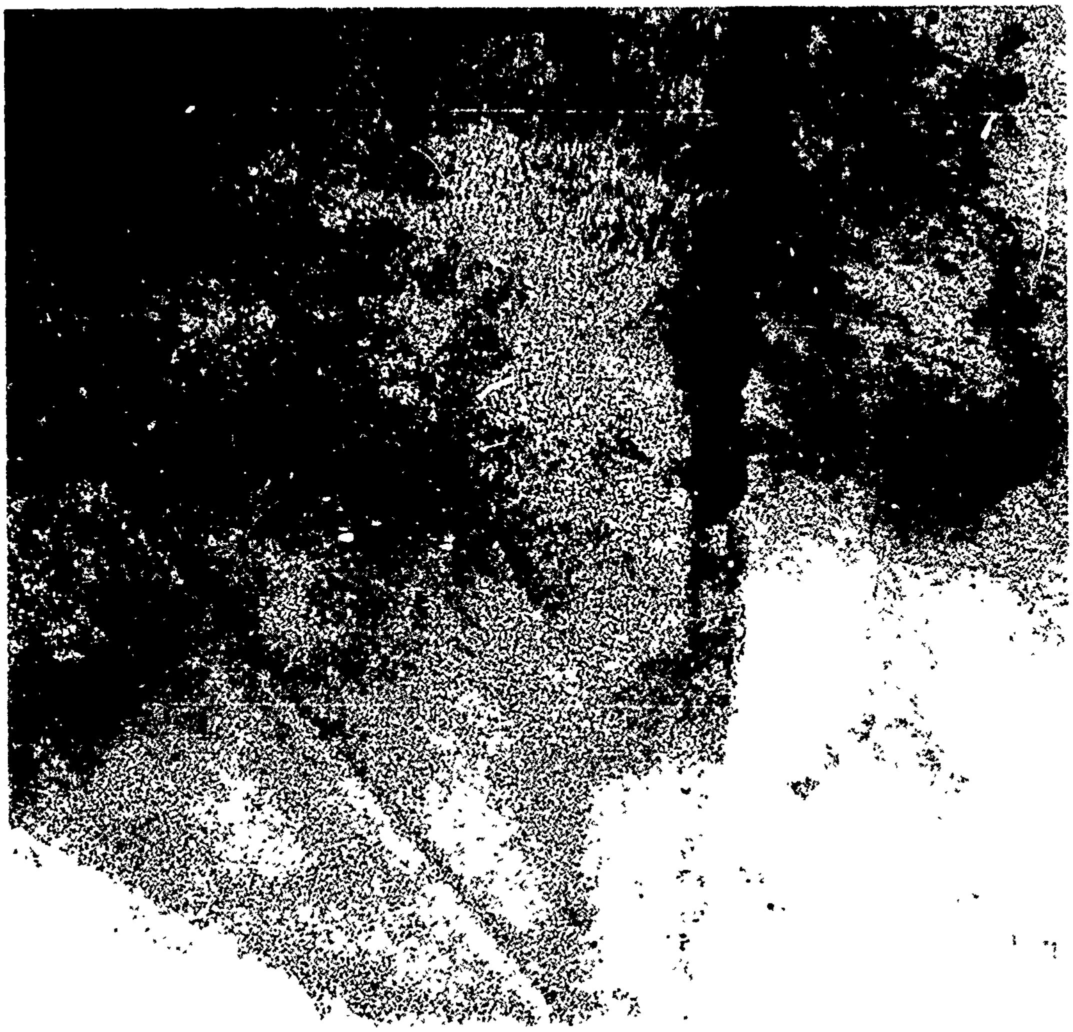
36,000X

Fig. F6b - Micrograph (TEM) representing the uniformly deformed regions of unrecrystallized material. Note the fractured rod-shaped particles.



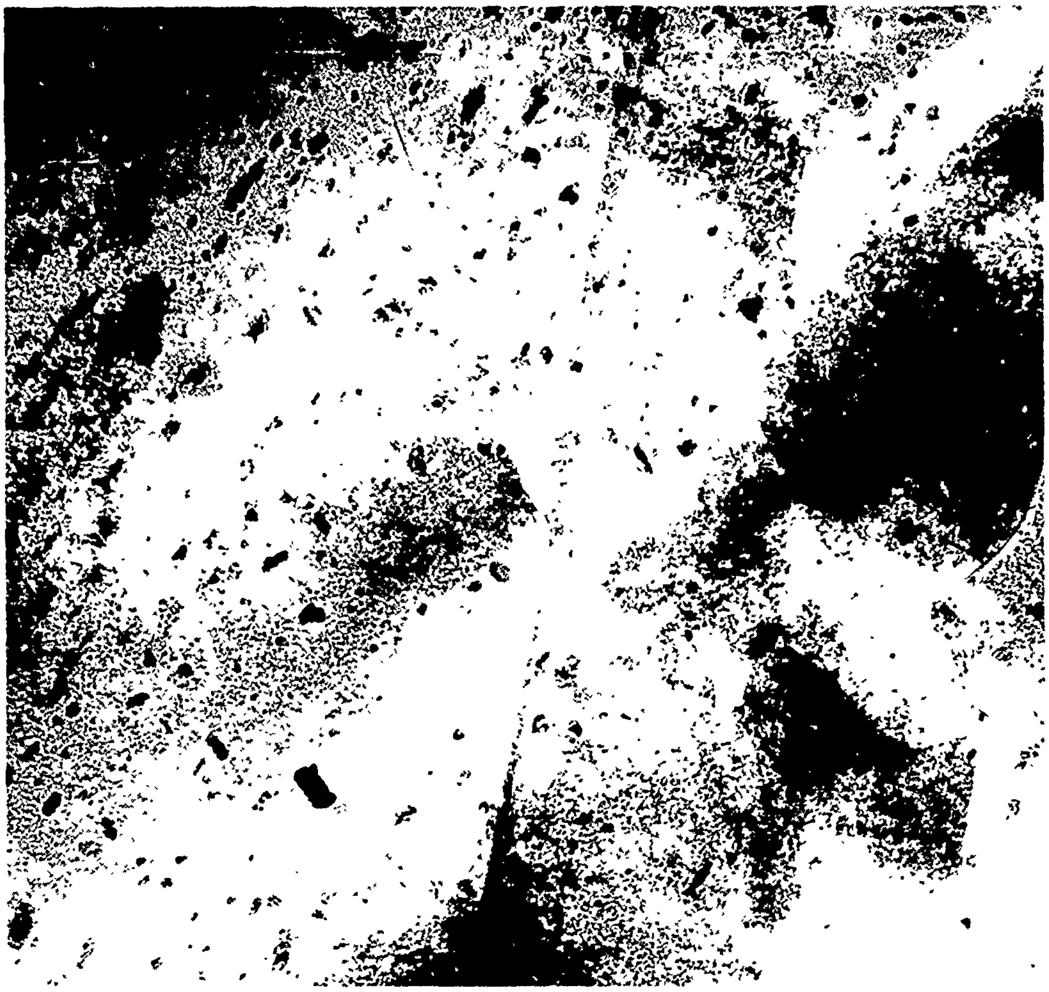
44,000X

Fig. F7a - Micrograph (TEM) showing the uniformly deformed regions of the recrystallized material. Note the η' particles with a few E particles inside the grain and the interaction between dislocation bands and the grain boundary.



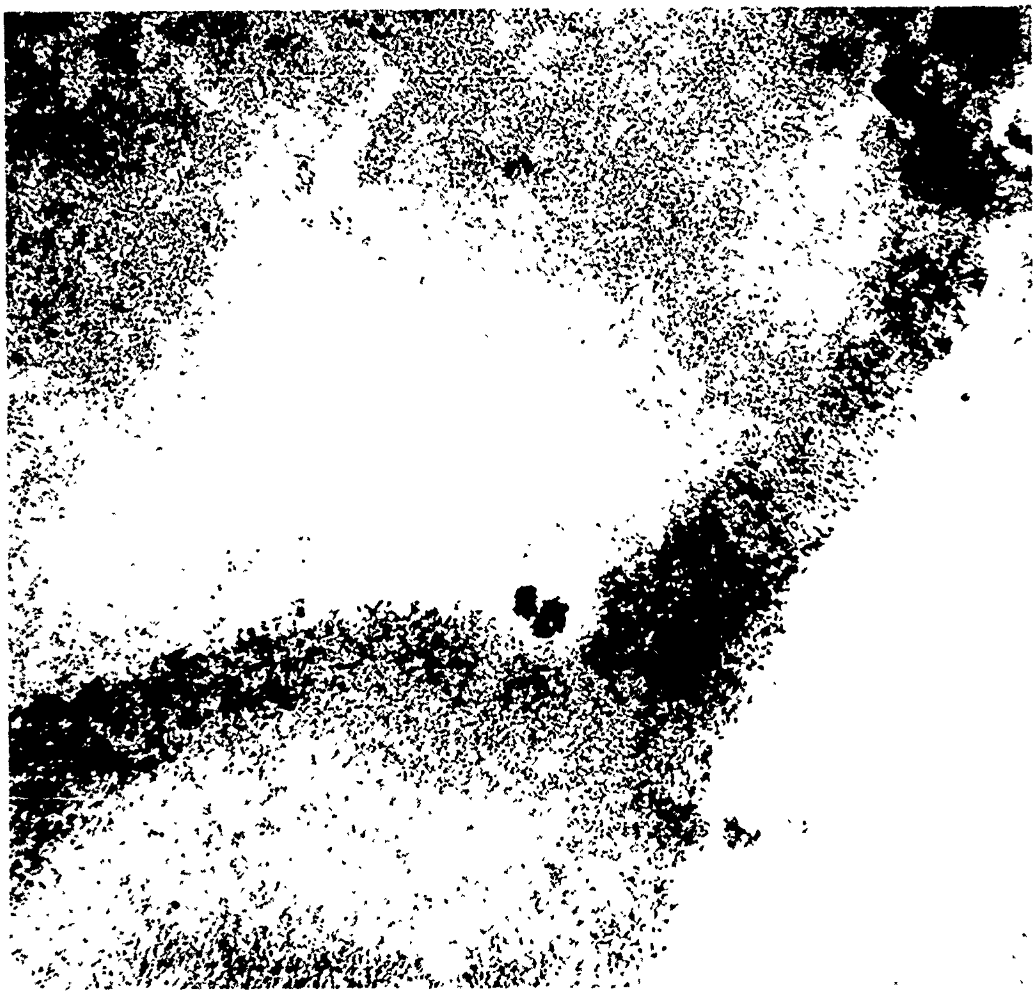
26,000X

Fig. F7b - Micrograph (TEM) showing the uniformly deformed regions of the recrystallized material. Note the preferential deformation of the grain boundary.



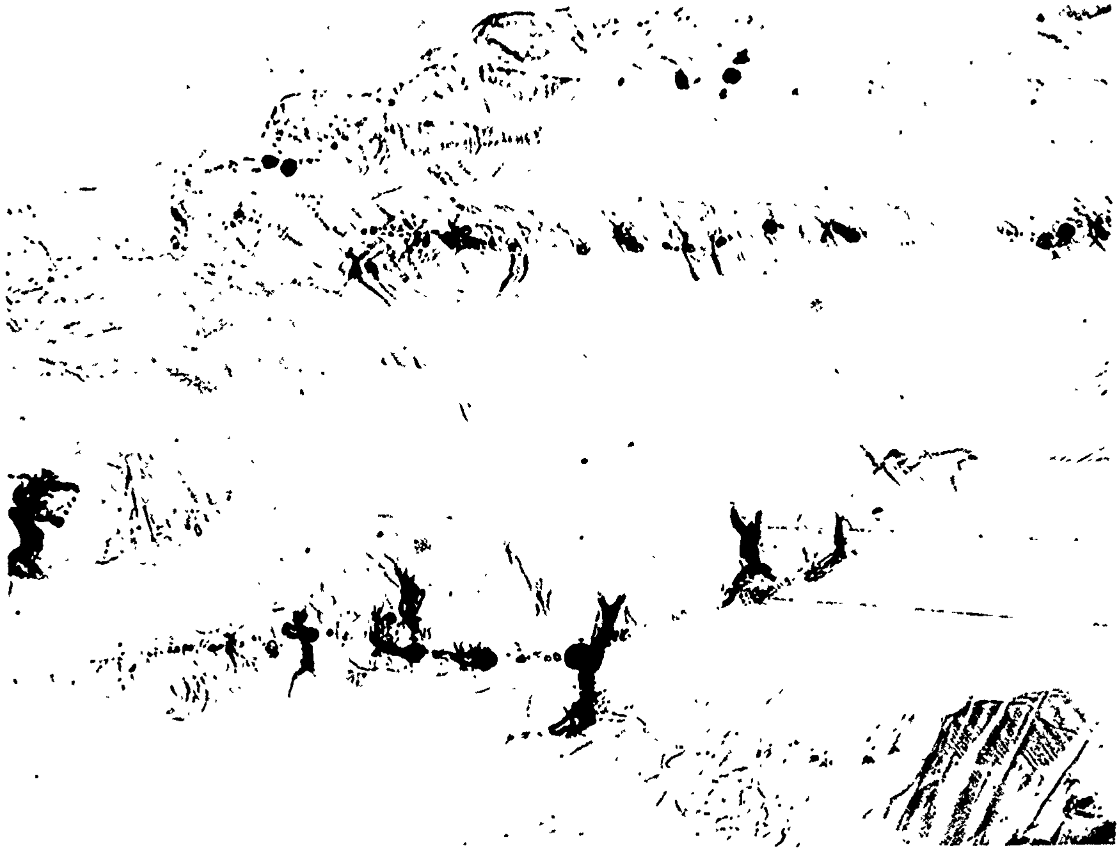
19,600X

Fig. F8a - Micrograph (TEM) showing the uniformly deformed regions of the recrystallized plus hot rolled material. Note the interaction between grain boundaries and dislocation bands.



44,000X

Fig. F8b - Micrograph (TEM) showing the uniformly deformed regions of the recrystallized plus hot rolled material. Note the preferential deformation at the grain boundary.

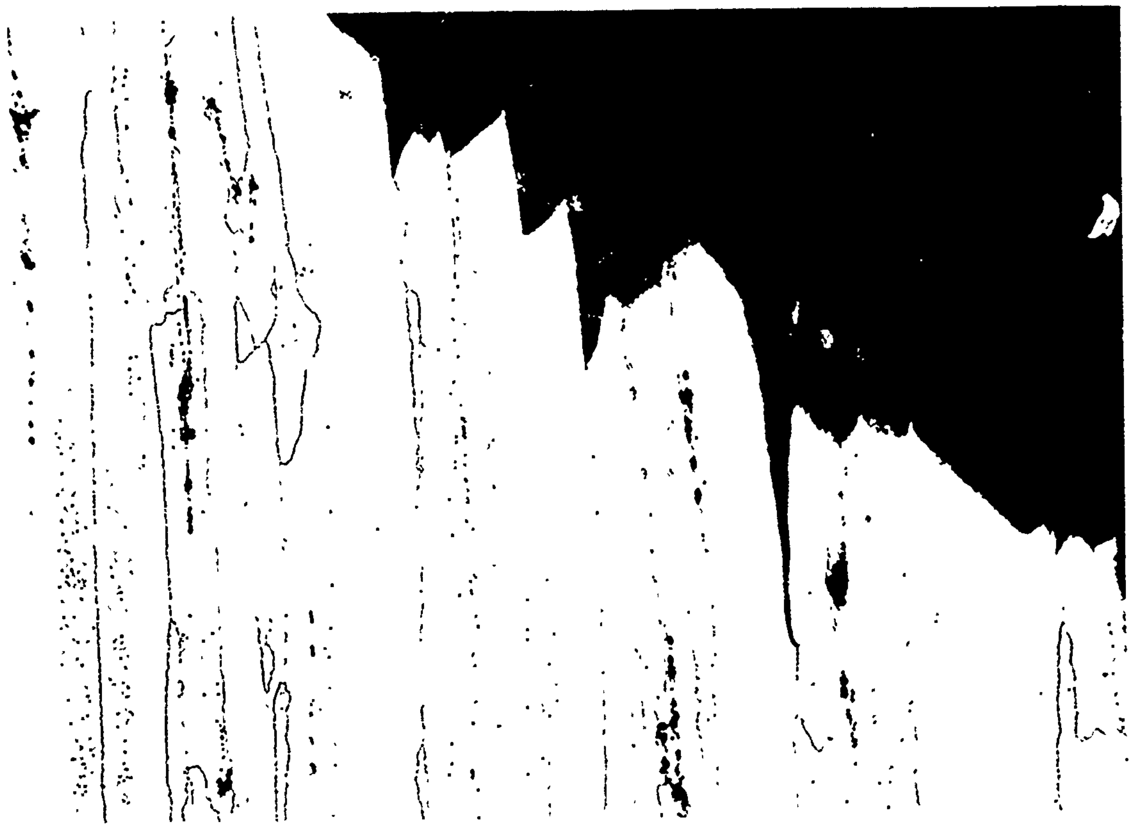


250X

Fig. F9a - Optical micrograph showing the slip line structure in the uniformly deformed region (L-T plane) of the unrecrystallized material. Note the well developed slip bands and the concentration of slip around large constituent particles.

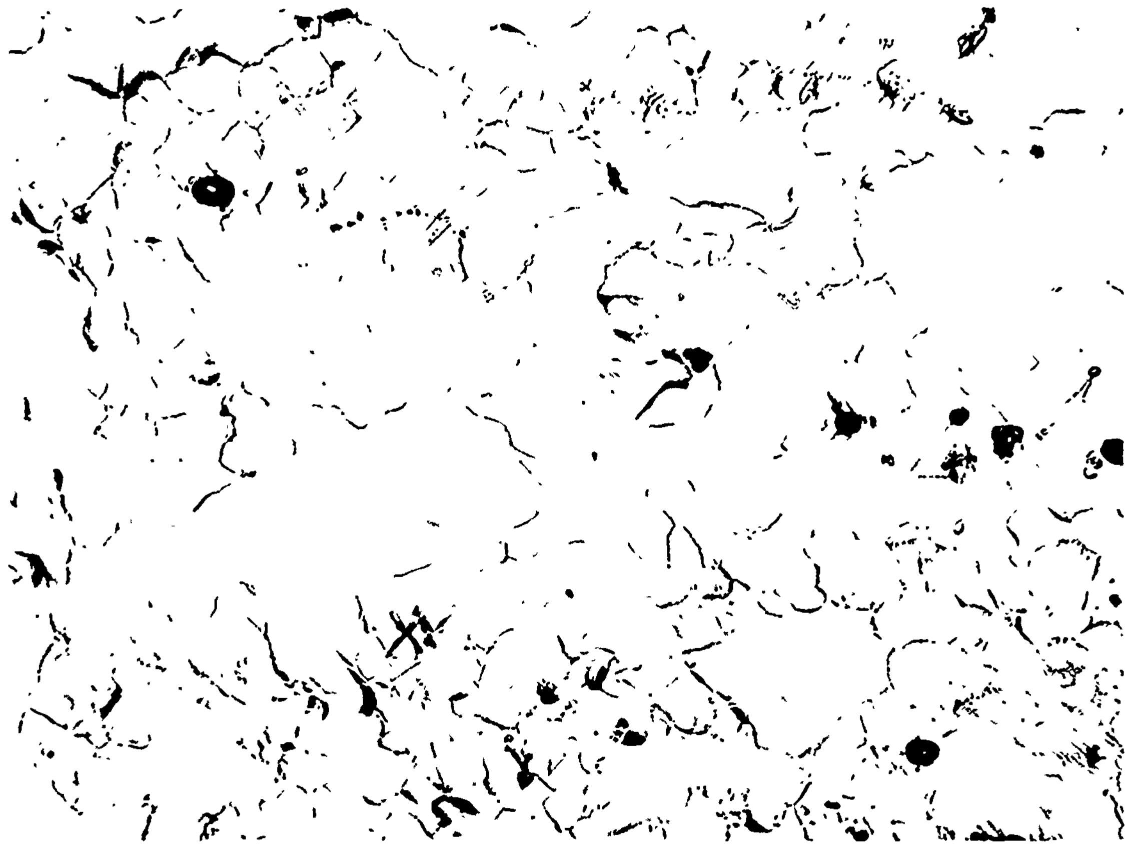
250X

Fig. F9b - Optical micrograph showing the slip line structure in the necked region (L-T plane) of the unrecrystallized material. Note that fracture predominantly followed slip bands.



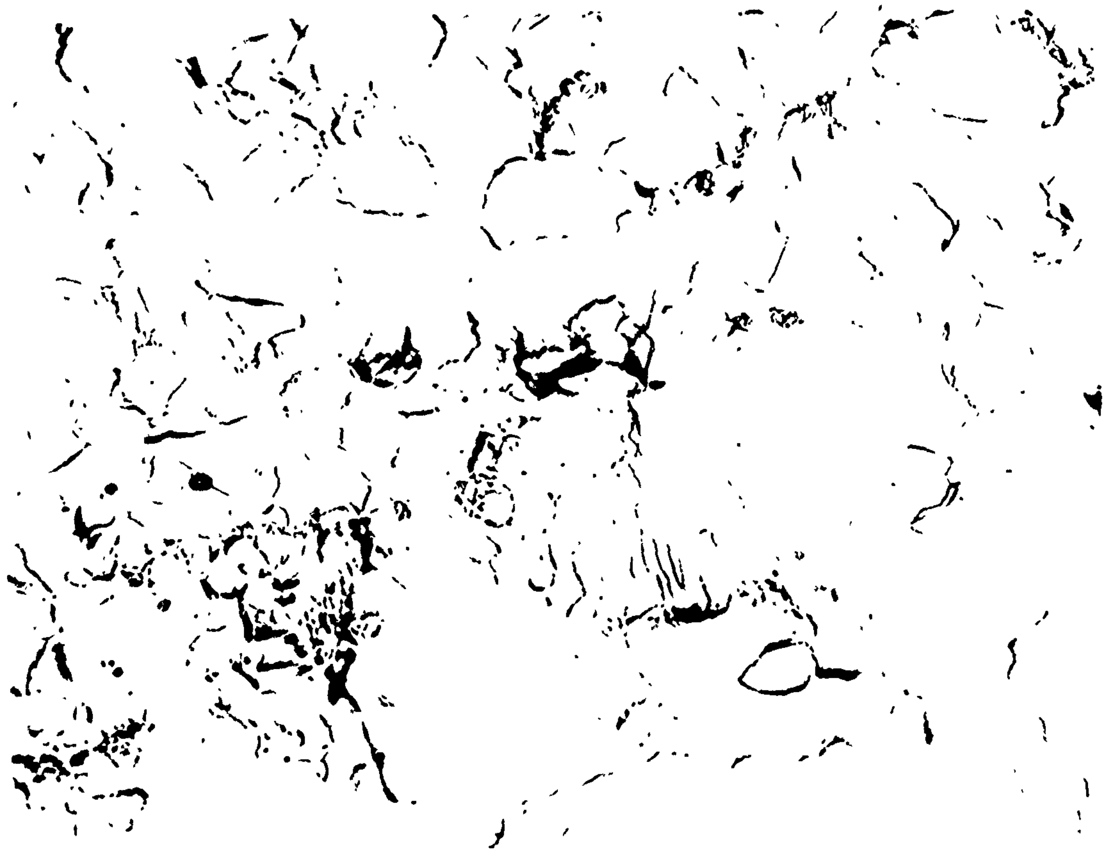
250X

Fig. F9c - Optical micrograph showing the fracture in the L-N plane of the unrecrystallized material. Note that fracture was initiated at the coarse constituents in many regions.



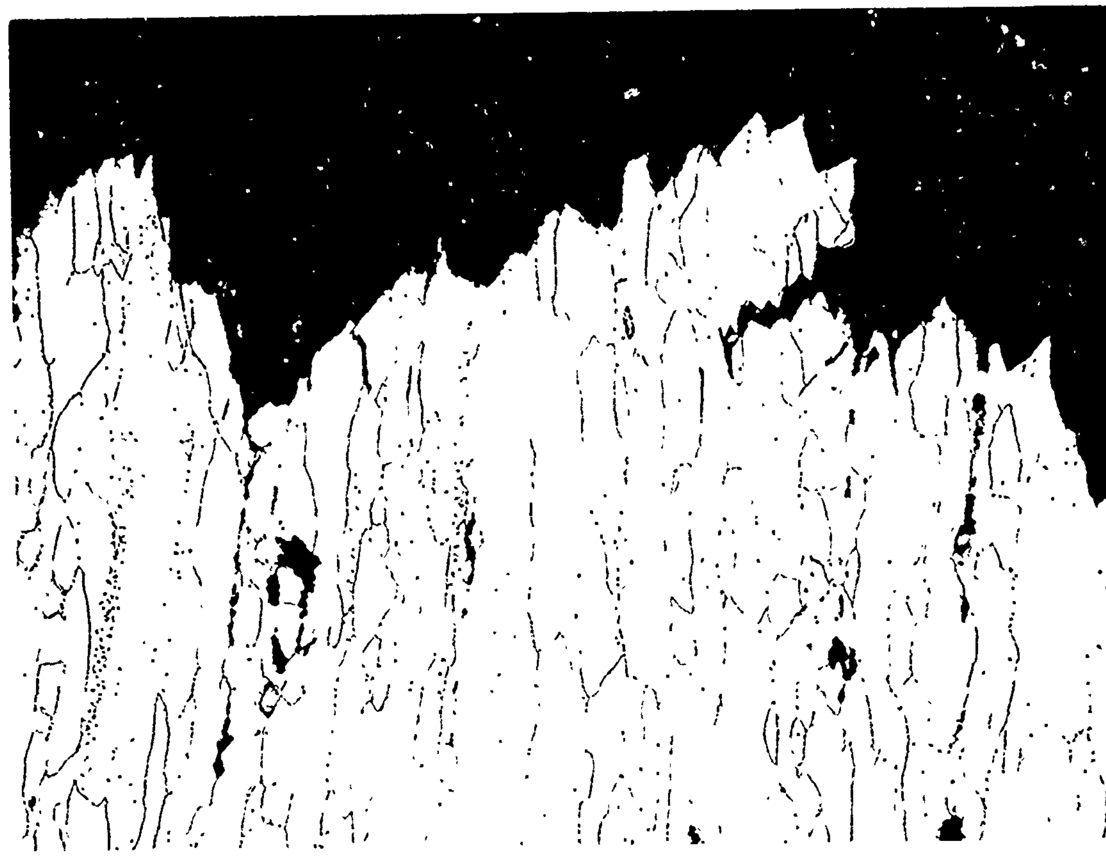
250X

Fig. F10a - Optical micrograph showing the slip line structure (L-T plane) in the uniformly deformed region of the recrystallized material. Note the grain boundary sliding in this material.



250X

Fig. F10b - Optical micrograph showing the sli[illegible] line structure (L-T plane) in the necked region of the recrystallized material. Note that cracking occurred mostly along grain boundaries.

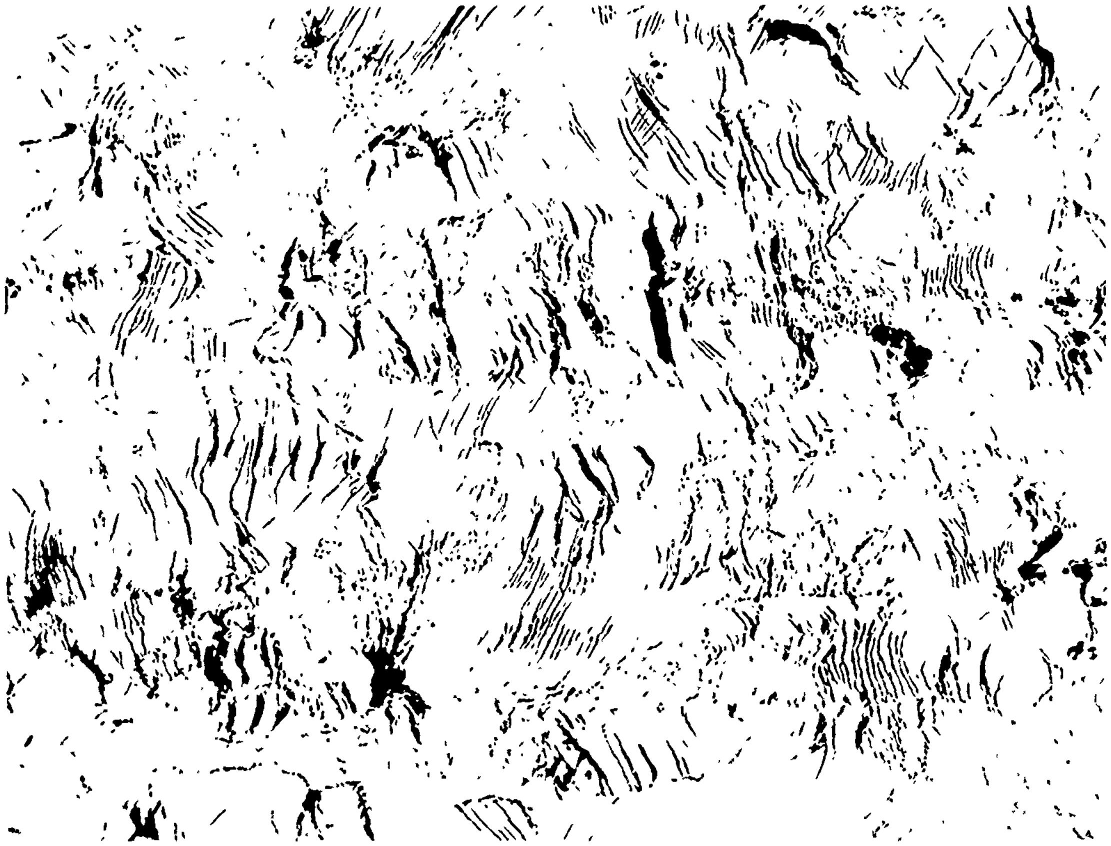


250X

Fig. F10c - Optical micrograph showing fracture in the L-N plane of the recrystallized material. Note that fracture path is predominantly intergranular.

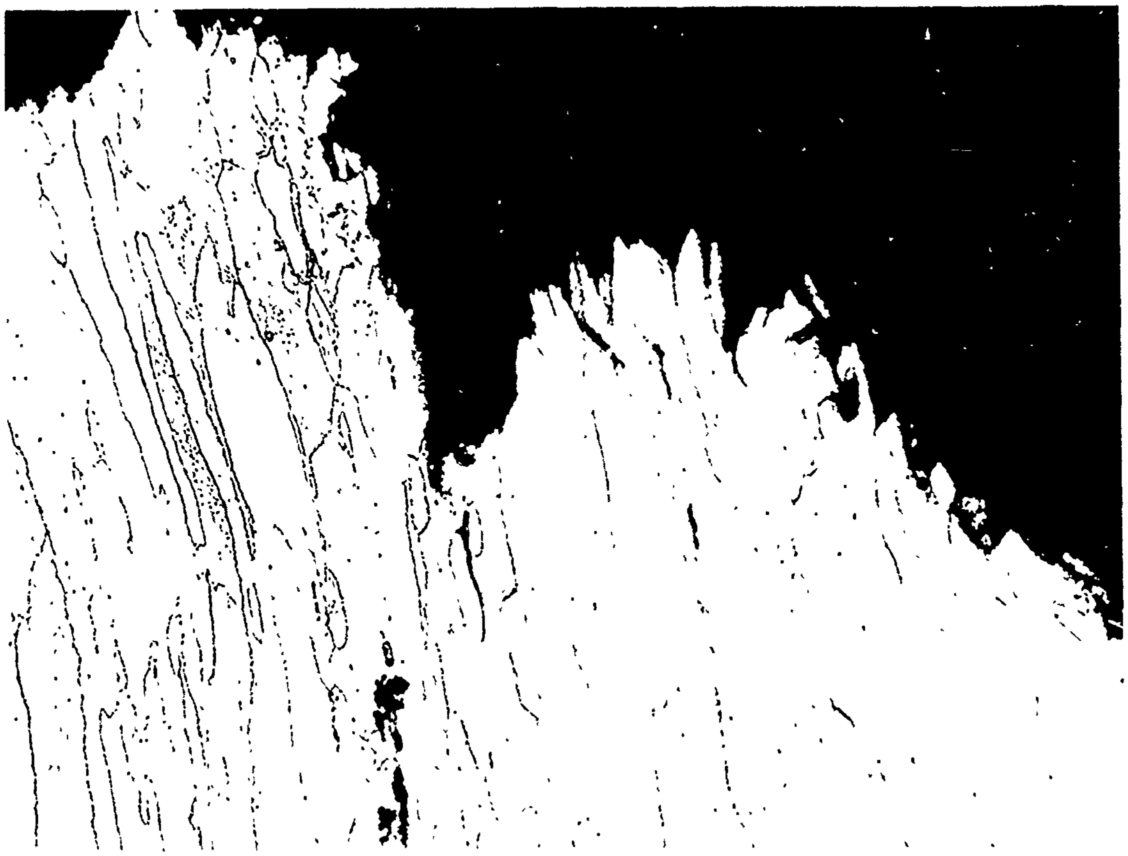
250X

Fig. F11a - Optical micrograph showing the slip line structures (L-T plane) in the uniformly deformed region of the recrystallized plus hot rolled material. Note the initiation of cracks at the grain boundaries and also at the slip bands.



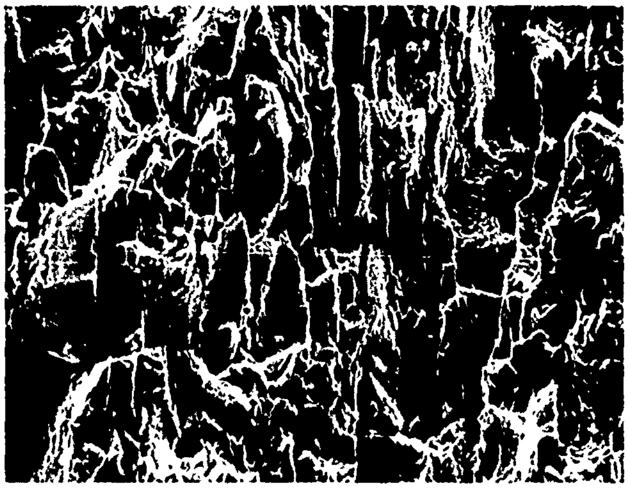
250X

Fig. F11b - Optical micrograph showing the slip line structures (L-T plane) in the necked region of the recrystallized plus hot rolled material. Note the intergranular-transgranular (mixed) mode of fracture.



250X

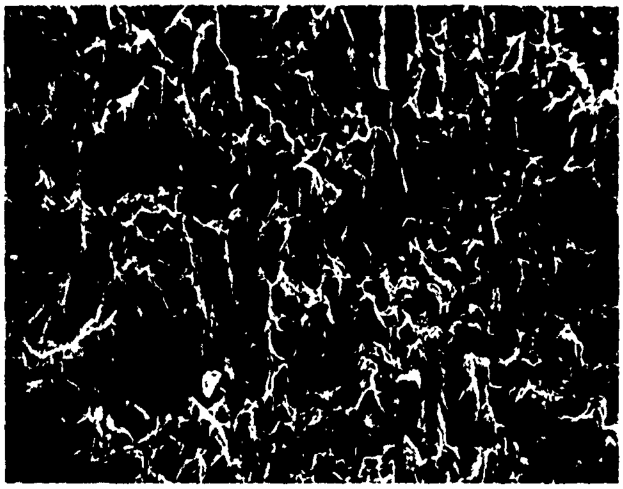
Fig. F11c - Optical micrograph showing the fracture in the L-N plane of recrystallized plus hot rolled material.



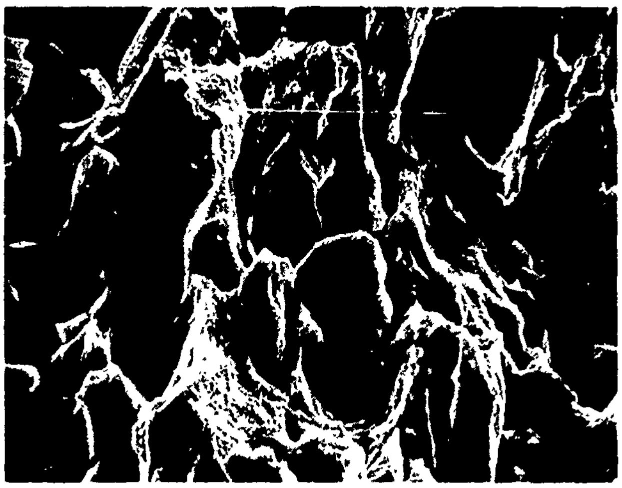
a. 200X

b. 1000X

Fig. F12 - Fractographs of fracture toughness specimen (L-T) of unrecrystallized material showing predominantly transgranular fracture.

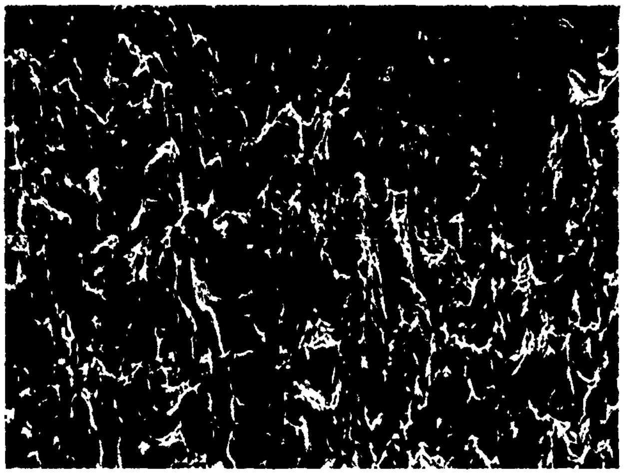


a. 200X



b. 1000X

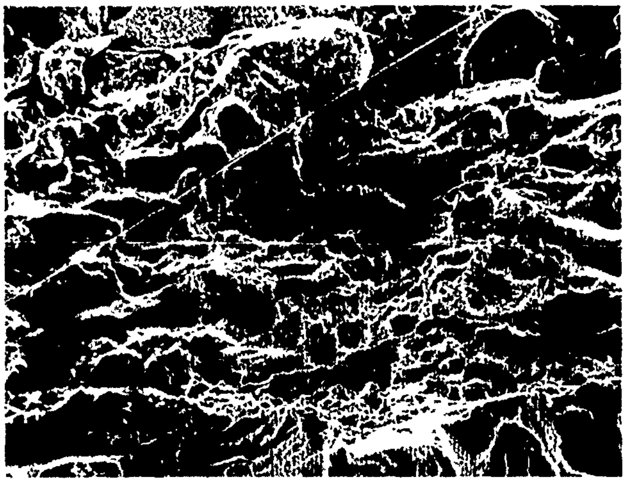
Fig. F13 - Fractographs of fracture toughness specimen (L-T) of recrystallized material showing predominantly intergranular fracture.



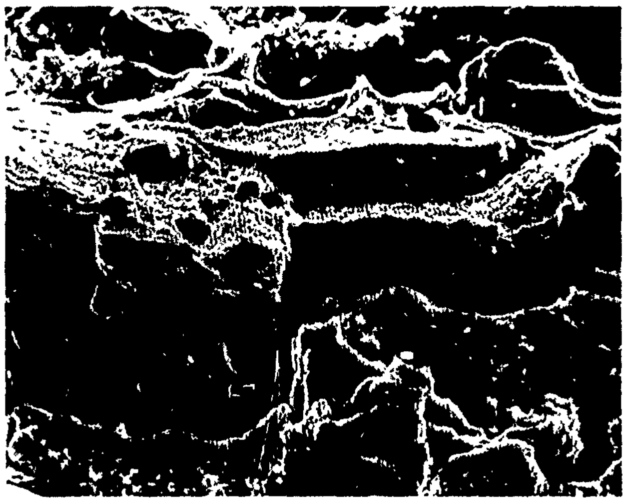
a. 200X

b. 1000X

Fig. F14 - Fractographs of fracture toughness specimen (L-T) of recrystallized plus hot rolled material showing a mixed mode intergranular-transgranular fracture.

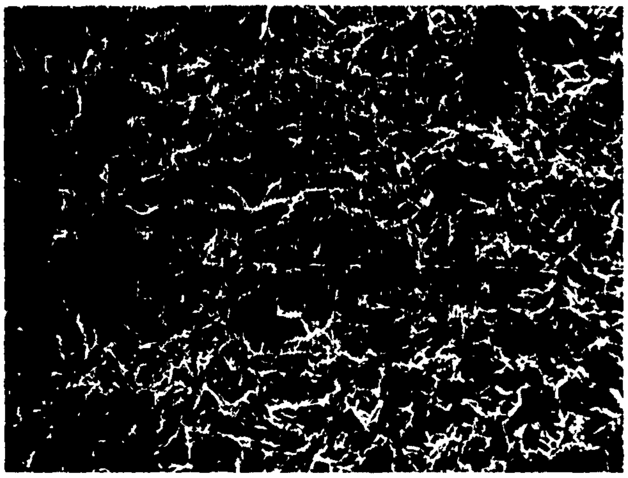


a. 100X

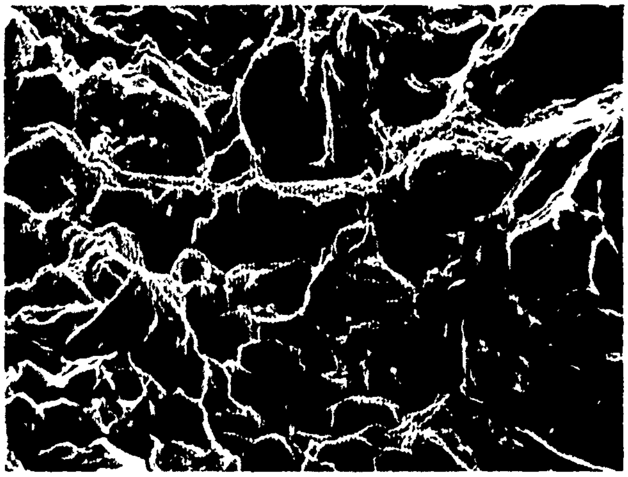


b. 500X

Fig. F15 - Fractographs of L notched tensile specimen of unrecrystallized material. Note the predominantly transgranular mode of fracture.

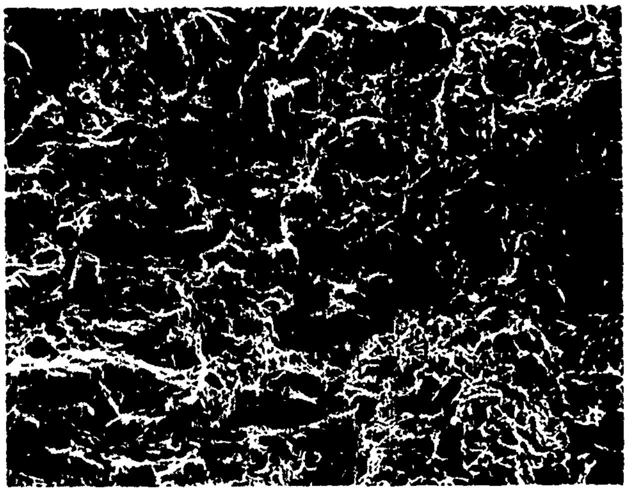


a. 100X

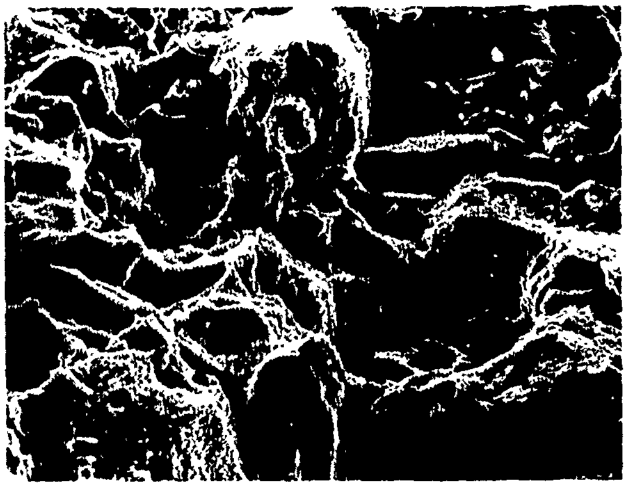


b. 500X

Fig. F16 - Fractographs of L notched tensile specimen of recrystallized material. Note the predominantly intergranular mode of fracture.



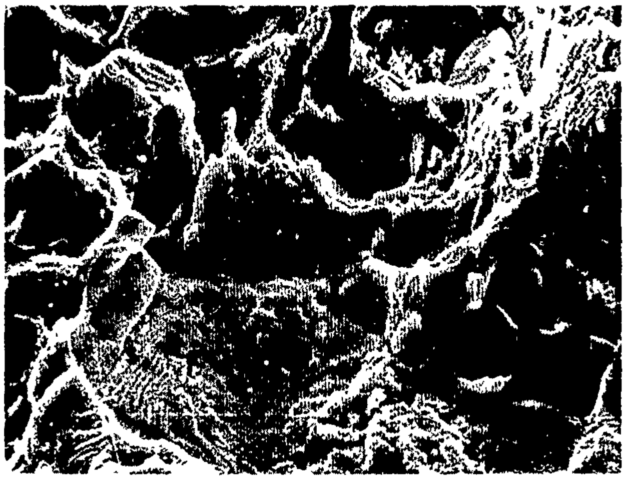
a. 100X



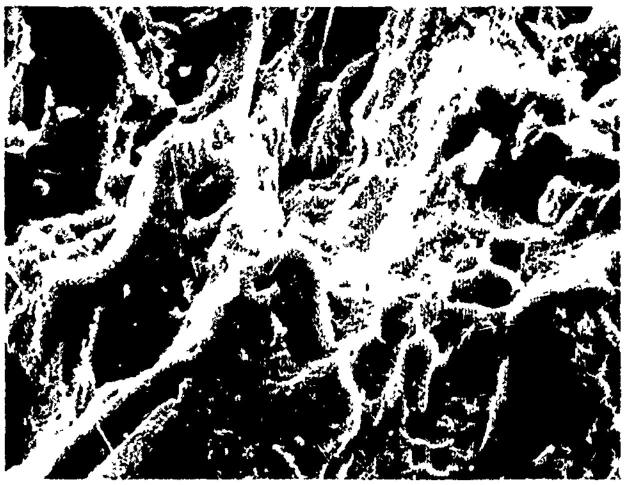
b. 500X

Fig. F17 - Fractographs of L notched tensile specimen of recrystallized plus hot rolled material. Note the mixed mode intergranular-transgranular fracture.

a. Unrecrystallized 1000X

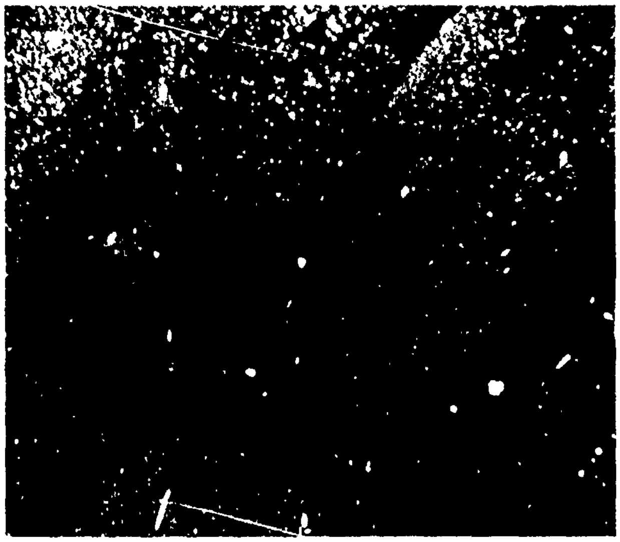


b. Recrystallized 1000X

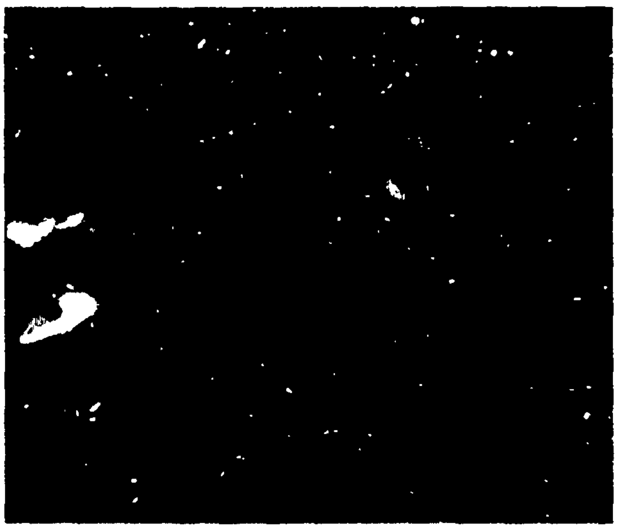


c. Recrystallized plus hot rolled 1000X

Fig. F18 - Scanning electron fractographs of fracture toughness specimens at the fatigue/overload transition regions. Shown are the fatigue precrack (f), the stretched zone (s), the cliff (c) and overload fracture (o).



a. Recrystallized 2000X



b. Recrystallized plus hot rolled 500X

Fig. 19 - Scanning electron micrographs of rapidly quenched samples.

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