SOLID ROCKET PLANT

EVALUATION OF HIGH-NICKEL STEEL FOR APPLICATION IN LARGE BOOSTER MOTOR FABRICATION

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EVALUATION OF HIGH-NICKEL STEEL FOR APPLICATION IN LARGE BOOSTER MOTOR FABRICATION

Third Quarterly Progress Report to
Aeronautical Systems Division
United States Air Force
Wright Patterson Air Force Base, Ohio

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PREFACE

The program reported herein was sponsored by the Aeronautical Systems Division, Wright Patterson Air Force Base, under Contract No. AF 33(657)8740, Task No. 738101. The work was performed under the direction of R. E. Anderson and P. P. Crimmins, with the assistance of the following research personnel: H. R. Smith, R. E. Handley, L. Albertin, and G. K. Hickox.

ABSTRACT

This report outlines the results of investigations conducted from January through March 1963 to determine the mechanical and metallurgical properties and weldability of the 18%-nickel maraging alloy steels. This work is being performed under Air Force Contract No. AF 33(657)-8740, Task No. 738101.

The information in this third quarterly report relates specifically to the results of studies conducted to (1) establish the mechanical and metallurgical properties, including fracture toughness, of parent-metal 18%-nickel alloy steels processed by different melting techniques; (2) determine the effect of varying weld-wire compositions on the mechanical and metallurgical properties of TIG-welded 1/2-in.-thick material; (3) determine the effect of the MIG and Submerged-Arc process on the mechanical and metallurgical properties of welded 1/2-in.-thick material; and (4) determine the fracture toughness of weld deposits and heat-affected zones. The selection of an optimum material was based on the results of these studies.

During this quarter, a supplemental program, which has increased the scope of fracture-toughness testing, was authorized by A.S.D. Progress made on this supplemental program is also presented herein.

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APPENDIXES

I. INTRODUCTION

The properties of 18%-nickel maraging steels are uniquely advantageous to the design and fabrication of large-diameter, solid-propellant rocket-motor cases. These advantages include: (1) potential yield strengths in the range of 200,000 to 300,000 psi; (2) exceptional toughness and crack resistance at these high strength levels; (3) simplified thermal processing, wherein a moderate-temperature aging cycle has replaced the austenitizing heat treatment that is generally used for low-alloy steels (which requires large, complex drop-bottom furnaces); and (4) good ductility. To fully define the properties and the heat-treating and welding techniques for the processing of this material, an evaluation and test program was initiated under Air Force Contract No. AF 33(657)-8740, Task 738101. The overall objectives of this program include determination of the effect of variables in mill processing, alloying, heat treatment, and welding; and preparation of material and processing specifications applicable to the fabrication of large-diameter (more than 200 in.) rocket motor chambers by rolling and welding. In addition to the basic study being performed under the original Research and Development Program, additional investigations of parent- and weld-metal fracture toughness have been initiated. These studies were included in a supplemental program and will be reported herein under Phase II, Task C—Crack Propagation.

The data presented in this report summarize the results of investigations conducted to date. Detailed information developed during the third quarter (January through March 1963) of the research program is presented and, where applicable, is related to data reported for the first and second quarters.

II. OBJECTIVES

This program is divided into four phases. The objective of each follows:

PHASE I: Establish the effect of mill practice on material quality and properties.

II, Objectives (cont.)

PHASE II: Develop adequate data to establish maximum usable strength levels by correlating tensile strength with fracture toughness and notch sensitivity.

PHASE III: Develop reliable welding techniques that will result in mechanical properties equivalent to those of parent material.

PHASE IV: Prepare material and process specification by use of the information generated in the subject program.

III. TECHNICAL PROGRESS SUMMARY

In accordance with the program outline presented as the first monthly report, dated 13 August 1962, and the supplemental program outlined herein in Phase II, Task C, the following technical progress has been achieved.

A. PHASE I, ESTABLISHMENT OF MILL PRACTICES

Eight steel mills and the International Nickel Co. were visited to discuss the effect of melting and mill-processing practices on the properties of 18%-nickel maraging steels. The results of these visits and subsequent literature surveys were presented in the previous Quarterly Reports. In general, the effects of mill processing variables on material properties were not available, because each company considers its control of melting parameters, breakdown and rolling practices, etc., as proprietary information. However, some of the influences of mill practices on material properties and quality are evident from the evaluations being conducted in this program.

III, Technical Progress Summary (cont.)

B. PHASE II, MATERIAL EVALUATION

1. Task A, Standard Material

a. Aging Response With Longitudinal Tests

The 18%-nickel alloy selected to provide a base-line evaluation is Bethlehem Steel Co. Heat 120D163. This heat was air-melted, vacuum-degassed, and rolled into 1/2-inch-thick plate. Evaluations required in this task have been completed and the results reported in the two previous quarterly reports.

In the past, some doubt as to the accuracy of reported chemical analyses has existed. During this reporting period, a "round-robin" chemical analysis of the Bethlehem material (Heat 120D163) was completed. Chemical analytical laboratories at Allegheny Ludlum, Bethlehem Steel, and Aerojet-General participated in this project, the results of which are shown in Figure 1. As indicated by this data, the results from all three laboratories showed good correlation. This close correlation indicates that the analytical procedures presently being employed at Aerojet-General are accurate within the limits shown in Figure 1.

In an effort to further improve these confidence limits, additional chemical analyses of the other materials being evaluated in this program are being conducted. Figure 2 presents the results of chemical analyses conducted to date on the additional materials being evaluated. As noted, there is some difference between the certified analyses reported by the material suppliers and the results of the AGC analyses. These differences are thought to result from the fact that analyses supplied by the mill represent ladle analyses. This would explain the differences shown in Figure 1 between the Bethlehem certified analyses and their subsequent analysis conducted in the "round robin". The difference between the ladle analysis and the chemical analysis of the plate would also indicate that the results of ladle analyses cannot be used as an acceptance criteria.

b. Transverse Direction

The effect of rolling direction on the mechanical properties of Bethlehem Heat 120D163 was determined by transverse smooth and notch tensile tests. The results indicated that the material was slightly anisotropic in that the transverse yield strengths were approximately 10 ksi higher than the longitudinal yield strength. This effect has been attributed to the rolling practice used in producing the plate. The amount of anisotropy will probably vary among producers, depending on the particular finishing and cross-rolling practice employed by each producer. The results of the completed investigation were reported in the second Quarterly Report (0705-82Q-2).

c. Solution Treating

The effect of solution-annealing (1500°F for 30 min) prior to aging was determined for Bethlehem Heat 120D163. The results of this task were also reported in the Second Quarterly Report (0750-82Q-2). In general, solution-annealing prior to aging increased the aged tensile properties in comparison to material tested in the as-rolled-and-aged condition. This effect would normally not be expected since the "hot—cold" working produced during rolling should result in higher as-rolled-and-aged strength levels. Further investigations are being conducted to determine the reasons for these effects.

III, B, Phase II, Material Evaluation (cont.)

2. Task B, Additional Materials

a. 250-ksi Air-Melted (United States Steel Corp.)

The initial test results obtained in the evaluation of this material (Report 0705-82Q-1) contained some scatter. Consequently, additional test specimens were processed and aged in a furnace with temperature control within ± 5°F. The average results of these tests are presented below (Test Series B) and compared with the results of the initial tests (Series A). Individual Test data for Test Series B are shown in Figure 3.

Test Series	Aging Treatment		Rolling Direction	0.2% Offset Yield Strength ksi	Ultimate Tensile Strength, ksi	Elong. in 1 in. %	Area Reduction %
	Temp, °F	Time, hr					
A	850	4	Long.	230.2	244.0	9.8	43.7
B			Long.	251.7	262.9	9.0	39.6
A	850	8	Long.	263.7	273.5	9.1	38.5
B			Long.	260.1	271.6	8.6	38.9
A	900	4	Long.	245.3	258.7	11.0	40.1
B	900	4	Long.	264.7	272.6	7.6	37.2
A			Trans.	240.5	255.0	9.9	41.9
B			Trans.	243.2	255.3	9.5	40.7
A	950	2	Long.	266.7	276.0	8.1	36.4
B			Long.	264.3	272.0	7.7	38.5
A	950	4	Long.	261.4	273.5	7.2	35.6
B			Long.	266.2	276.3	7.6	39.2

III, B, Phase II, Material Evaluation (cont.)

In general, the average results of the two test series agree quite well, except for data at the 850°F, 4-hr., aging cycle and at the 900°F, 4-hr (longitudinal orientation) aging cycle. The reason for the differences may arise either from the furnace temperature control encountered in aging the specimens for Test Series A or from the fact that both cycles represent a transitional aging treatment between a partially and fully aged condition. Additional tests to verify these phenomena are in progress.

b. 250-ksi Vacuum-Arc-Remelted (Republic Steel Corp.)

Three heats of material were obtained for evaluation. The composition of each heat is shown in Figure 2. Previous data reported in the first and second Quarterly reports (0705-82Q-1 and 2) indicated that Heat 3888471 was defective because of the presence of massive inclusions tentatively identified as titanium sulphides. The analysis of this material showed a high titanium content, but the sulphur was within the specification limits (0.1 max) for the alloy (Figure 2). Further tests to definitely establish the nature of these inclusions are in progress. However, in view of the high inclusion ratings obtained for this material, no further properties evaluations of this heat are planned.

The two additional heats (3888472 and 3888473) have been "spot" tested at one aging temperature. The results of these tests were reported in the second quarterly report and indicated that the heats are of acceptable quality. Also, representative photomicrographs shown in Figures 4 and 5 indicate that the inclusion content and microstructure of both heats are satisfactory and meet the AGC material specification (refer to Appendix B), although some inclusion stringers similar to those previously reported for the standard material were found in material representative of Heat 3888473 (see Figure 4). Additional tensile testing to establish the aging response of both heats is currently in process.

III, B, Phase II, Material Evaluation (cont.)

c. 200-ksi Vacuum-Degassed (Lukens Steel Co.)

This material was supplied to the Lukens Steel Co. by the Allegheny Ludlum Steel Co. (Heat 28889) and rolled by Lukens to 1/2-in.-thick plate. The chemical analysis of the alloy is shown in Figure 2. Test data and aging-response curves were presented in the second quarterly report (0705-82Q-2) and indicated that the 200-ksi yield-strength level was obtained by aging at 900°F for 4 hours. Higher strength levels (210- to 215-ksi yield strength) were obtained by aging for longer times (8 and 16 hours) at 850°F and 900°F. Typical results of metallographic studies to evaluate material microstructure and inclusion content are shown in Figures 6 and 7. The results indicate that the material is of satisfactory metallurgical quality.

d. 225-ksi Air-Melted (Allegheny-Ludlum)

Aging-response studies to evaluate the tensile properties of 225-ksi-yield-strength, air-melted 18%-nickel maraging steel have been completed. The material used in these studies was air-melted 1/2-in.-thick plate (Heat 10675) supplied by the Allegheny Ludlum Steel Corp. Testing was conducted with material aged in the as-received condition, as well as with material that had been solution-annealed at 1500°F for 30 minutes prior to aging. Four-in.-square billet material from the same heat was also supplied by Allegheny Ludlum and is currently being tested. The average results of the tensile tests conducted on specimens obtained from the 1/2-in. plate aged at various times and temperatures are summarized below and plotted in Figures 8 and 9. Individual test data are shown in Figure 10.

III, B, Phase II, Material Evaluation (cont.)

Aging Treatment		Rolling	Solution-Annealed 1500°F for 30 min. and Aged				As-Received-and-Aged			
Temp, °F	Time, hr	Direction	0.2% Y.S.	UTS	% El*	R/A	0.2% Y.S.	UTS	% El*	R/A
850	4	Long.	225.0	231.6	10.9	58.9	214.0	222.0	11.8	58.5
	8	Long.	222.0	235.3	12.9	58.2	217.1	224.8	11.5	56.1
		Trans.	224.3	231.9	11.4	54.3	217.2	226.8	10.9	53.8
	16	Long.	235.2	241.8	10.6	55.4	227.8	237.0	11.6	53.8
900	2	Long.	225.8	230.5	12.3	57.6	204.8	217.4	12.6	57.2
	4	Long.	225.1	235.5	12.2	55.4	214.3	228.3	10.3	52.3
		Trans.	232.4	238.3	10.8	57.1	217.5	226.4	11.4	57.2
	8	Long.	234.7	242.1	11.4	54.3	225.6	234.8	10.7	50.9
		Trans.	245.2	250.8	11.5	55.4	228.2	237.4	11.2	52.8
	16	Long.	239.6	247.1	9.2	52.6	234.6	243.4	9.2	49.4
950	2	Long.	233.0	236.7	10.6	56.0	220.1	226.9	11.2	56.6
	4	Long.	229.1	237.4	11.7	55.7	222.9	231.0	10.3	56.4

* Percent Elongation, 1-in. gage length

As indicated by the above data, in the as-rolled-and-aged condition this material developed properties in excess of 200-ksi yield strength. Aging proceeds at 850 and 900°F for all times up to 16 hours. At 950°F there is some indication that overaging has occurred after the 4-hour cycle. At the 210- to 225-ksi yield-strength level, the steel has excellent ductility, as measured by percent elongation and reduction of area. A slight anisotropic condition was also observed in that the transverse properties are approximately 10 to 12 ksi higher than those in the longitudinal direction. This effect has been observed in other maraging steels which have previously been tested and is thought to be the result of the particular rolling practice employed in producing the plate.

The general effects noted above for the material in the as-rolled-and-aged condition are also found in material that has been solution annealed at 1500°F prior to aging; except that solution-annealing reduces the difference between transverse and longitudinal properties that was found in material aged in the as-rolled condition. In addition, solution-treating prior to aging has resulted in an increase in yield strength of approximately 10 to 15 ksi and is accompanied by no significant change in ductility as measured by % elongation and reduction in area. This effect has also been previously observed in testing the Bethlehem 250-ksi material (Heat 120D163).

The results of metallurgical evaluations of both the 225-ksi air-melted 1/2-in. plate and the 4-in.-square billet are shown in Figures 11 through 15. Fields illustrating the typical inclusion content and microstructure of the 1/2-in.-plate material are shown in Figures 11 and 12 and are typical for this type of material. Typical macrostructure, inclusion content, and microstructure of the 4-in.-square billet material are shown at three locations within the billet in Figures 13 through 15. Although the microstructure and inclusion contents are considered satisfactory, the macrographs (Figure 13) indicate some presence of alloy segregation, particularly in the center and near the edge of the billet. The effects of this segregation will be evaluated through the current aging-response tests being conducted on this material.

e. 300-ksi Vacuum-Arc-Remelted (Vanadium Alloys Steel Co.)

This material was procured as 1/2-in.-thick plate and 4-in.-square bar stock. Tensile-property evaluations using material aged in the as-received condition have been completed and plotted in Figure 16. The average results of smooth and notched tensile tests are shown below. Individual test data are shown in Figure 17. Evaluations of both the billet material and the solution-annealed-and-aged plate material are in progress, as are fracture-toughness tests.

III, B, Phase II, Material Evaluation (cont.)

Aging Treatment Temp, °F	Time, hr	Rolling Direction	0.2% Y.S. ksi	UTS ksi	% El*	R/A %	NTS ksi
850	8	Long.	294.4	304.8	8.4	42.2	294.2
850	16	Long.	302.0	313.4	7.9	37.5	276.8
900	2	Long.	285.2	293.0	8.8	41.1	331.0
		Trans.	282.0	296.1	8.6	40.5	--
900	4	Long.	292.2	301.4	9.4	42.3	325.6
		Trans.	293.6	302.9	8.1	36.9	265.9
900	8	Long.	300.4	310.1	9.0	42.2	286.4
		Trans.	301.9	310.1	8.1	38.0	275.1
900	16	Long.	306.3	315.3	8.5	37.9	260.6
950	2	Long.	289.9	301.2	9.3	43.2	323.0
		Trans.	--	--	--	--	343.7
950	4	Long.	296.6	306.6	8.2	38.8	271.5
950	8	Long.	290.8	304.0	8.2	37.9	255.4

* 1-in. gage length

The data presented above indicate that the 300-ksi yield-strength level is attained by aging at 900°F for either 8 or 16 hours and at 850°F for 16 hours. In each instance, good ductility, as measured by % elongation and reduction in area, is achieved; however, the notch tensile strength is lower than the tensile ultimate strength and may indicate low fracture toughness. This factor will be further evaluated by means of slow notch bend and precracked-impact tests.

The aging response as measured by both the ultimate and yield strengths is comparable to that reported previously for the other 18%-nickel maraging steels evaluated in this program; i.e., aging is still proceeding at 850°F and 900°F for times up to and including 16 hours; overaging occurs at 950°F on aging at 8 hours. However, there is little difference in the ductility

(% elongation and reduction in area) as a function of aging cycle. It is also significant to note that there is little difference in properties as a function of specimen orientation in respect to the plate rolling direction.

The results of metallurgical evaluations of the 1/2-in. plate and 4-in.-square billet are shown in Figures 18 through 21. A typical field illustrating the inclusion content of the 1/2-in.-thick plate is shown in Figure 18 and indicates that the material is of extremely high quality and superior in inclusion rating to the other plate materials evaluated to date. Microstructure evaluations for the plate are currently in process.

Typical macrostructure, inclusion content, and microstructure of the 4-in.-square billet are shown at three locations within the billet in Figures 19 through 21. These illustrations indicate that the billet material is of high metallurgical quality, uniform throughout, and superior in inclusion rating to the air-melted 225-ksi 4-in.-square billet material previously evaluated.

3. Task C, Crack Propagation

a. General

The results of fracture-toughness (G_c) studies with the standard material (Bethlehem Heat 120D163), conducted under the basic program plan, have been reported in the previous quarterly reports. These studies were conducted by use of slow notch bend tests. In addition to these studies, supplemental fracture-toughness evaluations that expand the overall fracture-toughness test program have been authorized. Under this supplemental program, two general areas are to be investigated, as outlined below. The progress to date in each area is also indicated.

III, B, Phase II, Material Evaluation (cont.)

b. Parent-Material Evaluations

(1) Standard Material, Bethelem Heat 120D163

The general objective of this task is to provide both additional baseline parent-metal fracture-toughness data and a comparison of results obtained from the following fracture-toughness testing techniques:

Slow Notch Bend Test
Partial-Thickness Crack Test
Center Notch Tensile Specimen
Precracked-Impact Test

All specimens are to be heat-treated in a group by solution-annealing (1500°F-30 min) and aging, using a cycle selected on the basis of previous evaluations.

The status of this phase is shown below; Figure 22 indicates the test results obtained to date.

Test Technique	Status
Slow Notch Bend	Complete
Precracked-Impact	Complete
Plate-size center notch tensile	Partially Complete
Plate-size partial-thickness crack	In test

The center notch tensile specimens are 8 in. wide by 32 in. long; the partial-thickness crack specimens are 28 in. long with a 3-in.-wide gage length.

It should be noted that these tests are partially complete; consequently, it is difficult to establish definite conclusions in regard to the comparison of results among the different test methods. It is also significant that extensive modifications have been made in both the slow notch bend test procedure and in the resultant calculation of fracture-toughness values.

III, B, Phase II, Material Evaluation (cont.)

These modifications are outlined in Appendix A of this report. One modification was required because of a modification in the formula by which the fracture-toughness (G) value is calculated. The net effect of this modification was to reduce by a factor of two the previously reported fracture-toughness values (G_c) obtained by use of the slow notch bend testing technique. These data have been corrected, and the true fracture-toughness values (G_c) are given in Figures 22 through 24. (Although the modified formula changes the numerical value of fracture toughness, the trends previously established remain the same.)

The second modification in the slow notch bend testing procedure results in a measurement of G_{nc} rather than G_c values. This revision, outlined in Appendix A, is required because of the inaccurate load—load deflection-curve slope measurements obtained in the calculation of G_c when materials of intermediate and high fracture-toughness are being evaluated. The G_{nc} value should closely approximate plane strain-fracture toughness (G_{ic}), which is of prime importance in evaluating the toughness of plate material. The data in Figure 22 show that the fracture-toughness (G_c) values obtained in both the precracked-impact test and the center notch tensile-specimen test indicate the same general toughness level, whereas the toughness values (G_c) obtained with the slow notch bend test are considerably lower. The latter values, however, are generally in agreement with the results shown in Figure 23, which were obtained during the original evaluation of the standard material. It should be noted that the fracture-toughness results (G_c) for the standard material obtained by the slow notch bend test were calculated by use of the original test procedure. Consequently, some inaccuracies in the slope measurements of the load—load deflection curve may have been encountered, which resulted in a toughness value intermediate between G_c and G_{nc}. This hypothesis will be further evaluated by use of slow notch bend test specimens, which will be obtained from the shoulder area of the center notch and partial-thickness crack tensile specimens currently being tested.

III, B, Phase II, Material Evaluation (cont.)

It is also significant to note the effect of fatigue cracking on the results of the center notch tensile test. As indicated in Figure 22, the effect of fatigue-cracking is significant, in that lower, more consistent fracture-toughness values are obtained. Since fatigue-cracking prior to testing has been recommended by the ASTM fracture-toughness committee, future test specimens of this type will be fatigue-cracked before they are tested.

Precracked-impact tests were performed at ambient temperatures and at -100, 0, +200, and +400°F to determine the variation in toughness as a function of test temperature. The results of these studies are shown in Figure 25 and are plotted as a function of test temperature in Figure 26. As indicated by these data, as the test temperature is raised or lowered, a corresponding general increase or decrease in toughness occurs with no clear indication of a transition temperature near room temperature.

(2) Additional Materials

The objective of this task is to provide fracture-toughness data for the additional 1/2-in.-thick plate materials evaluated in Phase II, Task B. The materials to be evaluated, the required test method to be employed, and the current status of each are shown below. Each material will be evaluated in both the as-rolled-and-aged and the solution-annealed-and-aged conditions.

Material	Tests to be Conducted	Status
Air-Melted-and-Degassed, 200-ksi (Lukens Steel Co.)	Slow notch bend Precracked-Impact	Complete Partially complete
Air-Melted, 225-ksi (Allegheny Ludlum Steel Corp.)	Slow notch bend Precracked-Impact	Complete In process
Air-Melted, 250-ksi (U. S. Steel Corp.)	Slow notch bend Precracked-Impact	Partially complete In process
Vacuum-Arc-Remelted, 250-ksi (Republic Steel Corp.)	Slow notch bend Precracked-Impact	In process In process
Vacuum-Arc-Remelted, 300-ksi (Vanadium Alloys Steel Co.)	Slow notch bend Precracked-Impact	In process In process

III, B, Phase II, Material Evaluation (cont.)

The results of tests conducted to date are presented in Figures 27 through 30 and are discussed below.

(a) 200-ksi Vacuum-Degassed (Lukens Steel Co.)

The results of slow notch bend tests conducted with the 200-ksi, air-melted and vacuum-degassed material in both the as-rolled-and-aged and the solution-annealed-and-aged conditions are shown in Figures 27 and 28, respectively. It should be noted that the fracture-toughness results shown in Figure 27 represent G_c values whereas those presented in Figure 28 represent G_{nc} values. Consequently, a direct comparison to determine the effects of solution annealing cannot be made until additional tests using the precracked-impact test specimens have been completed. However, the fracture-toughness values (G_c) shown in Figure 27 are significantly higher than those previously reported (Figures 22 through 24) for both the Bethlehem material (Heat 120D163) and the U. S. Steel material (Heat X-13371) at 245- to 265-ksi yield strength. There also is a toughness difference in the 200-ksi material as a function of specimen orientation; the best combination of longitudinal and transverse fracture toughness is obtained after aging for either 4 hr at 900°F or 8 hr at 850°F.

Figure 29 indicates the results of initial precracked-impact tests conducted to evaluate the fracture toughness (G_c) of the 200-ksi, vacuum-degassed material. In addition to the parent metal, the toughness of the weld and that of the heat-affected zone were also evaluated. Welding was performed with 250-ksi weld-wire composition by the TIG process. As indicated by the data in Figure 29, the fracture toughness (W/A) of the parent material is high and is comparable to that obtained with low-alloy steels, such as Ladish D6ac and HMS M-255, at the 160- to 180-ksi yield-strength level. The parent-metal tests results (W/A) also indicate that fracture-toughness values (W/A)of 1100 in.-lb/in.^{2} obtained by use of the precracked-impact test are

III, B, Phase II, Material Evaluation (cont.)

comparable to toughness values (G_{nc}) of approximately 150 in.-lb/in.^{2} obtained in the slow notch bend test. This correlation will be further evaluated during the additional fracture-toughness tests required in this program.

It is also apparent from the data shown in Figure 29 that the fracture toughness of the heat-affected zone is lower than that of the parent metal and may indicate a potential problem area that will be further evaluated. The toughness of the weld zone is considerably lower than that of either the parent metal or the heat-affected zone. This latter effect was expected because 250-ksi-yield-strength weld wire was used for welding. Further, it is significant to note that solution-annealing following welding and prior to aging did not improve the toughness of either the weld or the heat-affected zone.

(b) 225-ksi Air-Melted (Allegheny Ludlum Steel Corp.)

The initial results of slow notch bend tests conducted on the 225-ksi air-melted material in the solution-annealed-and-aged (1500°F for 30 min) condition are shown in Figure 30, and indicate that the toughness of this material is comparable to that of the 200-ksi vacuum-degassed alloy (see Figure 28). Further, there is no significant difference in toughness in respect to specimen orientation; the best toughness values are obtained after the 900°F, 4-hr aging treatment. Additional tests to evaluate this material with both the slow notch bend and the precracked-impact tests are currently in progress.

(c) Additional Materials Evaluated Under an AGC Test Program

In addition to the materials tested in this program, two heats of vacuum-degassed 260- to 275-ksi, 18%-nickel maraging steel have been evaluated in slow notch bend and precracked-impact tests. The results of these studies are shown in Figure 31. In general, these data substantiate that previously obtained in evaluating the 250- to 260-ksi standard material (Figure 23). The G_{nc} values obtained by the slow notch bend test for both the 260-ksi (Heat 120D298) and 270- to 275-ksi (Heat 120D097) materials are considerable lower than those for the 200- and 225-ksi alloys previously discussed. The precracked-impact test results (W/A) are also proportionally lower (400 to 450 in.-lb/in.^{2} vs 1100 in.-lb/in.^{2}) than those shown in Figure 29 for the 200-ksi vacuum-degassed material. Also, on the basis of the data in Figure 31, it appears that fracture-toughness values (W/A) of 350 to 450 in.-lb/in.^{2} obtained with the precracked impact test are comparable to fracture-toughness values (G_{nc}) of approximately 90 to 140 in.-lb/in.^{2} obtained with the slow notch bend test.

(3) Optimum Material

The objective of this task is to provide fracture-toughness data for the optimum material by means of the precracked-impact and slow notch bend test specimens. Selection of the chemical composition of the optimum material was based on the results of aging-response and fracture-toughness tests conducted on the standard and additional materials. This optimum material will be procured as 3/4-in.-thick plate and 1-in.-and 4-in.-thick ring-rolled forgings. Test specimens in both the solution-annealed-and-aged and the as-rolled-and-aged (or as-forged-and-aged) conditions will be tested. Longitudinal- and transverse-oriented specimens from the 3/4-in.-thick plate and 1-in.-thick ring-rolled forging will be evaluated, along with longitudinal, transverse, and short transverse specimens from the 4-in.-thick ring-rolled forging.

(4) Weld- and Heat-Affected-Zone Evaluations

The objective of this task is to provide fracture-toughness data for both the weld and heat-affected zones of welded 18%-nickel maraging steel. These studies will be conducted with the optimum material and two weld-wire compositions selected on the basis of welding investigations currently in process. Two welding techniques will be used for processing the test plates, and both slow notch bend and precracked-impact tests will be used to evaluate fracture toughness.

4. Material Quality

A discussion of initial studies to evaluate the effects of prior (mill) processing on material quality was presented in the second Quarterly Report (0705-82Q-2). In general, portions of the material processed by the three major melting techniques being evaluated were found defective. In most instances, the defects were inclusions, stringers, alloy segregation, or defects such as internal laminations resulting from localized concentrations of inclusions. These effects have been further evaluated with ultrasonic nondestructive testing techniques and an 18- by 24-in. section of the 1/2-in.-thick, standard plate material (Bethlehem Heat 120D163).

To determine the presence of internal flaws, the 18- by 24-in. section of the standard material was ultrasonically inspected by means of a 5-megacycle, 1/2-in. transducer and the longitudinal-mode-and-pulse-echo technique. The instrument (Sonoray Model 5) was calibrated so that the signal representing the first back reflection reached the top grid line on the instrument's scale. Figure 32 depicts the initial pulse and the first two reflections from the back of the plate. It is significant to note that the attenuation losses are negligible, as evidenced by the very minor difference in the first and second back-reflection signal amplitudes, and permit the direct measurement of flaw indications without compensating for attenuation losses.

The sensitivity used for the inspection was dictated primarily by the predominance of strong signal reflections from discontinuities present in the plate. At the settings used, reflections from a 13/64-in.-dia flat-bottom hole that was located 3/8 in. from the transducer had a signal amplitude of 60% of full scale. Signals from many discontinuities found in the plate exceeded this amplitude. Since the second back-reflection was not needed for the inspection, the oscilloscope presentation was adjusted so that only the initial pulse and the first back-reflection would be seen (Figure 32b). The instrument was calibrated in such a manner that a full-scale back-reflection signal from the back surface of the plate was located three grid spaces to the right of the initial pulse representing the front surface (see Figure 32b). The plate was slowly scanned with the transducer restricted to a straight-line movement parallel to the edge of the plate. This was repeated at 1/4-in. intervals until the entire plate was inspected. The area and signal intensity associated with each discontinuity was recorded on the plate and on a map of the plate (Figure 33). A typical oscilloscope trace of a internal defect is shown in Figure 32c. In this instance, the signal amplitude is in excess of the 60% of full scale associated with a 13/64-in. flat-bottomed hole, and the location of the defect is about 1-1/2 grid spaces to the right of the initial (contact surface) pulse. The latter observation positions the defect approximately half way through the thickness of the plate. Because the initial impulse obscured information concerning the quality of the plate near the transducer to a depth of approximately 3/16 in., the plate was scanned from both sides.

Three intense ultrasonic indications were checked by metallographic inspection at locations P, R, and S shown on the ultrasonic map in Figure 33. During mounting of these specimens, subsurface cracks were observed. Figure 34 shows the defect at location R at two different magnifications and indicates the presence of gross aluminate stringers. Similar defects are shown in Figures 35 and 36 for sections P and S respectively.

Attempts to detect these defects by means of a shear mode of vibration were unsuccessful. Several angles of incidence, transducers of different frequencies, and various sensitivity levels were employed without success. In view of both this result and the results of the longitudinal scans, it was assumed that the attitude of the discontinuities found was parallel to the plate surfaces. This assumption was verified by the subsequent metallurgical evaluations. It is further significant to note that no transverse thickness defects were found during the ultrasonic inspection, which indicates that most plate defects, such as internal laminations, seams, etc., would probably be oriented in the most favorable attitude, i.e., parallel to the plate surfaces.

Although the contact method was used in this investigation, either the immersion, or the contact-immersion, technique is superior and is recommended for the ultrasonic inspection of plates and forgings used in the fabrication of large-diameter booster motors. Furthermore, no surface defects have been found on any of the plate materials inspected by dye-penetrant or magnetic-particle techniques. However, surface-quality inspection by means of these tests is also recommended for plate and forgings used in the fabrication of large booster motors.

In addition to the metallurgical tests conducted on the standard and additional materials evaluated in the ASD program, similar investigations were conducted at Aerojet-General on Bethlehem Heats 120D298 and 120G097. The results of these studies were essentially the same as those from the studies of the standard material (Bethlehem Heat 120D163), except that pronounced banding was present in material (1/2-in.-thick plate) representative of Heat 120D298. This effect is shown in Figure 37. No such banding or alloy segregation was found in the vacuum-arc-remelted material evaluated to date. However, it is significant that banding has not been shown to have a detrimental effect on tensile and fracture-toughness properties.

5. Optimum Material

Although the results of the metallurgical, aging-response and fracture-toughness studies that are being performed on the standard and additional materials have not been completely determined, sufficient data exists to permit

III, B, Phase II, Material Evaluation (cont.)

the selection of a strength level and a chemical composition for the optimum material. The selection of the material is based on the best combination of strength and fracture toughness. From the data previously discussed under Task C, Crack Propagation, and summarized in Figure 38, it is evident that for plate thicknesses of 1/2 in. and greater, material yield strengths in excess of approximately 240 ksi are accompanied by questionable fracture-toughness values. However, the fracture toughness of 1/2-in.-thick 18%-nickel maraging-steel plate at 200- to 235-ksi yield strength is significantly higher and compares favorably with that of low-alloy-steel-plate material, such as Ladish D6aC and AMS-M-255 at the 160- to 180-ksi yield-strength level. Consequently, the use of the 18%-nickel maraging steel at a yield-strength level of 200 to 235 ksi is recommended.

In an effort to establish the effect of cobalt, molybdenum and titanium contents on the yield strength of the 18%-nickel maraging steel, a multiple regression analysis of the variation in yield strength vs chemical composition has been performed. The heats of material evaluated to date in the ASD-sponsored program, along with thirteen additional heats evaluated under separate Aerojet-General company-sponsored programs, were used in this study. On the basis of the results of this study, the following approximate equation, which indicates the expected 0.2% offset yield strength as a function of Cobalt, Molybdenum and Titanium content, has been developed:

$$\text{Yield strength (ksi)} = 15.1 + 9.1\ )\%\ \text{Co}) + 28.3\ (\%\ \text{Mo}) + 80.1\ (\%\ \text{Ti}).$$

The application of this equation to determine the strength-level-vs-chemical-composition limits indicates that material produced to restricted titanium, cobalt and molybdenum ranges, which can be controlled by the steel mills, will vary as much as 35 ksi in yield strength. This effect has also been established in the aging response studies conducted on both the standard and additional materials. Consequently, to maintain the yield strength at a level that exhibits high fracture toughness (below 240-ksi yield strength) it is

III, B, Phase II, Material Evaluation (cont.)

necessary to specify a chemical composition that will result in a maximum allowable yield strength of approximately 235 ksi. Because of allowable variations in molybdenum, cobalt and titanium contents, the 200-class material could result in material of 235-ksi yield strength. The fracture-toughness data developed to date also indicates that it would be desirable to obtain the required strength level through increased molybdenum and cobalt contents while restricting the titanium to the lowest possible content. In view of these considerations, the following chemical composition has been selected for the optimum material.

Element	Minimum	Maximum
Carbon	--	0.03
Manganese	--	0.10
Phosphorous	--	0.025
Sulphur	--	0.01
Nickel	17.5	18.5
Titanium	0.05	0.25
Aluminum	0.05	0.15
Cobalt	7.5	8.0
Molybdenum	4.0	4.5

Purchase requests for this alloy in the form of 3/4-in.-thick plate and 1-in.- and 4-in.-thick ring-rolled forgings have been forwarded to eight steel mills. The specification, and amendments thereto, used for this request are shown in Appendix B. It is significant to note that the melting technique was not specified since the results of aging-response and fracture-toughness studies have indicated that any one of air-melt, air-melt-and-vacuum-degassed, or vacuum-arc-remelted material will be suitable. However, the material quality must meet the requirements outlined in Appendix B. It is also significant to note that all material will be ultrasonically and magnetic-particle inspected at the mill. By mutual agreement of ASD and Aerojet-General, the 200-ksi material was selected as an optimum alloy, and the specifications and inspection requirements shown in Appendix B were adopted.

III, Technical Progress Summary (cont.)

C. PHASE III, WELDING STUDIES

1. Task A, Effect of Weld-Deposit Composition

a. Weld-Deposit Chemistry Variations in TIG Welds

The chemical composition of tungsten inert-gas weld deposits made with six wires has been determined. The base material used was Bethlehem 1/2-in.-thick plate from Heat 120D163. The weld wires used were Special-Metals Heat 34312 and Allegheny-Ludlum Heats 7C-090, 7C-091, 7C-092, 7C-093 and 7C-094. Chemical analyses of these materials were made early in the program and reported in the last quarterly report. The variances in chemical composition reported by three laboratories led to a "round robin" to establish chemical analytical procedures and a subsequent Aerojet-General analysis that is considered accurate. The results of this analysis for the titanium, cobalt and molybdenum contents of TIG weld deposits, weld wire and parent metal are listed in Figure 39.

The data in Figure 39 indicate that the molybdenum content of the weld deposit approximates an intermediate value between the weld wire and base-plate material with little apparent molybdenum loss in transfer across the arc. In most instances the cobalt content of the weld also approximates an average between the base plate and the weld wire. The data for the 7C-090 wire indicates that there may be some cobalt loss during welding, although the analysis of the remaining weld deposits indicates that the relatively large difference between the wire and weld-deposit cobalt content for weld wire 7C-090 is due to a tendency for dilution between the wire and parent metal.

It should be noted that the chemical analyses of multiple-pass welds are approximate and that the results depend on many factors, such as location in the weld, segregation inherent in weld zones, etc. Consequently, the data in Figure 39 should be used to indicate general trends rather than for

III, C, Phase III, Welding Studies (cont.)

quantitative comparisons among the analyses of the weld deposit, weld wire and base plate. When considered in this respect, these data indicate that little molybdenum or cobalt are lost during the TIG welding process and that the resultant weld-deposit chemistry for molybdenum and cobalt tends toward values intermediate between the compositions of both the wire and the base plate. However, the data in Figure 39 for titanium indicate that there is a loss of this element during TIG welding with the loss being more severe for the higher titanium-content weld wires. This effect is shown by a comparison of the results for the 7C-091 and 7C-094 wires with the results for the 7C-093 and 34312 wires. In the former instances, titanium losses of 0.71% and 0.41% were encountered, whereas losses of only 0.03% and 0.02% titanium were shown for the 7C-093 and 34312 weld wires. These general effects have been reported by other investigators, including International Nickel Corp.

b. Relation of Weld-Deposit Chemistry to Weld Properties

The tensile properties, the notch tensile strength, and the radiographic quality of TIG welds in 1/2-in.-thick plate made with six different weld wires have been reported in previous reports. These results are summarized in Figure 40 and show the transverse-weld tensile and notch tensile (kt = 10) properties obtained for two different test series. Test-Series-A specimens were aged in furnace equipment with inadequate temperature control, whereas the second series (B) were aged in equipment having temperature control within 900°F ± 5°F. Consequently, the data for the Test Series B are considered more accurate and should be used to compare the properties obtained with the different weld wires.

On the basis of the tensile data, it is difficult to determine an optimum weld-wire composition since both the ultimate and yield strengths of the six weld wires differ only slightly. However, the high notch tensile-strength values indicate that either the 7C-093 or the 34312 wire composition would be preferable. The reason for the close agreement in the tensile properties of welds

III, C, Phase III, Welding Studies (cont.)

processed with weld wires 7C-090, 7C-091, 7C-092 and 7C-094 can be established by referring to the results of typical metallurgical evaluations of weld deposits made with these wires. These results are shown in Figures 41 and 42 for weld wires 7C-091 and 7C-092, respectively, and indicate that the tensile-specimen failures occurred predominately in the heat-affected zone adjacent to the weld-fusion line. Consequently, the strength of the heat-affected zone at the failure location, rather than the strength of the weld zone, has been measured.

In view of the high titanium content shown in Figure 39 for these weld deposits (except 7C-090), weld strength levels higher than that of the parent metal, with accompanying low notch tensile strengths, would be expected in these welds. The 7C-090 composition is considered undesirable because of the poor weld quality obtained with this wire. Conversely, the results of metallurgical investigations of weld deposits made with the 7C-093 and 34312 weld wires (Figures 43 and 44) show that failure of the tensile specimens occurred predominately through the weld deposit. In these instances, actual weld strength rather than parent-metal and/or heat-affected-zone properties were measured. These wire compositions also produce weld deposits of acceptable quality in regard to inclusion content and porosity.

Referring to the weld microstructures shown in Figures 41 through 44, an as-yet unidentified phase occurs between the larger dendritic grains. This phase is thought to be austenite formed as the result of alloy segregation, which might be expected in these areas. X-ray defraction studies to determine the nature of this phase are planned. In other respects, the microstructures shown in the weld deposits are considered typical of multipass welds in the 18%-nickel maraging steel.

In Figures 45 through 50, microhardness traverses of TIG welds made with the six wires are compared graphically with the tensile-specimen failure location. By comparing these figures with weld-deposit

III, C, Phase III, Welding Studies (cont.)

chemical composition shown in Figure 39, the relationship between weld-deposit titanium content, microhardness after aging, and tensile-specimen failure location is further illustrated. It should be noted that the gage length of the tensile specimen is located in the center of the original plate weld. Consequently the microhardness results in this area are considered representative of the center of the tensile specimen. The data shown in Figures 45, 48, and 50 for the 7C-090, 7C-093 and 34312 weld wires, respectively, indicate failure in the weld and a corresponding softened zone in the weld at the approximate failure location. As indicated in Figure 39, these welds possessed the lowest titanium content of the welds processed. Comparison of these results with Figures 46, 47 and 49, which represent weld deposits of relatively high titanium content, shows that failures of the high titanium-content welds have occurred in the heat-affected zone rather than in the weld.

On the basis of the previous discussion, it appears that the tensile and notch tensile strengths of the 18%-nickel maraging-steel TIG welds are closely associated with the weld-zone titanium content. It is also apparent that complex weld-wire—parent-metal dilution effects and weld microstructural effects associated with multipass welding have a pronounced effect on the weld-zone properties. This is illustrated by the fact that even though all the weld zones evaluated contained a higher percentage of titanium than the parent metal, failure was encountered in the weld zone of tensile specimens representing the lower weld titanium contents (0.57% and 0.64%). Since these titanium contents are significantly higher than that of the plate material (0.48%), it is reasonable to assume that the weld-zone alloying elements, including titanium, are in a form which does not permit either solution- or precipitation-strengthening to the same degree as in the parent metal, or that other microstructural effects, such as the dendritic structure, retained austenite, etc., are overriding factors.

III, C, Phase III, Welding Studies (cont.)

The separation of these effects in multiple-pass welds is an exceedingly difficult task. Moreover, a more complete understanding of the effects of these phenomena is required. In an effort to accomplish this task, it is planned to weld a test plate that contains successively shorter weld beads, which will enable an evaluation of how an increased number of weld passes affects the microstructures of both the weld and the heat-affected zones. After each suceeding pass, chemical analyses and metallurgical evaluations in both the as-welded and the welded-and-aged condition will be performed on both specimens representative of the root pass and composite weld structures representing the weld until the full 1/2-in. plate thickness has been joined. The 7C-093 weld wire and Bethlehem Heat 120D163 base plate will be used in these studies.

On the basis of the results obtained to date, the 7C-093 weld wire has been selected for weld-zone aging-response studies. As indicated in the previous discussions and by the mechanical properties shown in Figure 40, this (7C-093) composition results in weld strengths that closely approximate the yield strength of the parent metal and that are accompanied by high notch tensile strengths. Also, the tensile-specimen failures were located in the weld zone rather than in the heat-affected zone, thus permitting an actual evaluation of weld-zone properties.

2. Submerged Arc Weld Process

Submerged-arc welds have been processed by use of the standard base-plate material (Bethlehem Heat 120D163) and the five weld wires used in previous studies (Heats 7C-090, 7C-091, 7C-092, 7C-093 and 7C-094). The flux used was Linde L 709-5. Longitudinal- and transverse-weld tensile specimens were aged at 900°F for 4 hr after welding and tested to determine mechanical properties. The results of these tests are presented in Figure 51. Lack of ductility in the specimens is evidenced by low elongations and reductions in area; also, the strengths varied considerably in the longitudinal-weld specimens,

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even within groups of specimens made with the same weld wire. The reasons for the variations in strength of the transverse-weld specimens have not been conclusively established, but the failures are generally located in the weld deposit. Figure 52 shows a typical submerged-arc transverse tensile specimen and microstructures. Very little of the unidentified phase present in the microstructure of the TIG welds can be found in the submerged-arc weld microstructures.

On the basis of the discussion presented for the TIG welding process, of the type of failure shown in Figure 52, and of the low weld strength of the longitudinal submerged-arc-welded tensile specimens, low titanium content was expected in the submerged-arc weld deposit. Chemical analyses of submerged-arc weld deposits that substantiate the low titanium content have been made. Figure 53 shows these data and indicates that the molybdenum and cobalt contents of the weld deposit follow the same general trends established for the TIG welds. However, a substantially greater titanium loss is encountered during submerged-arc welding in comparison with TIG welding. There also appears to be no definite relationship between the titanium content of the weld wire and that of the corresponding weld deposit, in that weld-deposit titanium contents of 0.37% and 0.50% are obtained with weld-wire compositions of 1.65% and 0.67%, respectively. In view of these results and because of the inferior tensile properties obtained to date with the submerged-arc welding process, additional welding tests with this process will be limited. Some work with specially formulated fluxes is planned, but most of the welding studies will be concentrated on the inert-gas process.

3. Metal-Arc Inert-Gas Welding

Metal-arc inert-gas welds have been processed with the standard Bethlehem plate material (Heat 120D163) and the 7C-093 and 7C-094 weld wires. Subsequent radiographic inspection indicated considerable weld porosity and some areas of incomplete fusion. This condition was encountered when both pure argon and argon plus 2% oxygen were employed as a shielding

III, C, Phase III, Welding Studies (cont.)

media. Although the quality was improved when pure argon was used, the quality of welds representing each condition was considered poor. However, to evaluate the tensile properties of MIG welds, transverse-weld test specimens were obtained from porosity-free areas, aged at 900°F for 4 hr and tested. The results of these tests are shown in Figure 54. As indicated by these data, the ultimate and yield strengths of the MIG welds are high and comparable to those previously reported for the TIG welds. However, the ductility, as measured by % elongation and reduction in area, is lower than that reported for the TIG welds.

The location of the specimen fractures has been determined and metallurgical investigations to further establish the characteristics of the MIG welds are being conducted. All the fractures are located in the weld zone. The results of chemical analyses of the MIG welds are shown in Figure 55 and indicate the same general trends shown for the TIG welds. The cobalt content of the weld deposit approximates a value intermediate between the wire and the base plate. During submerged-arc welding, a small amount of molybdenum may be lost, but the loss in titanium is significant. Additional studies are currently being conducted to improve the quality of the MIG welds. This work will include the use of a TIG root pass and variations in shielding-gas composition and welding travel rates.

4. Weld-Restraint Testing

Weld-restraint tests are normally employed to evaluate the effects of different base-plate and weld-wire compositions on weld cracking sensitivity. However, this test is normally used only when weld cracking has been shown to be a problem. Since this phenomena has not been encountered in the welding of the 18%-nickel maraging steels, in either this program or other independent R & D programs at Aerojet-General, only limited weld-restraint tests are planned. This work will be conducted primarily to establish the general weld-restraint stress level at which cracking would occur. The "U-bar" fixtures to accomplish this are currently being designed, and testing will commence as soon as possible. The standard material (Bethlehem Heat 120D163) and the 7C-093 weld wire will be used in these tests.

Source	Composition, Wt %									
	C	Mn	P	S	Si	Ni	Al	Ti	Mo	Co
Original										
Bethlehem Certified Ladle Analysis	.017	.06	.005	.004	.18	17.84	.12	.55	4.80	8.25
"Round Robin" Results										
Bethlehem Check Analysis	.020	.05	.008	.006	.17	18.24	.060	.46	4.49	7.59
Allegheny Ludlum Check Analysis	-	-	-	-	-	18.45	.055	.48	4.49	7.90
Aerojet-General Check Analysis	.016	-	.005	.003	-	18.60	.060	.48	4.95	8.00
AGC Confidence Level Associated with Analytical Technique for Each Element										
Wet	50 PTA	±.02	±.002	±.002	±.02	±.20	±.02	±.04	±.15	±.20
X-Ray	-	-	-	-	-	±.20	-	±.04	±.15	±.20
Spectrographic	-	±.02	-	-	-	-	±.02	±.04	-	-

"Round Robin" Chemical Analysis of Bethlehem Plate, Heat 120D163

Figure 1

Material Source & Heat No.	Composition, wt %									
	C	Mn	P	S	Si	Ni	Co	Mo	Ti	Al
U. S. Steel, Ht. # 13371 - vendor certified analysis	.02	.04	.004	.009	.08	17.83	7.41	4.70	.46	.11
AGC Analysis	.023	-	.003	.009	.06	18.65	8.05	4.90	.52	.05
Republic Steel, Ht. # 3888471 - vendor certified analysis	.025	.11	.006	.004	.09	18.74	8.86	4.75	.75	.08
AGC Analysis	.019	-	.005	.006	-	18.90	9.0	5.20	.81	.08
Republic Steel, Ht # 3888472 - vendor certified analysis	.026	.11	.006	.006	.07	18.46	8.82	4.80	.62	.08
AGC Analysis	.019	.025	.006	.003	.08	18.60	9.10	5.10	.62	.07
Republic Steel, Ht # 3888473 - vendor certified analysis	.026	.08	.006	.007	.05	18.38	8.68	4.80	.67	.07
AGC Analysis	.020	.03	.005	.003	.07	18.80	8.82	4.85	.65	.07
Bethlehem Steel, Ht. # 1200163 - vendor certified analysis	.017	.06	.005	.004	.18	17.84	8.25	4.80	.55	.12
AGC Analysis	.016	-	.005	.003	-	18.60	8.00	4.95	.48	.06
Lukens Steel, (Allegheny Ludlum Ht. # 28889) - vendor certified analysis	.026	.03	.005	.010	.08	17.89	8.52	3.30	.09	.012
AGC Analysis	.020	.02	.005	.008	.07	18.00	8.51	3.30	.19	.07
Allegheny Ludlum Ht. # 10675 - vendor certified analysis	.008	.04	.001	.003	.02	17.69	8.60	3.16	.44	.17
AGC Analysis	.020	.028	.006	.003	.09	17.40	8.50	3.26	.42	.30
Vanadium Alloys Ht. # 07148 - vendor certified analysis	.02	.04	.005	.007	.04	19.00	9.28	5.00	.68	.24
AGC Analysis	.018	.03	.006	.003	.09	18.7	9.30	5.12	.65	.39

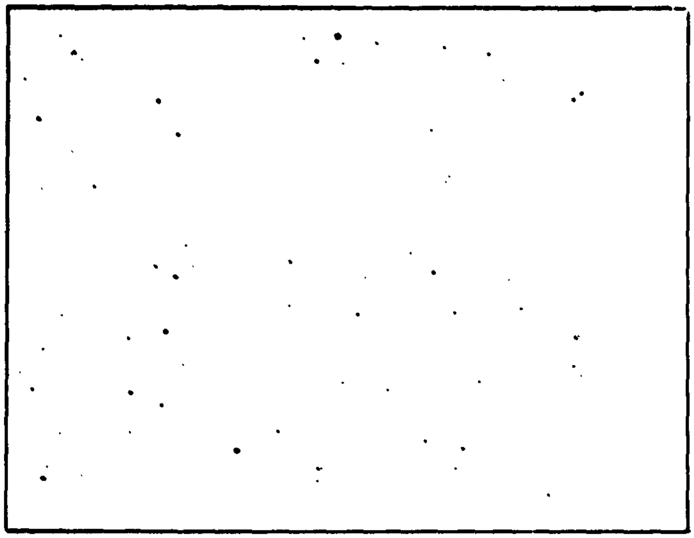
Chemical Analyses of 18%-Nickel Maraging Steels

Figure 2

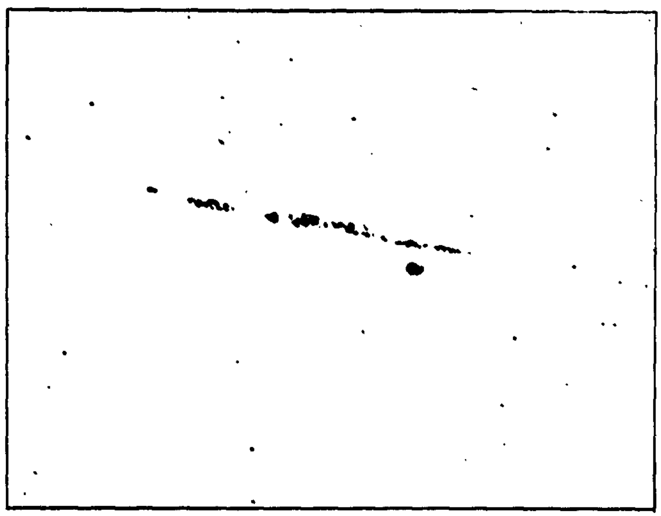
Aging Treatment Temp(°F)	Time, (hr)	Rolling Direction	Yield Strength at 0.2% Offset ksi	Ultimate Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction in Area, %
850°	4	Longitudinal	251.0	262.0	8.4	38.8
		"	253.5	263.6	9.1	39.5
		"	250.5	263.0	9.5	40.6
		Ave	251.7	262.9	9.0	39.6
850	8	Transverse	260.6	272.2	8.2	38.3
		"	259.5	271.0	8.8	40.6
		"	260.1	271.7	8.9	37.7
		Ave	260.1	271.6	8.6	38.9
900	4	Longitudinal	264.1	272.7	6.6	33.3
		"	264.5	272.0	8.0	38.2
		"	265.5	273.0	8.2	40.0
		Ave	264.7	272.6	7.6	37.2
		Transverse	244.4	257.0	-	38.9
		"	243.4	255.5	9.4	40.8
		"	241.9	253.5	9.6	42.4
		Ave	243.2	255.3	9.5	40.7
950	2	Longitudinal	266.0	273.0	8.4	41.8
		"	264.5	271.5	8.6	40.6
		"	262.5	271.5	6.0	33.2
		Ave	264.3	272.0	7.7	38.5
950	4	Longitudinal	266.0	277.5	8.1	40.0
		"	266.5	276.0	7.7	39.4
		"	266.0	275.5	7.1	38.2
		Ave	266.2	276.3	7.6	39.2

Mechanical Properties of Air-Melted 18%-Nickel Maraging-Steel 1/2-in. -Plate (United States Steel Corp. Heat 13371)

Figure 3



Typical Inclusion Content
Heat 3888472
Heat 3888473

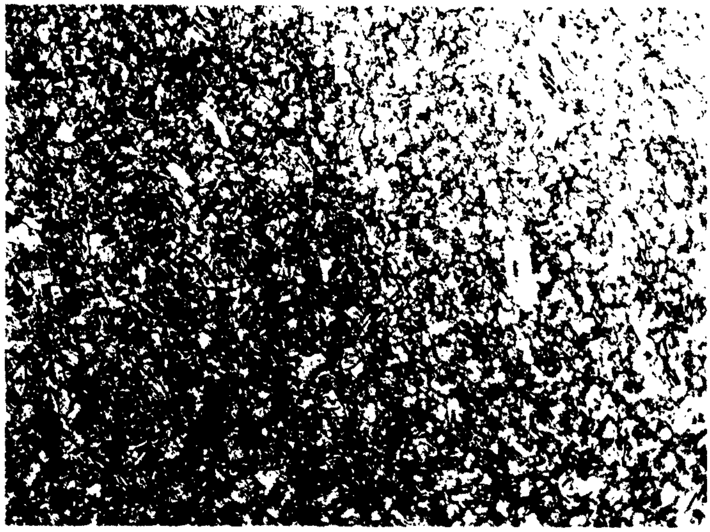


Inclusion Stringer
Heat 3888473

Unetched Mag: 100X

Typical Inclusion Content of 250-ksi, Vacuum-Arc-Remelted 18%-Nickel Maraging-Steel Plate (Republic Heats 3888472 and 3888473)

Figure 4



Heat 3888473

Heat 3888472

Etch: Marbles   Mag: 100X

Typical Microstructure of 250-ksi, Vacuum-Arc-Remelted 18%-Nickel Marag
Steel Plate (Republic Heats 3888472 and 3888473)

Figure 5

Unetched   Mag: 100X

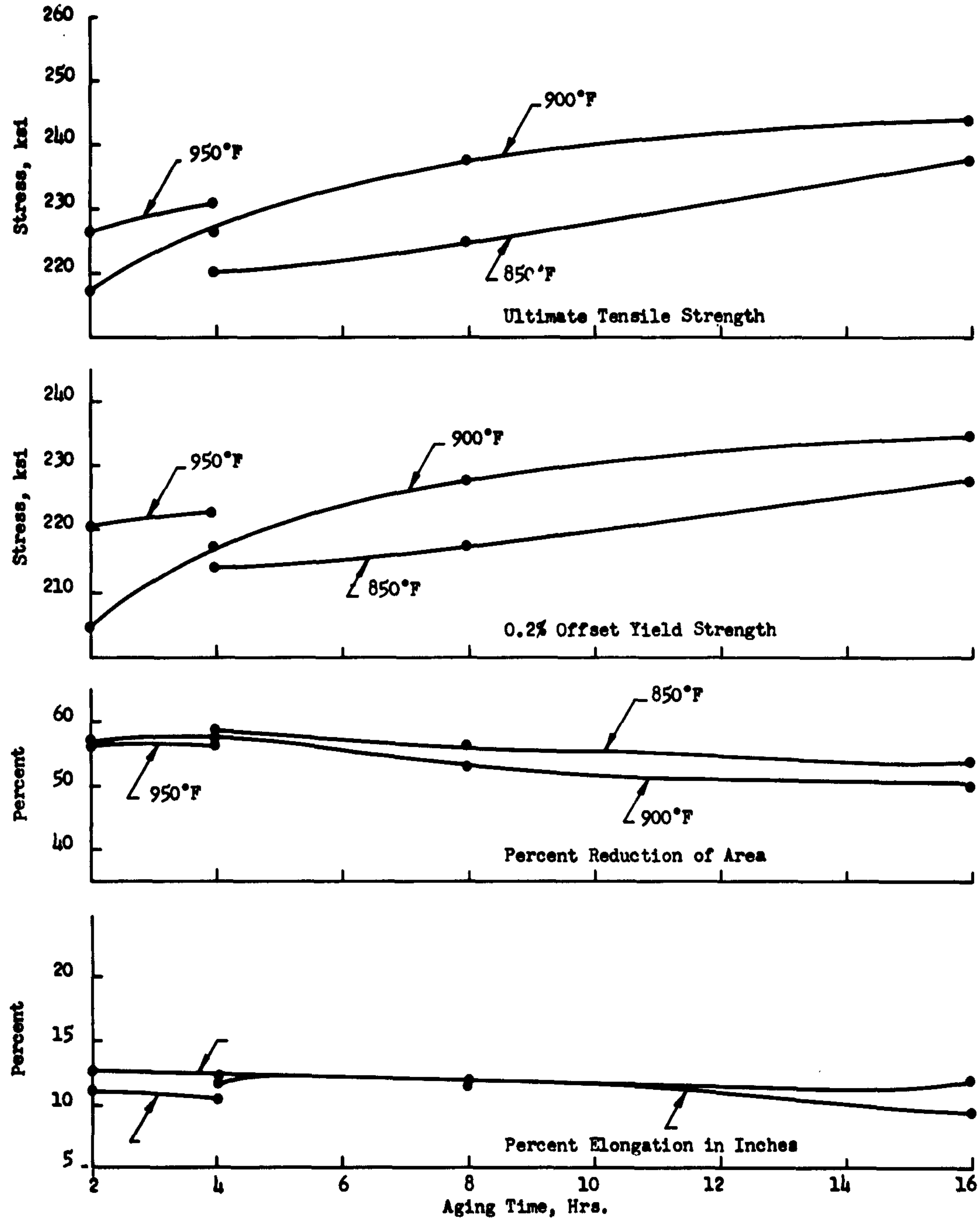
Typical Inclusion Content of 200-ksi, Air-Melted and Vacuum-Degassed 18%-Nickel Maraging-Steel Plate; Lukens Steel Co. (Allegheny-Ludlum Heat 28889)

Figure 6

Etch: Marbles **Mag: 100X**

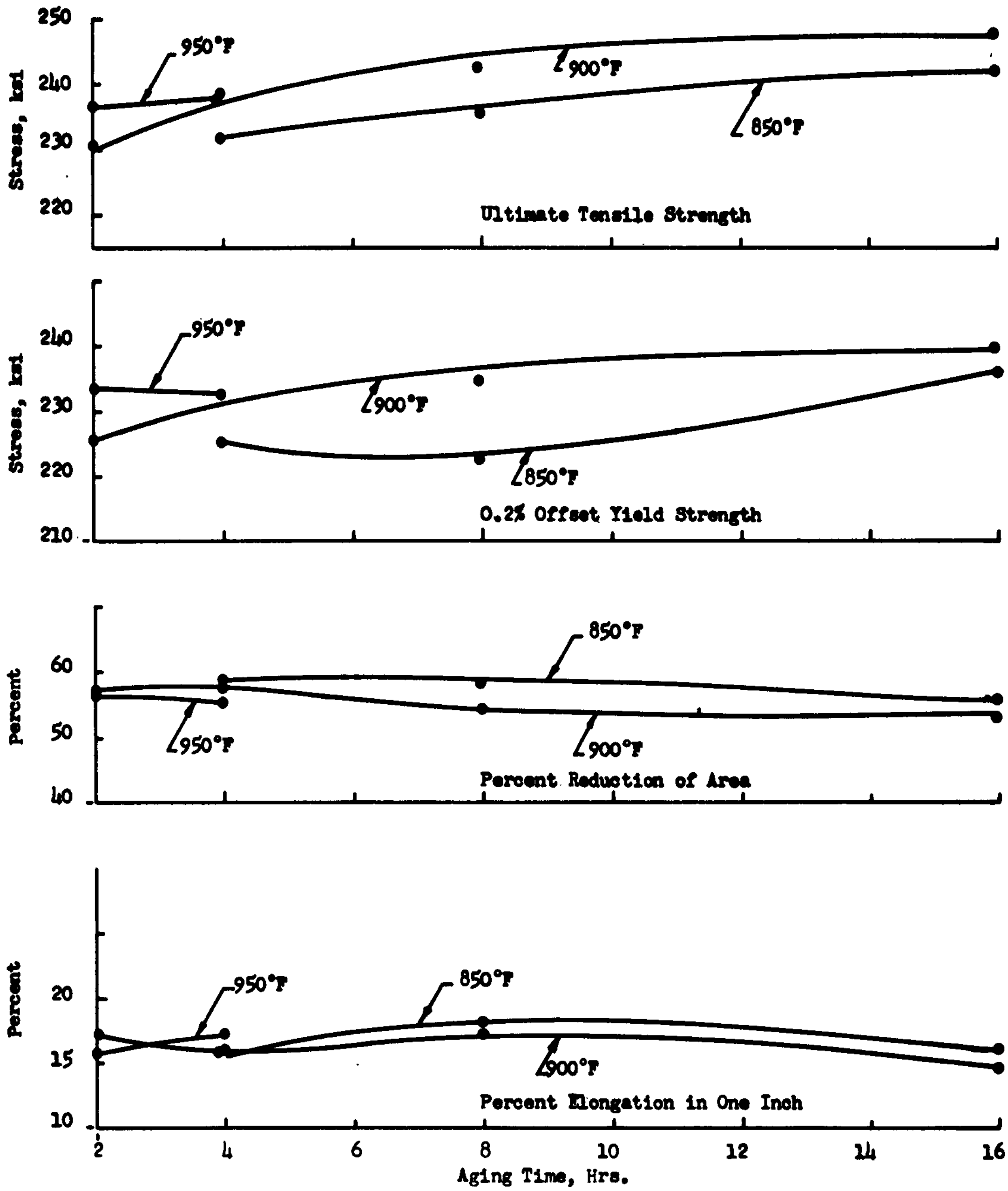
Typical Microstructure of 200-ksi, Air-Melted and Vacuum-Degassed 18%-Nickel Maraging-Steel Plate Lukens Steel Co. (Allegheny-Ludlum Heat 28889)

Figure 7



Effect of Time and Aging Temperature on the Tensile Properties of 18%-Nickel Maraging Steel, Allegheny-Ludlum Heat 10675 as-Rolled-and-Aged Condition, Longitudinal Orientation

Figure 8



Effect of Time and Aging Temperature on the Tensile Properties of 18%-Nickel Maraging Steel, Allegheny-Ludlum Heat 10675; Solution-Annealed (1500°F for 30 min) and Aged, Logitudinal Orientation

Figure 9

Aging Treatment Temp. °F	Time, hrs	Orientation	Solution Annealed and Aged: Yield Strength at 0.2% Offset ksi	Ultimate Tensile Strength ksi	Elongation in 1 inch %	Reduction of Area, %	As Rolled and Aged: Yield Strength at 0.2% Offset ksi	Ultimate Tensile Strength	Elongation in 1 inch %	Reduction of Area, %
850	4	Longitudinal	228.3	235.3	10.5	58.7	208.4	219.9	12.1	59.4
		"	230.7	235.2	11.5	60.0	217.9	221.0	11.2	58.4
		"	215.9	224.4	10.8	58.1	215.6	219.2	12.0	57.7
		Ave	225.0	231.6	10.9	58.9	214.0	220.0	11.8	58.5
850	8	Longitudinal	224.2	232.3	11.0	58.3	217.2	225.2	11.8	56.3
		"	215.6	238.4	11.9	59.3	216.9	225.1	11.9	58.0
		"	226.1	235.2	15.7	57.0	217.2	224.2	10.8	54.1
		Ave	222.0	235.3	12.9	58.2	217.1	224.8	11.5	56.1
		Transverse	230.2	234.5	11.5	53.5	216.4	227.1	10.6	53.7
		"	225.6	234.1	10.8	56.0	218.4	226.1	10.9	52.7
		"	217.2	227.3	12.0	53.5	216.7	227.3	11.3	55.1
		Ave	224.3	231.9	11.4	54.3	217.2	226.8	10.9	53.8
850	16	Longitudinal	227.5	235.5	9.5	56.7	229.3	238.4	12.3	51.9
		"	246.9	249.5	11.5	54.3	226.3	235.3	10.8	53.1
		"	231.3	240.4	10.8	55.1	227.3	237.4	11.8	56.3
		Ave	235.2	241.8	10.6	55.4	227.8	237.0	11.6	53.8
900	2	Longitudinal	228.6	232.2	11.9	58.0	204.5	217.2	12.4	58.7
		"	221.5	227.1	12.6	58.0	203.7	217.9	12.5	54.7
		"	227.3	232.3	12.5	57.3	206.1	217.2	12.8	58.3
		Ave	225.8	230.5	12.3	57.6	204.8	217.4	12.6	57.2
900	4	Longitudinal	228.1	234.2	10.6	54.3	217.2	227.3	11.0	58.3
		"	231.7	238.3	10.6	58.4	217.2	225.2	11.2	55.7
		"	237.4	242.4	11.1	58.7	218.2	225.9	10.8	57.7
		Ave	232.4	238.3	10.8	57.1	217.5	226.1	11.0	57.2
		Transverse	222.1	234.5	12.6	55.6	215.4	228.5	10.5	53.5
		"	227.9	233.5	12.7	55.1	217.2	229.3	11.0	52.5
		"	225.4	237.5	11.2	55.5	210.3	227.1	9.5	50.9
		Ave	225.1	235.5	12.2	55.4	214.3	228.3	10.3	52.3

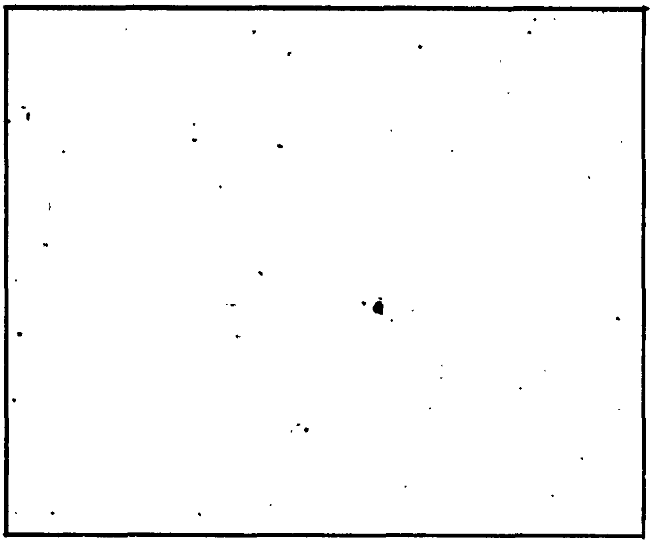
Mechanical Properties of Air-Metlted 18%-Nickel Maraging-Steel 1/2-in. Plate (Allegheny-Ludlum Heat 10675)

Figure 10, Sheet 1 of 2

Aging Treatment Temp. °F	Aging Treatment Time, Hrs	Orientation	Solution Annealed and Aged: Yield Strength at 0.2% Offset ksi	Solution Annealed and Aged: Ultimate Tensile Strength ksi	Solution Annealed and Aged: Elongation in 1 inch %	Solution Annealed and Aged: Reduction of Area, %	As Rolled and Aged: Yield Strength at 0.2% Offset ksi	As Rolled and Aged: Ultimate Tensile Strength	As Rolled and Aged: Elongation in 1 inch %	As Rolled and Aged: Reduction of Area, %
900	8	Transverse	245.9	252.5	11.3	54.7	227.9	235.5	11.5	51.7
		"	246.9	251.5	11.1	56.4	230.1	239.3	11.1	52.7
		"	242.9	248.5	12.0	55.1	226.5	237.5	11.0	53.9
		Ave	245.2	250.8	11.5	55.4	228.2	237.4	11.2	52.8
		Longitudinal	237.0	246.5	12.1	54.5	224.4	235.5	11.3	52.9
		"	229.8	236.4	10.7	53.1	225.5	234.5	10.1	49.6
		"	237.3	243.4	11.3	55.3	226.9	234.5	10.6	50.0
		Ave	234.7	242.1	11.4	54.3	225.6	234.8	10.7	50.9
900	16	Longitudinal	239.9	247.5	10.0	51.3	238.3	245.4	9.0	50.5
		"	241.5	248.5	9.1	52.9	232.3	242.4	9.4	46.8
		"	237.4	245.4	8.6	53.5	233.3	242.4	9.1	50.9
		Ave	239.6	247.1	9.2	52.6	234.6	243.4	9.2	49.4
950	2	Longitudinal	222.8	229.0	9.9	57.7	220.5	228.1	12.1	55.3
		"	237.4	240.4	11.8	55.7	220.7	226.3	11.0	56.7
		"	238.8	240.8	10.3	54.7	219.2	226.3	10.5	57.7
		Ave	233.0	236.7	10.6	56.0	220.1	226.9	11.2	56.6
950	4	Longitudinal	233.2	238.3	12.0	57.4	223.7	230.3	10.3	57.3
		"	227.9	236.4	11.5	54.1	222.2	230.3	10.0	55.7
		"	226.3	237.4	11.5	55.7	223.0	232.3	10.7	56.3
		Ave	229.1	237.4	11.7	55.7	222.9	231.0	10.3	56.4

Mechanical Properties of Air-Melted 18%-Nickel Maraging-Steel 1/2-in. Plate (Allegheny-Ludlum Heat 10675)

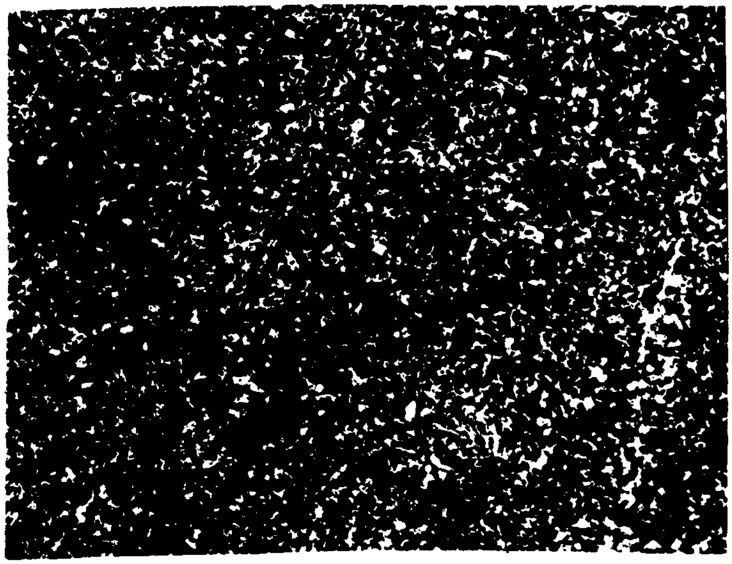
Figure 10, Sheet 2 of 2



Unetched Mag: 100X

Typical Inclusion Content of 225-ksi, Air-Melted 18%-Nickel Maraging-Steel Plate (Allegheny-Ludlum Heat 10675)

Figure 11



Etch: Marbles | Mag: 100X

Typical Microstructure of 225-ksi, Air-Melted 18%-Nickel Maraging-Steel Plate
(Allegheny-Ludlum Heat 10675)

Figure 12

Magnification: 1X

"B" End

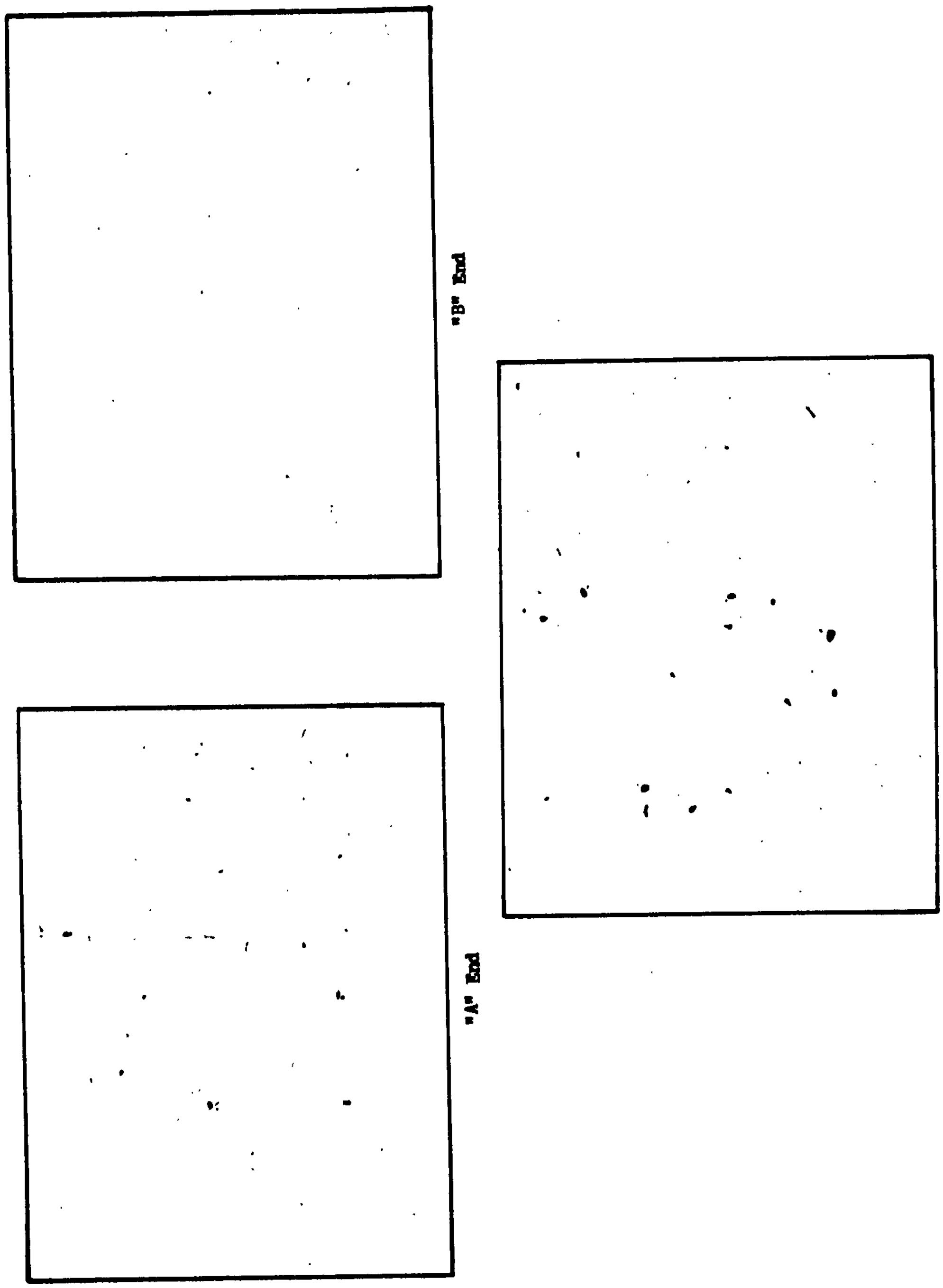
Middle

"A" End

Etch: 70% HCl + 30% HNO_3

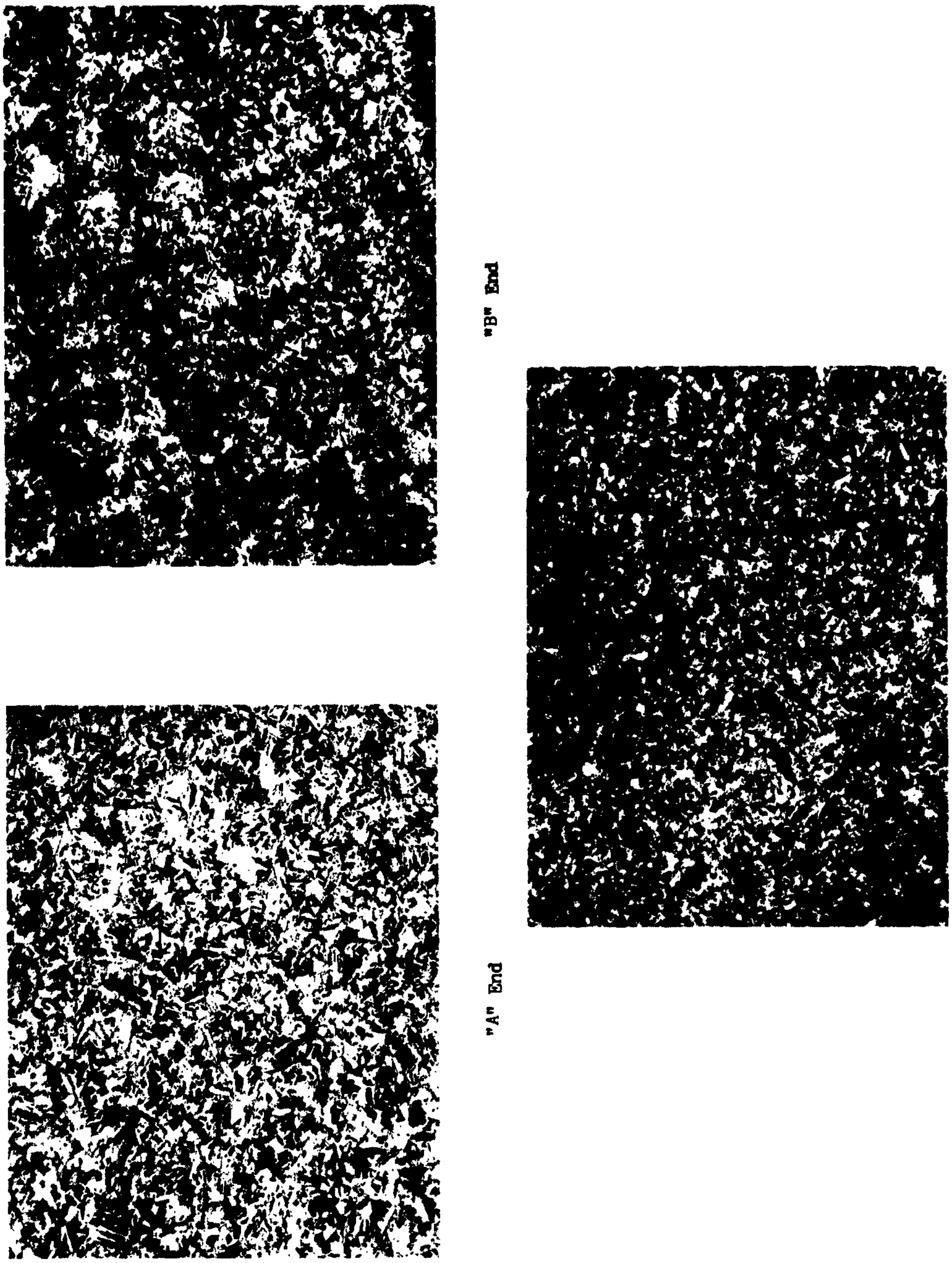
Typical Macrostructure of 4-in.-Square Billet; 225-ksi, Air-Melted 18%-Nickel Maraging Steel Supplied by Allegheny-Ludlum (Heat 10675)

Figure 13



Typical Inclusion Content of a 4-in.-Square Billet; 225-ksi, Air-Melted 18%-Nickel Maraging Steel Supplied by Allegheny-Ludlum Steel Corp. (Heat 10675)

Figure 14

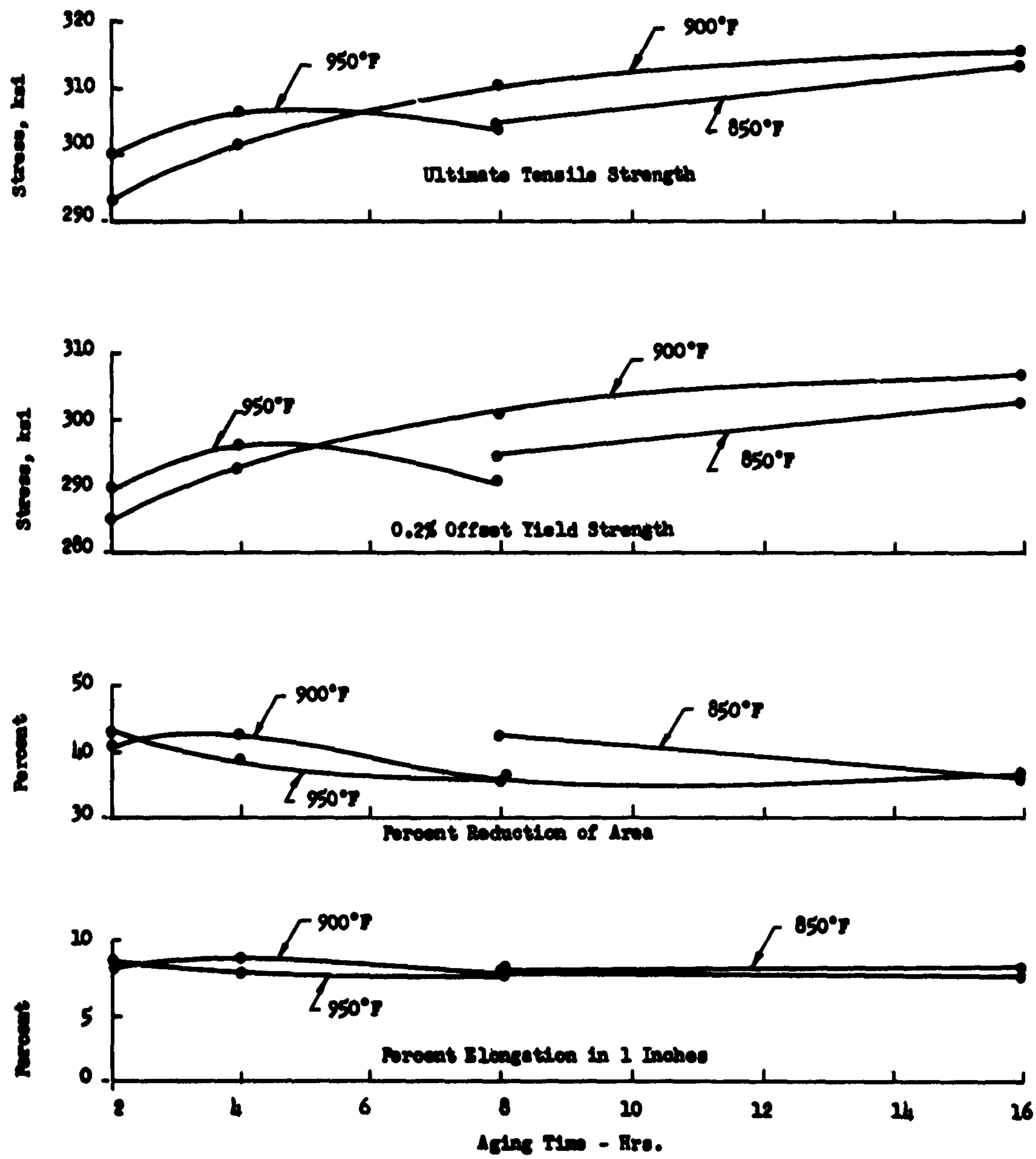


Etch: Marbles

Mag. 100X

Typical Microstructures Found in a 4-in. -Square Billet; 225-ksi, Air-Melted 18%-Nickel Maraging Steel Supplied by Allegheny-Ludlum Steel Corp. (Heat 10675)

Figure 15



Effect of Time and Aging Temperature on the Tensile Properties of 18%-Nickel Maraging Steel, Vanadium-Alloys Heat 07148; as-Rolled-and-Aged Condition, Longitudinal Orientation

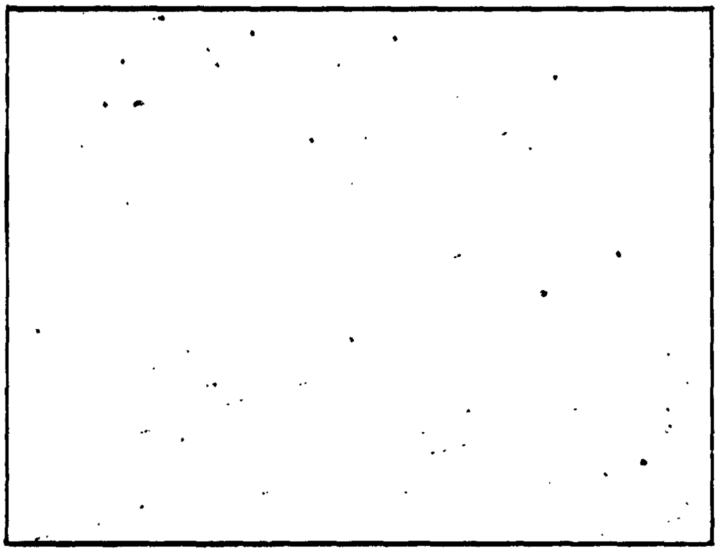
Figure 16

Aging Treatment		Rolling Direction	0.2% Y.S	U.T.S.	%El*	R/A	N.T.S.
Temp. °F	Time, hrs						
850	8	Longitudinal	295.6	304.1	8.2	43.2	248.5
		"	293.6	302.6	8.0	42.4	287.6
		"	293.9	307.6	9.0	41.0	346.5
		Ave	294.4	304.8	8.4	42.2	294.2
							283.5
850	16	Longitudinal	300.1	313.7	8.8	39.0	270.5
		"	304.0	313.1	7.0	36.0	276.4
		Ave	302	313.4	7.9	37.5	276.8
900	2	Longitudinal	286.5	292.9	8.5	41.6	329.7
		"	285.6	291.6	9.4	38.8	321.9
		"	283.6	294.5	8.4	43.0	341.4
		Ave	285.2	293.0	8.8	41.1	331.0
		Transverse	280.6	296.6	8.5	43.6	
		"	285.8	297.2	8.6	38.7	
		"	279.6	294.4	8.6	39.2	
		Ave	282.0	296.1	8.6	40.5	
900	4	Longitudinal	293.4	301.3	9.4	42.8	305.0
		"	291.9	299.7	9.3	43.6	341.1
		"	291.7	303.2	9.4	40.5	330.7
		Ave	292.2	301.4	9.4	42.3	325.6
		Transverse	295.2	302.7	8.0	36.7	260.1
		"	293.2	303.2	7.8	37.5	266.4
		"	292.4	302.8	8.5	36.6	271.2
		Ave	293.6	302.9	8.1	36.9	265.9
900	8	Longitudinal	301.5	310.1	8.9	42.8	300.9
		"	300.0	309.6	9.5	40.2	262.2
		"	299.7	310.6	8.6	43.7	296.1
		Ave	300.4	310.1	9.0	42.2	286.4
		Transverse	302.1	310.1	8.2	37.0	327.5
		"	301.8	310.1	8.0	39.2	242.8
		"	-	-	-	-	255.1
		Ave	301.9	310.1	8.1	38.0	275.1

* 1" Gage length

Mechanical Properties of Vacuum-Arc-Remelted Vanadium-Alloys 18%-Nickel Maraging-Steel 1/2-in. Plate (Heat 10675)

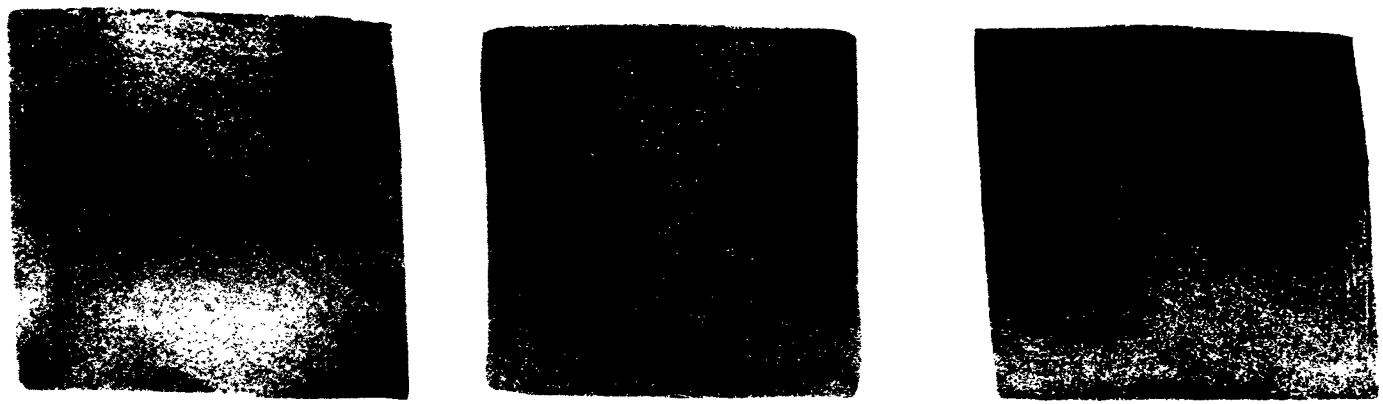
Figure 17



Unetched Mag: 100X

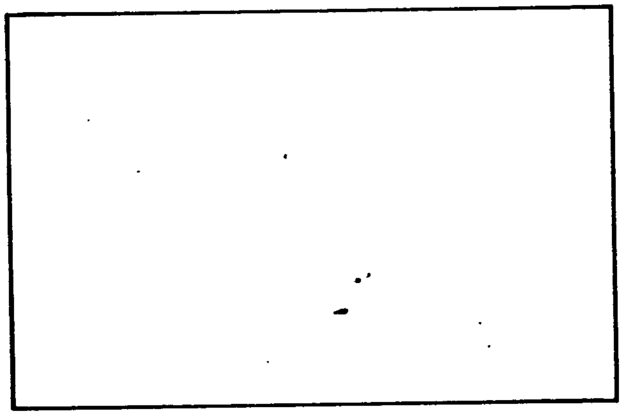
Typical Inclusion Content of 300-ksi, Vacuum-Arc-Remelted 18%-Nickel Maraging-Steel Plate (Vanadium-Alloys Heat 07148)

Figure 18

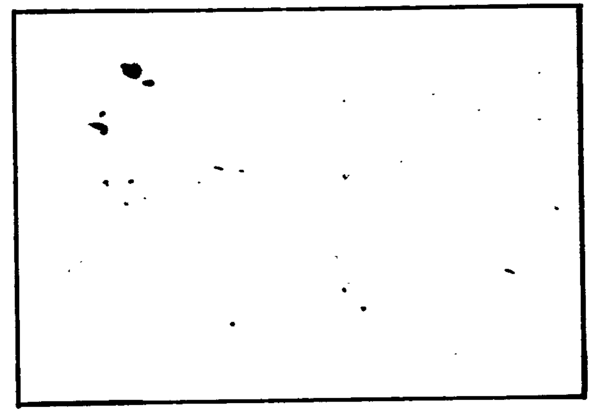


Typical Macrostructure of 4-in. -Square Billet; 300-ksi, Vacuum-Arc-Remelted 18%-Nickel Maraging Steel Supplied by Vanadium Alloys Steel Co. (Heat 07148)

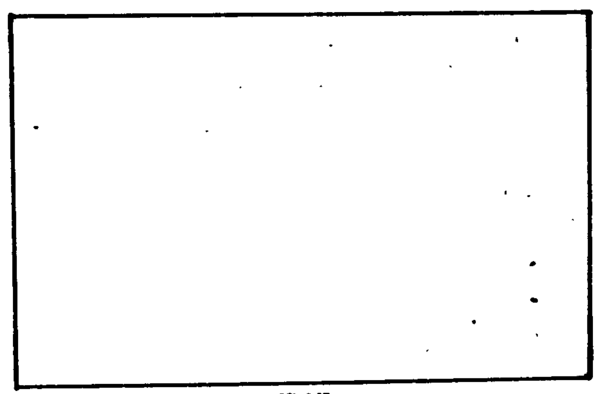
Figure 19



"A" End



"B" End



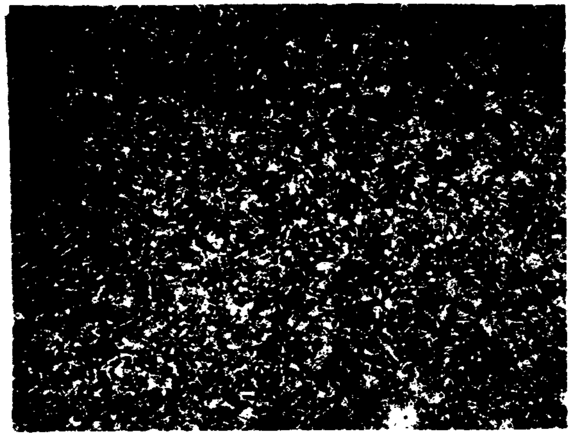
Middle

Unetched

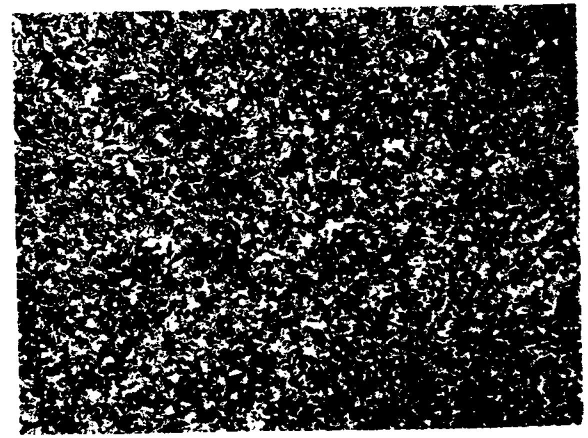
Mag: 100X

Typical Inclusion Content of a 4-in.-Square Billet; 300 ksi, Vacuum-Arc-Remelted 18%-Nickel Maraging Steel Supplied by Vanadium Alloys Steel Co. (Heat 07148)

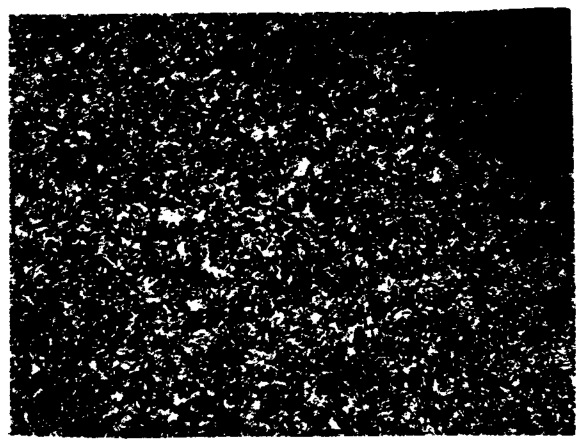
Figure 20



"A" End



"B" End



Middle

Etch: Marbles

Mag. 100X

Typical Microstructures Found in a 4-in.-Square Billet; 300-ksi, Vacuum-Arc-Remelted 18%-Nickel Maraging Steel Supplied by Vanadium Alloys Steel Co. (Heat 07148)

Material - Bethlehem Heat 120D163 (Air Melt & Vacuum Degas)

Condition - Solution Annealled (1500°F - 30 min) and Aged at 900°F - 4 hr

Strength - .2% Offset Yield Strength - 258 ksi - Longitudinal
265 ksi - Transverse

	Slow Notch Bend Test G_c (in-lb/in^2)		Precracked Impact W/A (in-lb/in^2)		Center Notch Tensile G_c (in-lb/in^2)
	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal
	111.5	240.5	376	342	432(1)
	181.5	106.5	329	364	422(1)
	236.5	189.5	392		1080(2)
	181.5	135.5			525(2)
	247.0	157.0			427(1)
Avg.	187.5	165.5	366	353	802(2)

(1) Fatigue cracked prior to testing.

(2) Not fatigue cracked prior to testing.

Comparison of Fracture Toughness by use of Different Test Methods

Figure 22

As Rolled and Aged Condition

Aging Cycle* Temp °F	Aging Cycle* Time hr	.2% Offset (1) Yield Strength (ksi)		G_c (in-lbs/in^2) Longitudinal	G_c (in-lbs/in^2) Transverse
850	4	241-/239		84.5	106.0
				202.5	151.0
				148.0	79.5
				118.0	123.0
					136.0
					151.0
			Average	138.2	124.4
850	8	248-/264		148.5	100.2
				164.0	92.5
				106.6	179.5
				259.0	92.5
					254.2
					196.4
			Average	169.5	152.6
900	4	248/245		245.8	203.0
				249.1	121.7
				239.7	111.8
				210.8	89.2
			Average	236.3	131.4
950	2	253-/256		97.4	159.5
				124.5	121.5
				148.5	192.5
				132.0	138.5
					135.9
			Average	125.6	149.6
950	4	254-/254		129.9	194.4
				151.0	158.7
				168.7	174.9
				123.5	192.5
				143.0	202.9
					170.9
			Average	143.2	182.4

* Air Melted and Vacuum Degassed

(1) Longitudinal/Transverse Yield Strength

Corrected Fracture Toughness (G_r), in-lb/in.^{2}, Aerojet-General Slow Notch Bend Test Method; Bethlehem Heat 120D163 (Air-Melt, and Vacuum-Degassed)

Figure 23

As Rolled and Aged

Aging Cycle Temp. °F	Aging Cycle Time hr	.2% Offset (1) Yield Strength	G_c (in-lb/in^2) Longitudinal	G_c (in-lb/in^2) Transverse
900	4	265/243	146.1	213.2
			155.5	198.3
			138.6	177.6
			139.0	233.0
			153.0	243.7
		Average	144.4	213.2

(1) Longitudinal/Transverse Yield Strength

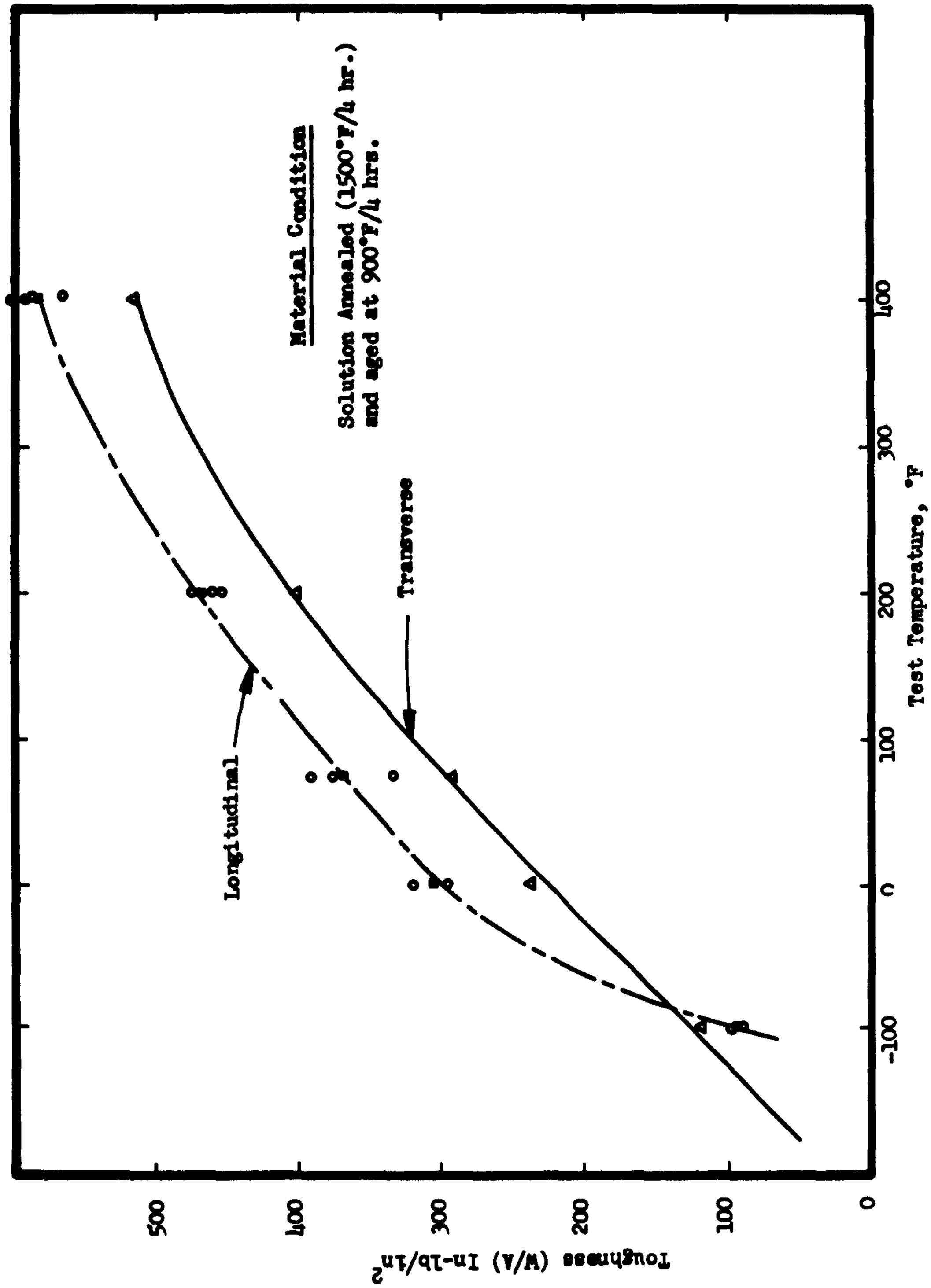
Corrected Fracture Toughness (G_c) in-lb/in.^{2}, Aerojet-General Slow Notch Bend Test Method; United-States-Steel-Corp. Heat X-1 3371 (Air-Melt)

Figure 24

Test Temperature, °F		Precrack Charpy Impact Toughness, W/A in-lbs/in.^{2} — Test Direction: Longitudinal	Transverse
400		605	524
		583	517
		584	501
		563	
	Ave.	584	514
200		472	408
		458	402
		450	394
	Ave.	460	401
Room Temp.		392	364
		329	342
		376	
	Ave.	366	353
0		296	271
		321	213
		293	230
	Ave.	303	238
-100		88	83
		87	141
		95	145
	Ave.	90	123

Results of Pre-Cracked Impact Testing at Various Test Temperatures; Bethlehem Heat 120D162, Solution-Annealed at 1500°F for 30 min and Aged at 900°F for 4 hr.

Figure 25



Effect of Test Temperature on Fracture Toughness (W/A), Precracked-Impact Test;
Bethlehem Heat 120D163

Figure 26

As Rolled and Aged Condition

Aging Cycle Temp. °F	Aging Cycle Time hr	.2% Offset (1) Yield Strength (ksi)		G_c (in-lb/in^2) Longitudinal	G_c (in-lb/in^2) Transverse
850	8	204/207		322.5	252.5
				389.9	319.0
				333.0	313.3
				332.0	396.0
				340.5	200.9
			Average	343.8	296.5
900	4	197/202		440.1	343.5
				450.0	389.3
				457.5	358.0
				520.0	320.5
			Average	470.0	352.8
950	2	204/209		503.0	250.0
				387.5	218.3
				506.8	339.0
					211.9
			Average	465.0	244.4

(1) Longitudinal/Transverse Yield Strength

Corrected Fracture Toughness (G_c) in-lb/in.^{2}, AGC Slow Notch Bend Test Method
Lukens (Allegheny-Ludlum Heat 28889), Air-Melted and Vacuum-Degassed

Figure 27

Solution Annealled (1500 °F/30min) and Aged Condition

Aging Treatment		0.2% Offset Yield Strength			Gnc, in-lbs/in²	
Temp. °F	Time hr	Longitudinal	Transverse		Longitudinal	Transverse
900	4	197	202		179	157
					154	191
					152	125
				Average	162	158
900	8	211	217		197	126
					194	153
					205	111
				Average	199	130

Fracture Toughness (G_{nc}) in-lbs/in.^{2}, Aerojet-General Slow Notch Bend Test Method; Lukens (Allegheny-Ludlum Heat 28889), Air-Melted and Vacuum-Degassed

Figure 28

Base Plate Material - Lukens (A&L 28889) - Air Melt and Vacuum Degassed.

Weld Wire & Process - 250 ksi Composition -Tungsten Invert Gas

Condition (1) - As Welded and Aged at 875°F/8 hours
Solution Annealled (1500°F/30 min) and aged 875°F/8 hours

Orientation - Transverse Weld and Longitudinal Parent Metal

Notch Location	W/A - in-lbs/in²	
	Sol Ann + Age	Age Only
Center of Weld	210 238	387 248
Heat Affected Zone .150" from Weld Center line	587 510	760 510
Heat Affected Zone .300" from Weld Center line	615 740	670 713
Parent Metal (1)	1135 1120	1110 1710

(1) Parent Metal .2% Offset Yield Strength
Sol. Anneal & Age - 198 ksi
Age Only - 203 ksi

Fracture Toughness (W/A) in-lb/in.², Precracked-Impact Test

Figure 29

Solution Annealed, (1500 F/30min) and Aged Condition
0.2% Offset

Aging Cycle		Yield Strength (ksi)			G_{nc} (in-lbs/in^2)	
Temp. °F	Time hr	Longitudinal	Transverse		Longitudinal	Transverse
850	8	222.0	224.3		157.5	157.2
					158.0	169.5
					116.6	114.0
				Average	144.0	146.9
900	4	232.4	225.1		149.4	161.3
					161.5	146.0
					193.0	152.0
					154.0	166.0
				Average	164.5	156.3
900	8	234.7	245.2		138.7	161.0
					173.0	140.2
					160.0	144.1
				Average	157.2	148.4

Fracture Toughness (G_{nc}) in-lb/in.^{2}, Aerojet-General Slow Notch Bend Test Method, Allegheny-Ludlum Heat 10675 (Air-Melted)

Figure 30

Material Condition: Solution Annealled (1500 °F/ hr) Prior to Forming & Aged at 875 °F/8 hr

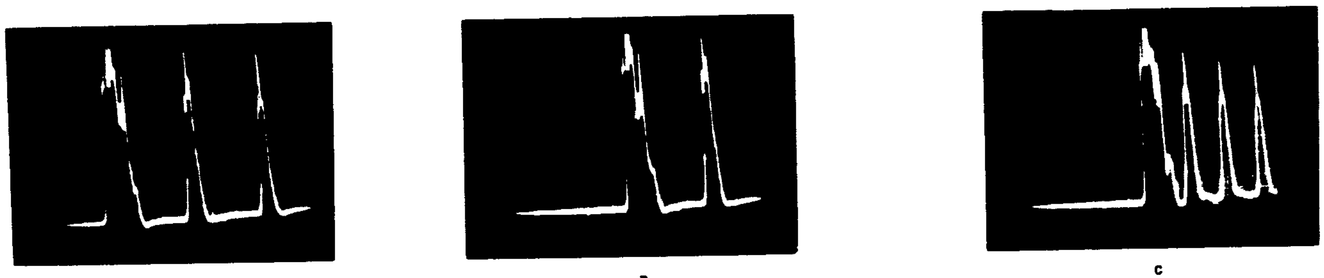
Material Thickness: 0.5 inches

.2% Yield (1) Strength (ksi)	Slow Notch Bend Test G_{nc} (in-lb/in²) Longitudinal	Slow Notch Bend Test G_{nc} (in-lb/in²) Transverse	Precracked Impact W/A (in-lb/in²) Longitudinal	Precracked Impact W/A (in-lb/in²) Transverse
Cylinder Section (Bethlehem Heat - 120D298) - As Rolled & Aged				
260/257	161.0	99.6	441	347
	134.6	104.3	433	359
	124.6	84.6	453	355
	115.7	123.6		
	64.2	121.0		
	132.5			
Average	122.1	107.2	442	347
Cylinder Transition Area (Bethlehem Heat 120D298) - As Swaged and Aged				
-/261		70.6		344
		79.2		340
		95.1		315
		92.6		
		100.5		
Average		88.6		333
Head (Bethlehem Heat 120D298) - As Formed and Aged				
265/268	123.7	122.2	412	350
	90.7	91.6	429	402
	133.5	58.6	464	428
	112.6	88.3		
	106.0	108.0		
Average	113.5	93.9	435	393
Skirt (Bethlehem Heat 120G097) - As Rolled and Aged				
270/275	57.6	46.5	216	233
	54.0	59.1	206	226
	49.7	55.8	213	224
	65.5	47.4		
	90.6			
	58.6			
Average	62.7	52.2	212	228

(1) Longitudinal/Transverse Yield Strength

Fracture Toughness of 18%-Nickel Maraging Steel Used for Fabrication of a 36-in.-dia Test Chamber

Figure 31



A

Initial Pulse and First and Second Back Reflection from the Plate Surface

B

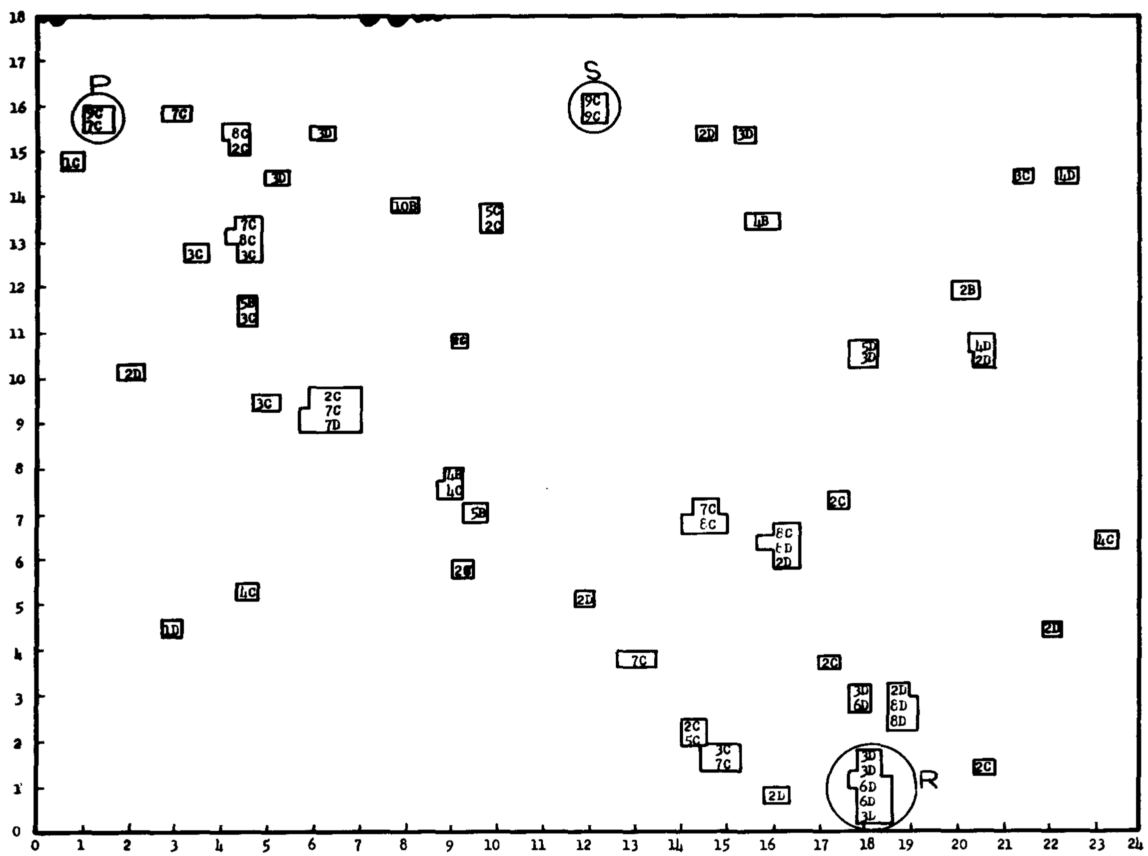
Initial Pulse and First Back Reflection from the Plate Surface

C

Initial Pulse and Three Back Reflections from an Internal Discontinuity

Typical Oscilloscope Traces Obtained During Ultrasonic Inspection of the Standard Material; Bethlehem Heat 120D163

Figure 32

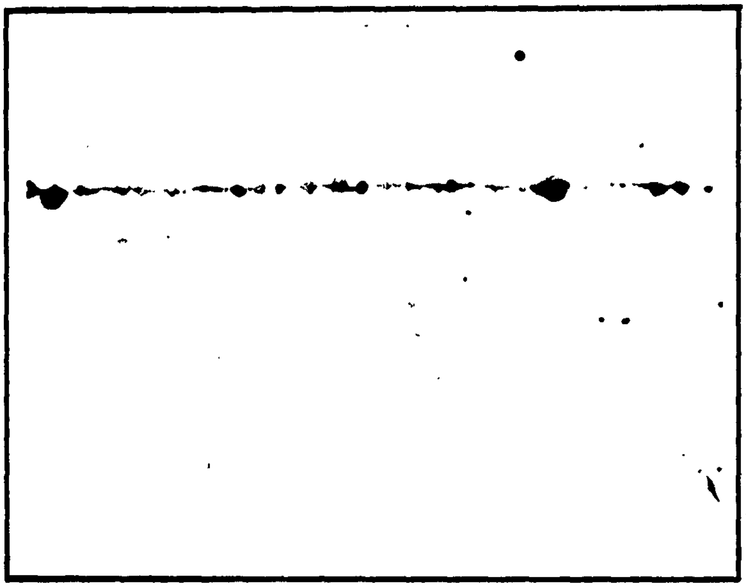


NOTES:

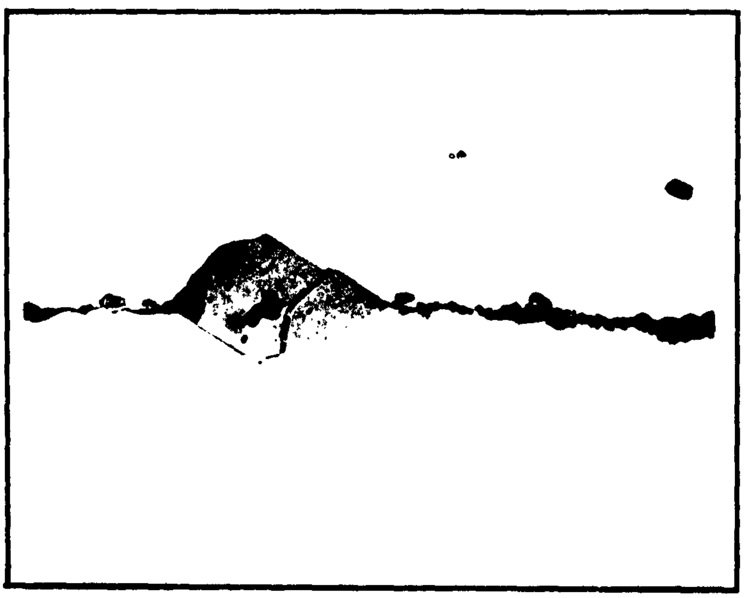
1. Ultrasonic inspection performed with a Branson Sonoray and a 5 megacycle, 1/2 inch transducer, employing a pulse-echo, longitudinal wave, contact technique.
2. Numbers indicate relative amplitude of signal return from discontinuities. At the settings used a relative amplitude of 10 was the signal return from the back surface of the plate.
3. Letters indicate relative depth of discontinuity, A = t/6, B = 2t/6, C = 3t/6, D = 4t/6, E = 5t/6, where t = plate thickness and depth is measured from surface depicted in plan view.
4. Configuration of plate edge indicated for reference purposes.
5. Scan increment of 1/4 inch used for transducer placement.
6. Dimensions in inches.
7. Calibration - 12/64 inch Flat-Bottom Hole

Contact Ultrasonic Test Results; 18%-Nickel Steel Plate, Side 1; (P, R and S Indicate Areas Evaluated by Metallographic Techniques)

Figure 33



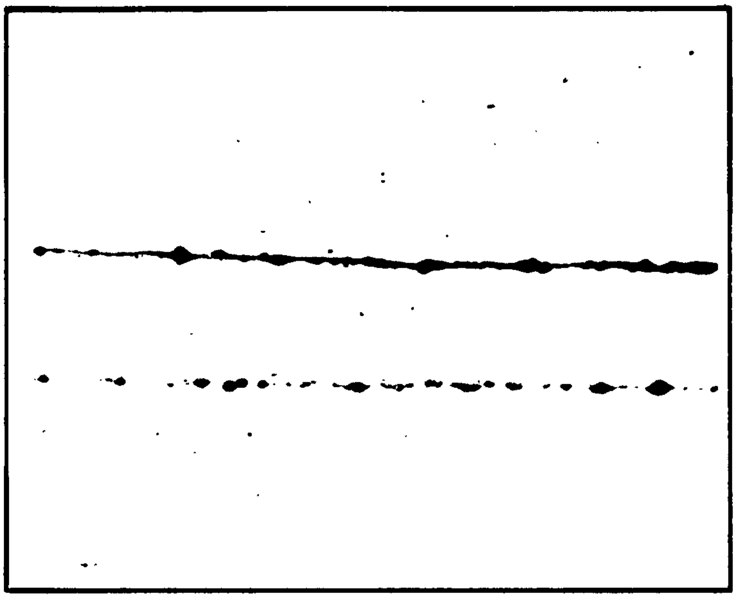
No Etchant Mag: 100X



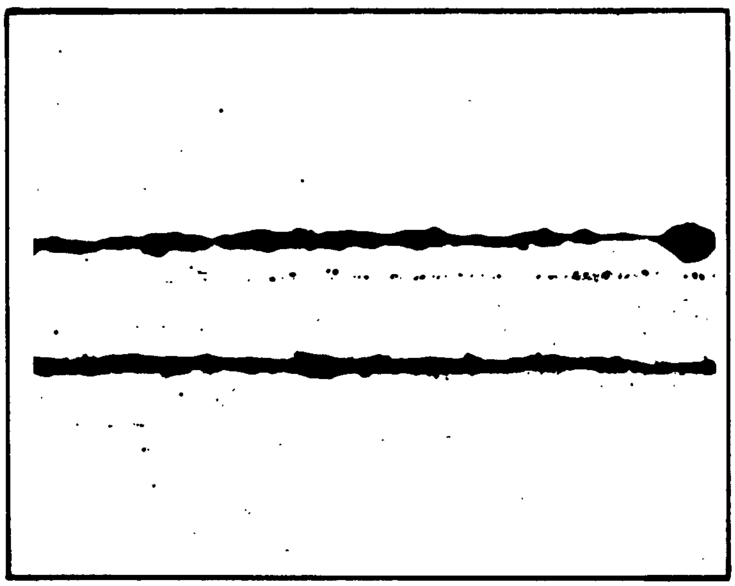
No Etchant Mag: 500X

Aluminate Stringer Found at Section P of Ultrasonic Indication Map (see Figure 33); Bethlehem 1/2-in.-Thick-Plate Material (Heat 120D163)

Figure 34



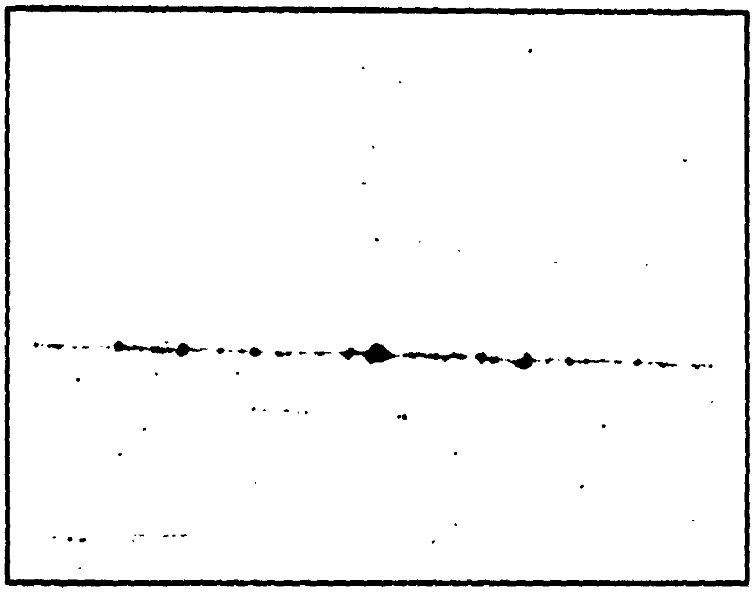
No Etchant Mag: 100X



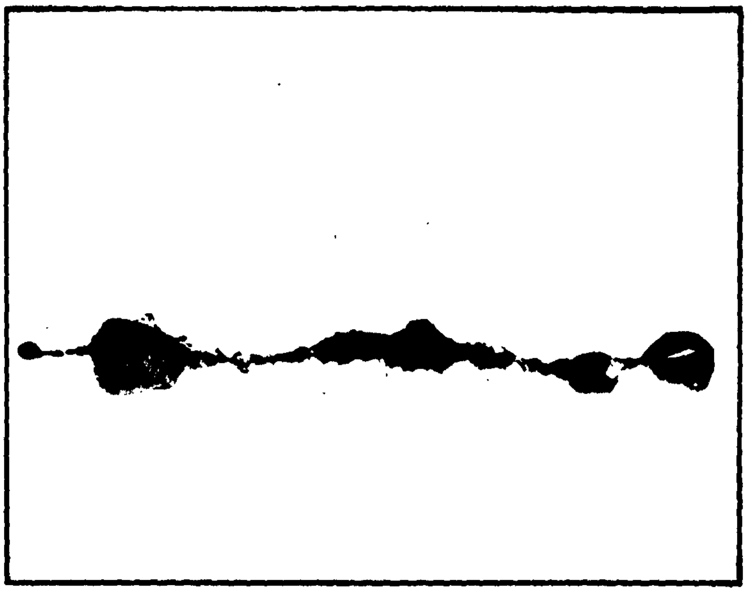
No Etchant Mag: 500X

Cracks Connecting Aluminate Stringers at Section R of Ultrasonic Indication Map (see Figure 33); Bethlehem 1/2-in. -Thick-Plate Material (Heat 120D163)

Figure 35



No Etchant Mag: 100X



No Etchant Mag: 500X

Aluminate Inclusions With Connecting Crack Found at Section S on Ultrasonic Indication Map (see Figure 33); Bethlehem 1/2-in.-Thick-Plate Material (Heat 120D163)

Figure 36

Etch: Marbles   Mag: 100X

Typical Banded Microstructure; 260 ksi, Air-Melted and Vacuum-Degassed 18%-Nickel Maraging-Steel Plate (Bethlehem Heat 120G298)

Figure 37

SUMMARY OF CURRENT TEST RESULTS (1)

Treatment (2)	.2% Offset Yield (3) Strength (ksi)	Fracture Toughness (G)-lb/in² Slow Notch Bend Test Longitudinal G_c	Longitudinal G_{nc}	Transverse G_c	Transverse G_{nc}	Precracked Impact (W/A) Longitudinal	Precracked Impact (W/A) Transverse
200 ksi Air Melted & Vacuum Degassed (Lukens A&L) Heat 28889							
As Rolled & Aged 900°F/4 Hr	197/202	470	-	353	-	1410	-
As Rolled & Aged 875°F/8 Hr	203	-	-	-	-	-	-
Solution Annealed and aged 875°F/8 Hr	198	-	-	-	-	1130	-
Solution Annealed and aged 900°F/4 Hr	197/202	-	165	-	161	-	-
225 ksi Air Melted (Allegheny Ludlum) Heat 10675							
Solution Annealed and aged 900°F/4 Hr	225/232	-	162	-	158	-	-
250 ksi Air Melted and Vacuum Degassed (Bethlehem) Heat 120D163							
As Rolled and Aged 900°F/4 Hr	248/245	236.3	-	131.4	-	-	-
Solution Annealed & aged 900°F/4 Hr	258/265	187.5	-	165.5	-	366	353
250 ksi Air Melted - U. S. Steel Heat 13371							
As Rolled and Aged 900°F/4 Hr	265	144	-	213	-	-	-
260 ksi Air Melted and Vacuum Degassed (Bethlehem) Heat 120D298							
S.A. & Rolled & Aged 875°F/8 Hr	260/257	-	122	-	107	442	354
S.A. Swaged & Aged 875°-8hr	---/261	-	-	-	89	-	333
S.A. Formed & Aged 875°F-8 hr	265/268	-	114	-	94	435	397

Summary of Current Test Results (1)

Figure 38

Treatment (2)	.2% Offset Yield Strength (ksi) (3)	Fracture Toughness (G)-lb/in^2					
		Slow Notch Bend Test				Precracked Impact (W/A)	
		Longitudinal		Transverse		Longitudinal	Transverse
		G_c	G_{nc}	G_c	G_{nc}		
270 ksi Air Melted & Vacuum Degassed (Bethlehem Heat 120G097							
S.A. Rolled & Aged 875°F/8hr	274/273	-	63	-	52	212	228

(1) Results shown are for the best Condition or Single Condition Evaluated.
(2) S.A. - Solution Annealed (1500°F - 30 Min); A.R. - As Rolled.
(3) Longitudinal/Transverse Yield Strength.

Summary of Current Test Results (1)

Figure 38

Wire Heat No.	Percent Titanium (Plate 0.48%)			Percent Cobalt (Plate 8.0%)			Percent Molybdenum (Plate 4.9%)		
	Weld	Wire	Change	Weld	Wire	Change	Weld	Wire	Change
7C-090	0.65	.83	-0.18	9.1	12.1	-3.0	4.2	4.0	+0.2
7C-091	0.94	1.65	-0.71	7.2	8.3	-1.1	4.5	4.0	+0.5
7C-092	0.80	0.95	-0.15	7.8	6.8	+1.0	4.9	5.1	-0.2
7C-093	0.64	0.67	-0.03	8.2	8.0	+0.2	4.6	4.7	-0.1
7C-094	0.81	1.22	-0.41	8.8	9.9	-1.1	4.3	4.6	-0.3
34312	0.57	0.59	-0.02	7.8	7.9	-0.1	4.5	4.5	0.0

Chemical Composition (Ti, Co, Mo) of Weld Wires, Parent-Metal and Tungsten Inert-Gas Weld Deposits; Bethlehem 1/2-in.-Thick 18%-Ni Base Plate

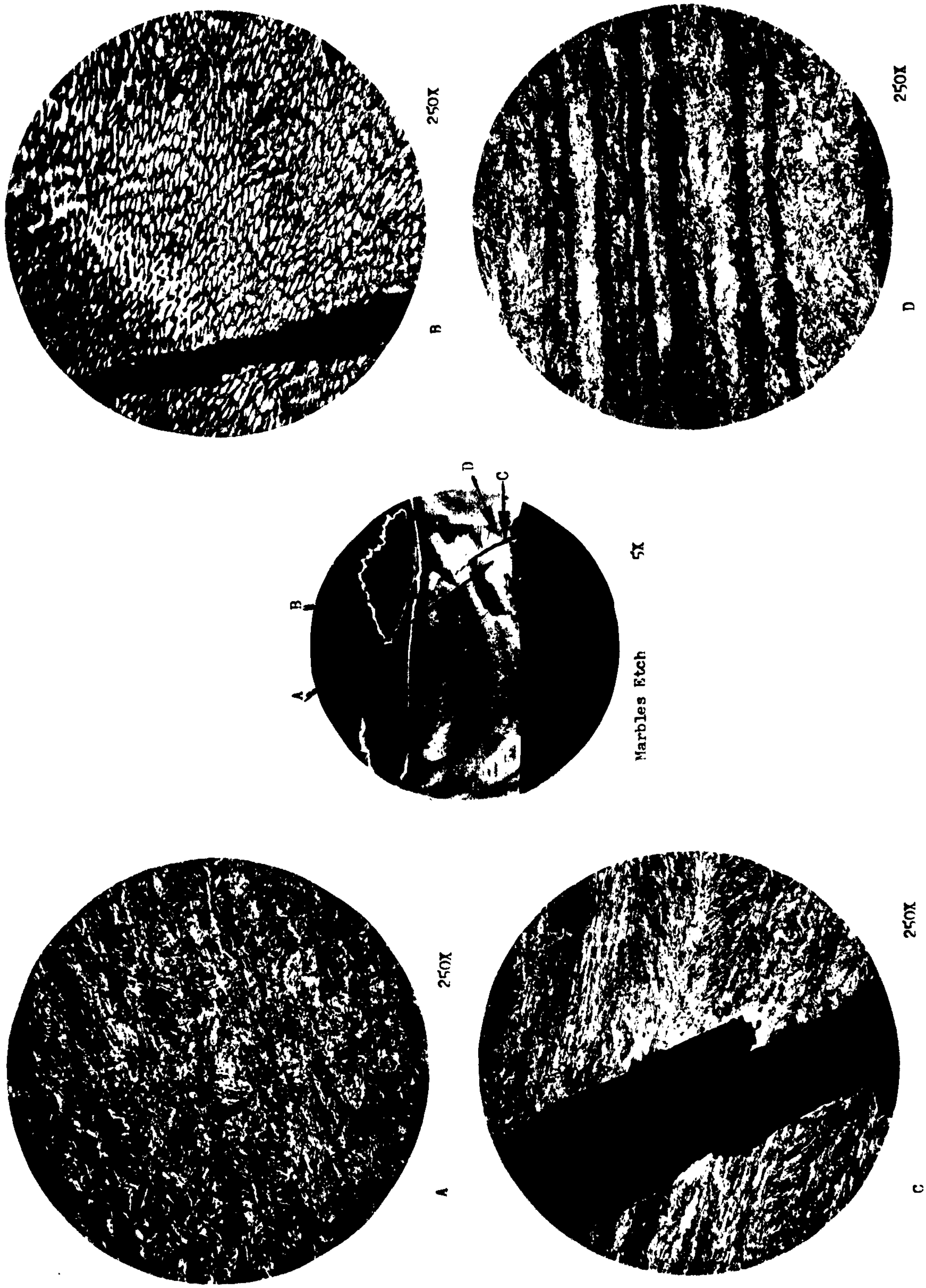
Figure 39

Weld Wire	.2% Offset Yield Strength		Ultimate Strength		% Elongation (1)		% Reduction in Area		Notch Tensile Strength		Weld Quality (2)			
	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	General	Scattered Porosity	Linear Porosity	Inclusions
7C-090														
Test Series A	250	247/253	261	255/266	6.9	6.6/7.3	37	35.4/38.6	250	229/264	R	R	R	A
Test Series B	246	244/248	258	257/258	4.7	2.0/6.0	25	8.0/34.5	229	169/304	-	-	-	-
7C-091														
Test Series A	252	247/257	264	259/269	6.0	5.0/7.1	28.3	25.5/31.2	179.6	170/193	R	A	A	A
Test Series B	244	243/244	256	254/258	7.2	6.5/8.0	37.9	32.5/43.0	185	166/218				
7C-092														
Test Series A	244	243/248	260	260	6.3	6.3	28.7	28.7	173	128/216	A	A	A	A
Test Series B	241	239/242	251	249/252	5.6	5.0/6.4	26.5	21/37	245	202/286				
7C-093														
Test Series A	250	250	260	258/262	5.6	4.8/7.0	24.2	19.6/27.5	261	259/277	A	A	A	A
Test Series B	240	239/241	247	246/248	6.1	3.9/8.2	31.6	25/38	298	260/340				
7C-094														
Test Series A	246	238/249.5	255	242/262	6.4	5.7/7.1	30.4	19.7/41.1	217	193/247	R	R	R	A
Test Series B	245	243/246	253	251/257	3.9	1.5/6.6	12.3	4.5/28	231	222/246				
34312														
Test Series A	250	248/252	259	258/260	5.8	4.9/6.6	26.1	20.6/29.6	212	151/291	A	A	A	A
Test Series B	233	230/236	236	232/242	8.2	7.1/9.2	44.0	39.5/46.5	333	322/346				

(1) 1" Gage Length
(2) A - Acceptable Quality
R - Rejectable Quality

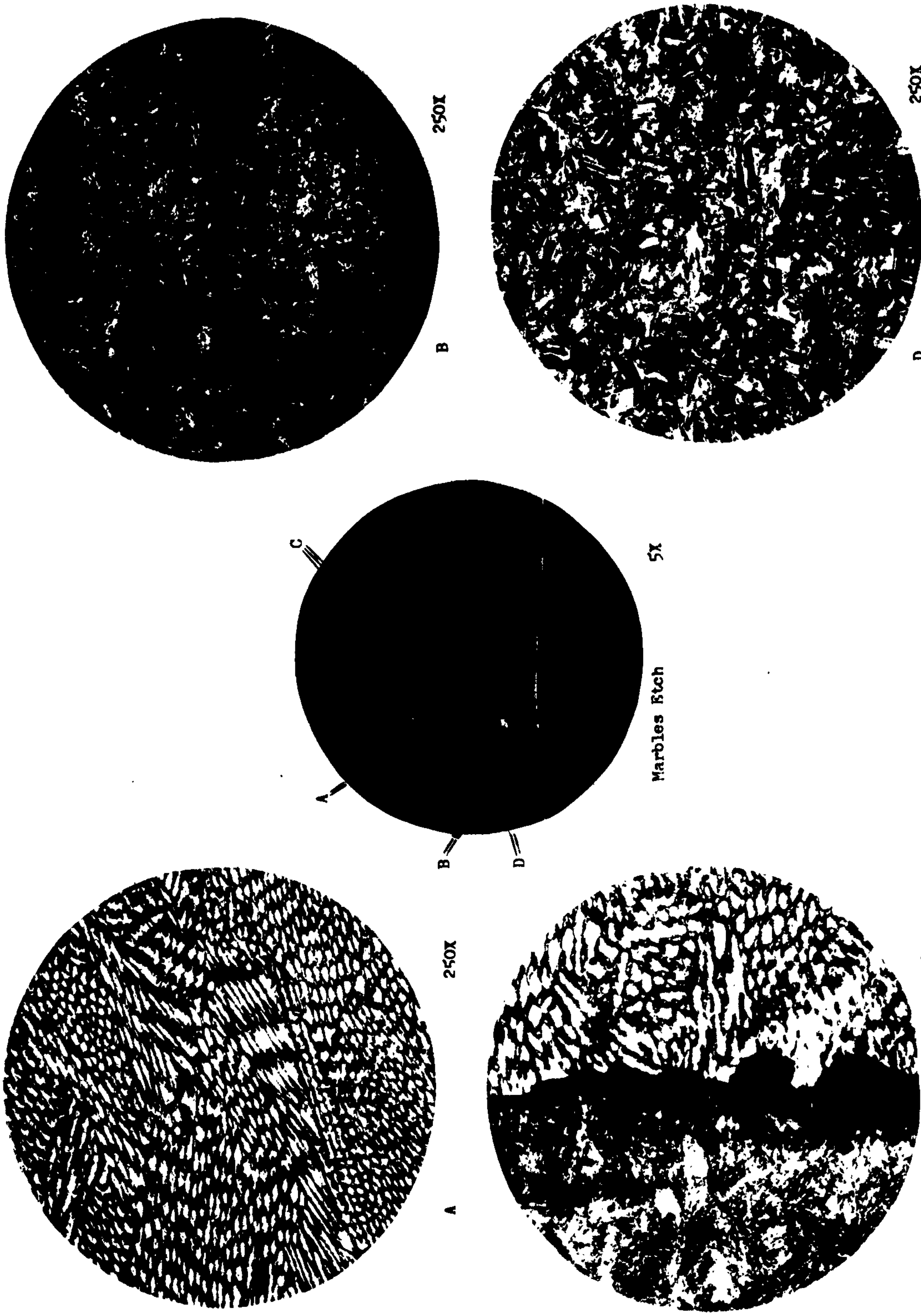
Summary of Mechanical Properties and Quality Data of Tungsten Inert-Gas Welds in 18%-Ni Maraging Steel Welded With Six Different Weld Wires (Aged at 900°F for 4 hrs

Figure 40



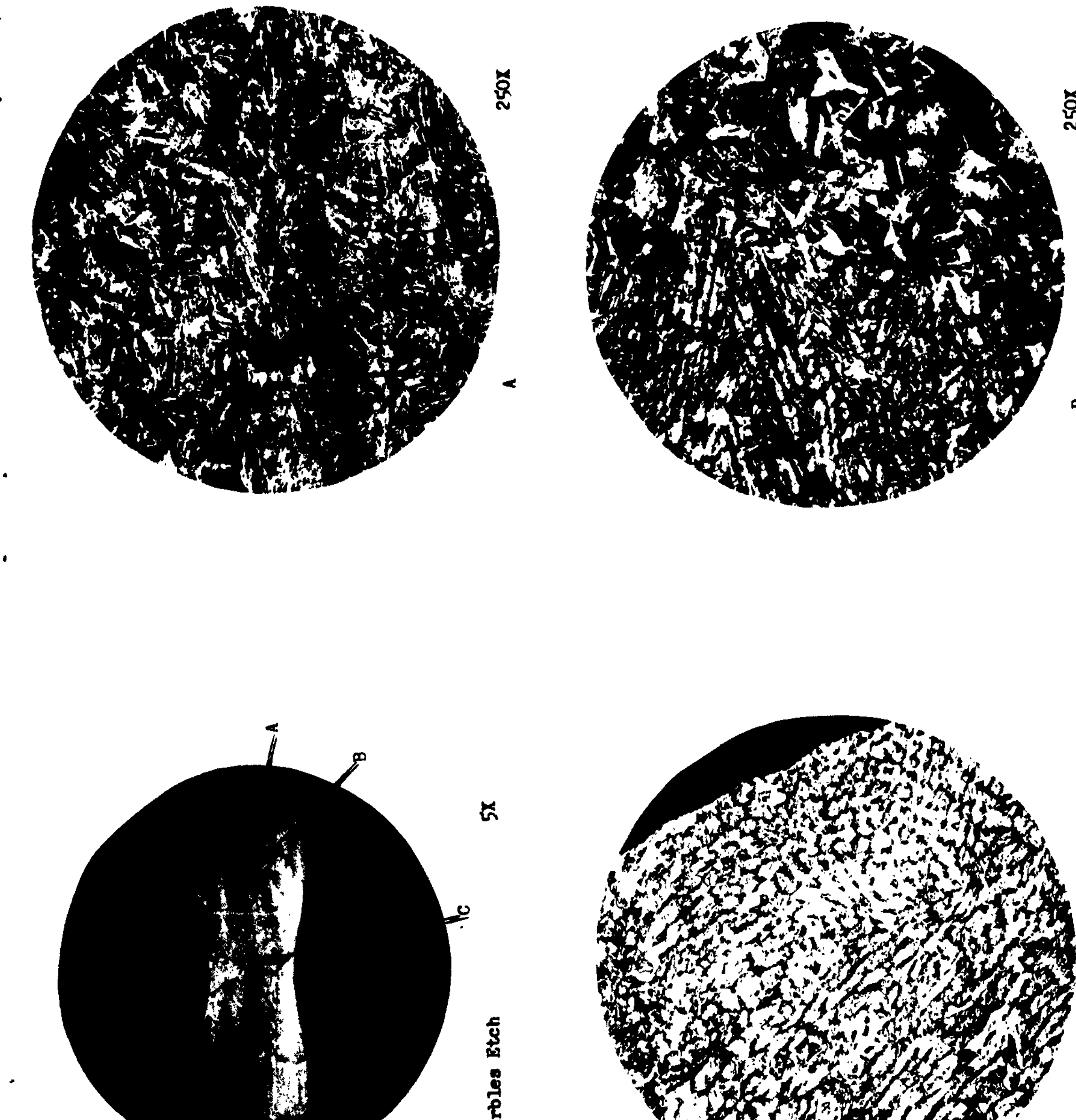
Typical Tensile Specimen Fracture and Microstructure, 1/2-in.-Thick, TIG-Welded 18%-Ni Maraging Steel. (7C-091 Weld Wire) as-Welded-and-Aged (900°F for 4 hr) Condition. Bethlehem Heat 120D163 Base-Plate Material

Figure 41



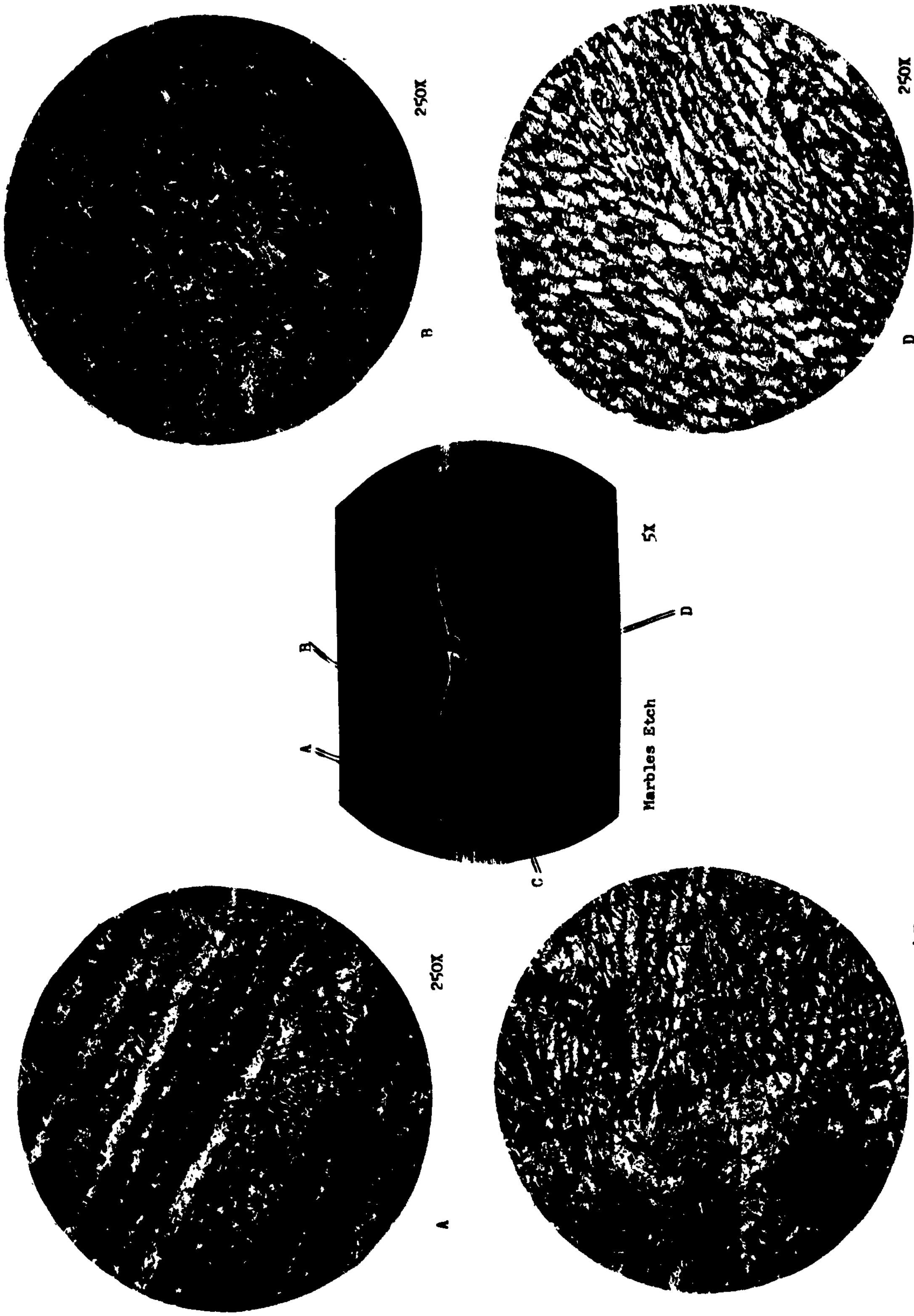
Typical Tensile-Specimen Fracture and Microstructure, 1/2-in.-Thick, TIG-Welded 18%-Ni Maraging Steel; (7C-092 Weld Wire) as-Welded-and-Aged (900°F for 4 hr) Condition; Bethlehem Heat 120D163 Base-Plate Material

Figure 42



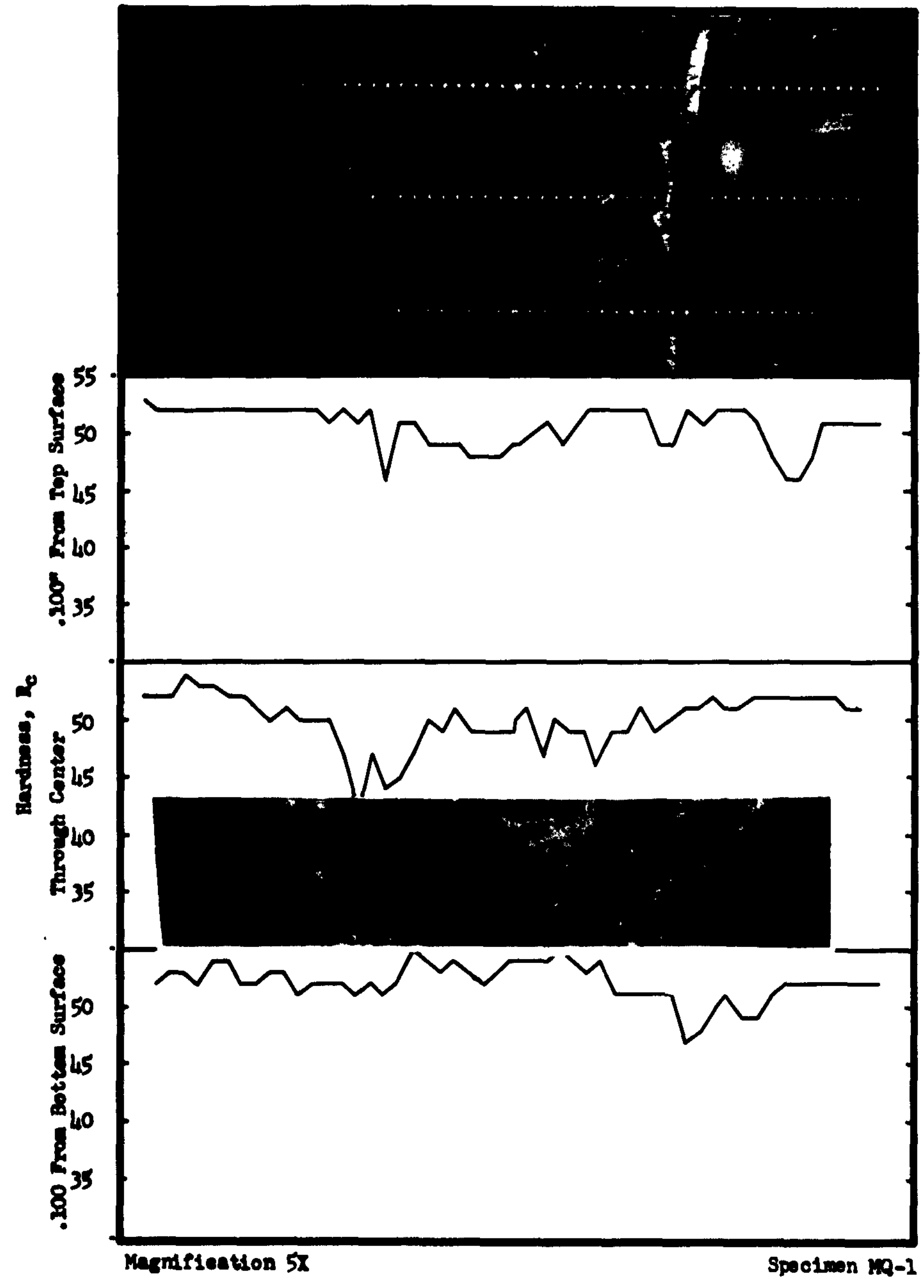
Typical Tensile-Specimen Fracture and Microstructure, 1/2-in.-Thick, TIG-Welded 18%-Ni Maraging Steel; (7C-093 Weld Wire) as-Welded-and-Aged (900°F for 4 hr) Condition; Bethlehem Heat 120D163 Base-Plate Material

Figure 43



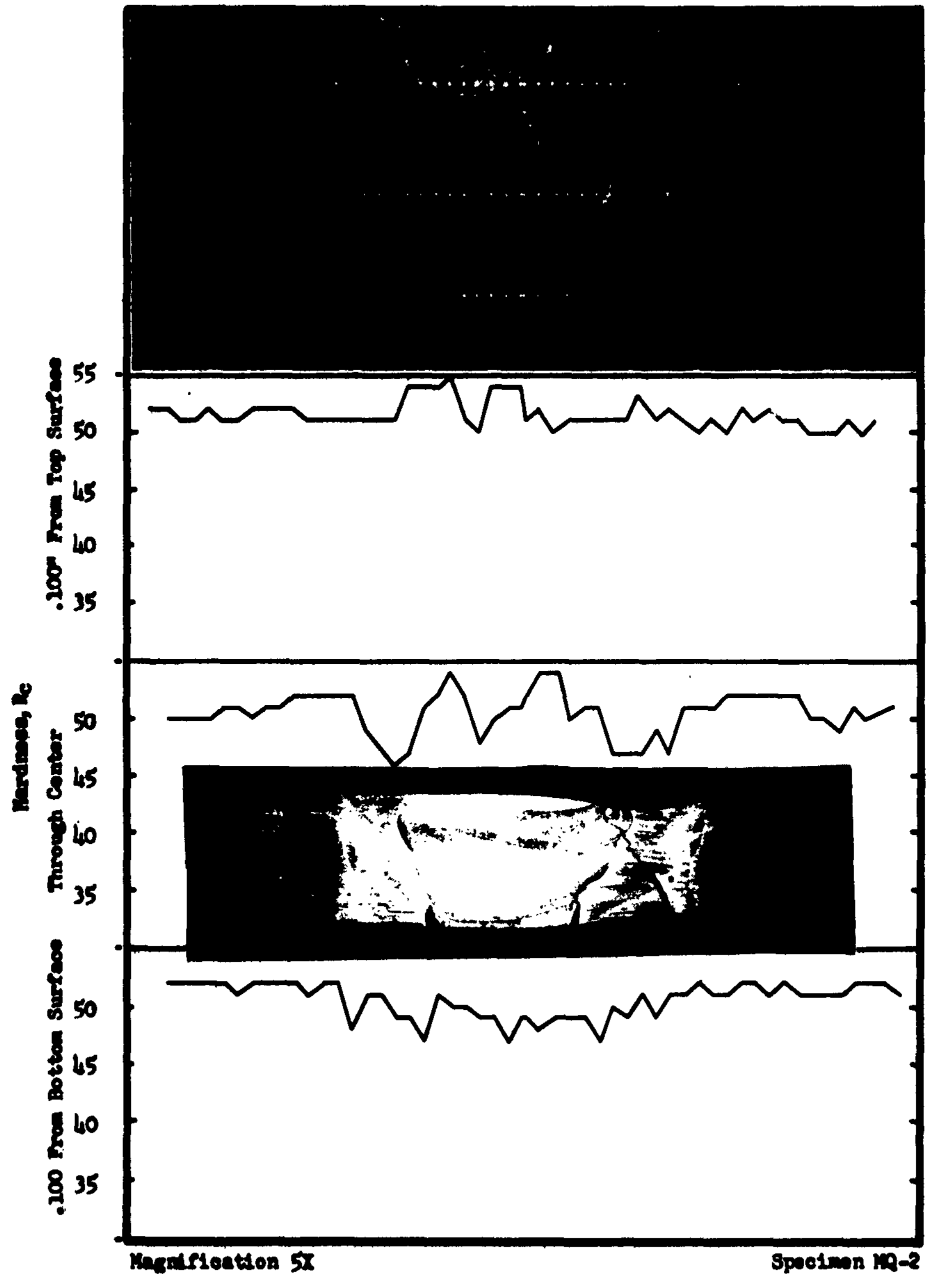
Typical Tensile-Specimen Fracture and Microstructure, 1/2-in.-Thick, TIG-Welded 18%-Ni Maraging Steel; (34312 Weld Wire) as-Welded-and-Aged (900°F for 4 hr) Condition; Bethlehem Heat 120D163 Base-Plate Material

Figure 44



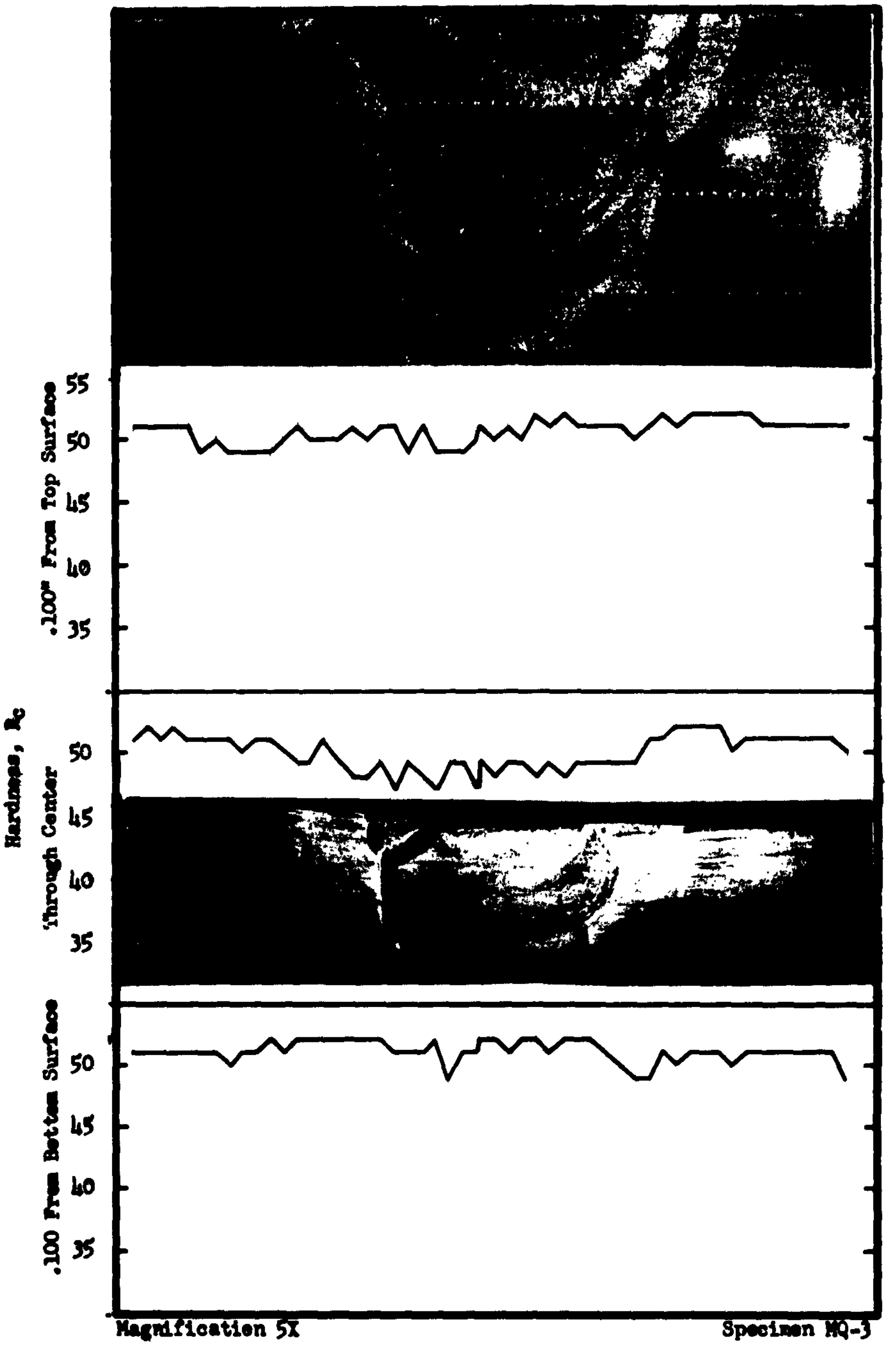
Hardness Curve, 18%-Ni Maraging Steel, 0.50 in. Thick; Aged for 4 hr at 900°F After Welding; Heat 7C-090

Figure 45



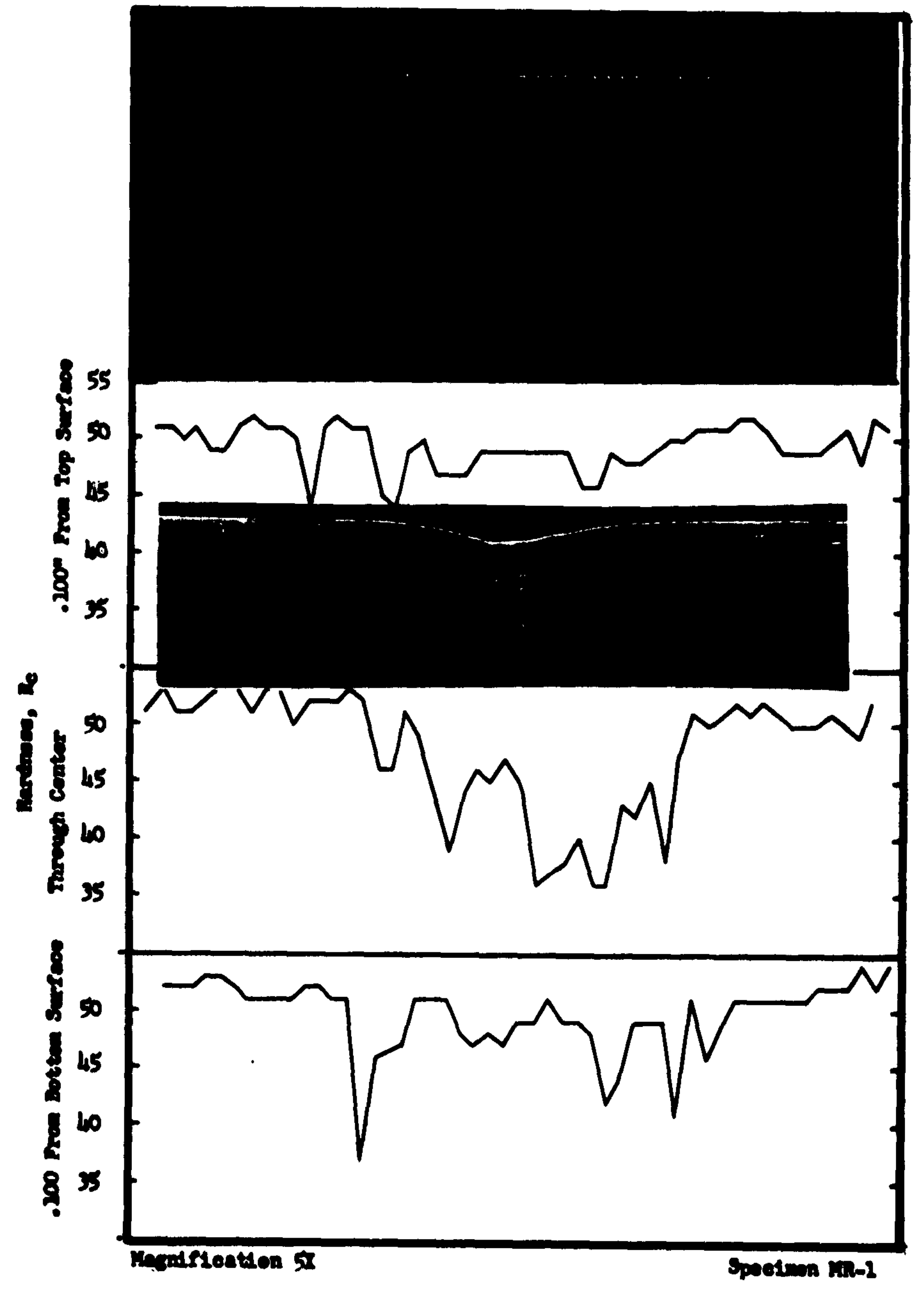
Hardness Curve, 18%-Ni Maraging Steel, 0.50 in. Thick; Aged for 4 hr at 900°F After Welding; Heat 7C-091 Weld Wire

Figure 46



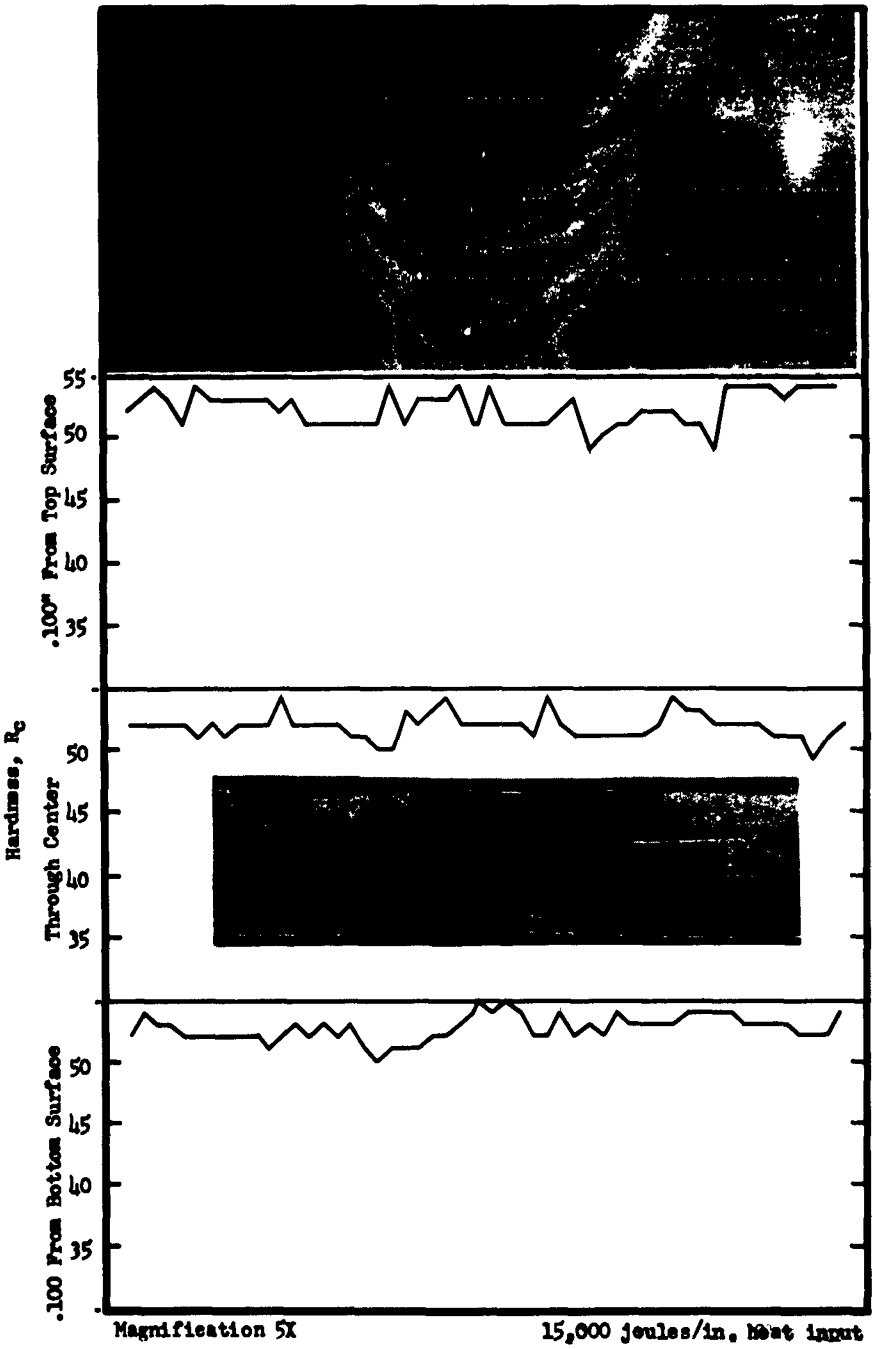
Hardness Curve, 18%-Ni Maraging Steel, 0.50 in. Thick; Aged for 4 hr at 900°F After Welding; Heat 7C-092 Weld Wire

Figure 47



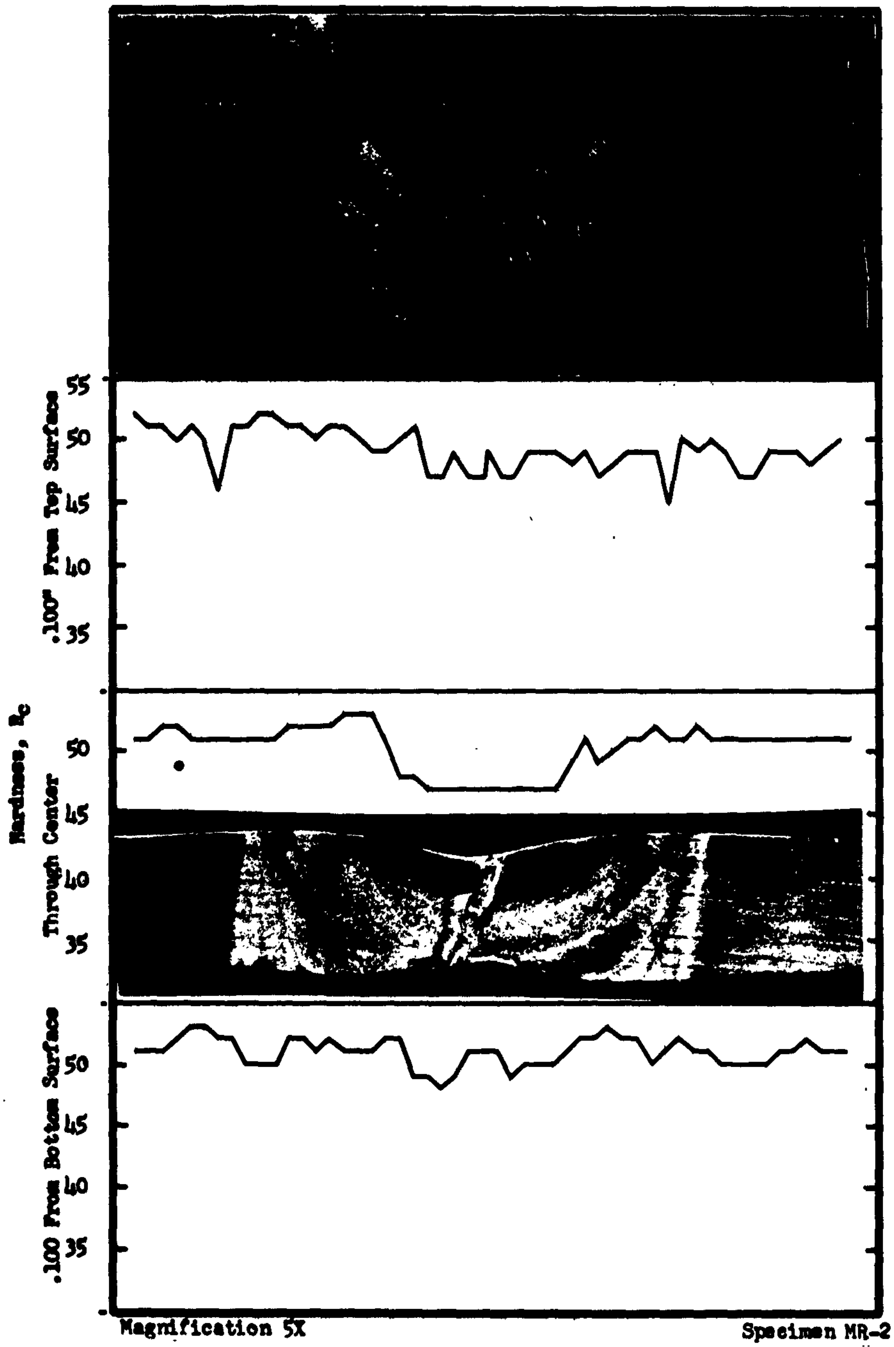
Hardness Curve, 18%-Ni Maraging Steel, 0.50 in. Thick; Aged for 4 hr at 900°F After Welding; Heat 7C-093 Weld Wire

Figure 48



Hardness, 18%-Ni Maraging Steel, 0.50-in.-Thick, Aged for 4 hr at 900°F After Welding; Heat 7C-094 Weld Wire

Figure 49



Hardness Curve, 18%-Ni Maraging Steel; 0.50 in. Thick, Aged for 4 hr at 900°F After Welding; Heat 34312 Weld Wire

Figure 50

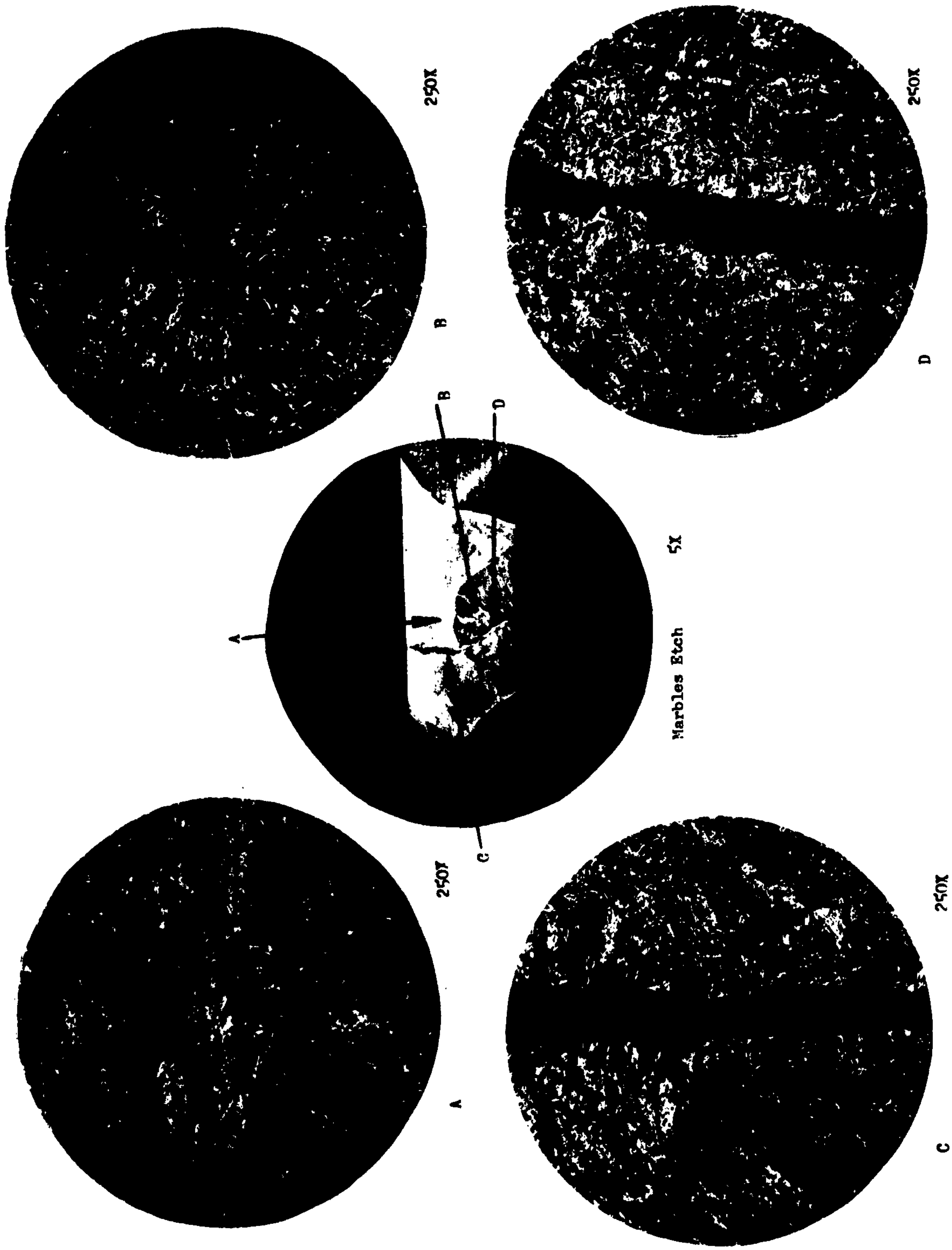
1/2-in.-Thick Base Plate (Bethlehem Heat No. 120D163)-Aged After Welding 900°F for 4 hr

	Longitudinal Weld Tensile				Transverse Weld Tensile				
Weld Wire	UTS	0.2% Offset YS, ksi	Elong. In 1-in., %	Area Reduction %	UTS	0.2% Offset YS, ksi	Elong. In 1-in., %	Area Reduction %	Failure Origin
7C090	257	238	1.8	4.1	260	243	1.5	0	Weld & HAZ*
	234	---	1.3	0	260	249	1.6	1.0	Weld & HAZ*
	113	---	-	0	259	248	1.5	0	Weld & HAZ*
					259	248	1.0	2.4	Weld & HAZ*
					218	---	0.5	0	Weld & HAZ*
7C091	254	228	1.0	0	251	237	1.0	0	Weld & HAZ*
	254	228	2.0	2.5	250	238	1.0	2.4	Weld & HAZ*
	228	---	-	0	233	227	0.5	1.0	Weld & HAZ*
					250	237	2.4	5.5	Weld & HAZ*
					235	---	1.0	2.4	Weld & HAZ*
7C092	203	---	0.5	0	232	222	2.0	4.0	Weld & HAZ*
	200	192	0.8	0	238	226	1.8	3.2	Weld & HAZ*
	232	209	1.8	2.4	236	223	1.8	3.2	Weld & HAZ*
					240	226	2.4	2.4	Weld & HAZ*
					238	227	2.7	1.6	Weld & HAZ*
7C093	Broke in Grips				238	229	1.3	3.3	Weld & HAZ*
	222	177	1.0	0.8	233	226	1.3	0.8	Weld & HAZ*
	216	---	1.5	0	242	227	1.5	3.2	Weld & HAZ*
					232	219	1.5	2.4	Weld & HAZ*
7C094	252	213	0.9	0	257	240	1.1	0.8	Weld & HAZ*
	241	217	1.4	0	256	245	1.0	2.4	Weld & HAZ*
	234	---	0.9	0	253	241	1.3	4.0	Weld & HAZ*
					244	239	1.3	0.8	Weld & HAZ*
					243	237	0.9	0.8	Weld & HAZ*

* Heat-Affected Zone

Mechanical Properties of Submerged-Arc-Welded 18%-Nickel Steel

Figure 51



Typical Tensile-Specimen Fracture and Microstructures in 1/2-in.-Thick Submerged-Arc Weld in 18%-Ni Maraging Steel. 7C-094 Weld Wire; as-Welded-and-Aged (900°F for 4 hr) Condition; Bethlehem Heat 120D163

Figure 52

Wire No. [1]	C	Mn	P	S	Ni	Co	Mo	Ti	Al
7C-090	.034	.11	.009	.006	18.6	9.8	4.65	.34	.04
7C-091	.034	.17	.007	.006	18.4	8.18	4.70	.37	.02
7C-092	.027	.16	.008	.005	18.3	7.63	3.98	.26	.02
7C-093	.031	.08	.004	.008	18.5	8.75	4.05	.50	.06
7C-094[2]									

(1) Refer to Figure 39 for weld-wire cobalt, molybdenum and titanium contents.

(2) Presently being rerun.

Chemical Analysis of Submerged-Arc Welds, 1/2-in.-Thick 18%-Ni Maraging Steel (Bethlehem Heat 120D163), Five Different Weld Wires

Figure 53

(Welded and Aged 900°F for 4 hours)

Weld Wire	Orientation	Y.S. at 0.2% Offset ksi	Ult. Tensile Strength ksi	Elong. in 1", %	Reduction in Area, %
7C-093	Transverse Weld	241.4	250.5	4.1	24.6
		243.4	249.5	2.8	17.5
		239.4	247.0	4.5	30.1
		238.4	248.5	2.2	19.5
		242.4	251.5	5.5	37.7
	Average	241.0	249.4	3.8	25.5
7C-094		251.5	266.2	5.1	17.5
		259.1	267.7	4.8	27.2
		252.5	268.2	7.2	30.1
		252.5	265.8	5.3	29.2
	Average	253.9	267.0	5.6	26.0

Mechanical Properties of MIG-Welded 18%-Nickel Maraging Steel, (Bethlehem Heat 120D163) Aged for 4 hr at 900°F After Welding

Figure 54

Material	Element, Wt%*		
	Co	Mo	Ti
7C-093 Weld Wire	8.0	4.7	0.67
	8.02	4.3	0.60
7C-094	9.9	4.6	1.22
	8.7	4.4	0.60
Base Plate	8.0	4.9	0.48

* Analysis limited to Cobalt, Molydenum, and Titanium

Chemical Analysis of Metallic-Arc Inert-Gas Welds, 1/2-in.-Thick 18%-Ni Maraging Steel (Bethlehem Heat 120D163)

Figure 55

Material	Element, Wt%*		
	Co	Mo	Ti
7C-093 Weld Wire	8.0 8.02	4.7 4.3	0.67 0.60
7C-094	9.9 8.7	4.6 4.4	1.22 0.60
Base Plate	8.0	4.9	0.48

* Analysis limited to Cobalt, Molydenum, and Titanium

Chemical Analysis of Metallic-Arc Inert-Gas Welds, 1/2-in.-Thick 18%-Ni Maraging Steel (Bethlehem Heat 120D163)

Figure 55

APPENDIX A

SLOW NOTCH BEND AND PRECRACKED-IMPACT TESTS

APPENDIX A

Procedure For Conducting the Slow Notch Bend And Precracked Impact Tests

Slow Notch Bend Test

A relationship exists between fracture toughness (G_c) and the spring constant in bending as a function of crack area. This relationship can be expressed as

$$G_c = \frac{F^2}{2} \left(\frac{d \frac{1}{M}}{d \frac{1}{A}} \right) \qquad (1)$$

where:

F = load at failure

M = spring constant as function of crack area

The spring constant of a bar in bending is defined as the load divided by the deflection of the load and is a function (in notched bars) of the cross-sectional minimum, or net, area beneath the notch. For a given material and given specimen width, the spring constant varies as the depth beneath the notch, or inversely, as the notch depth.

In notched bars containing an induced crack at the notch root, the crack effectively increases notch depth and therefore, influences the spring constant. If the variation of spring constant with crack depth is accurately known, then measurement of the spring constant in a given test specimen results in an inferred crack length.

In order to obtain the relationship between spring constant and notch or crack depth a series of calibration bars containing varying notch depths (from 0 to approximately 0.400 inches deep) are prepared. The spring constant for each bar is determined by loading elastically to a given load and autographically recording the load-deflection curve. The spring constant of the bar is determined by the slope of the curve as

$$M = \frac{L}{eb} \tag{2}$$

where:

L = change in applied load

e = change in deflection caused by the load

b = specimen width

Three of four loadings and unloadings per bar will increase the accuracy of the slope measurement. When the reciprocal of the spring constants, 1/M, is plotted against equivalent notch depths, a curve such as that shown in Figure 2A results.

The equation of the curve relating spring constant to notch or crack depth (a) is of the form

$$\frac{1}{M} = Mo + Qa^2 + Ra^3 + Sa^4 \tag{3}$$

where:

Mo = intercept on the 1/M axis (or the reciprocal of the spring constant of a no-notch bar)

Q, R, S = constants defining the position of the curve with respect to the variables 1/M and (a)

The values of the constants can be determined by the solution of three simultaneous equations involving three unknowns (Q, R and S) formulated by substituting in equation (3) three values for 1/M and (a) taken from the calibration curve.

To determine the fracture toughness of a given specimen, the specimen is loaded to failure and the load-deflection curve is autographically recorded as shown in Figure 1A. The slope of the load-deflection curves is constant until the crack starts growing (point X in Figure 1A). At this point, the deflection proceeds with less and less required load as the crack propagates. At the point where the slope becomes zero (point Y in Figure 1A), instability occurs and the crack propagates to failure without additional load. The slope of the load-deflection curve is easily and accurately measured to the point where crack propagation begins. The strain-energy release rate, G, at this point is nearly equivalent to the plane strain-fracture toughness of the material (and is hereafter referred to as G_{nc}). However, depending upon the toughness of the material, a great deal of difficulty sometimes arises in estimating the slope during crack propagation, and an error can exist in G_c. For this reason, and for the reason that in thick sections, plane strain propagation is nearly always the mode of failure, it has been decided to report the fracture-toughness value as G_{nc} rather than as G_c.

After having obtained the load-deflection curve as described above, the spring constant can be calculated, as in equation (2), by substituting width (b) and values for both load (L) and deflection (e) at the beginning of crack propagation (point X in Figure 1A). Reference to the previously constructed calibration curve gives the value of crack depth (a) as a function of the reciprocal of the spring constant determined for the test.

As has been mentioned, the fracture toughness of a material is a function of the derivative of the spring-constant reciprocal, 1/M, with respect to crack area A. This function can be obtained by differentiating equation (3) with respect to crack depth (a) as

$$\frac{d\,\overset{1}{\overline{M}}}{dA} = 2Qa + 3Ra^2 + 4Sa^3 \qquad (4)$$

Division by specimen width, b, gives the proper function as

$$\frac{d\,\overset{1}{\overline{M}}}{dA} = \frac{d\,\overset{1}{\overline{M}}}{b\,da} = \frac{1}{b}\,(2Qa + 3Ra^2 + 4Sa^3)$$

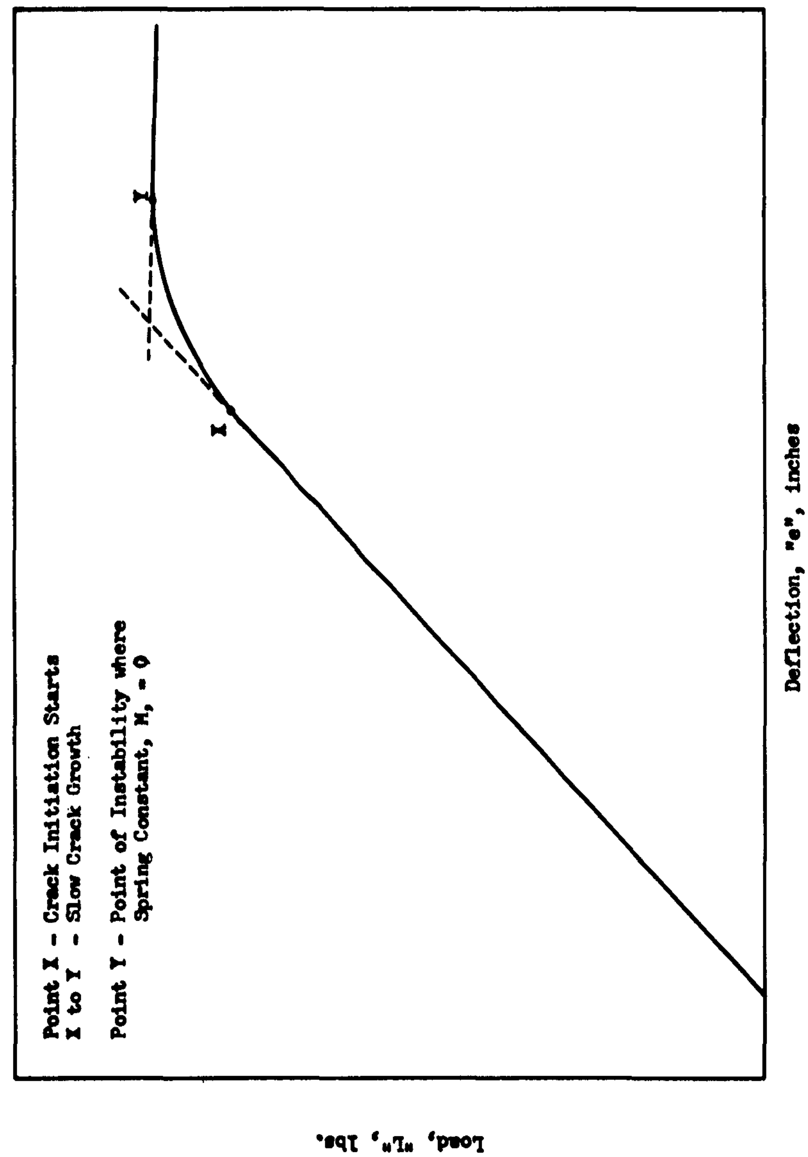
Substituting this function in equation (1) yields

$$G_c = \frac{F^2}{2b}\,(2Qa + 3Ra^2 + 4Sa^3) \qquad (5)$$

where G_c is the strain-energy release rate at the onset of catastrophic failure, F is the load at failure, b is the specimen width, Q, R and S are constants (the solution of which was covered above), and a is the crack depth at the onset of catastrophic failure. By using the load at the beginning of slow crack propagation (point X in Figure 1A) and the corresponding crack depth, the same formula yields a value for G_{nc} (plane strain-fracture toughness).

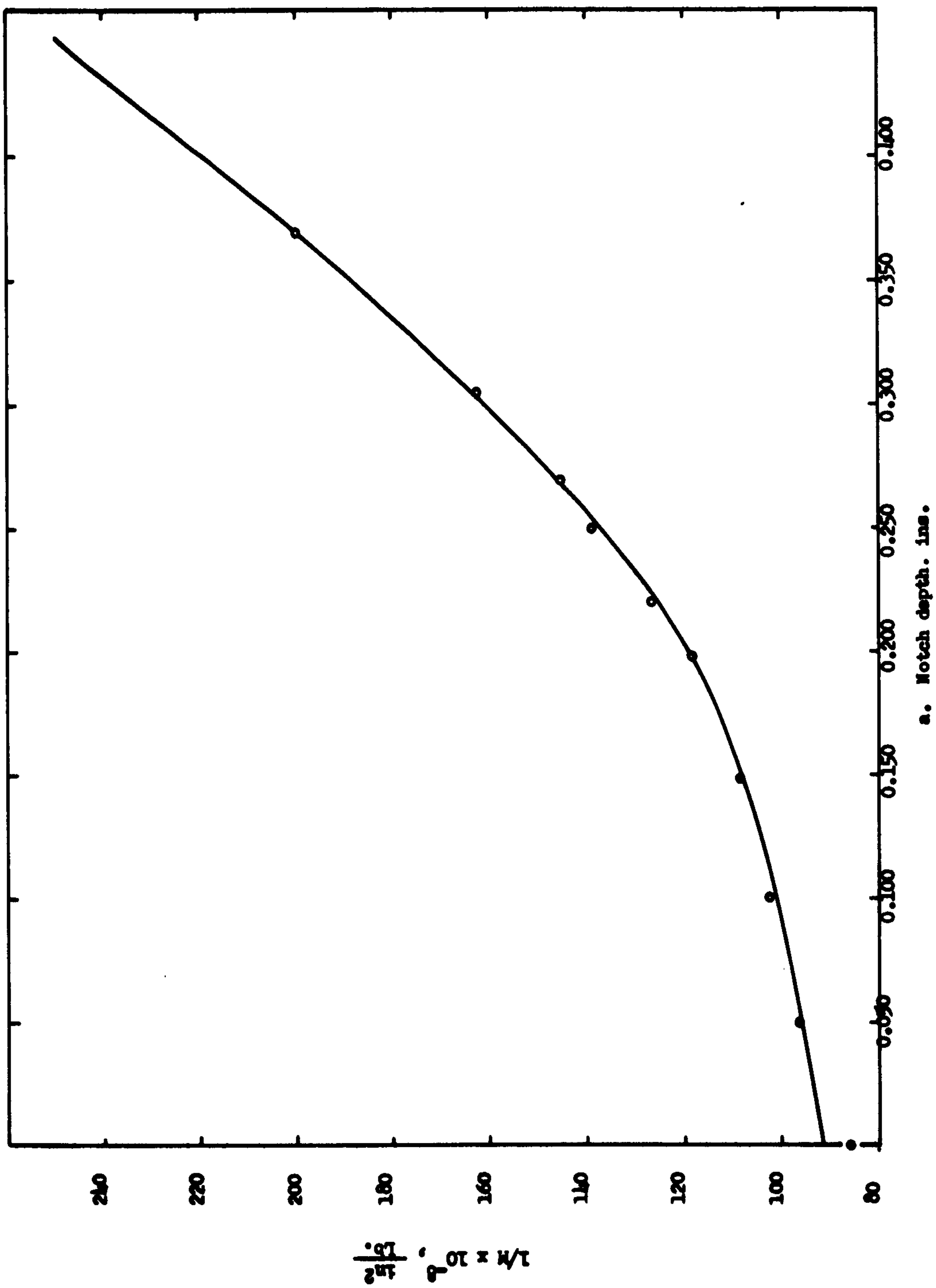
Precracked-Impact Test

A measure of fracture toughness can also be determined by the precracked-impact test. This test is similar to the conventional Charpy test in that the specimen is impact-loaded in bending and the energy in in.-lb required to break the specimen is recorded. However, the specimen is fatigue-cracked prior to testing and the in.-lb of energy required to cause failure is divided by the net section area under the fatigue crack. The resulting value is (W/A). Fracture toughness (W/A) measured by this technique is approximately equivalent to G_c rather than to G_{nc} in that shear surfaces formed during crack propagation influence the energy required to cause failure.



Schematic Illustration of a Typical Slow Notch Bend Test, Load-Load Deflection Curve Obtained in Testing Materials of High and Intermediate Fracture Toughness.

Figure 1A



A Typical Calibration Curve Relating Reciprocal of the Spring Constant (1/M) to Notch Depth for an 18%-Nickel Maraging Steel - Slow Notch Bend Test

Figure 2A

APPENDIX B

MATERIAL SPECIFICATIONS: PROCUREMENT OF OPTIMUM MATERIAL

AEROJET-GENERAL CORPORATION

CODE IDENT. NO. 13310

AGC-34276A
Amendment 1
17 December 1962

DEVELOPMENT MATERIAL SPECIFICATION

STEEL PLATES, SHEETS, STRIPS, BARS, AND FORGINGS
MARAGING: HIGH-STRENGTH, 18 PERCENT NICKEL

This amendment forms a part of Aerojet-General Corporation Development Material Specification AGC-34276A.

Paragraph 3.4 Delete and substitute:

"3.4 Mechanical properties.- The material shall be capable of meeting the strengths specified below. In order to insure that the strength level is attained, tensile specimens shall be solution annealed as specified in 3.3 and aged at temperatures of 850 to 950° F for two to eight hours. Sufficient aging time-temperature cycles within these limits shall be evaluated to accurately establish the aging response of each heat of material being procured and to insure that the required strength can be reliably and consistently attained.

Class	Yield Strength (KSI at 0.2 % Offset)
200	200
235	235
250	250
300	300 "

Paragraph 4.2.2 (a) Delete and substitute:

"(a) Chemical composition Each sheet, plate, or strip"

Paragraph 4.2.3.1, first sentence: Delete and substitute.

"At least one sample for chemical analysis shall be taken from each bar or forging."

Paragraph 4.2.3.5 Delete and substitute:

"4.2.3.5 Tensile specimens.- Three or more tensile test specimens shall be selected from the same bar or forging, physical condition, and size as the material that is submitted for acceptance. When forgings are made in multiple from a single forging; that is, forged in one piece and cut apart during machining, test samples from the large forging shall apply to the individual units. Test specimens shall be solution annealed as indicated in 3.3 for 30 minutes, air cooled to room temperature, and aged at temperatures of 850 to 950°F for two to eight hours."

Authorized for Release:

J. H. Yetto, Manager
Engineering Specifications
Solid Rocket Plant
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AEROJET-GENERAL CORPORATION
CODE IDENT. NO. 13310

AGC-34276A
7 December 1962

Superseding
AGC-34276
19 June 1962

DEVELOPMENT MATERIAL SPECIFICATION

STEEL PLATES, SHEETS, STRIPS, BARS, AND FORGINGS MARAGING: HIGH-STRENGTH, 18 PERCENT NICKEL

1. SCOPE

1.1 Scope. - This specification covers maraging steel alloys in plate, sheet, strip, bar, and forging.

1.2 Classification. - The material shall be of the following types, grades, and classes.

Type I	Sheet, strip, and plate
Type II	Bars and forgings
Grade A	Forgings requiring all tests
Grade B	Forgings not requiring grain flow and inclusion rating tests

Class	Yield Strength - KSI
200	200
235	235
250	250
300	300

2. APPLICABLE DOCUMENTS

2.1 Department of Defense documents. - The following documents listed in the Department of Defense Index of Specifications and Standards, of the issue in effect on the date of invitation for bids, shall form a part of this specification to the extent specified herein.

SPECIFICATIONS

Military

MIL-C-16173	Corrosion Preventive Compound Solvent Cutback, Cold-Applications

MIL-I-6868	Inspection Process, Magnetic Particle

STANDARDS

Federal

Fed. Test Method Std. No. 151	Metals: Test Methods
Fed. Std. No. 183	Continuous Identification Markings of Iron and Steel Products

(Copies of specifications, standards, drawings, and publications required by contractors in connection with specific procurement functions should be obtained as indicated in the Department of Defense Index of Specifications and Standards.

2.2 Other documents. - The following documents, of the issue in effect on the date of invitation for bids, shall form a part of this specification to the extent specified herein.

SPECIFICATIONS

Society of Automotive Engineers

AMS-2251	Tolerances - Alloy Steel Parts (Aeronautical Material Specifications)
AMS-2252	Tolerances - Alloy Steel Sheet. Strip and Plate
AMS-2300	Premium Aircraft Quality Steel Cleanliness
AMS-2630	Ultrasonic Inspection
AMS-2808	Identification, Forgings

(Application for copies should be addressed to Society of Automotive Engineers, Inc., 485 Lexington Ave., New York 17, New York.)

STANDARD

American Society for Testing Materials

ASTM E 45	Recommended Practice for Determining the Inclusion Content of Steel

(Copies may be obtained from the American Society for Testing Materials, 1916 Race Street, Philadelphia 3, Pennsylvania.)

3. REQUIREMENTS

3.1 Chemical composition. - The steel shall contain the indicated percentages of the following elements, together with those additives listed in 3.2.1.

	Material Class							
	200		235		250		300	
Element	Min	Max	Min	Max	Min	Max	Min	Max
Carbon	---	0.03	---	0.03	---	0.03	---	0.03
Manganese	---	0.10	---	0.10	---	0.10	---	0.10
Silicon	---	0.10	---	0.10	---	0.10	---	0.10
Phosphorus	---	0.025	---	0.025	---	0.025	---	0.025
Sulfur	---	0.01	---	0.01	---	0.01	---	0.01
Nickel	17.5	19.0	17.5	18.5	18.0	19.0	18.0	19.0
Titanium	0.10	0.25	0.25	0.40	0.40	0.65	0.65	0.85
Aluminum	0.05	0.15	0.05	0.15	0.05	0.15	0.1	0.4
Cobalt	6.5	7.5	6.5	7.5	7.0	8.0	8.0	10.0
Molybdenum	3.5	4.5	4.5	5.5	4.5	5.5	4.5	5.5

3.2 Melting practice. - The melting practice used in the manufacture of the steel shall be in accordance with the following, as specified in the purchase order:

	Material Class			
Melting practice	200	235	250	300
(a) Air melted	X			
(b) Vacuum degassed	X	X	X	
(c) Vacuum-induction melted	X	X	X	
(d) Vacuum-arc remelted		X	X	X

3.2.1 Additives. - The supplier shall certify that the indicated amounts of the following materials were added to the steel during melting:

Material	Amount, Percent
(a) Boron	0.003
(b) Zirconium	0.02
(c) Calcium	0.06 in increments of 0.02

3.3 Solution treatment. - The material shall be furnished in the solution-treated condition. Solution treatment shall be such that the material is maintained at a temperature of 1500 ± 25°F for one hour per inch of cross section.

3.4 Mechanical properties. - The material shall be capable of meeting the required yield strength (0.2 percent offset) indicated by the material class being procured. In order to insure this strength level is attained, tensile specimens will be solution annealed as indicated in 3.3, and aged at temperatures of 850 to 950°F for times of two to eight hours. Sufficient aging time-temperature cycles within these limits shall be evaluated to accurately establish the aging response of each heat of material being procured and to insure that the required minimum yield strength can be reliably attained.

3.5 Grain size. - The grain size of type I material shall be determined and the results reported. The grain size of type II material shall be five or finer when tested in accordance with Standard Fed. Test Method Std. No. 151; however, a heat of type II material predominately five or finer, with occasional grains as large as three, shall be acceptable.

3.6 Grain flow. - Forging stock shall be of such size and dimensions that the work accomplished, in forming to finished shape, shall result in approximately uniform grain size throughout. The forging techniques employed shall produce an internal grain flow pattern in such a way that the direction of flow in highly-stressed areas shall be essentially parallel to the principal stresses, as specified in applicable engineering documents. The grain flow pattern shall be essentially free from re-entrant and from sharply folded lines. This requirement does not apply to grade B forgings and bar stock.

3.7 Inclusion rating. - Inclusion-rating tests shall be made and the results reported. The inclusion rating shall be based on the worst area of inclusions found in the test specimens evaluated and shall not exceed the following when tested in accordance with Standard ASTM E 45.

Series	
Thin	Heavy
A 1-1/2	A 1
B 1-1/2	B 1
C 1-1/2	C 1
D 2	D 1-1/2

This requirement does not apply to grade B material.

3.8 Tolerances. - Tolerances for type I material shall be in accordance with Specification AMS-2252. Tolerances for bar stock shall be in accordance with Specification AMS-2251. Tolerances for forgings shall be as specified on applicable drawings.

3.9 Cleaning. - All forgings shall be thoroughly cleaned by tumbling, machining, shot or sand blasting, pickling, or other processes approved by the procuring activity.

3.10 Identification marking. - Each piece of material shall be identified with the following information:

(a) Number and revision letter of this specification
(b) Supplier identification
(c) Supplier heat number
(d) Material classification
(e) Drawing number of machined forging (if applicable)
(f) Serial number of forging (if applicable)
(g) Nominal thickness (if applicable)

3.10.1 Type I material. - Each piece of type I material shall be marked with ink in accordance with Standard Fed. Std. No. 183.

3.10.2 Type II material. -

3.10.2.1 Bars. - The identification characters shall be not less than 3/8 inch in height, shall be applied using a suitable marking fluid, and shall be capable of being removed in hot alkaline cleaning solution without rubbing. The characters shall be sufficiently durable to withstand ordinary handling.

3.10.2.1.1 Marking location. - Each bar shall be marked in lengthwise rows of characters, recurring at intervals of not greater than two feet, with the rows not greater than three inches apart and alternately staggered.

3.10.2.2 Forgings. - Forgings shall be marked in accordance with Specification AMS-2808 .

3.11 Reports. - The supplier shall submit, with each shipment, three copies of a certified melting practice and test report of the results for each heat of material in the shipment. In addition, this report shall include:

(a) Name of the supplier
(b) The testing laboratory used for tests
(c) Purchase order number
(d) Number and revision letter of this specification
(e) Physical dimensions or referenced engineering document
(f) Grade of forging (if applicable)
(g) Quantity from each heat
(h) Type and class of material

3.11.1 Forging stock size. - When forgings are supplied, the size of stock used to make the forgings shall also be included.

3.12 Workmanship. - Material furnished under this specification shall be uniform in quality and shall be free from tears, cracks, seams, laps, internal ruptures, imbedded scale, segregations, or other defects that could detrimentally affect the suitability of the material for the purpose intended.

4. QUALITY ASSURANCE

4.1 Supplier responsibility. -

4.1.1 Inspection. - Unless otherwise specified, the supplier is responsible for the performance of all inspection requirements specified herein and may use any facilities acceptable to the Aerojet-General Corporation (AGC).

4.1.2 Processing changes. - The supplier shall make no changes in processing techniques or other factors affecting the quality of the product without prior approval of AGC.

4.2 Sampling. -

4.2.1 Lot size. - Each heat shall constitute a lot.

4.2.2 Sampling of type I material. - Preparation of samples for type I material shall be in accordance with Standard Fed. Test Method Std. No. 151. Selection of samples shall be as follows:

	Test Requirement	Frequency of Sampling
(a)	Chemical composition	Each lot of sheet, plate, or strip
(b)	Grain size	One sample from each sheet, plate, or strip
(c)	Inclusion content	Each sheet, plate, or strip
(d)	Mechanical properties	Each sheet, plate, or strip
(e)	Thickness	Each sheet, plate, or strip
(f)	Visual examination	Each sheet, plate, or strip
(g)	Magnetic particle	Each sheet, plate, or strip
(h)	Ultrasonic	Each sheet, plate, or strip

4.2.3 Sampling of type II material. - Sampling of type II material shall be in accordance with the following:

4.2.3.1 Chemical. - At least one sample for chemical analysis shall be taken from each heat of steel represented in the forgings or bars. Samples shall be taken from any point midway between the surface and center of solid forgings or bars where the sections exceed one and one-half inches, or at any point midway between the inner and outer surfaces of the wall of hollow forgings. For forgings or bars where the section is one and one-half inches or less, samples shall be taken by drilling entirely through the material, the surface drillings being discarded. Upon approval of the procuring activity, samples may be taken from broken tensile specimens. Each sample shall consist of not less than two ounces of material. Samples for chemical analysis may be waived, at the discretion of the procuring activity, provided that all the material under inspection can be identified as being made from a heat or heats previously analyzed and found to be in accordance with the requirements of this specification.

4.2.3.2 Grain flow. - After the forging technique has been established, one forging (grade A only) shall be selected to represent grain flow. If the forging practice is altered, one additional forging shall be submitted.

4.2.3.3 Grain size. - One or more samples shall be selected from each heat of steel represented in a shipment.

4.2.3.4 Inclusion rating. - Sampling for inclusion rating shall be in accordance with Specification AMS-2300.

4.2.3.5 Tensile specimens. - Three or more tensile test specimens, from the same heat, physical condition, and size as the material that is submitted for acceptance, shall be selected from each processing condition of bars or forgings. When forgings are made in multiple from a single forging; that is, forged in one piece and cut apart during machining, tests on samples from the large forging shall apply to the individual units. Test specimens shall be solution annealed as indicated in 3.5 for 30 minutes, air cooled to room temperature and aged at temperatures of 850 to 950°F for times of two to eight hours.

4.2.3.5.1 Location of tensile specimens. - Whenever practicable, the samples for tensile test specimens shall be taken from the material in a section where the least reduction takes place. When this is not practicable because of the size or shape of the forging or bar, or because of the excessive cost of destroying a component part, test specimens shall be taken from a full-size prolongation of the material in the direction of maximum reduction. When neither of these methods are possible, a separate test coupon may be prepared from the same bar, billet, or bloom as the forging or bar it represents. The percentage reduction given this coupon shall be not greater than the minimum amount of reduction given the forging.

4.2.5.2 Sample processing. - No further forging or hot reduction shall be performed on the material for test samples, after the samples have been separated from the parent material. The test samples, if made separately from the forging, shall be heat-treated with the forgings they represent.

4.3 Test methods. - The following test methods shall be used to determine conformance with requirements of section 3.

4.3.1 Chemical composition. - Chemical analysis shall be determined in accordance with Standard Fed. Test Method Std. No. 151 by wet chemical, spectro-chemical, or other approved analytical methods. In the event of dispute, analysis shall be by wet chemical methods, except for carbon which shall be by the cumbustion method.

4.3.2 Standard test methods. - The following standard test methods shall be used:

	Requirement	Test Method
(a)	Mechanical properties (3.4)	Fed. Test Method Std. No. 151, Method 211
(b)	Grain size (3.5)	Method 311 (Std. No. 151)
(c)	Grain flow (3.6)	Method 321 (Std. No. 151)* (this is not required on bars and grade B forgings)
(d)	Inclusion rating (3.7)	ASTM E 45 (this is not required for grade B forgings)
(e)	Tolerances (3.8)	
	Type I material	AMS-2252
	Type II material - bars	AMS-2251
	Type II material - forgings	Visual
(f)	Cleaning (3.9) (forgings only)	Visual
(g)	Marking (3.10)	Visual
(h)	Reports	Visual
(i)	Workmanship	
	Types I and II	Visual AMS-2630 (Ultrasonic Inspection) MIL-I-6868 (Magnetic particle)

*This test method shall be used to check grain flow structure and may be waived, at the discretion of the procuring activity, when the size of the forging is so large as to make sectioning impracticable.

4.4 Retest. - Rejected parts shall not be re-submitted for inspection without furnishing full particulars concerning previous rejection, and measures taken to overcome the defects.

5. PREPARATION FOR DELIVERY

5.1 Preservation. - Unless otherwise specified, all material shall be prepared for storage by coating with corrosion preventive compound that conforms to the requirements of Specification MIL-C-16173, grade 2.

6. NOTES

6.1 Ordering data. - Procurement documents should specify the following:

(a) Material type
(b) Form (sheet, strip, plate, bars, or forgings)

(c) Number and revision letter of this specification
(d) Grade (of forging) (if applicable)
(e) Place of inspection
(f) Lot size
(g) Place of delivery
(h) Marking location (if applicable)
(i) Forming process (if applicable
(j) Tensile coupon specimen location (if applicable)

6.2 Supersession information. - If the classification type (1.2) is not specified, the requirements for type I will govern.

Authorized for Release:

J. H. Yetto, Manager
Engineering Specifications
Solid Rocket Plant
Sacramento

APPENDIX B

EXCEPTIONS TO SPECIFICATION AGC 34276A - PROCUREMENT OF OPTIMUM MATERIAL

Section 3.1 Chemical Composition - The steel shall contain the indicated percentages of the following elements together with those additives listed in 3.2 of AGC 34276A

Element	Min	Max
Carbon	-	0.03
Manganese	-	0.10
Silicon	-	0.10
Phosphorous	-	0.025
Sulphur	-	0.01
Nickel	17.5	18.5
Titanium	0.05	0.25
Aluminum	0.05	0.15
Cobalt	7.5	8.0
Molybdenum	4.0	4.5

3.2 Melting Practice - The material shall be produced by the air melt, air melt and vacuum degassed or the vacuum arc remelt technique.

3.2.1 Additives - same

3.3 Solution treatment - delete

3.4 Mechanical Properties - The material shall be capable of meeting the required yield strength (0.2% offset) of 200 ksi minimum and 235 ksi maximum. In order to ensure this strength level is reliably attained, 3 tensile specimens from the plate and 3 from excess forged material shall be aged at 900°F for 8 hours. The test results shall be identified by item, heat number, etc., and forwarded to AGC for acceptance.

3.5 Grain size - same

3.6 Grain flow - delete

3.7 Inclusion Rating - Rating shall be:

Thin	Heavy
A 2	A 1 1/2
B 2	B 1 1/2
C 2	C 1 1/2
D 2 1/2	D 2

titanium compounds shall be rated by using the B series shown above.

3.8 Tolerances - delete

3.9 Cleaning - same

3.10 Identification Marking - same for all sub-sections

3.11 Reports - same for all sub-sections

3.12 Workmanship - same

4.1.1 Inspection - same

4.1.2 Processing changes - delete

4.2.2 Sampling of Type I Material - Selection of samples shall be as follows:

	Test Requirements	Frequency of Sampling
(a)	chemical composition	Top and bottom of ingot
(b)	grain size	Plate
(c)	Inclusion content	Plate
(d)	Mechanical properties	See Section 3.4
(e)	Thickness	Delete
(f)	Visual	Plate and forgings
(g)	Magnetic particle	Plate
(h)	Ultrasonic	Plate

4.2.3 Sampling of Type II Material (forgings)

	Test Requirements	Frequency of Sampling
(a)	chemical analysis	Delete (see Section 4.2.2.(a)
(b)	grain size	1 from each forging
(c)	Inclusion content	1 from each forging
(d)	Mechanical properties	See Section 3.4
(e)	Visual	Each forging
(f)	Magnetic particle	Each forging
(g)	Ultrasonic	Each forging

4.2.3.1 through 5 - delete

4.2.3.5.1 - See Section 3.4

4.2.5.2 - Sample Processing - same

4.3 - Test Methods - same

4.3.1 - Chemical Composition - same

4.3.2 - Standard Test Methods - the following standard test methods shall be used:

	Requirement	Test Method
(a)	Mechanical Properties (3.4)	Same
(b)	Grain size (3.5)	Same
(c)	Grain flow (3.6)	Delete
(d)	Inclusion rating (3.7)	Same
(e)	Tolerances	Delete
(f)	Cleaning (3.9)	Same
(g)	Marking (3.10)	Same
(h)	Reports	Same
(i)	Workmanship	
	Type I & II	Visual AGC 36235A (Magnetic Particle) AGC 36163* (Ultrasonic Inspection)

*Exceptions noted below refer to Paragraphs of AGC 36163

Section 1.2 Classification - change to the ultrasonic inspection scan shall cover the entire surface of each piece.

Section 3.1 Acceptance rejection criteria shall be defined as follows:

(a) Pieces showing a single indication oriented parallel to the surface of the piece greater than the response from a 12/64 inch diameter flat bottom hole at the estimated discontinuity depth shall be rejected and subject to negotiable acceptance.

(b) Pieces showing indications oriented parallel to the surface of the piece greater than the response from a 12/64 inch diameter flat bottom hole at the estimated discontinuity depth, whose indicated centers are less than one inch apart, shall be rejected.

(c) Any flaws indicating a length greater than 3/4 inch are not acceptable.

(d) Pieces containing multiple discontinuities of such size and frequencies, as to reduce the back reflection pattern to 50 percent or less of the normal back reflection in the same geometry, shall be rejected; noting that the crystal shall be perpendicular to the front and back surfaces.

(e) Pieces showing indications observed by the shear wave method exceeding 3% of the thickness of the material shall be cause for rejection.

Section 4.4.1 Immersion Method - Contact method of inspection shall be permitted.

The remainder of the Sections of 34276A shall remain as written.