1949

Composition and property variation of two steels, Welding Journal, Vol. 28, p. 227-s, 1949, Reprint No. 66.(49-3)

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Recommended Citation

Osborn, C. J.; Scotchbrook, A. F.; Stout, R. D.; and Johnston, B. G., "Composition and property variation of two steels, Welding Journal, Vol. 28, p. 227-s, 1949, Reprint No. 66.(49-3)" (1949). *Fritz Laboratory Reports.* Paper 1444.
http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/1444

This draft incorporates the revisions of the text which were suggested at the last two project meetings. Tables I, V, VI, Figs. 1, 7a, 7b, 8b, 10b, 11b, 12 and 13 have been left out. Figs. 2, 3, 4, 5 and 6 have been consolidated into Tables I + II.

If there is time after our study of this draft, perhaps we can go on with revision of Report # 3.

AS

THE EFFECT OF FABRICATION PROCESSES ON STEELS USED IN PRESSURE VESSELS

PROGRESS REPORT~~S~~ NO~~S~~ 2

WITHIN HEAT VARIATION OF COMPOSITION AND PROPERTIES IN A RIMMING AND AN ALUMINUM-KILLED STEEL

by C. J. Osborn[1], A. F. Scotchbrook[2], R. D. Stout[3], and B. G. Johnston[4]

FOREWORD

This is the second of ~~xxx~~ a series of reports (see reference 10) describing the results of work performed at Lehigh University for the Fabrication Division of the Pressure Vessel Research Committee of The Welding Research Council. The underlying purpose of the work is to study the effect of fabrication processes involving plastic strain with or without subsequent heat-treatment, welding or strain aging, on the relative tendency of various steels toward brittle failure at low temperature. Two steels, one rimmed and the other aluminum killed, each in two plate thicknesses (5/8" and 1 1/4"), were obtained for the initial part of the project.

This report presents the results of a series of tests suggested by the Materials Division of the Pressure Vessel Research Committee to determine the variation of composition and mechanical propebties within the two heats of steel being used in the main investigation. Since the steels investigated

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are being used for other research programs sponsored by the Pressure Vessel Research Committee, it is felt that ~~publication~~ of these results should be ~~made a~~ published ~~is of interest to the~~ profession ~~public~~, ~~in spite of the fact that the variations are of the nature and within the range found in other materials by other investigators.~~ ? ?

INTRODUCTION

The tendency of a steel to fail in a brittle fashion is of tremendous practical importance in engineering structures and much is already known concerning the factors which govern this tendency. It is known, for example, that chemical composition exerts an important influence on the mode of failure and that, other things being equal, the transition temperature of a steel rises with an increase in its carbon content.[1] Other elements, notably manganese[2] and nitrogen[3], are also considered by some to affect the transition temperature. The influence of chemical composition on strength and ductility is also well-known.

However, it is also known that within a single heat of steel, and even within a single ingot or plate, there occur marked differences in composition. These arise both from the different times of holding in the ladle before pouring successive ingots, and from segregation and rimming effects during solidification of the ingots. Since such composition differences may well be of appreciable magnitude, their distribution and their influence on fracture characteristics and other physical properties become matters of considerable importance to the engineer.

The present investigation was performed on two heats of steel, whose prior histories were completely known, in order to obtain information on these and allied questions. One heat, aluminum-killed, had been supplied to A. S. T. M. Specification

A-201 and the other, a rimming steel, to A. S. T. M. Specification A-70. The former, an aluminum-killed heat, had been cast into 9 big-end-up hot-topped ingots, 34" x 66", each weighing 30,450 lb.* The Pressure Vessel Research Committee obtained plates from ingots numbered 1, 2, 3, XXXX 4, 5, and 9; ingots 1 and 3 were rolled to 5/8" thickness, and the others to 1 1/4" thickness. The top halves of ingots 1, 2, and 4 were mill-normalized. Ingots 1, 3, 4, and 9 were used in the present investigation. The rimming steel heat had been cast into four groups of bottom-poured ingots. Each ingto was rolled ~~to~~ into one plate and cut to a length of 24'-0", 24'-0" x 6'-0", the six 5/8" plates for the Pressure Vessel Research Committee coming from the first group and the six 1 1/4" plates from the third. One plate of each thickness was used in this investigation.

The following tests were performed at ~~various~~ selected places within the ~~selected~~ chosen ingots:

1. Chemical Analyses
2. Macroscopic Inspection: controlled deep etch; sulphur prints.
3. Microscopic Inspection: as-rolled metallographic; inclusion count; grain coarsening tests; McQuaid Ehn tests.
4. Mechanical Tests: strip tensiles; 0.505" tensiles; Brinell hardness; Charpy keyhole specimens, single and double width.

Each of these will be discussed individually.

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* Other particulars concerning the mill histories of both heats are given in an Appendix of this report.

I. Chemical Composition

The distribution of alloying elements and impurities in killed and rimmed steel ingots has been investigated at considerable length by the Iron and Steel Institute, Committee on the Heterogeneity of Steel Ingots.[4-9]

In the present investigation, samples for chemical analysis were taken from the A-201 ingots 1, 4, and 9 at the top, middle and bottom center, and from ingot 9 at the top and middle edge; also from one small and one large A-70 ingot at the top, middle and bottom center, and top and bottom edge.

The results for the A-201 (Al-killed) steel are given in Table I. The following observations may be made, ~~concerning them~~:

1. Concerning composition differences from ingot to ingot within the heat, the last ingot (No. 9) appears to be lower in carbon, manganese, silicon, aluminum, alumina, and nitrogen than the two earlier ingots, but it appears to be appreciably higher in sulphur and slightly higher in phosphorus and copper, ~~and chromium.~~ Nickel, chromium tungsten, vanadium, and molybdenum were approximately the same in all ingots. The decreasing carbon, manganese, silicon and aluminum contents probably result from oxidation in the ladle. The increasing sulphur content may be due to density segregation of sulphides in the ladle.
2. On the vertical centerline of each ingot carbon, manganese, phosphorus, sulphur, and silicon appear to decrease slightly from top to bottom. In Ingot 9, aluminum *increases* markedly from top to bottom.
3. From the limited results available (Ingot No. 9) it appears that at least sulphur and phosphorus increase

from the edge to center of the ingot. The British investigators[5,6] found phosphorus segregation of the order shown in Fig. 4 only in ingots much larger than Ingot No. 9. Otherwise the magnitude and pattern of segregation is much as indicated by Hatfield.[4,5,6]

4. The maximum and minumum values of carbon content recorded are at the top and bottom center respectively of Ingot No. 4; the range is .14% to .18%.

Results for the A-70 (rimming steel) are given in Table II. Significant features are:

1. The group of larger ingots rolled to 1 1/4" was cast some 10 minutes after the group of smaller ingots. The average compositions of the two ingots were not very different except with regard to alumihum which was appreciably higher in the large ingot owing to a further addition of aluminum to reduce gassing in this group.
2. Manganese, phosphorus, silicon, nickel, copper, chromium, tungsten, vanadium, molybdenum and nitrogen segregated very little in either of the ingots examined.
3. Carbon, sulphur and alumina contents were appreciably higher at the top center of the ingot than elsewhere, while the aluminum content was a minimum at this point.
4. The maximum and minumum values of carbon content recorded occurred at the top of the small ingot (No. 7), the range being .14% to .25%. This is a greater range than was observed in the A-201 steel but is not inconsistent with previous reports on rimming steel ingots.[6]

II. Macroscopic Inspection

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A [redacted] deep etch and a sulphur print were made on plate samples from the top, middle and bottom center of A-201 ingots 1, 4, and 9, and A-70 ingots 2 and 7. All samples were longitudinal.

The sulphur prints were made by applying Velox F-3 photographic paper soaked in 4% sulphuric acid to a ground surface for 10 minutes. Copies of some of the prints are shown in Figs. 1 and 2. In all cases it was clear that sulphur had segregated to the top of the ingot. The low sulphur content of the rim as seen in Fig. 2 was very marked.

The deep etch treatment consisted of 30 minutes of 50% hydrochloric acid at 150°F. Some of the results are shown in Figs. 3 and 4. Here the greater cleanliness at the bottom of the ingots is evident from the less severe attack during etching. The dirt or other unsoundness discovered by the deep etch appears coarser and less uniform in the A-70 ingot than in the A-201. The controlled etch did not show any significant difference between ingots of the same heat.

III. Microscopic Inspection

Using samples from the same locations as the xxxx macro-specimens, inclusion counts were first made on the unetched specimens according to A. S. T. M. Specification E 45-46T, Method A. The predominant type of inclusion in both steels was the globular oxide. There was no great difference between the two steels in regard to the number and distribution of non-metallic inclusions and within each heat there seemed to be little variation from ingot to ingot.

The microstructures at the top, middle, and bottom cen of A-201 ingots 1, and 9 are shown in Figs. 5 and 6. The v fine grain size produced by mill-normalizing is noteworthy in the top of ingot 1. The as-rolled samples of 5/8" plate from Ingot 1 have a finer grain size than the samples of 1 1/4" plate taken from the corresponding positions in ingot 9.

Fig. 7 shows microstructures at the top, middle, and bottom center of A-70 ingot 2. It is evident that the carbon content increased from the bottom to the top of the ingot; again the 5/8" plate had a finer grain size than the 1 1/4" plate.

The grain-coarsening characteristics of the two steels were studied by two methods on samples from the middle of A-201 ingots 1 and 9, and A-70 ingots 2 and 7; i.e., one 5/8" and one 1 1/4" plate from each heat.

McQuaid-Ehn tests were made at 1675°F in accordance with A. S. T. M. Specification E 19-46 and the following results were obtained:

	McQuaid-Ehn Grain Size
A-201, 5/8" plate (Ingot 1)	8
A-201, 1 1/4" plate (Ingot 9)	8
A-70, 5/8" plate (Ingot 7)	3
A-70, 1 1/4" plate (Ingot 2)	4

In addition to the standard McQuaid-Ehn test, a series of grain-coarsening tests was run on the same four plates by holding small samples for one hour at each of the following temperatures:

1350°F, 1500°F, 1650° 1800°F, 1950°F, and 2100°F.

Samples at the four higher temperatures were transferred to another furnace at 1500°F for an hour before water quenching; those at 1350°F and 1500°F were water quenched directly. All quenched samples were tempered at 800°F. This procedure gave microstructures in which the austenitic grain size was outlined by ferrite in a dark matrix of tempered martensite.

From the results (Table III) of these tests it can be seen that both the rimming and the aluminum-killed steels have a sharp coarsening temperature or temperature range. In the rimming steel this is about 1800°F, while in the killed steel it is slightly higher, although not above 1950°F. A sharp coarsening temperature or temperature range is characteristic of steels containing aluminum or certain other grain refining elements such as vandium and titanium; the heat records and chemical analyses show that aluminum was added to both of these steels.

It is noteworthy that the long holding time (8 hours) at 1675°F in the McQuaid-Ehn test caused the rimming steel to coarsen, ~~very markedly~~ so that this test indicated ~~very~~ different results for the two steels. On the other hand, the grain coarsening results in Table II do not indicate such a marked difference.

IV. Mechanical Tests

A. Strip Tensile Tests

Using the A. S. T. M. standard rectangular tensile test-piece (for example see Specification A-201-46) the tensile properties were investigated at the following locations within the two heats:

A-201 (Al-killed steel) - Ingots 1, 3, 4, and 9 at the top, middle, and bottom center.

A-70 (rimming steel) - Ingot 2 and 7 at the top, middle, and bottom center.

Duplicate specimens were tested both parallel and transverse to the rolling direction and the average results of these duplicate tests are given in Tables ~~III and~~ IV and V. Some conclusions may be drawn from these results.

(i) The ductility, as shown by the % reduction of area, was invariably less in the transverse specimens than in the parallel specimens from the same location; this difference seemed greater in the case of the A-201 than the A-70 steel.

(ii) Although the plates were fairly uniform, there was a general increase in ductility and decrease in strength from the top to bottom of all ingots.

(iii) As affected ~~[illegible]~~ the greater cooling rates following rolling, the 5/8" plates showed appreciably higher yield points and slightly higher strength that 1 1/4" plates from the same heat, i.e., comparing plates from corresponding positions within the ingots.

(iv) ~~[illegible]~~ Mill normalizing ~~[illegible]~~ caused no significant change in the tensile properties of the A-201 plates as tested.

B. Tensile Tests on .505" Bars

Some additional information on the tensile properties of the two steels was obtained from ~~the~~ standard .505" diameter bar specimens. In addition to measurements of ductility, the following values were recorded:

Duplicate specimens oriented parallel and transverse to the rolling direction were taken from the top edge and center, middle edge and center, and bottom center of ingot 9, and the top and bottom center of ingot 2.

$$\text{Nominal Yield Point} = \frac{\text{Yield Load}}{\text{Original Area}}$$

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$$\text{Nominal Maximum Stress} \neq \frac{\text{Maximum Load}}{\text{Original Area}}$$

$$\text{Nominal Breaking Stress} \neq \frac{\text{Breaking Load}}{\text{Original Area}}$$

$$\text{True Breaking Stress} = \frac{\text{Breaking Load}}{\text{Area at Breaking}}$$

These results lead to essentially the same conclusions as did the strip tensile results.

(1) The ductility as expressed by % Elongation and % reduction ? in area was approximately 5% higher in parallel than in transverse specimens. In the case of A-201 material, the yield point was about 2,500 psi higher for the longitudinal specimens, while the A-70 specimens showed no significant difference with orientation. Nominal breaking stress was about 5,000 psi lower in the parallel specimens for the A$201~~m~~ material, and about 1,300 for the A-70 material. The true breaking stress averaged about 8,500 psi higher for parallel specimens. The nominal maximum stress, did not vary much with orientation.

(2) In both ingots from top to bottom there was a general increase in ductility of about 5% and decrease in strength of about 5,000 psi for the nominal maximum stress. From center to edge [illegible] of the A-201 ingot the ductility increased ? about 1.5% and the nominal ~~maximum~~ stress decreased about 1000 psi. These trends are consistent with the chemical segregation reported earlier.

Mill Test Reports

Comparing laboratory data with the tensile results given in the mill test reports, the discrepancy between yield points measured at the laboratory and at the mill was very striking. The slower loading rate used in the research laboratory, .006 inches per minute crosshead speed up to yield point for .505" specimens, determined a yield point sometimes as much as 10,000 p.s.i. lower than that determined at the mill. This divergence is well-known and it should be remembered when the possibility of increasing design stresses is considered.

C. Brinell Hardness

The Brinell hardness was determined at the same locations as the strip tensile survey, using a 3000 kg. load and a 10 mm. ball. Three impressions were made at each location.

The average hardness for both steels was 160 and is was clear that in general the hardness decreases from top to bottom of an ingot, the difference from top to bottom being of the order of 10 points Brinell.

D. Charpy Transition Curves

Charpy impact tests were ~~[illegible]~~ performed on samples from the same locations as the strip tensile specimens. The standard keyhole notched specimen was used in this survey (A. S. T. M. Specification E23-41T, Fig. 3, Type B), all specimens being cut with the notch perpendicular to the plate surface and the long axis of the specimen parallel to the rolling direction. Twenty-four specimens were taken from each location and four of these were tested at each of six selected temperatures. ~~In addition to~~ The total energy absorbed by each specimen during testing, ~~which can be~~ was read directly from the Charpy machine, ~~for each specimen~~ ~~[illegible]~~, and the % lateral contraction below the notch, and the % cleavage in the fracture surface were measured after testing.

The method of plotting results was the same as described for other notch tests in a previous paper on this work[10] and the transition temperatures reported in Table V were defined as before, as the temperature at which the curve has a value equal to the arithmetic mean of its maximum and minumum values.

In addition to the standard key-hole Charpy specimen a survey of the 1 1/4" plates was made using the double width Charpy specimen shown in Fig. 12. The results of this survey are also given in Table V.

Significant features of the results are:

1. The Charpy transition temperature according to any of the three brittleness criteria used was considerably lower for normalized plate than for as-rolled plates from the same ingot.
2. Disregarding the two normalized plates in Table V, the transition temperatures generally decreased from the top to bottom of an ingot. This effect was most marked in the % cleavage transition temperatures, where the difference between top and bottom of an ingot was as high as 35°F with the single width specimens and as high as 46°F using double width specimens. Using the criterion of energy absorption, the change in transition temperature within an ingot was much less.
3. The transition temperature for 5/8" plate was appreciably lower than for the corresponding 1 1/4" material.
4. Transition temperatures for A-70 rimming steel were about 70° higher than those for A-201 killed steel.

5. Transition temperatures using fracture appearance as the criterion of brittleness were invariably higher (by as much as 50°F) than those obtained using eigher of the other criteria.

6. Transition temperatures obtained with double width specimens were higher than the corresponding temperatures obtained with single width specimens.

~~Items 5 and 6 are of particular interest in connection with the ideas advanced in Progress Report No. 1.[10]~~

SUMMARY

An investigation has been conducted into the variation of chemical composition and physical properties within plates rolled to two thicknesses from two heats of steel, one conforming to A.S.T.M. Specification A-201, the other to A-70. Both heats exhibited segregation and property variation generally of the type and magnitude to be expected.

The chemical composition was found to vary approximately as indicated by the extensive work of Hatfield and his collaborators.

In tension tests, the ductility was found to increase and the strength to decrease from top to bottom and from center to edge of an ingot. In Charpy tests, both single and double width, the transition temperature became lower from top to bottom of all ingots. These effects were all consistent with the observed chemical segregation.

¶ Yield points determined in the laboratory were invariably much lower than those quoted by the mill test reports for the same material.

Normalized plates had greater ductibity and much lower Charpy transition temperatures than similar plates as rolled.

Plates of 5/8" thickness had a higher yield point, greater strength , and lower transition temperatures than 1 1/4" plate.

The rimming steel had a slightly lower grain coarsening temperature and much higher Charpy transition temperatures than the killed steel.

ACKNOWLEDGMENT

This project was carried out jointly by the Fritz Engineering Laboratory of the Civil Engineering Department and by the Metallurgy Department of Lehigh University. It was sponsored by the Pressure Vessel Research Committee of the Welding Research Council, which is directed by Mr. William Spraragen. Mr. Walter Samans is Chairman of the Pressure Vessel Research Committee, Mr. Russell J. Love former Executive Secretary and Mr. Boniface E. Rossi current Executive Secretary. The Fabrication Division of PVRC gave technical guidance and approval of various stages of the work, under the guidance of Chairman Harry Boardman. The Materials Division of PVRC was responsible for the initial planning of the investigation and acknowledgment is due in particular to Chairman D. B. Rossheim and Mr. R. H. Caughey for assistance in this respect.

TABLE I

Chemical Composition of E-201 Ingots

Ingot 1	C	Mn	P	S	Si	Cu	Ni	Cr	W	V	Mo	Al	Al_2O_3	N_2
Rolled to 5/8"														
Top center	.17	.57	.020	.021	.21	.06	.05	.04	.04	.02	.01	.041	.004	.005
Middle center	.17	.56	.020	.022	.21	.06	.05	.04	.04	.02	.01	.041	.003	.005
Bottom center	.15	.54	.018	.020	.20	.05	.05	.04	.04	.02	.01	.038	.004	.004
Ingot 4														
Rolled to 1 1/4"														
Top center	.13	.55	.020	.022	.20	.06	.06	.04	.04	.02	.01	.045	.003	.004
Middle center	.15	.55	.020	.019	.20	.07	.06	.05	.04	.02	.01	.041	.006	.004
Bottom center	.14	.53	.019	.018	.20	.06	.05	.04	.04	.02	.01	.040	.003	.004
INGOT 9														
Rolled to 1 1/4"														
Top edge	.16	.53	.014	.023	.19	.06	.05	.04	.04	.02	.01	.038	.004	.004
Top center	.16	.54	.022	.026	.19	.07	.06	.05	.04	.02	.01	.027	.002	.003
Middle edge	.17	.55	.014	.023	.18	.06	.05	.04	.04	.02	.01	.034	.004	.004
Middle center	.15	.53	.020	.025	.19	.08	.05	.04	.04	.02	.01	.026	.002	.003
Bottom center	.15	.54	.019	.023	.18	.08	.06	.05	.04	.02	.01	.042	.005	.004

~~Table II~~

~~Chemical Composition of A-70 Ingots~~

~~INGOT 2~~

~~Rollet to 1 1/4"~~

TABLE II

Chemical Composition of A-70 Ingots

INGOT 2	C	Mn	P	S	Si	Cu	Ni	Cr	W	V	Mo	Al	Al_2O_3 %	N_2
Rolled to 1 1/4"														
Top edge	.22	.36	.020	.034	.02	.14	.10	.04	.04	.02	.01	.017	.004	.004
Top center	.23	.35	.017	.032	.02	.15	.10	.04	.04	.02	.01	.007	.005	.005
Middle center	.20	.35	.018	.028	.02	.15	.09	.04	.04	.02	.01	.038	.003	.003
Bottom edge	.14	.34	018	.020	.01	.14	.09	.04	.04	.02	.01	.019	.002	.003
Bottom center	.18	.34	.018	.028	.02	.15	.09	.04	.04	.02	.01	.038	.003	.003
INGOT 7														
Rolled to 5/8"														
Top edge	.14	.36	.018	.017	.02	.12	.09	.04	.04	.02	.01	.012	.002	.004
Top center	.25	.37	.020	.035	.02	.14	.10	.04	.04	.02	.01	.005	.003	.005
Middle center	.22	.37	.019	.028	.02	.12	.10	.04	.04	.02	.01	.010	.002	.004
Bottom edge	.13	.35	.020	.021	.02	.12	.09	.04	.04	.02	.01	.012	.002	.003
Bottom center	.19	.36	.019	.020	.02	.13	.10	.04	.04	.02	.01	.028	.002	.003

THE EFFECT OF FABRICATION PROCESSES ON STEELS USED IN PRESSURE VESSELS

PROGRESS REPORT NO. 2

WITHIN HEAT VARIATION OF COMPOSITION AND PROPERTIES IN A RIMMING AND AN ALUMINUM-KILLED STEEL

by C. J. Osborn[1], A. F. Scotchbrook[2], R. D. Stout[3],
and B. G. Johnston[4]

FOREWORD

This is the second of a series of reports (see reference 10) describing the results of work performed at Lehigh University for the Fabrication Division of the Pressure Vessel Research Committee of The Welding Research Council. The underlying purpose of the work is to study the effect of fabrication processes involving plastic strain with or without subsequent heat-treatment, welding or strain aging, on the relative tendency of various steels toward brittle failure at low temperature. Two steels, one rimmed and the other aluminum killed, each in two plate thicknesses (5/8" and 1 1/4"), were obtained for the initial part of the project.

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1. Pressure Vessel Research Committee Fellow at Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pa.
2. Assistant Research Engineer, Fritz Engineering Laboratory, Lehigh University.
3. Associate Professor of Metallurgy, Lehigh University.
4. Director, Fritz Engineering Laboratory, and Professor of Civil Engineering, Lehigh University.

This report presents the results of a series of tests suggested by the Materials Division of the Pressure Vessel Research Committee to determine the variation of composition and mechanical properties within the two heats of steel being used in the main investigation.

INTRODUCTION

The tendency of a steel to fail in a brittle fashion is of tremendous practical importance in engineering structures and much is already known concerning the factors which govern this tendency. It is known, for example, that chemical composition exerts an important influence on the mode of failure and that, other things being equal, the transition temperature of a steel increases with its carbon content.[1] Other elements, notably manganese[2] and nitrogen[3], are also considered by some to affect the transition temperature. In the simple tension test, too, the influence of chemical composition on strength and ductility is well-known.

However, it is also known that within a single heat of steel, and even within a single ingot or plate, there occur marked differences in composition. These arise both from the different times of holding in the ladle before pouring successive ingots, and from segregation and rimming effects during solidification of the ingots. Since such composition differences may well be of appreciable magnitude, their distribution and their influence on fracture characteristics and other physical properties become matters of considerable importance to the engineer.

The present investigation was performed on two heats of steel, whose prior history was completely known, in order to obtain information on these and allied questions. One heat, aluminum-killed, had been supplied to A. S. T. M. Specification A-201 and the other, a rimming steel, to A. S. T. M. Specification A-70. The former, aluminum-killed, heat had been cast into 9 big-end-up hot-topped ingots, 34" x 66", each weighing 50,450 lb.* The Pressure Vessel Research Committee obtained plates from ingots numbered 1, 2, 3, 4, 5, and 9, as shown in Fig. 1, and ingots 1, 3, 4, and 9 were used in the present investigation. The rimming steel heat had been cast into four groups of bottom-poured ingots, the six 5/8" plates for the Pressure Vessel Research Committee coming from the first group** and the six 1 1/4" plates from the third.** One plate of each thickness was used in this investigation.

The following tests were performed at various places within the selected ingots:

1. Chemical Analyses
2. Macroscopic Inspection: controlled deep etch; sulphur prints.
3. Microscopic Inspection: as-rolled metallographic; inclusion count; grain coarsening tests; McQuaid Ehn tests.
4. Mechanical Tests: strip tensiles; Brinell hardness; Charpy keyhole, single and double width, transition curves.

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* Other particulars concerning the mill histories of both heats are given in an Appendix of this report.

** Each ingot rolled to one plate, 24' - 0" x 6' - 0".

Each of these will be discussed individually.

I. Chemical Composition

The distribution of alloying elements and impurities in steel ingots has been investigated at considerable length by The Iron and Steel Institute, Committee on the Heterogeneity of Steel Ingots. The findings of this Committee regarding segregation in killed steel were summarized by Hatfield,[4] and later reports gave the results of work on rimming steel.[7,8,9] The relevant reports of the Committee are listed[4-9] as references at the end of this report.

In the present investigation, samples for analysis were taken from the A-201 ingots 1, 4, and 9 at the top, middle and bottom center, and from ingot 9 at the top and middle edge; also from one small and one large A-70 ingot at the top, middle and bottom center, and top and bottom edge.

The results for the A-201 (Al-killed) steel are given in Figs. 2, 3, and 4. The following significant observations may be made concerning them:

1. Concerning composition differences from ingot to ingot within the heat, the last ingot (No. 9) appears to be lower in carbon, manganese, silicon, aluminum, alumina, and nitrogen than the two earlier ingots, but it appears to be appreciably higher in sulphur and slightly higher in phosphorus, copper, and chromium. Nickel, tungsten, vanadium, and molybdenum were approximately the same in all ingots. The decreasing carbon, manganese, silicon and aluminum contents probably result from oxidation in the

ladle. The increasing sulphur content may be due to density segregation of sulphides in the ladle.

2. On the vertical centerline of each ingot carbon, manganese, phosphorus, sulphur, and silicon appear to decrease slightly from top to bottom. In Ingot 9, aluminum <u>increases</u> markedly from top to bottom.
3. From the limited results available (Ingot No. 9) it appears that at least sulphur and phosphorus increase from the edge to center of the ingot. The British investigators[5,6] found phosphorus segregation of the order shown in Fig. 4 only in ingots much larger than Ingot No. 9. Otherwise the magnitude and pattern of segregation is much as indicated by Hatfield.[4,5,6]
4. The maximum and minimum values of carbon content recorded are at the top and bottom center respectively of Ingot No. 4; the range is .14% to .18%.

Results for the A-70 (rimming steel) are given in Figs. 5 and 6. Significant features are:

1. The group of larger ingots (Fig. 5) was cast some 10 minutes after the group of smaller ingots (Fig. 6). The average compositions of the two ingots were not very different except with regard to aluminum which was appreciably higher in the large ingot owing to a further addition of aluminum to reduce gassing in this group.
2. Manganese, phosphorus, silicon, nickel, copper, chromium, tungsten, vanadium, molybdenum and nitrogen segregated very little in either of the ingots examined.

3. Carbon, sulphur and alumina contents were appreciably higher at the top center of the ingot than elsewhere, while the aluminum content was a minimum at this point.
4. The maximum and minimum values of carbon content recorded occurred at the top of the small ingot (No. 7, Fig. 6), the range being .14% to .25%. This is a greater range than was observed in the A-201 steel but is not inconsistent with previous reports on rimming steel ingots.[6]

II. Macroscopic Inspection

A controlled deep etch and a sulphur print were made on plate samples from the top, middle and bottom center of A-201 ingots 1, 4, and 9, and A-70 ingots 2 and 7. All samples were longitudinal.

The sulphur prints were made by applying Velox F-3 photographic paper soaked in 4% sulphuric acid to a ground surface for 10 minutes. Copies of the prints are shown in Figs. 7 and 8. In all cases it is clear that sulphur has segregated to the top of the ingot. The low sulphur content of the rim is very marked in Figs. 8a and 8b.

The deep etch treatment consisted of 30 minutes in 50% hydrochloric acid at 150°F. Some of the results are shown in Figs. 9a and 9b. Here the greater cleanliness at the bottom of the ingots is evident from the less severe attack during etching. The dirt or other unsoundness discovered by the deep etch appears coarser and less uniform in the A-70 ingot than in the A-201. As the controlled etch did not show any significant difference between ingots of the same heat, only one ingot from each heat is shown in Fig. 9.

III. Microscopic Inspection

Using samples from the same locations as the macrospecimens, inclusion counts were first made on the unetched specimens according to A. S. T. M. Specification E 45-46T, Method A. The results are given in Table 1. The predominant type of inclusion in both steels is the globular oxide. There is no great difference between the two steels in regard to the number and distribution of non-metallic inclusions and within each heat there seems to be little variation from ingot to ingot.

The microstructures at the top, middle, and bottom center of A-201 ingots 1, 4, and 9 are shown in Figs. 10 a, b, and c respectively. The top plates from ingots 1 and 4 were normalized and the very fine grain size produced by this treatment is noteworthy in both ingots. A. S. T. M. grain size numbers (ferritic) are listed in Table 1. It is evident from the micrographs in Fig. 10 that the as-rolled samples of 5/8" plate from Ingot 1 have a finer grain size than the sample of 1 1/4" plate taken from the corresponding positions in Ingots 4 and 9.

Figs. 11a and b show microstructures at the top, middle, and bottom center of A-70 ingots 2 and 7 respectively. It is evident that the 5/8" plate (Fig. 11b) has a finer grain size than the 1 1/4" plate (Fig. 11a); also that the carbon content increases from the bottom to the top of each ingot.

The grain-coarsening characteristics of the two steels were studied by two methods on samples from the middle of A-201 ingots 1 and 9, and A-70 ingots 2 and 7; i.e., one 5/8" and one 1 1/4" plate from each heat.

McQuaid-Ehn tests were made at 1675°F in accordance with A. S. T. M. Specification E 19-46 and the following results were obtained:

	McQuaid-Ehn Grain Size
A-201, 5/8" plate (Ingot 1)	8
A-201, 1 1/4" plate (Ingot 9)	8
A-70, 5/8" plate (Ingot 7)	3
A-70, 1 1/4" plate (Ingot 2)	4

In addition to the standard McQuaid-Ehn test, a series of grain-coarsening tests was run on the same four plates by holding small samples for one hour at each of the following temperatures:

1350°F, 1500°F, 1650°F, 1800°F, 1950°F, and
2100°F.

Samples at the four higher temperatures were transferred to another furnace at 1500°F for an hour before water quenching; those at 1350°F and 1500°F were water quenched directly. All quenched samples were tempered at 800°F. This procedure gave microstructures in which the austenitic grain size was outlined by ferrite in a dark matrix of tempered martensite.

From the results (Table II) of these tests it can be seen that both the rimming and the aluminum-killed steels have a sharp coarsening temperature or temperature range. In the rimming steel this is about 1800°F, while in the killed steel it is slightly higher, although not above 1950°F. A sharp coarsening temperature or temperature range is characteristic of steels containing aluminum or certain other grain refining elements such as vanadium and titanium; the heat records and chemical analyses show that aluminum was added to both of these steels.

It is noteworthy that the long annealing time (8 hours) at 1675°F in the McQuaid-Ehn test caused the rimming steel to coarsen very markedly, so that this test indicated very different results for the two steels. On the other hand, the results in Table II do not indicate such a marked difference.

IV. Mechanical Tests

A. Strip Tensile Tests

Using the A. S. T. M. standard rectangular tensile test-piece (for example see Specification A 201-46) the tensile properties were investigated at the following locations within the two heats:

A-201 (Al-killed steel) - Ingots 1, 3, 4, and 9 at the top, middle, and bottom center.

A-70 (rimming steel) - Ingots 2 and 7 at the top, middle, and bottom center.

Duplicate specimens were tested both parallel and transverse to the rolling direction and the average results of these duplicate tests are given in Tables III and IV. Some conclusions may be drawn from these tables.

(i) The ductility, as shown by the % reduction of area, was invariably less in the transverse specimens than in the longitudinal specimens from the same location and the % elongation (8" gage length) usually showed this effect also. The yield stress and maximum stress were generally slightly lower in the transverse direction.

(ii) Although the plates were fairly uniform, there was a general increase in ductility and decrease in strength from the top to bottom of all ingots.

(iii) The 5/8" plates showed appreciably higher yield points and slightly higher strength and ductility than 1 1/4" plates from the same heat, i.e., comparing plates from corresponding positions within the ingots.

(iv) The mill normalizing had caused no significant change in the tensile properties of the A-201 plates.

B. Tensile Tests on .505" Bars

Some additional information on the tensile properties of the two steels is given in Table V. These results were obtained on the standard .505" diameter bar specimens.

% Elongation was measured on a 2" gauge length

% R.A. (Reduction of area) = $\frac{A_o - A_b}{A_o}$ x 100 where

A_o = initial cross-sectional area

A_b = cross-sectional area at breaking

A_m = " " " " maximum load

$\epsilon = \ln \frac{A_o}{A_b}$; ϵ_u = (uniform ductility) = $\ln \frac{A_o}{A_m}$

ϵ_n = (necking ductility) = $\ln \frac{A_m}{A_b}$

$$\text{Nominal Yield Point} = \frac{\text{Yield Load}}{A_o}$$

$$\text{Nominal Maximum Stress} = \frac{\text{Maximum Load}}{A_o}$$

$$\text{Nominal Breaking Stress} = \frac{\text{Breaking Load}}{A_o}$$

$$\text{True Breaking Stress} \doteq \frac{\text{Breaking Load}}{A_b}$$

The results in Table V lead to essentially the same conclusions as did the strip tensile results.

(1) The ductility (% Elong., % R.A., ϵ and ϵ_n), yield point (A-201 plates only) and true breaking stress were appreciably higher in longitudinal than in transverse specimens. Nominal breaking stress was appreciably lower in the longitudinal specimens. Nominal maximum stress, and yield point (A-70 plate only), did not vary much with orientation and the results for ϵ_u were erratic.

(2) In both ingots there was a general increase in ductility and decrease in strength from top to bottom and, in the A-201 ingot, from center to edge. These trends are consistent with the chemical segregation reported earlier.

Mill Test Reports

Comparing Tables III, IV, and V with the tensile results given in the mill test reports (see Appendix), the discrepancy between yield points measured at the laboratory and at the mill is very striking. The slower loading rate used in the research laboratory determined a yield point sometimes as much as 10,000 p.s.i. lower than that determined at the mill. This divergence is well-known and it should be remembered when the possibility of increasing design stresses is considered.

C. Brinell Hardness

The Brinell hardness was determined at the same locations as the strip tensile survey, using a 3000 kg. load and a 10 mm. ball. Three impressions were made at each location.

From the results, summarized in Table VI it is clear that in general the hardness decreases from top to bottom of an ingot, the difference from top to bottom being of the order of 10 points Brinell.

D. Charpy Transition Curves

Charpy impact tests were performed on samples from the same locations as the strip tensile specimens. The standard keyhole notched specimen was used in this survey (A. S. T. M. Specification E23-41T, Fig. 3, Type B), all specimens being cut with the notch perpendicular to the plate surface and the long axis of the specimen parallel to the rolling direction. See Fig. 12. Twenty-four specimens were taken from each location and these were tested four at each of six selected temperatures. In addition to the total energy absorbed during testing, which can be read directly from the Charpy machine, the following measurements were made on each test-piece:

(1) The % lateral contraction below the notch after testing,

(2) The % cleavage in the fracture surface after testing.

The method of plotting results was the same as described for other notch tests in a previous paper on this work[10] and the transition temperatures reported in Table VII were defined as before, as the temperature at which the curve has a value equal to the arithmetic mean of its maximum and minumum values. For an example, see Fig. 13.

In addition to the standard key-hole Charpy specimen a survey of the 1 1/4" plates was made using the double width Charpy specimen shown in Fig. 12. The results of this survey are also given in Table VII.

Significant features of the results are:

1. The Charpy transition temperature according to any of the three brittleness criteria used **was considerably lower for** normalized plate than for as-rolled plates from the same ingot.
2. Disregarding the two normalized plates in Table VII, the transition temperatures generally decreased from the top to bottom of an ingot. This effect was most marked in the % cleavage transition temperatures, where the difference between top and bottom of an ingot was as high as 35°F with the single width specimens and as high as 46°F using double width specimens. Using the common brittleness criterion of energy absorption, the change in transition temperature within an ingot was much less.
3. The transition temperature for 5/8" plate was appreciably lower than for the corresponding 1 1/4" material.

4. Transition temperatures using fracture appearance as the criterion of brittleness were invariably higher (by as much as 50°F) than those obtained using either of the other criteria.
5. Transition temperatures obtained with double width specimens were higher than the corresponding temperatures obtained with single width specimens.

Items 4 and 5 are of particular interest in connection with the ideas advanced in Progress Report No. 1.[10]

SUMMARY

An investigation has been conducted into the variation of chemical composition and physical properties within plates rolled from two heats of steel, one conforming to A. S. T. M. Specification A-201, the other to A-70. Both heats exhibited segregation and property variation generally of the type and magnitude to be expected.

The chemical composition was found to vary approximately as indicated by the extensive work of Hatfield and his collaborators.

In tension tests, the ductility was found to increase and the strength to decrease from top to bottom and from center to edge of an ingot. In Charpy tests, both single and double width, the transition temperature decreased from top to bottom of all ingots. These effects were all consistent with the observed chemical segregation.

Yield points and ultimate strengths determined in the laboratory were invariably

much lower than those quoted by the mill test reports for the same material.

Normalized plates had greater ductility and much lower Charpy transition temperatures than similar plates as rolled. Similar differences were observed between 5/8" plate and 1 1/4" plate from the same heat.

ACKNOWLEDGMENTS

This project was carried out jointly by the Fritz Engineering Laboratory of the Civil Engineering Department and by the Metallurgy Department of Lehigh University. It was sponsored by the Pressure Vessel Research Committee of the Welding Research Council, which is directed by Mr. William Spraragen. Mr. Walter Samans is Chairman of the Pressure Vessel Research Committee, Mr. Russell J. Love former Executive Secretary and Mr. Boniface E. Rossi current Executive Secretary. The Fabrication Division of PVRC gave technical guidance and approval of various stages of the work, under the guidance of Chairman Harry Boardman. The Materials Division of PVRC was responsible for the initial planning of the investigation and acknowledgment is due in particular to Chairman D. B. Rossheim and Mr. R. H. Caughey for assistance in this respect.

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Appendix

MILL HISTORY OF THE TWO PVRC HEATS

A. Mill History of Killed Steel Plates, A.S.T.M. A-201

1. Open Hearth

a) Material charged:

Hot Metal	327,000 lb.
Lime	32,000 lb.
Ore	72,000 lb.

b) Working of heat: Melt Analysis 1.22% C

Furnace Additions

Lime	5,000 lb.
Ore	900 lb.
Si Mn	2,700 lb.
Mn (80%)	600 lb.

Time of working 3 hrs. 5 mins.

Tap Analysis 0.14% C; 0.15% Mn.
Tapping Temperature 3060/3080°F
Ladle Additions

Coal	100 lb.
50% Si	2,000 lb.
80% Mn	700 lb.
Aluminum	550 lb.

(corresponding to 2.4 lb. per ton)

c) Pouring: Total weight of steel 460,650 lb.

9 big-end-up hot topped ingots, 34" x 66", were poured, the weight of each being 50,450 lb.

Total pouring time (9 ingots) 45 mins.
Pouring temperature, Start 2910°F
Finish 2870°F

d) Ladle Analysis

Ingot No.	C	Mn	P	S	Si	Ni	Cr	Mo	Cu
2	.16	.54	.012	.024	.20	.04	.02	.01	.06
4	.15	.53	-	-	-	-	-	-	-
9	.16	.52	.016	-	-	-	-	-	-

2. Rolling

a) Slab Mill: Ingots 1, 2, 3, 4, 5, and 9 were sent to the slabbing mill soaking pits.

Time from pouring to charging 7 hrs. 30 mins.
Time in pits 16 hrs. 30 mins.
Temperature drawn 2400°F
Slab sizes rolled

Ingots Nos.	Slabs from each	Slab Size
1, 3	4	60" x 5 1/2" x 103 ½
2, 4, 5, 9	2	60" x 9 1/2" x 118 ¼

b) <u>Finishing Mill</u> Plates were rolled 12 days after slabbing.

Heating time: 5/8" Gauge - 3 hrs.
1 1/4" Gauge - 3 hrs. 15 mins.

Drawing Temperature: 2375°F

The finishing temperatures and test results on all as rolled plates are given in the following table:

Ingot No.	Plate No.	Finish Temp. °F	Gauge	Y.P. p.s.i.	T.S. p.s.i.	% Elong.	Bend Test
1	7437-T	1890	5/8"	-	63300	-	
1	7438-B	1880	"	38480	63380	32.0	O.K.
1	T	"	"	-	64070	-	
3	7427-B	1820	"	42520	63950	28.2	O.K.
3	T	"	"	-	63270	-	
3	7428-B	1820	"	41340	64240	30.7	O.K.
3	T	"	"	-	62560	-	
3	7429-B	1880	"	40380	63920	32.7	O.K.
3	T	"	"	-	63150	-	
3	7430-B	1840	"	41110	64280	31.5	O.K.
3	T	"	"	-	63270	-	

Ingot No.	Plate No.	Finish Temp. °F	Gauge	Y.P. p.s.i.	T.S. p.s.i.	% Elong.	Bend Test
4	7433-B	1880	1 1/4"	38550	62850	29.2	O.K.
4	T	"	"	-	62320	-	
5	7431-T	1890	"	-	63180	-	
5	7432-B	1890	"	37780	63330	29.2	O.K.
5	T	"	"	-	61330	-	
9	7435-B	1880	"	37280	63040	27.7	O.K.
9	T	"	"	-	62750	-	
9	7436-B	1890	"	38920	63050	30.0	O.K.
9	T	"	"	-	63040	-	

3. Heat Treatment

Four plates of each thickness were heated to 1580°F, equalized, maintained 1 hour and air cooled. Finishing temperatures and physical properties on these plates were as follows:

Ingot No.	Plate No.	Finish Temp. °F	Gauge	Y.P. p.s.i.	T.S. p.s.i.	% Elong.	Bend Test
1	7439-B	1840	5/8"	38040	58700	34.2	O.K.
1	T	"	"	-	58570	-	-
1	7440-B	1870	"	39680	61260	34.5	O.K.
1	T	"	"	-	60880	-	-
2	7442-B	1900	1 1/4"	36940	59130	37.0	O.K.
2	T	"	"	-	58850	-	-
4	7434-B	1900	"	37020	60730	36.0	O.K.
4	T	"	"	-	60330	-	-

4. Summary

The following steel was received:

11 plates	5/8" x 72" x 288"	as rolled	40,885 lb.
4 plates	5/8" x 72" x 288"	normalized	15,150 lb.
9 plates	1 1/4" x 72" x 288"	as rolled	67,950 lb.
4 plates	1 1/4" x 72" x 288"	normalized	30,170 lb.

Total weight = 154,155 lb.

All plates fell within the specification range of physical properties.

B. Mill History of Rimming Steel Plates, A.S.T.M. A-70

1. Open Hearth

a) Material Charged:

Scrap	138,600 lb.
Pig	74,000 lb.
Lime	6,300 lb.
Limestone	4,000 lb.

b) Working of heat:

Melt Analysis 0.74% C

Furnace Additions:

Lime	2,000 lb.
Roll Scale	3,000 lb.
FeMn (80%)	1,050 lb.
Spiegel	840 lb.
Fluorspar	200 lb.

Time of working: 2 hrs. 3 mins.
Tap Analysis: 0.14% C; 16.00% FeO in slag
Tapping Temperature: 2980°F
Ladle Additions:

Coal	280 lb.
Aluminum	10 lb.
CaO	750 lb.

c) Pouring: Total weight of steel 187,000 lb.

8 bottom-poured ingots 34" x 14" were poured to a depth of 46", each weighing 5050 lb.
6 bottom-poured ingots 48" x 17" were poured to a depth of 55 1/2", each weighing 10,500 lb.

Two groups of ingots for other orders were also poured from this heat.

Pouring time:	34" x 14" group	5.40 min.
	48" x 17" group	7.83 min.
	Total	26 min.
Pouring Temperature:	34" x 14" group	2875°F
	48" x 17" group	2860°F

d) Ladle Analysis

C	Mn	P	S	Ni	Cr	Cu
.25	.36	.016	.031	.15	.058	.19

2. Rolling

a) Slab Mill: 6 small and 6 large ingots were conditioned and rolled.

Time from pouring to charging in pits		42/44 hours
Soaking:	Small ingots	7 hrs. 20 mins. at 2350°F
	Large ingots	11 hrs. 25 mins. at 2370°F
Slab thickness:	small	3.40"
	large	5.75"
Slab temperature:	small	2000°F
	large	1980°F

b) <u>Finishing Mill</u>: All slabs ran straight through the finish mill without intermediate heating.

Individual finishing temperatures are given in the following table together with the mill test results:

Ingot No.	Plate Gauge	Finish Temp. °F	Y.P. p.s.i.	T.S. p.s.i.	% Elong.
1	1 1/4"	2000°F	-	58800	-
			39100	59700	29.5
2	"	2000°F	-	60200	-
			39600	59700	30.0
3	"	2000°F	-	59100	-
			38900	58600	32.0
4	"	2000°F	-	59400	-
			38500	59000	29.5
7	5/8"	2000°F	-	55400	-
			39600	62800	27.5
9	"	2000°F	-	63800	-
			38600	63300	27.0
11	"	2000°F	-	63800	-
			37300	64500	27.5
12	"	2000°F	-	62700	-
			39100	63000	27.5

All bend tests satisfactory.

3. Heat Treatment

Two plates of each thickness were heated to 1630°F, equalized, held 1 hour per inch of section and air colled. Finishing temperatures and test results on these plates were as follows:

Ingot No.	Plate Gauge	Finish Temp. °F	Y.P. p.s.i.	T.S. p.s.i.	% Elong.
5	1 1/4"	2000°F	-	61200	-
			38300	60500	28.5
6	"	1980°F	-	61000	-
			38700	60200	27.5
8	5/8	2010°F	-	63200	-
			39900	64400	27.5
10	"	2010°F	-	63400	-
			38800	62300	27.0

All bend tests satisfactory

4. Summary

The rimmed steel received was comprised of the following:

4 plates	5/8" x 72" x 288"	as rolled	15055 lb.
2 plates	5/8" x 72" x 288"	normalized	7530 lb.
4 plates	1 1/4" x 72" x 288"	as rolled	29970 lb.
2 plates	1 1/4" x 72" x 288"	normalized	14980 lb.
		Total weight =	67535 lb.

All plates fell within the specification range of physical properties.

Table I. Inclusion Counts and Grain Size

	Sulfide Type		Alumina Type		Silicate Type		Globular Type Oxide		Grain Size
A-70									
Ingot 7 (5/8")									
top			3T	2H	2T	2H	3T	2H	8
middle			2T		3T	2H	3T	2H	8
bottom			2T	2H	2T	4H	3T	3H	8
Ingot 2 (1$\frac{1}{4}$")									
top		1H	2T				5T	5H	7
middle	2T	1H		2H	3T	3H	4T	5H	7
bottom						4H	4T		7
A-201									
Ingot 1 (5/8")									
top				3H	4T		2T	2H	10
middle			3T	3H	4T	4H	4T	4H	7 1/2
bottom				3H	5T	3H	3T	3H	7 1/2
Ingot 4 (1$\frac{1}{4}$")									
top			2T	3H	5T	4H	4T		8
middle			2T	3H	4T	4H	3T	4H	7
bottom				4H	3T	3H	4T		7
Ingot 9 (1$\frac{1}{4}$")									
top				4H	4T	5H	5T		7
middle			4T	2H		5H	5T	3H	7
bottom				4H	4T		3T	4H	7

Key - Sulfide Type —— -
Alumina Type •-•-•·
Silicate Type ∼∼∼
Globular Type Oxides ∵.

T = Thin
H = Heavy
1 = Sparse distribution
5 = Heavy distribution

Table II. Grain-Coarsening Results

Heated 1 hour at temp. °F	A. S. T. M. Grain Size No. 5/8" A-201	1 1/4" A-201	5/8" A-70	1 1/4" A-70
1350	8	7	8	7
1500	7	7	7	7
1650	7	7	7	7
1800	7	6	7 + 3	7 + 3
1950	7 + 3	1 - 3	3	3
2100	3	1 - 3	2 - 3	2 - 3

TABLE III

TENSILE PROPERTIES OF A-201 PLATES

Ingot	Position	Orientation to Rolling Direction	Upper Yield Point p.s.i.	Lower Yield Point p.s.i.	Nominal Maximum p.s.i.	%Elongation	%Reduction of Area
1	Top*	Parallel	37,100	36,850	60,250	33.8	59.6
"	"	Transverse	38,400	38,000	59,500	30.1	58.5
"	Middle	Parallel	35,600	35,100	60,600	30.5	56.9
"	"	Transverse	36,000	35,800	60,600	31.2	55.8
"	Bottom	Parallel	34,800	34,400	58,700	32.2	66.4
"	"	Transverse	35,500	34,600	58,750	31.7	58.6
3	Top	Parallel	36,900	35,750	61,800	29.8	58.8
"	"	Transverse	37,300	36,700	61,650	29.0	57.4
"	Middle	Parallel	35,900	35,600	60,750	32.8	64.1
"	"	Transverse	35,800	35,400	60,300	-	54.9
"	Bottom	Parallel	36,100	35,700	59,600	28.9	65.1
"	"	Transverse	35,300	34,900	58,600	31.6	59.9
4	Top*	Parallel	32,800	32,600	59,600	30.5	60.9
"	"	Transverse	32,600	32,300	59,200	31.8	54.1
"	Middle	Parallel	31,800	31,400	59,500	34.9	61.8
"	"	Transverse	32,300	31,800	59,100	32.9	53.6
"	Bottom	Parallel	31,400	31,000	56,700	35.1	64.7
"	"	Transverse	31,600	30,700	56,400	33.1	58.8
9	Top	Parallel	31,500	31,300	59,700	32.6	57.1
"	"	Transverse	32,500	31,200	59,800	31.0	49.2
"	Middle	Parallel	32,500	31,300	59,800	29.7	60.0
"	"	Transverse	31,700	31,200	59,500	-	51.1
"	Bottom	Parallel	30,600	29,900	57,300	35.0	63.2
"	"	Transverse	29,900	29,100	55,400	34.5	55.5

* Normalized
Ingots 1 and 3 are 5/8" plate; 4 and 9 are 1 1/4"
Results are average of duplicate tests.

TABLE IV

TENSILE PROPERTIES OF A-70 PLATES

Ingot	Position	Orientation to Rolling Direction	Upper Yield Point p.s.i.	Lower Yield Point p.s.i.	Nominal Maximum p.s.i.	%Elongation	%Reduction of Area
7	Top	Parallel	35,600	34,200	61,000	30.5	56.3
"	"	Transverse	35,900	35,500	60,800	27.2	54.5
"	Middle	Parallel	34,000	33,300	58,400	30.7	59.3
"	"	Transverse	33,600	33,500	58,000	29.3	55.8
"	Bottom	Parallel	32,200	30,400	55,600	31.0	61.4
"	"	Transverse	32,500	32,200	56,100	28.1	58.1
2	Top	Parallel	29,500	27,800	57,500	31.5	56.3
"	"	Transverse	29,100	28,000	57,200	30.8	52.5
"	Middle	Parallel	28,800	27,300	55,700	33.2	55.8
"	"	Transverse	27,700	27,200	55,000	29.4	53.5
"	Bottom	Parallel	27,200	25,500	53,400	33.6	58.1
"	"	Transverse	26,700	26,300	53,100	33.6	55.8

Ingot 7 is 5/8" plate; 2 is 1-1/4"

TABLE V. TENSILE PROPERTIES IN TWO INGOTS

		% Elong.	% R.A.	ϵ	ϵ_u	ϵ_n	Nom.Y.P. p.s.i.	Nom.Br.Str. p.s.i.	True Br.Str. p.s.i.	Nom. Max. p.s.i.
A-201 Ingot No. 9, 1 1/4" plates										
Top edge	L	41.0	64.7	1.041	.210	.832	33,330	44,600	126,400	62,000
" "	T	37.5	56.6	.844	.197	.647	31,860	50,700	116,800	62,000
Top center	L	38.5	62.0	.969	.185	.782	33,900	48,500	127,400	64,000
" "	T	37.8	54.8	.799	.187	.613	31,800	52,200	116,000	63,800
Middle edge	L	40.0	65.7	1.027	.229	.844	33,900	44,200	129,700	60,800
" "	T	33.5	58.9	.893	.170	.720	31,500	50,200	122,400	62,000
Middle center	L	39.5	63.2	1.001	.166	.836	32,100	45,800	124,500	62,300
" "	T	34.5	56.5	.836	.175	.661	30,900	51,000	115,000	61,300
Bottom center	L	42.8	67.2	1.113	.215	.898	33,200	40,400	122,900	58,700
" "	T	42.5	63.2	1.005	.227	.778	28,900	44,000	120,300	58,100
A-70 Ingot No. 2, 1 1/4" plates										
Top center	L	37.3	56.3	.825	.185	.641	29,300	50,200	114,400	62,200
" "	T	31.2	54.2	.780	.200	.580	29,400	51,700	112,700	62,300
Bottom center	L	40.9	62.4	.990	.178	.812	29,290	43,800	116,700	55,700
" "	T	33.6	55.8	.817	.204	.613	30,550	45,000	102,000	55,900

L, Longitudinal, or parallel to direction of rolling.

T, Transverse, or perpendicular to direction of rolling.

Table VI. BRINELL HARDNESS SURVEY

A-201 HEAT

Ingot No. 1			Ingot No. 3		
Top*	157	B.H.N.	Top	165	B.H.N.
Middle	166	B.H.N.	Middle	157	B.H.N.
Bottom	161	B.H.N.	Bottom	160	B.H.N.
Ingot No. 4			**Ingot No. 9**		
Top*	157	B.H.N.	Top	166	B.H.N.
Middle	159	B.H.N.	Middle	159	B.H.N.
Bottom	155	B.H.N.	Bottom	157	B.H.N.

A-70 HEAT

Ingot No. 2			Ingot No. 7		
Top	164	B.H.N.	Top	169	B.H.N.
Middle	158	B.H.N.	Middle	158	B.H.N.
Bottom	157	B.H.N.	Bottom	152	B.H.N.

---

* Normalized plate

Table VII. CHARPY TRANSITION TEMPERATURES (°F) AT VARIOUS LOCATIONS ACCORDING TO 3 CRITERIA

	Single Width Specimen			Double Width Specimen		
	Energy	% Cleavage	% Contraction	Energy	% Cleavage	% Contraction
A-201 Steel (Aluminum-killed)						
Ingot 1, Top*	-80	-52	-92			
Middle	-50	---	-50			
Bottom	-60	-18	-52			
Ingot 3, Top	-61	-13	-62			
Middle	-61	-33	-66			
Bottom	-70	-42	-69			
Ingot 4, Top*	-47	-28	-44	-29	-19	-35
Middle	-22	+12	-27	-17	+20	-17
Bottom	-35	-10	-38	-17	+14	-32
Ingot 9, Top	-25	+25	-26	+ 2	+42	- 7
Middle	-33	- 8	-38	-15	+34	-17
Bottom	-38	-10	-41	+10	+25	+ 2
A-70 Steel (Rimming)						
Ingot 2, Top	+57	+65	+37	+63	+116	+42
Middle	+56	+68	+31	+50	+92	+31
Bottom	+34	+47	+27	+42	+70	+29
Ingot 7, Top	+ 8	+48	+ 8			
Middle	+12	+40	- 6			
Bottom	+ 4	+33	- 2			

* Normalized plate

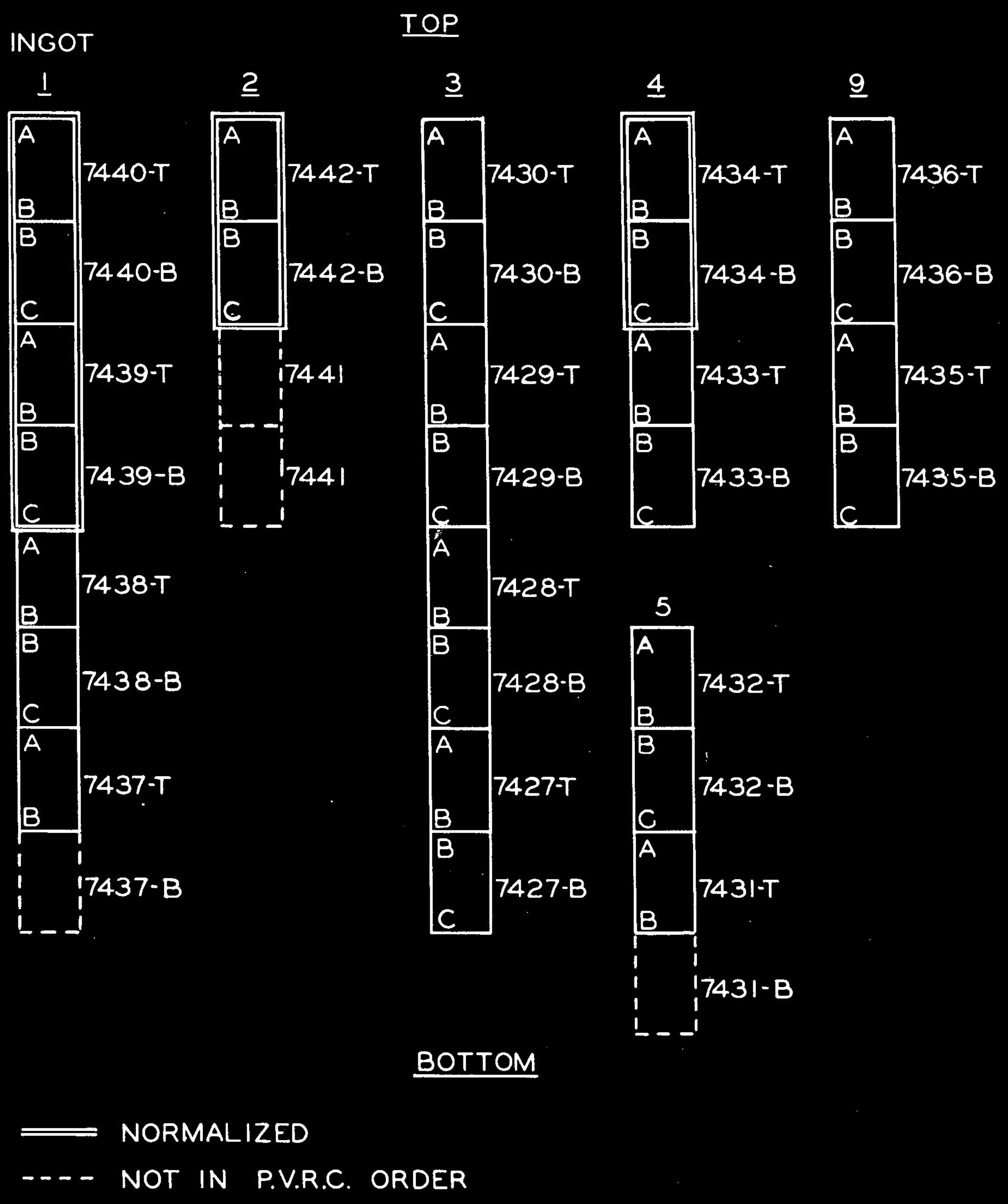


FIG. 1 LOCATION OF PLATES WITHIN A-201 HEAT

INGOTS 1 AND 3 WERE ROLLED TO 5/8" PLATE, OTHERS TO 1 1/4" PLATE.
ALL PLATES 24" X 6'.

Top

* C .17; Mn .57; P .020;
S .021; Si .21; Cu .06;
Al .041; Al_2O_3 .004; N_2 .005;

C .17; Mn .55; P .020;
* S .022; Si .21; Cu .06;
Al .041; Al_2O_3 .003; N_2 .005.

C .15; Mn .54; P .018;
S .020; Si .20; Cu .05;
Al .038; Al_2O_3 .004; N_2 .004.
*

Bottom

Fig. 2 % Composition in A-201 Ingot No. 1.

* Analyses apply at positions indicated by asterisks.

Notes:

(1) The following analyses held for all positions Ni .05; Cr. .04; W .04; V .02; Mo .01.

(2) This was a 34" x 66" ingot weighing 50,450 lb. and rolled to 5/8" plate.

Top

*	C	.18;	Mn	.55;	P	.020;
	S	.022;	Ni	.05;	Cr	.04;
	Cu	.06;			Al	.045;
	Al_2O_3	.003;			N_2	.004.

	C	.15;	Mn	.55;	P	.020;
	S	.019;	Ni	.06;	Cr	.05;
*	Cu	.07;			Al	.041;
	Al_2O_3	.006;			N_2	.004.

	C	.14;	Mn	.53;	P	.019;
	S	.018;	Ni	.05;	Cr	.04;
	Cu	.06;			Al	.040;
	Al_2O_3	.003;			N_2	.004;
*						

Bottom

Fig. 3. % Composition in A-201 Ingot No. 4.

* Analyses apply at positions indicated by asterisks.

Notes:

(1) The following analyses held for all positions Si .20; W .04; V .02; Mo .01.

(2) This was a 34" x 66" ingot weighing 50,450 lb. and rolled to 1 1/4" plate.

Top

*	C	.16;	Mn	.53;	P	.014;
	S	.023;	Si	.19;	Ni	.05;
	Cr	.04;	Cu	.06;	Al	.038;
	Al_2O_3	.004;			N_2	.004.

*	C	.16;	Mn	.54;	P	.022;
	S	.026;	Si	.19;	Ni	.06;
	Cr	.05;	Cu	.07;	Al	.027;
	Al_2O_3	.002;			N_2	.003.

	C	.17;	Mn	.55;	P	.014;
	S	.023;	Si	.18;	Ni	.05;
*	Cr	.04;	Cu	.06;	Al	.034;
	Al_2O_3	.004;			N_2	.004.

	C	.15;	Mn	.53;	P	.020;
	S	.025;	Si	.19;	Ni	.05;
*	Cr	.04;	Cu	.08;	Al	.026;
	Al_2O_3	.002;			N_2	.003.

	C	.15;	Mn	.54;	P	.019;
	S	.023;	Si	.18;	Ni	.06;
	Cr	.05;	Cu	.08;	Al	.042;
	Al_2O_3	.005;			N_2	.004.
*						

Bottom

Fig. 4 % Composition in A-201 Ingot No. 9

* Analyses apply at positions indicated by asterisks.

Notes:

(1) The following analyses held for all positions W .04; V .02; Mo .01.

(2) This was a 34" x 66" ingot weighing 50,450 lb. and rolled to 1 1/4" plate.

Top

* C .22; Mn .36;
P .020; S .034;
Si .02; Ni .10;
Cr .04; Cu .14;
Al .017; Al_2O_3 .004;
N_2 .004;

* C .23; Mn .35;
P .017; S .032;
Si .02; Ni .10;
Cr .04; Cu .15;
Al .007; Al_2O_3 .005;
N_2 .005;

C .20; Mn .35;
P .018; S .028;
Si .02; Ni .10;
* Cr .05; Cu .14;
Al .021; Al_2O_3 .003;
N_2 .003;

C .14; Mn .34;
P .018; S .020;
Si .01; Ni .09;
Cr .04; Cu .14;
Al .019; Al_2O_3 .002;
N_2 .003;
*

C .18; Mn .34;
P .018; S .028;
Si .02; Ni .09;
Cr .04; Cu .15;
Al .038; Al_2O_3 .003;
N_2 .003;
*

Bottom

Fig. 5: % Composition in A-70 Ingot No. 2.

* Analyses apply at positions indicated by asterisks.

Notes:

(1) The following analyses held for all positions: W .04; V .02; Mo .01.

(2) This was a 48" x 17" ingot weighing 10,500 lb. and rolled to 1 1/4" plate.

Top

* C .14; Mn .36; P .018;
S .017; Ni .09; Cu .12;
Al .012; Al_2O_3 .002; N_2 .004.

* C .25; Mn .37; P .020;
S .035; Ni .10; Cu .14;
Al .005; Al_2O_3 .003; N_2 .005.

C .22; Mn .37; P .019;
* S .028 Ni .10; Cu .12;
Al .010; Al_2O_3 .002; N_2 .004.

C .18; Mn .35; P .020;
S .021; Ni .09; Cu .12;
* Al .012; Al_2O_3 .002; N_2 .003;

C .19; Mn .36; P .019;
S .020; Ni .10; Cu .13;
* Al .028; Al_2O_3 .002; N_2 .003;

Bottom

Fig. 6 % Composition in A-70 Ingot No. 7.

* Analyses apply at positions indicated by asterisks.

Notes:

(1) The following analyses held for all positions; Si .02; Cr .04; W .04; V .02; Mo .01.

(2) This was a 34" x 14" ingot weighing 5,050 lb. and rolled to 5/8" plate.

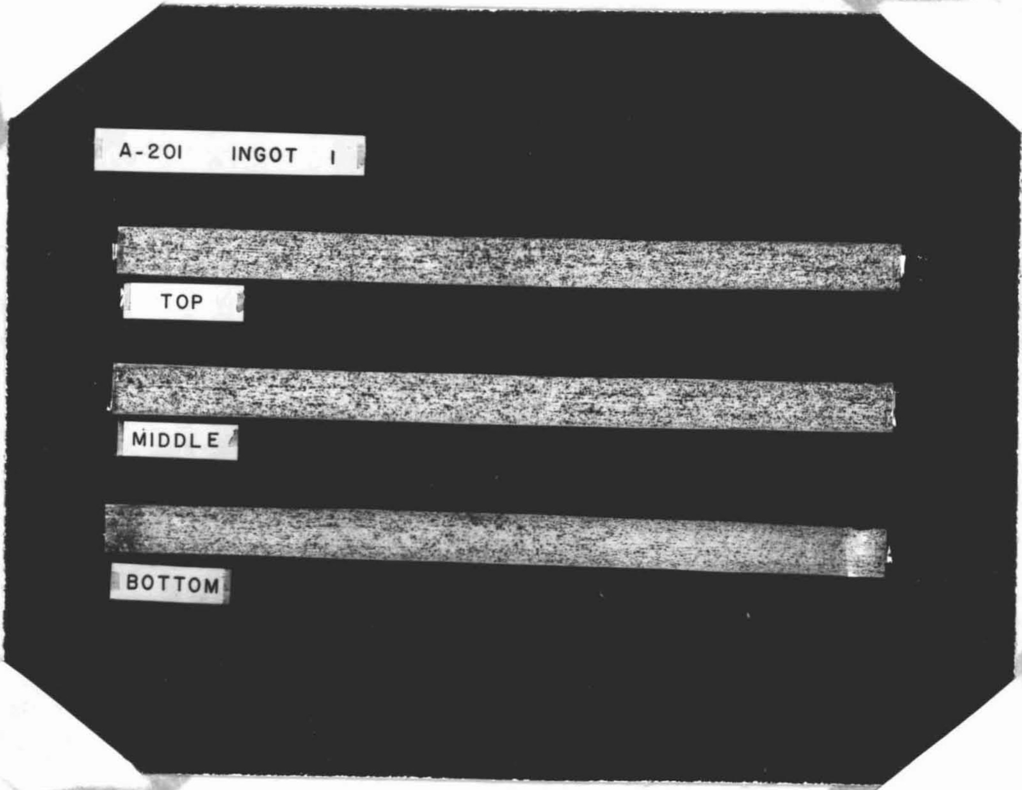


Fig. 7a Sulphur prints of A-201, Ingot 1

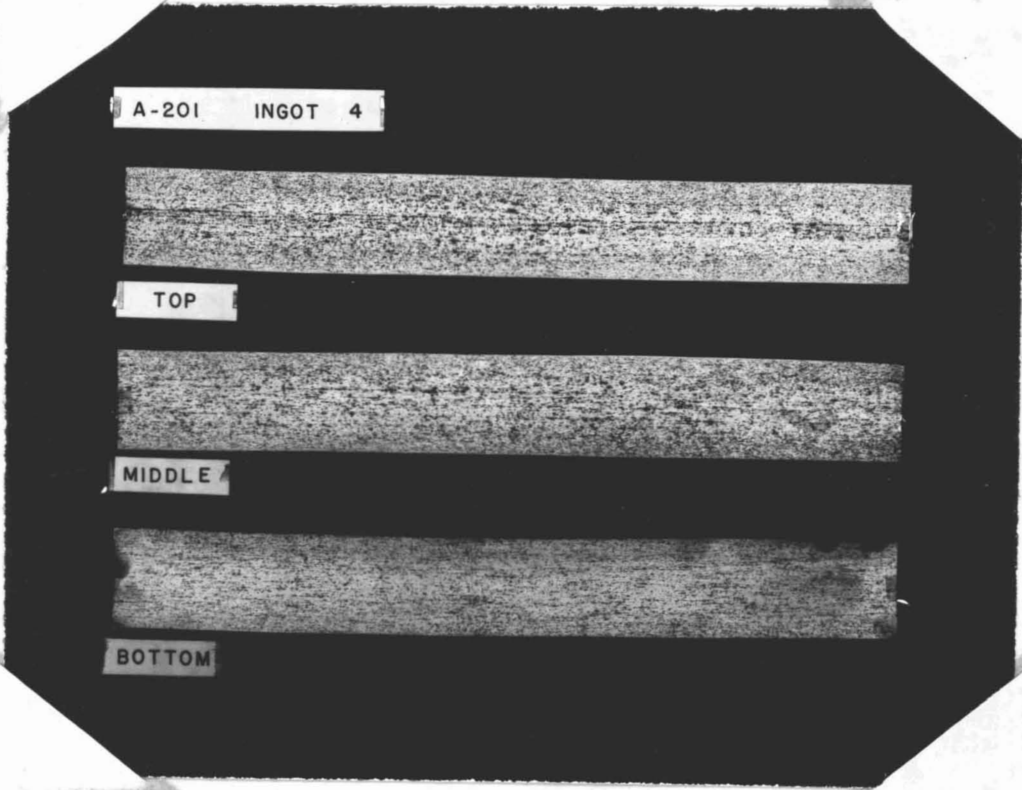


Fig. 7b Sulphur prints of A-201, Ingot 4

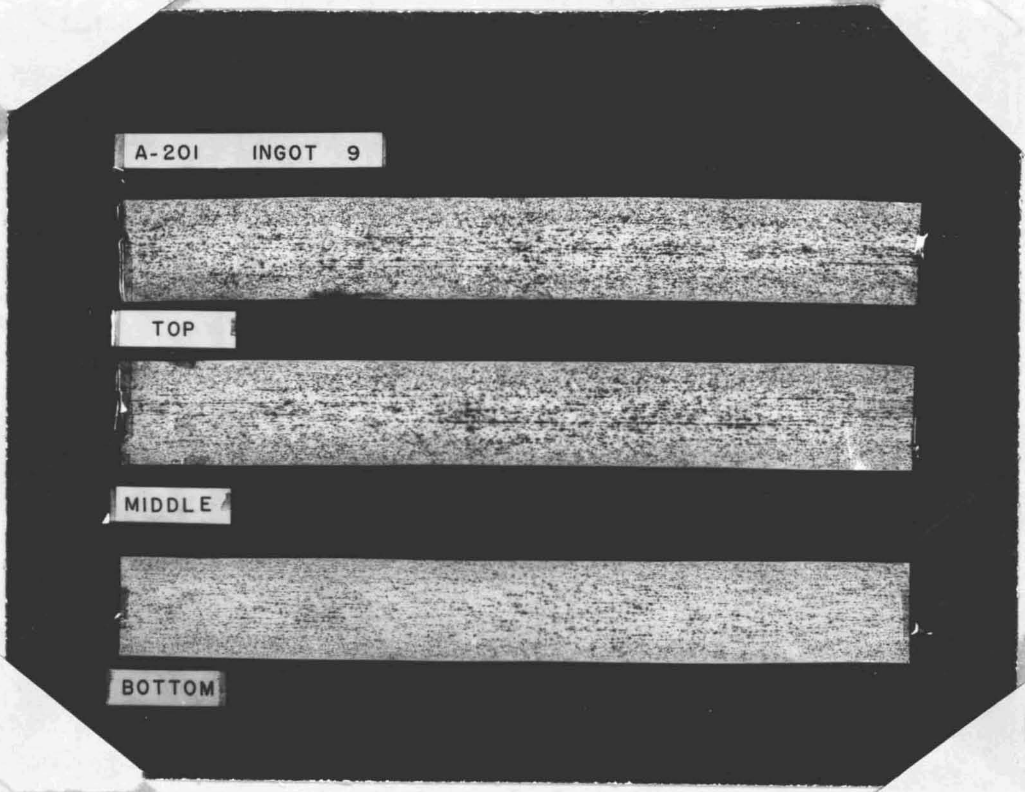


Fig. 7c Sulphur prints of A-201, Ingot 9

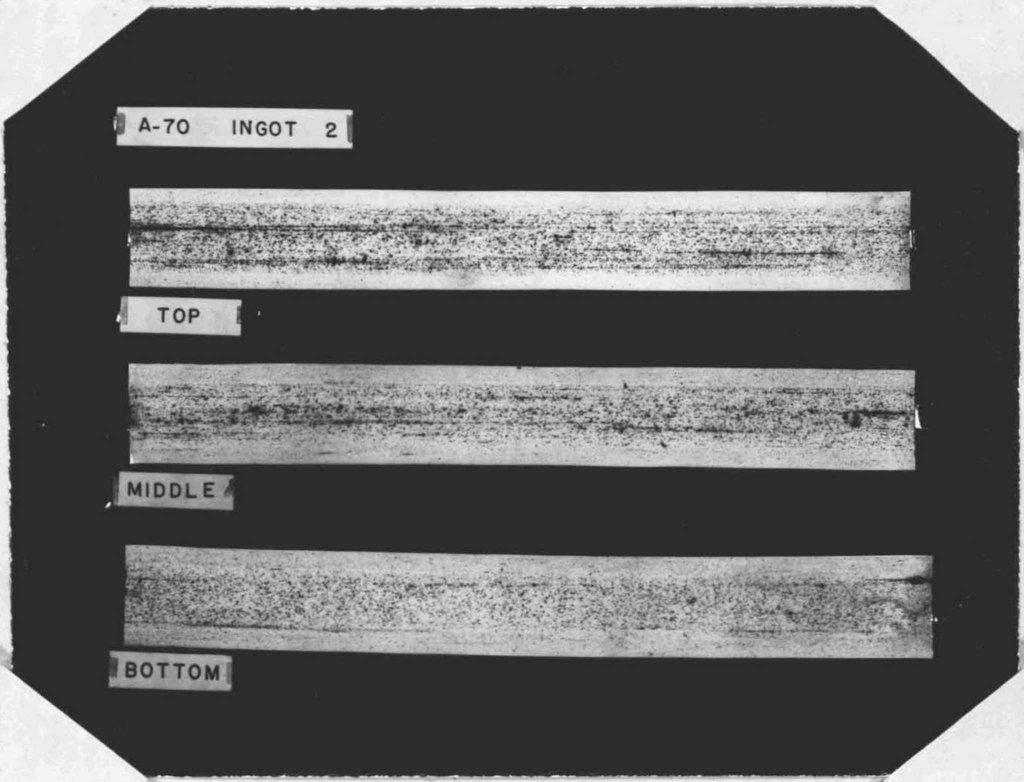


Fig. 8a Sulphur prints of A-70, Ingot 2

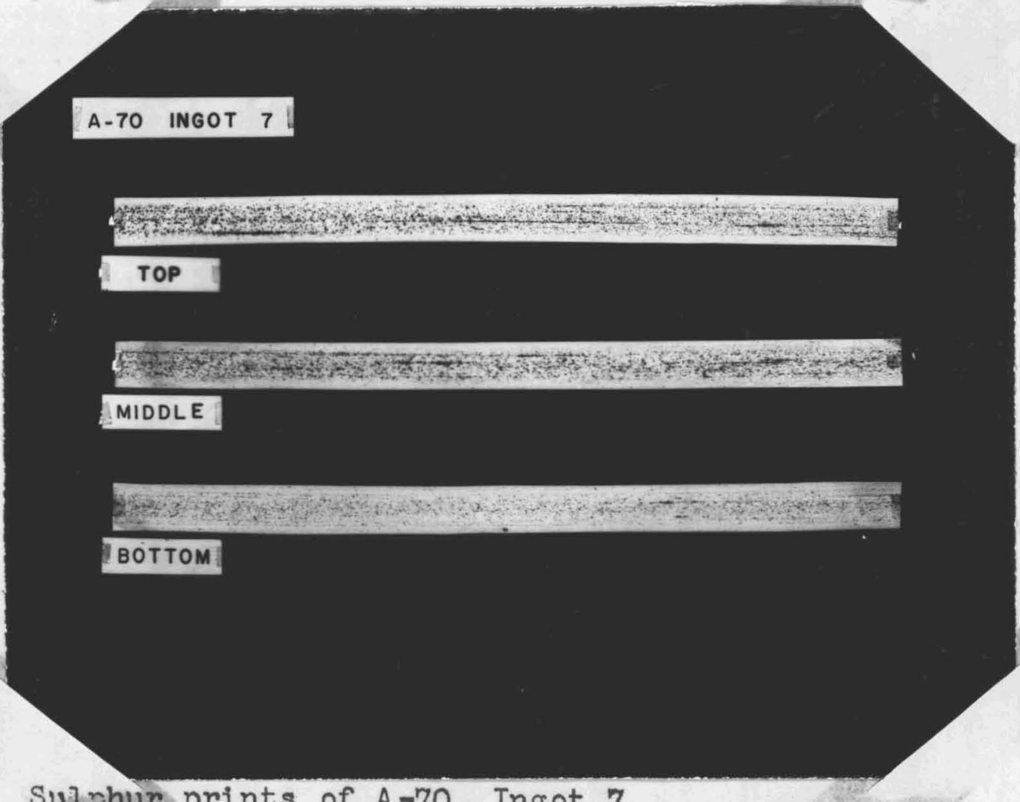


Fig. 8b Sulphur prints of A-70, Ingot 7

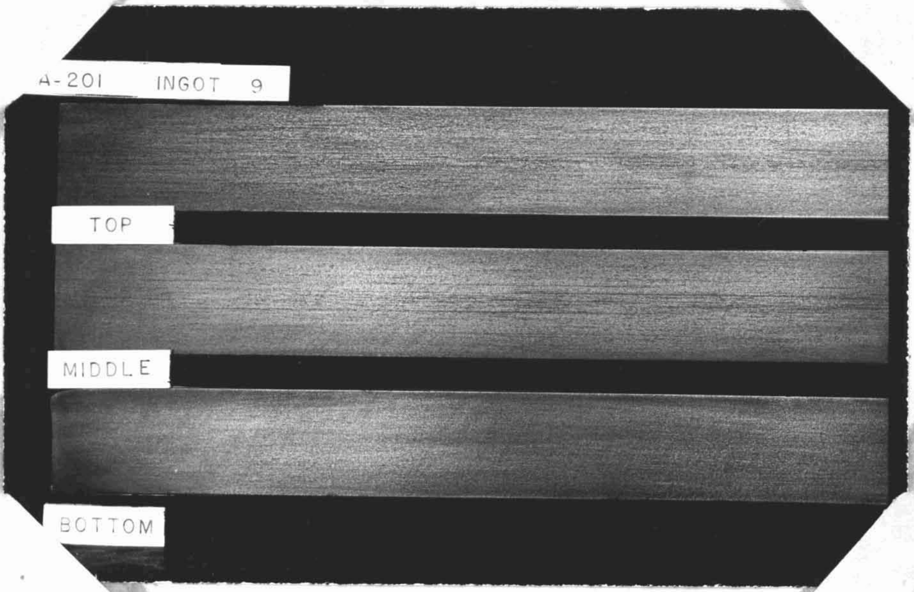


Fig. 9a Deep-etch specimens from A-201, Ingot 9

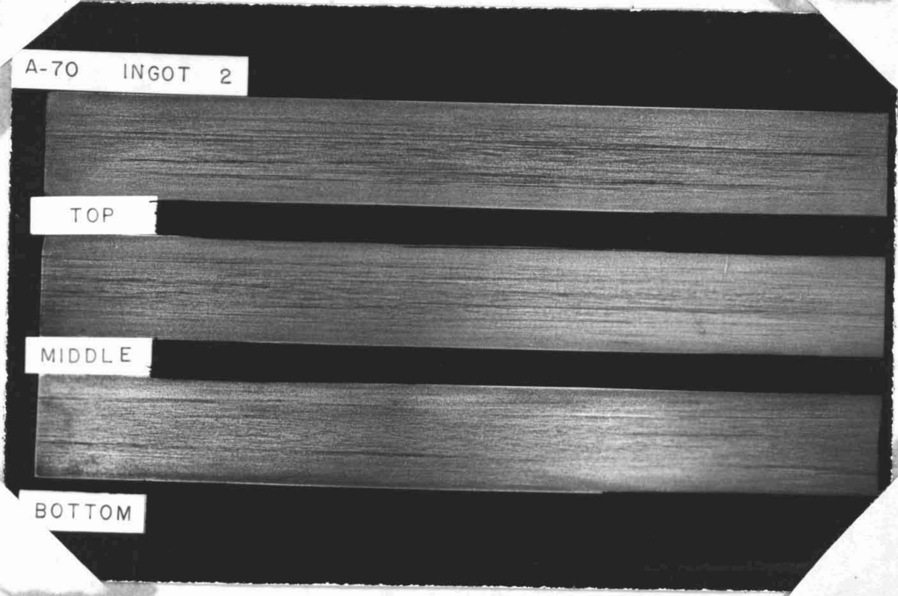
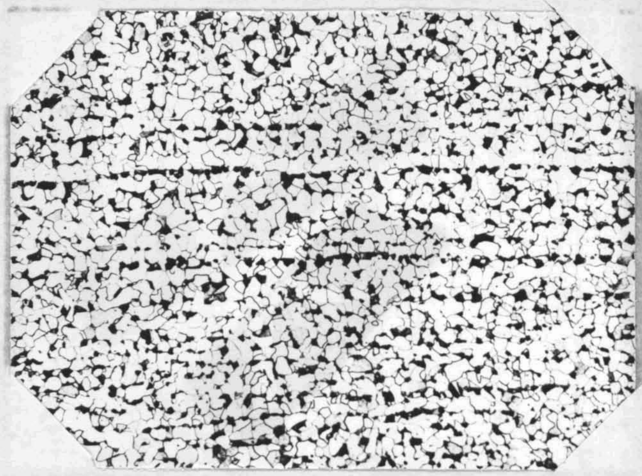
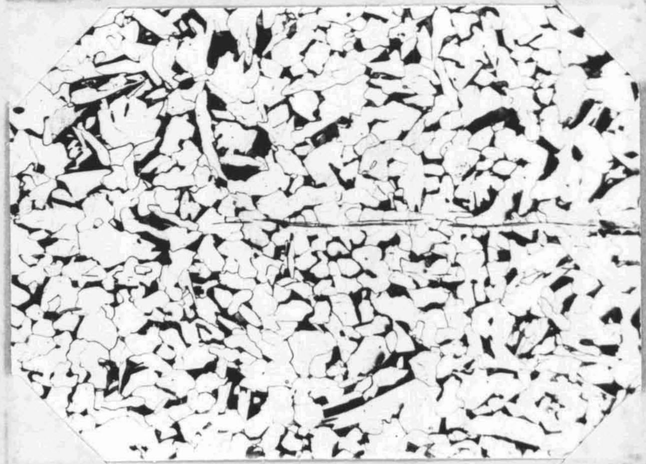


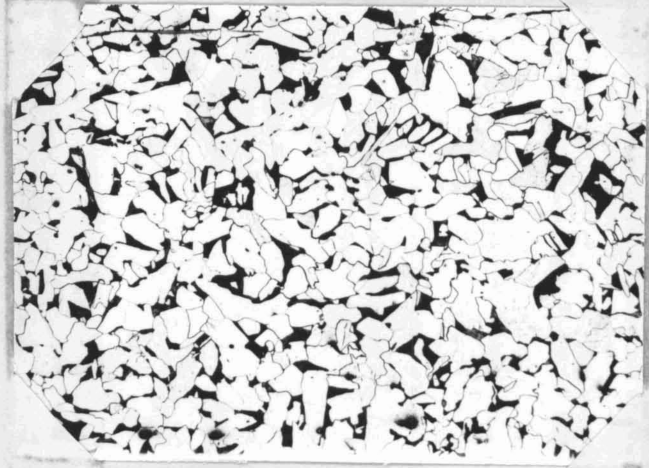
Fig. 9b Deep-etch specimens from A-70, Ingot 2



Top



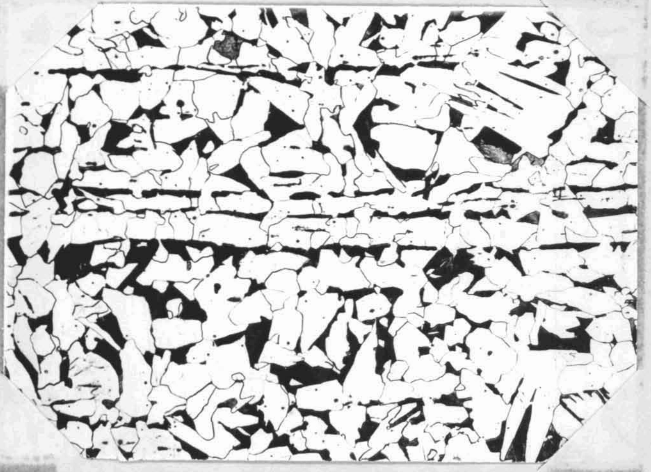
Middle



Bottom

Fig. 10a A-201, Ingot 1

Top



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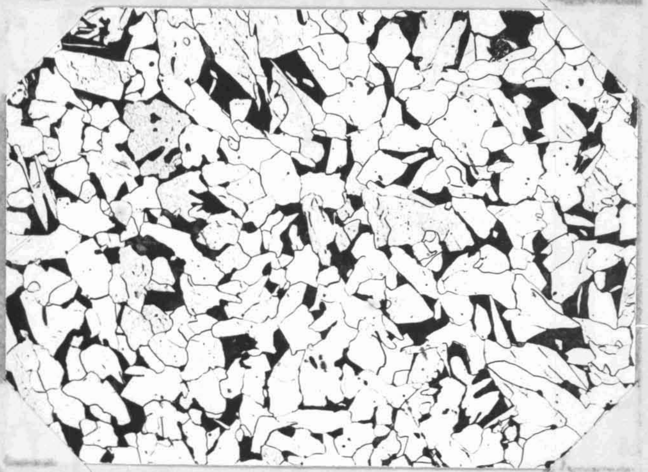
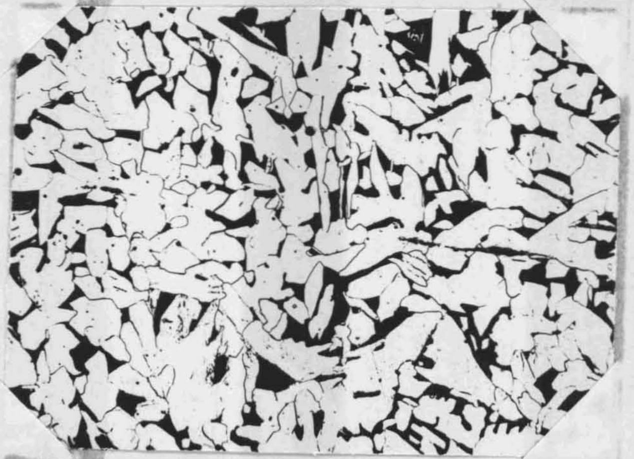


Bottom

Fig. 10b A-201, Ingot 4

Micrographs at 100x, Nital etch



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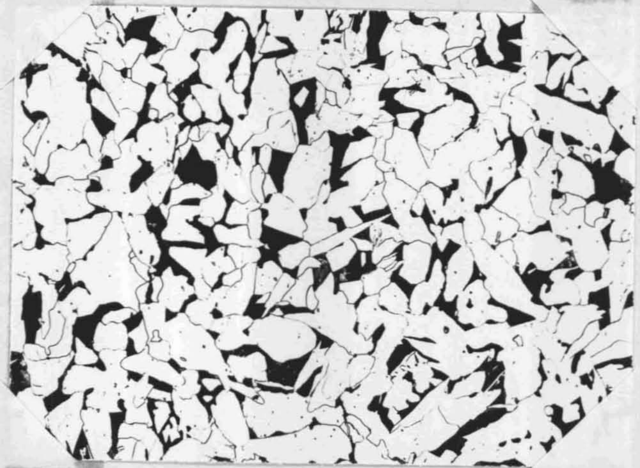

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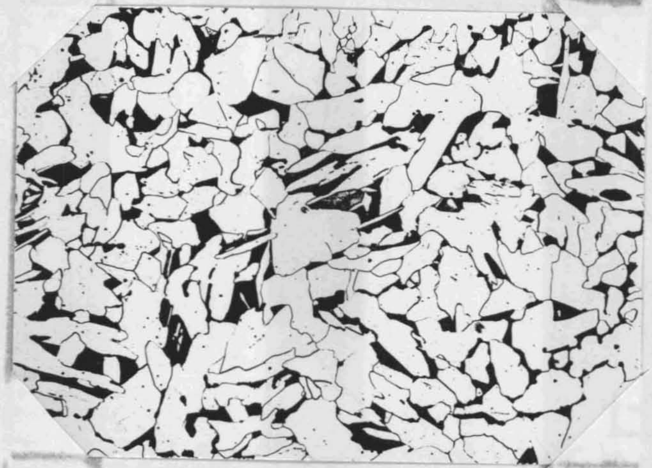
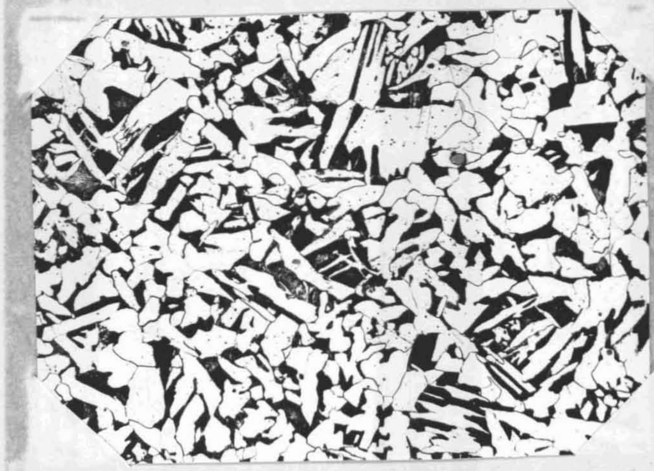


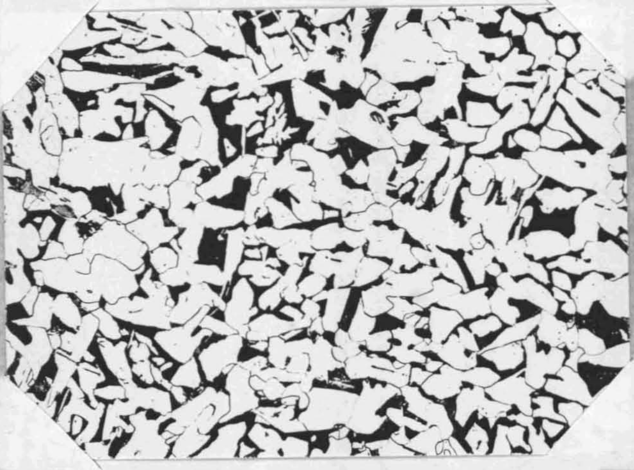
Bottom

Fig. 10c A-201, Ingot 9

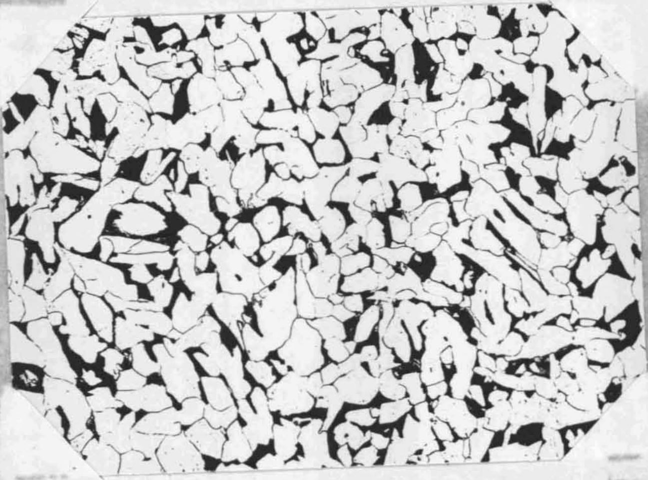
Micrographs at 100x, Nital etch



Top

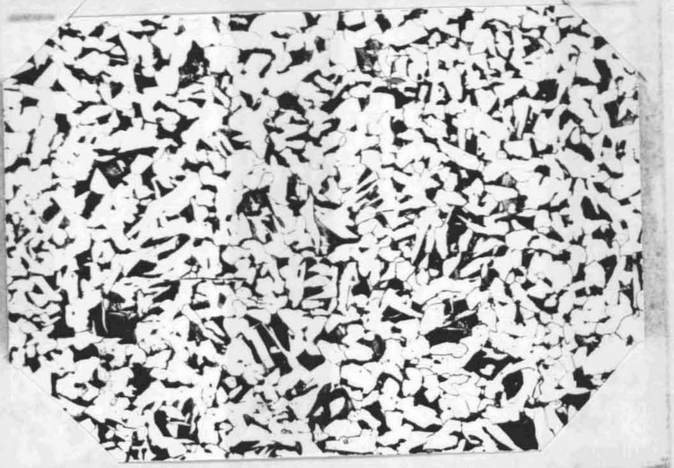


Middle

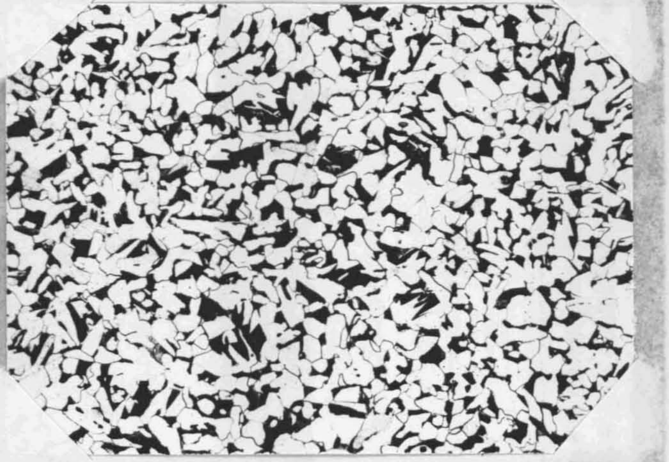


Bottom

Fig. 11a A-70, Ingot 2



Top



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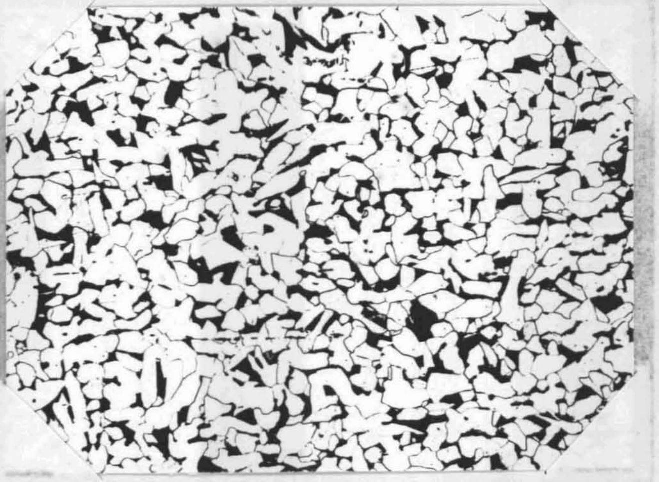

Bottom

Fig. 11b A-70, Ingot 7

Micrographs at 100x, Nital etch

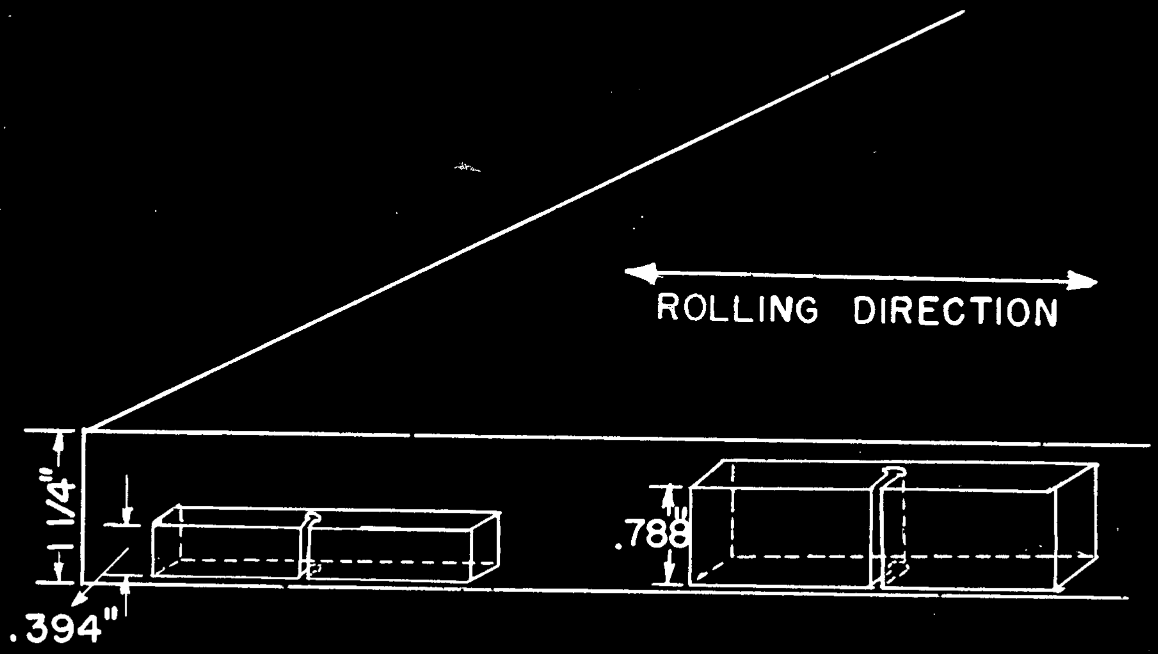

FIG. 12 _ ORIENTATION OF SINGLE AND DOUBLE-WIDTH CHARPY SPECIMENS IN 1 1/4" PLATE. EXCEPT FOR DOUBLE WIDTH AS SHOWN, THESE ARE STANDARD KEYHOLE-NOTCH SPECIMENS (A.S.T.M. E23-41T).

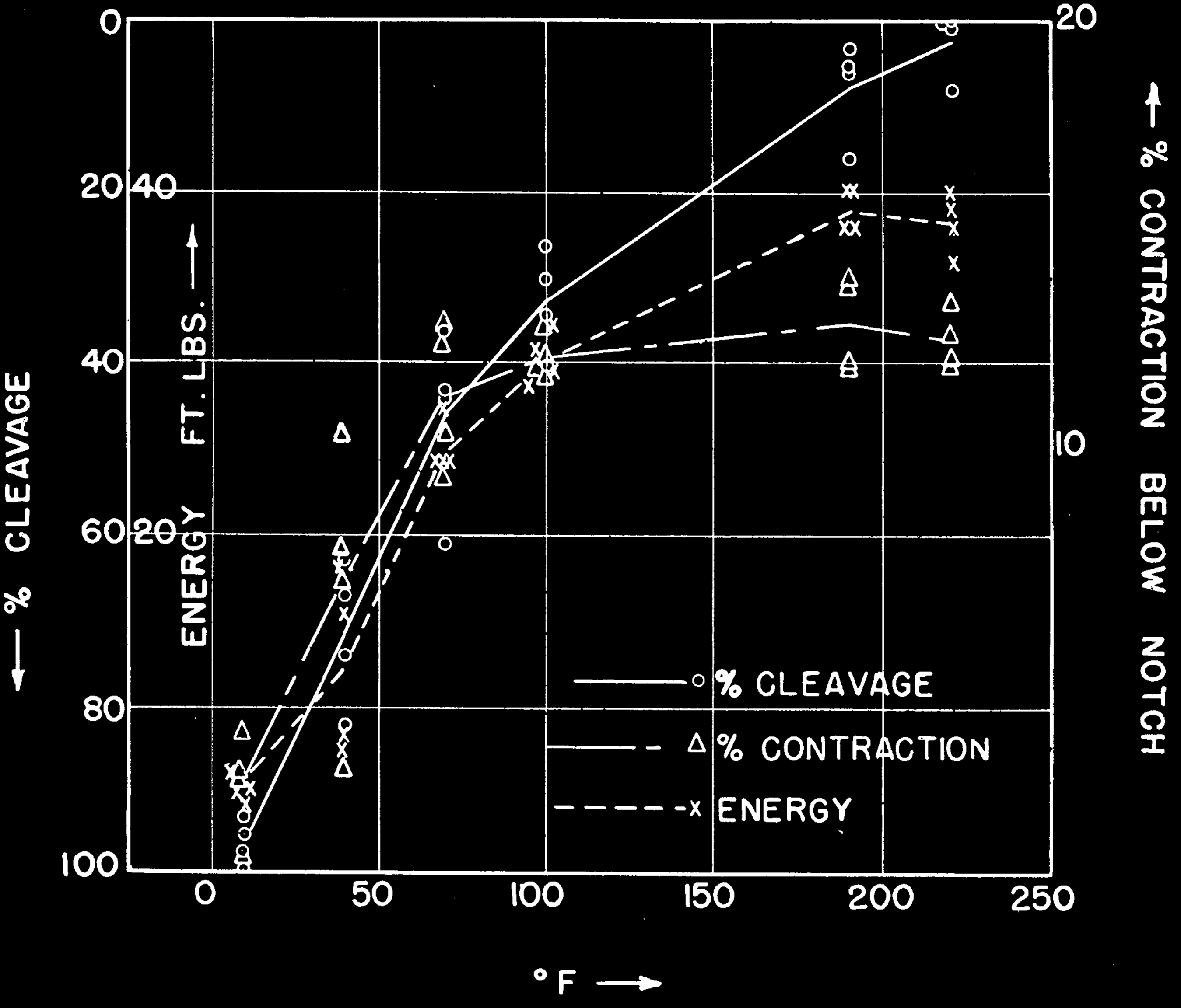

FIG. 13 CHARPY TRANSITION CURVES FOR A-70, 1 1/4" MATERIAL. STANDARD KEYHOLE-NOTCH SPECIMEN.