U. S. NAVAL AIR ENGINEERING CENTER

PHILADELPHIA, PENNSYLVANIA

AERONAUTICAL MATERIALS LABORATORY

REPORT NO. NAEC-AML-1947 DATE 21 May 1964

EVALUATION OF AIR MELTED AND VACUUM MELTED AISI 4340 STEEL

PROBLEM ASSIGNMENT NO. 10-23 UNDER BUREAU OF NAVAL WEAPONS WEPTASK RRMA 02 018/200 1/R007 05 01

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AD 600727
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ABSTRACT

This report compares the mechanical properties of air-melted versus three different types of vacuum-melted AISI 4340 steel.

Cleanliness, hardenability, tensile, impact, fatigue properties and fracture toughness characteristics are compared at two strength levels (200-220 ksi and 260-280 ksi). Particular emphasis was placed on transverse mechanical properties. Susceptibilities to hydrogen embrittlement of the variously different processed materials are also compared.

In general, the data indicate that vacuum melting offers a significant improvement in mechanical properties over air-melted steel in the transverse grain direction. In particular, the fracture toughness, impact strength, fatigue, ductility and resistance to hydrogen embrittlement are significantly enhanced by the vacuum melting process. ( )

I. INTRODUCTION

A. Background

1. The current concern for very clean, high strength aircraft quality steels has influenced increased production by vacuum melting techniques. As a result, vacuum melted steels have entered the steel market at substantial increases in price and with purported improvements in mechanical properties. In view of this development, the Naval Weapons Plant began an investigation to determine whether the increased cost of vacuum melted steel is accompanied by a commensurate improvement in mechanical properties.

2. In 1961, following the disestablishment of the Naval Weapons Plant, the problem assignment was transferred to the Aeronautical Materials Laboratory for completion. Prior to this date, however, a test program of broad scope was initiated by the Naval Weapons Plant. By the time the problem assignment was transferred to the Aeronautical Materials Laboratory, material shortages and economic considerations necessitated a revision of the original test program. In the revision, emphasis was shifted from the use of mid-radius longitudinal test specimens to center-of-the-billet transverse type. Consistent with these requirements, this report presents the results of transverse tensile, impact, fracture toughness, fatigue and hydrogen embrittlement studies conducted by the Aeronautical Materials Laboratory and supplemented by the information obtained from the U. S. Naval Weapons Plant Report No. Ser. 144-722.2 and from the literature.

B. Object

To demonstrate the effects of various vacuum melting techniques on the properties of the 4340 steel and to ascertain the extent of the changes in the properties affected as compared with the air-melted aircraft quality steel bar stock.

II. EXPERIMENTAL PROCEDURE

A. Material

1. Processing History

Three special heats (No. 44085, 05076, and 05233) were prepared for the Naval Weapons Plant by the Crucible Steel Company of America. From these heats, four groups of billets were finished rolled into 4 inch square cross-sections and cut into 8-foot lengths. Each batch having the same pedigree was identified by either of the legends AM, VAR, VIM, or VIR. These designations are described as follows:

AM - Electric furnace air melt heat no. 44085

VAR - Part of heat no. 44085 vacuum remelted as consumable electrodes

VIM - Vacuum induction melted heat nos. 05076 and 05233

VIR - Part of VIM heats 05076 and 05233 vacuum remelted as consumable electrodes

A flow chart showing the processing history of the test materials is presented in Plate 1.

2. Chemical Composition

The chemical compositions were determined of each batch of material by conventional wet analysis. In addition, a gas analysis was conducted on samples of each group of materials. This included oxygen and nitrogen determinations by vacuum fusion analysis and hydrogen determinations by the hot extraction method.

3. Cleanliness

The internal cleanliness of the different materials was determined on the basis of:

a. Sulphur Distribution
b. Inclusion Content - Macroscopic
c. Inclusion Content - Microscopic

a. Inclusion Content

(1) Sulphur Distribution

Sulphur prints were made from cross-sections of the different materials using conventional techniques.

(2) Macroscopic Method

Both the ASTM specification E45-51 and the Allison step-down methods were used to determine the inclusion ratings of the various steel bars macroscopically.

(3) Microscopic Method

Each batch of steel was tested in accordance with ASTM Specification E45-51 to determine the average JK inclusion ratings.

4. Microstructure

Metallographic specimens were removed from the center-of-the-bar test specimens of the different materials and prepared for microscopic examination. Photomicrographs were prepared of typical microstructures representing the upper and lower strength levels.

5. Heat Treatment

All tests were conducted with specimens heat treated to two strength levels (200-220 ksi and 260-280 ksi). These strength levels were obtained with a common austenitizing temperature of 1550°F with an oil quench followed by a 775°F or 400°F tempering temperature.

6. Hardenability

Hardenability determinations were made of the different materials using standard type 2-A test blanks in accordance with Method 711.1 of Federal Test Method Standard No. 151.

B. Tensile

1. Smooth Specimens

From each batch of steel a minimum of six standard .505 longitudinal mid-radius tensile blanks were removed. In addition to these specimens, an equal number of center-of-the-bar transverse .505" tensile blanks were prepared. A sketch showing the method of sampling the test bars is presented in Plate 2. Half of the longitudinal and one half of the transverse specimens were heat treated to the 260-280 ksi strength range. The remaining specimens in each group were heat treated to the 200-220 ksi strength level. After heat treatment, all specimens were finished machined and tested.

2. Notched Specimens

From each batch of steel, six notched transverse center-of-the-bar tensile specimens were prepared. A sketch of the test specimen showing the notch configuration is presented in Plate 3. Half of these specimens were heat treated to the upper strength level and the remainder to the lower strength level.

The notched-unnotched tensile ratios were determined for each material. The material was considered to be notch sensitive when the ratio was less than 1.0.

C. Impact

Thirty transverse grain direction standard V-notch Charpy impact specimens were prepared from near-center locations of each 4 inch square billet of AM, VAR, VIR, and two heats of VIM steel. Material shortages prevented tests with both heats of VIR material. One half of the specimens were heat treated to the 260-280 ksi strength range and the remainder to the 200-220 ksi strength level. Specimens at both strength levels were tested in triplicate at room temperature, 0°F, -40°F, -100°F and -200°F. All temperatures below room temperature, with the exception of -200°F, were obtained with an acetone-dry ice bath. The -200°F temperature was obtained in a controlled cold box using liquid nitrogen as the refrigerant.

D. Fracture Toughness

Only the VAR material was furnished in sheet form for fracture toughness tests. However, fracture toughness data on identical VAR, VIR, AM and VIM material was made available by the Crucible Steel Company of America. This latter data is included in this report.

All fracture toughness data reported was obtained on NRL center notch type specimens. All specimens were pre-cracked by fatigue prior to testing. The fracture toughness parameter K_c was obtained as a function of critical crack length.

E. Hydrogen Embrittlement

Ninety-six tensile specimens of the type shown in Plate 2 were rough machined and heat treated to 260-280 ksi strength range prior to finish machining. Material shortages dictated that these transverse specimens be extracted from near-center-of-the-bar locations rather than from the exact center as originally planned. The 96 test specimens were divided into six groups of 16 specimens bearing the following processing histories:

2A VAR	1C AM	2D VIM	3D VIM	1E VIR	2E VIR
Ht. 44085	Ht. 44085	Ht. 05076	Ht. 05233	Ht. 05233	Ht. 05076

The above materials can be identified by referring to paragraph II.A.1. and the flow chart shown in Plate 1. From each of these groups, three samples were tensile tested as heat treated. The remaining specimens were cyanide cadmium plated to introduce hydrogen into the surface. Three of the plated specimens from each of the six groups were tensile tested to compare with the unplated three. All of the remaining plated specimens were used to establish static fatigue limit curves. These curves were obtained by plotting static load versus time-to-failure. The load was varied until a 500-hour limit was sustained.

F. Fatigue

Forty rotating beam type fatigue blanks were extracted from near-center locations of the transverse grain direction of each group of 4 inch square billets of AM, VAR, VIR, and each of the two heats of VIM material. Material shortages did not permit tests with both heats of VIR steel. Half of each of these groups was used for notched type fatigue specimens shown in Plate 2, while the other half was used for the smooth type test specimens. Each group selected for unnotched or notched specimen blanks was again divided into two equal groups for heat treatment to either the 200-220 ksi strength level or to the 260-280 ksi strength range. After heat treatment, the 200 test blanks were finish machined and tested to establish fatigue limit curves.

III. RESULTS

A. Material

1. Chemical Composition

The results of chemical analyses are tabulated in Table 1. Also shown in Table 1 are the gas content determinations for hydrogen, oxygen and nitrogen. As indicated, all of the test material meets the chemical composition requirements of AMS Specification 6415E for 4340 steel. Results show that the sulphur and phosphorus contents are much lower in the vacuum melted steels than in the air melted steels. This cannot be attributed to the vacuum melting process, but instead, it indicates that the raw materials used in making the vacuum melted steel contained less sulphur and phosphorus. As would be expected, the vacuum processed materials were significantly lower in gas content than the air melted material.

2. Cleanliness

a. Sulphur Distribution

Examination of sulphur prints and macroetched specimens (see Plates 4 to 9) indicate that the VIR steel is the cleanest material. The VIM steel was next in order of cleanliness followed by the VAR steel. The least clean, by comparison, was the AM material.

Normally, the VAR steel would be expected to be cleaner than the VIM steel. The reversal of this order of cleanliness between these two steels is believed to be attributable to the use of raw materials of higher purity in making the VIM steel.

b. Macroscopic Method

The ASTM macroscopic method E45-51 indicated that the AM, VAR, and VIR specimens were essentially free of inclusions. However, in two induction melted (VIM) specimens, a total of three inclusions were observed through the area sectioned.

In one specimen, inclusions 1/32-inch and 1/16-inch in length were observed, while in the second specimen, one inclusion 1/32-inch in length was noted. Since the ASTM specification gives weighted values only to those inclusions which are over 1/16-inch in length, all bars would be considered very clean.

c. Allison Step-Down Method

The frequency of inclusions as computed by the Allison step-down method is listed below:

Steel	Frequency of Inclusions
AM	0.0081
VAR	0
VIM	0.0072
VIR	0.0027

The only engineering material specification available from the Allison Division of General Motors Corporation is one for special high quality SAE 9310 steel. The maximum frequency rating permitted in this specification is 0.50. Again, by comparison, all bars would be classified as very clean.

d. Microscopic Method

Results of tests conducted in accordance with ASTM Specification E45-51 to determine the average JK inclusion rating for sections removed from mid-radius billet locations of the different steels are tabulated below:

Steel	Sulfide	Alumina	Silicate	Oxide	Total
AM	2.6	1.0	2.1	1.0	6.7
VAR	1.4	0.2	0.3	1.4	3.3
VIM	0.5	0.1	0.1	1.2	1.9
VIR	0.5	0	0.2	0.9	1.6

All of the above JK ratings represent thin type inclusions with the smaller number indicating the cleaner steel. This method confirms the order of cleanliness determined macroscopically.

3. Microstructure

Although specimens removed from mid-radius locations of the various billets were relatively free of non-metallic inclusions, microstructural examination of center-of-the-billet samples of AM and VAR materials disclosed the presence of inclusion stringers of the type shown in Plate 10. In addition, the AM, VAR, and VIM material exhibited microstructural banding of the type shown in Fig. 1 of Plate 11. The VIR material was singularly free of both stringer type inclusions and banding. (See Fig. 2 of Plate 11). After heat treatment to either strength level, all material exhibited tempered martensitic structures typical of AISI 4340 steel. Photomicrographs showing typical microstructures are presented in Plate 12.

4. Hardenability

The Jominy hardenability data is tabulated in Table 2. As indicated, all test bars complied with the hardenability requirements of AMS Specification 6415E for 4340 steel which requires Rockwell "C" 50 at 20 sixteenths from the quenched end.

B. Tensile Properties

1. Smooth Specimens

a. The smooth bar tensile properties of the various test materials are tabulated in Tables 3 and 4 and are shown graphically in Plates 13, 14, and 15.

b. Longitudinal

A comparison of the longitudinal tensile properties of the AM and various vacuum melted materials indicate that the materials are undistinguishable with respect to longitudinal tensile properties at both high and low strength levels.

c. Longitudinal vs Transverse Tensile Properties

(1) Lower Strength Level (200-220 ksi)

Both longitudinal and transverse tensile specimens exhibit similar tensile strengths at the lower strength level. With respect to tensile ductility, however, the reduction of area and elongation values for transverse specimens were significantly lower than for longitudinal specimens of similar processing history.

(2) Higher Strength Level (260-280 ksi)

At the higher strength level, the AM and VAR transverse tensile properties were markedly inferior to both VIM and VIR transverse and to AM and VAR longitudinal tensile properties. Further comparison reveals that the VIM and VIR transverse tensile properties closely approach the tensile test results obtained with VIM and VIR longitudinal test specimens.

d. Transverse

In both strength and ductility, the tensile properties of VIM and VIR transverse materials at the higher strength level were superior to the AM and VAR material. At the lower strength level, however, the superior tensile properties of VIM and VIR steel over AM and VAR steel is reflected in reduction of area and elongation properties only.

2. Notched Specimens

Notched transverse tensile strength was compared with unnotched transverse strength at both strength levels. The results indicated that both air and vacuum melted material were notch sensitive at the higher strength level with the AM and VAR material possessing the greater notch sensitivity. At the lower strength level, the AM and VAR material only was notch sensitive. (See Table 5 and Plates 13 and 14.)

C. Impact Properties

1. The results of Charpy V-notch impact tests are presented in tabular form in Tables 6 and 7 and shown graphically in Plates 16, 17 and 18. In general, the test results indicate that for transverse grain direction, the cleaner the steel, the higher the impact resistance at all test temperatures. Specifically, the VIR material was slightly superior to VIM and both VIM and VIR material were markedly superior to AM and VAR material. AM material exhibited the lowest impact resistance of all four materials.

2. It should be noted that the impact values obtained for the higher tempering temperature (775°F) were lower at all test temperatures than the values obtained for the lower tempering temperature. This fact indicates that the 775°F tempering temperature is within the temper brittle range.

D. Fracture Toughness

Fracture toughness data obtained on the VAR material together with that furnished by the Crucible Steel Company is tabulated below:

AM[1]	VAR[1]	VAR[2]	VIM[1]	VIR[1]
K_c 1000 psi $\sqrt{in.}$	K_c 1000 psi $\sqrt{in.}$	K_c 1000 psi $\sqrt{in.}$	K_c 1000 psi $\sqrt{in.}$	K_c* 1000 psi $\sqrt{in.}$
80	75.1	115	205	197

*Based on percent shear; all other values based on critical crack length.

[1]Crucible Steel Company

[2]Aeronautical Materials Laboratory

As indicated above, with the exception of the VAR material, vacuum melting results in a marked improvement in fracture toughness. The relatively poor performance of the VAR material in the fracture toughness tests is consistent with its performance in other tests.

E. Hydrogen Embrittlement

1. Results of hydrogen embrittlement tests are presented in Table 8 and are also shown graphically in Plates 19 and 20. As indicated the VIR and VIM material was significantly less sensitive to the embrittling effects associated with hydrogen adsorption than was the AM and VAR material.

2. It is to be noted that the unplated 0.160 inch diameter notched transverse tensile specimens extracted from near-center-of-the-bar locations (see Plate 2) exhibited significantly less notch sensitivity than did 0.505 inch diameter notched transverse tensile test specimens extracted from the exact center-of-the-billet locations. An explanation for this behavior is offered in the Analysis of Results.

F. Fatigue Properties

The results of fatigue tests are presented in tabular form in Tables 9 to 18 and are shown graphically in Plates 21 to 24.

In general, the data indicate that the fatigue limits of the various test materials is related to the degree of cleanliness; the cleanest material exhibiting the highest fatigue limit in both the notched and unnotched conditions at both strength levels.

Somewhat erratic behavior was observed in tests of the VAR material. Similarly, the VIM-2D and VIM-3D materials exhibited anomalous behavior. Failures outside the notched gage sections were obtained with the VIM-2D material, while the unnotched VIM-3D material exhibited an abnormally low fatigue limit. The erratic and anomalous behavior of these materials is discussed in the Analysis of Results.

IV. ANALYSIS OF RESULTS

A. Material

The major objectives of vacuum melting techniques are as follows:

1. To lower gas content;
2. To control composition more closely;
3. To improve cleanliness;
4. To o[illegible] ingot structures free from center porosity and segregation

The degree to which these were accomplished in this study is examined. As a natural consequence of the attainment of the above objectives, certain mechanical properties should be proportionately improved. The degree to which this was obtained will also be examined.

The first objective was achieved with the test materials reported herein. The oxygen content diminishes from 0.006 ppm to 0.0003 ppm and the nitrogen content from 0.0082 ppm to 0.0005 ppm for the AM and VIR material, respectively. The hydrogen contents for the AM and VAR materials are not significantly different. In this respect, it has been pointed out that the VAR material was not representative of the cleanliness of material processed by this method. This feature may account for the essentially unchanged hydrogen content of the VAR material as compared with the AM material from which it was processed.

The hydrogen content of the VIM material is not significantly different from the AM or VAR material. However, in this case, it should be noted that this comparison is not valid since the VIM heat was made from different material. The VIR material, which is a remelt of the VIM material, does however show a reduced hydrogen content.

Since the next three objectives are interrelated, they are discussed together. Original plans called for very close control of the composition variables, but it was learned after receipt of the test material that raw materials of higher purity were used to produce the VIM and VIR heats. Nominally, all materials, with the exception of the low phosphorus and sulphur content for the VIM and VIR heats, were indistinguishable with respect to chemical composition. However, the effect of the use of raw materials of variant purity became apparent after macroscopic examination unexpectedly rated VAR material second to VIM steel with respect to material cleanliness. Subsequent microscopic inspection before and after heat treatment revealed evidence of microstructural banding in all but the VIR material. In addition to banding, AM and VAR material possessed stringer type inclusions. Although somewhat reduced during remelting by vacuum arc techniques, the stringers were still present in the VAR remelt of the AM material. No stringers were found in the VIM or VIR material. This observation was a reflection of the use of higher purity raw materials to produce the VIM and VIR materials. The presence of inclusion type stringers and banding undoubtedly contributed to the erratic and unfavorable performances of AM and VAR material in the mechanical tests. This conclusion was concurred in by the Crucible Steel Company of America, the supplier of the material. On the other hand, the minimal presence of banding-promoting elements as a result of the use of higher purity raw materials had doubtlessly contributed to the improved mechanical properties performance of VIM and VIR material. The presence of banding in VIM material and its absence in VIR material is attributable to melting practices.

As was pointed out previously, material shortages prevented carrying out all tests from the same locations in the test bars. Consequently, the test specimens were extracted from those locations that would reflect the poorest properties of the material. In all cases, however, for a given test, all specimens were extracted from the same location in each test bar. Therefore, all reported data must be viewed in light of the following:

1. Raw materials used to prepare all test materials were not identical;

2. Because of limited test material, all specimens were not extracted from the same locations.

B. Mechanical Properties

Although some anomalies were encountered in certain specific mechanical properties tests of the various test materials, in general, the vacuum melting process offers a marked improvement in the transverse grain direction for tensile ductility, notched tensile strength, impact strength, fracture toughness, fatigue limit and resistance to hydrogen embrittlement. More specifically, the vacuum induction remelt (VIR) material exhibited an approximate two fold increase in fracture toughness, notched tensile strength and impact resistance over air melted (AM) material. Similarly, transverse tensile ductility was increased 10% and 25%, respectively for elongation and reduction in area measurements. The fatigue limit was increased by a factor of one and a half.

It should be noted, however, that steel with the cleanliness and microstructure necessary to effect the improvement in properties noted above was obtained with the use of high purity raw materials in combination with vacuum melting techniques. Vacuum melting alone cannot be expected to produce material that is ultra clean if the raw materials used to process a heat are of sub-standard purity. It cannot be overemphasized, that while vacuum melting significantly reduces the content of certain gases, it will not significantly lower the inclusion content. In support of this, the VIR material, which was processed from high purity raw materials and subsequently vacuum arc remelted, exhibited mechanical properties superior to the VAR material which was a vacuum arc remelt of a parent heat made from lower purity raw materials. Summarizing, if the vacuum melting process is to produce materials which exhibit superior mechanical properties, then each step in the preparation of a heat must be carefully oriented toward the production of an ultra clean material.

The anomalous behavior referred to above, was in each case, found to be directly related to cleanliness and microstructural homogeneity. For instance, in all but the air melted material, the ultimate strength of the 0.160 inch diameter unplated notched (hydrogen embrittlement tensile type) specimens possessed notched to unnotched strength ratios exceeding unity. In contrast, all of the 0.505 inch diameter notched tensile samples extracted from the exact center-of-the-billet locations exhibited lower notch tensile ratios than did these 0.160 inch near-center-of-the-billet (see Plate 2) specimens. The detrimental effects of the decreased soundness associated with the center-of-the-billet specimens would account for their lower notched strength.

With respect to the fatigue tests, the unusual behavior of some of these specimens was also determined to be related to material cleanliness. The cases in point were the VAR, VIM-3D and VIM-2D steels. The VAR and VIM-3D materials exhibited erratic behavior and relatively poor fatigue properties, whereas several test specimens of the VIM-2D material failed through the filleted area adjacent to the shoulder section (see Plate 3) rather than through the notched gage section. Microscopic examination of sections removed from the VAR test specimens in the area of failure revealed a banded structure with a dispersion of fine non-metallic stringers. Sections removed from the parent AM material exhibited a similar microstructure with somewhat thicker inclusion type stringers. (See Plate 10.) This was the only significant difference noted between the two materials. Undoubtedly, this condition contributed to the cause of the erratic performance of the AM and VAR material in fatigue and other tests. Although the inclusion stringers were absent in the VIM-3D material, the persistence of a banded structure in this material is suspected of causing the relatively poor fatigue properties.

In the attempt to understand the cause of the premature failure of the VIM-2D notched specimens, the broken samples were sectioned through the failed filleted area adjacent to the shoulder section, mounted, and inspected metallographically. Throughout the sectioned area fine, scattered inclusions were noted. Reexamination of the macro-etched bottom section of the VIM-2D billet from which these specimens were extracted (see Plate 6) also revealed evidence of fine inclusion type pits throughout the areas which coincided with the filleted area adjacent to the shoulder section of the extracted fatigue specimens. (See Plate 2.) It is considered that the presence of this fine dispersion of inclusions in combination with the filleted shoulder areas of these specimens produced a stress concentration greater than that provided by the notch. This condition would account for the selective failure of these specimens through the filleted shoulder section.

In summary, the erratic behavior of the fatigue and notched tensile specimens herein discussed are believed to be associated with the presence of inclusions and/or banding.

V. CONCLUSIONS

1. The gas content of vacuum melted steel is lower than that of air melted steel.

2. The vacuum melting process in itself does not insure ultra clean steel.

3. The VIR and VIM steels which were processed from higher purity raw materials were markedly superior to AM and VAR material with respect to cleanliness and microstructural homogeneity.

4. Hardenability of air and vacuum melted steels of the same nominal composition are similar.

5. Significant improvements in the mechanical properties in the transverse grain direction are dependent upon the degree of cleanliness and microstructural homogeneity. Consistent with this, the following conclusions related to the mechanical properties in the transverse grain direction are drawn:

a. The unnotched transverse tensile properties of the very clean VIM and VIR steels closely approach the longitudinal tensile properties in both strength and ductility at both the upper and lower strength levels. At the lower strength level, the ductility of the AM and VAR steels, as measured by percent reduction in area in the transverse grain direction, was significantly lower (40%) than in the longitudinal direction. At the upper strength level, both strength and ductility were significantly lower in the transverse grain direction (14%-32% lower in strength and 32% lower in reduction in area).

b. The notched strength of the VIR and VIM steels is significantly higher than that of the AM and VAR steels at both strength levels. (Approximately 80% higher at both the upper and lower strength levels.)

c. At the 260-280 ksi strength level, the VIM and VIR steels exhibit significantly less susceptibility to hydrogen embrittlement than the AM and VAR steels. Based on a 500-hour static fatigue limit, the VIM and VIR steels were approximately similar with respect to susceptibility to hydrogen embrittlement, however, in comparing them with AM and VAR steels the static fatigue limits were from two to five times higher for the VIM and VIR steels.

d. The much cleaner VIM and VIR steels showed the most significant improvement in the fatigue limit, fracture toughness and impact strength properties over the AM and VAR material. The VIM and VIR steels show a two-fold increase in transverse impact strength and fracture toughness and a 50% increase in the fatigue limit over the AM and VAR steels.

VI. RECOMMENDATIONS

In view of the significant improvements in mechanical properties associated with vacuum melted steel which possesses ultra clean and homogeneous microstructures, serious consideration of their use should be given to those applications requiring that transverse grain direction properties closely approach longitudinal grain direction properties. Particular attention is directed to the consideration of their use where ductility, fracture toughness and fatigue strength are important design considerations in the transverse grain direction.

CHEMICAL COMPOSITION

Material	C	Si	S	P	Mn	Ni	Cr	Mo	H_2 (PPM)	O_2	N_2
AM	.40	.27	.024	.010	.77	1.76	.82	.27	2.0	.0060	.0082
VAR	.40	.27	.018	.018	.62*	1.76	.81	.20	2.3	.0021	.0018
VIM	.39	.25	.005	.010	.77	1.85	.82	.30	2.2	.0005	.0008
VIR	.39	.29	.005	.010	.59*	1.84	.80	.25	0.9	.0003	.0005

*Typical values for consumable electrode melted material.

TABLE 1

JOMINY HARDNESS TRAVERSE (ROCKWELL "C")

DISTANCE FROM QUENCHED END IN SIXTEENTHS OF AN INCH

Material	1	3	5	7	9	12	16	20	26	32
AM	58.5	57.0	55.5	55.0	54.5	54.5	54.0	53.5	53.5	53.0
AM	59.0	57.0	56.5	56.0	55.5	55.5	55.0	55.0	54.5	54.0
AM	56.5	56.5	55.0	54.5	54.5	54.0	54.0	53.5	53.5	52.5
AM	57.0	57.0	56.0	56.0	56.0	55.0	54.0	54.0	52.0	50.0
AM	58.0	56.0	56.0	56.0	56.0	55.0	55.0	54.0	53.0	51.0
VAR	57.0	56.0	54.5	54.0	54.0	53.5	53.5	52.0	52.0	51.5
VAR	57.0	56.0	55.5	55.5	55.0	55.0	54.5	54.5	53.5	52.0
VAR	58.0	57.0	56.5	56.5	56.0	55.5	55.0	52.5	46.5	42.5
VIM	58.0	57.0	57.0	56.5	56.0	56.0	55.0	55.0	55.0	55.0
VIM	57.5	56.0	54.5	54.5	54.0	53.5	53.5	53.5	53.0	52.5
VIM	58.5	57.0	56.5	56.0	55.5	55.0	55.0	54.5	54.0	53.5
VIR	57.5	55.5	55.0	55.0	55.0	54.5	54.0	54.0	54.0	54.0
VIR	57.5	56.0	55.0	55.0	55.0	54.5	54.5	54.5	54.0	54.0

TABLE 2

UNNOTCHED TENSILE PROPERTIES OF TRANSVERSE AND LONGITUDINAL TENSILE SPECIMENS HEAT TREATED TO THE 260-280 KSI STRENGTH LEVEL

			Longitudinal				Transverse			
Matl	Bar		Ult. (psi)	Yield (psi) .2% Offset	R.A. (%)	Elong. (%)	Ult. (psi)	Yield (psi) .2% Offset	R.A. (%)	Elong. (%)
AM	1C	1	287,500	207,500	30.5	11.0	182,500	No Yield	--	1.0
		2	276,000	205,000	6.2*	2.5	209,500	195,000	--	1.5
		3	276,000	204,000	6.2*	3.0	179,500	No Yield	--	1.5
		Avg.	280,500	205,500	--	5.5	190,500	---	--	1.3
VAR	2A	1	283,000	206,500	37.5	14.0	236,000	216,200	3.5	2.0
		2	285,000	210,000	36.6	12.5	238,000	215,000	3.5	2.0
		3	283,000	208,000	34.1	13.0	265,700	213,400	4.5	2.5
		Avg.	283,600	208,000	36.0	13.2	246,500	214,800	3.8	2.2
VIM	2D	1	286,000	205,000	29.2	11.0	267,700	206,500	27.1	8.5
		2	286,000	209,000	29.8	11.5	269,700	208,000	27.1	9.0
		3	290,000	210,000	18.8	10.0	268,200	210,400	29.2	9.0
		Avg.	287,300	208,000	25.9	10.8	268,500	208,300	27.8	8.8
VIM	3D	1	287,500	205,000	25.5	11.0	262,900	205,000	22.3	7.0
		2	290,000	205,000	24.8	11.0	266,200	207,000	15.9	6.0
		3	285,000	206,000	13.4	4.5	264,200	208,000	3.9	4.0
		Avg.	287,500	205,300	21.2	8.8	264,400	206,700	14.0	5.7
VIR	2E	1	280,000	207,500	41.6	13.0	278,600	205,000	31.8	10.0
		2	275,000	207,500	45.1	14.0	280,000	210,400	26.5	9.5
		3	280,000	208,000	43.4	14.5	280,700	210,000	26.8	9.5
		Avg.	278,000	207,700	43.4	13.8	279,800	208,500	28.4	9.8

*Broke in Gage Marks.

TABLE 3

UNNOTCHED TENSILE PROPERTIES OF TRANSVERSE AND LONGITUDINAL TENSILE SPECIMENS HEAT TREATED TO THE 200-220 KSI STRENGTH LEVEL

			Longitudinal				Transverse			
Matl	Bar		Ult. (psi)	Yield (psi) .2% Offset	R.A. (%)	Elong. (%)	Ult. (psi)	Yield (psi) .2% Offset	R.A. (%)	Elong. (%)
AM	1C	1	216,000	206,000	48.3	12.0	211,500	192,500	2.5	2.0
		2	217,000	205,000	46.9	10.5	217,900	192,800	3.9	2.5
		3	216,000	204,000	47.8	12.0	217,500	194,500	2.5	2.5
		Avg.	216,200	205,000	47.8	11.5	215,600	193,200	3.0	2.3
VAR	2A	1	205,000	190,000	46.3	13.0	220,900	195,000	2.5	4.0
		2	208,000	190,000	45.1	13.5	220,100	195,000	4.5	4.0
		3	206,000	190,000	47.2	13.0	224,300	203,000	10.0	4.0
		Avg.	206,300	190,000	46.2	13.2	221,700	195,600	5.7	4.0
VIM	2D	1	215,000	194,000	54.4	13.0	207,200	186,300	44.1	10.5
		2	216,500	200,000	53.1	13.0	206,500	185,600	36.2	9.0
		3	215,000	199,000	53.9	13.0	208,400	186,600	40.5	10.5
		Avg.	215,300	198,000	53.8	13.0	207,300	186,100	40.3	10.0
VIM	3D	1	216,000	199,500	53.3	16.5	205,700	189,000	17.4	5.0
		2	216,000	199,500	53.1	14.0	206,200	190,000	25.8	6.5
		3	214,000	199,500	54.4	13.0	205,50C	190,000	14.1	5.0
		Avg.	215,300	199,500	53.6	14.5	205,800	189,700	19.1	6.0
VIR	2E	1	207,000	194,000	55.7	14.0	--------------No Specimens--------------			
		2	203,500	195,000	55.2	13.5				
		3	209,000	197,000	56.5	14.5				
		Avg.	206,000	195,300	55.8	14.0				

TABLE 4

NOTCHED TRANSVERSE TENSILE STRENGTH

Material	Load (lb)	Breaking Strength (psi)	Notched/Unnotched Ratio
		200-220 ksi Strength Range	
AM-1	25,000	125,000	
2	28,200	141,700	0.65
3	30,000	150,000	
		Avg. 138,900	
VAR-1	30,750	153,700	
2	29,150	146,300	0.71
3	35,000	175,000	
		Avg. 158,350	
VIM-2D-1	51,200	257,300	
2	48,800	245,200	1.23
3	53,500	266,200	
		Avg. 256,250	
VIM-3D-1	49,250	246,200	
2	48,100	240,500	1.19
3	48,500	242,500	
		Avg. 246,400	
		260-280 ksi Strength Range	
AM-1	27,000	135,000	
2	28,150	140,700	0.75
3	30,000	150,000	
		Avg. 141,900	
VAR-1	33,100	165,500	
2	33,150	165,700	0.66
3	31,950	158,900	
		Avg. 163,350	
VIM-2D-1	50,400	252,000	
2	51,000	253,700	0.96
3	52,300	261,500	
		Avg. 255,750	

TABLE 5

Material	Load (lb)	Breaking Strength (psi)	Notched / Unnotched Ratio
		260-280 ksi Strength Range (continued)	
VIM-3D-1	47,500	238,700	
2	48,600	243,000	0.89
3	49,400	247,000	
		Avg. 242,900	
VIR-1	45,000	225,000	
2	45,300	226,500	0.82
3	47,300	236,500	
		Avg. 229,350	

IMPACT TEST RESULTS*FOR V-NOTCH CHARPY SPECIMENS AT THE 260-280 KSI STRENGTH LEVEL

Material		Test Temp. 75°F (ft-lb)	Test Temp. 0°F (ft-lb)	Test Temp. -40°F (ft-lb)	Test Temp. -100°F (ft-lb)	Test Temp. -200°F (ft-lb)
AM-1		10	7	6	4	3
2		10	5	5	4	3
3		7	5	4	5	4
	Avg.	9.0	5.6	5.0	4.3	3.3
VAR-1		10	7	6	6	4
2		14	6	8	5	5
3		10	7	6	6	4
	Avg.	11.3	6.6	6.6	5.6	4.3
VIM-2D-1		14	16	11	10	5
2		16	15	13	9	6
3		12	17	14	10	6
	Avg.	14.0	16.0	12.6	9.6	5.6
VIM-3D-1		15	14	16	12	6
2		15	10	15	9	7
3		15	15	13	11	6
	Avg.	15.0	13.0	14.6	10.6	6.3
VIR-1		18	16	15	14	8
2		17	15	12	14	7
3		17	16	15	12	8
	Avg.	17.3	15.6	14.0	13.3	7.6

*Transverse grain direction

TABLE 6

IMPACT TEST RESULTS*FOR V-NOTCH CHARPY SPECIMENS AT THE 200-220 KSI STRENGTH LEVEL

Material		Test Temp. 75°F (ft-lb)	Test Temp. 0°F (ft-lb)	Test Temp. -40°F (ft-lb)	Test Temp. -100°F (ft-lb)	Test Temp. -200°F (ft-lb)
AM-1		4	5	3	2	1
2		3	4	2	2	1
3		4	4	3	2	1
	Avg.	3.6	4.3	2.6	2.0	1.0
VAR-1		7	4	5	2	2
2		7	4	5	3	1
3		5	4	4	3	2
	Avg.	6.3	4.0	4.6	2.6	1.6
VIM-2D-1		14	10	10	7	5
2		16	14	8	9	5
3		15	12	9	9	6
	Avg.	15.0	12.0	9.0	8.3	5.3
VIM-3D-1		18	10	8	8	3
2		15	13	10	8	5
3		14	12	11	8	2
	Avg.	15.6	11.6	9.6	8.0	3.3
VIR-1		16	12	12	7	5
2		17	14	11	9	5
3		15	15	13	10	5
	Avg.	16.0	13.6	12.0	8.6	5.0

*Transverse grain direction

TABLE 7

COMPARISON OF TENSILE STRENGTH FOR PLATED AND UNPLATED NOTCHED TRANSVERSE TENSILE SPECIMENS

Cyanide Cadmium Plated (ksi)

	VIR (1E)	VIR (2E)	VIM (2D)	VIM (3D)	VAR (2A)	AM (1C)
	347	327	355	328	178	167.5
	345	312	338	311	161	122.5
	295	328	317	347	193	188.5
Avg.	329	322.3	336.7	328.7	177.3	159.5

Unplated (ksi)

	VIR (1E)	VIR (2E)	VIM (2D)	VIM (3D)	VAR (2A)	AM (1C)
	347	341	368	326	301	211
	345	316	316	326	273	244
	333	331	316	329	310	249
Avg.	341.7	329.3	333.3	327	294.7	234.7

TABLE 8

FATIGUE DATA FOR NOTCHED SPECIMENS OF AM (1C) 4340 STEEL AT THE HIGH AND LOW STRENGTH LEVELS

High Strength (260-280 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	50	85,000	Failed
2	45	60,000	Failed
3	40	204,000	Failed
4	35	158,000	Failed
5	30	186,000	Failed
6	20	20,000,000	No Failure
7	25	1,203,000	Failed
8	23	-----	Broke on Loading
9	23	373,000	Failed
6A*	80	16,000	Failed

Low Strength (200-220 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	80	15,000	Failed
2	50	73,000	Failed
3	40	139,000	Failed
4	30	378,000	Failed
5	25	1,218,000	Failed
6	23	739,000	Failed
7	21	1,333,000	Failed
8	19	2,218,000	Failed
9	17	18,439,000	Failed
10	16	1,518,000	Failed

*Rerun at higher stress for specimen that did not fail below 20 million cycles.

TABLE 9

FATIGUE DATA FOR SMOOTH SPECIMENS OF AM (1C) 4340 STEEL AT THE HIGH AND LOW STRENGTH LEVELS

High Strength (260-280 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	100	156,000	Failed
2	95	2,951,000	Failed
3	93	95,000	Failed
4	90	7,097,000	Failed
5	88	1,669,000	Failed
6	85	148,000	Failed
7	80	3,095,000	Failed
8	75	20,000,000	No Failure
9	78	20,000,000	No Failure
10	79	8,686,000	Failed
8A*	120	60,000	Failed
9A*	140	20,000	Failed

Low Strength (200-220 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	110	49,000	Failed
2	100	49,000	Failed
3	90	131,000	Failed
4	80	81,000	Failed
5	70	1,732,000	Failed
6	68	20,000,000	No Failure
7	69	20,000,000	No Failure
8	75	20,000,000	No Failure
9	75	7,367,000	Failed
7A*	120	19,000	Failed

*Rerun at higher stress for specimen that did not fail below 20 million cycles.

TABLE 10

FATIGUE DATA FOR NOTCHED SPECIMENS OF VAR (2A) 4340 STEEL AT THE HIGH AND LOW STRENGTH LEVELS

High Strength (260-280 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	40	97,000	Failed
2	30	271,000	Failed
3	25	347,000	Failed
4	23	575,000	Failed
5	20	664,000	Failed
6	17	20,000,000	No Failure
7	18	872,000	Failed
8	60	30,000	Failed
6A*	50	66,000	Failed

Low Strength (200-220 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	80	18,000	Failed
2	17	4,470,000	Failed
3	15	5,945,000	Failed
4	15	2,719,000	Failed
5	13	30,749,000	Nc Failure
6	14	2,622,000	Failed
7	50	46,000	Failed
8	40	93,000	Failed
9	30	263,000	Failed
10	20	579,000	Failed

*Rerun at higher stress for specimens that did not fail below 20 million cycles.

TABLE 11

FATIGUE DATA FOR SMOOTH SPECIMENS OF VAR (2A) 4340 STEEL AT THE HIGH AND LOW STRENGTH LEVELS

High Strength (260-280 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	100	1,435,000	Failed
2	95	1,814,000	Failed
3	92	628,000	Broke in Shoulder
4	90	25,000	Broke in Shoulder
5	90	704,000	Failed
6	85	20,000,000	No Failure
7	88	2,057,000	Failed
8	86	20,000,000	No Failure
9	110	269,000	Failed
6A*	150	16,000	Failed
8A*	130	24,000	Failed

Low Strength (200-220 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	110	26,000	Failed
2	75	514,000	Failed
3	70	21,356,000	Failed
4	72	2,503,000	Failed
5	71	537,000	Failed
6	120	23,000	Failed
7	100	64,000	Failed
8	90	171,000	Failed
9	80	144,000	Failed
10	71	320,000	Failed

*Rerun at higher stress for specimens that did not fail below 20 million cycles.

TABLE 12

FATIGUE DATA FOR NOTCHED SPECIMENS OF VIM (2D) 4340
STEEL AT THE HIGH AND LOW STRENGTH LEVELS

High Strength (260-280) ksi

Specimen	Stress (ksi)	Cycles	Remarks
1	100	7,000	Failed
2	40	742,000	Broke Outside Notch
3	35	2,038,000	Broke Outside Notch
4	30	1,453,000	Broke Outside Notch
5	25	1,598,000	Broke Outside Notch
6	35	2,183,000	Broke Outside Notch
7	35	195,000	Failed
8	30	1,222,000	Broke Outside Notch
9	25	600,000	Failed

Low Strength (200-220 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	20	20,000,000	No Failure
2	30	430,000	Failed
3	25	20,000,000	No Failure
4	28	20,000,000	No Failure
5	29	1,235,000	Failed
6	70	23,000	Failed
7	35	270,000	Failed
8	40	142,000	Failed
1A*	80	18,000	Failed
3A*	60	36,000	Failed
4A*	50	95,000	Failed

*Rerun at higher stress for specimens that did not fail below 20 million cycles.

TABLE 13

FATIGUE DATA FOR SMOOTH SPECIMENS OF VIM (2D) 4340 STEEL AT THE HIGH AND LOW STRENGTH LEVELS

High Strength (260-280 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	100	684,000	Failed
2	95	324,000	Failed
3	90	10,485,000	Failed
4	88	1,745,000	Failed
5	85	5,872,000	Failed
6	82	20,000,000	No Failure
7	83	2,586,000	Failed
8	110	239,000	Failed
9	130	26,000	Failed
6A*	150	19,000	Failed

Low Strength (200-220 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	80	7,570,000	Failed
2	78	20,000,000	No Failure
3	79	579,000	Failed
4	120	58,000	Failed
5	110	48,000	Failed
6	100	120,000	Failed
7	90	2,236,000	Failed
8	85	369,000	Failed
9	90	429,000	Failed
10	95	936,000	Failed

*Rerun at higher stress for specimens that did not fail below 20 million cycles.

TABLE 14

FATIGUE DATA FOR NOTCHED SPECIMENS OF VIM (3D) 4340 STEEL AT THE HIGH AND LOW STRENGTH LEVELS

High Strength (260-280 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	40	242,000	Failed
2	38	246,000	Failed
3	35	288,000	Failed
4	30	302,000	Failed
5	25	20,000,000	No Failure
6	27	388,000	Failed
7	26	12,872,000	Failed
8	60	43,000	Failed
5A*	80	15,000	Failed

Low Strength (200-220 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	40	215,000	Failed
2	30	337,000	Failed
3	25	20,000,000	No Failure
4	27	20,000,000	No Failure
5	28	20,000,000	No Failure
6	29	543,000	Failed
7	50	60,000	Failed
8	35	152,000	Failed
3A*	80	16,000	Failed
4A*	70	24,000	Failed
5A*	60	38,000	Failed

*Rerun at higher stress for specimens that did not fail below 20 million cycles.

TABLE 15

FATIGUE DATA FOR SMOOTH SPECIMENS OF VIM (3D) 4340 STEEL AT THE HIGH AND LOW STRENGTH LEVELS

High Strength (260-280 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	100	66,000	Failed
2	90	65,000	Failed
3	90	150,000	Failed
4	85	79,000	Failed
5	80	21,997,000	Failed
6	82	34,000	Failed
7	83	942,000	Failed
8	120	175,000	Failed

Low Strength (200-220 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	80	83,000	Failed
2	66	456,000	Failed
3	70	162,000	Failed
4	62	31,233,000	No Failure
5	63	453,000	Failed
6	100	32,000	Failed
7	90	132,000	Failed
8	85	142,000	Failed
4A*	110	55,000	Failed

*Rerun at higher stress for specimens that did not fail below 20 million cycles.

TABLE 16

FATIGUE DATA FOR NOTCHED SPECIMENS OF VIR (2E) 4340 STEEL AT THE HIGH AND LOW STRENGTH LEVELS

High Strength (260-280 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	80	14,000	Failed
2	40	172,000	Failed
3	30	13,241,000	Failed
4	27	4,101,000	Broke in Shoulder
5	27	3,976,000	Broke in Shoulder
6	25	20,000,000	No Failure
7	27	20,000,000	No Failure
8	28	20,000,000	No Failure
9	35	2,050,000	Broke in Shoulder
6A*	50	87,000	Failed
7A*	60	59,000	Failed
8A*	70	26,000	Failed

Low Strength (200-220 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	40	183,000	Failed
2	30	20.000,000	No Failure
3	35	20,000,000	No Failure
4	38	948,000	Failed
5	37	20,000,000	No Failure
6	50	64,000	Failed
7	60	37,000	Failed
8	45	129,000	Failed
9	70	21,000	Failed
2A*	80	17,000	Failed
3A*	70	22,000	Failed

*Rerun at higher stress for specimen that did not fail below 20 million cycles.

TABLE 17

FATIGUE DATA FOR SMOOTH SPECIMENS OF VIR (2E) 4340 STEEL AT THE HIGH AND LOW STRENGTH LEVELS

High Strength (260-280 ksi)

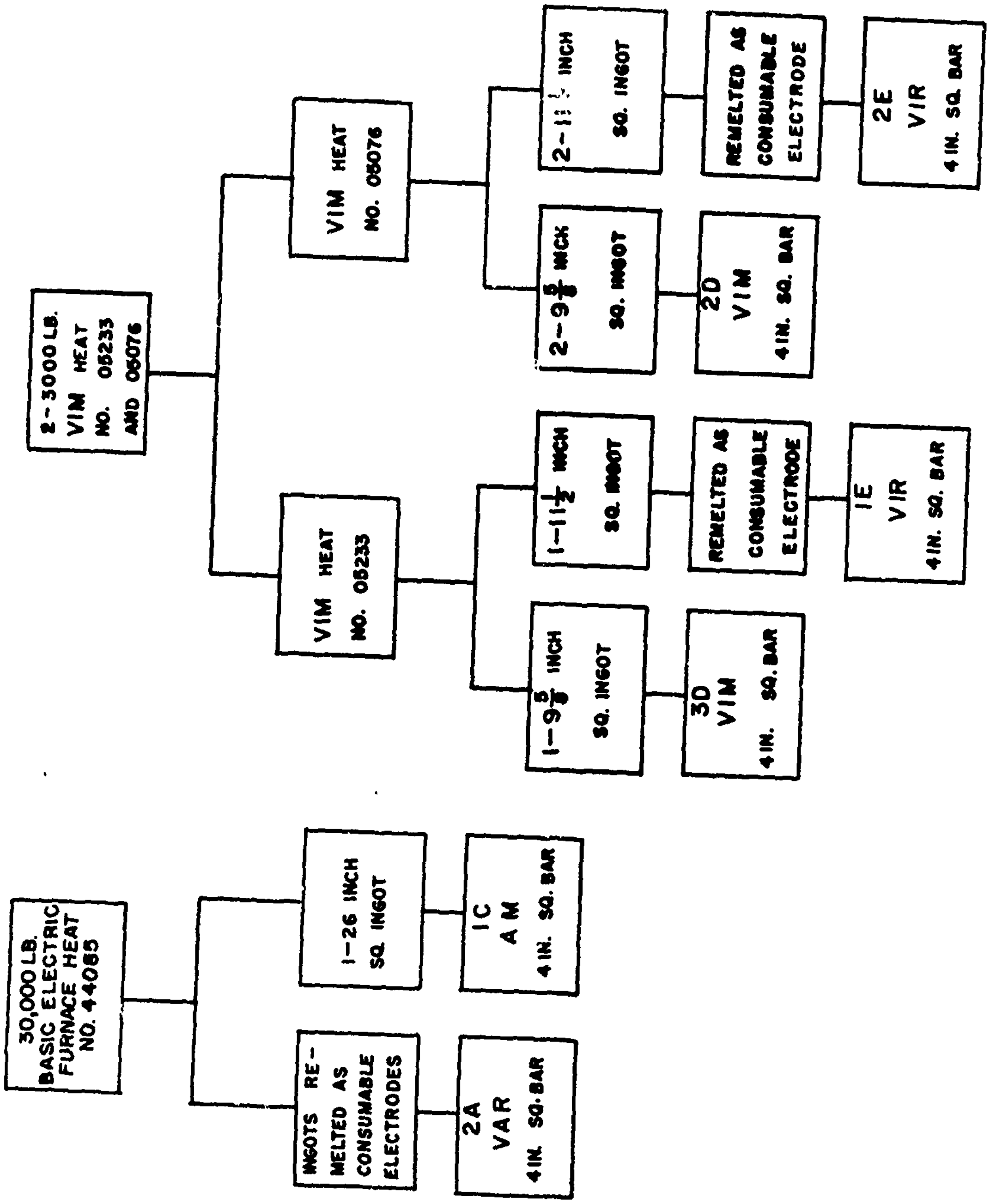
Specimen	Stress (ksi)	Cycles	Remarks
1	100	20,000,000	No Failure
2	110	20,000,000	No Failure
3	120	5,998,000	Failed
4	115	9,196,000	Failed
5	113	20,000,000	No Failure
6	140	273,000	Failed
7	130	1,931,000	Failed
8	114	1,018,000	Failed
9	125	1,180,000	Failed
10	114	11,346,000	Failed
1A*	150	59,000	Failed
2A*	160	56,000	Failed
5A*	160	35,000	Failed

Low Strength (200-220 ksi)

Specimen	Stress (ksi)	Cycles	Remarks
1	100	569,000	Failed
2	95	20,000,000	No Failure
3	98	32,766,000	Failed
4	99	4,894,000	Failed
5	110	325,000	Failed
6	120	125,000	Failed
7	130	58,000	Failed
8	140	33,000	Failed
9	105	680,000	Failed
2A*	160	----	Specimen Overheated but did not break

*Rerun at higher stress for specimen that did not fail below 20 million cycles.

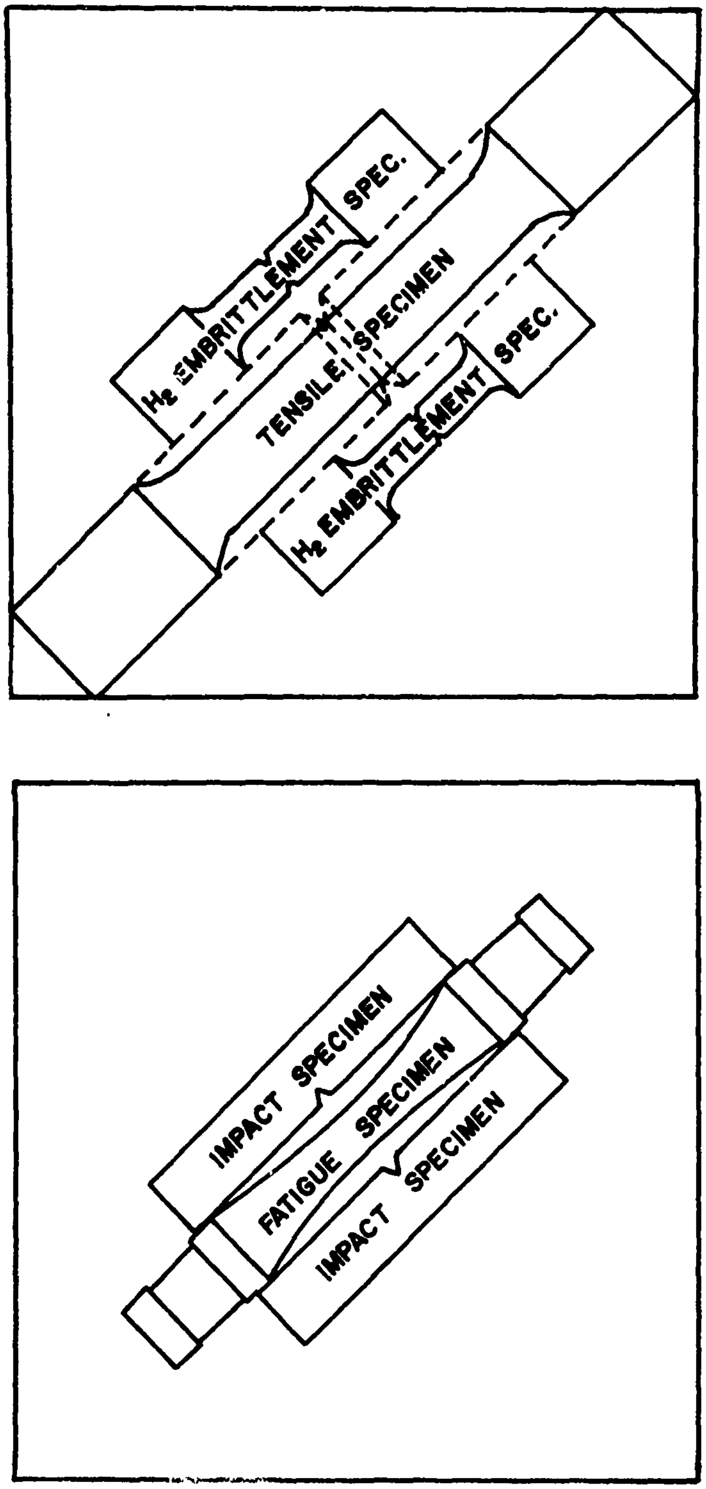
TABLE 18



HEAT FLOW CHART

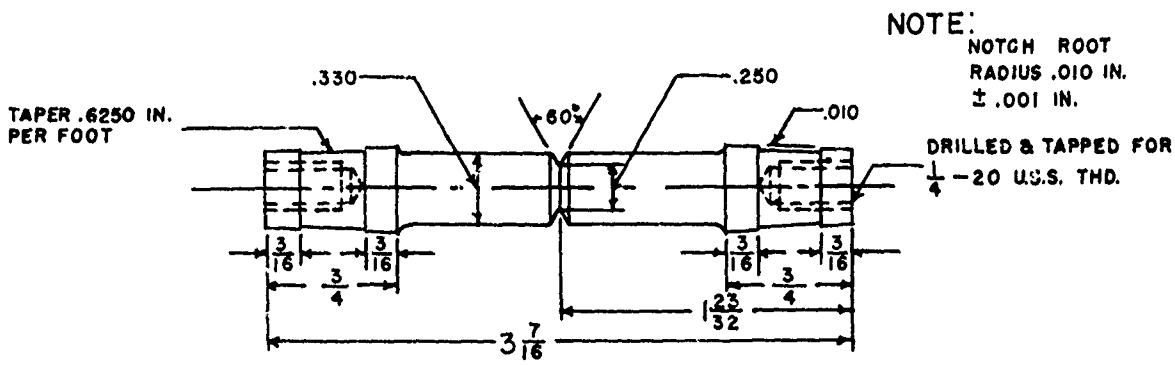
PHOTO NO: CAN-360677(L)-5-64

PLATE NO. 1

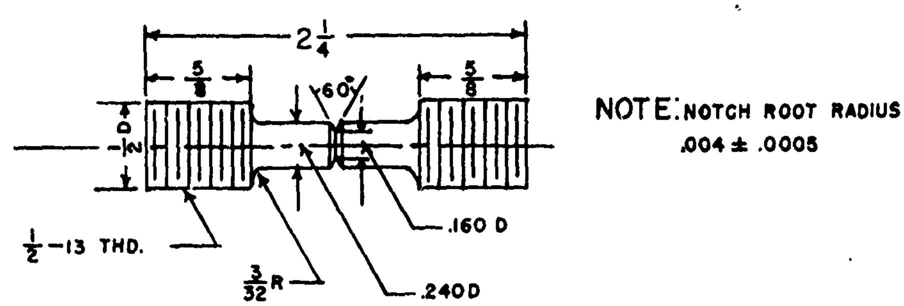


LOCATION OF TRANSVERSE TEST SPECIMENS REMOVED FROM 4 IN. SQ. BILLETS OF AIR AND VACUUM MELTED 4340 STEEL

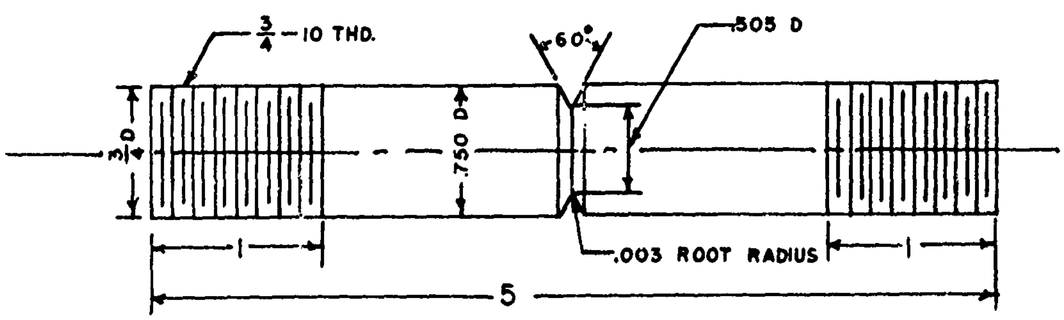
PHOTO NO: CAN-360678(L)-5-64



NOTCHED FATIGUE SPECIMEN

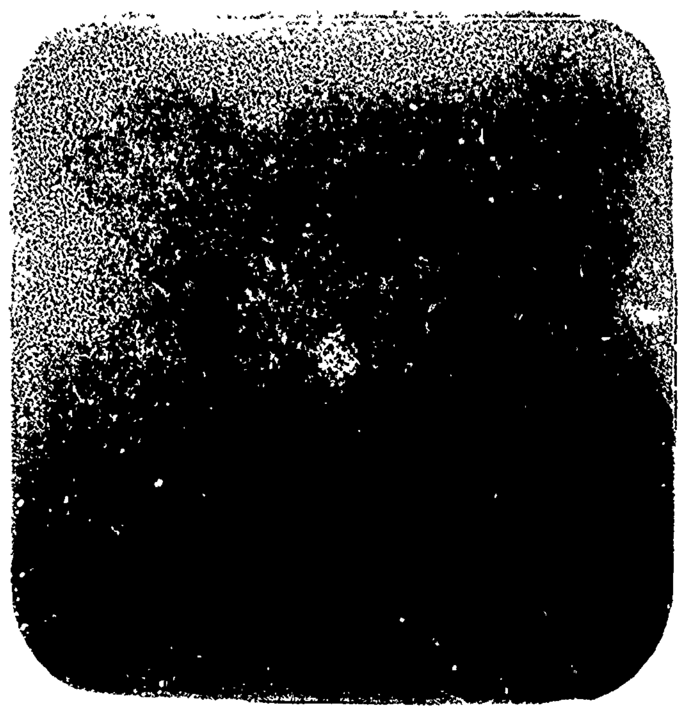


HYDROGEN EMBRITTLEMENT NOTCHED TENSILE SPECIMEN



NOTCHED TENSILE SPECIMEN

NOTCHED TENSILE AND FATIGUE SPECIMENS USED FOR TESTS

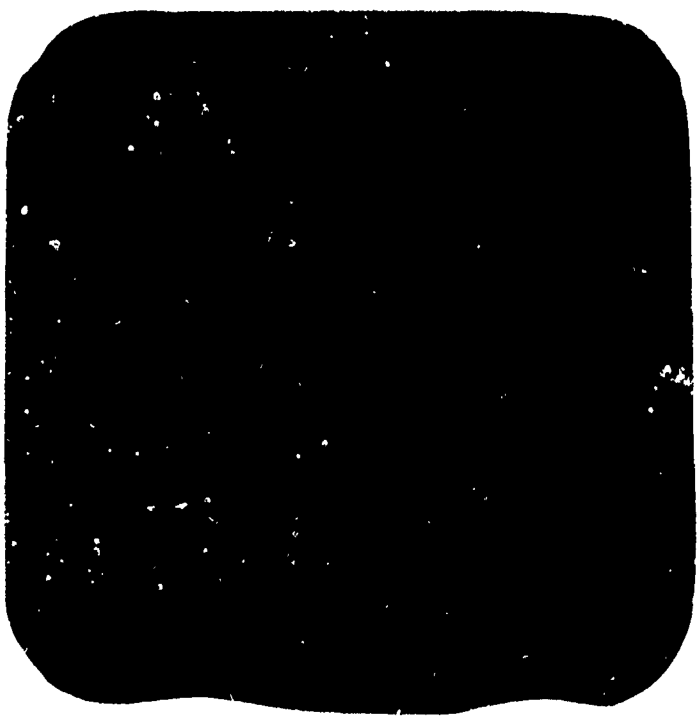


MAGNIFICATION: 1X

TOP

1. ETCHED 45 MIN.
1:1 HCL AT 160° F

2. CLEANED 2% NITAL

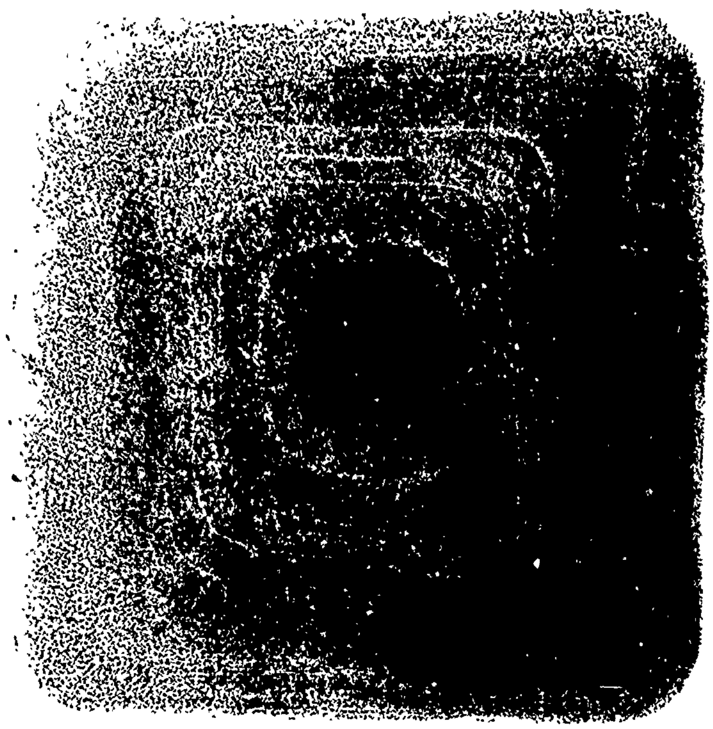


BOTTOM

MACROETCHED TOP AND BOTTOM BILL[illegible] SECTIONS
OF AM(IC) 4340 STEEL

PHOTO NO: CAN-360680(L)-5-64

PLATE NO. 4

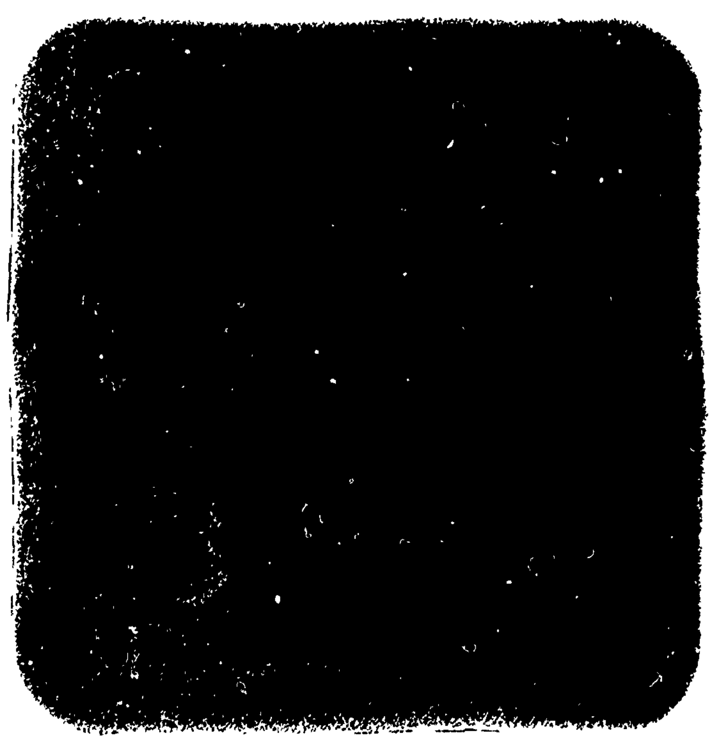


MAGNIFICATION: 1X

TOP

1. ETCHED 45 MIN.
1:1 HCL AT 160°F

2. CLEANED 2% NITAL



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BOTTOM

MACROETCHED TOP AND BOTTOM BILLET SECTIONS OF VAR(2A) 4340 STEEL

PHOTO NO: CAN-360681(L)-5-64

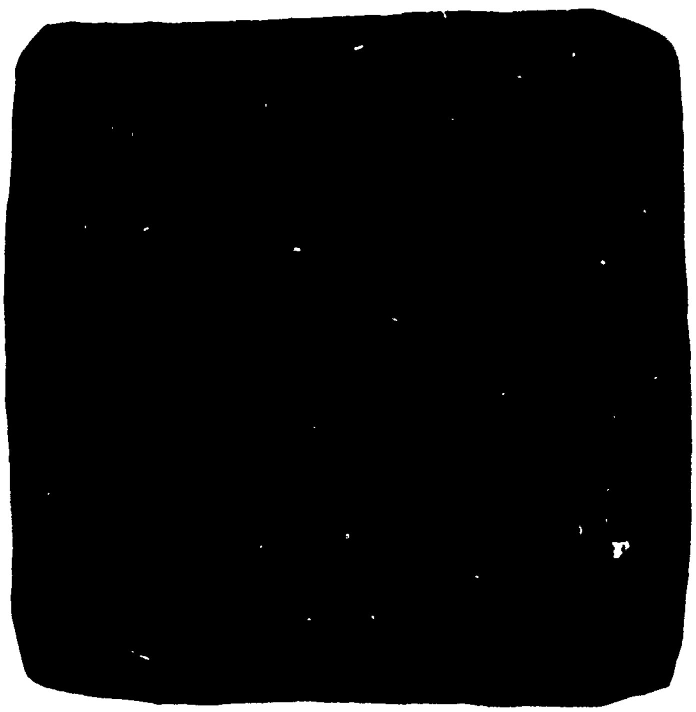
PLATE NO. 5

TOP

1. ETCHED 45 MIN.
1:1 HCL AT 160° F

MAGNIFICATION: 1X

2. CLEANED 2% NITAL

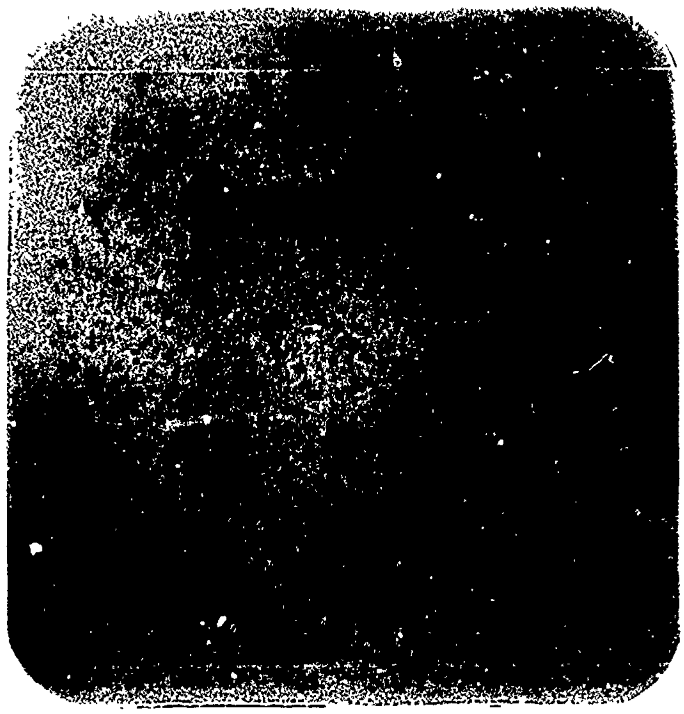


BOTTOM

MACROETCHED TOP AND BOTTOM BILLET SECTIONS
OF VIM (2D) 4340 STEEL

PHOTO NO: CAN-360682(L)-5-64

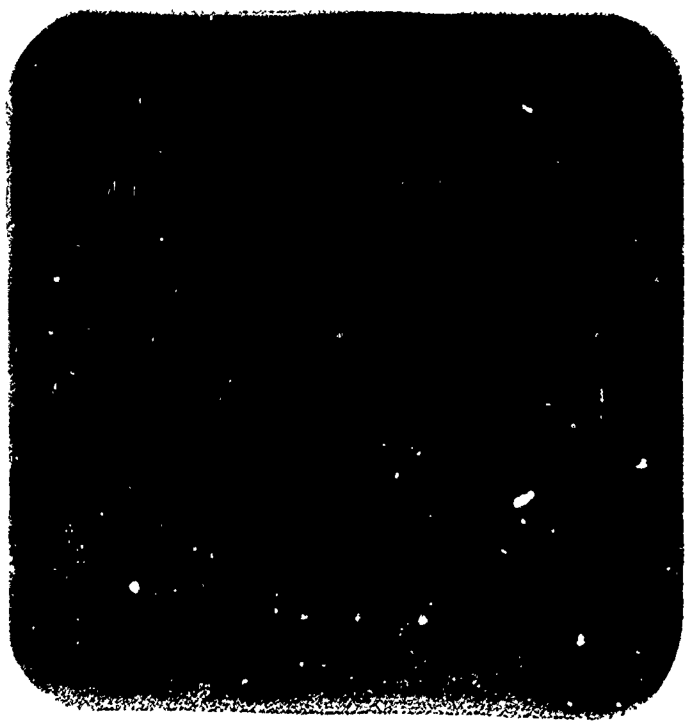
PLATE NO. 6



TOP

MAGNIFICATION: 1X

1. ETCHED 45 MIN.
1:1 HCL AT 160° F
2. CLEANED 2% NITAL



BOTTOM

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MACROETCHED TOP AND BOTTOM BILLET SECTIONS OF VIM(3D) 4340 STEEL

PHOTO NO: CAN-360683(L)-5-64

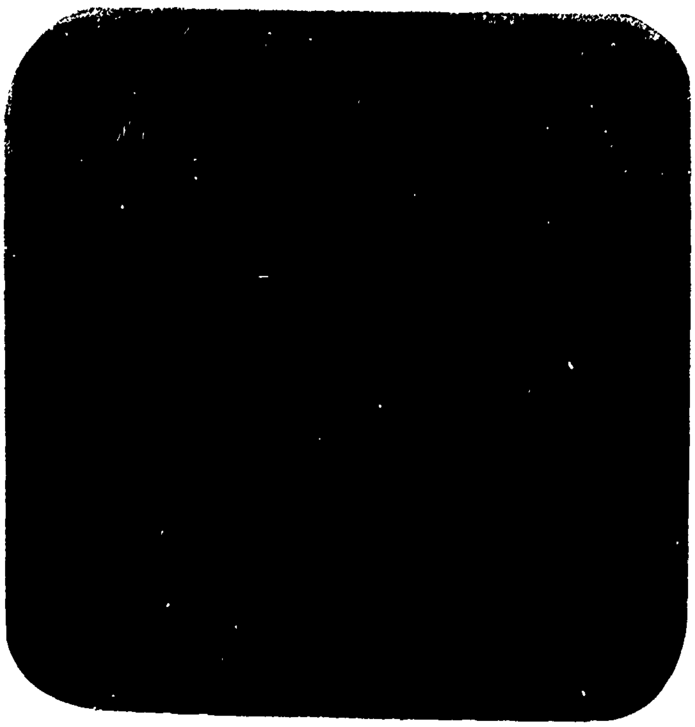
PLATE NO. 7

MAGNIFICATION: 1X

TOP

1. ETCHED 45 MIN. 1:1 HCL AT 160° F

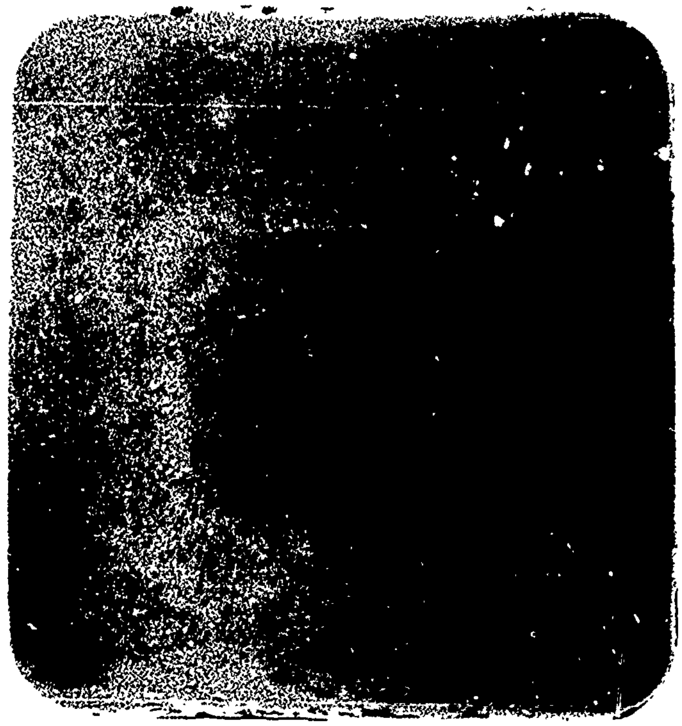
2. CLEANED 2% NITAL



BOTTOM

MACROETCHED TOP AND BOTTOM BILLET SECTIONS OF VIR(1E) 4340 STEEL

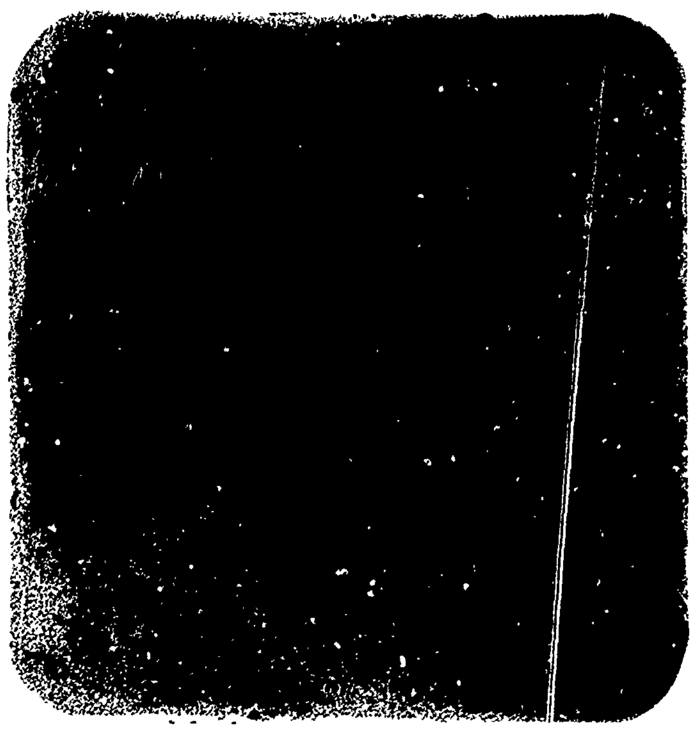
O NO: CAN-360684(L)-5-64



MAGNIFICATION: 1X

TOP

1. ETCHED 45 MIN.
   1:1 HCL AT 160° F
2. CLEANED 2% NITAL



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BOTTOM

MACROETCHED TOP AND BOTTOM BILLET SECTIONS OF VIR(2E) 4340 STEEL

PHOTO NO: CAN-360685(L)-5-64

PLATE NO. 9

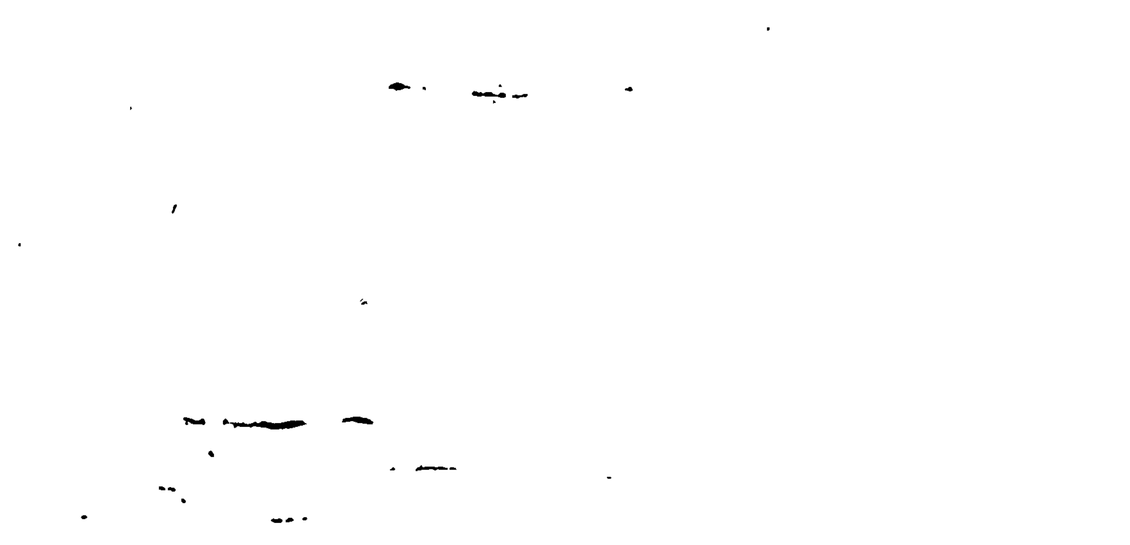

FIG. 1 MAT'L: AM

UNETCHED — MAG. 100X

FIG. 2 MAT'L: VAR

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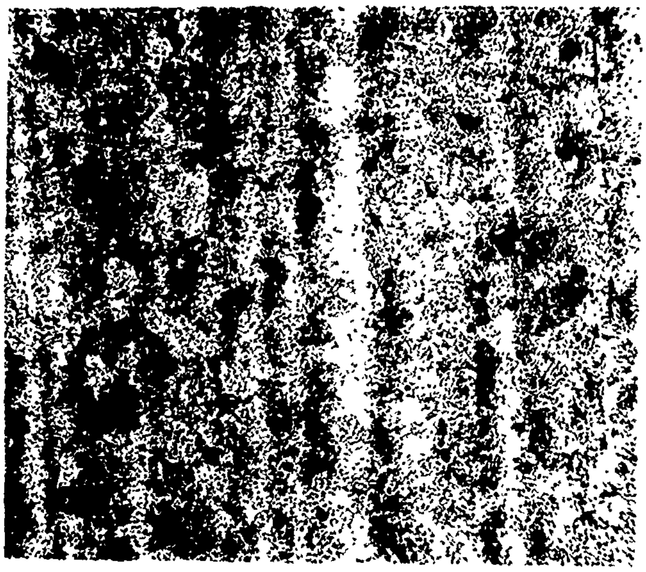
TYPICAL INCLUSION TYPE STRINGERS PRESENT IN AM AND VAR MATERIAL

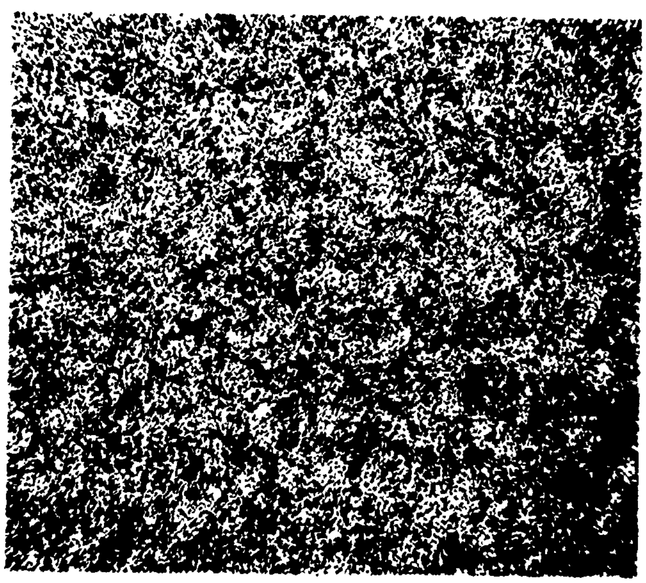
PHOTO NO: CAN-360686(L)-5-64



BANDING - TYPICAL OF AM, VAR, AND VIM MATERIAL

FIG. 1

ETCH: 2% NITAL MAG. 75X



UNBANDED VIR MATERIAL

FIG. 2

MICROSTRUCTURES TYPICAL OF AM, VAR, VIM AND VIR MATERIALS

PHOTO NO: CAN-360687(L)-5-64

PLATE NO. 11

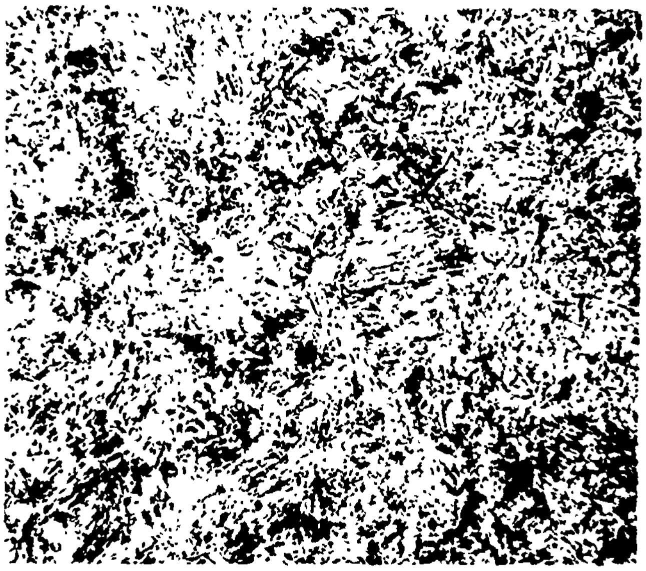


FIG. I TEMPERED 400 °F

ETCHED: 2% NITAL MAG. 250X

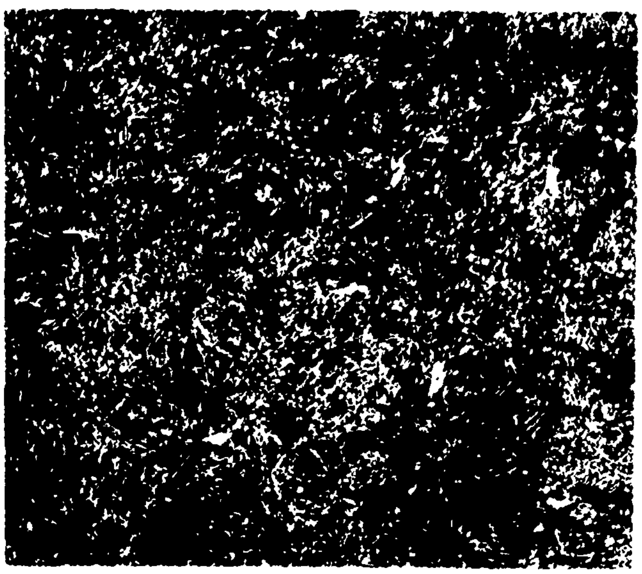
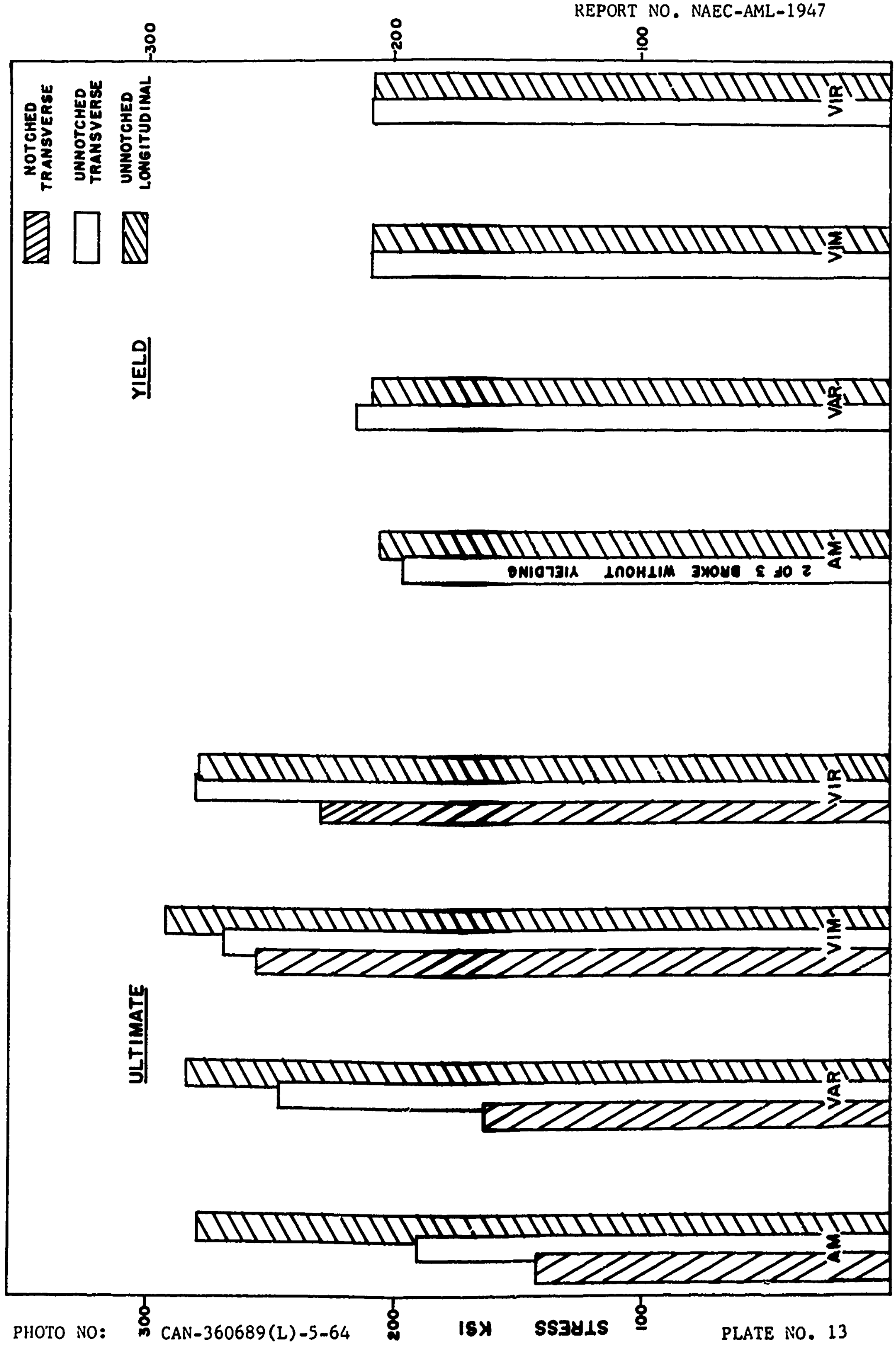


FIG. 2 TEMPERED 775° F

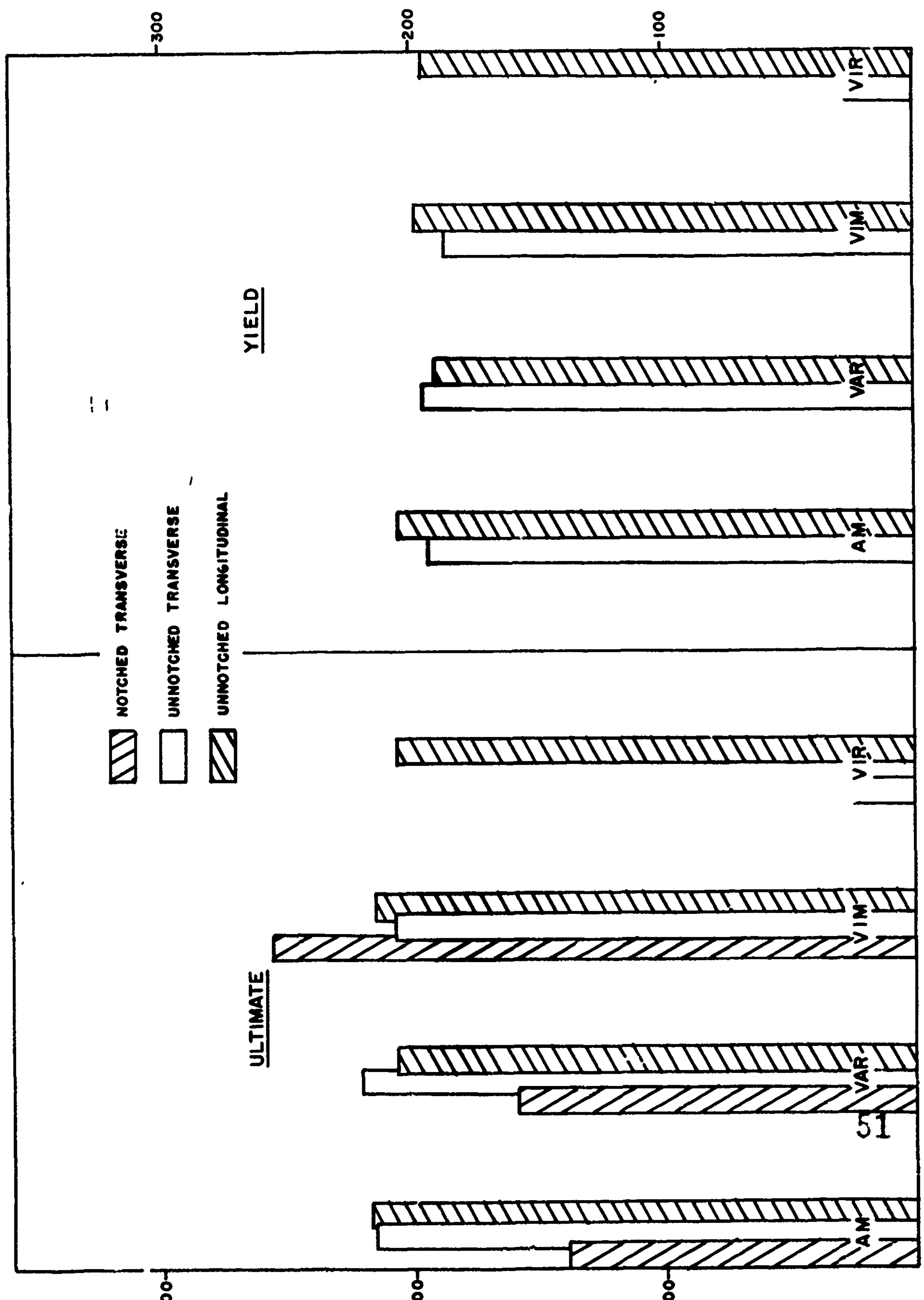
TYPICAL MICROSTRUCTURES OF MATERIALS HEAT TREATED TO THE 260-280 KSI AND 200-220 KSI STRENGTH RANGES

PHOTO NO: CAN-360688(L)-5-64



TENSILE STRENGTH OF VACUUM AND AIR MELTED 4340 STEEL HEAT TREATED TO 260-280 KSI

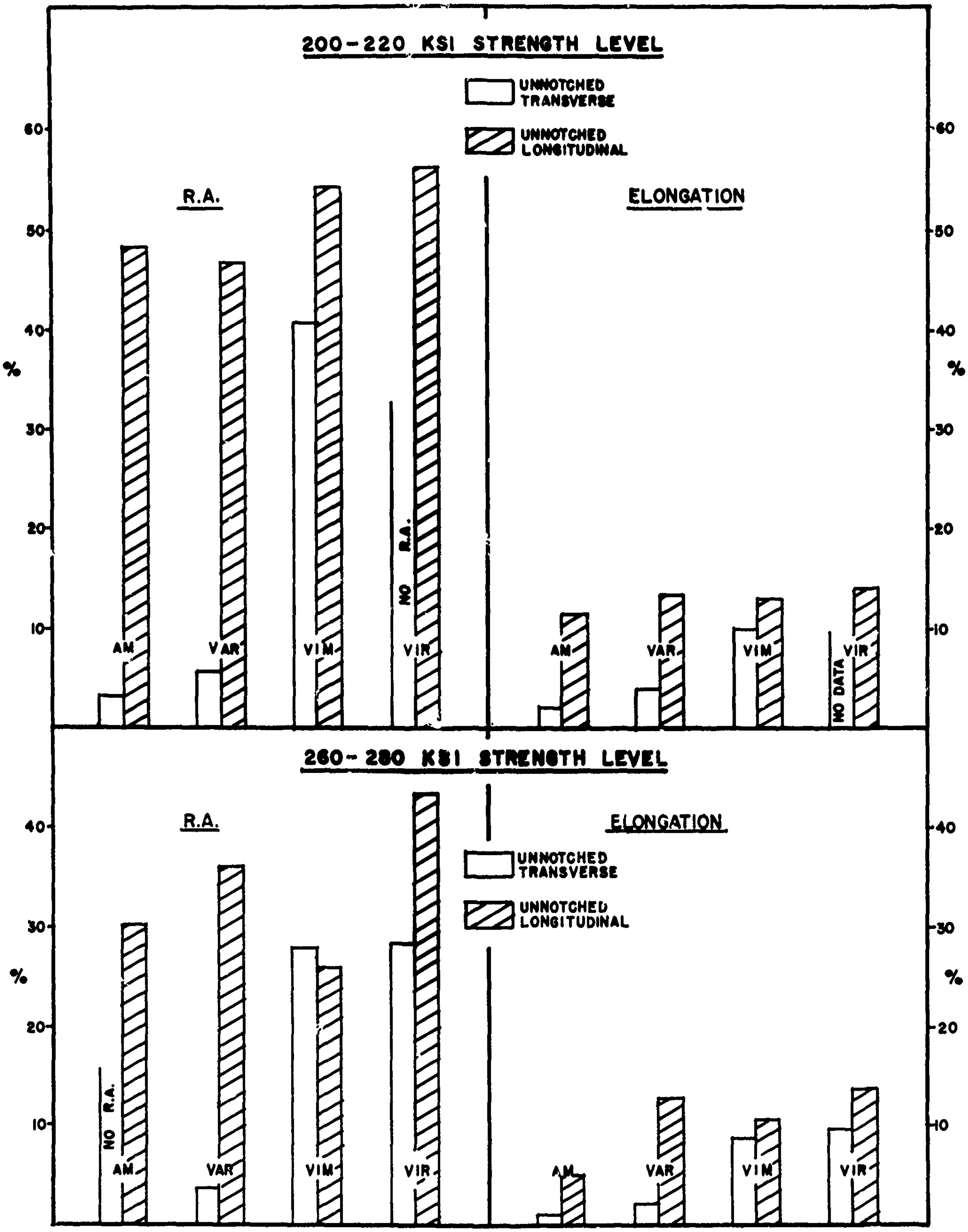
PHOTO NO: CAN-360689(L)-5-64



TENSILE STRENGTH OF VACUUM AND AIR MELTED 4340 STEEL HEAT TREATED TO 200-220 KSI

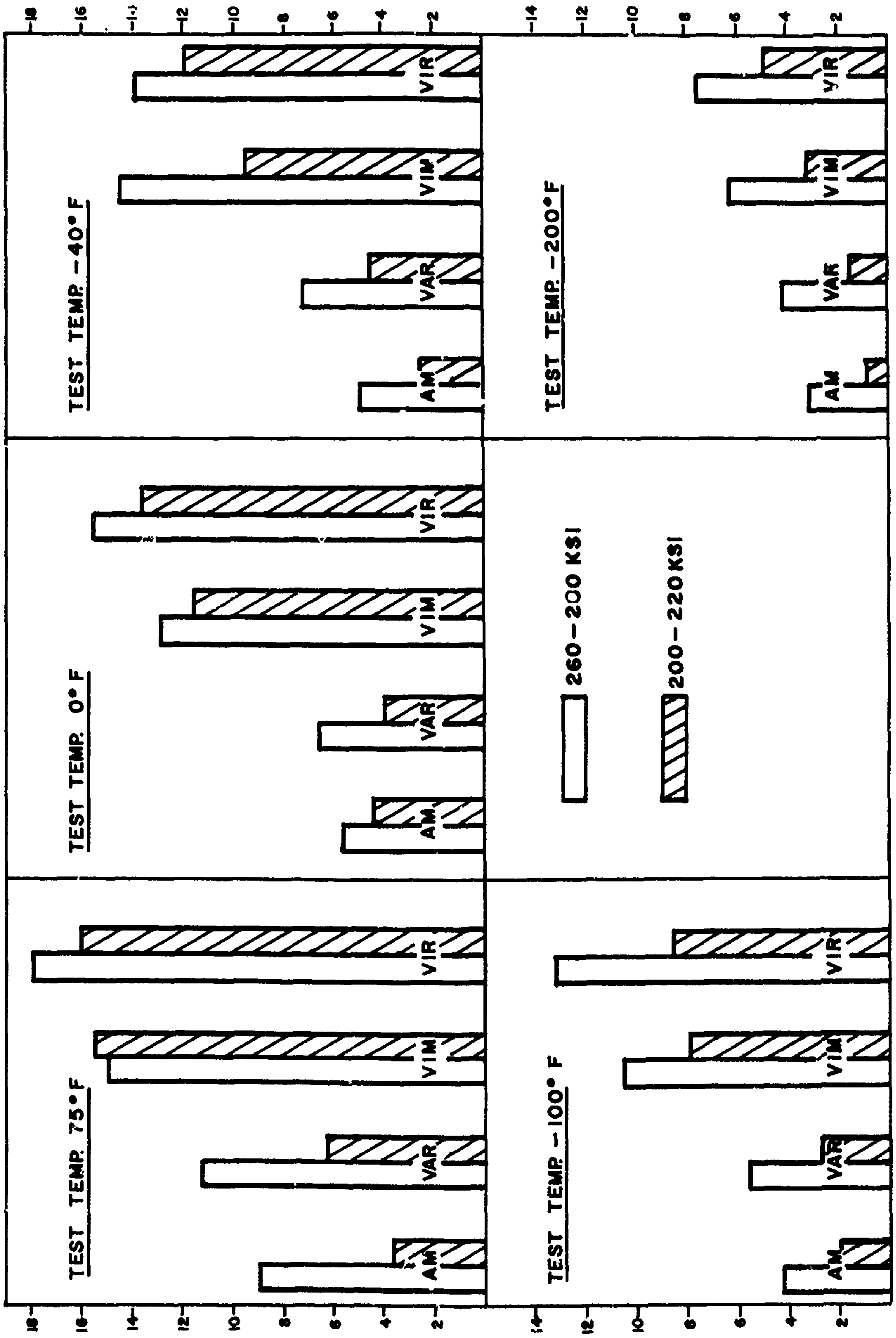
PHOTO NO: CAN-360690(L)-5-64

PLATE NO. 14



R.A. AND ELONGATION VALUES FOR AIR AND VACUUM MELTED 4340 STEEL

PHOTO NO: CAN-360691(L)-5-64 PLATE NO. 15



RESULTS OF V-NOTCH CHARPY IMPACT TESTS IN THE TRANSVERSE GRAIN DIRECTION

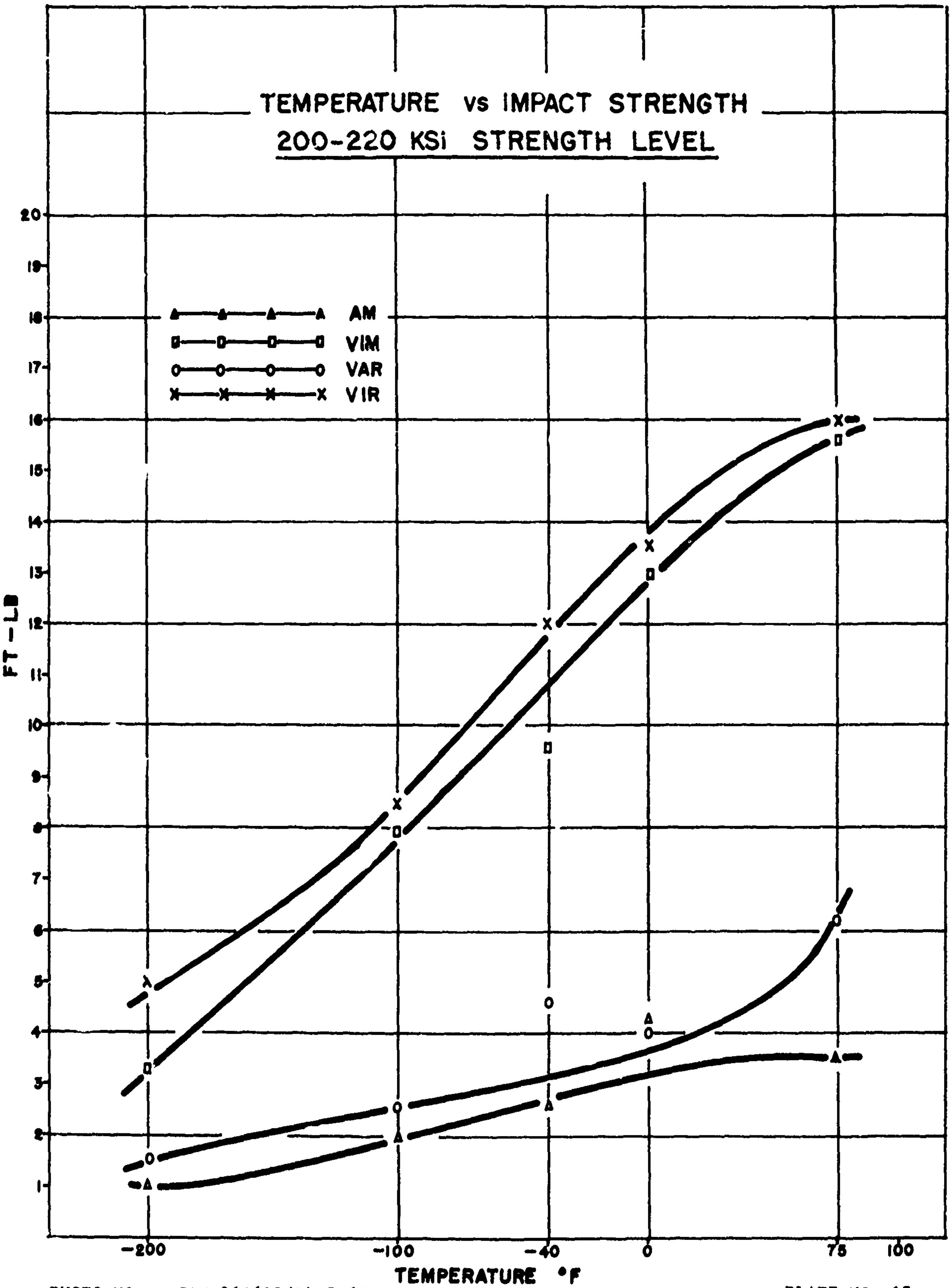


PHOTO NO: CAN-360693(L)-5-64

PLATE NO. 17

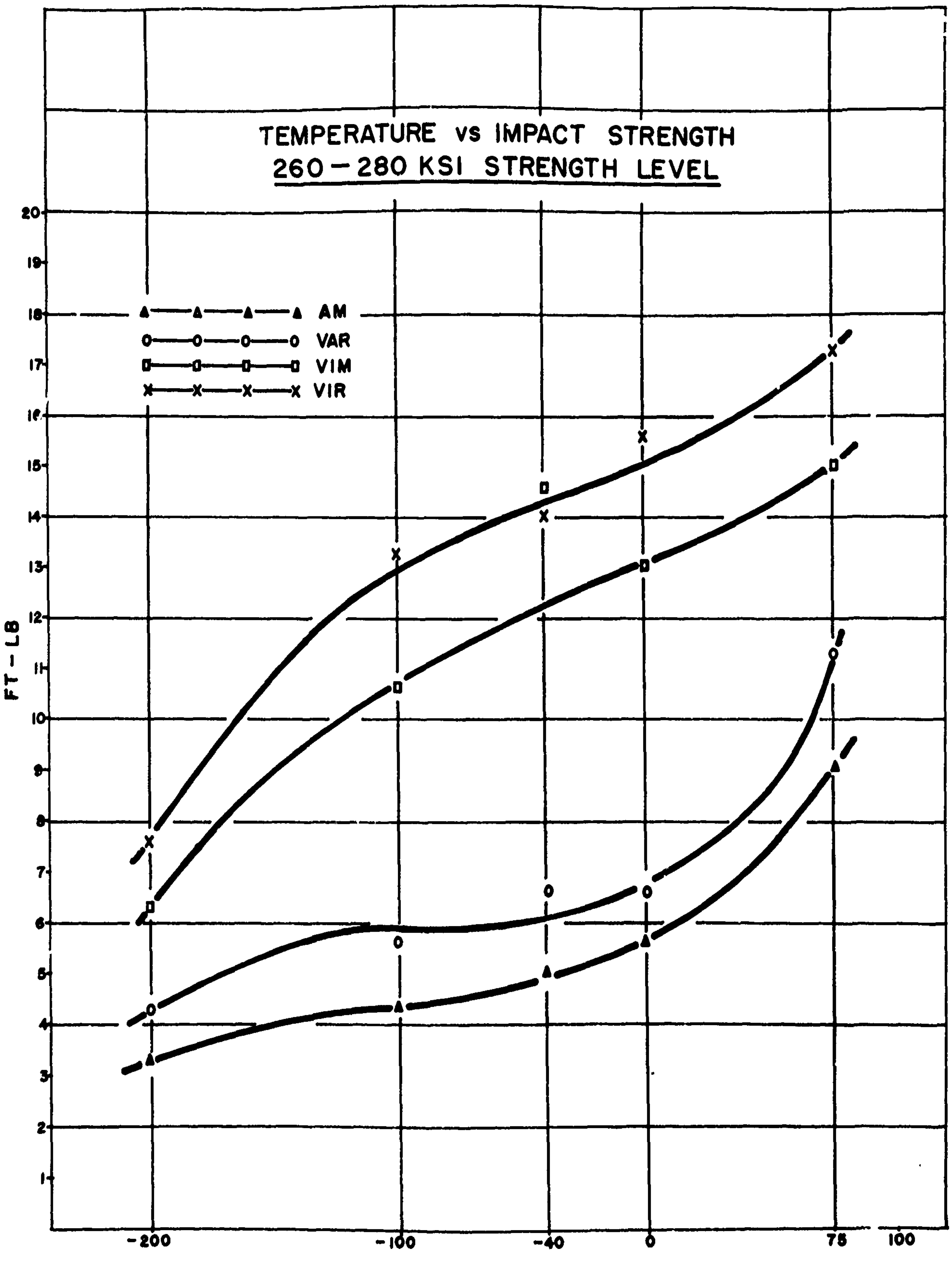
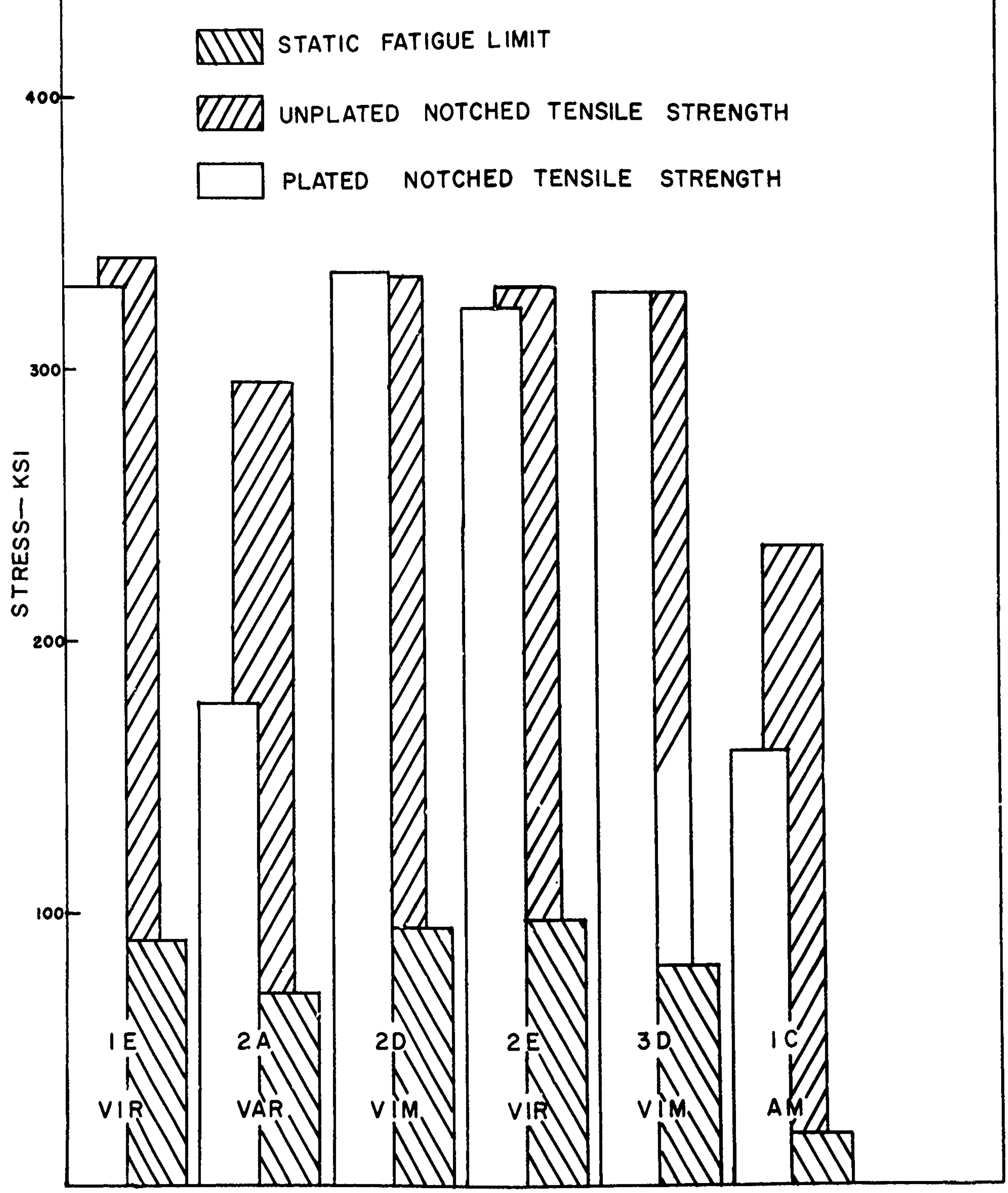


PHOTO NO: CAN-360694(L)-5-64

PLATE NO. 18

RESULTS OF STATIC FATIGUE, UNPLATED AND PLATED NOTCHED TENSILE STRENGTH TESTS



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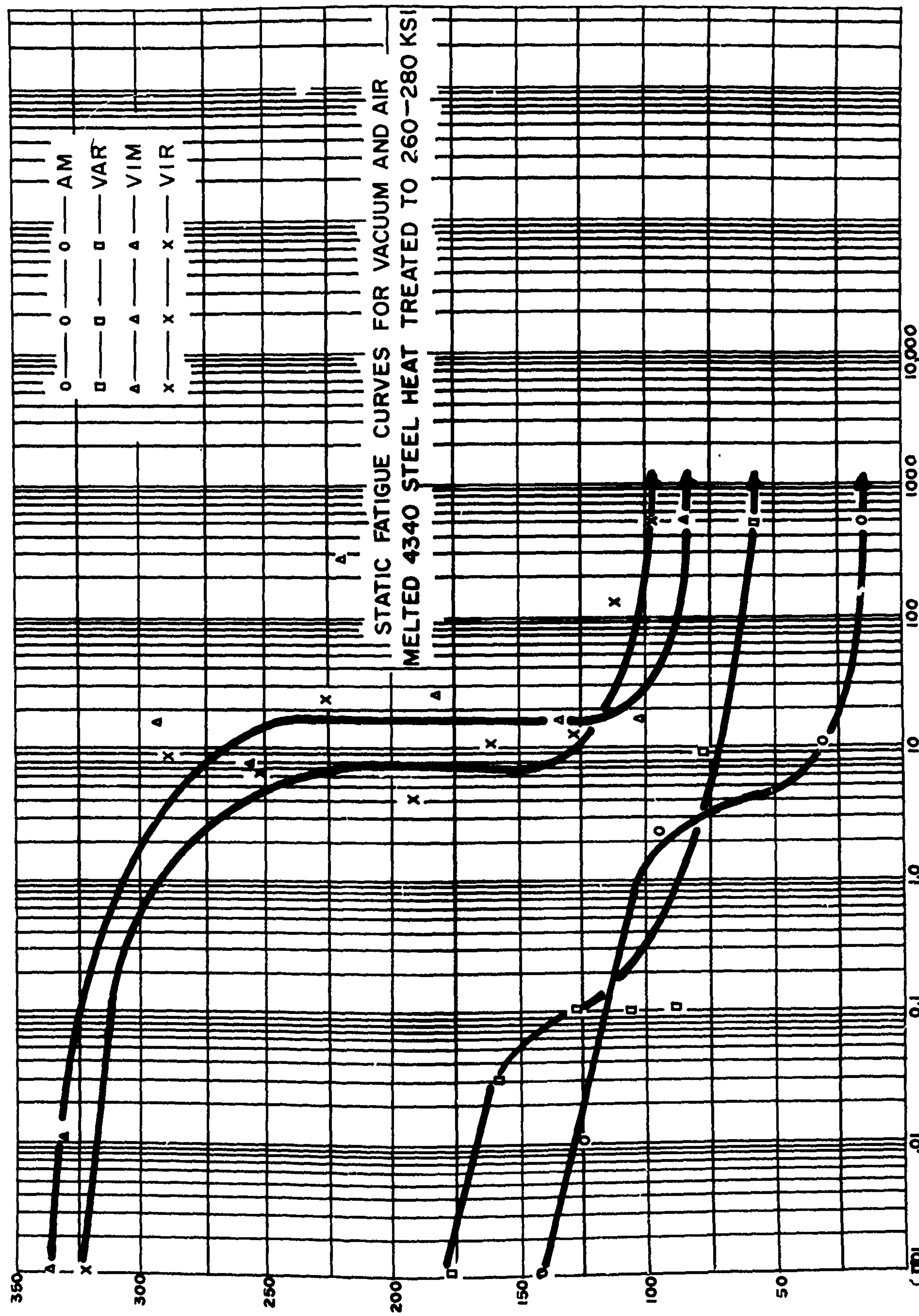
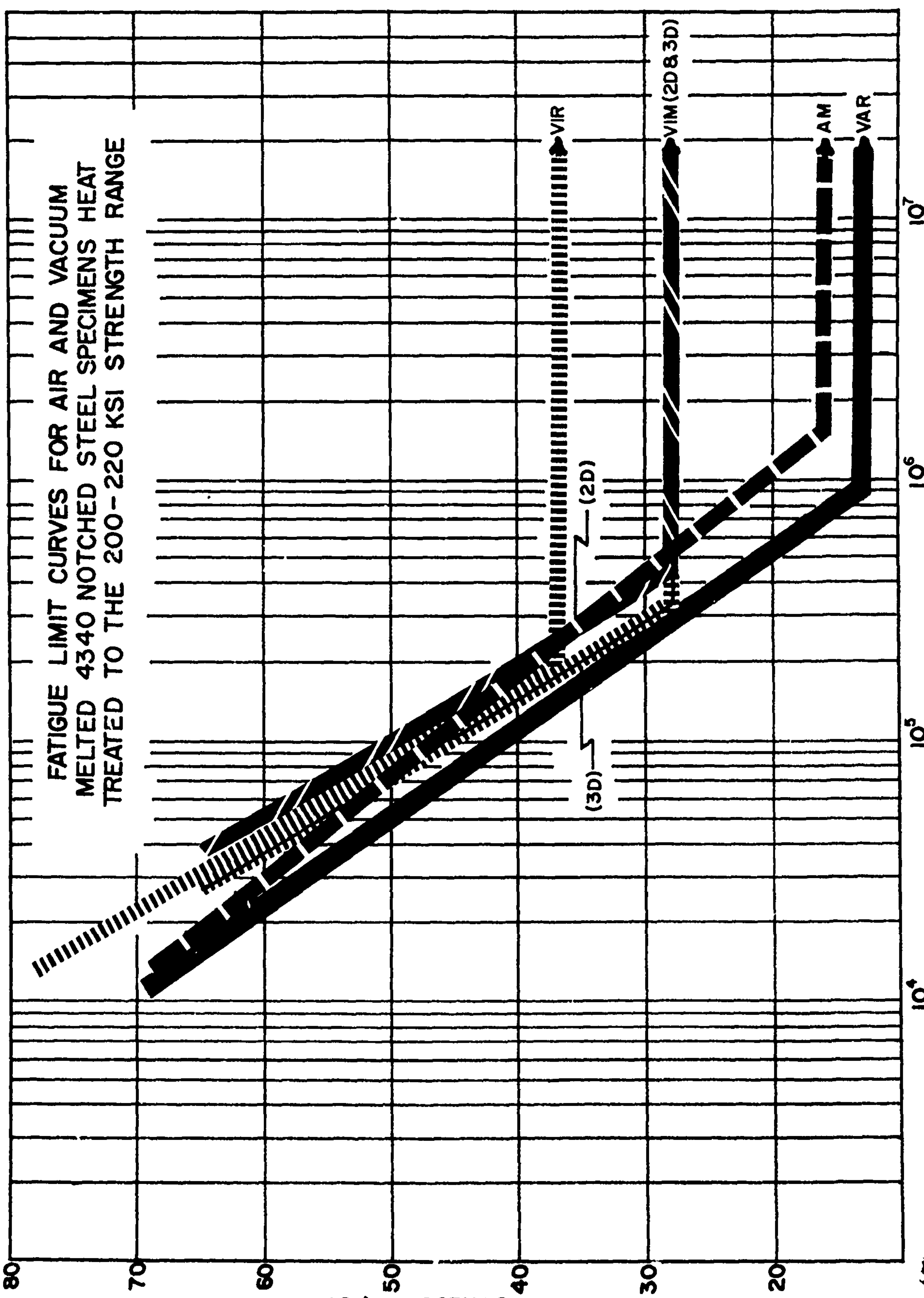
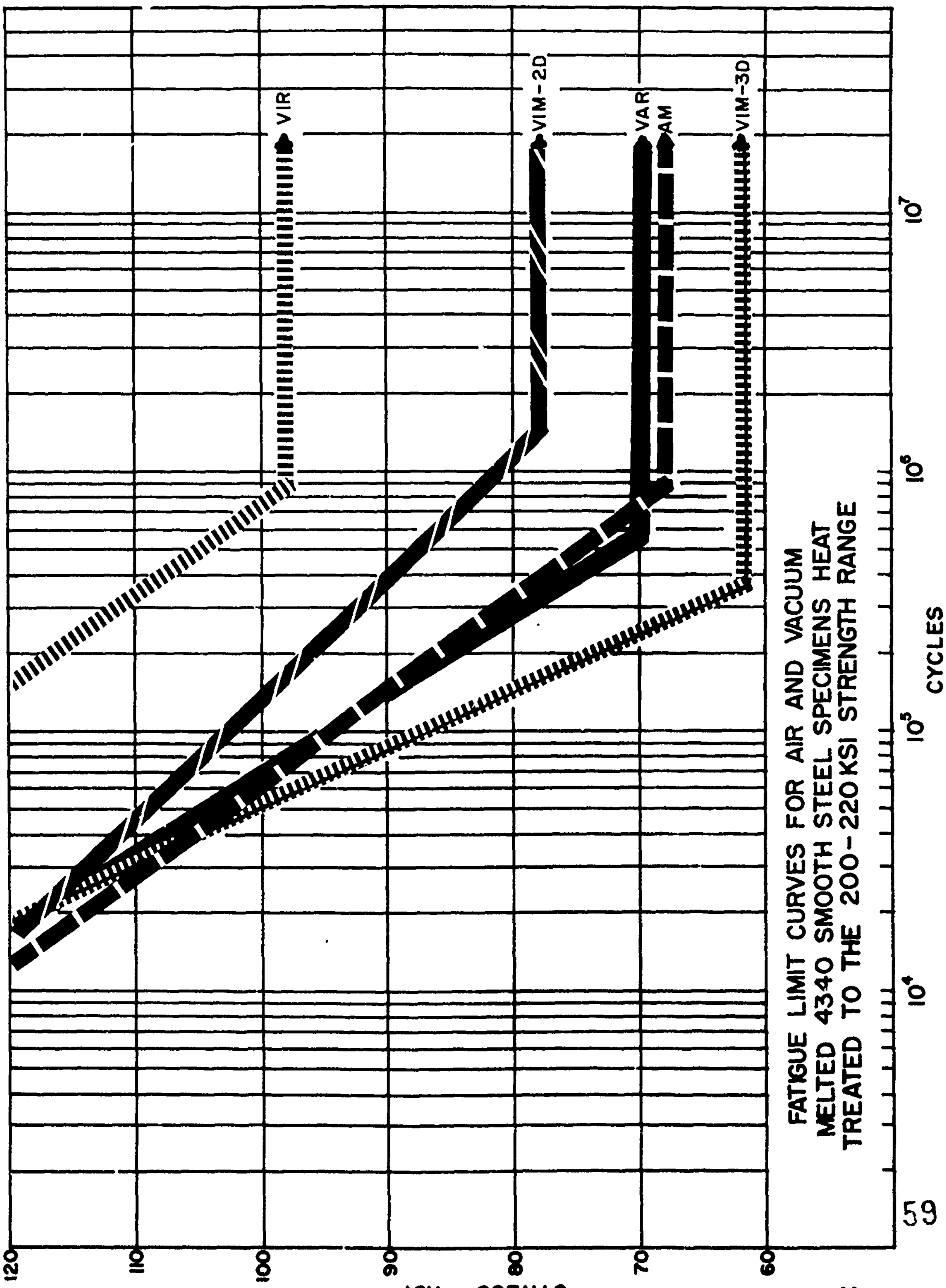
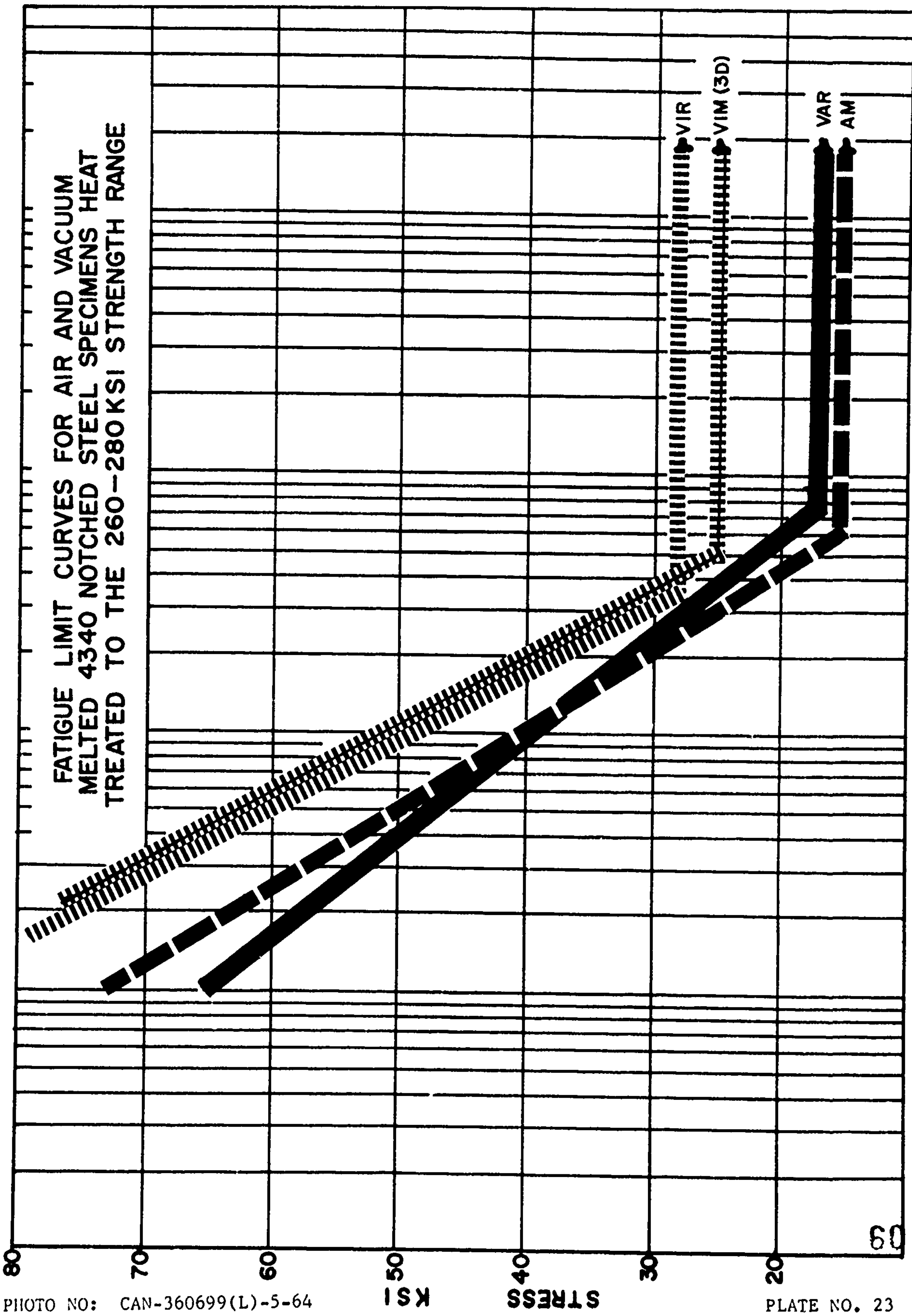
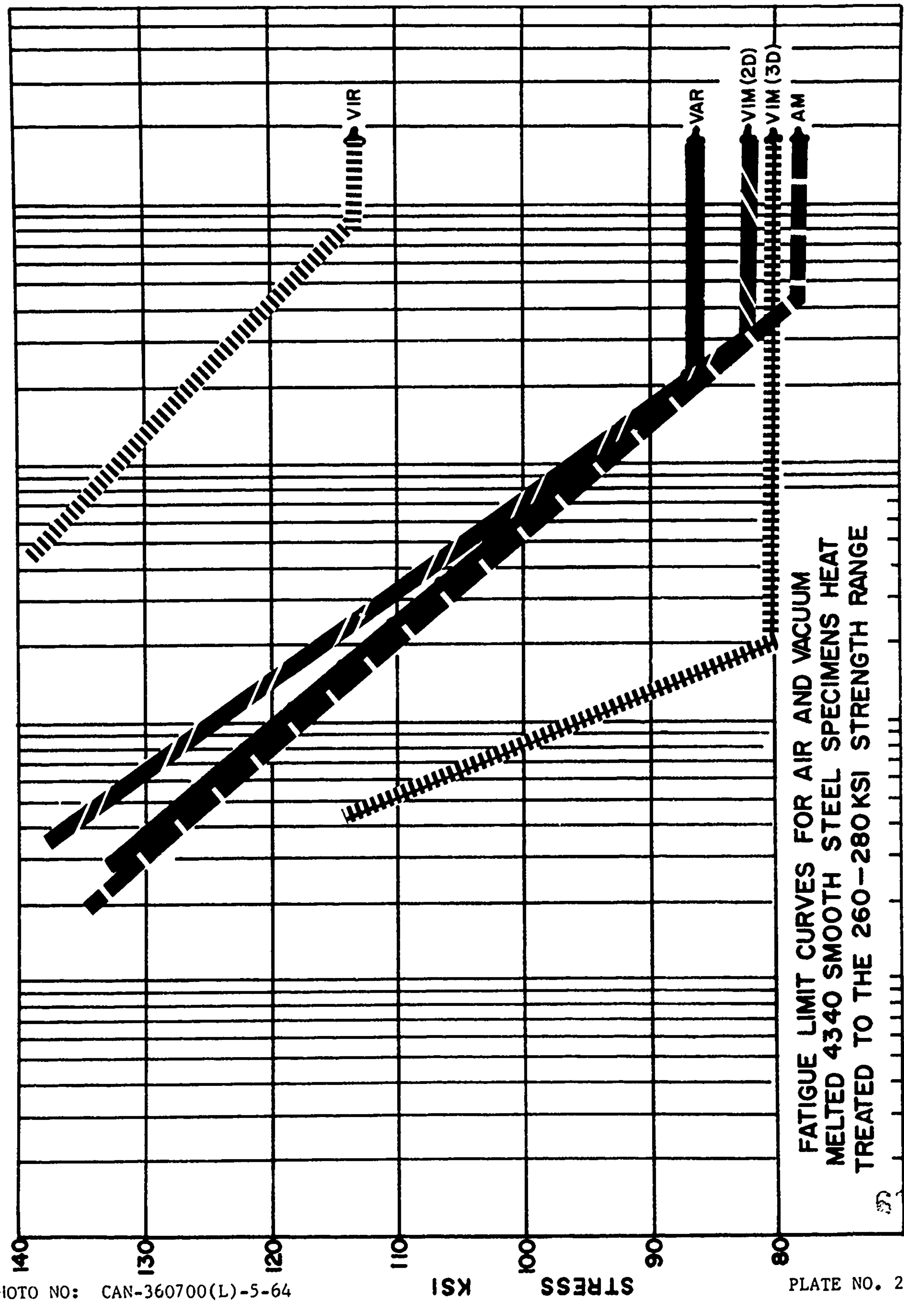

STATIC FATIGUE CURVES FOR VACUUM AND AIR
MELTED 4340 STEEL HEAT TREATED TO 260-280 KSI
o——o——o——AM
□——□——□——VAR
Δ——Δ——Δ——VIM
x——x——x——VIR
TIME — HOURS
.001
.01
0.1
1.0
10
100
1000
10,000
STRESS — KSI
350
300
250
200
150
100
50


FATIGUE LIMIT CURVES FOR AIR AND VACUUM MELTED 4340 NOTCHED STEEL SPECIMENS HEAT TREATED TO THE 200-220 KSI STRENGTH RANGE
VIR
VIM(2D&3D)
AM
VAR
(2D)
(3D)
CYCLES
10^4
10^5
10^6
10^7
STRESS KSI
80
70
60
50
40
30
20



FATIGUE LIMIT CURVES FOR AIR AND VACUUM MELTED 4340 SMOOTH STEEL SPECIMENS HEAT TREATED TO THE 200-220 KSI STRENGTH RANGE


FATIGUE LIMIT CURVES FOR AIR AND VACUUM
MELTED 4340 NOTCHED STEEL SPECIMENS HEAT
TREATED TO THE 260–280 KSI STRENGTH RANGE
VIR
VIM (3D)
VAR
AM
CYCLES
10^4
10^5
10^6
10^7
STRESS
KSI
80
70
60
50
40
30
20


FATIGUE LIMIT CURVES FOR AIR AND VACUUM MELTED 4340 SMOOTH STEEL SPECIMENS HEAT TREATED TO THE 260—280KSI STRENGTH RANGE
VIR
VAR
VIM (2D)
VIM (3D)
AM
CYCLES
10^4
10^5
10^6
10^7
STRESS KSI
140
130
120
110
100
90
80