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SOME MECHANICAL AND BALLISTIC PROPERTIES OF TITANIUM AND TITANIUM ALLOYS

BY

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WATERTOWN ARSENAL LABORATORY

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Title of O.O. Project:	Investigation of Properties of Titanium
WAL Project No:	10.47S, 8.260

TITLE

Some Mechanical and Ballistic Properties of Titanium and Titanium Alloys

OBJECT

To conduct a preliminary evaluation of titanium metal and titanium alloys, as an armor and as a structural material.

SUMMARY

Titanium metal and a few alloys of titanium procured from a number of sources were subjected to various mechanical and ballistic tests in order to evaluate their applicability to Ordnance materiel in the form of armor and structural members.

The mechanical tests included hardness measurements, room and elevated temperature tensile tests, and notched-bar impact tests over a range of temperatures.

Sheet material was subjected to ballistic tests with fragment-simulating projectiles to compare their ballistic performance with standard types of steel armor employed in personnel armor applications. Plate material was ballistically tested with scale model artillery-type armor-piercing projectiles. Conventional steel armor having thicknesses of equivalent weight per unit area was also subjected to ballistic tests in order to permit a comparison to be made between the ballistic performance of titanium and steel armor.

CONCLUSIONS

1. Tensile properties of titanium can be varied widely by alloying and heat treatment. For elevated temperature applications (above 700°F), unalloyed titanium shows only limited promise.

2. The fact that higher strength-weight ratios are possible with titanium alloys than with aluminum and iron alloys makes titanium and its alloys of extreme interest to the Ordnance Department in the development of light-weight Ordnance materiel.

3. The titanium and its alloys tested by notched-bar impact tests all exhibit transitions of the type found in steel; that is, an increase in impact strength with increasing temperature over a moderately narrow temperature range. This temperature range is usually at higher temperatures for titanium than for heat treated alloy steel. This high transition temperature is undesirable for applications where toughness is required. Approximate transition temperatures for the titanium tested are as follows: Bureau of Mines powder metallurgy produced titanium, 925°F; melted, cast and forged titanium, 100°F; titanium-chromium-aluminum alloy, 1250°F.

4. The strain hardening exponent of titanium is approximately 0.14. This value is about the same as that for steel, but lower than that for copper.

5. In thin sheet form, the titanium and its alloys which were ballistically tested with fragment-simulating projectiles were inferior to their equivalent weights of Hadfield manganese steel for use as personnel armor. The tests did, however, show some promise in that the alloyed titanium approached the performance level of Hadfield manganese steel.

6. The thicker plates of unalloyed titanium which were ballistically tested both at 0° and 45° obliquity with scale model artillery-type projectiles were superior to their equivalent weights of heat treated alloy steel armor.

7. A good correlation exists between the notched-bar impact properties and the ballistic characteristics of the unalloyed titanium tested. Material having low toughness in the notched-bar impact test exhibits a tendency to crack and back-spall.

8. The limited ballistic and mechanical tests conducted upon the available titanium and titanium alloys justify further investigation of titanium alloys for application as armor and as a structural material for Ordnance equipment.

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INTRODUCTION

Data obtainable on the mechanical properties of unalloyed, commercially pure titanium have indicated that this material has a high strength/weight ratio. This would make it of value to the Ordnance Department especially if its properties could be improved by alloying and heat treating, as is possible with steel.

Titanium and titanium alloys are now being produced in commercial purities by several companies using different methods. Therefore, titanium from a number of sources was evaluated in order to compare the properties of titanium produced by different methods as well as to compare titanium with other materials now being used in Ordnance materiel.

Titanium was obtained from the U. S. Bureau of Mines in the form of plates six inches wide, six to eight inches long, and from one-eighth to approximately three-quarters of an inch thick. Four plates of each thickness were received. This material had been produced in a powder form by the magnesium reduction of titanium tetrachloride.[1] The powder was pressed and, except in the case of the three-quarter inch plates, sintered in vacuum at about 1000°C. The titanium was then sealed in iron sheaths, hot rolled at around 900°C and quenched from the rolling temperature.

Each plate was numbered by the Bureau of Mines. Only those pieces having the same identification numbers were assumed to have the same chemical composition. This assumption was necessary because the type of analysis desired was a gas analysis which is quite difficult to obtain accurately on titanium. No such analysis is available at the time of this writing.

Titanium was also received from several other sources in limited quantities. The first two of these pieces consisted of 0.080" thick sheets which had been prepared by Company B by induction melting sponge titanium in a graphite crucible and forging and rolling the resulting ingot to sheet. The original sponge had been produced by Company A. A similar sheet was received from Company C, differing from the one mentioned above mainly in the melting procedure. It, too, was melted from Company A sponge, but it was arc melted in a water-cooled copper furnace which excluded the possibility of carbon pickup. All of the melting was done under an inert atmosphere. Another sheet from Company C, prepared from an arc-melted ingot, was an intentional alloy of iron and chromium and showed considerably higher hardness and less ductility than the sheets of commercially pure metal.

The last lot of titanium was received from Company D in the form of a forged bar deliberately alloyed with chromium and aluminum. This bar was used only for impact and tensile tests, being too small for ballistic evaluation.

A tabulation of source, method of preparation, identification number, tests performed, and size of the titanium used is shown in Table I. The chemical compositions of titanium metal and alloys are listed in Table II. Microstructures of these commercially pure samples and alloy samples of titanium are contained in a report by Miss M. R. Norton, which is included as Appendix B of this report.

TEST PROCEDURE

Mechanical Tests

Mechanical test specimens were machined from one-eighth, one-quarter, one-half and approximately three-quarter inch thick plates from the Bureau of Mines, having the same identification numbers as those plates tested ballistically. Both longitudinal and transverse test specimens were obtained wherever the amount of material permitted.

Twenty V-notch Charpy bars (ten longitudinal and ten transverse) were obtained from each of the Bureau of Mines plates No. 286-157 and No. PS-255-403. These bars were tested at temperatures ranging from -319°F (-195°C) to 1472°F (800°C) by the use of liquid coolants for temperatures below room temperature, a circulating air furnace for temperatures from room temperature to 572°F (300°C), and a tube furnace for temperatures above 572°F. All specimens were kept at temperature for twenty to thirty minutes and tested within five seconds after removal from the coolant or furnace. Room temperature hardness readings were taken on those bars tested at room temperature, and at about 700°F, 900°F, 1100°F and 1475°F to determine what permanent effect, if any, the temperature had on the hardness.

From the material left after machining of the Charpy bars several tensile bars were obtained for testing at room temperature.

Bureau of Mines plate No. PS-254-402 was machined into ten longitudinal and ten transverse 0.357 inch diameter tensile bars for high temperature, short time, tensile tests. One transverse bar and one longitudinal bar were pulled at each test temperature. The test temperatures varied from room temperature to 1000°F (538°C) in approximately 100°F intervals. Room temperature hardness readings were taken on the broken bars.

To determine the effect of tempering on the quenched material, Bureau of Mines plate No. PS-256-404 was cut in half and one-half was tempered in a salt bath at 1500°F (815°C) for one hour and air cooled. Tensile and Charpy specimens were then machined from both the aged and the unaged halves.

True stress-true strain tests were made on one longitudinal specimen and one transverse specimen from Bureau of Mines plate No. S-257-194. This test was made at a strain rate of approximately 0.05 min.$^{-1}$ Simultaneous load and diameter measurements were made and the true stresses and true strains were calculated from these measurements.

The forged Ti-Cr-Al alloy bar, No. X, was cut into twelve standard Charpy V-notch specimens. The bars were tested at temperatures ranging from -319°F (-195°C) to 1481°F (805°C) in the same manner as described before. Hardness tests were made on all bars before they were broken and on selected bars after fracture. From the remaining stock one 0.252 inch diameter and one 0.113 inch diameter tensile specimens were machined. These specimens were tested at room temperature. A broken Charpy bar was machined into a dilatometric specimen and this was tested in vacuum up to 1742°F (950°C).

From the undamaged thin sheet left after ballistic testing (Nos. 1 and 2, No. 106, No. 133), flat tensile specimens were machined. Both longitudinal and transverse specimens were taken wherever the amount of material permitted.

No accurate measurement of strain rates was made, but in the plastic range the strain rates on tensile tests (except for the true stress-true strain test) were of the order of 0.4 minutes.$^{-1}$

Ballistic Tests

Ballistic tests were conducted upon the sheet and plate material as described in Table I. The sheet materials, varying from 0.065" to 0.080" in thickness, were ballistically tested with the 17 grain caliber .22 T37 fragment-simulating projectile[2] since the materials in this range of thickness correspond closely in weight/sq. ft. of area with the materials employed in the standard types of personnel armor. The ballistic properties of standard personnel armor materials have previously been determined with the caliber .22 T37 projectile. Some of the sheet materials were also tested with the caliber .30 M1 carbine ball ammunition in order to evaluate their resistance to shock impact of fragments of relatively large mass.

The .117" and .243" thick titanium plates were ballistically tested with caliber .30 M2 ball ammunition. Steel armor of these thicknesses is customarily tested with caliber .30 ball ammunition, reference U. S. Army Specification No. 57-115-11, "Armor Plate: Steel, Rolled, Homogeneous (1/8" to 4")".

The .490" and .670" thick titanium plates were ballistically tested at obliquities of 0° and 45°, using the caliber .40 scale models* of the 90 MM AP T33 shot which had been developed at the Watertown Arsenal Laboratory for use in scale model ballistic studies connected with terminal ballistic research programs.

In addition, for the purpose of obtaining comparable terminal ballistic data on conventional steel armor of thicknesses having the same weight/unit area as the .490" and .670" thick titanium plates, 0.284" and 0.388" thick steel plates were prepared from a typical alloy steel armor plate** heat treated to a hardness of 320 Brinell.

DATA & DISCUSSION

Tensile Tests

The results of short time tensile tests at both room and elevated temperatures are tabulated in Table III and plotted in Figures 1, 2 and 3.

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* The caliber .40 scale model projectiles are exact models of the 90 MM AP T33 (M77) monobloc projectiles. They are made of FXS-318 Mn-Mo steel and are completely quenched out to martensite and then base tempered by high frequency induction heating to give a hardness pattern varying from Rockwell C 62 in the nose and ogive region, to Rockwell C 60 at the bourrelet, and tapering to Rockwell C 45 at the base. The projectiles are fitted in plastic carriers and fired in caliber .50 tubes.

** Composition:

C	Mn	Cr	Ni	Mo	V
.26	.23	1.04	3.49	.42	.06

, manufactured by Company E, Heat No. T2L296.

The tensile strength of Bureau of Mines titanium drops quite rapidly with increasing temperature, leveling off slightly at about 600°F. The yield strength drops almost as fast as the tensile strength with increasing temperature, but levels off markedly at 500°F and drops only slightly from 500°F to 1000°F. The curves shown in Figure 1 closely parallel those published by Remington Arms Co. except that the Remington material, which was made by casting and rolling rather than by the powder metallurgy process, has slightly higher strength at all temperatures.[3]

Both reduction in area and elongation values reach a maximum at 500°F, drop rapidly and then level off or increase slightly before dropping again between 900°F and 1000°F. Only two bars were broken at each temperature and, because of the inhomogeneous nature of the material, results were sometimes inconsistent. However, the close agreement in shape of both the transverse and longitudinal elongation and reduction in area curves would indicate that the erratic behavior of these curves is not due entirely to scatter, but to the effect of temperature on the prior heat treatment. Room temperature hardness readings on the tensile bars tested at elevated temperatures show too wide a scatter to draw any conclusions about the possible aging or tempering effect of the high temperature tensile testing. However, the increase in scatter at the higher temperatures (especially in yield strength values) may be due to an aging, tempering or stress relief effect since no close control of time at temperature was exercised.[4] This effect might also account for the erratic behavior of the elongation and reduction in area curves shown in Figures 2 and 3.

Tensile tests on the other titanium samples were too few to give anything but a rough indication of what to expect from material prepared in different ways. It is evident, however, that a wide range of tensile strength and ductility combinations can be obtained by the proper alloying of titanium.

From the listing of nominal strength/weight ratios of the commercially pure metals and alloys of titanium, aluminum, and iron given in Table VI, it can be seen that titanium compares very favorably with aluminum alloys and steel. It is this fact which makes titanium of such potential value to the Ordnance Department as a structural material in Ordnance equipment.

Notched-bar Impact Tests

The results of the impact tests (see Table IV and Figure 4) made on Plate No. S-286-157 and No. PS-255-403 from the Bureau of Mines showed higher energy values for the one-half inch sintered plate than for the three-quarter inch unsintered plate. Transverse bar energy values were three to five foot-pounds lower than those of the longitudinal bars showing slight directional properties due to rolling. This effect was also noticeable on the plates tested ballistically as evidenced by the transverse cracks shown in Figure 4, Appendix A. However, the "transition temperatures" of both transverse and longitudinal bars of titanium were approximately the same. This is not usually true of transverse and longitudinal specimens of steel.[5]

The variation of impact energy with temperature is slight on this material up to about 600°F at which point the energy absorbed in fracture rises and continues to do so until 950°F. At this temperature the energy value levels off again. Except for the color of the oxide or nitride film formed, the fractured surfaces resemble more closely the "crystalline" fracture of steel than they do the fibrous fracture of steel, although the resemblance is not exact. This is true regardless of the temperature of testing.

Because of the large temperature range over which a limited number of specimens were tested, fewer points than desired were obtained at temperatures around 950°F. However, the specimens tested do indicate, despite some scatter, a marked increase in impact strength over a relatively small temperature range. Whether this increase is due to a transition from brittle to ductile fracture could not be determined from the appearance of the fractured surfaces, but it is conceivable that the porosity of the material made visual classification of the fractures impossible.

It is also possible that the difference in porosity between the sintered and the unsintered plates caused the difference in energy levels shown in Figure 4. The unsintered plate would contain more voids than the sintered plate and therefore would show poorer impact strength (see Appendix B, Fig. 6F and Fig. 7F). This is shown in Figure 4. Differences in chemical composition (primarily in nitrogen and oxygen analyses) could also account for the difference in energy levels, but these differences could not be checked with the equipment available.

No permanent hardness change occurred in the specimens during heating, testing and air cooling which was not within the scatter of readings on one specimen.

The drop in impact energy at about 1500°F of one of the specimens from Plate PS-255-403 could be due to gas (oxygen or nitrogen) absorption at the elevated temperature or to a defect in the bar itself. Any porosity in the specimen cross-section behind the notch could materially affect the impact energy, and it was probably variations of this nature which caused the scatter of results at the lower temperatures. It is interesting to note in connection with this, that preliminary data on cast and forged titanium included in Figure 4 shows much less scatter than data from titanium plate formed from powder, probably because of the more uniform nature of the cast material.

This cast and forged material also exhibits a much sharper "transition" than does the sheath rolled plate.

For design purposes a low transition temperature is preferable to a high one because the lower the transition temperature, the lower is the minimum temperature at which the material will be tough in service. This is especially important in material which will be used at low temperatures.

The titanium tested thus far has a high transition temperature when compared with most steels. However, if the transition temperature can be lowered by alloying or if the energy level below the transition temperature can be kept above about twenty foot-pounds, titanium will become much more valuable as a structural and as an armor material.

The data from which the Remington Arms Co., Inc. originally plotted a straight line is replotted in Figure 4 to show how a transition could exist in the titanium they tested, but might be unnoticed because of lack of data above and below the transition range.[6]

Impact data on the titanium alloy bar (No. X) are plotted in Fig. 5. The energy values were quite low at temperatures below 1200°F (650°C) but above this temperature they rose sharply. The fractured surfaces of the specimens appeared brittle below 1200°F (650°C) and fibrous above 1270°F (687°C). Because of discoloration due to oxidation of the freshly broken surfaces the fractures of specimens broken between these two temperatures were hard to classify as either brittle or fibrous. Hardness tests indicated that some permanent change was occurring in specimens tested above 1110°F (600°C). However, a dilatometric test showed no phase change occurred below 1742°F (950°C), so that the permanent softening was believed due to a tempering or to an overaging effect.

Tempering Treatment

The effect of a one hour heat treatment at 1500°F (815°C) in salt followed by an air cool on the Bureau of Mines Plate No. 256-404 is shown in Table V. The impact energy was decreased while the hardness rose slightly. Tensile strength rose slightly and yield strength increased markedly.

These results seem to indicate an aging effect of some sort which could be due to an impurity (probably iron, possibly oxygen or nitrogen) present.[7] Another possible explanation for the changes in tensile and yield strengths may be that stresses set up in the piece by rolling at too low a temperature or quenching after rolling were relieved by the tempering treatment. This effect could, as it does in steel, materially raise the yield strength while only slightly increasing the tensile strength.[4] Each or both of the above effects may account for the data in Table III.

True Stress - True Strain Tests

Figure 6 represents the data taken on two true stress - true strain tests made on sheath rolled Bureau of Mines titanium. The true stress value (s) was obtained from the ratio of load to actual area, and the true strain (e) was found by taking the natural logarithm of the ratio of original area to actual area.

These data when plotted on a logarithmic scale fall on straight lines, the equations of which are of the form $s = Ke^m$ where K is a proportionality constant and m is the slope of the straight line, often called the strain hardening exponent. The data taken on the longitudinal specimen fall substantially on one straight line ($m = 0.14$) as shown in Figure 6. However, in the region of strains of 0.05 to 0.10 there seems to be a slight drop in slope followed by a rise in slope, as indicated by the data points. Because these variations were so small, only one straight line was drawn through the data points. The measurements on the transverse bar, in contrast to those on the longitudinal specimen, showed two distinct lines of different slope, intersecting at a strain of 0.045. The first line had a slope of only 0.065 while the second line had the same slope as found on the longitudinal specimen, 0.14. Similar results showing two distinct lines have been obtained by Hollomon[8] on steel and by French and Hibbard[9] on copper alloys.

The value of strain hardening exponent ($m = 0.14$) for titanium is low in comparison with that of copper alloys (m = 0.4 to 0.6)[9] and about the same as that for most steels (m = 0.1 to 0.2).

Ballistic Tests

The round-by-round record of the ballistic tests conducted upon the titanium and steel armor plates as well as photographs of the fronts and backs of all plates tested are included in Appendix A. A summary of the results of the ballistic tests is contained in Table VII, and a comparison of the ballistic properties of titanium and steel armor having the same weight/unit area is contained in Table VIII.

The data presented in Tables VII and VIII show that dead soft, unalloyed titanium sheet material in the thickness range of 0.065" to 0.080" (equivalent in weight/unit area to 0.037" to 0.046" of steel) is inferior to Hadfield manganese steel in resistance to penetration by the caliber .22 T37 fragment-simulating projectile. The performance of both the 0.080" thick titanium sheet manufactured by Company B, and the 0.065" thick material manufactured by Company C indicated good ductility; the latter material performed, in addition, very well when impacted by a caliber .30 carbine ball at a velocity of 930 ft/sec (see Figures 2 and 3 of Appendix A).

The hard titanium alloy plate manufactured by Company C (0.075" thick, 325 Brinell) has a ballistic limit which approximates that of the thickness of Hadfield manganese steel having the same weight per unit area, but the material is excessively brittle, cracking extensively in the longitudinal direction when impacted by caliber .22 T37 projectiles, and fracturing longitudinally when impacted by a caliber .30 carbine ball at a velocity of 1010 ft/sec (see Figure 2 of Appendix A).

The limited tests described above indicate that titanium or titanium alloys having hardnesses intermediate between the dead soft condition and the hardness of plate No. 133 (325 Brinell) may have a combination of strength and ductility sufficient for good ballistic resistance to attack by fragments.

Ballistic tests conducted with the caliber .30 M2 ball ammunition upon the two thinnest plates manufactured by the Bureau of Mines indicated excessive brittleness, with extensive cracking occurring in a direction parallel to the rolling direction (see Figure 4 of Appendix A). In spite of the brittle behavior of plates Nos. S-301-273 and S-298-252, the latter plate, 0.243" in thickness, possesses a ballistic limit considerably in excess of heat-treated alloy steel armor having the same weight/unit area (.140" thick) (see Table VIII).

The ballistic tests which were conducted upon the two thicker titanium plates manufactured by the Bureau of Mines and upon heat-treated steel armor of equivalent weights/unit area demonstrate that titanium, even as processed by the powder metallurgy process which does not confer optimum properties on the product, compares very favorably with the best steel armor when subjected to tests with scale model artillery type armor-piercing projectiles. In every case, both at 0° and 45° obliquity, the titanium plates had ballistic limits somewhat in excess of those of the steel plates of equivalent weight/unit area (see Table II).

In view of the above results, the ballistic properties of properly processed and heat-treated titanium alloys of higher strength levels should be extremely promising.

It is to be noted that a good correlation exists between the ballistic performance of the two thicker titanium plates and their mechanical properties. The thinner plate, No. S-286-157, .490" thick, showed relatively ductile performance in the ballistic test and a moderately high energy absorption in the notched-bar impact test, having an impact energy of approximately 20 ft. lbs. at room temperature. The thicker plate, No. 403, .670" thick, back spalled and cracked excessively (see Figure 6, Appendix A). This plate showed an impact energy of only approximately 5 ft. lbs. at room temperature. Thus, the same type of correlation between ballistic and mechanical properties which has been demonstrated to hold for steel armor seems to be applicable to titanium armor.

Since plate No. S-286-157 had better toughness and did not back-spall under ballistic attack, this plate had a considerably high ballistic limit at 45° obliquity as compared to the equivalent steel armor than did the thicker, more brittle titanium plate have over its equivalent steel armor.

The longitudinal cracking which occurred in several of the titanium plates tested is associated with the fact that these materials were rolled into sheet or plate form by being worked and elongated primarily in one direction. Similar undesirable directionality has also been evidenced in straight-away rolled steel armor. It is necessary to have well cross-rolled material for optimum ballistic performance. The ballistic data reported herein should consequently be assessed in the light of the more or less undesirable characteristics conferred upon the materials tested by unfavorable processing techniques used in their manufacture; namely, straight-away rolling and, in the case of the Bureau of Mines plates, the powder metallurgy process used to obtain the solid plates.

GENERAL CONSIDERATIONS

On the basis of strength-weight ratios, titanium and titanium alloys compare very favorably with the aluminum alloys and with steels. This relatively high strength-weight ratio is desirable for most engineering applications, and is even more desirable for aircraft or Ordnance applications where decreased weight means longer ranges or greater mobility.

The notched-bar impact tests conducted on the materials investigated provided information regarding the existence of a transition from tough to brittle behavior over some temperature range as found in the majority of steels. This is the first known demonstration of the above fact since none of the available literature contains any reference to a transition in impact behavior in titanium or its alloys. It is believed that an extensive investigation of the influence of alloying and heat treatment upon the impact energy level and the transition temperature should be undertaken, since many of the Ordnance applications where titanium and its alloys appear to offer considerable promise demand a combination of high strength and high toughness.

The relatively meager ballistic data accumulated as the result of this study justify an investigation, of a considerably enlarged magnitude, into the applicability of titanium alloys as armor. The fact that soft, unalloyed titanium processed in a manner not conducive to the development of optimum mechanical properties, nevertheless had ballistic resistance characteristics at least as good as the equivalent weights of good quality heat-treated alloy steel armor, justifies high expectations that titanium alloys may make excellent armor materials.

The corrosion resistant properties of titanium are excellent. Exactly what this means in savings on maintenance, painting, plating, and replacement costs cannot yet be translated into dollar terms, but it seems evident that the use of titanium could make such savings appreciable.

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CODE SHEET

Company A - E. I. DuPont de Nemours

Company B - Remington Arms Co.

Company C - Allegheny-Ludlum Steel Corp.

Company D - P. R. Mallory Co.

Company E - Carnegie-Illinois Steel Corp.

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TABLE I

Titanium Metal and Titanium Alloys Tested

Source	Description of Material: Type of Metal	Description of Material: Method of Preparation	Plate Number	No. of Plates	Thickness	Size	Tests Performed
Bureau of Mines	Commercially pure Ti	Ti metal powder, compacted, presintered, and sheath rolled.	S-301-273	4	.117"	6"x6"	1 plate-Tensile 1 plate-Ballistic & Hardness
Bureau of Mines	Commercially pure Ti	Ti metal powder, compacted, presintered, and sheath rolled.	S-298-252	4	.243"	6"x6"	1 plate-Tensile 1 plate-Ballistic & Hardness
Bureau of Mines	Commercially pure Ti	Ti metal powder, compacted, presintered, and sheath rolled.	S-286-157	2	.490"	6"x6"	1 plate-V-notch Impact, Hardness, and Room and Elevated Temperature Tensile 1 plate-Ballistic & Hardness
Bureau of Mines	Commercially pure Ti	Ti metal powder, compacted, presintered, and sheath rolled.	S-287-194	2	.490"	6"x6"	1 plate-True Stress-True Strain

TABLE I (con't)

Source	Description of Material: Type of Metal	Description of Material: Method of Preparation	Plate Number	No. of Plates	Thickness	Size	Tests Performed
Bureau of Mines	Commercially pure Ti	Ti metal powder, compacted, sheath rolled with no pre-sinter.	PS-255-403	2	.670"	6"x8"	1 plate-V-notch Impact, Hardness, & Room & Elevated Temperature Tensile 1 plate-Ballistic & Hardness
Bureau of Mines	Commercially pure Ti	Ti metal powder, compacted, sheath rolled with no pre-sinter.	PS-254-402	1	Approx 3/4"	6"x8"	Elevated Temperature Tensile
Bureau of Mines	Commercially pure Ti	Ti metal powder, compacted, sheath rolled with no pre-sinter.	PS-256-404	1	Approx 3/4"	6"x8"	Mechanical Properties after Heat Treatment at Watertown Arsenal
Company B	Commercially pure Ti	Company A sponge, induction melted in graphite, cast, and hot rolled.	1 & 2	2	.080"	6"x6"	Tensile, Hardness, & Ballistic
Company C	Commercially pure Ti	Company A sponge, arc melted in copper crucible, cast, & hot rolled.	106	1	.065"	6"x12"	Tensile, Hardness, & Ballistic

TABLE I (con't)

Source	Description of Material: Type of Metal	Description of Material: Method of Preparation	Plate Number	No. of Plates	Thickness	Size	Tests Performed
Company C	Ti alloy containing Fe & Cr	Company A sponge, arc melted & alloyed in copper crucible, cast, hot rolled, & heat treated	133	1	.075"	4"x12"	Tensile, Hardness, & Ballistic
Company D	Ti alloy containing Cr & Al.	Method of preparation unknown, metal supplied in form of forged bar	X	1	--	1/2"x 1/2"x 30" long	Notched bar impact, Hardness, & Room Temperature Tensile

TABLE II

Chemical Analysis of Titanium Metal and Titanium Alloys Tested

Source	Plate Number	Analysis H	O	N	C	Fe	Cr	W	Al	Mg	Ca	Si
Bureau of Mines[1]	S-301-273 S-298-252 S-286-157 PS-255-403 PS-254-402 PS-256-404	.7	.1-.2			.15				.3	.036	.005
Company A sponge[2]	1 & 2			.37	.29	.13	Trace		Trace			Trace
	106			.26	.025	.11	Trace		Trace			Trace
Company C alloy[2]	133			.078	.04	1.47	2.73	Trace				
Company D alloy[3]	X			.022	.49		4.61		3.13			

1 Typical Analysis of Bureau of Mines Titanium 10
2 Analyzed at Watertown Arsenal
3 Analysis Furnished by Company D

TABLE III

Tensile Properties of Titanium and Titanium Alloys at Room and Elevated Temperatures

Specimen: 0.357" diameter, 1.4" gage length
unless otherwise noted
T - Transverse L - Longitudinal
Approximate strain rate in plastic range:
0.4 min.$^{-1}$

Specimen Identification	Testing Temperature in °F	Tensile Strength in psi	Yield Strength in psi (0.1% set)	% Elongation in 1.4 inches	% Reduction of Area	Room Temperature Hardness As Taken	Room Temperature Hardness BHN Converted
Bureau of Mines Plate No. PS-255-403 T	75	71,800	57,000	5.7	8.4	Rockwell A unless noted	
Plate No. PS-255-403 L	75	78,400	44,500	8.6	10.9		
Plate No. PS-255-403 T	500	34,000	19,500	12.1	14.0		
Plate No. PS-255-403 T	950	18,900	14,200	4.3	10.3		
Plate No. S-298-157 T	75	75,000	51,000	21.4	37.6		

TABLE III (con't)

Specimen Identification	Testing Temperature in °F	Tensile Strength in psi	Yield Strength in psi (0.1% set)	% Elongation in 1.4 inches	% Reduction of Area	Room Temperature Hardness As Taken	Room Temperature Hardness BHN Converted
Plate No. S-298-157 T	500	35,700	17,000	31.5	44.5*		
Plate No. S-298-157 T	950	22,160	12,600	13.6	44.5*		
Plate No. PS-254-402 T	80	82,400	50,500	7.9	8.7	52.5	165
Plate No. PS-254-402 L	80	77,500	47,500	5.7	9.8	50.0	153
Plate No. PS-254-402 T	200	69,000	38,500	12.9	13.5	53.0	169
Plate No. PS-254-402 L	200	69,200	36,500	15.7	20.6	50.0	153
Plate No. PS-254-402 T	300	59,000	36,000	14.3	17.6	52.5	165

* These values of Reduction of Area are approximate because the cross-sections of the broken bars were elliptical.

TABLE III (con't)

Specimen Identification	Testing Temperature in °F	Tensile Strength in psi	Yield Strength in psi (0.1% set)	% Elongation in 1.4 inches	% Reduction of Area	Room Temperature Hardness	
						As Taken	BHN Converted
Plate No. PS-254-402 L	300	57,800	29,500	18.6	25.5	50.5	155
Plate No. PS-254-402 T	400	47,000	23,500	20.0	21.1	53.0	169
Plate No. PS-254-402 L	400	47,300	21,500	21.4	28.9	51.0	159
Plate No. PS-254-402 T	500	39,000	20,800	22.9	27.5	52.0	162
Plate No. PS-254-402 L	500	39,000	18,000	22.9	31.7	51.0	159
Plate No. PS-254-402 T	600	32,900	21,000	16.4	16.6	53.0	169
Plate No. PS-254-402 L	600	32,000	16,900	17.1	25.5	52.5	165
Plate No. PS-254-402 T	700	28,000	18,600	14.3	19.6	52.0	152
Plate No. PS-254-402 L	700	30,000	21,000	17.1	28.9	52.5	165

TABLE III (con't)

Specimen Identification	Testing Temperature in °F	Tensile Strength in psi	Yield Strength in psi (0.1% set)	% Elongation in 1.4 inches	% Reduction of Area	Room Temperature Hardness As Taken	Room Temperature Hardness BHN Converted
Plate No. PS-254-402 T	800	25,600	17,000	12.9	18.6	52.5	165
Plate No. PS-254-402 L	800	26,400	16,200	17.9	28.4	52.5	165
Plate No. PS-254-402 T	900	22,700	16,400	10.7	17.1	52.0	162
Plate No. PS-254-402 L	900	21,800	13,800	17.9	27.9	51.0	159
Plate No. PS-254-402 T	1000	20,600	11,400	7.1	12.4	52.0	162
Plate No. PS-254-402 L	1000	19,900	13,000	11.4	19.6	51.5	160
Plate No. S-301-273 T	70	92,400	59,000	3.5	Strip Tensile no R.A.		171
Plate No. S-301-273 L	70	100,200	58,300	8.0	Strip Tensile no R.A.		171

TABLE III (con't)

Specimen Identification	Testing Temperature in °F	Tensile Strength in psi	Yield Strength in psi (0.1% set)	% Elongation in 1.4 inches	% Reduction of Area	Room Temperature Hardness As Taken	Room Temperature Hardness BHN Converted
Plate No. S-298-252 T	70	86,400	57,800	9.0	Strip Tensile no R.A.		192
Plate No. S-298-252 L	70	85,700	49,200	12.5	Strip Tensile no R.A.		192
Company B Plate No.1 T	70	100,000	81,800	25.0	Strip Tensile no R.A.	R_b 93	200
Company B Plate No.2 L	70	95,000	76,600	28.0	Strip Tensile no R.A.	R_b 93	200
Company C Plate 106 T	70	88,700	45,000	19.0	Strip Tensile no R.A.	R_b 96	216
Company C Plate 106 L	70	84,700	63,400	15.5	Strip Tensile no R.A.	R_b 96	216
Company C Plate 106 L	70	83,900	64,300	15.5	Strip Tensile no R.A.	R_b 96	216

TABLE III (con't)

Specimen Identification	Testing Temperature in °F	Tensile Strength in psi	Yield Strength in psi (0.1% set)	% Elongation in 1.4 inches	% Reduction of Area	Room Temperature Hardness: As Taken	Room Temperature Hardness: BHN Converted
Company C Plate 133 L	70	143,000	120,000	18.0	Strip Tensile no R.A.	R_c33.5	325
Company D Plate No. X 0.252" diam. Specimen L	70	192,000	Broke Brittly at Flaw in bar			R_c41.5	387
Company D Plate No. X 0.113" diam. Specimen L	70	203,000	190,000 (0.01% set)	5.2	12.0	R_c41.5	387

TABLE IV

Impact Data on Titanium and Titanium Alloys

Specimens were standard V-Notch Charpy Bars
Energy Values are in Foot-Pounds

Testing Temperature		Energy Absorbed in Fracture, Bureau of Mines Sheath Rolled Plates			
		Plate No. S-286-157		Plate No. PS-255-403	
°F	°C	Transverse	Longitudinal	Transverse	Longitudinal
-319	-195		18.1		
-103	- 75	20.1	25.0		
- 40	- 40	19.4	25.4		
75	24	19.4	25.0	3.1	6.1
212	100			5.1	8.0
446	230		22.2	5.1	8.0
554	290	22.2	19.4	5.1	7.7
673	356		28.0		10.0
703	373	24.7		5.8	
775	413	27.6		8.0	
810	432		35.8		12.6
842	450	34.6		8.3	
860	460		27.3		11.8
896	480	37.4	37.4	8.3	
945	507	39.9		10.6	15.5
1103	595	38.6	39.1	10.6	14.5
1472	800		39.3		7.2

TABLE IV (con't)

Company A sponge, arc melted, cast, forged
Quite similar to Plate 10X in preparation

Testing Temperature °F	Testing Temperature °C	Energy Absorbed in Fracture
-319	-195	3.8
- 40	- 40	4.8
32	0	6.6
59	15	7.2
82	28	14.2
140	60	15.1

Plate Number X

Testing Temperature °F	Testing Temperature °C	Energy Absorbed in Fracture
-319	-195	1.2
70	21	4.6
307	153	6.4
550	284	8.0
842	450	7.2
1105	600	7.2
1202	650	13.3
1224	662	15.5
1247	675	26.9
1269	687	33.4
1294	701	51.9
1481	805	107.7

TABLE V

Effect of Aging at 1500°F for 1 Hour on Bureau of Mines Titanium (Plate No. PS-256-404)

Impact Data

Specimen: V-notch Charpy Bar. Energy in Foot Pounds

Testing Temperature °F	Testing Temperature °C	Unaged Transverse	Unaged Longitudinal	Aged Transverse	Aged Longitudinal
-40	- 40	3.8	5.3	3.1	4.6
79	26	3.6	5.8	2.8	4.6
212	100	5.8	9.2	4.6	8.9
342	172	6.9	9.2	6.4	9.4

Room Temperature Tensile Data

Specimen: 0.357 inch Diameter Bar

	Unaged Transverse	Unaged Longitudinal	Aged Transverse	Aged Longitudinal
Tensile Strength	83,500	81,000	86,400	85,700
Yield Strength (0.1% set)	57,200	52,500	69,000	63,000
% Elongation	9.5	14.3	8.6	13.8
% Reduction of Area	11.9	18.9	9.6	17.4

Each value is the average of data from three tensile specimens.

	Unaged	Aged
Hardness Rockwell A	56	58

TABLE VI

Comparison of Titanium and Titanium Alloys with Iron and Aluminum and their Alloys

	Commercially Pure Metal			Metal Alloyed and Heat Treated		
	Al	Fe	Ti	Al	Fe	Ti
Tensile Strength in psi	13,000	50,000	75,000	88,000	230,000	203,000
Specific Gravity	2.71	7.87	4.54	2.8	7.9	4.6
Strength-Weight Ratio	4,800	6,350	16,500	31,400	35,000	44,000

TABLE VII

Ballistic Properties of Titanium and an Alloy of Titanium

Plate No.	Thickness	Manufacturer	Hardness	Projectile	Obliquity	Ballistic Limit f/s	Ballistic Limit Criterion
106	0.065"	Company C	214	Cal. .22 T 37	0°	1050	Protection B.L. (V_{50})
133	0.075"	Company C	325	Cal. .22 T 37	0°	>1590	Protection B.L.
#1 and #2	0.080"	Company B	197	Cal. .22 T 37	0°	1445	Protection B.L. (V_{50})
S-301-273	0.117"	Bureau of Mines	171	Cal. .30 M2 Ball	0°	885	Army B. L.
S-298-252	0.243"	Bureau of Mines	192	Cal. .30 M2 Ball	0°	1840	Army B. L.
S-286-157	0.490"	Bureau of Mines	170	Cal. .40 Scale Model of 90 MM AP T33	0°	1435	Protection B.L.
S-286-157	0.490"	Bureau of Mines	170	Cal. .40 Scale Model of 90 MM AP T33	45°	2315	Protection B.L.

TABLE VII (con't)

Plate No.	Thick-ness	Manufacturer	Hard-ness	Projectile	Obliquity	Ballistic Limit f/s	Ballistic Limit Criterion
PS-255-403	0.670"	Bureau of Mines	207	Cal. .40 Scale Model of 90 MM AP T33	0°	1830	Protection B.L.
PS-255-403	0.670"	Bureau of Mines	207	Cal. .40 Scale Model of 90 MM AP T33	45°	2900	Protection B.L.

TABLE VIII

Comparison of Ballistic Properties of Titanium and Steel Armor Plate

Titanium Plate No.	Thickness	Thickness of Steel Armor having same weight/unit Area	Type of Steel Armor	Projectile	Obliquity	Ballistic Limit f/s of Titanium	Ballistic Limit f/s of Equivalent Thickness of Steel Armor	Source of Data on Steel Armor
106	0.065"	0.037"	Hadfield Manganese Stl.	Cal..22 T 37	0°	1050	1560	WAL 710/747 "Resume of Programs on Development of Body Armor Undertaken at Watertown Arsenal during World War II"
133 (Ti Alloy)	0.075"	0.043"	Hadfield Manganese Stl.	Cal..22 T 37	0°	>1590	1640	
#1 and #2	0.080"	0.046"	Hadfield Manganese Stl.	Cal..22 T 37	0°	1445	1690	
S-301-273	0.117"	0.068"	--	Cal..30 M2 Ball	0°	885	--	--
S-298-252	0.243"	0.140"	Heat Treated Alloy Stl. 360-400 BHN	Cal..30 M2 Ball	0°	1840	Approx. 1750	A.P.G. Report AD-335 "Effect of Hardness on Ballistic Properties of Thin Rolled Homo. Armor"

TABLE VIII (con't)

Titanium Plate No.	Thickness	Thickness of Steel Armor having same weight/unit Area	Type of Steel Armor	Projectile	Obliquity	Ballistic Limit f/s of Titanium	Ballistic Limit f/s of Equivalent Thickness of Steel Armor	Source of Data on Steel Armor
S-286-157	0.490"	0.284"	Heat Treated Alloy Stl. 320 BHN	Cal..40 Scale Model of 90MM AP T33	0°	1435	1390	Appendix A
S-286-157	0.490"	0.284"	--	Cal..40 Scale Model of 90MM AP T33	45°	2315	2080	Appendix A
PS-255-403	0.670"	0.388"	Heat Treated Alloy Stl. 320 BHN	Cal..40 Scale Model of 90MM AP T33	0°	1830	1805	Appendix A
PS-255-403	0.670"	0.388"	Heat Treated Alloy Stl. 320 BHN	Cal..40 Scale Model of 90MM AP T33	45°	2900	2875	Appendix A

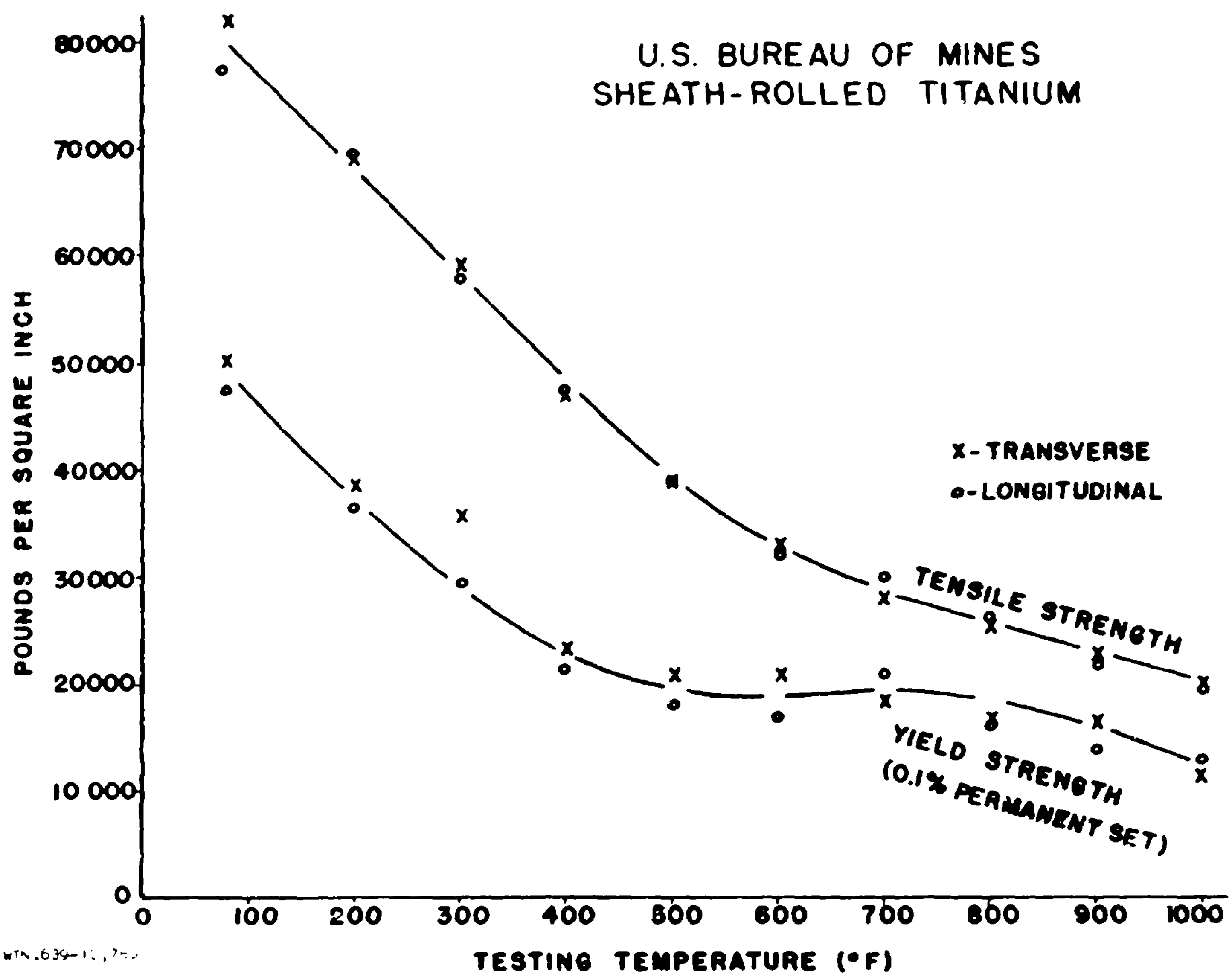

FIGURE I TENSILE AND YIELD STRENGTHS VS TESTING TEMPERATURE

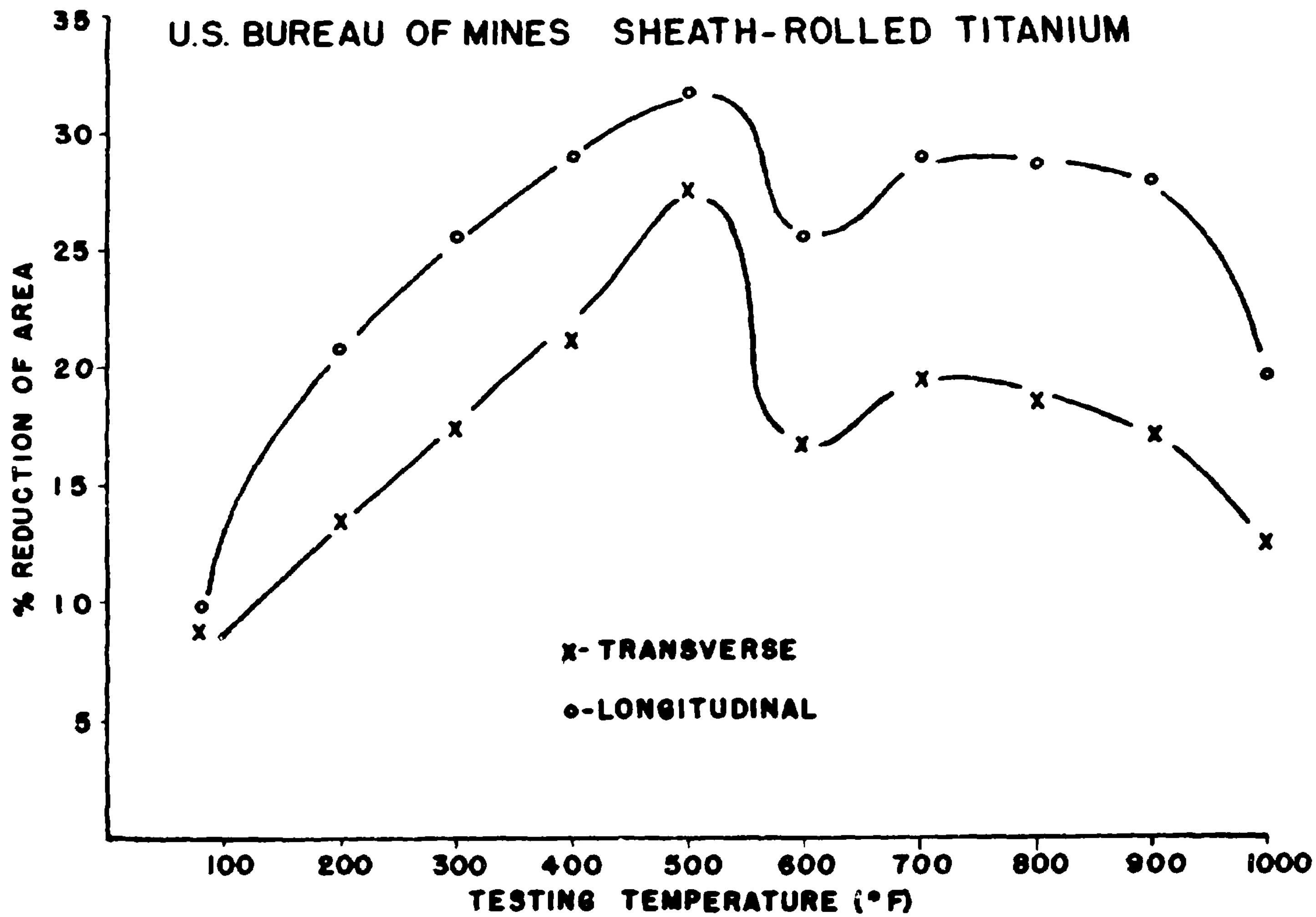

FIGURE 2 PER CENT REDUCTION OF AREA
VS TESTING TEMPERATURE

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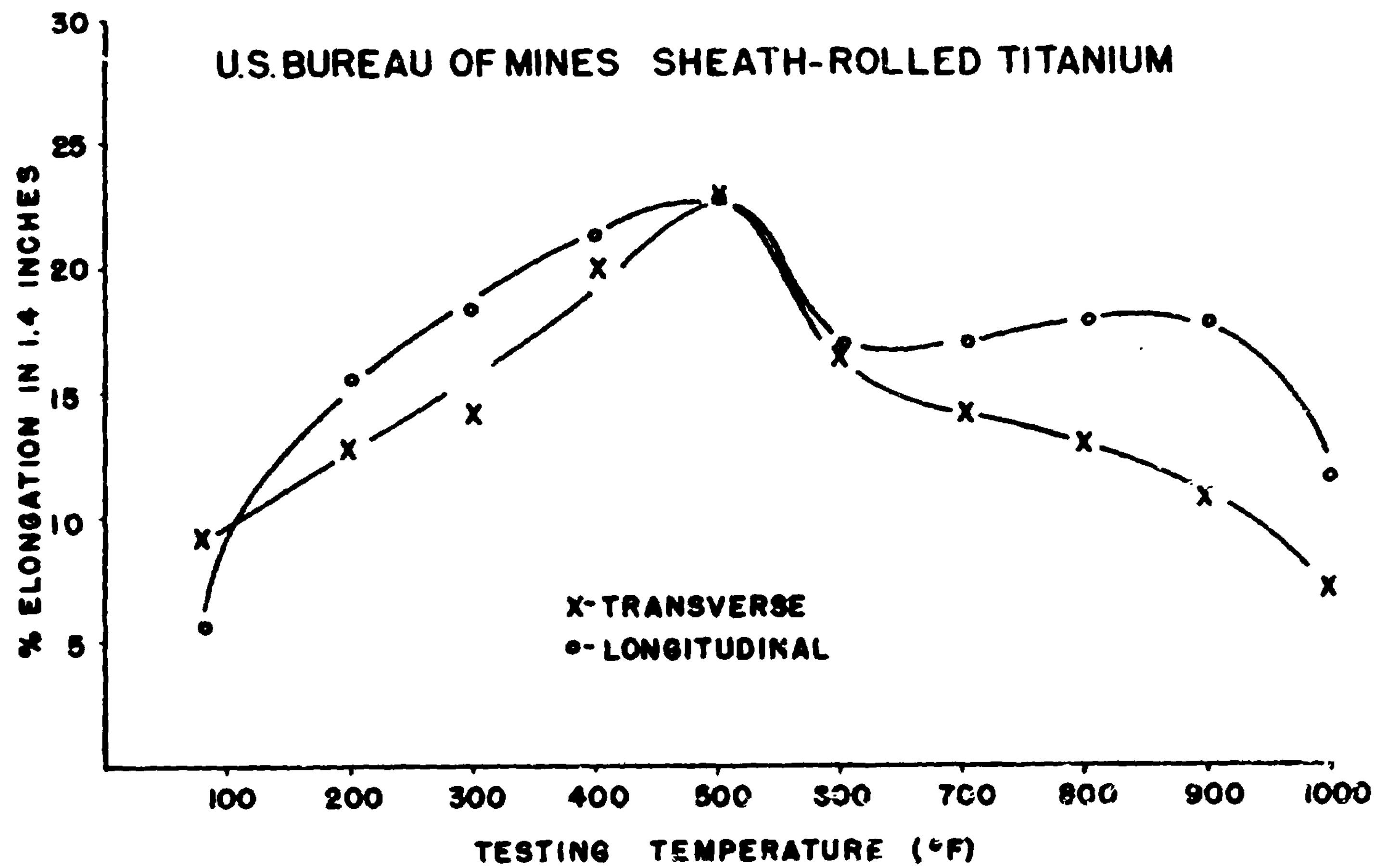

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FIGURE 3 PER CENT ELONGATION VS TESTING TEMPERATURE

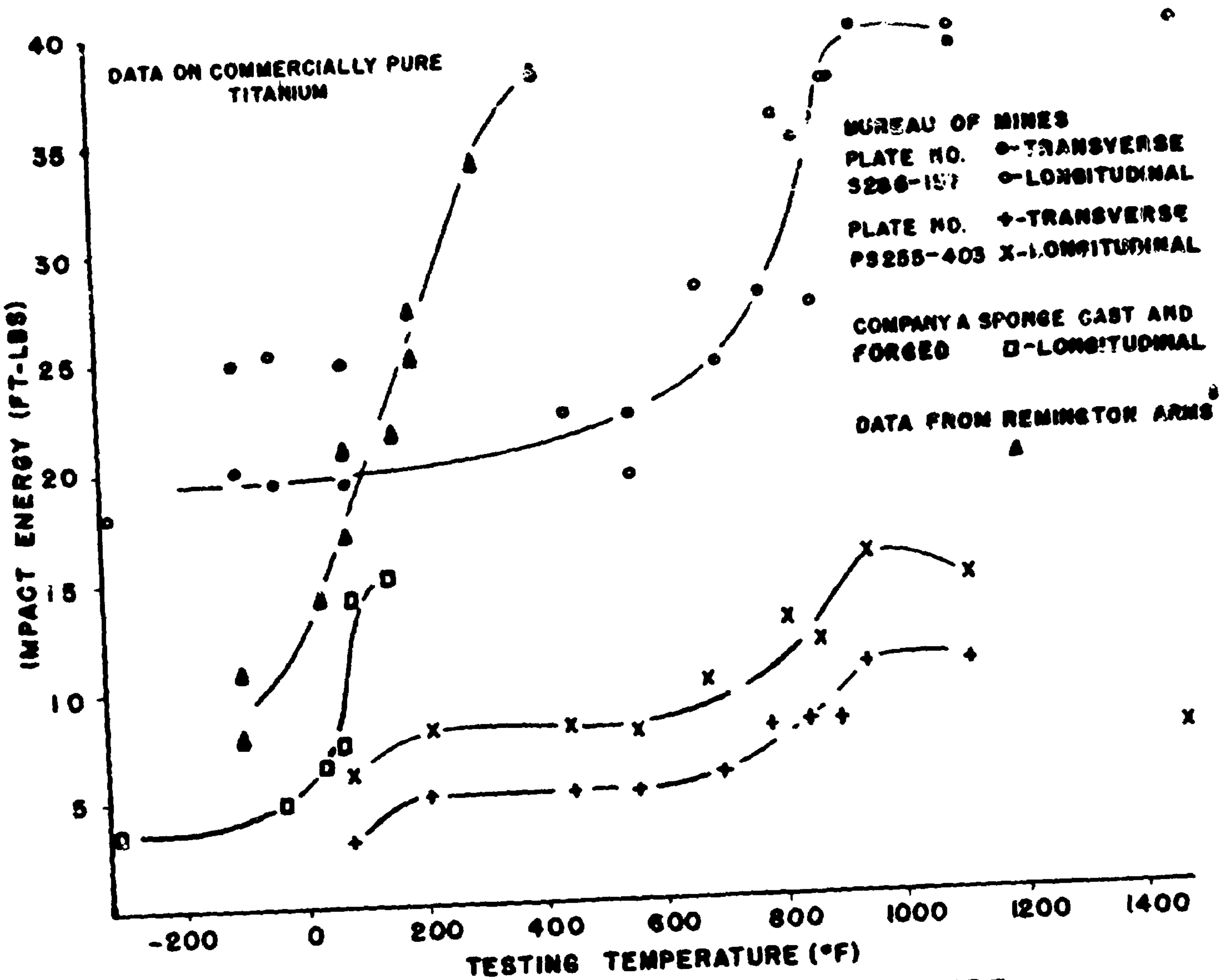

FIGURE 4 IMPACT ENERGY VS TESTING TEMPERATURE
STANDARD V-NOTCH CHARPY SPECIMENS

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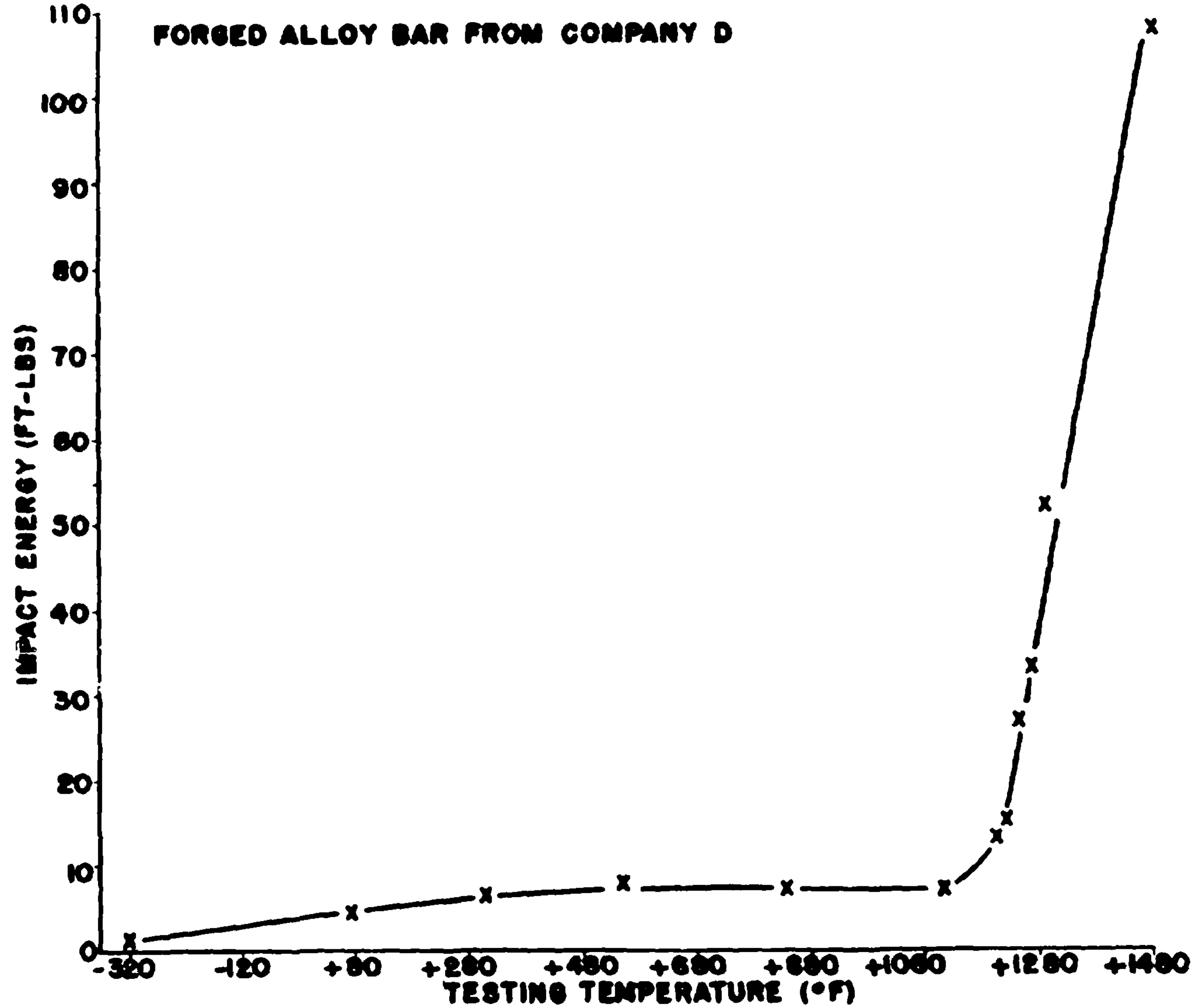

FIGURE 5 IMPACT ENERGY VS TESTING TEMPERATURE
STANDARD V-NOTCH CHARPY SPECIMENS

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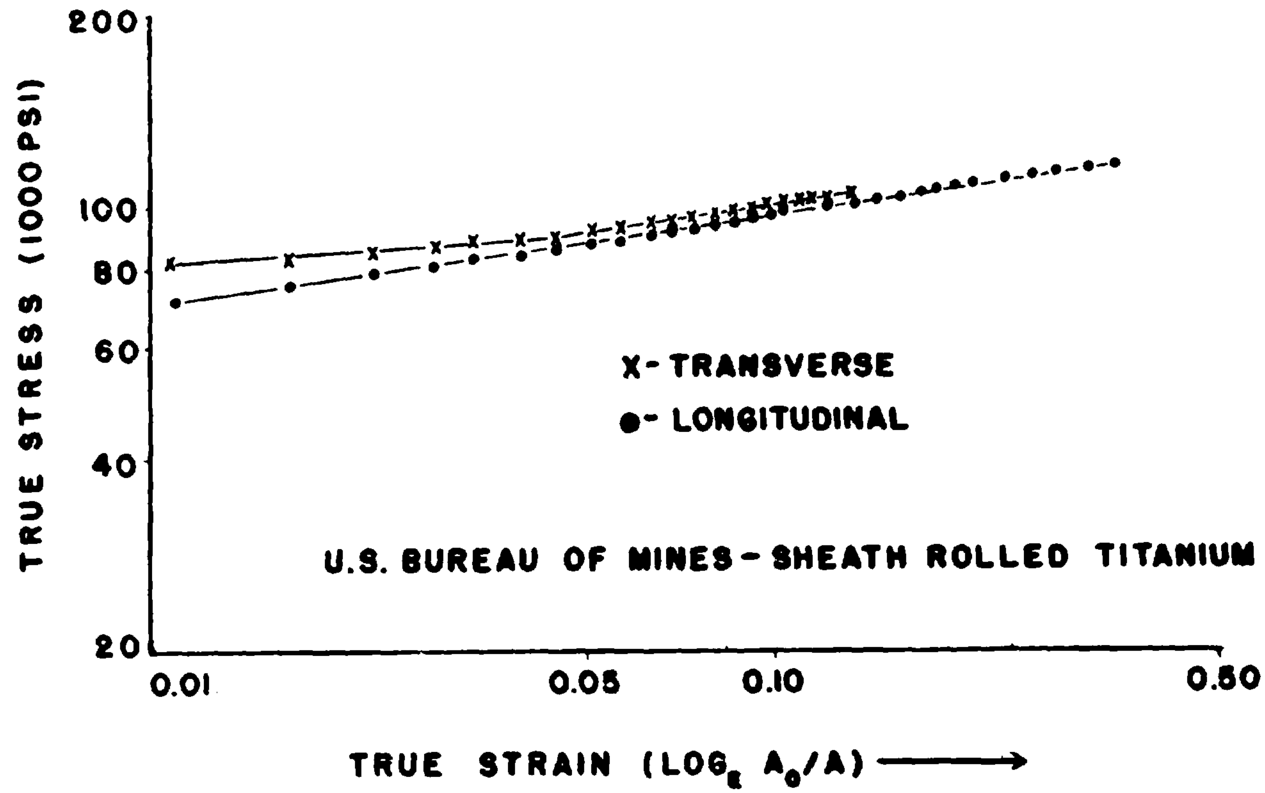

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FIGURE 6 TRUE STRESS VS TRUE STRAIN

APPENDIX A

APPENDIX A

DETAILED RESULTS OF BALLISTIC TESTS ON TITANIUM AND STEEL ARMOR PLATES AND PHOTOGRAPHS OF PLATES AFTER BALLISTIC TESTING

APPENDIX A

GLOSSARY OF SYMBOLS

PP - Partial Penetration

CP - Complete Penetration

PTP - Projectile passed through the plate

FPTP - Projectile failed to pass through the plate

MB - Medium bulge

LB - Large bulge

CIP - Projectile stuck in plate

APPENDIX A

DETAILED RESULTS OF BALLISTIC TESTS ON TITANIUM AND STEEL ARMOR

Plate No. - 106

Thickness - 0.065" 6" x 12"

Description of Material - Arc melted titanium metal hot rolled inte sheet. Manufactured by Company C.

Hardness - Rockwell B96 (214 Brinell)

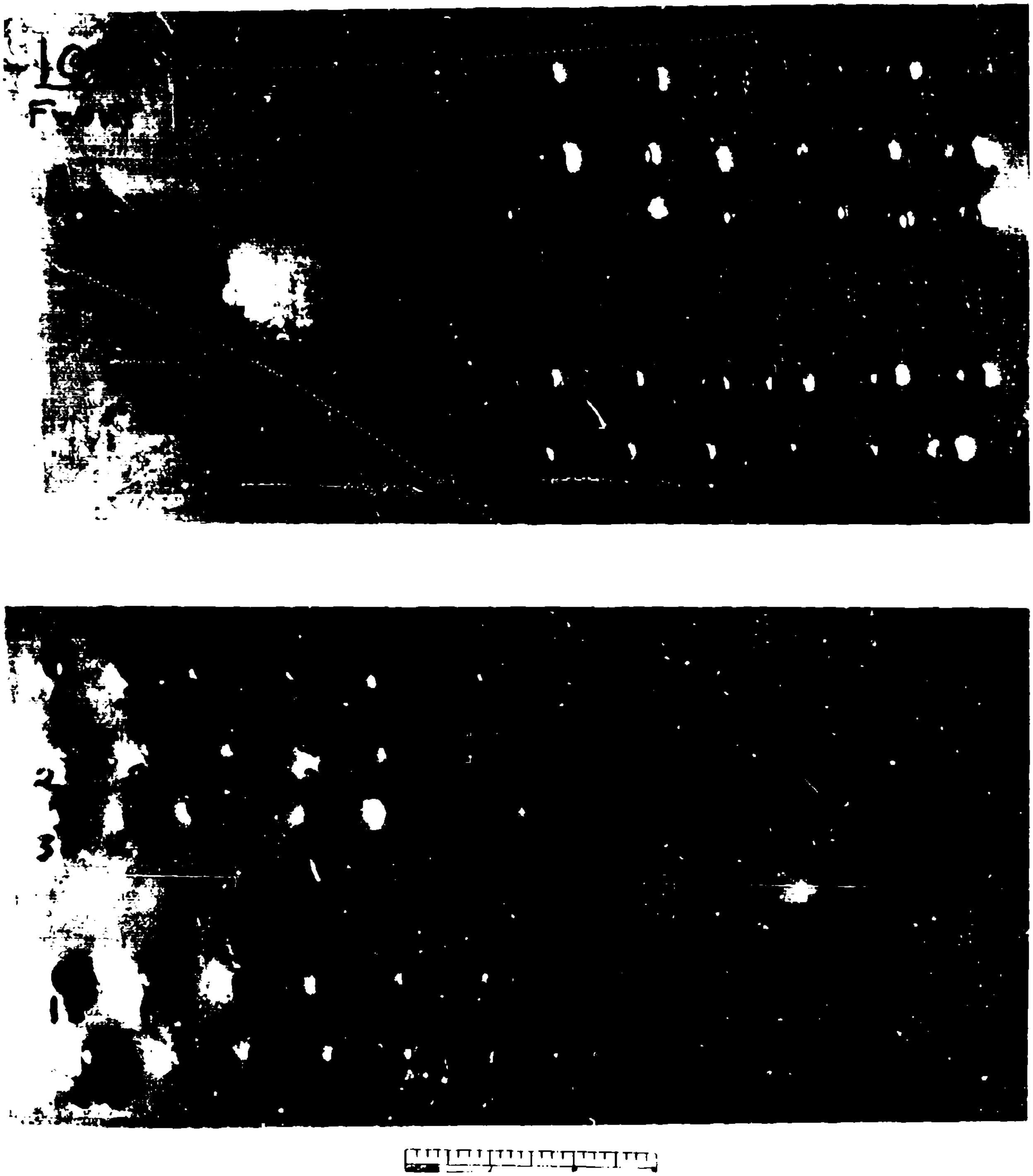
Tested 17 grain cal .22 T37 fragment simulating projectile:

Round No.	Striking Velocity f/s	Result	Round No.	Striking Velocity f/s	Result
1	1330	CP,PTP	17	1030	PP,bulge
2	1220	CP,PTP	18	1105	CP,PTP
3	1275	CP,PTP	19	995	PP,3/8"
4	1265	CP,PTP			crack on back
5	1170	CP,PTP	20	1115	CP,PTP
6	1195	CP,PTP	21	1025	PP,1/8"
7	1235	CP,PTP			crack on back
8	1125	CP,PTP	22	1100	CP,PTP
9	1095	CP,PTP	23	985	PP,1/4"
10	1055	CP,PTP			crack on back
11	895	PP,bulge	24	1060	PP,bulge
12	1150	PP,bulge	25	1080	CP,PTP
13	1065	CP,PTP	26	1090	PP,1/4"
14	1105	CP,PTP			crack on back
15	1055	CP,PTP	27	1045	CP,PTP
16	1110	CP,PTP,	28	1030	CP,PTP
		petal hinged	29	1025	CP,PTP
		back	30	1035	PP,bulge

Protection Ballistic Limit (V_{50}) = 1050 ft/sec

Tested with cal. .30 M1 carbine ball ammunition:

Round No.	Striking Velocity f/s	Result
1	930	PP,large bulge, no crack



WATERTOWN ARSENAL

COMPANY C, PLATE 106, .065" THICK TITANIUM AFTER BALLISTIC TESTING WITH CAL. .22 T37 AND CAL. .30 CARBINE BALL AMMUNITION. WTN.710-2454

FIGURE 1

Plate No. 133

Thickness - 0.075"   Size - 4" x 12"

Description of Material - Titanium Alloy; arc melted, hot rolled, and heat treated. Manufactured by Company C.

Hardness - Rockwell C 33.5 (315 Brinell)

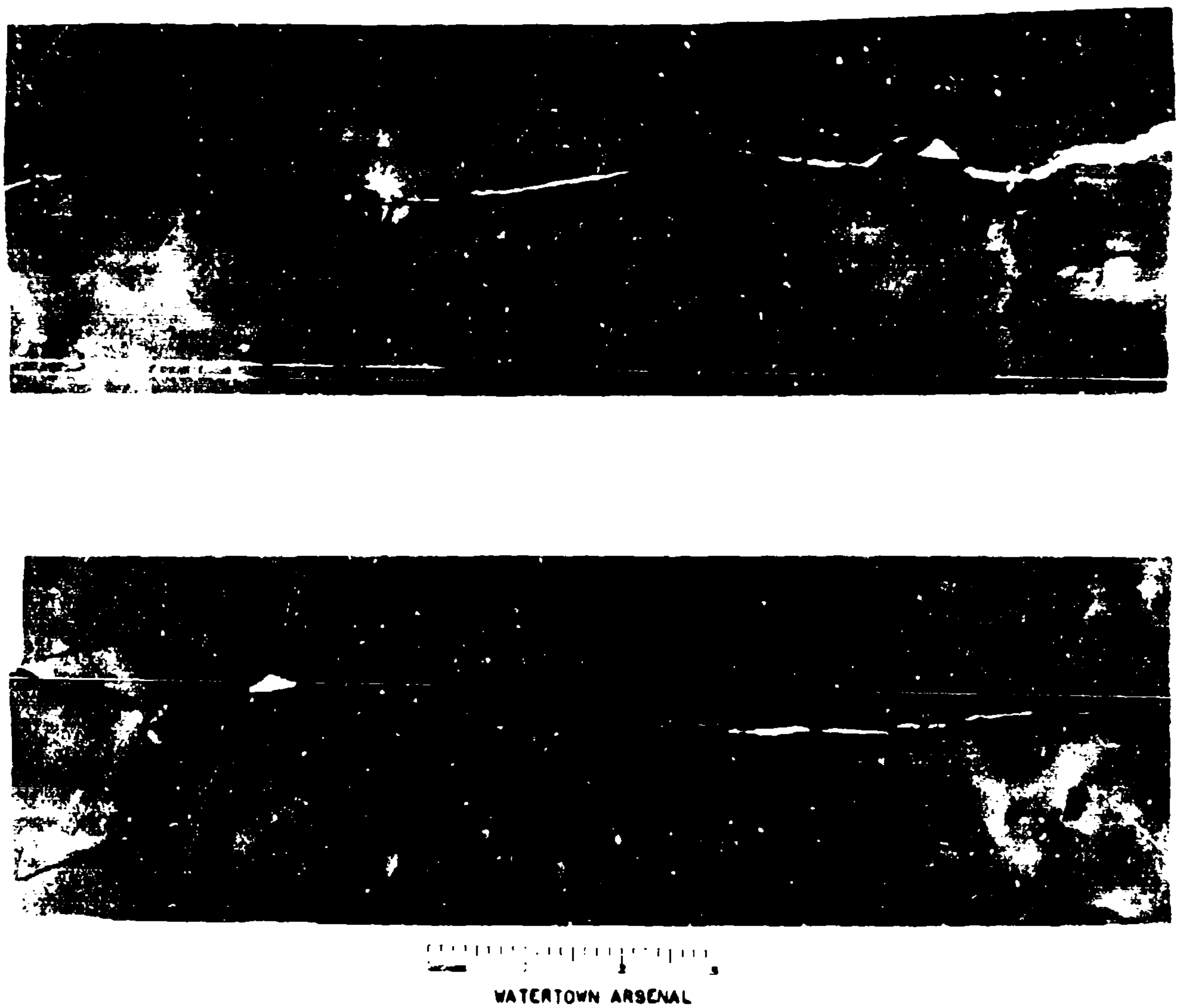
Tested with 17 grain cal. .22 T37 fragment simulating projectile:

Round No.	Striking Velocity f/s	Result
1	Velocity lost	PP, 1 1/4" crack through impact
2	1270	PP, 1 3/8" crack through impact
3	1335	PP, 1 3/4" crack through impact
4	Velocity lost	PP, 4 1/2" crack through impact to edge of plate
5	1520	PP, 2" crack through impact to edge of plate
6	1590	PP, 1 1/2" crack to edge of plate

Protection Ballistic Limit - above 1590 ft/sec

Tested with cal. .30 M1 carbine ball ammunition:

Round No.	Striking Velocity f/s	Result
1	1010	Plate broke longitudinally into 2 large and 3 small pieces



WATERTOWN ARSENAL

COMPANY C, PLATE 133, .075" THICK TITANIUM ALLOY AFTER BALLISTIC TESTING WITH CAL. .22 T37 AND CAL. .30 CARBINE BALL AMMUNITION. WTN.710-2455

FIGURE 2

Plate No. 1

Thickness - 0.080"   Size - 6" x 6"

Description of Material - Graphite crucible cast titanium metal, hot rolled into sheet. Manufactured by Company B.

Hardness - Rockwell B93 (197 Brinell)

Tested with cal. .22 T37 fragment simulating projectile:

Round No.	Striking Velocity f/s	Results
1	1140	PP,bulge
2	1250	PP,bulge
3	1340	PP, 5/16" and 3/16" cracks
4	1555	PP, Petal hinged back
5	1725	CP,PTP
6	1550	CP,PTP
7	1650	CP,PTP
8	1570	CP,PTP
9	1575	CP,PTP
10	1590	CP,PTP
11	1520	CP,PTP
12	1565	CP,PTP
13	1590	CP,PTP
14	1530	CP,PTP
15	1530	CP,PTP

Plate No. 2

Thickness - Same as Plate #1   **Size - 6" x 6"**

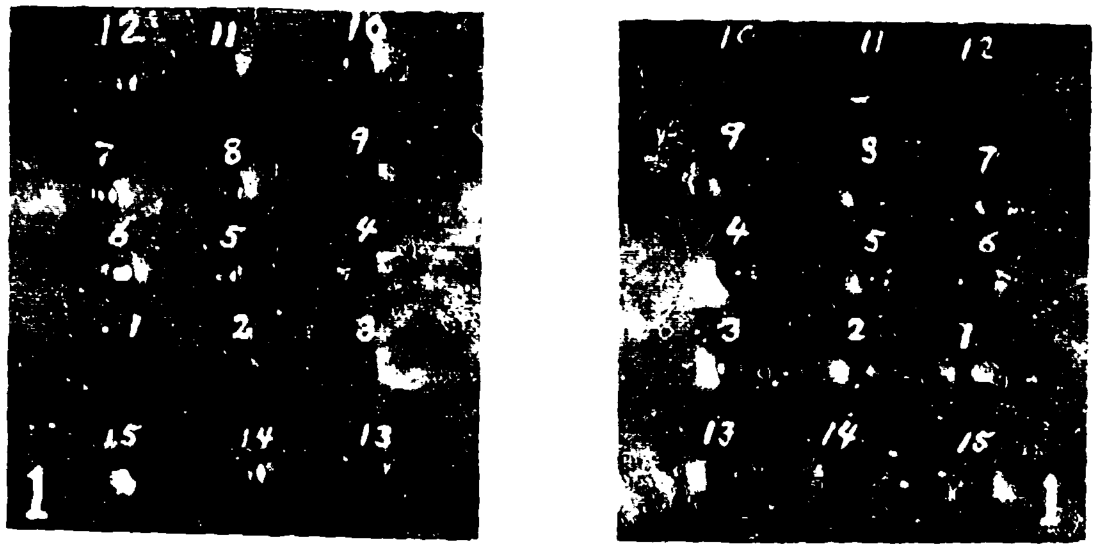
Description of Material - Same as Plate #1, Manufactured by Company B

Hardness - Same as Plate #1

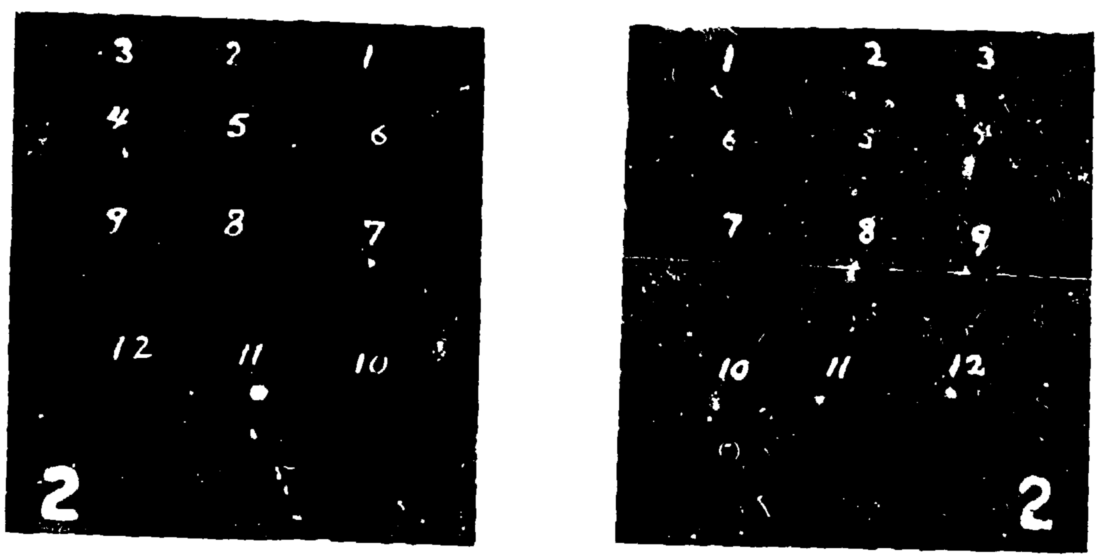
Tested with Cal. .22 T37 fragment simulating projectile:

Round No.	Striking Velocity ft/sec	Result
1	1510	CP,PTP
2	1475	CP,PTP
3	1440	CP,PTP
4	1515	CP,PTP
5	1390	PP,bulge
6	1400	PP,3/8" crack
7	1420	CP,PTP
8	1430	PP,3/8" crack
9	1325	PP,1/4" crack
10	1320	PP, 5/16" crack
11	1430	CP,PTP
12	1335	PP, 3/16" and 1/4" cracks

Protection Ballistic Limit (V_{50}) = 1445 ft/sec.



FRONT PLATE I BACK



WATERTOWN ARSENAL

COMPANY B, TITANIUM PLATES AFTER BALLISTIC TESTING WITH CAL. .22 T37 FRAGMENT SIMULATING PROJECTILES.

WTN.715-2437

FIGURE 3

Plate No. - 3-301-273

Thickness - 0.117" Size - 6" x 6"

Description of Material - Powder metallurgy product, sheath rolled in iron. Manufactured by Bureau of Mines.

Hardness - 171 Brinell

Tested with cal. .30 M2 ball ammunition:

Round No.	Striking Velocity f/s	Results
1	860	PP, slight bulge
2	1055	CP, FPTP, 1 3/4" - longitudinal crack 1/2" - transverse crack
3	1055	CP, FPTP, 1 7/8" - longitudinal crack 3/8" - transverse crack
4	910	CP, FPTP, 1 1/2" - longitudinal crack.

Army Ballistic Limit - 885 ft/sec.

Plate No. S-298-252

Thickness - 0.243"   Size - 6" x 6"

Description of Material - Powder metallurgy product, sheath rolled in iron. Manufactured by Bureau of Mines

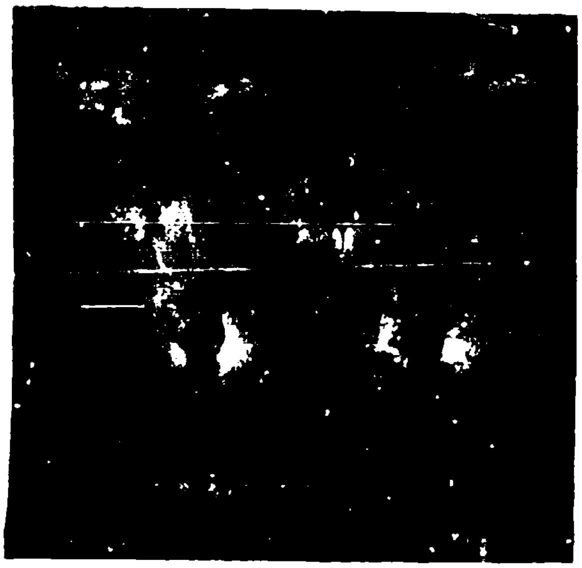
Hardness - 192 Brinell

Tested with cal. .30 M2 ball ammunition:

Round No.	Striking Velocity f/s	Results
1	1670	PP, MB, 5/8" Longitudinal crack
2	1800	PP, MB, 1" longitudinal crack
3	1880	CP, LB, star cracks, punching started
4	2010	CP, 5/8" and 1/4" piece broken out

Army Ballistic Limit - 1840 ft/sec

FRONT PLATE NO. 5 - 301 - 273 0.117" THICK BACK



FRONT PLATE NO. 5 - 298 - 252 0.243" THICK BACK

BUREAU OF MINES SHEATH-ROLLED TITANIUM AFTER BALLISTIC TESTING WITH CALIBER .30 M2

WTN.710-2436

FIGURE 4

Plate No. S-286-157

Thickness - 0.490" Size - 6" x 6"

Description of Material - Powder metallurgy product, sheath rolled in iron. Manufactured by Bureau of Mines

Hardness - 170 Brinell

Tested with cal. .40 scale models of 90 MM AP T33 shot:

Round No.	Obliquity	Striking Velocity f/s	Results
41	0°	1360	PP,CIP,LB,star cracking
42	0°	1700	CP,PTP,petals thrown off back
43	0°	1345	PP,CIP,star cracks, punching started
44	0°	1330	PP,CIP,star cracking
50	0°	1510	CP,PTP,petals thrown off back
45	45°	1645	PP,SB, no cracks
46	45°	2240	PP,SB, no cracks
47	45°	2170	PP,SB, no cracks
48	45°	2460	CP,PTP,exit 13/16" x 5/8"
49	45°	2390	CP,PTP,exit 13/16" x 9/16"

Protection Ballistic Limit - 0° obliquity - 1435 ft/sec

Protection Ballistic Limit - 45° obliquity - 2315 ft/sec

Plate No. 403

Thickness - .670"   Size - 6" x 8"

Description of Material - Powder Metallurgy product, sheath rolled in iron   Manufactured by Bureau of Mines

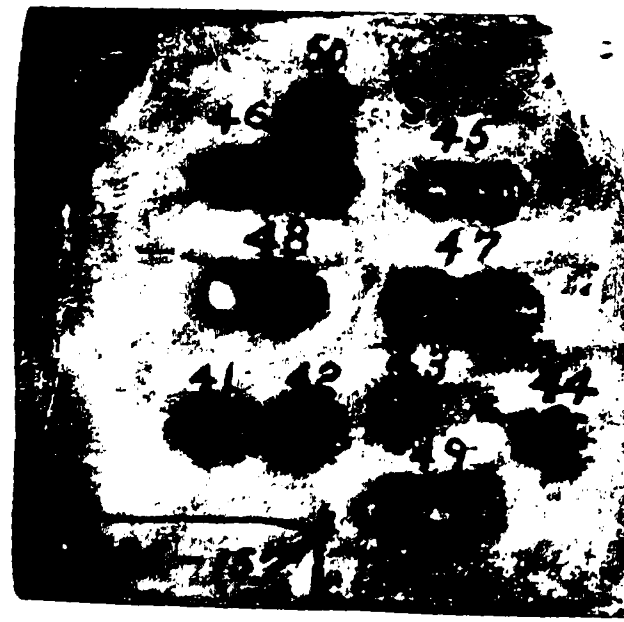
Hardness - 207 Brinell

Tested with cal. .40 scale models of 90 MM AP T33 shot:

Round No.	Obliquity	Striking Velocity f/s	Results
25	0°	1760	Struck edge of plate, disregard
26	0°	1720	PP,CIP,MB,star cracks on back
27	0°	1765	PP,CIP,MB,star cracks on back
28	0°	1780	PP,CIP,MB,star cracks on back
29	0°	1860	CP,PTP,1 1/8" x 1 1/16" back spall
30	0°	1800	PP,LB,star cracks, back spall started
31	45°	2845	PP,MB,1 3/8" longitudinal crack in back
32	45°	2950	CP,PTP,1 1/4" x 1" back spall
33	45°	2850	PP,MB,1 1/4" longitudinal crack in back
34	45°	2950	CP,PTP,1 3/8" x 1 1/4" back spall

Protection Ballistic Limit - 0° obliquity - 1830 ft/sec

Protection Ballistic Limit - 45° obliquity - 2900 ft/sec

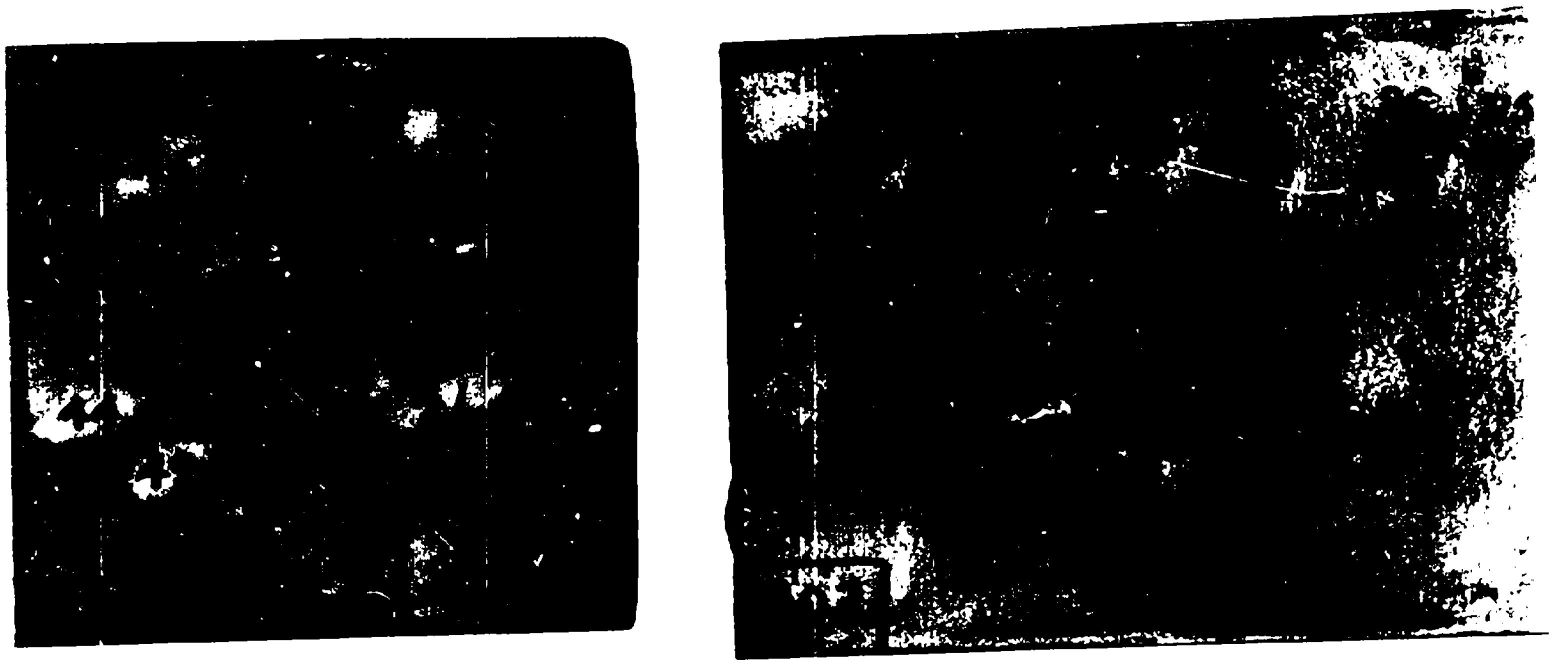


WATERTOWN ARSENAL

BUREAU OF MINES SHEATH ROLLED TITANIUM AFTER BALLISTIC TESTING WITH CALIBER .40 SCALE MODEL OF 90MM AP T33 SHOT FRONTS OF PLATES. NO. 403 - .670" THICK, NO. 8-286-157 - .490" THICK.

WTN.710-2456

FIGURE 5



WATERTOWN ARSENAL

BUREAU OF MINES SHEATH ROLLED TITANIUM AFTER BALLISTIC TESTING WITH CALIBER .40 SCALE MODEL OF 90MM AP T33 SHOT
BACKS OF PLATES. NO. 403 - .670" THICK, NO. 8-286-157 - .490" THICK.

WTN.710-2457

FIGURE 6

Plates #1 and #2

Thickness - 0.284 Size - 6" x 9"

Description of Material - Heat treated alloy steel armor plate

Hardness - 320 Brinell

Tested with cal. .40 scale models of 90MM AP T33 shot:

Round No.	Obliquity	Striking Velocity f/s	Results
1	0°	1735	CP,PTP,petalling
2	0°	2170	CP,PTP,petalling
3	0°	1360	PP,LB
4	0°	1320	PP,Disregard, projectile yawed
5	0°	1760	CP,PTP,petalling
6	0°	1805	CP,PTP,petalling
7	0°	2025	CP,PTP,petalling
35	0°	2670	CP,PTP,petalling
36	0°	2790	CP,PTP,petalling, petals all off
37	0°	1000	PP,MB
38	0°	1210	PP,MB
39	0°	1500	CP,PTP,petalling
40	0°	1465	CP,PTP,petalling
51	0°	1555	CP,PTP,petalling
52	0°	2030	CP,PTP,petalling
53	0°	1565	CP,PTP,petalling
54	0°	1135	PP,MB
55	0°	1420	CP,CIP,petalling
8	45°	2215	CP,CIP
9	45°	2115	CP,PTP
10	45°	1715	PP,MB
11	45°	1870	PP,MB,knocked out Round #8
12	45°	1980	PP,LB, 1/4" crack on back
13	45°	2220	CP,PTP
14	45°	2195	CP,FPTP,base intact in plate
15	45°	2050	PP,MB

Protection Ballistic Limit - 0° obliquity - 1390 ft/sec
Protection Ballistic Limit - 45° obliquity - 2080 ft/sec

Plate No. 3

Thickness - 0.388"   Size - 6" x 9"

Description of Material - Heat treated alloy steel armor plate

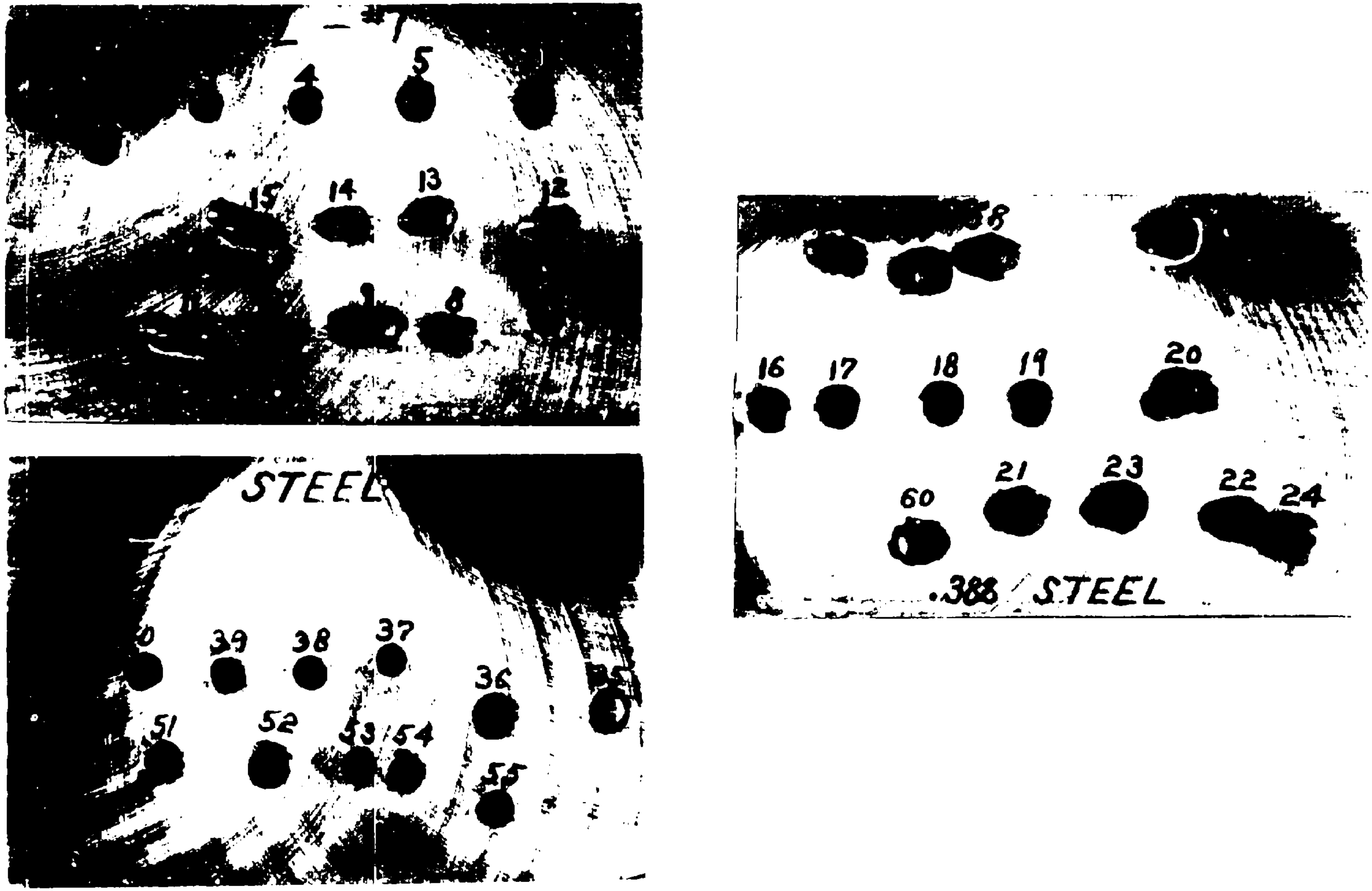
Hardness - 320 Brinell

Tested with cal. .40 scale models of 90 MM T33 shot:

Round No.	Obliquity	Striking Velocity f/s	Results
16	0°	1635	PP,LB
17	0°	1735	PP,LB,star cracking
18	0°	1805	CP,CIP,petalling
19	0°	1800	PP,CIP,star cracking, nose of projectile visible
20	45°	2865	PP,LB
21	45°	3120	CP,PTP,exit 1/2" x 1/2"
22	45°	2900	CP,PTP,exit 1/2" x 7/16"
23	45°	3080	CP,PTP,exit 9/16" x 1/2"
24	45°	2950	CP,PTP,exit 5/8" x 5/8"
56	45°	2260	PP,MB
57	45°	3065	CP,PTP,exit 5/8" x 7/16"
58	45°	2740	Disregard, too close to Round #57
59	45°	2905	CP,PTP,exit 1/2" x 1/2"
60	45°	2885	CP,PTP,exit 7/16" x 7/16"

Protection Ballistic Limit - 0° obliquity - 1805 ft/sec

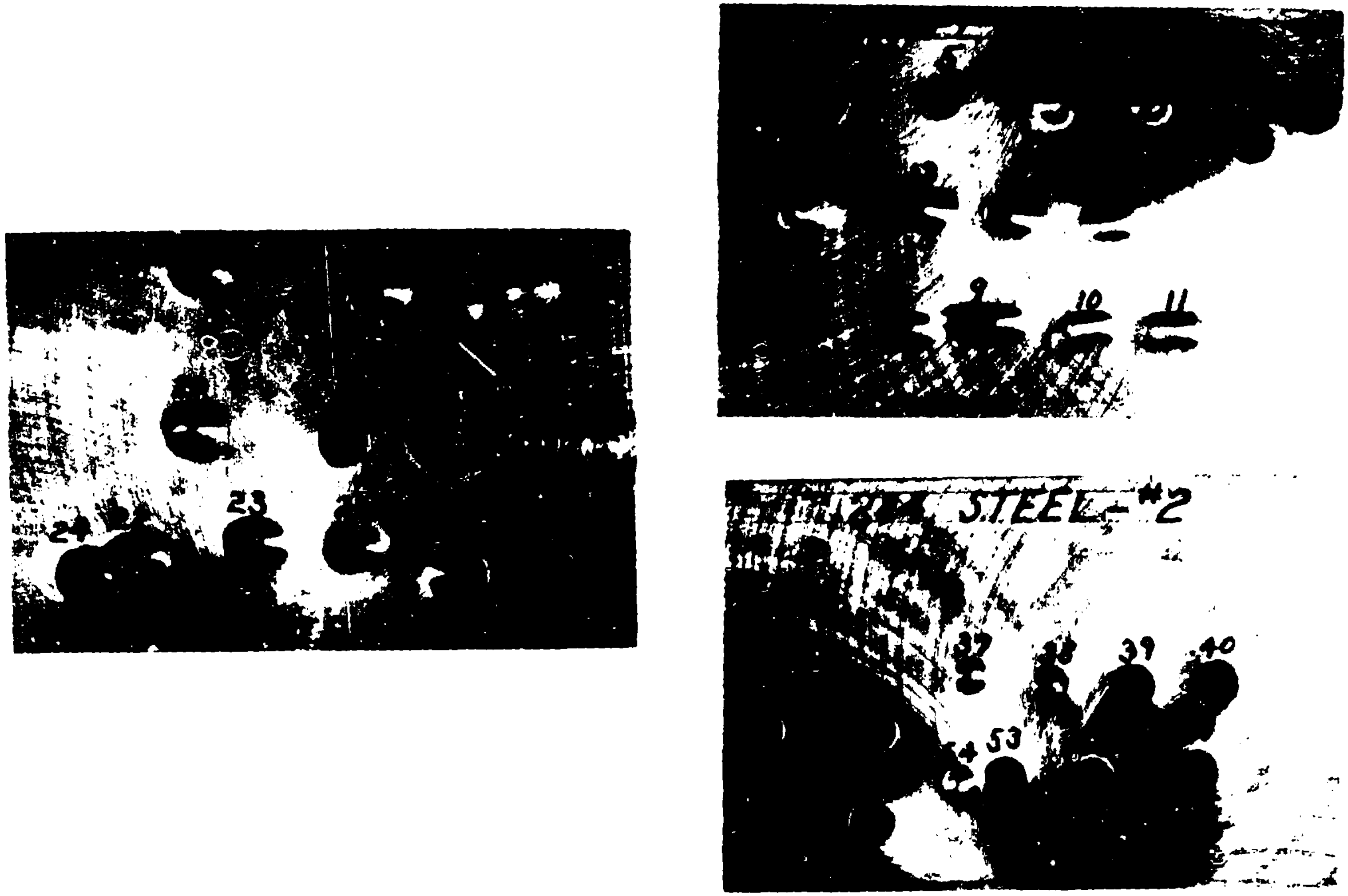
Protection Ballistic Limit - 45° obliquity - 2875 ft/sec



WATERTOWN ARSENAL

STEEL ARMOR AFTER BALLISTIC TESTING WITH CALIBER .40 SCALE MODEL OF 90MM AP T33 SHOT. FRONTS OF PLATES.
WTN.710-2458

FIGURE 7



WATERTOWN ARSENAL

STEEL ARMOR AFTER BALLISTIC TESTING WITH CALIBER .40 SCALE MODEL OF 90MM AP T33 SHOT. BACKS OF PLATES.
WTN.710-2459

FIGURE 8

APPENDIX B

MICROSTRUCTURAL CHARACTERISTICS
OF
SEVERAL TITANIUM AND TITANIUM ALLOY SPECIMENS

WAL 401/16

O.O. PROJECT TB4-103B

M. R. NORTON
Metallurgist

WATERTOWN ARSENAL LABORATORY

Authorized by:	RAD ORDTB 8-9687, 9 Jan 1948 ORDTB 9-10979, 11 May 1949	24 May 1950
OO Project No.:	TB4-103B	
Report No.:	401/16	
Priority:	1C	
Title of OO Project:	Investigation of Properties of Titanium	
WAL Project No.:	10.47S	

TITLE

Microstructural Characteristics of Several Titanium and Titanium Alloy Specimens

OBJECT

To obtain and describe the microstructures of specimens of titanium and titanium alloys acquired by this Laboratory in preparation for and in connection with investigations of the properties of titanium.

SUMMARY

Microstructures of a number of titanium and titanium alloy specimens have been recorded. Polishing and etching techniques for such specimens have been outlined and discussed. The microstructures have been described in detail and in some cases, have been compared with published photomicrographs. Special discussion has been devoted to those specimens for which physical and ballistic test data are presented in Report No. WAL 401/17.

CONCLUSIONS

1. Metallographic techniques for titanium and its alloys can withstand considerable improvement. Further work on this subject is considered essential.

2. The microstructures of the two commercially pure titanium plates obtained from melted titanium sponge contain equiaxed grains of alpha titanium and an unidentified phase. The structure may be associated with good physical and ballistic properties.

3. The microstructures of the four commercially pure titanium plates obtained from titanium metal powder display excessive lack of uniformity. Structures are mostly mixtures of equiaxed alpha titanium and acicular alpha titanium. They compare unfavorably with published structures of similar material. The structures are generally associated with inferior impact data and with cracking during ballistic testing. One plate was an exception.

4. The Fe-Cr titanium alloy possesses a severely banded structure. This condition may be associated with longitudinal cracking in ballistic test.

5. The Cr-Al titanium alloy has an extremely inhomogeneous structure. This complete lack of uniformity is reflected in poor impact properties.

M. R. Norton

M. R. NORTON
Metallurgist

APPROVED:

J. L. MARTIN
Director of Laboratory

INTRODUCTION

This report contains a record of metallographic data obtained on an assortment of titanium and titanium alloy specimens which became available from time to time during the past year. The work was initiated in anticipation of the current Laboratory program for evaluating the properties of titanium, a program in which structure studies are essential. The original intent was to acquire experience with metallographic techniques for titanium. It developed, later, that a Laboratory investigation of the physical and ballistic properties of titanium had included tests on much of the same material. Thus it seems advisable to present the group of microstructures obtained to date as an adjunct to Report No. WAL 401/17. Results of additional experiments with metallographic techniques will be incorporated in a future report.

The material used in these studies is described below. An asterisk indicates the items for which physical property data are recorded in Report No. WAL 401/17. The available chemical compositions are listed in Table II of the above-mentioned report.

Source	Identification As Received	Type of Metal	Method of Fabrication	Microstructure Illustrated in
Co. Y	None	Iodide Ti rod	3/8" Ti deposited on 3 mm W wire cold swaged to 3/16" diam. (approx.)	Figs. 1A, 1B
Co. C	None	Commercially pure Ti sheet	Company A sponge melted in water-cooled Cu crucible, hot rolled to 0.05"	Figs. 2A, 2B
Co. B	None	Commercially pure Ti sheet	Company A sponge melted in graphite, rolling practice unavailable	Fig. 3
Co. Y*	#8-301-273	Commercially pure Ti sheet	Ti powder, compacted, presintered and sheath rolled to 0.117"	Figs. 4A, 4B
Co. Y*	#8-298-252	Commercially pure Ti sheet	Ti powder, compacted, presintered and sheath rolled to 0.243"	Figs. 5A, 5B
Co. Y*	#8-286-157	Commercially pure Ti sheet	Ti powder, compacted, presintered and sheath rolled to 0.490"	Figs. 6A, 6B, 6C, 6D, 6E, 6F

Source	Identification As Received	Type of Metal	Method of Fabrication	Microstructure Illustrated in
Co. Y*	#PS-255-403	Commercially pure Ti sheet	Ti powder, compacted, sheath rolled, with no presinter, to 0.670"	Figs. 7A,7B, 7C,7D,7E,7F
Co. C*	#133	Ti alloy containing Fe and Cr sheet	Company A sponge, arc melted and alloyed in Cu crucible, cast, hot-rolled to 0.075" and heat treated	Figs. 8A,8B, 8C,8D,8E
Co. D*	X	Ti alloy containing Cr and Al metal -- received as-forged bar 1/2"x1/2"x30"	Method of preparation unavailable	Figs. 9A,9B, 9C,9D,9E, 9F,9G,9H, 9I

* Same as material used for Report No. WAL 401/17.

DATA AND DISCUSSION

Metallographic Polishing

Some elaborate practices for polishing titanium and its alloys have been published recently. The procedure used for the present study did not differ greatly from conventional methods. Care in applying the procedure was found to be highly essential.

Initial surfacing was accomplished with a Blanchard grinder on a wet surface grinder, removing sufficiently any material affected by the cut-off wheel. Samples were then ground on #240, #320, and #400 grit silicon carbide abrasive papers followed by (1) polishing with one or more grades of diamond powder or (2) by additional grinding with extremely fine aluminum oxide papers (#500, #600, and #800 grit). Final polishing was always effected with carefully levigated alumina.

By avoiding procedures which induce deep, deformed layers of metal it was found that titanium does not require repeated polishing and etching to remove such layers. (This is true of other metals, too.) The possible effect of polishing on the microstructure was suspected in two cases, as will be noted later. The improvement of polishing techniques continues to be one objective in the current investigation of the metallography of titanium.

Etching*

With the metallography of titanium and its alloys still in the development stage, there are at present no standardized etchants for these metals. Lacking handbook information, it becomes necessary to depend upon current literature for suggested etching reagents or to devise new ones. Publications emanating from the Bureau of Mines[1], Battelle Memorial Institute[2], Remington Arms[3], and P. R. Mallory Company[4], indicate a preference for hydrofluoric acid in various concentrations as well as mixtures of hydrofluoric acid and nitric acid. One British paper[5] on the tensile properties of titanium illustrates the use of a boiling, 50% aqueous, solution of hydrochloric acid.

Two etchants were employed to obtain the microstructures described below, namely, hydrofluoric acid and a 50% aqueous solution of hydrochloric acid. When concentrated, the hydrofluoric acid attacked the metals rather severely. Etching times of one to twenty seconds proved to be more than adequate for most specimens. Plates Nos. S-286-157 and PS-255-403, however, required an immersion of eight minutes and 5 minutes respectively before structure was revealed. The 50% aqueous solution of hydrochloric acid was found to be more easily handled when used hot instead of boiling and the attack was sufficiently effective. This solution revealed structure in seventy seconds on the two plates which had required five and eight minutes immersion in hydrofluoric acid. Conversely, the specimens which were etched for shorter times in HF required a longer immersion in the hot, 50% hydrochloric acid solution.

Tests of the mixed-acids reagent will be made as the work progresses. There appears to be a definite need for some experiments to discover adequate etching reagents for titanium and titanium alloys. Mr. W. P. Clancy of this Laboratory has recently obtained come interesting preliminary results with alkaline-base etchants. Further investigation of these solutions is being pursued.

Structure of Swaged Iodide Titanium Rod

This rod was received in the as-swaged condition. It had been manufactured by Company Y, and had consisted of a 3/8" deposit of titanium on a 3 mm tungsten wire core. Swaging had reduced the diameter approximately 50%. No heat treatments or physical tests of this material have been conducted during the present investigation.

Figure 1A (X200) shows the structure as revealed by hot, 50% HCl. The Widmanstatten-like structure in the lower left corner indicates the tungsten core. It is surrounded by a circular area of fine structure which suggests that diffusion of the tungsten may have occurred. A line

* See Page 10

of small, white areas may be seen extending horizontally to the right of the core. Above and below this line more white patches outline regions which may represent the grains of the originally deposited metal.

Figure 1B (X200) shows the structure produced by concentrated HF on the same sample. Note that the white patches of Figure 1A are now dark. The core material, too, has been blackened appearing smaller than it does in Figure 1A. The fact that these two constituents are not identical was indicated by another etching treatment. A mixture of H_2O_2 and NaOH left the entire specimen, except the core area, unattacked.

In both Figures 1A and 1B the microstructure appears as a disorganized mass resulting from the deformation during swaging. It is planned to heat treat some of this material to produce equiaxed grains.

Commercially Pure Titanium Sheet

The structures of Figures 2A and 2B (X200) were obtained from titanium sheet which had been made by Company C from Company A titanium sponge, melted in a water-cooled copper crucible and hot-rolled to 0.05". Both 50% HCl and concentrated HF revealed equiaxed grains of alpha titanium. The details within these grains give rise to speculation. They appear as dark needle-like streaks in Figure 2B. Upon careful examination one may see similar lines within the grains of Figure 2A. This feature of the structure resembles the unidentified precipitate which Jaffee and Campbell[2] observed in iodide titanium and which they attributed to deformation during polishing. The material is not likely to be a carbide phase because the metal was melted in a water-cooled copper crucible. Evidence of what might be considered carbide is shown in Figure 3, which portrays the structure of another commercially pure titanium sheet. In this case, the Company A sponge was melted by Company B in graphite. The dark spots and elongated black streaks visible in the microstructure might well be carbides. They differ from the needle-like particles in Figure 2B. In addition, they bear no resemblance to the evidence of deformation one might expect to stem from polishing. Since both samples were of a similar hardness and were subjected to the same polishing procedure, one should expect to find polishing effects in both. The absence of so-called polishing effects in Figure 3 indicates that the unidentified details in Figures 2A and 2B may be valid portions of the microstructure. There remains the possibility that the dark details are nitrides. The chemical composition of the sheet is not available. Further study will be devoted to the structural details of this specimen.

The titanium sheet structure illustrated in Figure 3 displays grains which are similar to, but somewhat larger than, the grains in the titanium sheet structure of Figures 2A and 2B. No physical test data or ballistic data were obtained for these sheets. The sheets are, however, similar to Sheets Nos. 1, 2, and 106 for which test results are recorded in Report No. WAL 401/17. Ballistic tests indicated that plates of this nature have good ductility.

Commercially Pure Titanium Sheet Prepared from Titanium Metal Powder

1. Plate No. S-301-273

This plate, manufactured by Company X, was obtained from titanium metal powder, presintered and sheath rolled to 0.117" thickness. The microstructure of a transverse section, etched with HF, is presented in Figures 4A and 4B (X200). Figure 4B, which typifies the center of the plate, shows the structure to be predominantly acicular alpha titanium (the structure resulting from the transformation which occurs during the quenching of beta titanium). The remaining structure is equiaxed alpha titanium. The latter was apparently unaffected during the rolling process. Figure 4A shows the structure at the edge of the plate. At the very outer surface there is a thin structureless layer. The region consists of a mixture of alpha titanium and acicular alpha titanium with more areas of the former than are present at the plate center. Ballistic data for this material, recorded in Report No. WAL 401/17, indicate that it is brittle and tends to crack in the direction parallel to rolling.

2. Plate No. S-298-252

This plate, manufactured by Company X, was obtained from titanium metal powder, presintered and sheath rolled to a thickness of 0.243". Microstructures may be seen in Figures 5A and 5B (X200). Like Plate No. S-301-273, this plate has a mixed microstructure. Here, however, the equiaxed alpha areas predominate, the remaining areas being acicular alpha titanium. The small black spots indicate a porosity which was absent in the thinner plate. Ballistic data for this material are recorded in Report No. WAL 401/17. It behaved well from the standpoint of penetration, but displayed brittleness and a tendency to crack in the direction parallel to rolling.

3. Plate No. S-286-157

This plate was manufactured by Company X from titanium metal powder compacted, presintered and sheath rolled to 0.490" thickness. Microstructures of transverse and longitudinal sections, revealed both with hot, 50% HCl and with HF, are presented in Figures 6A, 6B, 6C, 6D, 6E and 6F (X200). Again the structure is inhomogeneous. Clear areas of alpha titanium are mixed with other areas containing sharp lines resembling slip lines. The latter could be due to mechanical deformation during polishing. These lines persisted after the specimen had been re-ground and re-etched, between acid etches. They were likewise visible when the specimen was etched with an alkaline reagent. The plate is less porous than Plate No. S-298-252 (Figure 5). Impact and ballistic data are recorded for this plate in Report No. WAL 401/17. The ballistic data are superior and the energy level in impact is higher than that for the other powdered metal plates tested.

4. Plate No. PS-255-403

This plate was manufactured by Company X from titanium metal powder, compacted, sheath rolled, with no presinter, to 0.670" thickness. Microstructures of transverse and longitudinal sections revealed both with hot, 50% HCl and concentrated HF, are shown in Figures 7A, 7B, 7C, 7D, 7E, and 7F. The structure is less uniform than that of any of the four plates made from metal powder. It consists chiefly of areas of alpha titanium alternating with areas of acicular alpha titanium. Considerable porosity is also present. All these conditions may be due to the lack of pre-sintering of this plate. Ballistic data and impact data for the material are recorded in Report No. WAL 401/17. The plate is inferior, ballistically, to Plate No. S-286-157. It also displays a low impact energy.

The microstructures of all four plates made from titanium metal powder are outstandingly lacking in uniformity. They bear practically no resemblance to the published photomicrographs[1] of plates made by a similar process. Poor physical properties might well be expected from these inhomogeneous materials.

Titanium Alloy Containing Fe and Cr

This titanium alloy sheet, manufactured by Company C, was prepared from Company A titanium sponge, arc melted in a copper crucible, cast, hot rolled to a thickness of 0.075", and heat treated. Microstructures are shown in Figures 8A, 8B, and 8C at X200, and in Figures 8D and 8E at X1000. The plate was severely banded. One peculiar band, approximately 0.0075" in width, was observed about 0.0075" from the plate edge. The band is visible in Figures 8A and 8B, after the sample was etched with concentrated HF, and in Figure 8E after an etching with 5% HF. The structure at the center of the sheet appears in Figures 8C and 8D. Note the light constituent which has been elongated in rolling and the gray areas which seem to contain a fine structure similar to that of the band as seen in Figure 8E. Ballistic data for this hard alloy sheet are given in Report No. WAL 701/17. It had good ballistic properties, but was brittle and cracked longitudinally. The reason for the longitudinal cracks is strongly evidenced by the banded microstructure.

Titanium Alloy Containing Cr and Al

The metal was received in the form of a forged bar 1/2"x1/2"x30" long. No processing history is available. The microstructure of this material is likewise characterised by extreme inhomogeneity. It is illustrated in Figures 9A (X10), 9C (X200), 9E (X1000), 9F (X1000), 9G and 9I (X3000). The unetched surface of this titanium bar displayed a large number of angular particles as shown in Figure 9B (X200) and 9D (X1000). The particles seem to be harder than the matrix and are on a slightly different level. Consequently they appear slightly out of focus when the etched structure is observed. Acid etching does not attack these particles.

Figure 9A (X10) represents practically the entire cross-section of the bar. The structure has an off-center appearance which suggests lack of uniform response to working of the metal. The light and dark areas of Figure 9A are shown again in Figure 9C (X200). The nature of the light areas is revealed in Figure 9E (X100 and Figure 9I (X3000). They consist of grains such as one might expect to find in a conventionally melted titanium alloy. The grains have a needle-like structure. The dark areas, on the other hand, display a structure typical of a powdered metal compact. Representative views are presented in Figure 9F (X1000), 9G (X3000), and 9H (X3000). Figure 9H is similar to Figure 9G, except that it was photographed with oblique illumination. In this illustration the smooth looking background areas of Figure 9G are shown to consist actually of clusters of fine particles. These particles are smaller than the large angular ones visible on the unetched surface. The angular particles might possibly be composed of titanium nitride. The excessive nonuniformity of microstructure could have been caused by incomplete melting. The poor microstructure is reflected in the extremely low impact values recorded for this specimen in Report No. WAL 401/17.

Composition of Etching Reagents

1. 50% aqueous solution of HCl:

   50 parts by volume HCl-specific gravity 1.19 (37.6%)
   50 parts by volume H_2O

2. Concentrated HF:

   HF-specific gravity 1.15 (48%)

3. 5% HF:

   5 parts by volume concentrated HF-specific gravity 1.15 (48%)
   95 parts by volume H_2O

4. H_2O_2 and NaOH:

   10 cc - 10% aqueous solution NaOH
   5 cc - 3% H_2O_2

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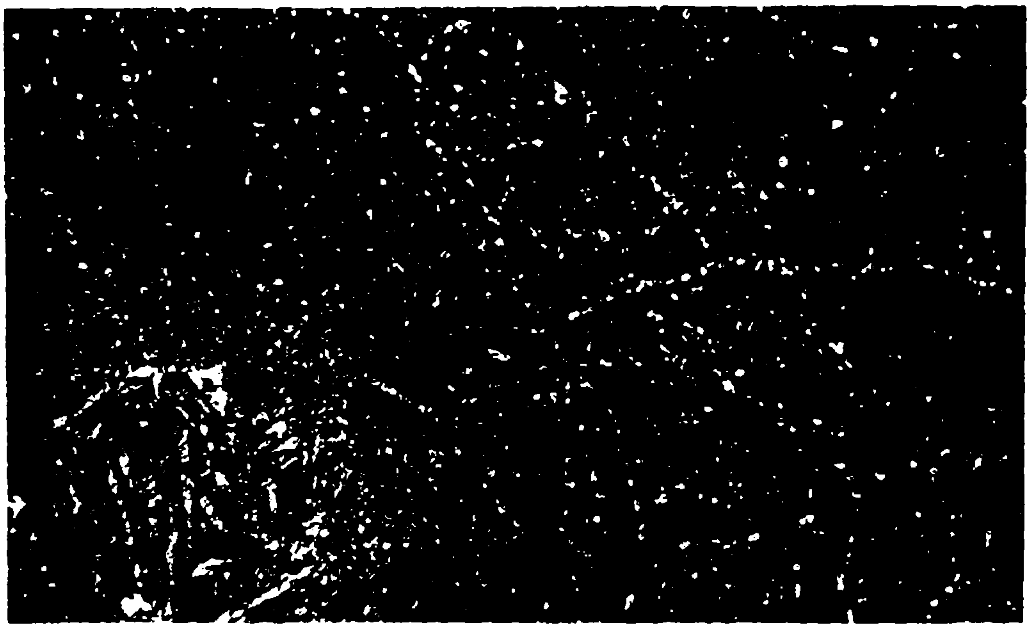
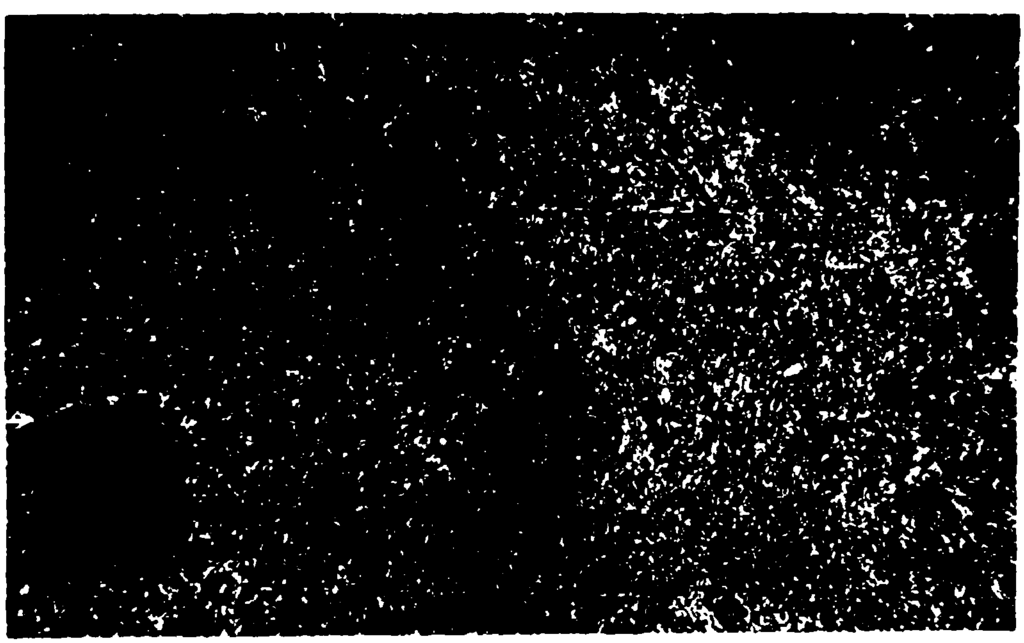


FIG. 1A x200 ETCHANT: 50% HCL

IODIDE Ti WITH 3MM W CORE. MADE BY Y COMPANY. ARROW INDICATES CORE.



WTN.630-IC,691

FIG. 1B x200 ETCHANT: HF

SAME SPECIMEN AS IN FIG. 1A, AFTER REGRINDING AND RE-ETCHING.

FIG. 2A x200 ETCHANT: 50% HCL FIG. 2B x200 ETCHANT: HF

Ti SHEET MADE BY C COMPANY FROM Ti SPONGE MELTED IN H_2O-COOLED Cu CRUCIBLE. HOT ROLLED TO 0.05". FIG. 2B SAME AS 2A AFTER REGRINDING AND RE-ETCHING.

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FIG. 3 x200 ETCHANT: HF

Ti SHEET MADE BY B COMPANY FROM Ti SPONGE INDUCTION MELTED IN GRAPHITE. ROLLING PRACTICE UNAVAILABLE.

FIG. 4A x200 ETCHANT: HF

COMMERCIALLY PURE TI PLATE #S-30.-273. SHEATH ROLLED BY X COMPANY TO 0.1.27". TRANSVERSE SECTION. ARROW INDICATES OUTER LAYER AT EDGE OF PLATE.

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FIG. 4B x200 ETCHANT: HF

SAME SPECIMEN AS IN FIG. 4A. STRUCTURE AT CENTER OF PLATE.

FIG. 5A   X200   ETCHANT: HF

COMMERCIALLY PURE Ti PLATE #S-293-252. SHEATH ROLLED BY X COMPANY TO 0.243"
ARROW INDICATES OUTER LAYER AT EDGE OF PLATE.

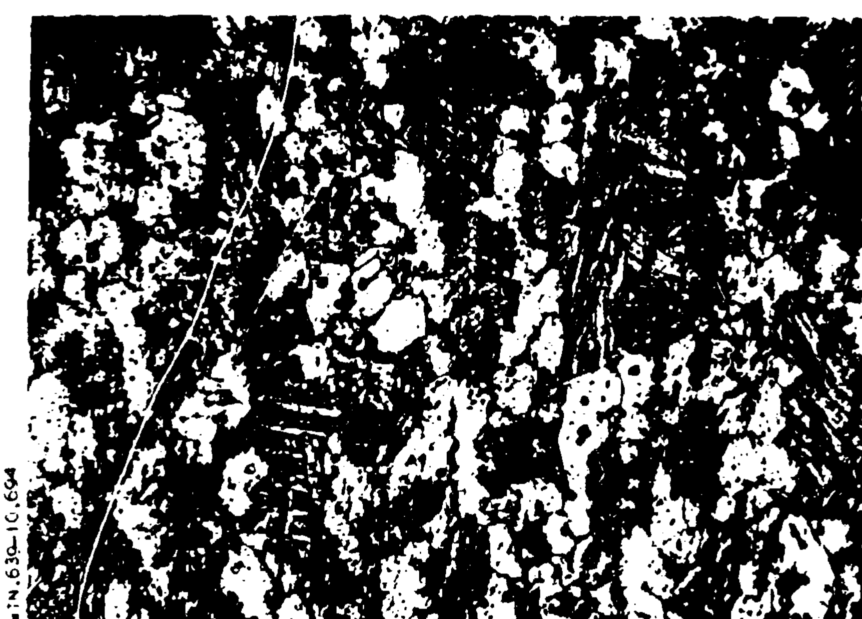

FIG. 5B   X200   ETCHANT: HF

SAME SPECIMEN AS IN FIG. 5A. STRUCTURE AT CENTER OF PLATE.

FIG. 5A X200 ETCHANT: 50% HCL
COMMERCIALLY PURE Ti PLATE #S-285-157. SHEATH ROLLED BY X COMPANY TO 0.49".
TRANSVERSE SECTION

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FIG. 5B X200 ETCHANT: 50% HCL
SAME AS FIG. 5A EXCEPT LONGITUDINAL SECTION

FIG. 6C x200 ETCHANT: 50% HCL
ANOTHER SPECIMEN FROM Ti PLATE #S-266-157. TRANSVERSE SECTION.

FIG. 6D x200 ETCHANT: 50% HCL
SAME AS FIG. 6C EXCEPT LONGITUDINAL SECTION.

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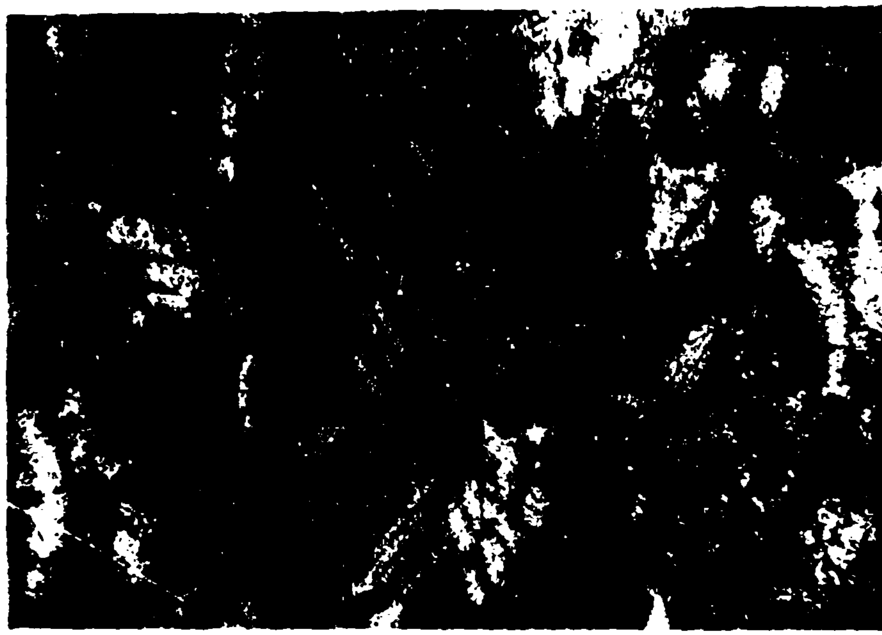

FIG. 6E x200 ETCHANT: HF

Ti PLATE #S-286-157. SAME TRANSVERSE SURFACE AS IN FIG. 6C AFTER REGRINDING AND RE-ETCHING.

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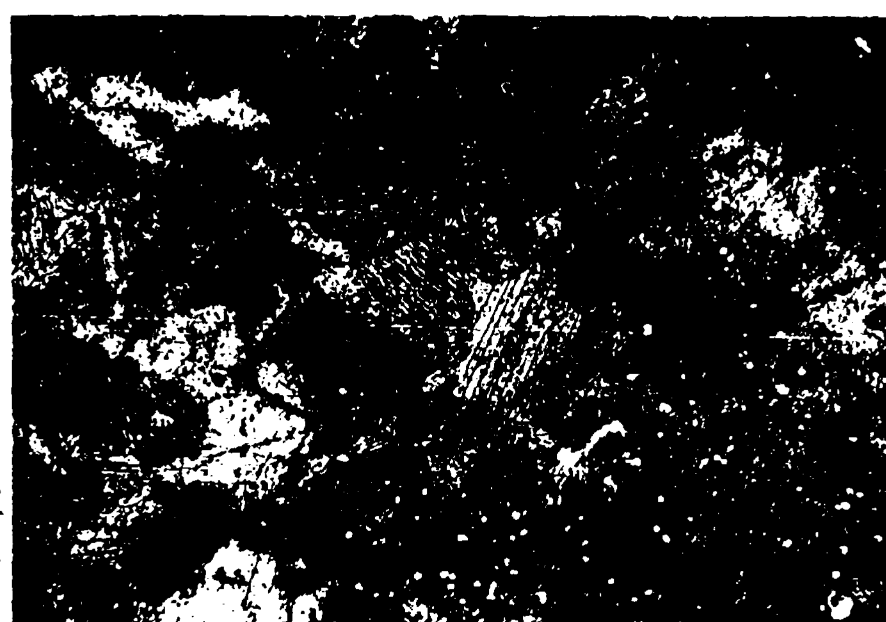

FIG. 6F x200 ETCHANT: HF

SAME LONGITUDINAL SURFACE AS IN FIG. 6D AFTER REGRINDING AND RE-ETCHING.

FIG. 7A ×200 ETCHANT: 50% HCl

COMMERCIALLY PURE Ti PLATE APS-255-403. SHEAT ROLLED BY X COMPANY TO 0.570". TRANSVERSE SECTION.

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FIG. 7B ×200 ETCHANT: 50% HCl

SAME AS FIG. 7A EXCEPT LONGITUDINAL SECTION.

FIG. 7C X200 ETCHANT: 50% HCl
ANOTHER SPECIMEN FROM Ti PLATE #PS-255-403. TRANSVERSE SECTION.

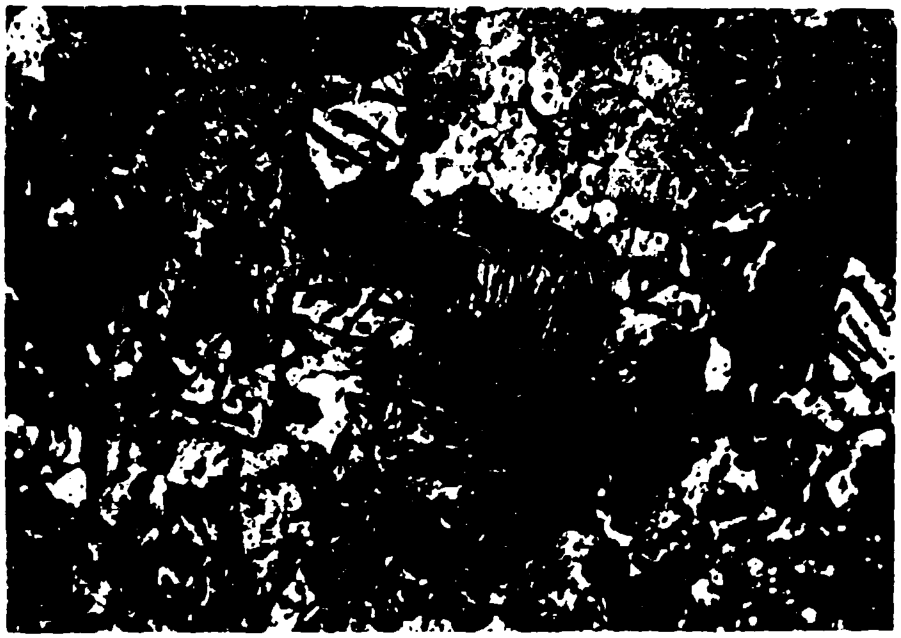

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FIG. 7D X200 ETCHANT: 50% HCl
SAME AS FIG. 7C EXCEPT LONGITUDINAL SECTION.

FIG. 7E X200 ETCHANT: HF

[illegible] PLATE XPS-2SS-433. SAME TRANSVERSE SURFACE AS IN FIG. 7C AFTER REGRINDING AND RE-ETCHING.

FIG. 7F X200 ETCHANT: HF

[illegible] SURFACE [illegible] FIG. 7D AFTER [illegible] AND [illegible]

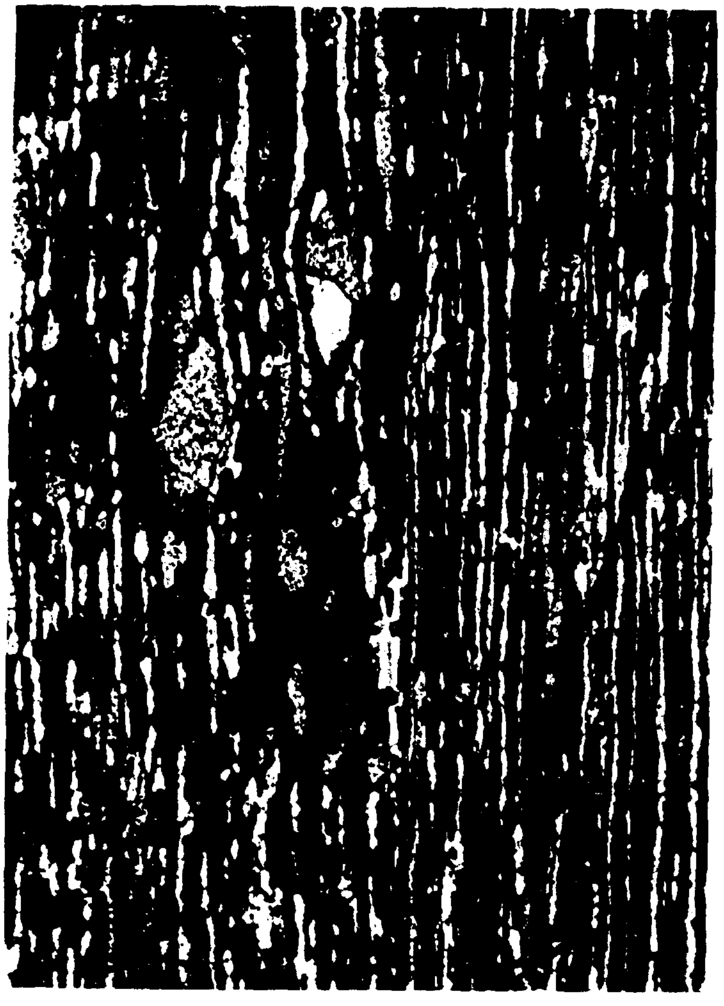

FIG. 8D X1000 ETCHANT: 5% HF FIG. 8E X1000 ETCHANT: 5% HF

C COMPANY'S TI ALLOY SHEET. SAME SPECIMEN AS SHOWN IN FIG. 8A. FIG. 8D TYPIFIES STRUCTURE AT CENTER OF SHEET. FIG. 8E REVEALS STRUCTURE WITHIN BROAD, WHITE BAND.

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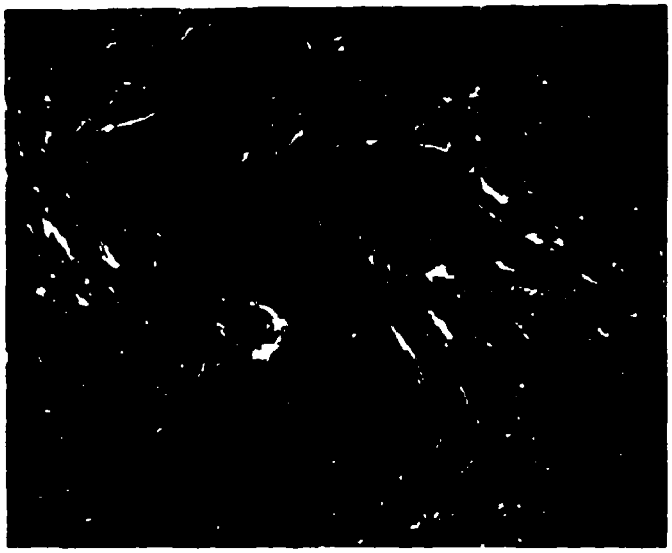

FIG. 9A X10 ETCHANT: HF

T ALLOY FORGED BAR 5" X 5" X 30" MANUFACTURED BY I COMPANY. HEAT TREATMENT UNAVAILABLE. APPROX. FULL SECTION OF THE BAR. STRUCTURE DEPICTED REVEALS EFFECT OF FORGING.

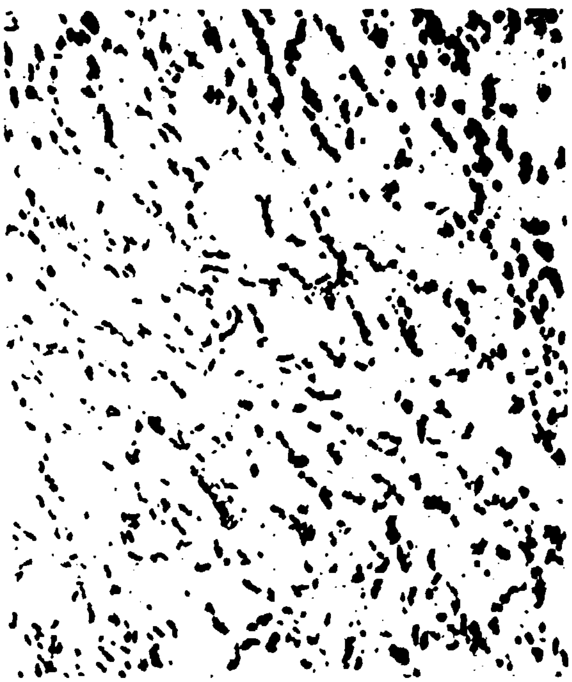

FIG. 9B X200 UNETCHED

HARD, ANGULAR PARTICLES WHICH APPEAR TO BE ABOVE THE MATRIX LEVEL.

FIG. 9C X200 ETCHANT: HF

PORTION OF FIG. 9A

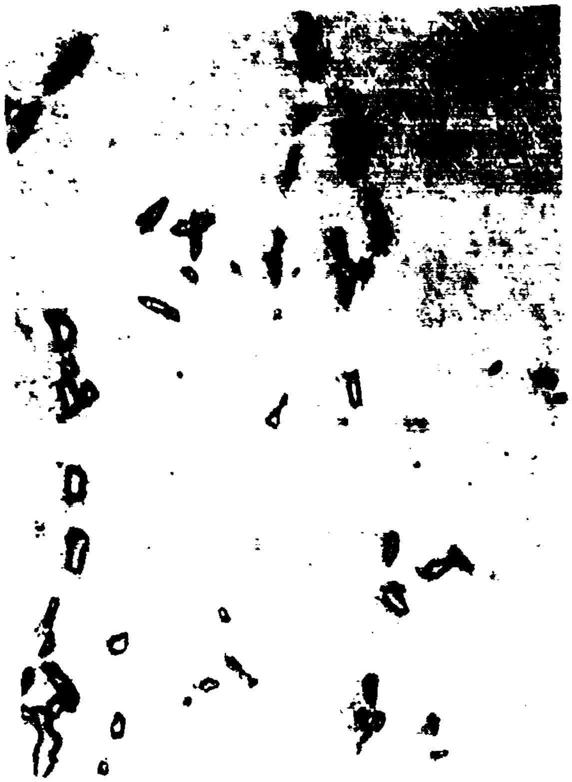

FIG. 9C X1000 UNETCHED
PORTION OF FIG. 9B

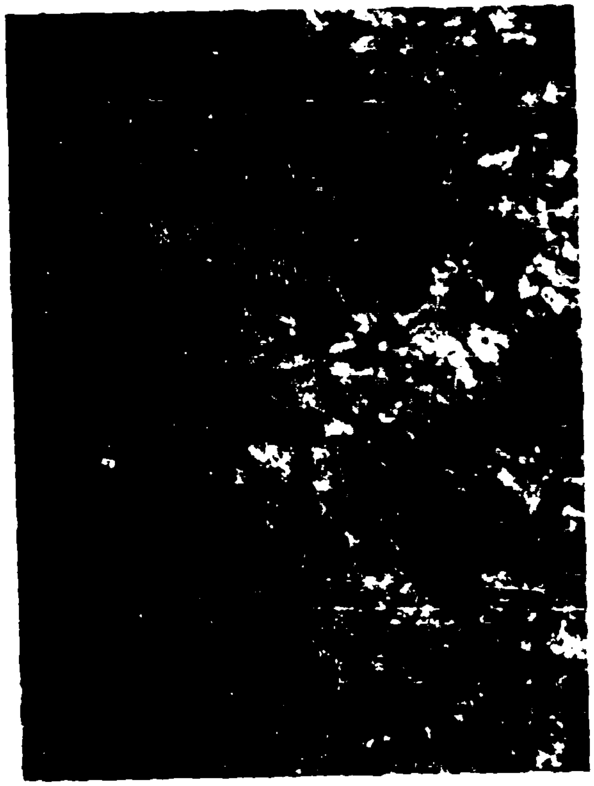

FIG. 9E X1000 ETCHANT: HF
PORTION OF FIG. 9C- "LIGHT AREA".
NOTE NEEDLE-LIKE STRUCTURE OF THE GRAINS.

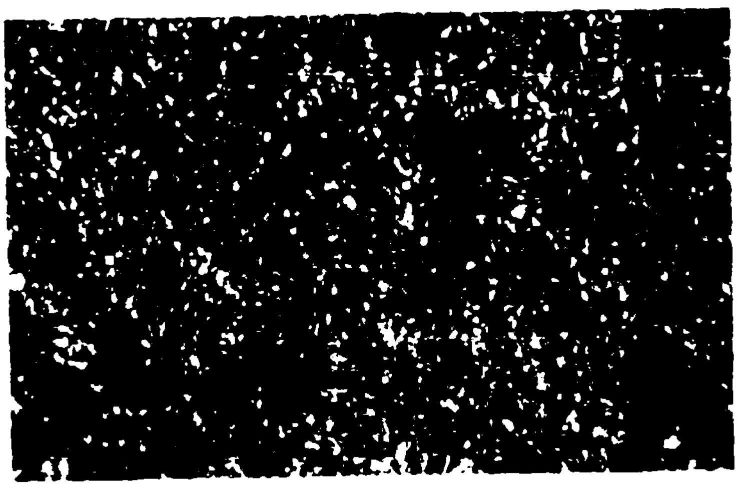

FIG. 9F X1000 ETCHANT: HF
PORTION OF FIG. 9C - "DARK AREA".

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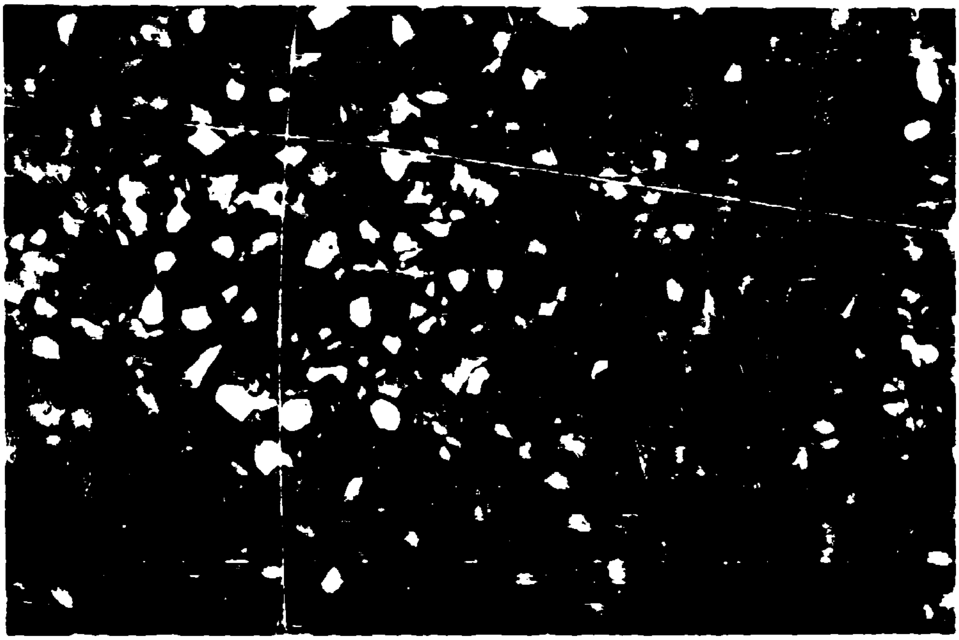
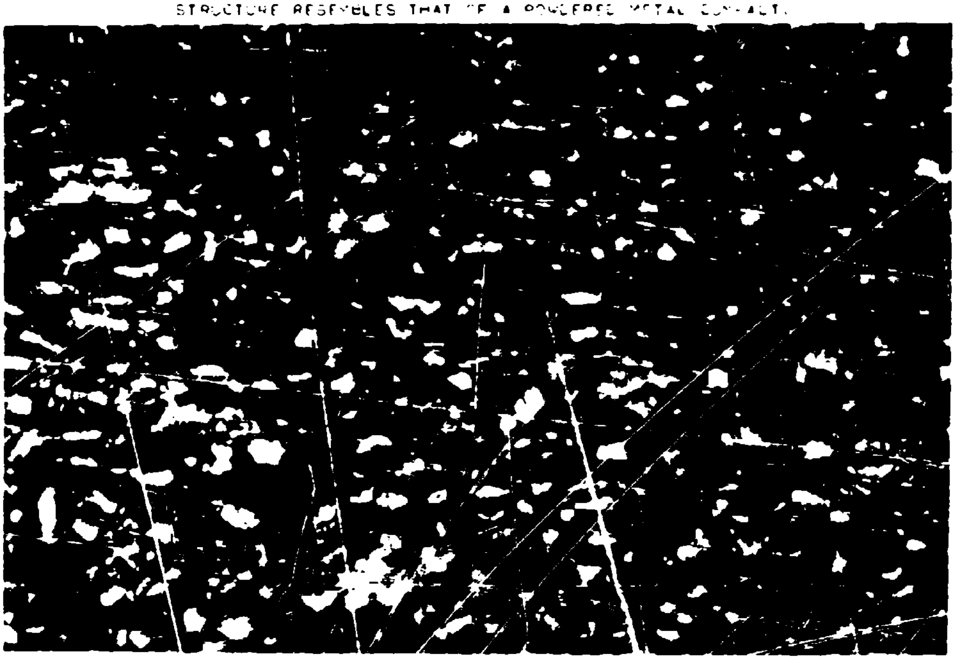


FIG. 9G — X3000 — ETCHANT: [illegible]

PORTION OF FIG. 9C – "DARK AREA".
STRUCTURE RESEMBLES THAT OF A POWDERED METAL COMPACT.



[illegible] — X3000 — ETCHANT: [illegible]

SAME [illegible] AREA AS IN FIG. [illegible] PHOTOGRAPHED WITH OBLIQUE ILLUMINATION.
NOTE THAT ENTIRE AREA IS [illegible] SEPARATE PARTICLES.

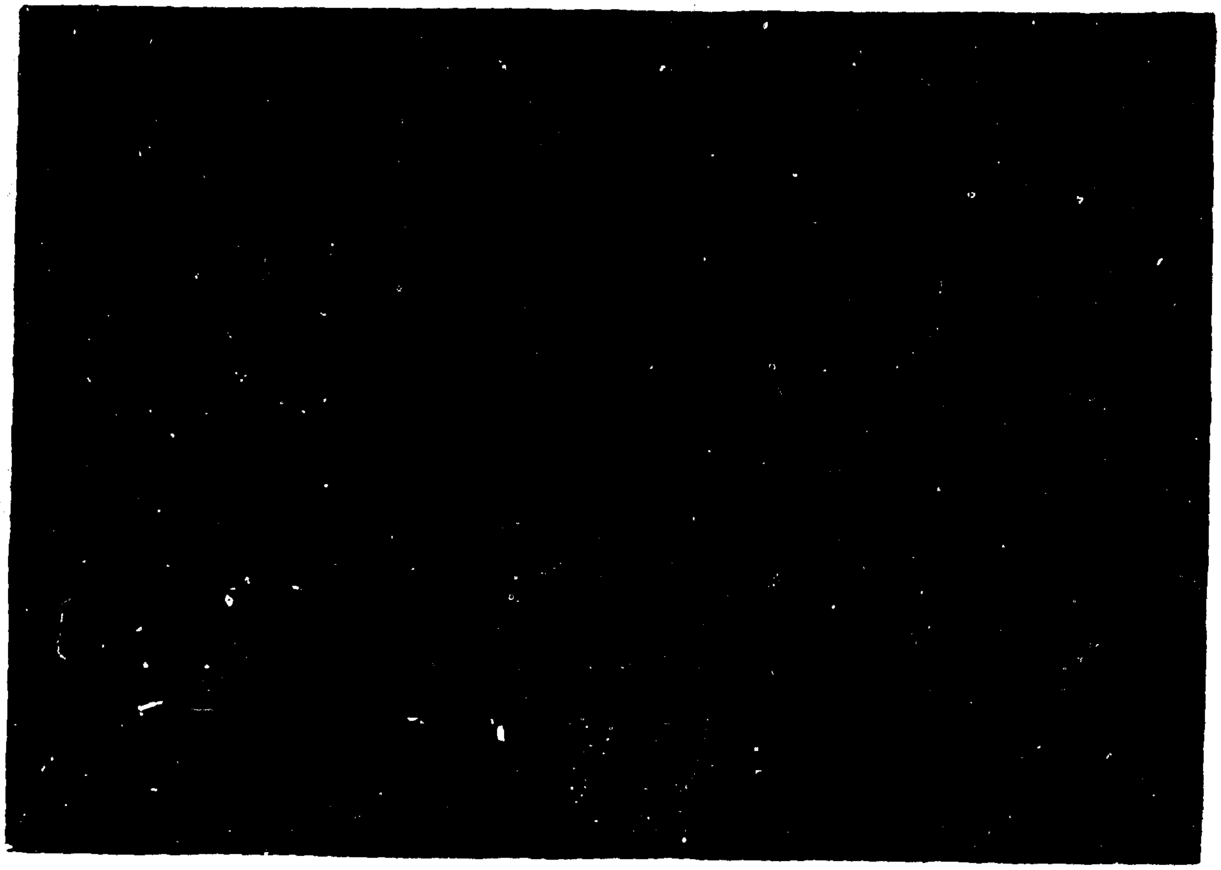


FIG. 9I x3000 ETCHANT: HF

PORTION OF FIG. 9C. NEEDLE-LIKE STRUCTURE WITHIN GRAINS OF "LIGHT AREAS" AT EXTREME LEFT IS AN ADJOINING "DARK AREA" WITH ITS PARTICLE STRUCTURE.