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ASD TR 61-446

DEVELOPMENT OF A Ti-Al-Cb ALLOY FOR USE AT 1200°-1800°F

TECHNICAL DOCUMENTARY REPORT No. ASD TR 61-446

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DIRECTORATE OF MATERIALS AND PROCESSES
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

PROJECT No. 7351, TASK No. 735105

(Prepared under Contract No. AF 33(616)-7262
by the Armour Research Foundation, Chicago, Ill.;
Joseph B. McAndrew and Charles R. Simcoe, authors)

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Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio
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2. Quaternary titanium with Sn, Hf, or Zr
3. Ternary titanium alloys

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FOREWORD

This report was prepared by Armour Research Foundation under USAF Contract No. AF 33(616)-7262, which was initiated under Project No. 7351, "Metallic Materials," Task No. 73519, "Titanium Metal and Alloys." It was administered under the direction of Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, with Mr. Paul Hendricks acting as Project Engineer.

This report covers the period from 1 May 1960 to 31 July 1961. Earlier work on the same program has been reported in WADD TR 60-99 (April, 1960).

Personnel of Armour Research Foundation who made major contributions to this program were: C. R. Simcoe, supervisor; J. B. McAndrew, project engineer; and J. E. Anderson, technician. The data reported are recorded in ARF Logbook No. C-1196. This report is identified as ARF Report 2201-15.

ABSTRACT

Titanium-base alloys containing major amounts of columbium and aluminum are being studied with the object of developing new high-temperature alloys of low density. This report presents the findings of the second year of this program, derived from the preparation and examination of (1) thirty-five quaternary alloys containing small additions of tin, hafnium, or zirconium, (2) four high-purity ternary alloys, and (3) ten-pound melts of Ti-15Cb-10Al and Ti-17.5Cb-15Al.

In a number of alloys, improved tensile properties and oxidation resistance resulted from the addition of tin, hafnium, or zirconium, and in some instances very high strength-density ratios were maintained up to 1800°F. The properties of high-purity alloys were similar to those of alloys prepared with sponge titanium. It is recommended that further effort should be directed toward the more highly alloyed compositions, including those containing hafnium and zicronium. In addition, six alloys previously prepared have been selected for continued study.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

I. PERLMUTTER
Chief, Physical Metallurgy Branch
Metals and Ceramics Laboratory
Directorate of Materials and Processes

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I. INTRODUCTION

Previous work has shown that the addition of substantial amounts of both aluminum and columbium to titanium produces alloys which are forgeable, light, oxidation resistant, and strong in short-time tests at elevated temperatures. This desirable combination of properties is sufficiently attractive to call for a complete investigation of the potential of the Ti-Al-Cb system, and the data reported here should help to provide a basis for comprehensive evaluation of this type of alloy. It has been our intention to proceed with a methodical experimental study as long as such an approach might be fruitful, leaving until a later time the fitting together of observed facts into a theoretical structure which might then suggest means for further improvement in properties.

The information reported here falls into three categories: (1) the effect of purity on several ternary alloys; (2) the effect of small additions of zirconium, hafnium, or tin on alloys containing 22.5% columbium at several levels of aluminum content; and (3) the preparation and evaluation of sheet from ten-pound ingots of Ti-17.5Cb-15Al and Ti-15Cb-10Al.

II. EXPERIMENTAL PROCEDURES

A. Materials

Except for the high-purity alloys, all melts were prepared with a single lot of magnesium-reduced sponge titanium containing 0.03% Fe and having a hardness of 96 BHN, according to the supplier. For the high-purity alloys, the titanium was E.P. ("electropotential") crystals of special purity.

Two lots of electron-beam-melted columbium were purchased. The supplier' analyses and hardness determinations for the ingots from which the lots were processed are shown in Table I. The material was received as 1/2 in. by 1/8 in. strip, which was then cold rolled to 0.030 in., sheared into small pieces suitable for melting, cleaned with CCl_4, and etched for two minutes in a solution containing 1 part HF, 5 parts HNO_3, 14 parts H_2O.

The aluminum was of 99.99% minimum purity, with the reported impurities being 0.002% Cu, 0.003% Fe, 0.001% Si, and 0.001% Mg.

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B. Master Alloys

For the ten-pound ingot of Ti-15Cb-10Al, a master alloy with the composition Cb-40Al was melted as a series of 175-g buttons, which were crushed and blended. For the ten-pound ingot of Ti-17.5Cb-15Al, a master alloy, Cb-46.15Al, was similarly prepared.

All of the quaternary and high-purity ternary alloys were made with the master alloy Ti-30Cb, which was melted as 100-g buttons, cold rolled to sheet, cut into small pieces, washed in CCl_4, and etched for two minutes in H_2O-HNO_3-HF solution.

C. Melting

The quaternary and high-purity ternary alloys were melted as 150-g pancake ingots by the nonconsumable-electrode arc melting process, each ingot being inverted and remelted four times to insure homogeneity. Each ingot was weighed after melting as a check against contamination, tungsten pickup, or loss of material.

The larger ingots of Ti-15Cb-10Al and Ti-17.5Cb-15Al were first melted in a nonconsumable-electrode, hopper-fed arc furnace. The resulting ingots were quartered longitudinally, and the four sections of each ingot were welded end to end to form a consumable electrode, which was remelted in a helium atmosphere. The final ingots were 4 in. in diameter and weighed 13 lb and 10 lb respectively.

D. Forging

Initial forging was done with a forge hammer, on flat-face dies. Forging of as-cast pancake ingots to rod by this method constitutes a severe test of forgeability. The rods were subsequently finished from approximately 1/2 in. diameter to 3/8 in. in swage blocks, also with the hammer. The 10-lb ingots were forged to 1.75-in. slab and conditioned for rolling by milling to 1.5-in. plate.

E. Rolling

The Ti-15Cb-10Al plate was cut into three pieces. The first of these was rolled from 1.5 in. to 0.078 in. at 1700°F, with reheating before each pass. The other two pieces were rolled to 0.150 in. at 1700°F; then one was finished to 0.082 in. at 1650°F, and the other was rolled to 0.078 in. at 1600°F.

An attempt was made to roll the Ti-17.5Cb-15Al plate at 1800°F. This temperature was too low, and the plate "alligatored" before appreciable reduction was obtained. The plate was salvaged by cutting into three smaller pieces and milling off the fractured surfaces. One piece was further sectioned and used to find the lowest feasible rolling temperatures, which were 2050°F for the initial rolling and 1950°F for finishing. The two remaining sections were then rolled to 0.075 in. at these temperatures.

All sheets were sandblasted before the final three passes to ensure good surface finish, although this did not seem to be really necessary, since the oxide was fairly thin and smooth. The finished sheets were again sandblasted and then pickled in H_2O-HNO_3-HF solution.

Rolling was done on a two-high mill, and the final sheet thickness was limited by the roll pressure obtainable.

F. Heat Treating

Heat treatment of sheet material (bend and tensile specimens) was carried out in air, and surface oxide was then removed on a belt sander.

Hounsfield Tensometer specimens were heat treated in sealed Vycor bulbs containing a partial pressure of argon. They were etched lightly before testing, as were similar specimens which had not been heat treated.

G. Oxidation

Oxidation exposures were made by placing the specimens in open porcelain crucibles in a muffle furnace at 1830°F (1000°C) for 100 hr. Upon removal from the furnace, the crucibles were covered so that any scale which spalled during cooling would be retained with the specimen. After the weight gains were determined, the depth of oxidation was measured by removing the oxide with abrasive until clean metal was reached, and remeasuring a selected dimension with micrometer calipers.

One set of 21 specimens was exposed in glazed porcelain crucibles. Although similar crucibles had been used successfully before, this exposure caused unusually severe attack, and the results were discarded. It is thought that the glaze contained sufficient chloride ion to cause accelerated attack. Eight of the same alloys were run again in unglazed crucibles, and the results were then consistent with previous data. (A control specimen of Ti-22.5Cb-12.5Al gave a direct correlation with previous oxidation runs.) Another set of 22 alloys was then run in unglazed crucibles, and, in this case also, the results appeared reasonable.

H. Density

Densities were determined by measuring, with an analytical balance, the loss of weight in water at room temperature. Some of the determinations were made on the ends of tensile specimens; in other cases, oxidation specimens were used prior to the oxidation exposure. The latter were cylinders 0.375 in. in diameter by 0.50 in. long, weighing a little more than 4 grams.

I. Bend Tests

Bend tests were performed in a Di-Acro guided bend fixture, the specimens being about 1/2 in. wide and 4 to 6 in. long. A specimen was considered to have passed the test if it did not exhibit cracks visible at 10X magnification after being bent to 180° before springback. The severity of bend is expressed as R_t, the ratio of mandrel radius to sheet thickness.

J. Tensile Tests

All tensile tests of the quaternary and high-purity ternary alloys were performed with the specimen shown in Fig. 1, using a Hounsfield Tonsometer equipped with a Wild-Barfield furnace and an electronic temperature controller. An auxiliary thermocouple and potentiometer provided a check of the temperature at the midpoint of the specimen, and the controller was adjusted to give the required potentiometer reading. The subzero tests were performed with the specimen immersed in a bath of dry ice and acetone, the temperature of which was measured with a thermometer.

The Tensometer was operated at a crosshead speed of 1/8 in/min, with a strain magnification of 8 to 1. This magnification is rather low, and the yield strength values are therefore designated as approximations.

Tensile specimens of Ti-15Cb-10Al and Ti-17.5Cb-15Al from the large ingots were as shown in Fig. 2. This design was not found to be very satisfactory for these alloys. Many specimens broke through the pin hole, and this occurred even when the thickness at the pin hole was left much greater than in the gage length. These sheet specimens were tested at room temperature on a 60,000-lb Baldwin-Southwark machine equipped with an autographic recorder and extensometer of the microformer type. The loading rate was from 200 to 400 lb/min.

K. Stress-Thermal Exposure

Stress-thermal exposure of sheet tensile specimens was carried out in air on conventional creep-rupture machines with 20 to 1 lever arms. Temperatures were controlled to ± 3°F along the gage length of the specimen.

L. Welding

Welds were made with the TIG process, and were of the bead-on-plate type, but with 100% penetration of the sheet.

III. EXPERIMENTAL RESULTS

A. Button Melts

1. Forging

The forging temperatures for various alloys are shown in Table II. With the exception of two buttons, all alloys were forged without difficulty at the temperatures shown. One button of Ti-22.5Cb-15Al-5Hf cracked at 2300°F and continued breaking up at 2350°F. A duplicate forged well at 2300°F. The reason for this is not known. Ti-22.5Cb-15Al-5Sn did not forge at 2250° or 2300°F, but did forge well at 2400°F.

It was judged that most of the alloys could have been forged at temperatures at least 100° or 200°F lower than those employed.

2. Density

Densities of the forged alloys are shown in Table III. They show no anomalies, and require no special comments.

3. Oxidation

The results of two oxidation runs are shown in Tables IV and V. The first was made with the ends from broken tensile specimens, and included one ternary alloy; the second was made with cylindrical specimens and included four ternary alloys for comparison.

4. Tensile Properties

Table VI shows short-time tensile properties of the button-melt alloys. Except as noted, all specimens were in the as-forged, air-cooled condition.

5. Metallography

Some photomicrographs of typical forged structures of the quaternary alloys are shown in Figures 3 to 16. It may be seen that the microstructures are rather complex, and a definitive interpretation of them should not be attempted at this time. It is evident that these are transformation structures, formed as a consequence of the high forging temperatures. Some interesting observations may be made even though information is lacking concerning phase relationships and transformation kinetics. Three alloys which had very good properties were those in which 1Zr, 1Hf, or 5Hf were added to Ti-22.5Cb-12.5Al (Figs. 5, 6, 7). These have similar structures in which a fine-grained transformation product is seen, with the prior large-grained β structure still visible. Ti-22.5Cb-12.5Al-1Hf and Ti-22.5Cb-12.5Al-5Hf appear remarkably similar in view of the difference in properties. Structures such as those of Ti-22Cb-10Al-1Zr (Fig. 4) and Ti-22.5Cb-7.5Al-1Sn (Fig. 8) are representative of many of the alloys not shown. Aluminum content appeared to be a stronger determinant of as-forged structure than did the quaternary additions, although this may be due, in part, to differences in forging temperatures.

B. Ten-Pound Ingots

1. Bend Tests

Neither Ti-15Cb-10Al nor Ti-17.5Cb-15Al showed much bend ductility in the as-rolled condition. Several simple heat treatments were applied to both alloys with the object of improving ductility and learning more about the heat-treatment response of the two alloys. The results of these tests are shown in Table VII.

2. Tensile Tests

Tables VIII and IX show the tensile properties of Ti-15Cb-10Al and Ti-17.5Cb-15Al sheet in the as-forged, heat-treated, and stress-thermally exposed conditions. The heat treatments were necessarily chosen on the basis of very limited information, and are not likely to be optimum.

3. Welds

Weld beads in the center of Ti-17.5Cb-15Al sheet caused transverse cracks to form at each end because of thermal stresses. The cracks extended into the base metal for 1/2 to 1 1/2 in. on each side of the weld. The sheet on which this was observed had been heat treated 1 1/2 hr at 1600°F, and was expected to have better ductility than the as-rolled sheet. Bend tests of the base metal showed that this was not the case.

Ti-15Cb-10Al welds did not show such cracks after welding. However, the welds in both alloys were brittle in bend tests. Fractures occurred in the heat-affected zone immediately adjacent to the weld in Ti-15Cb-10Al, and in both heat-affected zone and weld metal in Ti-17.5Cb-15Al.

IV. DISCUSSION

From this investigation, a number of facts have been learned that indicate clearly in which directions further progress may be expected and what difficulties require primary attention. Certainly a great deal remains to be done, yet the summation of available data is quite encouraging. The more important findings will be enumerated and discussed individually.

1. Tensile properties of the high-purity alloys in the as-forged condition did not deviate in a consistent fashion from the properties of corresponding sponge-base alloys. The differences observed were such as might be accounted for by random variations in structure established during the forging operation. The very high strength of the Ti-20Cb-17.5Al specimen tested at 1200°F is noteworthy (UTS 185,000 psi, YS 164,000 psi, elongation 2.5%, RA 3.5%). This specimen had a yield-strength-to-density ratio of about 1,000,000. It remains to be seen whether such strength can be obtained consistently and in combination with other necessary properties; but, if such an achievement could be realized, it would represent a considerable advancement in the technology of high-temperature alloys.

2. Zirconium additions up to 2%, and tin or hafnium up to 5% were beneficial rather than harmful with respect to oxidation resistance. Weight gains as low as 4.4 mg/cm^2 were measured after a 1830°F(1000°C) exposure for 100 hr, and in most cases the loss of metal through oxidation amounted to less than

0.001 in. This is sufficient oxidation resistance to suggest testing at higher temperatures, and also to encourage experimenting with alloys with columbium contents other than 22.5%.

3. Improved high-temperature strength and greater ductility were obtained by the addition of hafnium or zirconium, and a few alloys containing tin were also better than the corresponding ternary alloys.

Table X compares the tensile properties of Ti-22.5Cb-10Al with those of the same alloy containing 0.5Zr or 1Hf. It may be seen that, whereas the ternary alloy was brittle at room temperature, the alloy with 0.5Zr had 3% elongation and 5% reduction in area, and the one with 1Hf had 9% elongation and 8% reduction in area. The room-temperature strengths of the quaternary alloys were lower, but this is of lesser importance in alloys intended for high-temperature use. At 1200°F, the alloys with hafnium and zirconium were lower in strength, but at 1400°F the alloy with 0.5Zr had 73% higher yield strength and that with 1Hf had 76% higher yield strength than the ternary. At 1600°F the yield strengths of the quaternary alloys were about double that of the ternary. These are certainly remarkable effects for such small additions.

Table XI shows a similar comparison for Ti-22.5Cb-12.5Al and the same alloy containing 1Hf or 1Zr. Again, the ternary alloy was brittle at room temperature, and the alloy with 1Hf had 6% elongation and 7% reduction in area, while that with 1Zr had 7% elongation and 13% reduction in area. The strengths of the quaternaries were lower at 1200°F; at 1400°F the yield strengths of the three were approximately the same, with the quaternaries having higher ultimate strengths and ductilities. At 1600°F the yield strength of the alloy with 1Hf was 17% higher, and that of the alloy with 1Zr was 10% higher than the ternary, with the quaternaries again having higher ductility.

Ti-22.5Cb-12.5Al-5Hf had the same room-temperature ductility as the alloy with 1Hf, but the high-temperature strength was further improved. The yield strength at 1600°F was 40% higher than that of the ternary alloy. At 1800°F, the yield strength of Ti-22.5Cb-12.5Al-5Hf was slightly higher than that of Ti-22.5Cb-12.5Al at 1600°F, and it was about 20% higher than that of Ti-22.5Cb-12.5Al-1Hf at 1800°F.

The alloy Ti-22.5Cb-15Al-0.5Zr was brittle in the as-forged condition at room temperature, but at 1600°F it had 29% higher yield strength than the same alloy without zirconium. The quaternary alloy (Ti-22.5Cb-15Al-0.5Zr) had, at 1800°F, an ultimate strength of 88,900 psi and a yield strength of approximately 79,000 psi. The ultimate-strength-to-density ratio is therefore 522,000 and the yield-strength-to-density ratio, 460,000. These are extremely high values for this temperature.

Ti-22.5Cb-15Al-5Sn was strong at 1600°F, having an ultimate strength of 109,300 psi and a yield of 96,000 psi. However, it was relatively weak at 1800°F, at which the ultimate was 47,800 psi and the yield was 37,000 psi.

The addition of 5% tin also improved the properties of Ti-22.5Cb-10Al. (In all of these alloys the quaternary addition replaces titanium.) The alloy with tin was slightly more ductile at room temperature and had 80% higher yield strength at 1600°F.

Other examples may be found in the data to illustrate the beneficial effects of zirconium, hafnium, or tin additions, but those cited above should suffice. Because the elevated temperature strength-density ratio is an outstanding property in these alloys, a comparison with other alloys may be of interest. At 1600°F, the ultimate tensile strength-density ratio of Ti-22.5Cb-12.5Al-5Hf in the as-forged condition is 50% higher than that of René 41, and 35% higher than that of Udimet 700. At 1800°F, it is 150% higher than René 41, 80% higher than Udimet 700, and higher than any of the refractory metal alloys of which we are aware. At 1800°F, the as-forged ultimate tensile strength-density ratio of Ti-22.5Cb-15Al-1/2Zr (522,000) is about 75% higher than that of any other commercial or experimental alloy which has come to our attention.

It seems clear that quaternary alloys should receive additional attention--particularly those containing hafnium and zirconium.

4. A number of tensile tests at temperatures below 1200°F showed large deviations from normal strength-vs.-temperature and ductility-vs.-temperature relationships. Such effects might be caused by: (1) chemical inhomogeneity of the specimen stock; (2) structural transformations occurring during test; (3) structural inhomogeneity derived from the forging operation; or (4) combinations of these. Additional specimens of Ti-22.5Cb-12.5Al-1Zr and Ti-22.5Cb-12.5Al-1Hf were prepared to obtain more information on this matter. In two out of three instances the anomalous behavior was not completely reproduced in duplicate tests. At 600°F the first specimen of Ti-22.5Cb-12.5Al-1Zr broke at 164,700 psi with no measurable yield or elongation and only 1% reduction in area. The duplicate had an ultimate strength of 166,300 psi, a yield of 148,000 psi, an elongation of 7.5% and a reduction in area of 5%. A third specimen was treated 16 hr at 1200°F and tested at 600°F. It had an ultimate strength of 166,900 psi, a yield of 155,000 psi, an elongation of 1%, and a reduction in area of 6%. Thus, although the ultimate strength was nearly the same in each case, the ductility varied significantly.

The same alloy (Ti-22.5Cb-12.5Al-1Zr) had, at 1000°F, an ultimate of 156,000 psi, a yield of 138,000 psi, an elongation of 6%, and a reduction in area of 8%. A duplicate specimen had an ultimate of 160,000 psi, a yield of 140,000 psi, an elongation of 4.5%, and a reduction in area of 11%. This is acceptable reproducibility for work of this nature. A third specimen was treated 16 hr at 1200°F and tested at 1000°F. It had an ultimate of 173,300 psi, a yield of 168,000 psi, an elongation of 1%, and a reduction in area of 1%, and was therefore significantly stronger and less ductile.

The first specimen of Ti-22.5Cb-12.5Al-1Hf tested at 400°F broke at 152,200 psi with no yield, no elongation, and 2% reduction in area. A duplicate had an ultimate of 126,400 psi, a yield of 95,000 psi, an elongation of 11%, and a reduction in area of 15%. A third specimen treated 16 hr at 1600°F and tested at 400°F had an ultimate of 131,500 psi, a yield of 95,000 psi, an elongation of 8.5%, and a reduction in area of 13%. Note that the heat-treated specimen matched one of the as-forged specimens very well, while the other was much different. This indicated that the discrepancy is not due to transformation occurring during testing.

Because the anomalies referred to above have been observed only at low test temperatures and in as-forged material, it does not seem likely that chemical inhomogeneity is a principal cause, although there is no assurance that such inhomogeneity does not occasionally occur with alloys such as these, which are composed of reactive metals with widely different melting points and densities.

The anomalous results at lower temperatures are therefore thought to be caused by structural or "cold" work variations introduced during finish forging of the bar stock from which specimens were cut. More evidence is needed for a final resolution of the question. That evidence can come from additional tensile tests and also from chemical and metallographic analyses of specimens which have already been tested.

5. Two specimens tested at -90°F in the as-forged condition had sufficient tensile ductility to suggest that there was not an abrupt transition to brittleness above this temperature. Ti-22.5Cb-12.5Al-1Zr had 169,100 psi ultimate, 151,000 psi yield, 3% elongation, and 7% reduction in area. Ti-22.5Cb-12.5Al-1Hf had 135,000 psi ultimate, 119,000 psi yield, 3% elongation, and 7.5% reduction in area.

6. Ti-15Cb-10Al could be rolled at temperatures as low as 1600°F. As-rolled sheet was not very bend ductile, but could be heat treated to pass bends as low as 2.5 t. Comparable improvement in tensile ductility by heat treatment was not obtained, although tensile strength was greatly lowered. A large percentage of the tensile specimens failed in a brittle manner at the pin holes, which is a strong indication of notch sensitivity.

7. During stress-thermal exposure of Ti-15Cb-10Al, it was noted that this material (heat treated prior to exposure) had low creep strength at 1500°, 1400°, and even 1200°F. A load of 5,000 psi for 167 hr at 1200°F caused about 2.3% creep. The initially low tensile ductility of the heat-treated Ti-15Cb-10Al sheet makes it difficult to derive significant information concerning stress-thermal embrittlement. Perhaps the most important conclusion to be reached is that this alloy is simply too lean in columbium and aluminum to meet the requirements of this program.

8. Ti-17.5Cb-15Al can be finish rolled at a temperature of 1950°F, but from the limited data available, 2000°F appears preferable. Sheet finish rolled at 1950°F passed the guided bend test at R_t=14, and failed at R_t=9. Sheet finished at 2000°F passed at R_t=12, but failed at R_t=10. Sheet finished at 2050°F failed a test at R_t=20.

The best bend ductility in heat-treated conditions was observed in material which had been finished at 1950°F and treated for 90 min at 1600°F, followed by air cooling; this passed a 4 t bend and failed 3 t. One of three specimens from the same sheet which were treated 90 min at 1750°F passed a 6 t bend and failed 4 t; the other two failed 10 t and 10.5 t tests. Such a large variation cannot be accounted for at this time, but should certainly receive further attention.

Other heat treatments which were tried did not improve bend ductility. However, none of these treatments included quenching.

Tensile ductility of the Ti-17.5Cb-15Al without heat treatment varied from 0 to 3.5% elongation. Two specimens finish rolled at 2000°F showed good duplication of tensile properties. Each had 3.5% elongation; ultimate tensile strengths were 139,000 and 140,000 psi; 0.1% yield strengths were 108,000 and 105,000 psi; and Young's moduli were 12.0 and 12.9 X 10^6 psi. In contrast to this, the sheet finish rolled at 1950°F had ultimate tensile strengths, in different specimens, of 104,000; 112,000; 133,600; and 148,000 psi, with moduli of 17.4, 17.1, 12.5, and 15.6 X 10^6 psi and ductilities of 0, 0, 3.5, and 2.5% elongation. Again, we do not know the cause of this variation, but the heat-treated specimens showed much better duplication, so that it is probable that 1950°F was a rather critical rolling temperature at which the temperature control was insufficient to ensure uniformity.

As with Ti-15Cb-10Al, there was a tendency for the Ti-17.5Cb-15Al tensile specimens to break through the pin holes, although the tendency was less pronounced in the latter alloy.

9. Stress-thermal exposures of Ti-17.5Cb-15Al were made with material previously heat treated at 1500°F or 1600°F. For both heat treatments the creep strength was low, though much better than that of Ti-15Cb-10Al. Despite the unexpectedly large amount of creep, the stress-thermal exposures did not cause embrittlement; they did, however further lower the strength, which had already been reduced by the prior heat treatments. Two specimens, the first stressed at 7,500 psi and 1500°F for 167 hr (5% creep), the second stressed at 10,000 psi and 1500°F for 170 hr (10% creep), had 4.5% elongation in subsequent room-temperature tensile test. This may be compared with two specimens in the same condition of heat treatment (6hr-1500°F-AC) tested without the stress-thermal exposure; of these, one had 3.5% elongation, the other 5%.

Similarly, a third specimen treated 90 min-1600°F-AC and stressed at 5,000 psi and 1500°F for 167 hr (4.6% creep) had an elongation of 3.3% in subsequent tensile test. The corresponding specimen without stress-thermal exposure had an elongation of 3.5%, but broke outside the gage length.

10. Among heat-treated specimens of Ti-17.5Cb-15Al, the best room-temperature tensile properties were found in a specimen heat treated 24hr-1400°F-AC. This had a 0.01% yield of 74,700 psi, an 0.1% yield of 77,000 psi, an 0.2% yield of 77,600 psi, an ultimate of 102,000 psi, a modulus of 12.6 X 10^6 psi, and an elongation of 5.5%. It had been finish rolled at 2000°F.

11. The brittleness of welds in Ti-15Cb-10Al and Ti-17.5Cb-15Al indicates lack of weldability. However, more work is necessary to find out whether this shortcoming is actually shared by more highly alloyed and more complex compositions.

V. RECOMMENDATIONS

From a consideration of the facts discussed above, it is recommended that additional exploratory work should be undertaken during the next year. This should be directed toward alloys of high columbium and aluminum content, including those containing quaternary additions of hafnium and zirconium. At the same time, additional investigation should be made of the following alloys:

Ti-22.5Cb-12.5Al-5Hf
Ti-22.5Cb-12.5Al-1Hf
Ti-22.5Cb-12.5Al-1Zr
Ti-22.5Cb-12.5Al-5Sn
Ti-22.5Cb-15Al-1Sn
Ti-22.5Cb-15Al-0.5Zr

For these, the following should be determined: (1) short-time tensile strength at higher temperatures than have been tried so far; (2) effects of heat treatment on structure and tensile properties at various temperatures; (3) effects of forging and rolling temperature on tensile properties; and (4) stress-rupture strengths.

It is recognized that the properties of notch sensitivity, weldability, and creep strength will require a great deal more attention, but it is felt that major efforts in these areas can best be undertaken when more information of a general nature has been accumulated.

VI. SUMMARY

Alloy additions of hafnium, tin, or zirconium to the base alloys Ti-22.5Cb-(7.5-15Al) were found to have favorable effects on oxidation resistance, high-temperature strength, and ductility. In some instances the improvement of high-temperature strength was concomitant with greater ductility at room temperature. Several alloys showed superlative strength-density ratios at temperatures up to 1800°F, the highest temperature investigated.

The properties observed in four high-purity alloys were similar to those of the same alloys prepared with sponge titanium.

Sheet prepared from two ternary alloys showed strong response to heat treatment. One of these--Ti-15Cb-10Al--is now considered to be too lean in columbium and aluminum to be serviceable in the temperature range with which this program is concerned. The other--Ti-17.5Cb-15Al--showed low creep strength in two heat-treated conditions, was not embrittled by stress-thermal exposure at 1500°F, was not weldable, and appeared to be notch sensitive. One heat-treated specimen passed a 4 t guided bend test; another passed 6 t.

Analysis of the information obtained thus far leads to two recommendations: (1) further exploratory work should be directed toward alloys of high columbium and aluminum content, including those containing hafnium and zirconium; and (2) additional investigation should be made of six alloys selected from those prepared during the past year.

TABLE I

ANALYSES OF COLUMBIUM INGOTS

Impurity	Analysis (ppm)			
	10.7-lb lot *		10-lb lot **	
	Top	Bottom	Top	Bottom
Al	<20	<20	<20	<20
B	<1	<1	<1	<1
C	<30	<30	<30	<30
Cd	<5	<5	<5	<5
Cr	<20	<20	<20	<20
Cu	<40	<40	<40	<40
Fe	<100	<100	<100	<100
H	----	----	0.9	1.1
Hf	80	80	<80	<80
Mg	<20	<20	<20	<20
Mn	<20	<20	<20	<20
Mo	<20	<20	<20	<20
N	98	76	35	55
Ni	<20	<20	<20	<20
O	110	135	110	120
Pb	<20	<20	<20	<20
Si	<100	<100	<100	<100
Sn	<20	<20	<20	<20
Ta	450	450	<300	360
Ti	<150	<150	<150	<150
V	<20	<20	<20	<20
W	78	61	<300	<300
Zn	<20	<20	<20	<20
Zr	<500	<500	<500	<500

* Hardness: 55.1-71.5 BHN; Average: 64

** Hardness: 54.1-65.5 BHN; Average: 59

TABLE II

FORGING TEMPERATURES

Alloy Composition (wt %)	Forging Temperature °F	Forging Temperature °C
Ti-15Cb-10Al	2200	1200
Ti-17.5Cb-15Al	2350	1290
Ti-20Cb-17.5Al	2350	1290
Ti-22.5Cb-12.5Al	2250	1230
Ti-22.5Cb-7.5Al-1.5Zr	2200	1200
Ti-22.5Cb-7.5Al-1Zr	2200	1200
Ti-22.5Cb-7.5Al-0.5Zr	2200	1200
Ti-22.5Cb-7.5Al-0.2Zr	2150	1175
Ti-22.5Cb-7.5Al-5Sn	2200	1200
Ti-22.5Cb-7.5Al-1Sn	2150	1175
Ti-22.5Cb-7.5Al-0.75Sn	1800	980
Ti-22.5Cb-7.5Al-0.5Sn	2150	1175
Ti-22.5Cb-10Al-1Zr	2200	1200
Ti-22.5Cb-10Al-0.5Zr	2200	1200
Ti-22.5Cb-10Al-0.2Zr	2200	1200
Ti-22.5Cb-10Al-5Sn	2200	1200
Ti-22.5Cb-10Al-2.5Sn	2200	1200
Ti-22.5Cb-10Al-1Sn	2200	1200
Ti-22.5Cb-10Al-0.5Sn	2200	1200
Ti-22.5Cb-10Al-5Hf	2200	1200
Ti-22.5Cb-10Al-1Hf	2200	1200
Ti-22.5Cb-12.5Al-2Zr	2200	1200
Ti-22.5Cb-12.5Al-1Zr	2200	1200
Ti-22.5Cb-12.5Al-0.5Zr	2250	1230
Ti-22.5Cb-12.5Al-0.2Zr	2200	1200

TABLE II (continued)

Alloy Composition (wt %)	Forging Temperature °F	~°C
Ti-22.5Cb-12.5Al-5Sn	2200	1200
Ti-22.5Cb-12.5Al-1Sn	2200	1200
Ti-22.5Cb-12.5Al-0.5Sn	2200	1200
Ti-22.5Cb-12.5Al-5Hf	2200	1200
Ti-22.5Cb-12.5Al-2.5Hf	2200	1200
Ti-22.5Cb-12.5Al-1Hf	2200	1200
Ti-22.5Cb-15Al-1.5Zr	2300	1260
Ti-22.5Cb-15Al-1Zr	2350	1290
Ti-22.5Cb-15Al-0.5Zr	2300	1260
Ti-22.5Cb-15Al-0.2Zr	2300	1260
Ti-22.5Cb-15Al-5Sn	2250,* 2300,* 2400	1230,* 1260,* 1315
Ti-22.5Cb-15Al-1Sn	2300	1260
Ti-22.5Cb-15Al-0.5Sn	2300	1260
Ti-22.5Cb-15Al-5Hf	2300	1260

* Did not forge at this temperature.

TABLE III

DENSITIES OF FORGED ALLOYS

Alloy Composition (wt %)	Density	
	g/cm^3	lb/in^3
Ti-15Cb-10Al	4.59	0.166
Ti-17.5Cb-15Al	4.56	0.165
Ti-20Cb-17.5Al	4.54	0.164
Ti-22.5Cb-12.5Al	4.72	0.170
Ti-22.5Cb-7.5Al-1.5Zr	4.86	0.175
Ti-22.5Cb-7.5Al-1Zr	4.87	0.176
Ti-22.5Cb-7.5Al-0.5Zr	4.85	0.175
Ti-22.5Cb-7.5Al-0.2Zr	4.86	0.175
Ti-22.5Cb-7.5Al-5Sn	5.01	0.181
Ti-22.5Cb-7.5Al-1Sn	4.88	0.176
Ti-22.5Cb-7.5Al-0.75Sn	4.86	0.175
Ti-22.5Cb-7.5Al-0.5Sn	4.86	0.175
Ti-22.5Cb-10Al-1Zr	4.82	0.174
Ti-22.5Cb-10Al-0.5Zr	4.81	0.174
Ti-22.5Cb-10Al-0.2Zr	4.80	0.173
Ti-22.5Cb-10Al-5Sn	4.96	0.179
Ti-22.5Cb-10Al-2.5Sn	4.85	0.175
Ti-22.5Cb-10Al-1Sn	4.82	0.174
Ti-22.5Cb-10Al-0.5Sn	4.78	0.172
Ti-22.5Cb-10Al-5Hf	4.93	0.178
Ti-22.5Cb-10Al-1Hf	4.82	0.174
Ti-22.5Cb-12.5Al-2Zr	4.75	0.172
Ti-22.5Cb-12.5Al-1Zr	4.76	0.172
Ti-22.5Cb-12.5Al-0.5Zr	4.75	0.172
Ti-22.5Cb-12.5Al-0.2Zr	4.72	0.170
Ti-22.5Cb-12.5Al-5Sn	4.88	0.176
Ti-22.5Cb-12.5Al-1Sn	4.75	0.172

TABLE III (continued)

Alloy Composition (wt %)	Density	
	g/cm^3	lb/in^3
Ti-22.5Cb-12.5Al-0.5Sn	4.74	0.171
Ti-22.5Cb-12.5Al-5Hf	4.90	0.177
Ti-22.5Cb-12.5Al-2.5Hf	4.80	0.173
Ti-22.5Cb-12.5Al-1Hf	4.78	0.173
Ti-22.5Cb-15Al-1.5Zr	4.69	0.169
Ti-22.5Cb-15Al-1Zr	4.70	0.170
Ti-22.5Cb-15Al-0.5Zr	4.70	0.170
Ti-22.5Cb-15Al-0.2Zr	4.66	0.168
Ti-22.5Cb-15Al-5Sn	4.82	0.174
Ti-22.5Cb-15Al-1Sn	4.71	0.170
Ti-22.5Cb-15Al-0.5Sn	4.68	0.169
Ti-22.5Cb-15Al-5Hf	4.82	0.174

TABLE IV

OXIDATION OF TITANIUM ALLOYS EXPOSED TO STILL AIR AT 1830°F (1000°C) FOR 84 HOURS

Alloy Composition (wt %)	Specimen Weight (g)	Weight Gain (g)	Depth of Oxidation (in.)
Ti-22.5Cb-7.5Al-0.5Zr	2.7958	0.032	0.003
Ti-22.5Cb-10Al-1Hf	2.7407	0.031	0.002
Ti-22.5Cb-12.5Al-1Zr	2.8460	0.024	0.001
Ti-22.5Cb-12.5Al-1Hf	2.8334	0.032	0.002
Ti-22.5Cb-12.5Al-5Hf	2.9837	0.027	<0.001
Ti-22.5Cb-15Al-0.5Zr	2.8073	0.027	0.001
Ti-22.5Cb-15Al-1Sn	2.8015	0.022	<0.001
Ti-22.5Cb-12.5Al	2.6019	0.036	<0.001

TABLE V

OXIDATION OF TITANIUM ALLOYS EXPOSED TO STILL AIR AT 1830°F (1000°C) FOR 100 HOURS

Alloy Composition (wt %)	Specimen Weight (g)*	Weight Gain (g)	Depth of Oxidation (in.)
Ti-22.5Cb-7.5Al-1.5Zr	4.3812	0.040	0.001+
Ti-22.5Cb-7.5Al-0.75Sn	4.4132	0.052	0.001
Ti-22.5Cb-10Al-2.5Sn	4.0925	0.035	<0.001
Ti-22.5Cb-10Al-0.5Sn	4.3296	0.046	0.002
Ti-22.5Cb-10Al-5Hf	4.4445	0.023	<0.001+
Ti-22.5Cb-12.5Al	4.2824	0.043	0.001
Ti-22.5Cb-12.5Al-2Zr	4.2803	0.036	<0.001
Ti-22.5Cb-12.5Al-1Zr	4.2558	0.021	<0.001+
Ti-22.5Cb-12.5Al-0.2Zr	4.2777	0.036	<0.001+
Ti-22.5Cb12.5Al-1Sn	4.3357	0.037	<0.001
Ti-22.5Cb-12.5Al-0.5Sn	4.2313	0.045	<0.001
Ti-22.5Cb-12.5Al-2.5Hf	4.3463	0.031	<0.001+
Ti-22.5Cb-12.5Al-1Hf (A)	4.1496	0.033	<0.001
Ti-22.5Cb-12.5Al-1Hf (B)	4.2858	0.024	<0.001+
Ti-22.5Cb-15Al-1.5Zr	4.2382	0.030	<0.001
Ti-22.5Cb-15Al-0.2Zr	4.1773	0.034	<0.001
Ti-22.5Cb-15Al-5Sn	4.3830	0.032	<0.001
Ti-22.5Cb-15Al-0.5Sn	4.2098	0.026	<0.001
Ti-22.5Cb-15Al-5Hf	4.0566	0.029	<0.001
Ti-20Cb-17.5Al	4.0945	0.037	<0.001
Ti-17.5Cb-15Al	4.2070	0.035	<0.001
Ti-15Cb-10Al	4.1698	0.072	0.002

* Area of these specimens 4.8 cm^2.

\+ Oxide did not spall on cooling.

TABLE VI

SHORT-TIME TENSILE DATA FOR TITANIUM ALLOYS

Alloy Composition (wt %)	Test Temp (°F)	UTS (psi)	0.2% YS (psi)	% El. in 0.7 in.	% RA
Ti-15Cb-10Al (High Purity)	RT	181,900	170,000	1.5	5
	800	142,700	127,000	10	23
	1200	121,800	108,000	19	62
	1400	78,000	69,000	12	22
	1600	32,600	26,000	26	46
Ti-17.5Cb-15Al (High Purity)	RT	123,000	---	--	3
	1000	122,000	88,000	11	14
	1200	129,600	103,000	8	14
	1400	70,300	50,000	36	45
	1600	61,000	52,000	67	>95
Ti-20Cb-17.5Al (High Purity)	RT	129,900	---	--	1
	1200	185,000	164,000	2.5	3.5
	1400	135,500	---	--	2
	1600	103,200	98,000	2.5	3
Ti-22.5Cb-12.5Al (High Purity)	RT	153,000	135,000	3	2.5
	1200	120,100	105,000	14	35
	1400	74,700	65,000	8	28
	1600	58,300	51,000	9.5	15
Ti-22.5Cb-7.5Al-1.5Zr	RT	176,100	---	--	2
	800	114,800	111,000	3	11
	1200	115,300	104,000	4.5	8
	1400	78,000	71,000	15	24
	1600	22,800	21,000	131	>90
Ti-22.5Cb-7.5Al-1Zr	RT	164,900	162,000	3	1
	800	157,000	146,000	4	4
	1200	144,900	136,000	4	7
	1400	142,700	116,000	10	15
	1600	65,300	54,000	20	52
Ti-22.5Cb-7.5Al-0.5Zr	RT	124,800	118,000	7	9
	1200	153,800	144,000	1	3
	1400	121,600	94,000	10	21
	1600	61,300	51,000	30	62

TABLE VI (continued)

Alloy Composition (wt %)	Test Temp (°F)	UTS (psi)	0.2% YS (psi)	% El. in 0.7 in.	% RA
Ti-22.5Cb-7.5Al-0.2Zr	RT	134,000	127,000	7	15
	800	169,400	----	0	0
	1200	151,500	138,000	1	8
	1400	134,000	123,000	15	39
	1600	64,600	50,000	21	50
Ti-22.5Cb-7.5Al-5Sn	RT	155,200	----	0	0
	1200	171,600	158,000	1	7
	1400	169,400	144,000	2	3
	1600	85,600	76,000	0	2
	1800	31,800	28,000	17	36
Ti-22.5Cb-7.5Al-1Sn	RT	131,500	129,000	6	6
	800	98,800	76,000	8	35
	1200	171,600	160,000	1	6
	1400	137,000	110,000	18	47
	1600	68,500	56,000	8	16
Ti-22.5Cb-7.5Al-0.75Sn	RT	211,700	193,000	1.5	2.5
	800	177,400	168,000	1.5	5
	1200	138,900	132,000	9.5	24
	1600	27,700	24,000	60	>90
Ti-22.5Cb-7.5Al-0.5Sn	RT	176,000	----	0	0
	800	173,800	167,000	1	3
	1200	118,600	105,000	10	15
	1400	129,600	114,000	2	9
	1600	61,500	52,000	20	41
Ti-22.5Cb-10Al-1Zr	RT	169,100	----	0	1
	1200	140,500	127,000	8	26
	1400	158,200	139,000	18	30
	1600	87,800	76,000	11	30
	1800	30,700	25,000	55	>95
Ti-22.5Cb-10Al-0.5Zr	RT	149,300	147,000	3	5
	1200	136,000	118,000	8	30
	1400	144,100	123,000	10	27
	1600	90,600	76,000	10	18

TABLE VI (continued)

Alloy Composition (wt %)	Test Temp (°F)	UTS (psi)	0.2% YS (psi)	% El. in 0.7 in.	% RA
Ti-22.5Cb-10Al-0.2Zr	RT	128,300	117,000	3	5
	800	176,200	169,000	1	3
	1200	118,600	103,000	4	6
	1400	149,300	129,000	22	74
	1600	84,800	71,000	22	45
Ti-22.5Cb-10Al-5Sn	RT	149,300	140,000	3	5
	800	113,100	87,000	12	27
	1200	147,900	132,000	7	21
	1400	114,200	105,000	17	16
	1600	80,200	69,000	47	>95
Ti-22.5Cb-10Al-2.5Sn	RT	171,300	169,000	1.5	5
	800	166,300	153,000	3	8
	1000	179,600	168,000	4.5	8
	1200	131,500	118,000	9.5	27
	1600	45,700	39,000	15	21
Ti-22.5Cb-10Al-1Sn	RT	144,900	140,000	3	6
	1200	173,500	164,000	2	2
	1400	151,500	136,000	10	21
	1600	78,000	63,000	17	21
	1800	37,900	32,000	18	21
Ti-22.5Cb-10Al-0.5Sn	RT	170,200	165,000	3	4
	1200	134,400	125,000	4.5	7
	1400	80,700	78,000	3	7.5
	1600	50,100	44,000	4.5	6
Ti-22.5Cb-10Al-5Hf	RT	170,500	---	—	5
	1200	168,000	154,000	5	8
	1400	98,300	85,000	8	16
	1600	54,600	48,000	5	5
Ti-22.5Cb-10Al-1Hf	RT	131,500	120,000	9	8
	1200	120,800	105,000	4	11
	1400	140,500	125,000	7	21
	1600	90,000	78,000	4	8
	1800	37,900	33,000	8	14

TABLE VI (continued)

Alloy Composition (wt %)	Test Temp (°F)	UTS (psi)	0.2% YS (psi)	% El. in 0.7 in.	% RA
Ti-22.5Cb-12.5Al-2Zr	RT	148,600	133,000	1.5	6
	1200	123,000	105,000	24	54
	1600	72,100	59,000	21	47
	1800	25,100	19,000	97	>90
Ti-22.5Cb-12.5Al-1Zr	-90	169,100	151,000	3	7
	RT	131,500	104,000	7	13
	400	138,200	123,000	3	8
	600(A)	164,700	---	--	4
	600(B)	166,300	148,000	7.5	5
	800	122,600	89,000	11	15
	1000(A)	156,000	138,000	6	8
	1000(B)	160,000	140,000	4.5	14
	1200	118,600	83,000	28	38
	1400	83,400	63,000	24	42
	1600	59,100	52,000	28	83
	1800	29,900	24,000	10	>90
Ti-22.5Cb-12.5Al-0.5Zr	RT	158,100	---	0	2
	800	160,300	129,000	12	21
	1200	107,600	83,000	28	59
	1400	116,400	101,000	14	32
	1600	106,500	92,000	8	11
	1800	54,900	45,000	7	14
Ti-22.5Cb-12.5Al-0.2Zr	RT	149,300	---	--*	--
	800	149,300	123,000	10	11
	1200	113,700	100,000	10	22
	1400	95,800	89,000	9	18
	1600	49,400	42,000	33	55
Ti-22.5Cb-12.5Al-5Sn	RT	98,800	---	0	0
	1200	107,000	75,000	10	13
	1400	102,500	84,000	7	14
	1600	79,800	71,000	5	14
	1800	74,700	60,000	7	14
Ti-22.5Cb-12.5Al-1Sn	RT	156,000	---	--	5
	1200	113,700	95,000	19	34
	1400	93,700	84,000	10	23
	1600	63,200	53,000	16	27

TABLE VI (continued)

Alloy Composition (wt %)	Test Temp (°F)	UTS (psi)	0.2% YS (psi)	% El. in 0.7 in.	% RA
Ti-22.5Cb-12.5Al-0.5Sn	RT	151,500	134,000	3	6
	1200	118,500	101,000	35	>95
	1400	123,200	112,000	3	7
	1600	70,300	57,000	12	18
Ti-22.5Cb-12.5Al-5Hf	RT	157,600	141,000	6	8
	1200	118,600	74,000	32	40
	1400	90,900	73,000	21	53
	1600	84,300	66,000	32	64
	1800	59,300	49,000	35	75
Ti-22.5Cb-12.5Al-2.5Hf	RT	156,800	143,000	3	9.5
	1200(A)	185,000	---	--	3.5
	1200(B)	147,100	133,000	4.5	12
	1400	70,300	61,000	61	74
	1600	64,200	52,000	18	21
Ti-22.5Cb-12.5Al-1Hf	-90	135,100	119,000	3	7.5
	RT	153,700	140,000	6	7
	400(A)	152,200	---	--	2
	400(B)	126,400	95,000	11	15
	600	147,100	131,000	3	12
	800	140,500	114,000	13	23
	1000	166,900	158,000	1.5	2
	1200	112,000	79,000	15	30
	1400	85,600	65,000	28	57
	1600	82,500	55,000	30	75
	1800	48,900	41,000	20	45
Ti-22.5Cb-15Al-1.5Zr	RT	148,600	146,000	1.5	4
	1200	133,100	106,000	11	17
	1600	94,000	83,000	13	17
	1800	48,300	38,000	45	60
Ti-22.5Cb-15Al-1Zr	RT	144,900	---	0	1
	1200	151,600	113,000	14	20
	1400	138,200	109,000	20	50
	1600	96,600	72,000	11	21

TABLE VI (continued)

Alloy Composition (wt %)	Test Temp (°F)	UTS (psi)	0.2% YS (psi)	% El. in 0.7 in.	% RA
Ti-22.5Cb-15Al-0.5Zr	RT	120,800	---	0	2
	1200	144,900	109,200	10	15
	1400	122,600	98,000	7	11
	1600	100,300	98,000	3	17
	1800	88,900	79,000	7	8
Ti-22.5Cb-15Al-0.2Zr	RT	153,700	---	--	1.5
	1200	129,300	100,000	10	13
	1400	128,600	108,000	7.5	9
	1600	91,100	74,000	12	16
Ti-22.5Cb-15Al-5Sn	RT	173,500	160,000	1.5	6
	1200	159,400	135,000	9.5	41
	1400	163,900	---	1.5	5
	1600	109,300	96,000	6	12
	1800	47,800	37,000	38	32
Ti-22.5Cb-15Al-1Sn	RT	125,200	123,000	1	3
	1200	123,000	101,000	5	6
	1400	83,400	65,000	7	20
	1600	88,900	70,000	5	5
	1800	91,100	81,000	7	11
Ti-22.5Cb-15Al-0.5Sn	RT	137,500	---	---	1.5
	1200	126,800	102,000	10	16
	1600	88,700	73,000	7.5	15
Ti-22.5Cb-15Al-5Hf	RT	175,700	---	---	2
	1200	166,600	149,000	4.5	18
	1600	90,700	78,000	23	46
	1800	42,600	35,000	99	>90
Ti-22.5Cb-7.5Al-0.75 Sn (Treated 16 hr-1200°F-AC)	RT	177,400	---	1.5	4

TABLE VI (continued)

Alloy Composition (wt %)	Test Temp (°F)	UTS (psi)	0.2% YS (psi)	% El. in 0.7 in	% RA
Ti-22.5Cb-12.5Al-1Zr	600	166,900	155,000	4	6
(Treated 16 hr-1200°F-AC)	800	140,700	119,000	11	27
	1000	173,300	168,000	1	4
Ti-22.5Cb-12.5Al-1Hf	RT	116,600	101,000	3	8
(Treated 16 hr-1600°F-AC)	400	131,500	95,000	8.5	13
	1000	120,100	80,000	31	44

* Broke at shoulder.

TABLE VII

GUIDED BEND TEST DATA FOR TITANIUM ALLOY SHEET
APPROXIMATELY 1/16-INCH THICKNESS

Alloy Composition (Nominal wt %)	Rolling Temp. (°F)	Heat Treatment	Pass (R_t)	Fail (R_t)	Failure Angle (deg)
Ti-15Cb-10Al	1650	6hr-1500°F-AC	9	5.5	
	1600	80min-1600°F-AC	4	3	
	1600	3hr-1600°F-AC	11	8	
	1700	80min-1600°F-AC	3	2	90
	1700	80min-1600°F-AC	2.5		
	1600	80min-1650°F-AC	6	4	
	1600	30min-1750°F-AC	6		
	1650	none	16	10	
	1700	80min-1650°F-AC	8	5.5	
	1600	3hr-1600°F-AC + 16hr-1450°F-AC		16	110
Ti-17.5Cb-15Al	2050-1950	none	14	9	120
	2050-1950	none	14	9	180
	2000-2050	none		20	130
	2050-2000	none	12	10	60
	2050-1950	6hr-1500°F-AC	15	9	20
	2050-1950	24hr-1500°F-AC		14	20
	2050-1950	90min-1600°F-AC	4	3	
	2050-1950	2hr-1650°F-AC	14	9	45
	2050-1950	90min-1750°F-AC	6	4	90
	2050-1950	90min-1750°F-AC	13	10.5	
	2050-1950	90min-1750°F-AC	16	10	
	2000-2050	90min-1700°F-AC	24	16	20
	2050-1950	90min-1700°F-AC	15	9.5	20
	2050-2000	90min-1700°F-AC	20	12	30

TABLE VIII

ROOM-TEMPERATURE TENSILE RESULTS FOR SHEET Ti-15Cb-10Al WITH SEVERAL HEAT TREATMENTS AND STRESS-THERMAL EXPOSURES

Rolling Temp (°F)	Prior Treatment	Yield Strength (psi) 0.01%	0.1%	0.2%	UTS (psi)	E psi x10^-6	Elong. % in 1 in.
1600	none	101,000	154,000	165,000	>172,000	15.9	*
1600	none	103,000	161,000	165,000	175,000	13.7	3.3
1650	none	93,800	129,000	142,000	174,000	14.6	3.5 **
1650	none	122,000	148,000	159,000	177,000	15.3	5
1600	6h-1500°F-AC	54,700	78,000	89,600	100,000	13.1	1.3
1600	6h-1500°F-AC	71,000	82,800	84,500	129,000	12.0	3.3 **
1600	6h-1500°F-AC + 45h-1400°F-5,000 psi	83,400	-------	-------	117,000	14.9	1.5
1600	6h-1500°F-AC + 3h-1500°F-5,000 psi	67,000	89,000	94,000	108,000	11.8	**
1650	6h-1500°F-AC	75,500	97,000	102,000	120,000	11.6	2 **
1650	6h-1500°F-AC	41,900?	80,500	86,500	99,400	15.3	<1
1650	6h-1500°F-AC + 1500°F-5,000 psi to 20% creep	-------	-------	-------	113,000	13.6	2
1600	80m-1600°F-AC	86,400	107,700	113,600	>125,000*	13.5	*
1650	80m-1600°F-AC	84,500	109,000	117,000	*	13.1	*
1650	80m-1600°F-AC	115,000	127,000	130,000	>130,000*	13.8	2 **
1600	80m-1650°F-AC	93,200	116,000	124,000	>127,000*	13.4	*
1600	80m-1650°F-AC + 167hr-1200°F-5,000 psi	48,800	-------	-------	-------	19.8	*

* Broke through pin hole. ** Broke outside gage length.

TABLE IX

ROOM-TEMPERATURE TENSILE RESULTS FOR SHEET Ti-17.5Cb-15Al

WITH SEVERAL HEAT TREATMENTS AND STRESS-THERMAL EXPOSURES

Rolling Temp (°F)	Prior Treatment	Yield Strength (psi) 0.01%	0.1%	0.2%	UTS (psi)	E psi x10^{-6}	Elong. % in 1 in.
2050-1950	none	82,600	100,000	107,300	133,600	12.5	3.5
2050-1950	6h-1500°F-AC	56,600	76,700	79,300	98,200	11.0	3.5
2050-1950	6h-1500°F-AC	66,500	68,600	69,500	94,600	11.5	5
2050-1950	6h-1500°F-AC + 167h-1500°F-7,500 psi	44,700	47,600	47,900	67,800	11.9	4.5
2050-1950	6h-1500°F-AC + 170h-1500°F-10,000 psi	40,800	49,600	50,500	75,000	14.4	4.5
2050-1950	90m-1600°F-AC	63,500	77,500	84,000	109,000	13.5	3.5 **
2050-1950	90m-1600°F-AC + 167h-1500°F-5,000 psi	49,100	50,600	50,800	66,900	11.4	3.3
2050-1950	90m-1750°F-AC	60,800	65,700	65,700	65,700	15.6	<1
2050-1950	90m-1750°F-AC	56,500	61,900	62,000	63,000	13.1	<1
2050-1950	none	91,400	------	------	112,000	17.1	0
2050-1950	none	76,700	------	------	104,000	17.4	0 **
2050-1950	none	70,000	107,500	117,000	148,000	15.6	2.5
2050-2000	none	92,000	108,000	114,000	139,000	12.0	3.5
2050-2000	none	86,000	105,000	------	140,000	12.9	3.5
2050-2000	24h-1400°F-AC	74,700	77,000	77,600	102,000	12.6	5.5
2050-2000	24h-1400°F-AC	71,000	74,000	75,000	84,000	12.1	*
2050-1950	none	80,000	------	------	151,000	14.8	2
2000-2050	none	------	------	------	94,000	15.2	1

* Broke at shoulder. ** Broke outside gage length.

TABLE X

TENSILE PROPERTIES OF Ti-22.5Cb-10Al AND TWO MODIFICATIONS

Alloy Composition (wt %)	Test Temp (°F)	UTS (psi)	~YS, psi 0.2% Offset	% El	% RA
Ti-22.5Cb-10Al*	RT	169,000	-------	0	0
Ti-22.5Cb-10Al-0.5Zr	RT	149,300	147,000	3	5
Ti-22.5Cb-10Al-1Hf	RT	131,500	120,000	9	8
Ti-22.5Cb-10Al	1200	147,000	134,000	6	12
Ti-22.5Cb-10Al-0.5Zr	1200	136,000	118,000	8	30
Ti-22.5Cb-10Al-1Hf	1200	120,800	105,000	4	11
Ti-22.5Cb-10Al	1400	84,000	71,000	8	11
Ti-22.5Cb-10Al-0.5Zr	1400	144,100	123,000	10	27
Ti-22.5Cb-10Al-1Hf	1400	140,500	125,000	7	21
Ti-22.5Cb-10Al	1600	43,000	38,000	~17	~34
Ti-22.5Cb-10Al-0.5Zr	1600	90,600	76,000	10	18
Ti-22.5Cb-10Al-1Hf	1600	90,000	78,000	4	18

* Data for the ternary alloy are from previous work, using the same experimental procedures.

TABLE XI

TENSILE PROPERTIES OF Ti-22.5Cb-12.5Al AND TWO MODIFICATIONS

Alloy Composition (wt %)	Test Temp (°F)	UTS (psi)	~YS, psi 0.2% Offset	% El	% RA
Ti-22.5Cb-12.5Al*	RT	160,000	-------	0	0
Ti-22.5Cb-12.5Al-1Hf	RT	153,700	140,000	6	7
Ti-22.5Cb-12.5Al-1Zr	RT	131,500	104,000	7	13
Ti-22.5Cb-12.5Al	1200	131,000	116,000	17	50
Ti-22.5Cb-12.5Al-1Hf	1200	112,000	79,000	15	30
Ti-22.5Cb-12.5Al-1Zr	1200	118,600	83,000	28	38
Ti-22.5Cb-12.5Al	1400	71,000	64,000	3	6
Ti-22.5Cb-12.5Al-1Hf	1400	85,600	65,000	28	57
Ti-22.5Cb-12.5Al-1Zr	1400	83,400	63,000	24	42
Ti-22.5Cb-12.5Al	1600	58,000	47,000	8	13
Ti-22.5Cb-12.5Al-1Hf	1600	82,500	55,000	30	75
Ti-22.5Cb-12.5Al-1Zr	1600	59,100	52,000	28	83

* Data for the ternary alloy are from previous work, using the same experimental procedures.

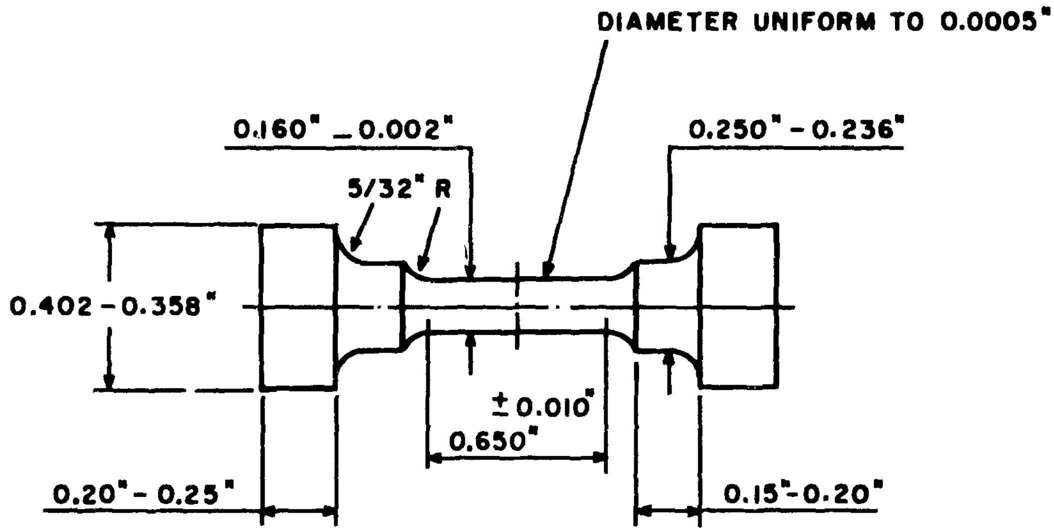


FIG. I HOUNSFIELD TENSILE TEST PIECE.

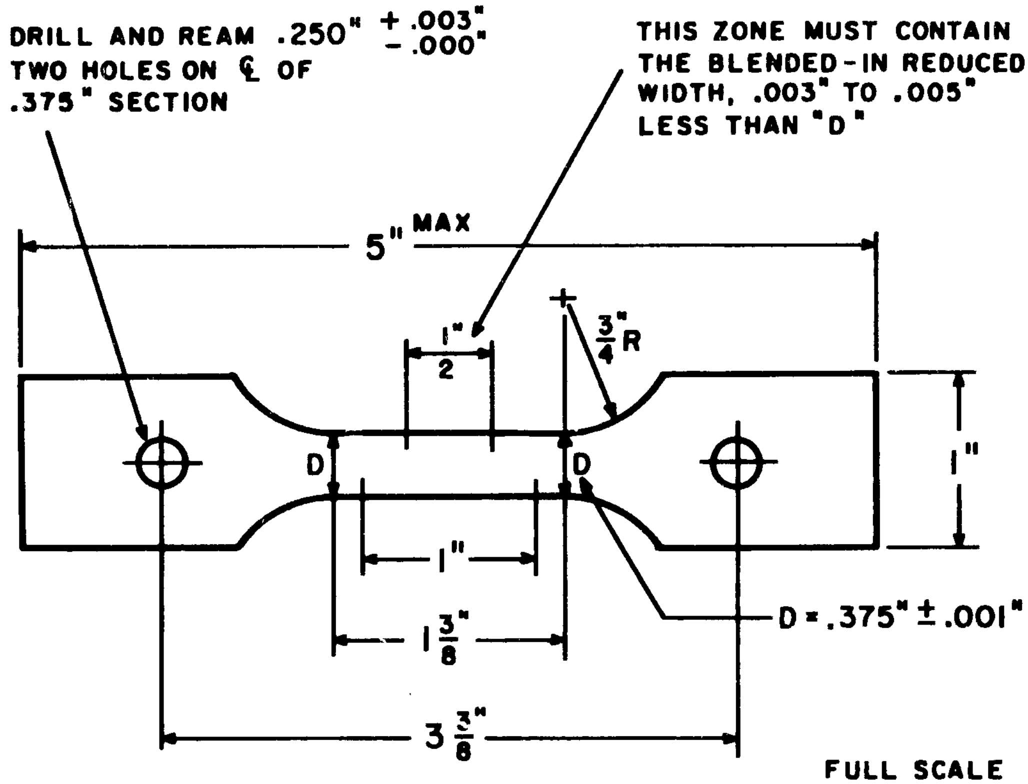
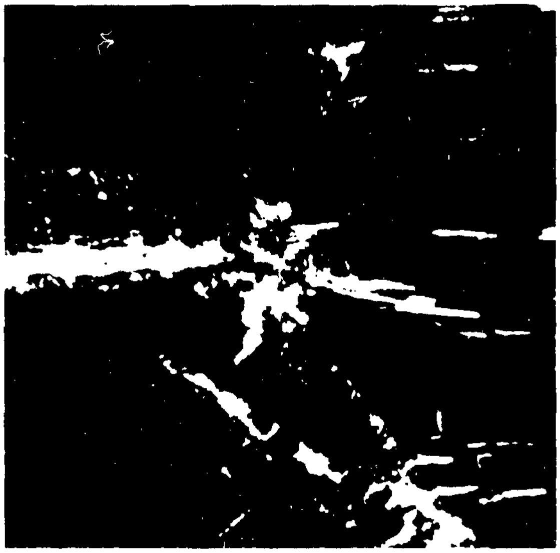


FIG. 2 SPECIFICATIONS FOR 1-INCH GAGE LENGTH SHEET TENSILE SPECIMEN.



Neg. No. 20663 X500

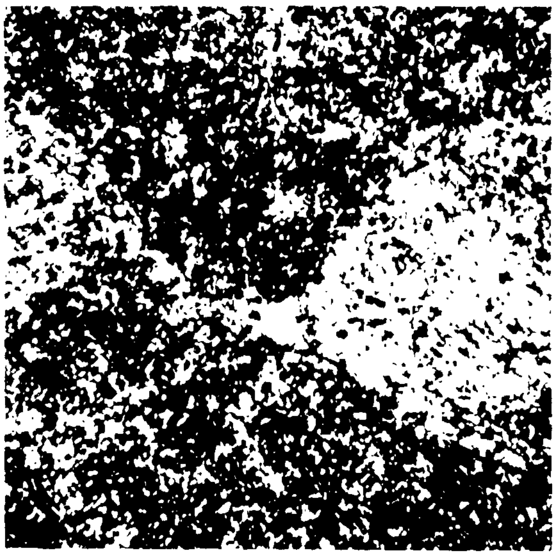
Figure 3

Ti-22.5Cb-7.5Al-1Zr. As forged.
Polarized light.

Neg. No. 20666 X500

Figure 4

Ti-22.5Cb-10Al-1Zr. As forged.
Polarized light.

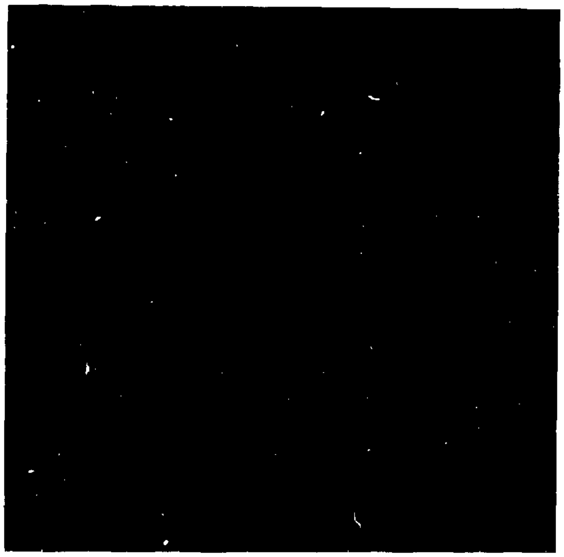


Neg. No. 20674 X500

Figure 5

Ti-22.5Cb-12.5Al-1Zr. As forged.
Polarized light.

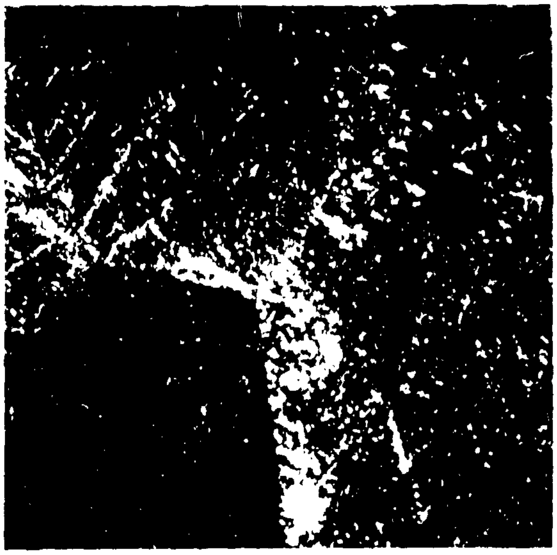
Etchant: HNO_3, HF, H_2O_2, glycerine



Neg. No. 20676 X500

Figure 6

Ti-22.5Cb-15Al-1Zr. As forged.
Polarized light.



Neg. No. 20667 X500

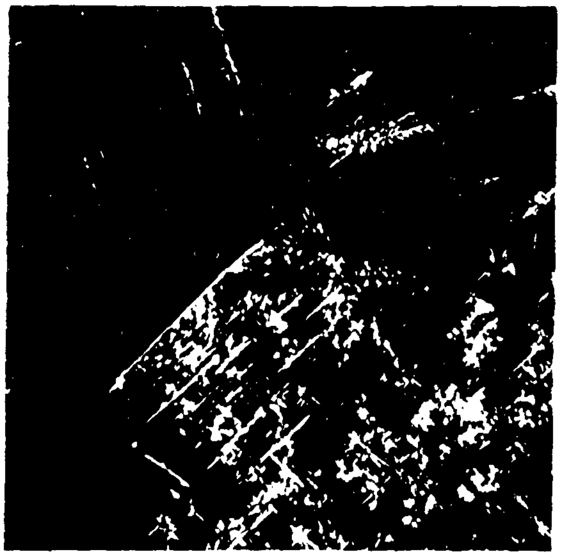
Figure 7

Ti-22.5Cb-10Al-0.5Zr. As forged.
Polarized light.

Neg. No. 20660 X500

Figure 8

Ti-22.5Cb-7.5Al-1Sn. As forged.
Polarized light.

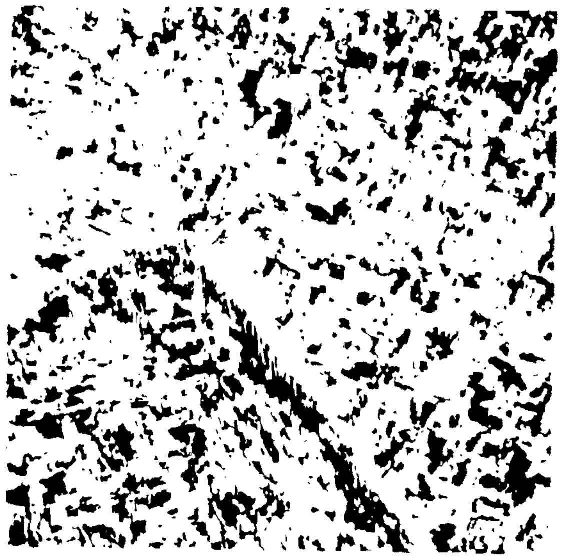


Neg. No. 20665 X500

Figure 9

Ti-22.5Cb-10Al-1Sn. As forged.
Polarized light.

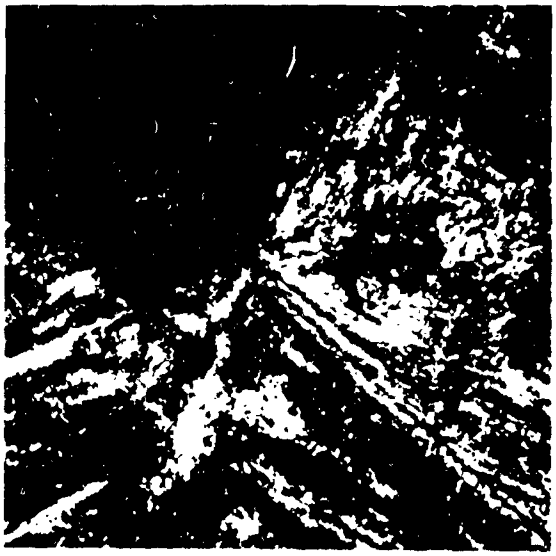
Etchant: HNO_3, HF, H_2O_2, glycerine



Neg. No. 20685 X500

Figure 10

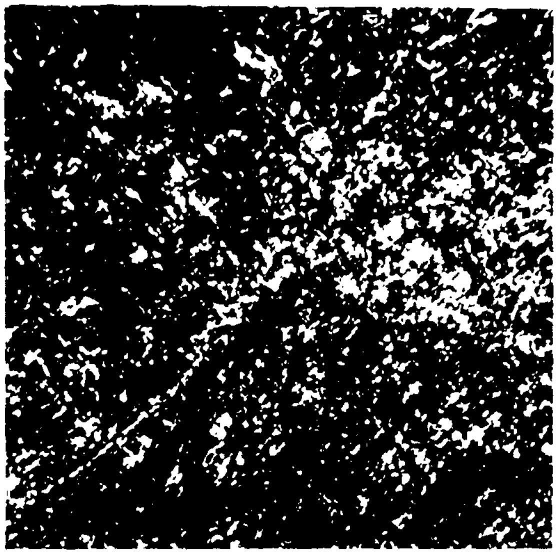
Ti-22.5Cb-15Al-0.5Zr. As forged.
Polarized light.



Neg. No. 20669 X500

Figure 11

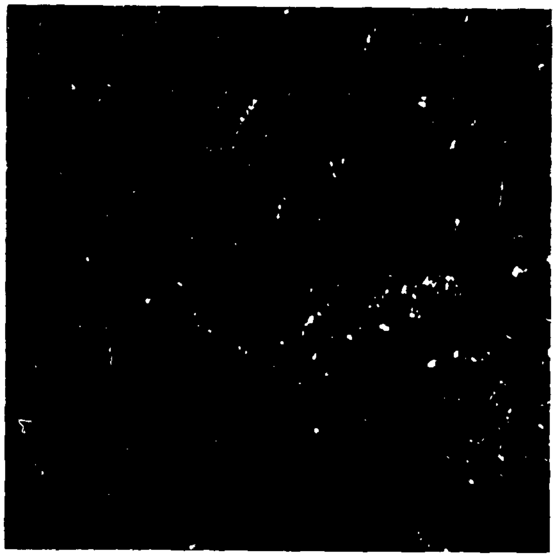
Ti-22.5Cb-7.5Al-5Sn. As forged. Polarized light.



Neg. No. 20678 X500

Figure 12

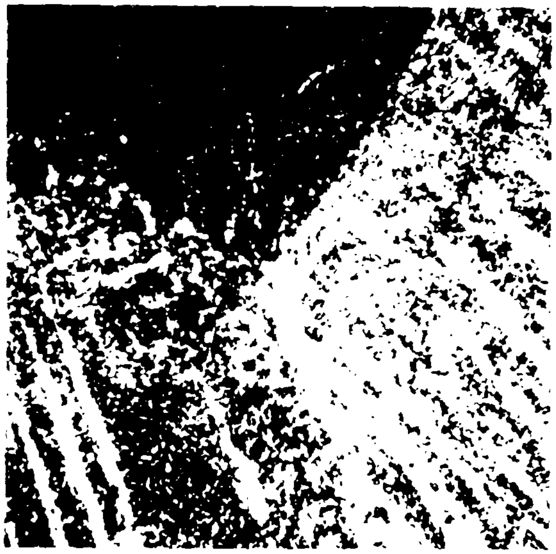
Ti-22.5Cb-10Al-5Sn. As forged. Polarized light.



Neg. No. 20664 X500

Figure 13

Ti-22.5Cb-12.5Al-5Sn. As forged. Polarized light.



Neg. No. 20668 X500

Figure 14

Ti-22.5Cb-10Al-1Hf. As forged. Polarized light.

Etchant: HNO_3, HF, H_2O_2, glycerine

Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio
Rpt. No. ASD TR 61-446. DEVELOPMENT OF A Ti-Al-Cb ALLOY FOR USE AT 1200°-1800°F. Final report. March 1962. 36p incl illus, and tables.

Unclassified report

Titanium-base alloys containing major amounts of columbium and aluminum are being studied with the object of developing new high-temperature alloys of low density. This report presents the findings of the second year of this program, derived from the preparation an and examination oft 35 quaternary alloys con-

(over)

1. Titanium alloys containing Al and Cb.
2. Quaternary titanium with Sn, Hf, or Zr
3. Ternary titanium alloys

I. AFSC Project 7351 Task 735105
II. Contract AF 33(616)-7262
III. Armour Research Foundation, Chicago, Illinois.
IV. J. B. McAndrew and C. R. Simcoe
V. Avl fr Ots
VI. In ASTIA collection

taining small additions of tin, hafnium, or zirconium; 4 high-purity ternary alloys; and ten-pound melts of Ti-15Cb-10Al and Ti-17.5Cb-15Al.

In a number of alloys, improved tensile properties and oxidation resistance resulted from the addition of tin, hafnium, or zirconium, and in some instances very high strength-density ratios were maintained up to 1800°F. The properties of high-purity alloys were similar to those of alloys prepared with sponge titanium. It is recommended that further effort should be directed toward the more highly alloyed compositions, including those containing hafnium and zirconium.

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