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A TECHNIQUE FOR EVALUATING TITANIUM ALLOYS BY MELTING, PROCESSING, AND TESTING MINIATURE INGOTS

Alastair G. S. Morton

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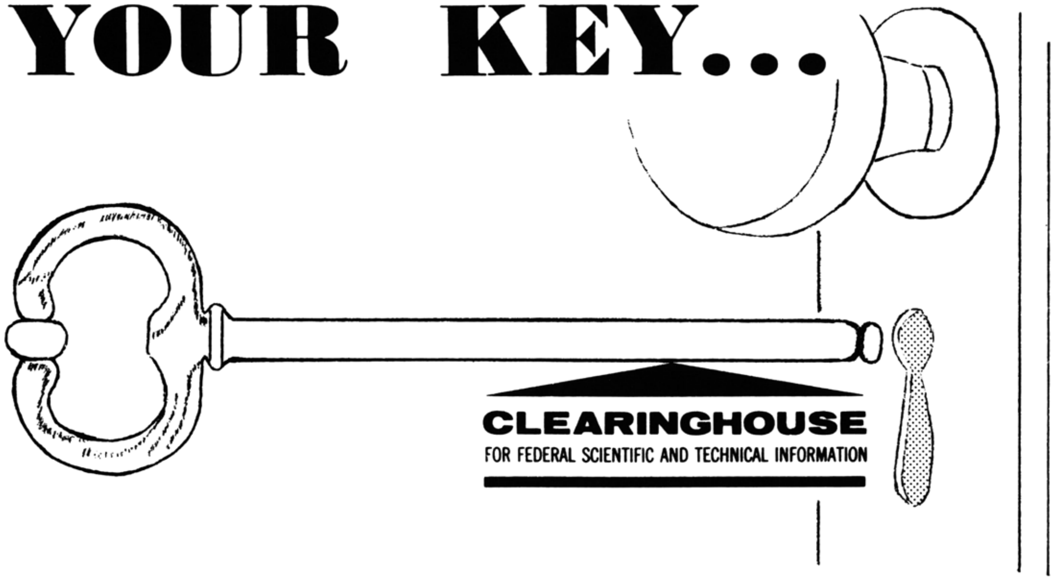
Annapolis, Maryland

July 1969



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By
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MATERIALS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

July 1969 Report 3048

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July 1969 MATLAB 351 Report 3048

ABSTRACT

A technique of melting, processing, and testing small (80-gram) rods of titanium alloys has been developed. The technique is designed for screening large numbers of alloy formulations to determine those with enough potential for further evaluation. The hearth plate of an arc button-melting furnace was modified to produce rod-ingots which are forged to a shape suitable for testing. Strength and toughness measurements are used to compare a series of alloys relatively, and with respect to their bulk properties. It is recognized that a number of factors, such as cooling rates and amount of forging, prevent duplication of production material properties. Nevertheless, the apparent alloying and microstructural effects and the degree of correlation with plate properties are discussed.

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A TECHNIQUE FOR EVALUATING TITANIUM ALLOYS BY MELTING, PROCESSING, AND TESTING MINIATURE INGOTS

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INTRODUCTION

OBJECTIVE

An ultimate goal in the development of alloy systems is the development of an ability of metallurgists to design alloys based on the interacting combinations of physical and mechanical properties of the elements. At present, however, alloy development involves a more empirical approach where large numbers of composition and thermal treatment combinations are produced and tested. Since material in any large quantity is expensive and time consuming to produce, it is extremely advantageous to utilize small melts of alloy combinations for screening purposes.

Preliminary screening tests cannot be expected to yield details of a material behavior but can characterize some of the mechanical properties and thus find the relative worth of various alloys and thermal-mechanical schedules. Ingot size can be increased when it is known what combinations of alloying elements hold promise of useful properties. This scale-up will then generate sufficient material for a complete mechanical property and thermal treatment evaluation.

Although many alloys in the titanium alloy system have been thoroughly investigated, much alloy development work remains to be done. Titanium alloys containing higher percentages of existing and new alloying elements must be screened to find new combinations with enough real potential for detailed study. The goal of this thesis is the development of such a screening method.

BACKGROUND

The production of ductile titanium by the Kroll[1] process became economically viable in the years 1948 to 1952 when annual

---

[1] Superscripts refer to similarly numbered entries in Appendix A.

:tion in the United States rose from 8 to 1075 tons.[2] In ırly 1950's, most of the alloy development done was empirical ıvolved the production of small button melts of widely ıg compositions and their subsequent fabrication and testing. ıjor application was seen to be in the then emerging aero- field; so most of the experimental buttons were processed .n sheet. This technique had two major advantages: enough was available for several tension and bend tests, and the strength increases due to rolling could be advantageously :ed.

)uring this period, well over 20 patents were issued cover- wide range of titanium alloy compositions. These patents .n sheet specimen mechanical properties of various alloys › 500 compositions in a single patent) and often the effects ırmal treatments on the alloys. One patent describes the 'ation of the alloys:

> "All of the [10 to 15 gram] alloys thus tested were prepared by forging at 1800°F to 0.08 in. sheet, then descaled, again rolled at 1400 F to 0.04 in., held for 15 minutes at 1400 F, furnace cooled therefrom to 1100 F, held one hour thereat, air cooled thence to room temperature and descaled before testing."[3]

'he preparation of specimens for heat treatment evaluation was ır except that the buttons were larger and rolled to thinner

> "Ingots weighing one-half pound [227 grams] each were prepared... .. ..by arc melting ......in a water cooled copper crucible and in an inert or argon atmosphere. The initial ingots thus produced were inverted and again arc melted as aforesaid to assure the production of a homogeneous alloy. The ingots as thus produced were forged at 980 C, cleaned up and rolled at 760 C into 0.01 in. sheet....."[4]

'his latter example was the only case where a patent men- ı large (greater than 50-gram) buttons. Typically then, ırly alloy development work utilized 10- to 15-gram ıs, arc melted, forged, then rolled to thin sheet.

Since the middle and late 1950's many potential applications of the material have been investigated. This has necessitated the production of experimental titanium alloys in various sizes and shapes based on economic considerations, alloy applications, and other factors such as the equipment capabilities at the researcher's disposal, the development stage of the alloy, and number of alloys being investigated, etc.

Some examples of alloy development techniques used for determining mechanical properties of small quantities of materials in thicknesses other than sheet are as follows:

- A series of 70 titanium alloys with various additions including aluminum, tin, and zirconium was prepared by D. N. Williams, et al.[5] The 3/4-pound doorknob shaped ingots were triple melted in a tungsten electrode arc melter. The ingots were hammer forged in air at a temperature that ensured working in the beta field, to approximately 0.6-inch-thick slabs. After being conditioned to remove surface defects, the alloys were rolled in air to 1/4-inch plate. The final plate size was approximately 2 1/2 x 8 inches, which yielded ten 2 1/4- x 1/4- x 1/4-inch tensile blanks, and twenty 1 1/8- x 1/4- x 1/4-inch impact blanks. The final tensile specimen was 0.135-inch diameter and 1.10-inch gage length. The microimpact specimens were a modified Izod type,[6] measuring 1.125 inches long by 0.225-inch diameter with a 0.0325-inch-deep circular notch. Two of the seventy compositions were selected for scale-up evaluation. The 20-pound ingots were consumable electrode melted twice to ensure homogeneity, then fabricated to 1-, 1/2, and 1/4-inch plates prior to mechanical testing.

- Small amounts of tin and zirconium were added to rods cut from commercial plates of three different alloys and melted twice in a hollow cathode discharge (HCD) melter.[7] The 2-pound ingots were scalped to remove surface irregularities prior to upset beta forging. The 1-inch-thick slabs were low-temperature cross-rolled to plate measuring 1/2 inch x 5 inches x 5 inches, then tested for strength and toughness. The HCD melting technique is similar to electron beam melting, but the 3-foot by 3/4-inch diameter electron beam is generated at a hot cathode by the ionization of argon gas. Chamber pressure during melting is approximately 1 micron, and the raw material is fed into the beam and drip melted into a water-cooled copper hearth 4 inches long by 2 inches in diameter.

- Margolin and Farrar[8] melted 22 complex titanium alloys, consisting of iron and copper additions, to a Ti-5Al-2Sn-2Mo-2V alloy and modifications of that base alloy. The material in the form of consumable electrodes was melted twice to a final ingot size of 3 3/4-inch diameter by 3 1/2 inch long. The ingot was scalped to remove about 1/8 inch from the diameter and the corners rounded before high-temperature forging to a 2-inch square bar. The bar was cut in half and reforged in the beta field to 1-inch square rod. The bars were cut again and subsequently forged to 1/2-inch squares. One tensile specimen followed by three impact specimens were cut along each rod and the sequence repeated until all the material was used. Four of the more promising compositions were subsequently scaled-up and melted as 30-pound ingots.[9] These were upset beta forged 20%,* then beta forged to 2-inch plate about 4 inches wide, then alpha + beta forged to 1-inch plate.

- Four 30-pound ingots with variations of Cb and Ta in a Ti-6Al-2Cb-1Ta base alloy were melted and fabricated by Reactive Metals, Incorporated, one of the two major producers. The plates were evaluated by Wolff, Aronin, and Abkowitz[10] as part of a plate alloy development program. The 30-pound ingots were triple melted then rough forged to 7/8-inch-thick flats which were subsequently rolled to 1/2-inch plate, 5 to 6 inches wide.

Research heats weighing about 100 pounds are often used to finally optimize some general composition before a full-scale commercial ingot (8,000-15,000 pounds) is ordered. These research heats, which are usually purchased from one of the two major producers, can be forged and rolled to a plate measuring about 1 inch x 18 inches x 30 inches. This is a large enough sample for a number of tests (creep, fatigue, etc.) to show effects of the elemental variations in plate material.

TITANIUM METALLURGY

Alloying Effects

Pure titanium transforms from the high-temperature beta phase (BCC) to the low-temperature stable alpha phase (HCP) at 1620° F.* Alloying elements produce a change in this transformation temperature and consequently change stable room-temperature structure and properties. Of interest in this investigation were three general classes of alloying elements, which can be distinguished by the effects produced upon adding small amounts to pure titanium. The resulting phase diagrams follow:

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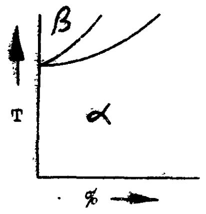
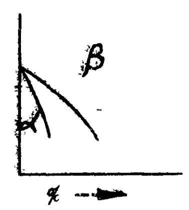
*Abbreviations used in this text are from the GPO Style Manual, 1967, unless otherwise noted.

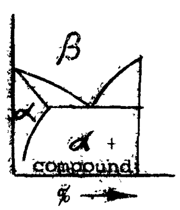
Sketch (a)



Sketch (b)



Sketch (c)



As shown above, Sketch (a), additions of alpha stabilizers such as aluminum (the most common alloying element) will cause the transformation temperature to rise, in effect extending the alpha field. Aluminum is a very good solid solution strengthener up to 5% to 8%, depending on other elements present and heat treatment. Although tin is not as effective, small amounts are often added for optimizing strength. Oxygen, nitrogen, and carbon, all of which occupy interstitial sites of the alpha phase primarily, are powerful strengtheners, but if present in large amounts (approximately 0.5% total) are most detrimental to the toughness properties.

Molybdenum, vanadium, tantalum, and columbium are the commonest beta stabilizers and have the effect on the phase diagram shown in Sketch (b). The elements are listed in order of decreasing effectiveness of retaining the beta field to room temperature. The solubility of these elements in alpha titanium is limited, particularly with Mo (0.5%) and V (2% to 3%).

In order of increasing activity, the beta eutectoid formers are manganese, iron, chromium, cobalt, nickel, copper, and silicon. Sketch (c) shows the effect of adding these elements to titanium. The manganese eutectoid reaction is so sluggish that compound rejection often cannot be detected after very long holding periods below the eutectoid temperature (1022° F). Thus, enriched beta phase may be retained down to room temperature between the alpha platelets. These elements are not usually present in more than trace amounts in the common commercial alloys because the eutectiod products are usually brittle.

'itanium alloys are classed in four general types, depending
ıposition: Alpha alloys are the various grades of pure
um with some oxygen added for strength; near-alpha alloys
n aluminum and tin with minor amounts of beta stabilizer;
beta alloys usually contain aluminum and significant
s of beta stabilizer; and the beta alloys which have high
tabilizer contents and minor aluminum. The types are named
heir stable room-temperature phases. In this investigation,
rst three types of alloys and three titanium-manganese
es were used.

tructure

he metallography of titanium is complicated because of the
different effects of the alloying elements, the slow nature
reactions, and the similarity of the different phases under
croscope. The alpha phase at room temperature can be equiaxed
cular, but is more often in the needle-like or platelet
These platelets can be so small as to be unresolvable at
The beta phase can exist at room temperature as retained
or transformed beta (actually very fine acicular alpha),
martensitically transform to alpha prime (also neddle-like)
uenching. Beta of certain critical compositions can also
orm to omega, an unresolvable (except by X-rays), very
e, metastable compound. The sluggish nature of some reac-
means that either annealing treatments must be very long
microstructure will contain nonequilibrium phases. For
e, Crossley[11] claims that much of the confusion surround-
e titanium-aluminum phase diagram results from the diffu-
f aluminum into two concentrations during working in the
+ beta phase field. This "partitioning" of aluminum persists,
e subsequent long-time anneals and gives rise to the spurious
ance of two phases.

sing

he development of an alloy involves two interrelated problems.
st obvious is the optimization of a particular alloy formula-
but equally important is the processing of the alloy into a
product. This area of fabrication development is difficult
processing is a very expensive operation and controlled
les are difficult to reproduce. A balance must be main-
between equipment capabilities (i.e., size and power of
g mills, etc.) and material property losses due to "easy"
ation. For example, the higher the forging temperature
sier it is to move and shape most metals. Often, however,
emperature forging causes irreplaceable loss of strength

properties. In titanium alloys high forging temperatures cause large beta-grain growth which in turn means larger alpha plate size and lower strength.

A great deal of effort has been expended by the titanium industry and a general processing scheme has evolved for each product. There are, of course, variations for each alloy composition and ingot size, but generally the fabricating schedule for plate products is as follows: Initial breakdown of ingots, as low as practical in the beta field (100° to 200° F above the beta transus), followed by rolling in the alpha + beta field (1750° to 1800° F). These temperatures are initial temperatures that will drop during processing by several hundred degrees.

It is the difficulty of reproducing industrial fabrication schedules that is the main disadvantage of small ingot-alloy development. Any ingot under 100 pounds cannot be realistically fabricated, and even 100- to 1000-pound ingots, when produced, are processed on a "best guess" basis. The rationalization of this difficulty is made on the basis of duplicating microstructures and thereby hoping to duplicate properties. This duplication of microstructures is important, because after structures with either more or less of a particular phase or morphology in the small melt alloys (than can be obtained in industrial size alloys) have been tested, improper conclusions could be drawn about scaled-up properties.

In spite of these severe limitations and the difficulty of performing heat treatment studies, small ingot properties have proved very useful and will continue to be so. Great care must be taken in interpretation of results and it must be realized that scale-up involves some speculation, since whatever information is available will always seem inadequate.

EXPERIMENTAL PROCEDURE

PURPOSE OF INVESTIGATION

The purpose of this investigation was to devise a technique to melt and forge very small ingots of titanium alloys and to determine their mechanical properties.

The general scheme for pursuing this investigation involved three separate but interrelated problems which may be outlined as follows:

- Part I - To determine the optimum shape of the miniature ingot. This shape must lend itself to homogeneous melting, and to a reasonable degree of hot forging, so that specimens for mechanical testing can be obtained efficiently.

- Part II - To determine material preparation, melting, and fabrication parameters to ensure homogeneity in the melted ingot and a uniform degree of hot work during forging.

- Part III - To determine the most suitable type of mechanical tests and specimen sizes. The results should be correlatable with composition and structure of both the small melts and commercial material of similar composition.

PART I

The Arc Button Melting Furnace

The melting equipment used in this investigation is a Model 124 arc button-melting furnace manufactured by Vacuum Industries, Incorporated, Somerville, Massachusetts. A schematic and photograph of the equipment appear in Figures 1 and 2. The water-cooled, stainless steel, outer jacket is capable of maintaining a 5 x 10^{-3} mm of Hg vacuum when pumped by a Welch Model 1402B mechanical pump. The atmosphere during melting is a 4 to 1 mixture of helium and argon at atmospheric pressure. Prior to melting, however, the chamber is pumped and backfilled with the gas mixture three times to ensure a contaminant-free atmosphere.

The water-cooled, stainless steel, electrode holder (stinger) is free to move through the use of a ball-swivel vacuum fitting. The tungsten electrode is press fitted, then peened into a threaded copper sleeve which screws into the end of the stinger. The negative power lead is connected below the insulated handle at the top of the stinger.

The water for cooling below the copper hearth plate is sealed with an O-ring, so that the plate can be easily removed for machining, etc. A mechanical arm in a ball-swivel vacuum feed through is used for turning buttons over and is controlled by a handle outside the chamber. Two sight ports penetrate the jacket and one can be used to admit light to the chamber when the arc is off. Both ports are equipped with glass shields which can be swung into place to screen the harmful arc radiation.

The console is equipped with controls to direct the separate cooling-water flow in the various components, power switches for the pump and vacuum gages, and meters for monitoring the pressure-vacuum and arc voltage and current.

Power is supplied to the melter from an Air Reduction Company Model 10DDR-24A1 1000 ampere d-c welding power supply. The high-frequency starting arc is generated by an Air Reduction Company Model HF-15-1-WG unit. The melter is capable of handling a 16-kw arc for less than 2 minutes continuously, and 12 kw for more sustained periods.

After the hearth depressions are filled with melting stock and the chamber is evacuated and back-filled with the helium-argon mixture, the arc can be struck. The electrode is lowered to within 1/4 inch of the material to be melted and the high-frequency starting arc is turned on. When the small broken-up high-frequency arcs have ionized a path between the electrode and the melt stock, the main power is turned on. The arc will radiate uniformly and can be easily controlled by the foot-operated amperage control switch. The arc is stopped by releasing the foot switch, thereby turning off the power. At least 10 minutes should be allowed for cooling before air is admitted to the chamber. It is possible to turn the button over with the mechanical arm without contaminating the gas atmosphere.

Characteristics Affecting Button Size and Shape

During melting, a button in the arc furnace consists of three parts. The material directly under the arc is, of course, molten and tends to circulate due to electromagnetic and other forces. The second portion of the button is that which is in direct contact with the water-cooled copper hearth, and it remains solid. The third section of the button, the "mushy" liquid-solid interface, is small because of the rapid heat flow to the copper hearth and is constantly moving as the arc is played over the liquid surface above. Frequently, the underside of a button does not make complete contact with the hearth but forms a bridge over the depression in the copper. When the liquid portion is deep enough, it will break through and flow under the solid part of the button, then freeze immediately. This action will expose new unmelted material to the arc and result in a nonuniform shape underneath. The size of the liquid zone is primarily dependent on the power of the arc, and since the voltage remains fairly stable, it is the current that is the controlling factor.

he factors affecting the shape of a button are surface n, gravity, and the shape of the hearth. Surface tension to draw a liquid into a sphere and gravity tends to make w out and be flat. The button is, of course, always cted by the shape of the hearth.

he size of buttons possible to melt is governed only by at-flow characteristics of the electrode-button-hearth uration. If both the electrode and power input are too or if the button-hearth contact area is too large, then lted portion of the button will be too small to give effec- iquid mixing. In effect, homogeneity decreases as button ncreases.

g Technique

he three stages of melting necessary to produce a sound are consolidation of the melt stock, homogenization, and ing.

he raw material for melting is usually either a loose or pacted powder and must be melted carefully to prevent y spilling out of the hearth depression. When the arc is and a layer of liquid metal covers the top of the powder, c power can be increased to give deeper penetration. After got solidifies, it can be turned over and the underside . This second melting could complete the consolidation and all traces of the original powder. The ingot should then ted two or three times under a high-power arc and turned ach time after cooling. This will ensure good homogeniza-

ollowing a series of meltings, the ingot is liable to have and folds where the liquid metal over ran the solid sides ttom. These irregularities must be smoothed out or they initiate cracks during subsequent forging operations. The ing is accomplished by turning the ingot so that the tinuities are on the top surface, then running a very low arc over them. The arc will melt just a small bead of under it and this can be moved along the folds. Thus, by elective remelting, a smooth even shape can be produced.

Determination of Shape

A series of round hearths of varying dimensions (shown in Figure 3) were machined in a 9 3/4-inch diameter, 1-inch-thick oxygen-free, high-conductivity (OFHC) copper hearth plate. After the hearth plate was installed and checked for leaks, melts were prepared in each of the various depressions. The charge consisted of small (5- to 10-gram) ram-pressed titanium slugs which were melted in a small hearth depression (Item (c) of Figure 3). The final buttons weighed from 60 to 85 grams and varied primarily in thickness and cross section, and secondarily in diameter.

Two rod-shaped hearths were then machined in the same hearth plate. These were both of the same shape but different lengths and depths (Items (d) and (e) of Figure 3). Melting titanium in these hearths was similar to melting in the circular hearths, but the electrode was swept back and forth over the melt rather than in a circular motion. At any given time during the rod melting, the liquid pool extended from one side of the rod to the other and almost from one end of the rod to the other. There was no difference between melting in the smaller rod depression and in the larger.

Depth of the Liquid Zone

Homogeneity of a button is a direct function of the size of the liquid zone during melting which for a given power input and electrode configuration is related to the contact area between the charge and the hearth plate. Simplifying further, the percent liquid in a melt is related to the surface area of the hearth depression. The two circular depressions, appearing in Items (a) and (b) of Figure 3 and the large rod depression, Item (e), have approximately the following surface areas: 2.9, 3.2, and 3.6 square inches. Thus, since the areas are similar, it is reasonable to expect that the percent liquid during melting is also similar.

A series of 10-gram buttons was laid on edge in a row in the rod-shaped depression and the arc was played over the top surface. Part of the buttons melted and flowed to fill the interstices. Observation of the sides and bottom of the solidified ingot permitted estimation of the percent of the ingot that had been liquid. This appeared to be 55% to 65%.

PART II

A series of titanium base alloy rods having widely varying mechanical properties was melted and fabricated before being machined into test specimens. The starting materials were the necessary metallic elements in pure granular form and were compacted, mixed in the desired ratios, melted, forged, then annealed before testing.

Alloy Compositions

In order of increasing expected strength, the following alloy formulations* were chosen:

- Pure titanium (plus minor oxygen).
- Pure titanium (plus minor manganese).
- Ti-1.5Al-1.5Mo.
- Ti-2Al-1V.
- Ti-6Al-2Cb-1Ta-0.8Mo.
- Ti-6Al-2Sn-1Mo-1V.
- Ti-6Al-2Sn-1Mo-1V-0.2O_2.

In addition to these alpha and alpha + beta alloys, the following two alpha + eutectoid compositions were prepared:

- Ti-1.5Mn.
- Ti-5Mn.

Of these nine alloy compositions, four were available in commercially produced plate form and thus data comparisons would be possible. Four of the alloys were prepared in duplicate; i.e., two separate ingots of the same composition were prepared, melted, and tested with one ingot being annealed only, and the other being forged, then annealed. The two ingots of Ti-6Al-2Cb-1Ta-0.8Mo were given identical treatment so that some indication of reproducibility would be possible. Table 1 summarizes the nominal and actual compositions of each rod.

---

*All numbers are percent by weight.

Table 1 - Composition of Rod-Melted Alloys

Titanium Alloy	Condition	Al	Sn	Mo	Cb	V	Mn	O_2	H_2
Commercially Pure	Forged							360	
0.4Mn	Forged						0.36	280	
1.5Mn	Forged						1.14	430	
5.0Mn	Forged						4.42	660	
2Al-1V	Annealed	1.82				0.93		330	
2Al-1V	Forged	2.09						235	38
1.5Al-1.5Mo	Forged	1.41		1.38				380	
6Al-2Cb-1Ta-0.8Mo	Forged			0.77	2.32			285	56
6Al-2Cb-1Ta-0.8Mo	Forged	3.47		0.77	2.23			282	
6Al-2Sn-1Mo-1V-0.08O_2	Annealed		2.12					210	15
6Al-2Sn-1Mo-1V-0.08O_2	Forged	4.56	1.97	0.98		0.94		340	41
		4.52	1.97	0.94		0.96		293	47
6Al-2Sn-1Mo-1V-0.2O_2	Annealed	5.79	1.98	1.02		0.95		1600	
6Al-2Sn-1Mo-1V-0.2O_2	Forged					0.96		1600	

Note: All compositions are in weight percent except O_2 and H_2 which are in ppm.

Titanium sponge is a course particle with many "spikes"
only a very small amount by weight will fill a hearth
ession. In order to have enough material in the hearth
roduce a 60- to 90-gram ingot, it is necessary to compact
naterial before melting. Compaction can be done in two
: by a ram press or by an isostatic press.

- Ram Pressing - A double acting die, 1 inch in
eter, is filled about 3 inches deep with titanium sponge
placed either in a tensile machine or a ram press. A
ressive load of 15,000 to 20,000 pounds will compact the
nium to a 1-inch diameter, 1/2-inch-long slug weighing 20
5 grams.

- Isostatic Pressing - A rubber tube with one open
1 1/2 inches in diameter and about 15 inches long is lined
a thin piece of titanium sheet then filled with titanium
ge. The sheet lining prevents the sharp sponge from
cing the tube. Placing the tube upright on a vibrating table
help the sponge settle and eliminate any "bridging." The
when full is sealed at the top with a rubber stopper and,
further precaution against leaks, electrical tape is
ped around the tube-stopper joint. A hypodermic needle
ected to a small vacuum pump (Welch Model 1400 or similar)
hen pushed through the stopper and the air in the bag
ved. After withdrawing the needle carefully (the hole
reseal itself), the tube assembly is placed in the chamber
n isostatic press. The oil in the chamber of the press
n Pressure Equipment Company Model LM11) is pressurized to
00 psi, squeezes the tube uniformly, and compacts the sponge
rod about 1 inch in diameter by 13 inches long. This rod
be cut into any length needed for melting.

The two methods of compaction both produce material that
% to 80% dense, but the isostatic method is quicker since
elds more rod at a time.

aration of Alloys

The elements for the alloy additions were available in
following forms shown in Table 2.

Elements Used for Alloy Additions

Element	Purity, %	Form	Size, microns
Ti	99.67[1]	Sponge	-
O_2	99.945	TiO_2 Powder	20 to 37
Mo	99.93	Powder	2 to 20
Sn	99.95	Shot	2800 to 4000
Cb + Ta	99.4	Al + Cb + Ta	
		Master Granules	<6300
Mn	99.5	Powder	30 to 44
V	99.8	Granules	<3150
Al	99.99	Shot	1410 to 4760

[1] Ti sponge analysis:
0.033% O_2, 0.007% N_2, 0.0026% H_2, 0.018% C, 0.145% Cl_2, 0.037% Fe, 0.086% Other.

Ideally, the alloying elements should be mixed with the sponge before compaction in order to give the most homogenous melt stock. However, since the materials are in a wide variety of sizes and shapes which prevent good mixing, and since only small amounts are involved, only pure titanium and Ti-6Al mixtures were compacted. The Mo, Mn, and TiO_2 powders were ran pressed separately into thin 1/2-inch diameter disks, and then broken into particle sizes suitable for handling with tweezers.

Four or five holes were drilled along the length of the compacted cylinders and the weighed alloy additions distributed evenly in the holes. In some cases, it was not possible to put all of the additions in the holes, and so they were spread along the bottom of the rod hearth depression underneath the melt stock. Either the molybdenum or vanadium was put into the holes last so that the high melting materials were on top and would prevent excessive vaporization losses of the lower melting tin and aluminum.

Melting

In addition to the prepared melt stock, a button of titanium to be used as a getter was placed in another depression in the hearth plate. The arc melter was prepared for melting and the getter button melted twice to remove any contaminants in the helium-argon atmosphere. The titanium getter not only picks up contamination while liquid, but also becomes badly discolored after cooling in the presence of oxygen.

The titanium alloy rod was melted size times before the edges were smoothed off with a small arc. The first two melts which initially liquified the sponge used an arc voltage of about 40 volts and current of 300 to 400 amperes. The electrode was moved slowly, and deliberately held over the higher melting particles until they melted and dissolved in the titanium liquid. The powerful arc melted everything as rapidly as possible and minimized vaporization losses. During these two initial melts (the rod cooled and was then turned over between melts), a great deal of spattering occurred. The resultant weight loss of 3% or 4% was considerable, but an examination of the scattered, minute, round particles indicated that they were probably all titanium. The spattering of the sponge is mostly due to the residual chlorine and magnesium (left from the reduction process of the ore) and other volatiles which are released during melting. The next four melts, using a current of 250 to 300 amperes, homogenized the rod. The arc was moved rapidly back and forth and the rod was kept liquid for as long as 1 minute. The ingot was allowed to cool between melts then rotated either 180° or 90° each time.

The final stage was the remelting of any uneven portion of the ingot (generally on the sides). This utilized an arc of less than 50 amperes which melted only a small circle of titanium about 1/8 to 1/4 inch in diameter. The rod was left to cool for 1/2 hour before it was removed from the chamber.

All the rods used in this investigation were prepared in the manner described above. The alloy additions to subsequent rods, however, were added to holes drilled in a solid rod rather than in the compacted rod. Thus, all the weight losses due to spattering occurred in an unweighed, unalloyed ingot where it made no difference. Weight losses during later melting of the alloyed rod were less than 0.1%.

Fabrication

All but three of the ingots received a duplex forging treatment and a final anneal. From all but these three, about 1/8 inch was cut off each end of the as-melted ingots to provide a flat spot for upset forging. Forging was done on a Wabash Ram Press which is capable of loading 150 tons on a 10-inch-diameter ram. The high-temperature upset forging was done at 2050° F, and the 35% to 40% reduction in height was taken in one pass. The shortened ingots were placed in a furnace at 1750° F prior to the second forging operation, which on each pass pressed the billet on alternate sides and lengthened it. One pass caused about 40% reduction in height, and temperature losses were such that a reheat was necessary between passes. After four passes, the blank was squared off and allowed to cool. Wire brushing removed the loose oxide scale.

All the forged blanks were given a 1400° F, 1/2-hour vacuum anneal (the vacuum was maintained at 1 x 10^{-6} mm Hg) The anneal served two purposes: First, it removed the hydrogen, and second, it recrystallized the material (or at least removed forging stresses).

The three ingots which were not forged received a 1750° F, 65-hour homogenization anneal in a vacuum furnace (1 x 10^{-6} mm Hg). These ingots were duplicates of compositions that had been forged.

Figure 4 is a photograph of the small ingot in various stages of preparation.

PART III

The final size and shape of the ingot was such that two basic mechanical test specimens could be obtained. First, a standard Charpy V-notch impact specimen was available after machining off the contaminated surface layers, and after testing it, a compression specimen could be machined from one of the broken halves.

Charpy Impact Test

The small as-forged bar had a rough surface and an oxygen-contaminated layer of 10- to 20-micron thick. The cross section of the bar was 1.7 to 2.0 cm on a side and a standard Charpy specimen is 1.0 cm square. Thus, 0.3 to 0.5 cm had to be removed from each surface in the machining operation and no gross contamination would exist in the test specimen.

PI-2 combination impact testing machine. Lateral expan- measurements were taken on the broken halves after testing.

:harpy specimens from the four commercially produced plates also machined and tested at room temperature. The compo- n of the commercial plates were similar to four of the ingots.

ession Test

A broken Charpy half is 10 mm square and about 2.7 cm long. pression specimen 10 mm in diameter and 20 mm long can y be machined from a broken half and still not contain d metal from the Charpy fractured surface. The ends of ompression specimen were flat and parallel and had a sur- finish of 6 microinches (rms).

The testing was done on a Baldwin-Southwark Universal ng machine, and strain readings were taken with a dial and from a load-compression diagram plotted autographically B-L-H Model Ts-M microformer-type compressometer, and an raphic recorder that simultaneously recorded load and com- ive strain. The testing arrangement is shown in Figure 5. train rate was 0.002 inch per inch per minute until the offset yield strength had been exceeded then the rate was ased to 0.05 inch per inch per minute. Loading was con- d until either the specimen failed (by cracking) or until s apparent that cracking would not occur.

In addition to the small compression specimens from each e 13 fabricated rods, 2 other sets of compression tests run. First, duplicate small specimens were run from the rcially produced plate of similar alloy composition to four e melted rods. Second, "standard" or larger size speci- were run from the same commercial plates. These specimens 1 7/8 inches long by 5/8 inch in diameter and were tested cordance with procedures outlined in ASTM Designation E9-61. rison of the two sets of data would show effects of specimen

Tests

Hardness measurements were taken on the Charpy specimens to testing. The Rockwell B and Rockwell C scales were and the readings converted to Brinell Hardness Numbers.

remachined for compression testing was used for microstructural examination and for chemical analysis. The chemical analysis was performed by the LeDoux Company, Teaneck, New Jersey, an independent testing laboratory with considerable experience in titanium alloy analysis.

The metallographic specimens were prepared by standard mechanical and electropolishing techniques. The electropolishing solution was 59% methanol, 35% butyl cellusolve, 6% perchloric acid, and polishing conditions were 36 volts for about 35 seconds. The etchant was an aqueous solution of 1% sulphuric acid, 2% hydrofluoric acid and 3% nitric acid, and was wiped over the specimen for 5 to 10 seconds. Photomicrographs were taken at 100X and 500X.

SUMMARY OF EXPERIMENTAL PROCEDURE

The order and relationship of the various stages of melting and testing are summarized in the flow chart in Figure 6. The broken lines are steps that were attempted but, for various reasons, not used in the final series of 13 alloys.

RESULTS

INGOT SHAPE

The two general shapes of ingots prepared were similar with respect to weight and homogeneity but differed significantly in two other characteristics. The lesser important of these differences is the manner in which the charge and alloying elements had to be added to the hearth depressions. The ram-pressed slugs which were used (owing to their more regular shape) would not fit well into the circular depressions. As a result, the pile of melting stock was considerably higher than the depression and quite irregular, making initial melting difficult. In addition, the ram-pressed slugs are more likely to be contaminated from the surface of the die and from handling than are the isostatically pressed rods. The addition of alloying elements in the slug/circular hearth combination is more difficult than with the 2-inch, isostatically pressed cylinders, since fewer and smaller holes can be drilled in the slugs.

The second and more important advantage of the rod-shaped ingot is the uniform degree of forging that can be achieved in the final blank. To quantify this degree of forging, it is necessary to assign numbers representative of the amount of hot work in each direction. These numbers are the sum of the percentage reductions in height in each of the three directions. First, the length is shortened in one pass (upset forged) by 40%. After reheating (1750° F), the ingot is turned on its side, forged in the second direction (say "x") and its height reduced 40%. After reheating again, the blank was reduced 40% in height in the third (as yet unforged) "y" direction. This forging, of course, causes lengthening in the other two directions. The blank was alternately forged in the x and y directions with reheats each time. Summing the individual height reductions in each direction gives:

z direction (length)	40
x direction	100
y direction	85

and the uniformity of forging in the x and y directions, and considerable work in the z direction are apparent. This is also reflected in the uniformity of microstructure in Figure 7.

A predicted set of numbers for forging a circular button to a similar blank size is:

z direction	0
x direction	150
y direction	90

which is considerably less uniform than the rod-shaped ingot.

CHEMICAL ANALYSIS

The results of the chemical analysis are listed in Table 1. The actual compositions are very close to the nominal compositions for all ingots except the high aluminum alloys and the manganese alloys. Even in two of the manganese binaries, the actual composition is off by only 10% to 12%. The third manganese binary (1.5% Mn) is off by about 30%, almost certainly due to manganese loss during the spattering on the initial melt.

The low aluminum alloys (2Al-1V and 1.5Al-1.5Mo) have quite accurate aluminum contents, but the 6% aluminum alloys are all considerably off composition. Two factors can account for these low aluminum results. First, the isostatic rod used for melting stock was a Ti-6Al alloy which consisted of aluminum particles (average size 2 to 3 mm in diameter) mixed in with the titanium sponge before compaction. Any uneveness in the distribution of the aluminum particles would made a significant change in the final ingot compositions. Second, the spattering was severe during initial melting (overall 3% to 5% weight loss) and although most of the material lost was titanium, some particles of aluminum may also have been lost. Since the aluminum granules were relatively large, any particle losses would be significant.

Oxygen pick-up during melting and processing was practically nonexistent. The oxygen contents reported in Table 1 are much lower than in normal commercial material. Standard commercial products contain 1600 to 2000 ppm oxygen, while special products (such as heavy plate) may have oxygen contents of 800 to 1200 ppm.

It is to be expected that the annealed alloys would have lower hydrogen contents than the forged material, since the long-time anneal was done in a vacuum furnace. This is confirmed for the only annealed alloy analyzed.

All future alloys melted by this technique will start with solid melting stock, as opposed to compacted sponge. Either pure titanium or alloy bars will be melted with the alloy additions being placed in the drilled holes. This will eliminate the spattering and final alloy compositions will be much closer to nominal compositions. Several rod ingots have been melted in this way and weight losses were less than 0.1%.

MICROSTRUCTURE

As mentioned earlier, the uniformity of forging the 6Al-2Cb-1Ta-0.8Mo alloy is well illustrated in Figure 7. This composite shows the microstructure in three mutually perpendicular planes, and is typical of the near-alpha alloys.

Figure 8 shows the microstructures of the three titanium-manganese binaries (nominally 0.4%, 1.5%, and 5.0% Mn) The 0.4% Mn alloy contains acicular alpha in an alpha matrix. The dark spots are either small beta particles due to contaminants or the cross sections of some alpha needles. The 1.5% Mn alloy should contain proeutectoid alpha in a maxtrix of alpha plus eutectoid TiMn. The reaction is sluggish, and it is probable that the matrix is a supersaturated alpha with

: small beta particles of precipitated TiMn. The nominal
ılloy microstructure is somewhat clearer since the pro-
:oid alpha is considerably more prevalent, and the matrix
:arly acicular alpha plus either enriched, metastable beta
in.

'igure 9 shows the photomicrographs of the two oxygen levels
: near-alpha Ti-6Al-2Sn-1Mo-1V alloy in both the annealed
orged conditions. The larger alpha plates in the higher
ı alloys are due to the alpha stabilizing effects of oxygen.
:finement of the alpha plate size due to hot working is also
:nt in both alloys.

ICAL TESTING

'he results of the Charpy impact and compression tests run
: 13 melted and fabricated ingots are listed in Table 3.
:ress/strain curves are shown in Figures 10 and 11.

'he notches in the Charpy specimens were machined without
l to direction (i.e., x or y direction), since identifi-
ı of sides was not maintained during fabrication. The
direction should make little, if any, difference because
ıeat flow during melting and degree of hot working were
:m. This is, at least, not disproved by the results of the
:lts of the 6Al-2Cb-1Ta-0.8Mo alloy. The Charpy numbers of
l 46 ft-lb are remarkably close considering the inherent
:r of the test and the slight differences in alloy chemistry.

In the compression tests the proportional limit is taken to
: lowest stress in the nonelastic portion of the stress/
ı curve, and the yield strength is the standard 0.2% offset
strength. No lubricants were used between the specimen
ınd the loading plates even though this would result in the
:r onset of nonuniaxial loading. It would be virtually
:ible to get a uniform coating consistently on all the
nen ends, and so they were simply cleaned thoroughly with
ıe.

In general, the results of all the tests are very consis-
vith respect to the normal increasing strength/decreasing
ıess relationship. The effects of the following three
:ters illustrate this.

Table 3

Mechanical Properties of Rod-Melted Specimens

Titanium Alloy	Condition	Compressive YS ksi	Charpy Impact (ft-lb RT)	Strain %	Hardness (Converted to BHN)	Lateral Expansion inches	
Commercially Pure	Forged	52	99	(1)	135	0.054	0.037
0.4Mn	Forged	36	211	(1)	107	0.066	0.065
1.5Mn	Forged	56	132	(1)	153	0.061	0.042
5Mn	Forged	80	44	38	236	0.024	0.023
2Al-1V	Annealed	53	102	43	159	0.060	0.034
2Al-1V	Forged	82	83	46	169	0.037	0.031
1.5Al-1.5Mo	Forged	67	96	(1)	174	0.056	0.031
6Al-2Cb-1Ta-0.8Mo	Forged	117	42	26	260	0.011	0.018
6Al-2Cb-1Ta-0.8Mo	Forged	116	46	18	-	0.025	0.022
6Al-2Sn-1Mo-1V(0.08% O_2)	Annealed	104	55	26	260	0.036	0.022
6Al-2Sn-1Mo-1V(0.08% O_2)	Forged	121	33	27	265	0.015	0.014
6Al-2Sn-1Mo-1V(0.2% O_2)	Annealed	125	37	22	297	0.018	0.012
6Al-2Sn-1Mo-1V(0.2% O_2)	Forged	158	12	18	322	0.003	0.003

[1] Specimen did not fail.
YS - Yield Strength
RT - Room Temperature
BHN - Brinell Hardness Number

Forging

Two ingots of each of three compositions were prepared and melted. One ingot of each alloy formulation was forged then annealed, and the other received only a homogenization anneal. These duplicate compositions and test results are summarized below in Table 4.

Table 4

Summary of Test Results for Three Compositions

	Condition	2Al-1V	6Al-2Sn-1Mo-1V	6Al-2Sn-1Mo-1V 0.2% O_2
YS, ksi	Annealed	53	104	125
	Forged	82	121	158
	Difference	29	17	33
Charpy Impact ft-lb	Annealed	102	55	37
	Forged	83	33	12
	Difference	19	22	25

The Charpy number differences of 19, 22, and 25 ft-lb are in the same order of magnitude, but in fact become greater as the amounts of alloying elements increase. The strength increases due to forging are also reasonably consistent (25±8 ksi), but again greatest in the most complex alloy.

Oxygen

The small table above also points out the effect that the increased oxygen content has on the 6Al-2Sn-1Mo-1V composition. Oxygen, an alpha stabilizer, takes interstitial positions in the lattice, thereby causing considerable strain. This manifests itself in higher strength and lower toughness in the bulk material. As the above results illustrate, the Charpy number drops 18 ft-lb in the annealed specimen, and 21 ft-lb in the forged specimen, while the yield strengths increase 21 and 37 ksi, respectively. The differences due to the increased oxygen are greater for the forged specimen, showing the synergistic effect of hot working.

Other Elements

As the amount of alpha and beta stabilizers increase, the strength increases and the toughness decreases. Generally, these elements cause solid-solution strengthening, and it is to be expected that these strength and toughness changes occur.

The ingots containing the two higher manganese additions had greater strength and toughness changes. Manganese additions in these percentages should cause the formation of a TiMn compound which precipitates in the eutectoid reaction,

$$\beta_{Ti} \rightarrow \alpha_{Ti} + TiMn.$$

The increased amounts of the TiMn compound, or if it fails to completely precipitate the enriched beta, cause the very large changes in strength and toughness. It is not known why the Ti-0 4Mn alloy revealed extremely low strength and high toughness, but this is being studied as part of a separate alloy development program.

STRESS-STRAIN-TOUGHNESS RELATIONSHIPS

Figure 12 is a graph of the yield strength versus Charpy impact number for the materials tested. The steeper line connects the series of manganese eutectoid-type alloys, and the other line is the alpha and alpha + beta type alloys.

Figure 13 shows the percent strain of failed specimens as a function of yield strength. Figure 14 is the graph of lateral expansion versus Charpy number. Figure 15 is a graph showing Brinell Hardness Number (converted from Rockwell B and Rockwell C) as a function of yield strength.

These graphs are included to illustrate the consistency of the data from the melted-rod ingots. All the slopes of the graphs show the expected relationships. There is, of course, some scatter due to the more or less pronounced secondary effects and inherent test scatter (particularly in the Charpy test), but no melted rod has a data point significantly far from the trend lines.

COMMERCIAL PLATE COMPARISONS

Table 5 lists the results of testing the Charpy and compression specimens machined from commercially produced plates of four alloys. The stress-strain curves of small specimens are drawn in Figure 16.

Mechanical Properties of Plate Specimens

Alloy	Charpy Impact (ft-lb at RT)	Compressive YS, ksi		Strain %	Hardness (Converted to BHN)
		Modified Specimen[1]	Standard Specimen[2]		
ercially Pure tanium	185	43	44	(3)	120
Al-2Cb-1Ta-0.8Mo	43	107	110	30	-
Al-2Sn-1Mo-1V .08%O_2)	34	122	121	20	260
Al-2Sn-1Mo-1V .2%O_2)	15	133	143	17	309

mm diameter by 20 mm long.
25-inch diameter by 1.875-inch long.
cimen did not fail.

two sizes of compression specimens were run in duplicate
the Charpy tests in triplicate, and the data shown in the
e are averages for the two or three specimens. In some
s, the yield strengths of individual specimens from the same
e varied as much as 5 ksi; so the difference in results
een the small and "standard" size compression specimens cannot
onsidered significant.

The lines drawn in the graphs of Figures 12 to 15 were based
he data points of the 13 melted rods. The "x" data points
hese figures are from the commercial plate specimens and fall
e to the lines. While the results of the rod melts and com-
ial plates are not exactly equal, they differ by a surpris-
y small amount. One particular limitation of the small
ts that could easily account for these differences is the
e variation of thermal histories experienced by the rods
commercial plates. This variation is, of course, due to the
differences which significantly affect cooling rate.
ough forging is initiated at comparable temperatures, heat
es are greater and the final working temperature is lower
the rods than for the commercial plates. The cooling times
r annealing treatments are also much less for the small ingots.

DISCUSSION OF RESULTS

ARC MELTING

The relative ease with which the rod ingots can be melted points up the versatility of arc melting. Too often the arc-melting furnace is thought capable of only melting circular buttons. Some other designs of melting furnaces incorporate fixed electrodes and rotatable hearth plates which, though most suited for circular button melting, need not be limited to it. The best ingot shape is determined by the size and final application of the button. Small sizes must almost invariably be melted in a circular hearth because of the natural tendency of the molten metal to spheroidize. In applications where expensive, exotic alloys are to be prepared for physical property measurement, the circular hearth is mandatory. However, in applications where a particular specimen shape is required for testing, consideration should be given to varying the hearth shape to best meet such requirements. Mechanical testing is a good example of such a particular application. If either uniform or anisotropic hot working is required before testing, there will be an optimum ingot shape which is probably not circular. While it may not be possible to melt an ingot in exactly the optimum shape, it certainly can be approached by varying hearth geometry.

MECHANICAL PROPERTIES

In order to compare the melting and fabricating techniques of small and large ingots, it is necessary to determine their mechanical properties. The mechanical properties of a series of small ingots then should be compared "internally" (i.e., relative to themselves) and "externally" (i.e., relative to corresponding commercial products). If the data show no abnormal tendencies to vary from expected metallurgical relationships involving strength, toughness, ductility, hardness, etc., and if the microstructures of the material conform to known phase morphologies, then the technique producing such data can be said to be valid. Furthermore, if the small ingot data can be shown to approximately correlate with test results of commercially produced material, then the small ingot techniques can be considered useful.

The relationship between strength, toughness, percent strain at failure, hardness and lateral expansion after Charpy testing as plotted in Figures 12 through 15 are all consistent over the large range of material properties tested. While it must emphasized that these tests are based on only one specimen, e reproducibility (of the 6Al-2Cb-1Ta-0.08Mo ingots) appears be good. Thus, the data from each ingot seem to be truly presentative of the material in the tested condition. This eans that in a series of alloys the technique can be used to etermine the effects of a varying parameter such as composi- ion (either major or minor alloying elements), forging schedule, heat treatment. As long as changes in the parameters are easonably large, systematic changes in material properties hould be detectable.

There are two ways to examine the correlation of the ingot ita and the commercial plate data. The first is to see how the operty relationships between strength, toughness, etc., of the late material compare to the trend lines drawn for the small igot data. This is shown in Figures 12 through 15. The second ay is to compare specific properties from corresponding alloys rod ingots and commercial plates. The second method is less istified because of the difficulty of obtaining corresponding iterial. Exact compositions can never be duplicated and plate ibrication cannot be reproduced accurately when ingot sizes iry.

In spite of these limitations, the rod ingot data can ve a rough estimate of what plate properties are likely to . In the example outlined earlier, full size commercial ats of Ti-6Al-2Cb-1Ta-0.8Mo have guaranteed minimum compres- ve yield strengths of 105 ksi in plate less than 2-inches ick. The difference in the value of properties between 1- d 2-inch-thick plate has been well documented and typically rengths are 5 ksi greater in 1-inch plate. Also, the 105 i is a guaranteed minimum and is naturally on the conserva- ve side. Thus, typical compressive yield strengths for this loy in 1-inch plate would vary between 110 and 120 ksi. though not specified by the manufacturer, Charpy impact data t room temperature) for 1-inch plate is typically 40 to 45 -lb. The rod ingot data for this alloy (duplicate results) re 116 ksi yield strength and 44 ft-lb impact energy, both num- rs are within the commercial plate range. This correlation is obably better than expected, but a general idea of plate operties is possible from the rod ingot data.

CONCLUSIONS

The following conclusions have been drawn:

- A series of small (90-gram) rod-shaped ingots of various titanium alloys were successfully melted in an arc-button furnace and uniformly forged to a form suitable for mechanical testing.

- In addition to chemical and microstructural analysis, the following mechanical properties were determined from the forged blanks: compressive yield strength, percent strain at failure, Charpy V-notch impact energy, lateral expansion after Charpy testing, and hardness.

- The relationships between the measured mechanical properties were consistent and reproducible. Thus, the technique can be used to show the effects on mechanical properties of varying parameters in a series of alloy rods.

- Based on the rod ingot data, a good estimate can be made of the strength and toughness properties of commercially produced 1-inch-thick plate.

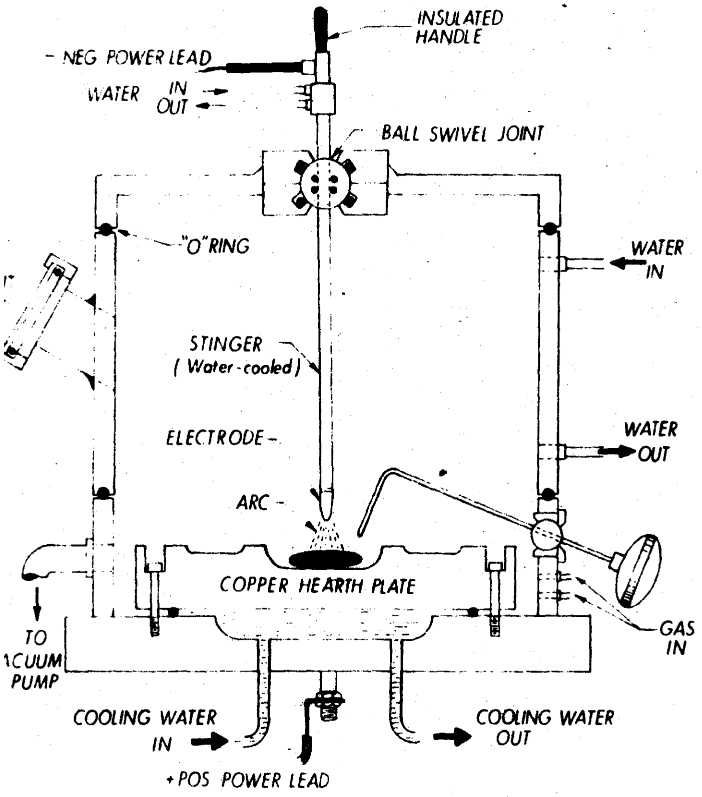


Figure 1

Schematic of Arc Button Melting Furnace

Item (a)

Close-up of Melting Chamber

Item (b)

Overall View of Console

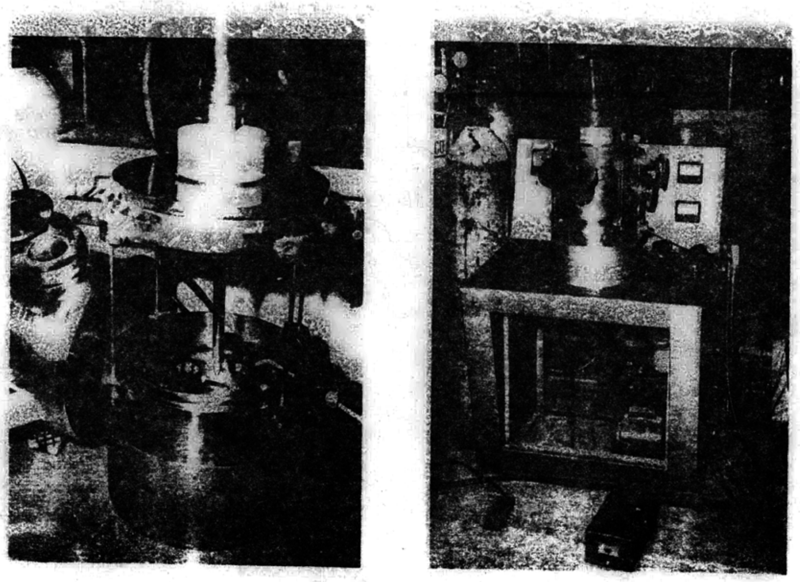
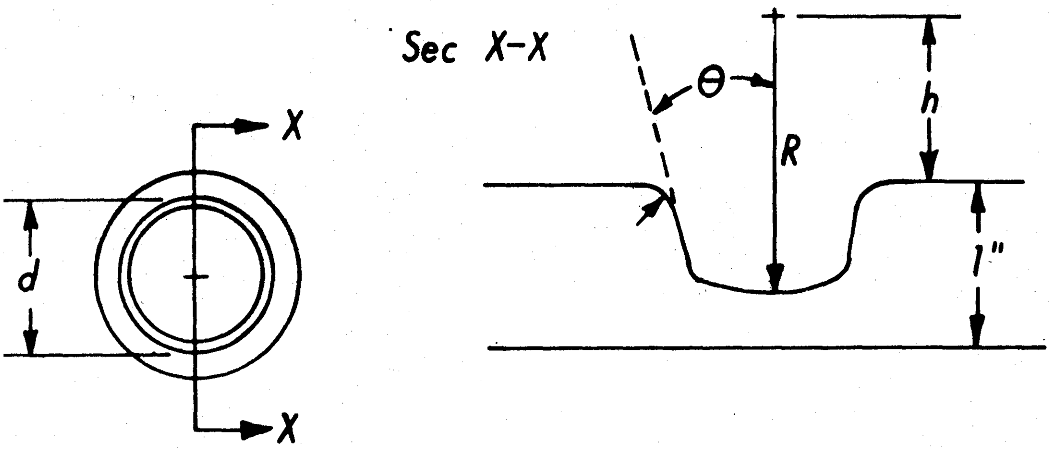
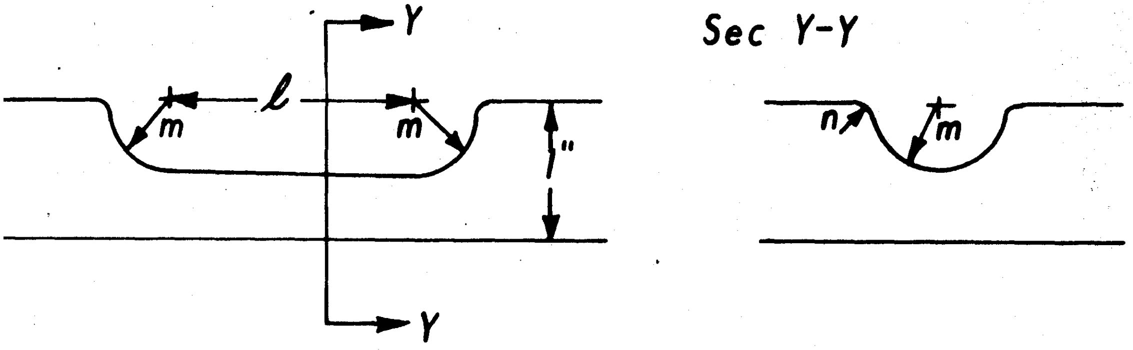


Figure 2 - Arc Button Melting Furnace



Hearth #	d	h	R	θ	r
A	$1\frac{5}{8}$"	1"	$1\frac{11}{16}$"	15°	$\frac{9}{32}$"
B	$1\frac{7}{8}$"	1"	$1\frac{5}{8}$"	10°	$\frac{9}{32}$"
C	1"	0	$\frac{1}{2}$"	0	0



Hearth	ℓ	m	n
D	2	$\frac{3}{8}$"	$\frac{9}{32}$"
E	$2\frac{1}{4}$	$\frac{1}{2}$"	$\frac{9}{32}$"

Figure 3

Hearth Dimensions

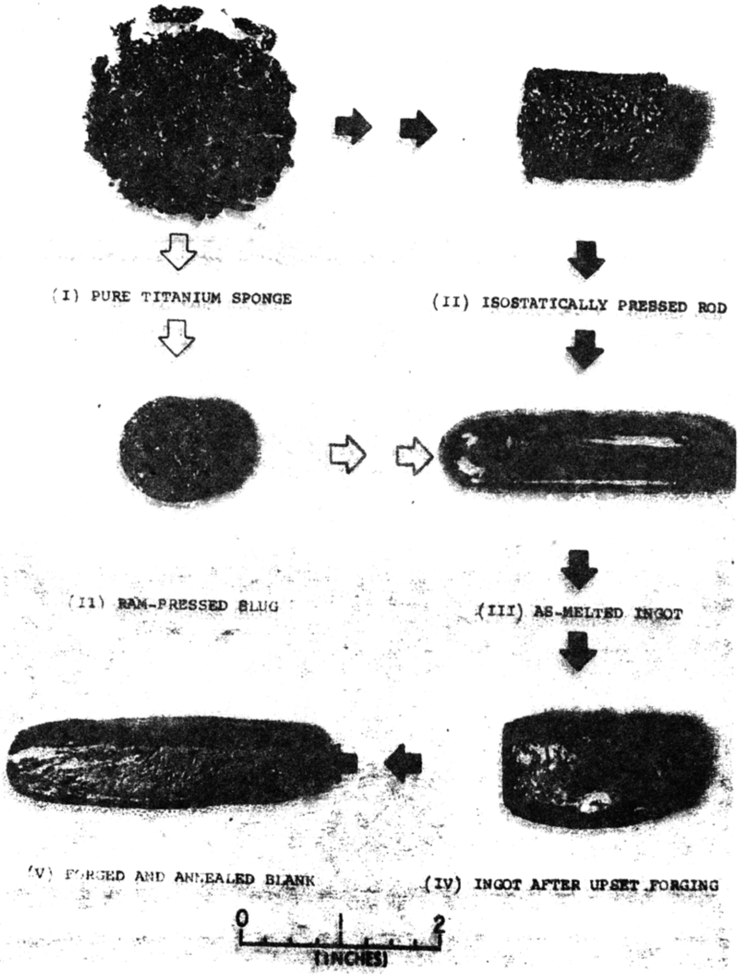


Figure 4
Various Stages of Material Preparation

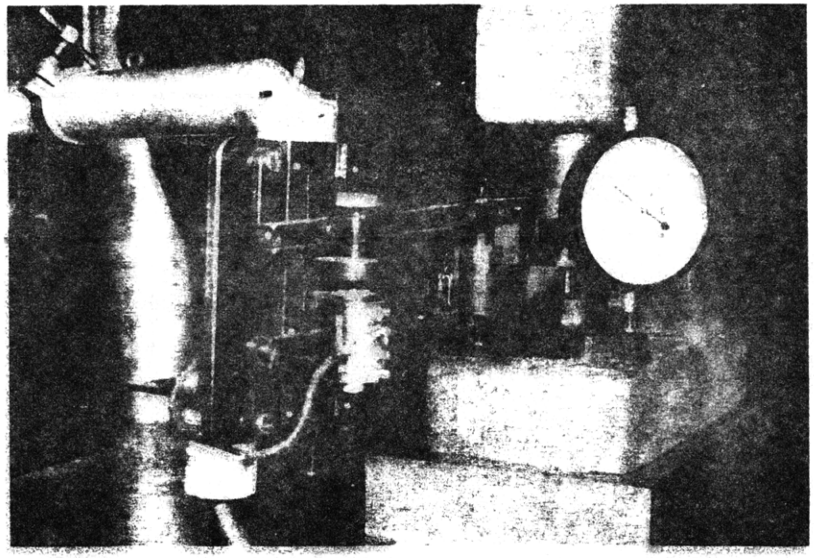


Figure 5

Compression Testing Arrangement

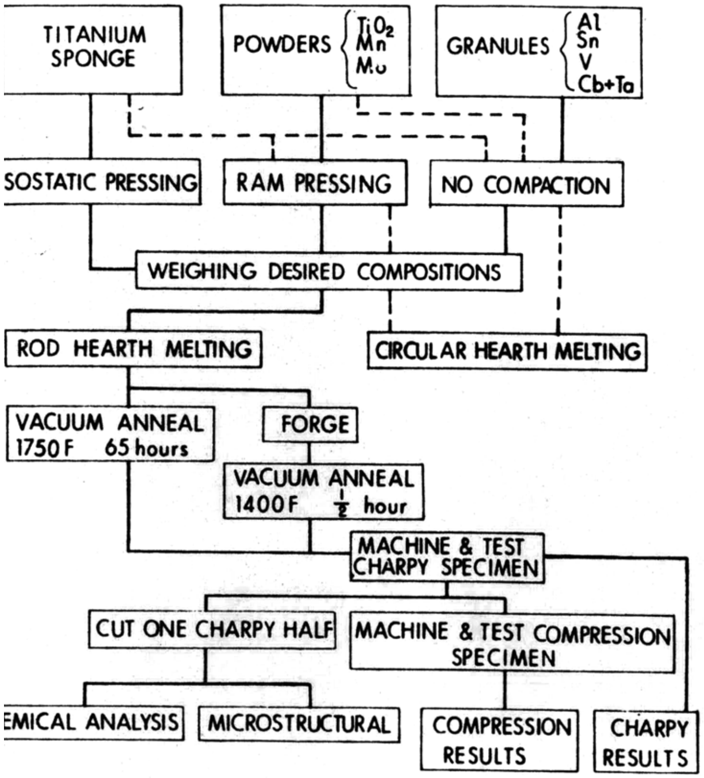


Figure 6

Flow Chart of Experimental Procedure

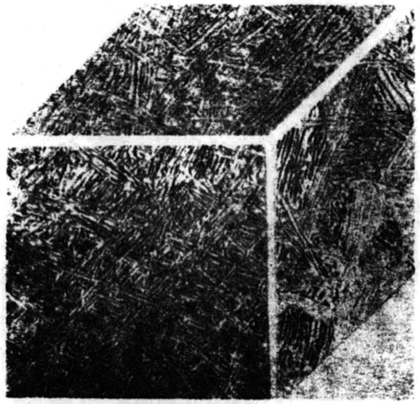
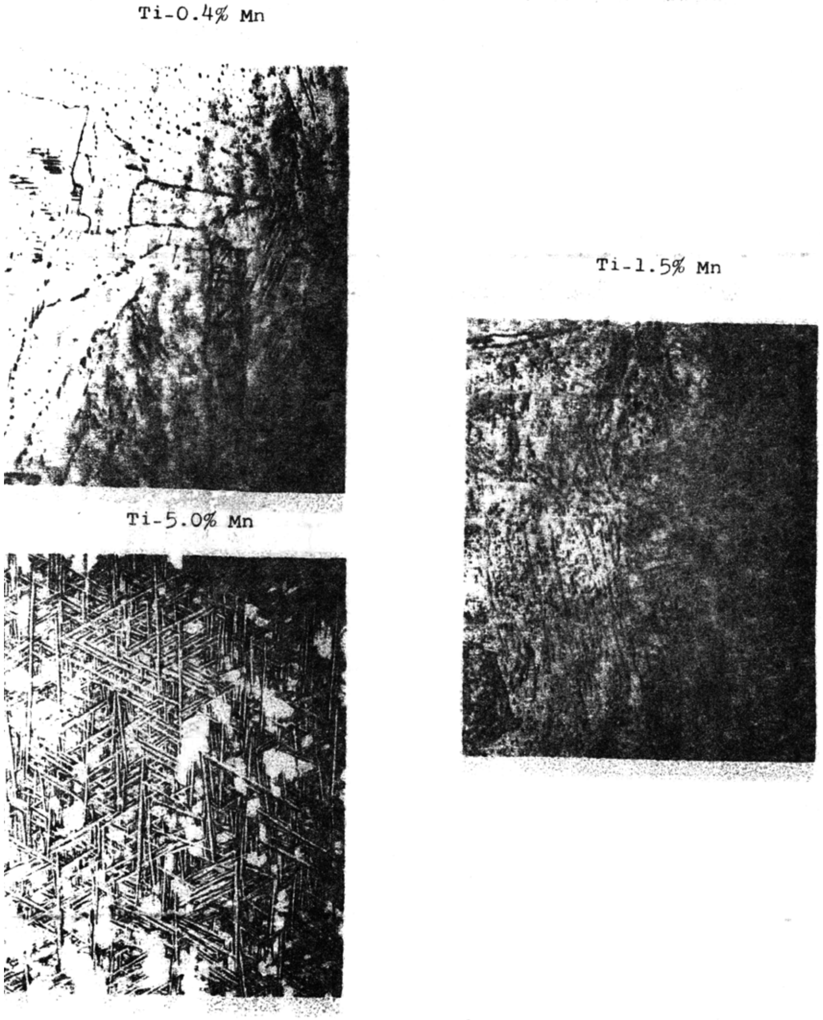


Figure 7
Three Mutually Perpendicular
Planes in the Ti-6Al-2Cb-1Ta-0.8Mo
Alloy (500X)



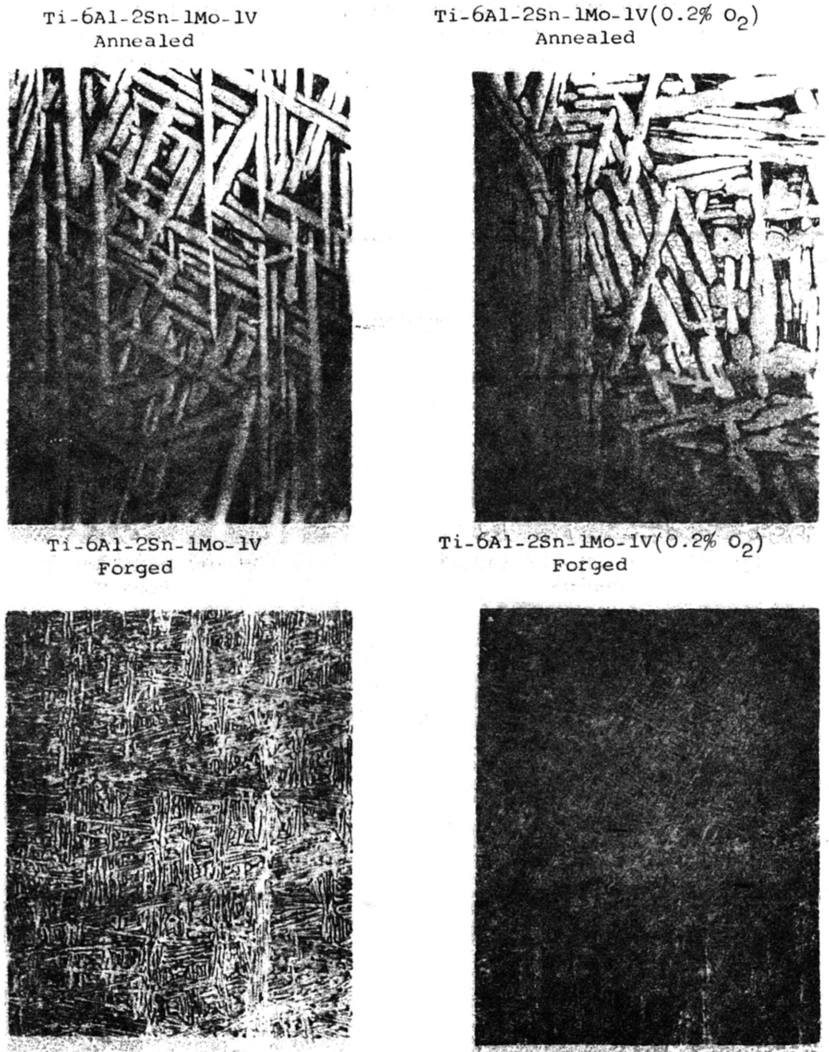
Ti-0.4% Mn

Ti-1.5% Mn

Ti-5.0% Mn

Figure 8

Forged Ti-Mn Alloys (Etch: 1% H_2SO_4, 2% HF, 3% HNO_3, 500X)



Ti-6Al-2Sn-1Mo-1V
Annealed

Ti-6Al-2Sn-1Mo-1V(0.2% O_2)
Annealed

Ti-6Al-2Sn-1Mo-1V
Forged

Ti-6Al-2Sn-1Mo-1V(0.2% O_2)
Forged

Figure 9

Forged and Annealed Ti-6Al-2Sn-1Mo-1V Alloys (500X)

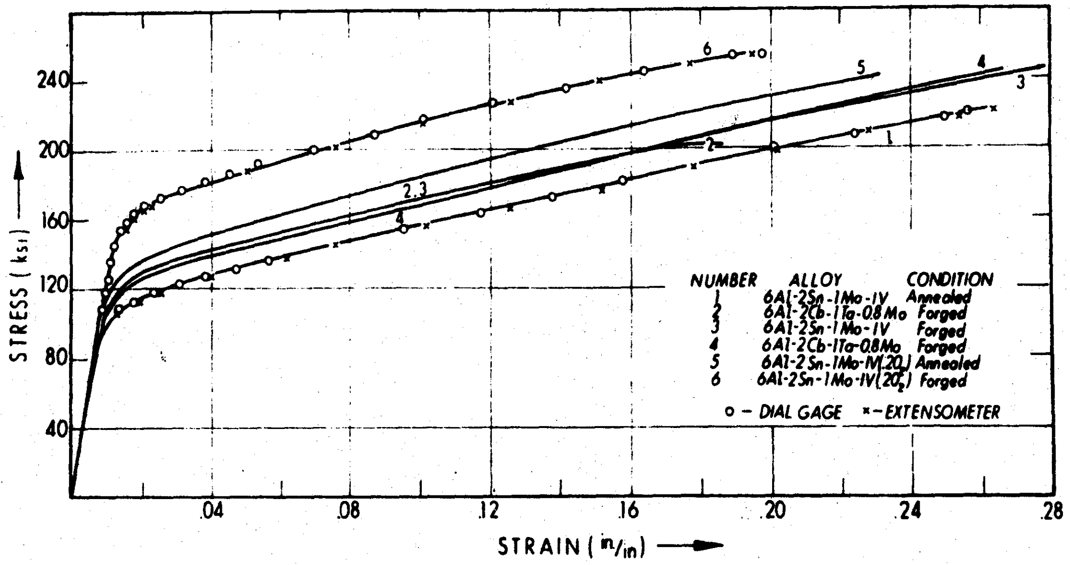


Figure 10

Stress-Strain Curves for Small Compression Specimens from Melted Rods

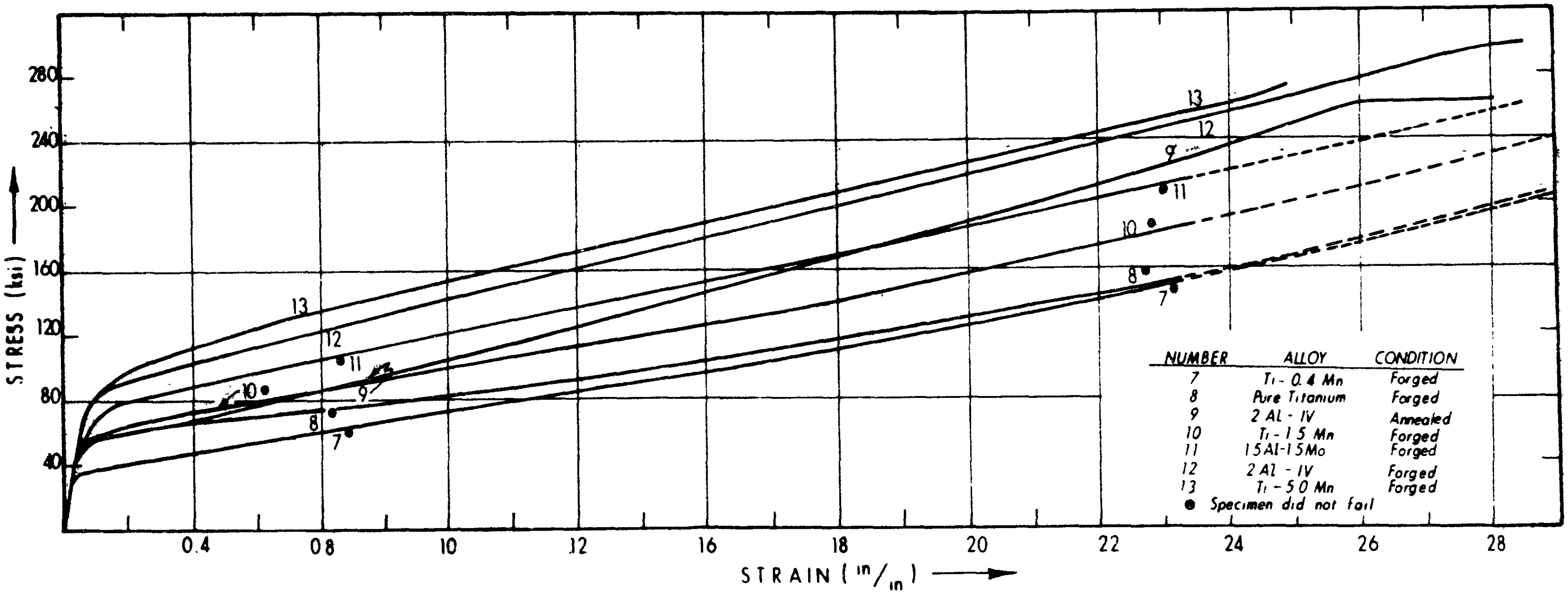


Figure 11

Stress-Strain Curves for Small Compression Specimens from Melted Rods

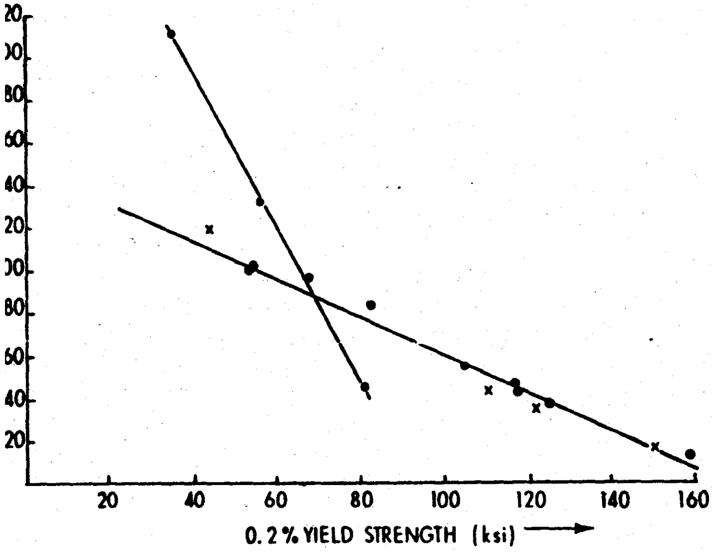


Figure 12

Charpy Impact Numbers as a Function of Yield Strength

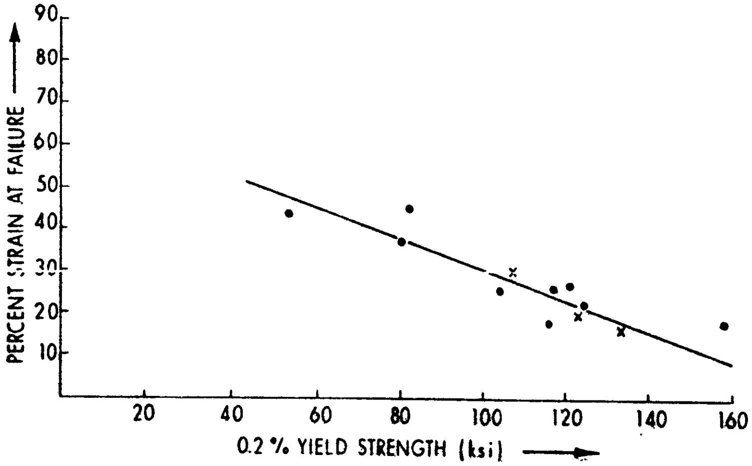


Figure 13

Percent Strain at Failure as a Function of Yield Strength

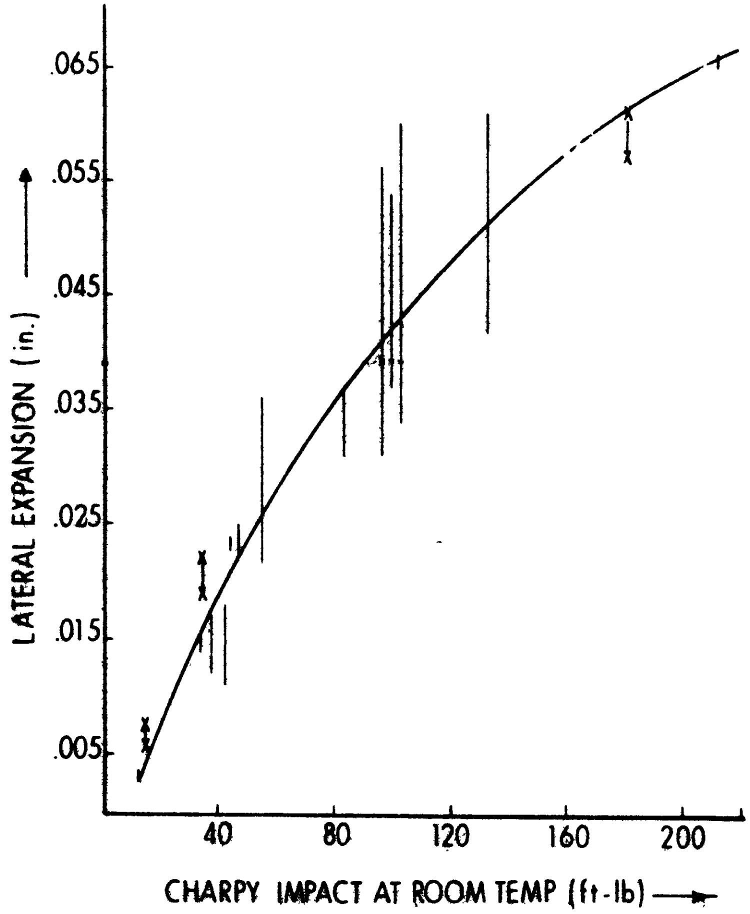


Figure 14

Lateral Expansion as a Function of Charpy Impact Numbers

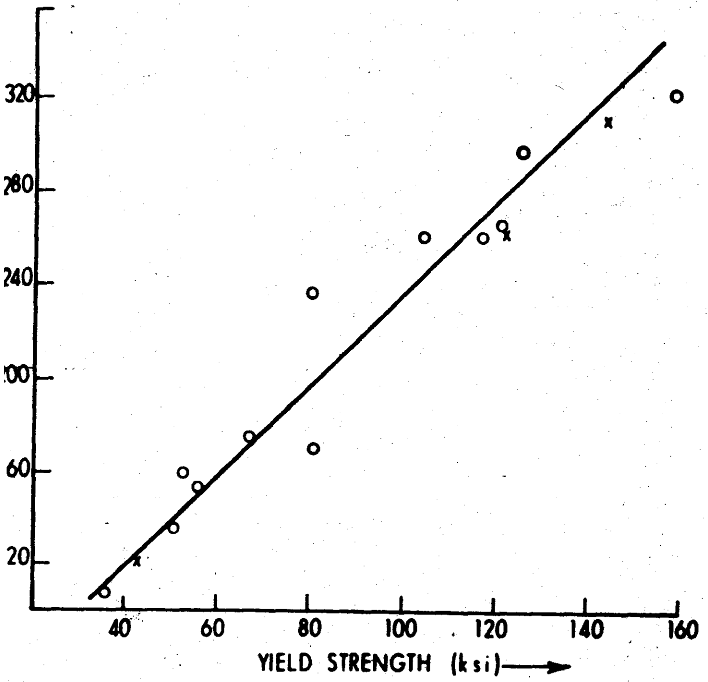


Figure 15

Hardness as a Function of Yield Strength

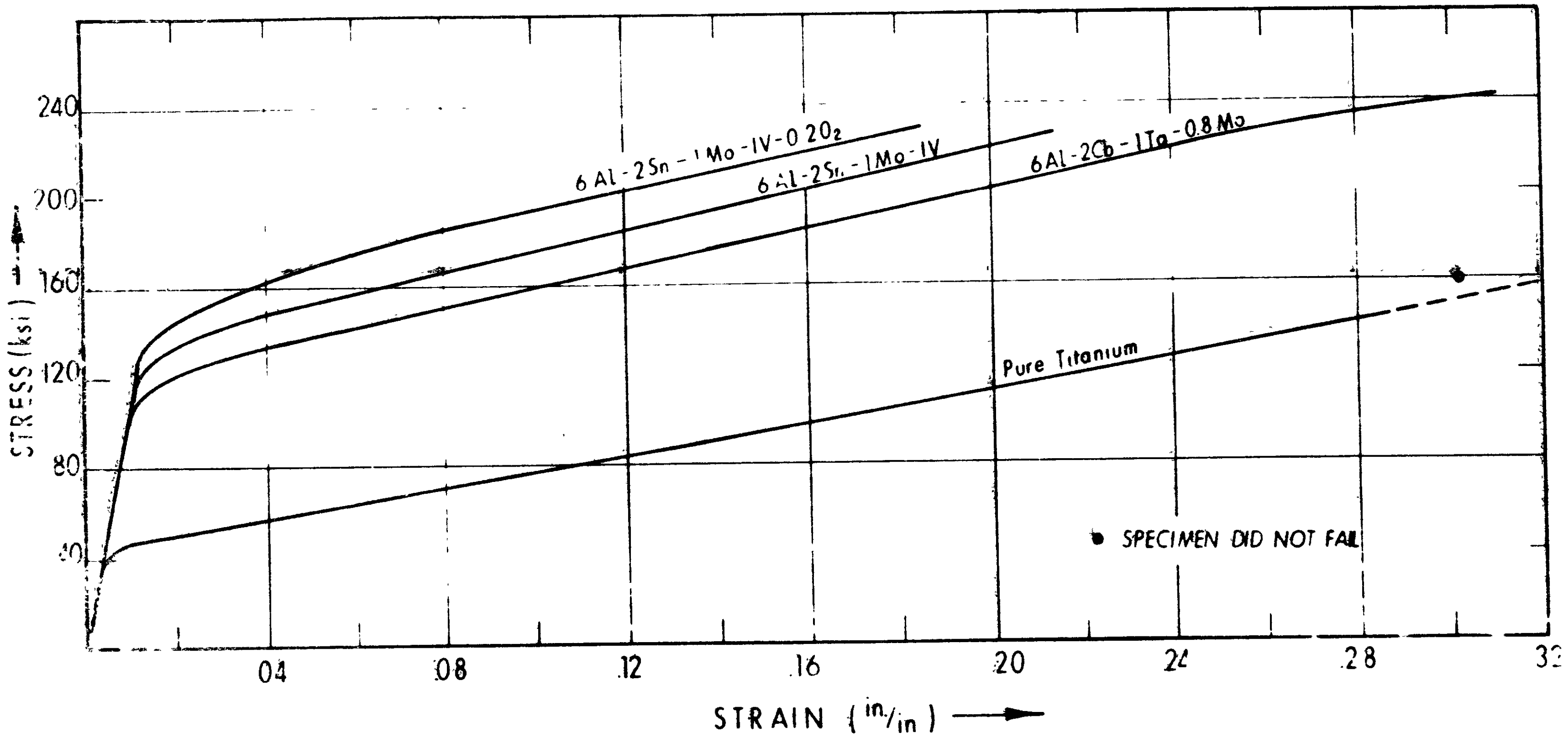


Figure 16

Stress-Strain Curves for Small Compression Specimens from Commercial Plates

Appendix A

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13. ABSTRACT

A technique of melting, processing, and testing small (80-gram) rods of titanium alloys has been developed. The technique is designed for screening large numbers of alloy formulations to determine those with enough potential for further evaluation. The hearth plate of an arc button-melting furnace was modified to produce rod-ingots which are forged to a shape suitable for testing. Strength and toughness measurements are used to compare a series of alloys relatively, and with respect to their bulk properties. It is recognized that a number of factors, such as cooling rates and amount of forging, prevent duplication of production material properties. Nevertheless, the apparent alloying and microstructural effects and the degree of correlation with plate properties are discussed.

(author)

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