RMI TITANIUM Company®

# RMI Metallography

## CONTENTS



## INTRODUCTION

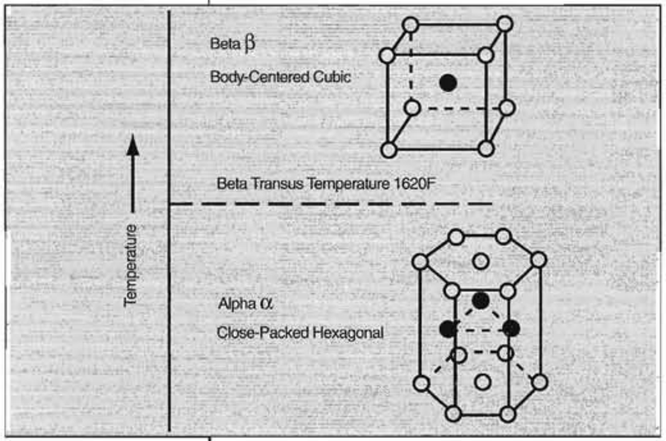
On the following pages is a study of the metallographic structure and constitution of titanium and titanium alloys prepared by the Research and Development Department of RMI Titanium Company. This RMI investigation has been carried out using the eyes of the metallurgist; the light microscope. Presented is a discussion of the microstructures of currently important commercial titanium alloys, along with an explanation of terminology commonly used for describing titanium microstructures. Photomicrographs illustrating various microstructural conditions are described. A brief discussion of alloy systems and metallographic procedures is also included. Terms employed by the industry are defined throughout the text and in the glossary beginning on page 26.

## PHYSICAL METALLURGY CONSIDERATIONS

The proper interpretation of microstructures of any alloy system requires some understanding of the phase relationships and constitution of the system being studied.

Titanium, being allotropic, can exist in two crystal forms known as alpha (which has a hexagonal close-packed crystal structure) and beta (which has a body-centered cubic structure). In unalloyed titanium, the alpha phase is stable at all temperatures up to 1620F where it transforms to the beta phase. This temperature is known as the beta transus temperature. The beta phase is stable from 1620F to the melting point. These phases are illustrated in Figure 1.

**Figure 1**
Crystal structure of unalloyed titanium.



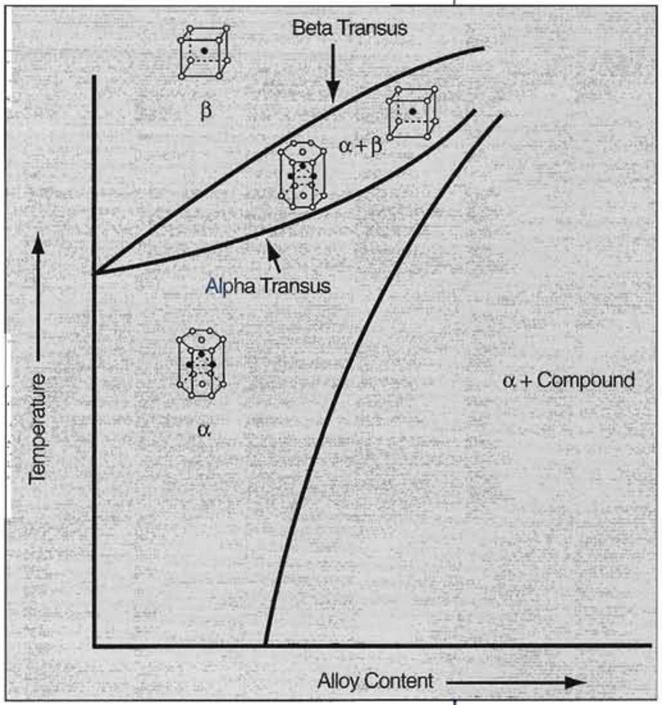

As alloying elements are added to pure titanium, they tend to change the temperature at which the phase transformation occurs and the amount of each phase present. Alloy additions to titanium, except tin and zirconium, tend to stabilize either the alpha or the beta phase. Elements called alpha stabilizers stabilize the alpha phase to higher temperatures and beta stabilizers stabilize the beta phase to lower temperatures. Two common alloying elements, tin (Sn) and zirconium (Zr), are considered neutral additions and dissolve equally in the alpha phase as well as the beta phase.

In attempting to describe microstructural changes based on constitution or equilibrium diagrams, it is convenient to use the binary systems. However, it should be kept in mind that the binary diagrams offer only an approximation of the actual conditions being considered since most commercial alloys of titanium are the ternary or quaternary type. Furthermore, production processes seldom approach equilibrium conditions.

## ALPHA STABILIZED SYSTEMS

Figure 2 represents a typical binary constitution diagram for an alpha stabilized system. In this system the addition element is more soluble in the alpha phase and an increase in the alloy content stabilizes the alpha phase to higher temperatures. That is, both the alpha and beta transi temperatures are raised with increasing alloy content. Some of the alloying elements of the substitutional type that belong to this system are aluminum, gallium and germanium. The interstitial alloying elements of the alpha stabilizing type are oxygen, nitrogen and carbon.

**Figure 2 Alpha Stabilized System**
Alpha stabilizing elements are aluminum, gallium, germanium, carbon, oxygen and nitrogen.



## BETA STABILIZED SYSTEMS

The beta stabilized systems can be broken down into two types: the beta isomorphous and the beta eutectoid. Figure 3 shows a typical binary constitution diagram for the beta isomorphous system. In this system the addition element is completely miscible in the beta phase and decomposition of beta to alpha plus eutectoid products does not occur even under equilibrium conditions. Increasing the alloy content decreases the alpha-to-beta transformation temperature. Alloying elements of the beta isomorphous type are vanadium, molybdenum, tantalum and columbium.

Figure 4 represents the binary phase diagram of the beta eutectoid system. In this system the addition element stabilizes the beta phase, but under equilibrium conditions the beta phase decomposes to form alpha and an intermetallic compound. The beta eutectoid elements are of two types: the active eutectoid and the sluggish eutectoid formers.

**Figure 3 Beta Isomorphous System**
**Alloying elements of the beta isomorphous type are vanadium, molybdenum, tantalum and columbium.**

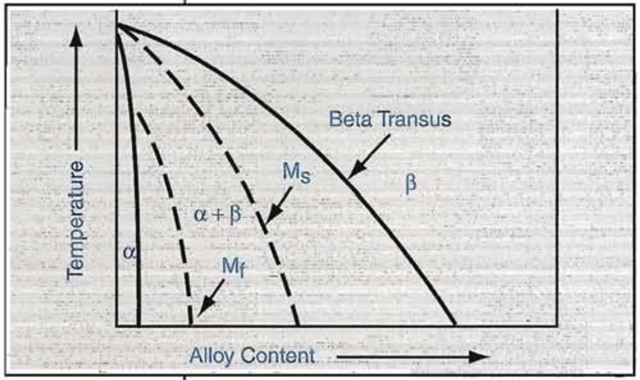
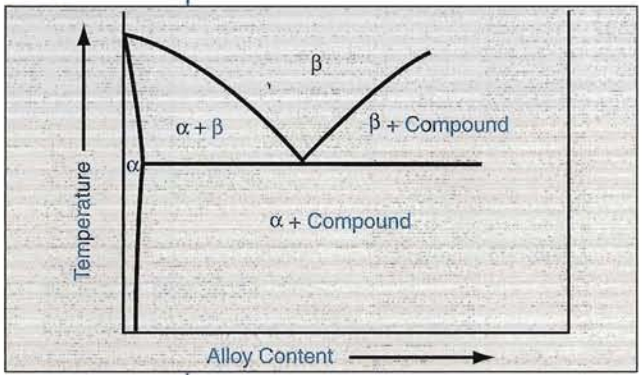



**Figure 4 Beta Eutectoid System**
**Alloying elements of the beta eutectoid type are manganese, iron, chromium, cobalt, nickel, copper and silicon.**




Active eutectoid formers, such as copper, nickel, cobalt and silicon, result in rapid decomposition of beta to a compound and alpha. Large amounts of elements of this type have not been used extensively in commercial alloys. The other eutectoid formers, such as chromium, iron and manganese are more sluggish in their eutectoid reactions and do not generally form compounds in most commercial alloys. Beta eutectoid elements arranged in order of increasing tendency to form compounds are shown in Table 1.

**TABLE 1 — Beta eutectoid elements in order of increasing tendency to form compounds.**

| Element | Eutectoid Composition Weight, % | Eutectoid Temp. F | Composition for Beta Retention on Quenching, Weight, % |
|---|---|---|---|
| Manganese | 20 | 1022 | 6.5 |
| Iron | 15 | 1112 | 4.0 |
| Chromium | 15 | 1247 | 8.0 |
| Cobalt | 9 | 1265 | 7.0 |
| Nickel | 7 | 1418 | 8.0 |
| Copper | 7 | 1454 | 13.0 |
| Silicon | 0.9 | 1580 | |

Tin and zirconium are interesting alloying elements in that they have extensive solid solubility in both the alpha and beta phases. These elements do not strongly promote phase stability, but do slow down the reaction kinetics and are useful strengthening agents. As a consequence, they are attractive additions for both alpha and beta alloys.

## ALLOY CLASSIFICATIONS

Among titanium alloys there are three structural types: alpha, mixtures of alpha and beta, and beta. Alloys that consist largely of the alpha phase are classified as alpha alloys. Alloys that contain mixtures of alpha and beta phases are classified as alpha-beta alloys, and alloys that consist largely of the beta phase are air cooling from the solution annealing temperature are termed beta alloys. It should be pointed out, however, that most commercial grades of unalloyed titanium and certain alpha alloys contain small amounts of beta stabilizing elements, while the beta alloys contain small amounts of alpha stabilizing elements as strengthening agents. Titanium alloys classified according to alloy system are given in Table 2.

TABLE 2 — Classification of Titanium Alloys

| Alpha | Alpha-Beta | Beta |
|---|---|---|
| RMI 0.2Pd | RMI 6Al-4V | RMI 13V-11Cr-3Al |
| RMI 5Al-2.5Sn | RMI 6Al-6V-2Sn | |
| RMI 8Al-1Mo-1V | RMI 8Mn | RMI 3Al-8V-6Cr-4Mo-4Zr |
| RMI 6Al-2Cb-1Ta-1Mo | RMI 7Al-4Mo | RMI 10V-2Fe-3Al |
| RMI 6Al-2Sn-4Zr-2Mo -0.08Si | RMI 6Al-2Sn-4Zr-6Mo | RMI 15V-3Cr-3Al-3Sn |
| | RMI 4.5Al-5Mo-1.5Cr | |
| RMI 5Al-6Sn-2Zr-0.80Mo -0.25Si | RMI 3Al-2.5V | |
| | RMI 5Al-2Sn-2Zr-4Cr-4Mo | |
| | RMI 6Al-2Sn-2Zr-2Cr-2Mo -0.25Si | |

Each system of titanium alloys has certain distinguishing characteristics.

**Alpha** — Alpha alloys are generally weldable and nonheat treatable. They have medium strength, good notch toughness and good resistance to creep at elevated temperatures. The addition of silicon enhances the creep strength of this type of alloy.

**Alpha-Beta** — Most of the alpha-beta alloys are considered heat treatable and some are weldable. Their strength levels are medium to high. Their forming qualities are good, but the creep strength is not as high as in most alpha alloys.

**Beta** — The beta or near-beta alloys are highly heat treatable. They are capable of high strengths, fair creep resistance and good formability.

RMI 3A1-8V-6Cr-4Mo-4Zr is a beta type alloy which has a good combination of properties in sheet, heavy sections, fasteners and spring applications.

## DESCRIPTION OF MICROSTRUCTURES

In the language used in describing titanium microstructures, some of the terms apply only to the alpha phase, while certain other terms can be used to describe either the alpha or beta phases.

To properly interpret structures, it is helpful (and in some cases essential) to have some knowledge of the alloy content, working temperature and prior thermal treatment of the material being examined. Occasionally, it is possible to recognize working temperature and thermal treatments without knowledge of a material's prior history. For example, acicular or needle-shaped structures result from cooling beta lean alloys from above their beta transus temperature. Equiaxed structures usually result from cold working followed by annealing above the recrystallization temperature. Serrated structures are produced in unalloyed titanium and alpha alloys by rapid cooling from temperatures above their beta transi. Plate-like structures result from slow cooling alpha or alpha-beta alloys from temperatures in the beta field or high in the alpha-beta field. These structures are readily recognized by their wide, elongated shape. Plate-like structures can also be developed by heating material with an acicular structure to temperatures high enough in the alpha-beta field to achieve grain growth.

Examining unetched alpha-beta alloys under plain polarized light can be useful in distinguishing alpha from beta. Alpha, which is optically active under polarized light, changes from light to dark as a microscope stage is rotated. Care should be exercised, however, in using this method, since equiaxed alpha is less active than other alpha configurations and may be mistaken for beta.

## Equiaxed Alpha

The term "equiaxed" refers to a polygonal structure in which individual grains have approximately equal dimensions in all directions. Equiaxed structures are usually developed by cold working followed by annealing above the recrystallization temperature. Figures 5 and 6 represent the equiaxed alpha structures in unalloyed titanium. Figure 5 illustrates the microstructure of unalloyed titanium sheet containing 0.03% iron. Improved corrosion resistance in certain environments is enhanced by the low iron content. In addition to alpha, Figure 6 also shows particles of spheroidal beta stabilized by small amounts of iron in the material. Small quantities of beta phase are common in unalloyed grades and in some alpha alloys. The presence of the beta particles aids in refining alpha grain size by inhibiting grain boundary migration. The beta phase also improves formability and increases the hydrogen solubility limit of unalloyed titanium and alpha alloys.

Figure 7 shows unalloyed titanium sheet with equiaxed alpha grains and titanium hydride needles in the structure. Figure 8 shows equiaxed alpha grains and titanium hydride needles in the RMI 5Al-2.5Sn alpha alloy.

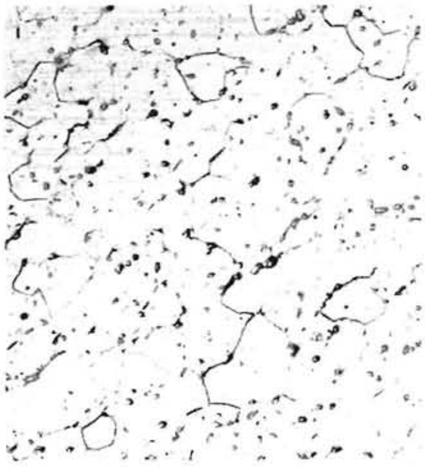


**Figure 6 100X**
RMI Unalloyed Ti Sheet, 0.17% iron
1300F/1 Hr.; Air Cool
Equiaxed alpha grains and beta spheroids
Etchant: 10%HF-5%$HNO_3$

**Figure 7 100X**
RMI Unalloyed Ti Sheet
1300F/1 Hr.; Air Cool
Equiaxed alpha grains and titanium hydride needles
Etchant: 10%HF-5%$HNO_3$

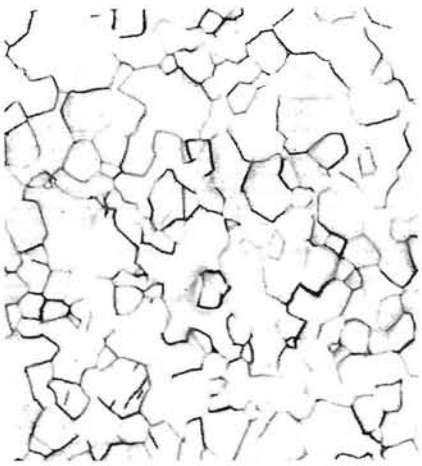


**Figure 5 100X**
Unalloyed Titanium Sheet, 0.03% iron
1300F/1Hr.; Air Cool
Equiaxed alpha grains
Etchant: 10%HF-5%$HNO_3$

**Figure 8 500X**
RMI 5Al-2.5Sn Sheet
1500F/30 Min.; Air Cool
4 Hrs. in 2% NaH at 720F
Equiaxed alpha grains and titanium hydride needles
Etchant: 10%HF-5%$HNO_3$

## Elongated Alpha

Elongated alpha is the term used to describe the elongated or fibrous shape of the alpha phase brought about by unidirectional working. The condition is commonly found in longitudinal sections prior to annealing. Figure 9 shows elongated alpha in heavily worked unalloyed titanium sheet. Figure 10 shows elongated alpha in a beta matrix as found in RMI 8Mn hot rolled sheet.

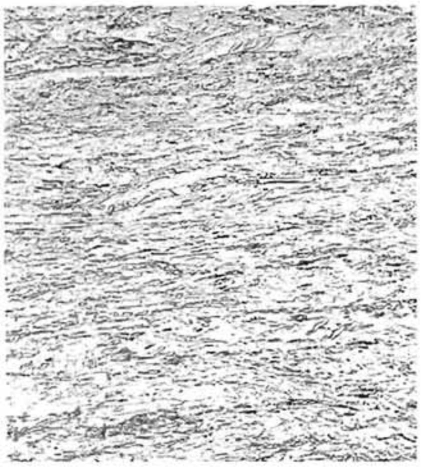


**Figure 9 250X**
RMI Unalloyed Ti Sheet as Hot Rolled
Elongated alpha and intergranular beta
Etchant: 10%HF-5%$HNO_3$

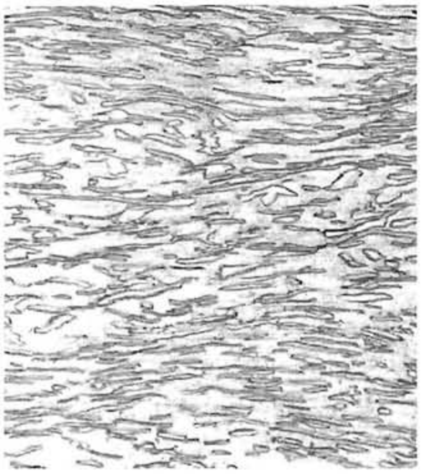


**Figure 10 500X**
RMI 8Mn Sheet as Hot Rolled
Elongated alpha in a beta matrix
Etchant: 2%HF-4%$HNO_3$

## Transformed Beta

Transformed beta is a general term used to describe alpha that is formed directly from the beta phase. The term should be limited in use, and should only be applied to describe structures where transformation kinetics are unknown or where grain morphology cannot be resolved. The terms serrated, acicular, plate-like, Widmanstätten and alpha-prime can be used to describe transformed beta structures in more detail.

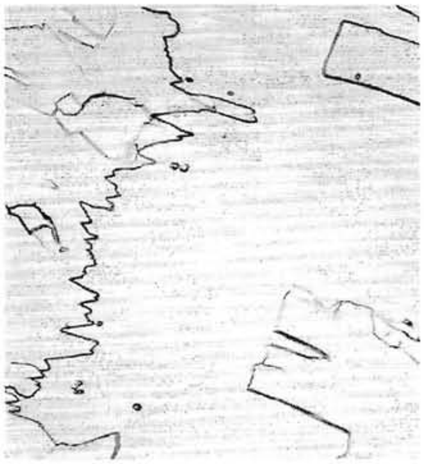


**Figure 12 250X**
RMI Ti - 6Al Bar 1900F/ 30 Min.; Water Quench Serrated alpha
Etchant: 10%HF-5%$HNO_3$

## Serrated Alpha

Serrated structures are characterized by irregular grain size and jagged grain boundaries. Structures of this type can be developed by rapid cooling high-purity titanium and alpha-stabilized alloys from above their beta transus temperatures. Figure 11 shows a serrated alpha structure of unalloyed titanium produced by water quenching from 1850F. Figure 12 shows serrated alpha in a Ti-6Al binary alloy quenched from 1900F.

**Figure 13 250X**
RMI Unalloyed Ti Bar (0.35% Fe) 1850F/30 Min.; Water Quench Acicular alpha + beta and prior beta grain boundaries
Etchant: 10%HF-5%$HNO_3$

The presence of small amounts of beta phase in commercially pure titanium or alpha alloys results in a transformation product of an acicular nature rather than of a serrated type. Since most commercially pure grades contain small amounts of iron (a beta stabilizer), these grades transform in the acicular rather than serrated configuration when quenched from the beta field. See Figure 13.

**Figure 11 500X**
Unalloyed Titanium Bar (0.03% Fe) 1850F/ 30 Min.; Water Quench Serrated alpha
Etchant: 10%HF-5%$HNO_3$

## Acicular Alpha

The terms acicular alpha and Widmanstätten are generally interchangeable. Both are used to describe a transformation product brought about through nucleation and growth. However, acicular, by definition, refers primarily to grains with a fine, needle-like appearance, whereas the Widmanstätten basket weave pattern can exist as fine acicular or coarse plate-like grains.

Figure 14 is a photomicrograph of the RMI 6Al-2Cb-1Ta-1Mo alloy showing acicular alpha and prior beta grain boundaries. As the alloy cools from a temperature in the beta field (1925F), alpha transforms first at the beta grain boundaries and leaves a definite outline of the prior beta grain size. Transformation from beta to alpha continues by nucleation and growth of the alpha phase. The grain size of the transformation product is governed by the rate of cooling.

## Widmanstätten

The Widmanstätten structure is characterized by its basket weave appearance and is formed as beta transforms to alpha on preferred crystallographic planes of the parent beta phase. These structures can be produced in alpha or alpha-beta alloys by cooling from temperatures in the beta field. Structures vary from acicular grains to thick plates depending upon cooling rates. Slow rates of cooling produce structures with plate-like appearance.

In alpha-beta alloys, where the beta phase is rich in solute, some beta will be retained between the alpha grains.

Figure 15 shows a Widmanstätten structure in the RMI 6Al-4V alloy developed by hot working entirely in the beta field (1900F).

Figure 16 shows a partial breakup of the Widmanstätten structure by forging, which was initiated in the beta field and completed in the alpha-beta field.

**Figure 14 200X**
RMI 6Al-2Cb-1Ta-1Mo 1" Plate 1925F/1 Hr.; Air Cool
Acicular alpha + beta with an alpha precipitate at the prior grain boundaries, called "grain boundary alpha"
Etchant: 10%HF-5%$HNO_3$

**Figure 15 500X**
RMI 6Al-4V Slab As forged 1900F
Widmanstätten alpha and beta and prior beta grain boundaries
Etchant: 10%HF-5%$HNO_3$

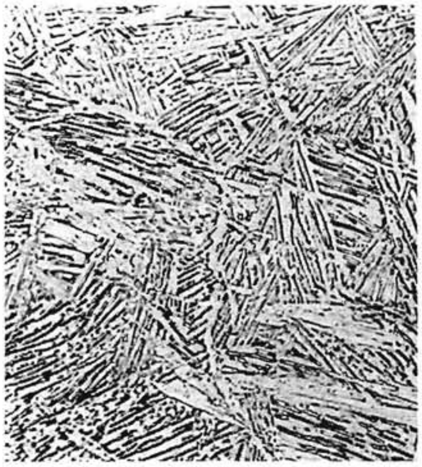


**Figure 16 500X**
RMI 6Al-4V Plate rolled at 1870F and annealed 1525F/1 Hr.; Furnace Cool to 1100F; Air Cool
Partially broken-up Widmanstätten structure with intergranular beta, and evidence of prior beta grain boundaries
Etchant: 10%HF-5%$HNO_3$

## Plate-like Alpha

Plate-like alpha structures are characterized by relatively wide elongated grains. They are developed in the alpha and alpha-beta alloys as a result of slow cooling from the beta field, or from a temperature high in the alpha-beta field. Figure 17 shows plate-like alpha in the RMI 5A1-2.5Sn alloy developed by furnace cooling the alloy from 1900F.

Alpha plates can also be formed in the central portion of large billets that have been forged in the beta field or high in the alpha-beta field. Figure 18 shows alpha plates in an 8-inch diameter billet of RMI 6A1-4V forged at a temperature high in the alpha-beta field.

## Primary Alpha

Primary alpha is alpha phase that remains untransformed as opposed to alpha formed by transformation from the beta phase. As a titanium alloy is heated to temperatures in the alpha-beta field, the amount and size of the primary alpha grains diminish as the beta transus temperature is approached. On the other hand, holding at temperatures in the alpha-beta field for a prolonged period of time results in growth of the primary alpha phase at the expense of beta until equilibrium is established. This is illustrated in the photo micrographs in Figures 19 and 20. In Figure 19 the material held one hour at 1750F contains approximately 25% primary alpha; in Figure 20 the material held four hours at 1750F contains approximately 35% primary alpha. Slow cooling from temperatures in the alpha-beta field also results in growth of the primary alpha phase.

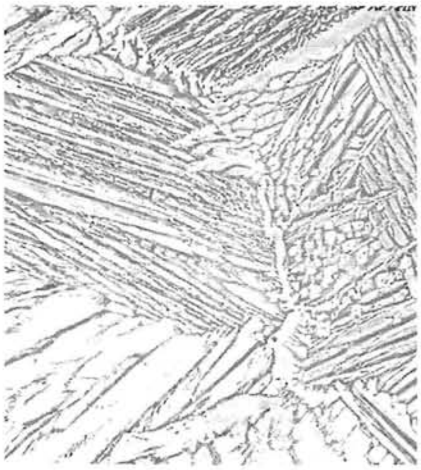


**Figure 17** **100X**
RMI 5Al-2.5Sn Billet
1900F/1 Hr.;
Furnace Cool
Coarse plate-like alpha
Etchant:
10%HF-5%$HNO_3$

**Figure 19** **500X**
RMI 6Al-4V Bar
1750F/1 Hr.;
Water Quench
Primary alpha in a transformed beta matrix consisting of alpha prime and beta
Etchant:
10%HF-5%$HNO_3$

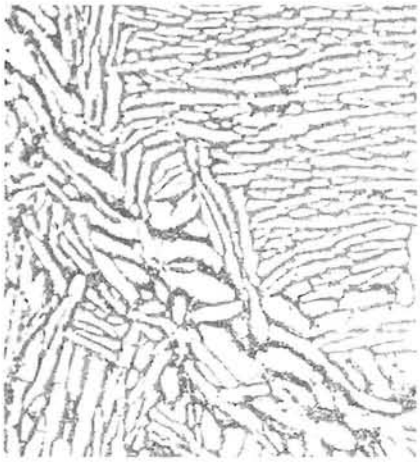


**Figure 18** **250X**
RMI 6Al-4V Billet
As forged
Plate-like alpha and intergranular beta
Etchant:
10%HF-5%$HNO_3$

**Figure 20** **500X**
RMI 6Al-4V Bar
1750F/4 Hrs.;
Water Quench
Primary alpha in a transformed beta matrix consisting of alpha prime and beta
Etchant:
10%HF-5%$HNO_3$

## Alpha-Prime

Alpha-prime, sometimes referred to as martensitic alpha, is a non-equilibrium supersaturated alpha structure formed by diffusionless transformation of the beta phase. The martensitic reaction occurs in beta lean alloys rapidly cooled below the $M_S$* temperature. Figure 21 shows alpha-prime in the RMI 6Al-4V alloy. The needle-like alpha-prime structure is similar to martensite in steel, in appearance as well as mode of formation. The crystal structure of alpha-prime of lean beta content is hexagonal. Alpha-prime formed from beta of high alloy content is face-centered cubic or face-centered tetragonal.

Aging alpha-prime results in the formation of equilibrium alpha plus beta and an increase in hardness and strength. Aged alpha-prime cannot usually be distinguished from unaged alpha-prime with the light microscope. See Figure 22.

**Figure 22 500X**
RMI 6Al-4V Bar
1750F/1 Hr.;
Water Quench
1000F/4 Hrs.;
Air Cool
Primarily alpha in an aged matrix consisting of precipitated alpha and residual beta
Etchant:
2%HF-4%$HNO_3$

**Figure 21 500X**
RMI 6Al-4V Bar
1850F/30 Min.;
Water Quench
Alpha-prime (martensitic alpha) + beta
Etchant:
10%HF-5%$HNO_3$

*The $M_S$ ("martensitic-start temperature") is the maximum temperature at which alpha-prime begins to form on cooling of the beta phase. See Figure 23 and Table 3.

TABLE 3 — The beta transus and $M_S$ Temperatures for three titanium alloys

| | Beta Transus Temp F | $M_S$ Temp F |
|---|---|---|
| RMI 6Al-4V | 1825 | 1525 |
| RMI 4Al-3Mo-1V | 1760 | 1560 |
| RMI 8Al-1Mo-1V | 1910 | 1600 |

# Metastable Beta

Metastable beta, a non-equilibrium phase, can be developed in alpha-beta alloys which contain sufficient amounts of beta-stabilizing elements to retain the beta phase at room temperature on rapid cooling from the alpha-beta phase field. The composition of the alloy must be such that the beta stabilizing element or elements depress the $M_S$ temperature below room temperature. If the amount of beta stabilizers in the alloy is so low that the $M_S$ temperature is above room temperature, or if an alpha-beta alloy is heated to temperatures high in the alpha-beta field so that the beta phase is lean in solute, alpha-prime will form on quenching.

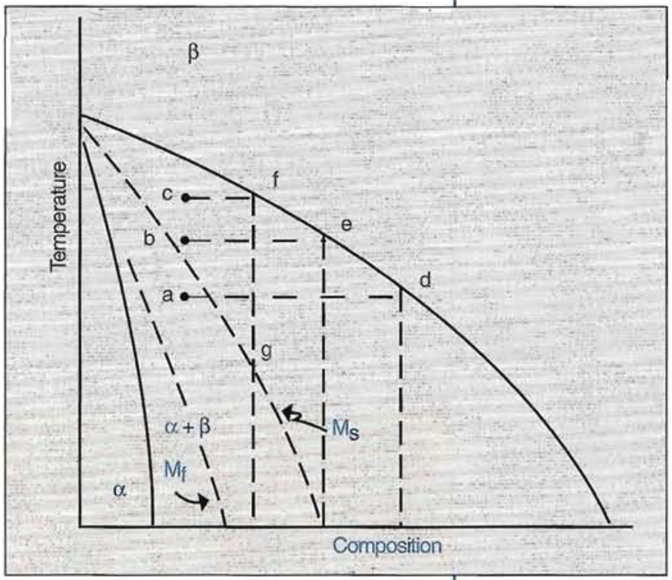
The various conditions under which metastable beta or alpha-prime may form are illustrated in Figure 23.

**Figure 23 (a) 500X**
Microstructure contains primary alpha in a metastable beta matrix after heating the billet at 1600F, 1/2 hour and water quenching

**Figure 23 (b) 500X**
Microstructure contains less of the primary alpha but more of the metastable beta in the matrix (than in *(a)*) after heating the billet at 1650F, 1/2 hour and water quenching

**Figure 23 (c) 500X**
Microstructure contains still less alpha (than in *(b)*) and more beta on heating the billet at 1700F, 1/4 hour. But the beta is now diluted and after water quenching, alpha prime forms

**Figure 23**
RMI Ti-6Al-2Sn-4Zr-6Mo Billet
Etchant: 10%HF-5%$HNO_3$



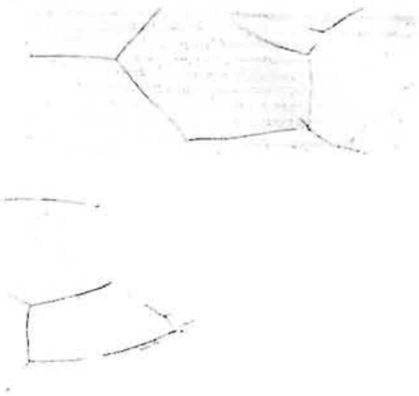
Aging of metastable beta transforms it to equilibrium alpha or eutectoid products or both. Figure 24 shows the Ti 6Al-4V alloy in the solution treated and aged condition. The beta phase in the center of the figure contains a fine needle-like structure which is due to the precipitation of the fine equilibrium alpha phase during the aging treatment. Eutectoid products are not present since vanadium is not an eutectoid former.

**Figure 24 2000X**
RMI 6Al-4V Billet
SEM photomicrograph showing the precipitation of a fine needle-like alpha phase in the metastable beta phase. The heat treatment employed was 1550F for 1 hour and water quenched followed by a 1000F for 8 hours with an air cool
Etchant:
10%HF-5%$HNO_3$

In recent years many new all-beta or metastable beta alloys have been developed. Most of these alloys are available commercially to varying degrees. These alloys contain large amounts of beta-stabilizing elements enabling them to retain an all-beta structure at room temperature after air cooling or water quenching from above the beta transus. Thus, the terms solution treating and annealing are synonymous for this alloy.

The metastable conditions of the beta phase makes it possible to age the alloy to high strength levels. Strengthening occurs through transformation of the beta phase to equilibrium alpha, beta and (with sufficient aging time) $TiCr_2$. Figure 25a shows the metastable beta condition; Figure 25b, the aged condition. It is unlikely that $TiCr_2$ is present due to the short aging treatment. Aging for 90 to 100 hours is necessary to form $TiCr_2$.

(a)



(b)

**Figure 25 100X**
RMI Beta-C™ (Ti-3Al-8V-6Cr-4Mo-4Zr) Sheet
(a) Structure shows metastable beta on heating the sheet at 1800F for 5 minutes and water quenching.
(b) The sample in (a) was aged at 975F, 8 hours and air cooled, thus resulting in an aged structure consisting of equilibrium alpha and beta
Etchant:
2%HF-4%$HNO_3$

Figure 26 shows a typical microstructure of the metastable beta alloy, 13V-11Cr-3Al alloy, in the solution treated condition. Usually, air cooling is sufficiently rapid to retain an all-beta structure in this alloy. The terms "solution treating" and "annealing" are therefore synonymous for this alloy. The metastable condition of the beta phase makes it possible to age the alloy to high strength levels. The strengthening occurs through the decomposition of the metastable beta phase.

The decomposition products are alpha, beta and, *after extended aging,* the intermetallic compound $TiCr_2$. Figure 27 shows a typical solution treated and aged microstructure of the alloy. It is unlikely that $TiCr_2$ is present because of the short aging treatment used.

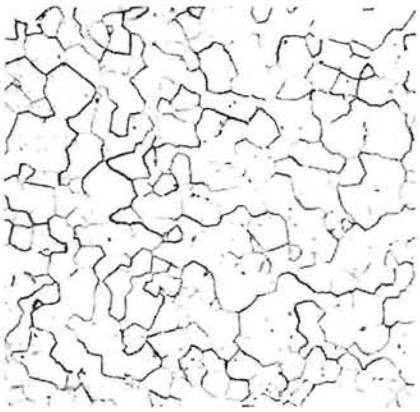


**Figure 26 250X**
RMI 13V-11Cr-3Al
3/8" dia. Bar
1450F/30 Min.;
Water Quench
Metastable beta
Etchant:
2%HF-4%$HNO_3$

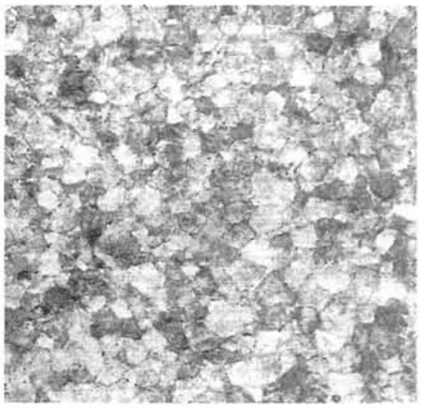


**Figure 27 250X**
RMI 13V-11Cr-3Al
3/8" dia. Bar
1450F/30 Min.;
Water Quench
900F/24 Hrs.;
Air Cool
Aged structure consisting of alpha and beta decomposition products
Etchant:
2%HF-4%$HNO_3$

## Spheroidal Beta

Spheroidal beta particles occur in unalloyed titanium and some alpha alloys that contain small amounts of beta stabilizing elements. Figure 28 shows spheroidal beta in the RMI 5Al-2.5Sn alloy which contains 0.3% iron.

Intergranular beta is the beta phase which occurs between the alpha grains in alpha-beta alloys having a continuous alpha phase matrix. Figure 29 shows this condition in a titanium alloy containing 8Al-1Mo-1V.

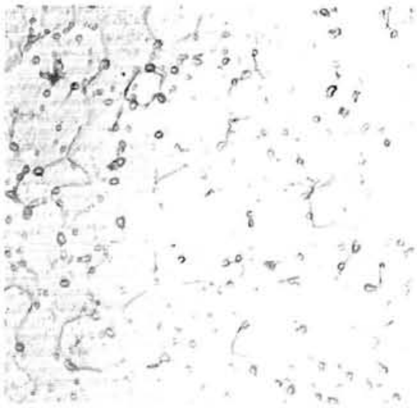


**Figure 28 250X**
RMI 5Al-2.5Sn
Sheet with 0.3% iron
1500F/30 Min.;
Air Cool
Equiaxed alpha and beta spheroids
Etchant:
10%HF-5%$HNO_3$

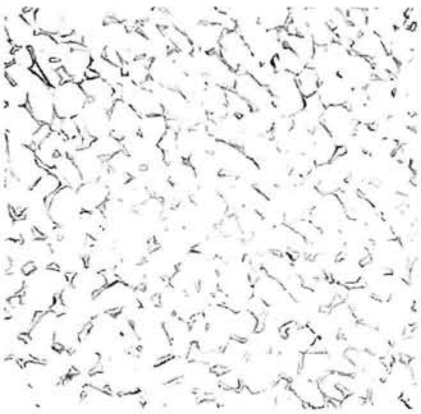


**Figure 29 250X**
RMI Ti-8Al-1Mo-1V Bar
Intergranular beta appears in between alpha grains after heating the bar at 1850F for 1 hour and furnace cooled to 1100F followed by an air cool
Etchant:
2%HF-4%$HNO_3$

## Omega

Omega is a non-equilibrium transition phase between metastable beta and equilibrium alpha. The phase is coherent with beta. Submicroscopic, it cannot be detected with the light microscope. Its presence is associated with high hardness and brittleness. The omega reaction takes place while aging certain metastable beta alloys. During the initial stages of aging, metastable beta transforms to omega plus beta that is slightly enriched in solute. As aging proceeds, omega breaks down and forms equilibrium alpha and a beta highly enriched in the beta stabilizing elements. In eutectoid-forming alloy systems, the reaction proceeds to alpha plus an intermetallic compound. Alloy additions including aluminum, oxygen, tin and zirconium tend to suppress the omega reaction and hence reduce its volume fraction. The mechanism is not clear how this is achieved. The alloy additions appear to promote separate nucleation and growth of the alpha phase after short aging times and/or reduce the maximum temperature of stability of the omega phase.

## Alpha Case

Alpha case is the term used to describe the alpha-stabilized hard surface of titanium resulting from high temperature oxygen enrichment. Titanium surfaces readily dissolve oxygen when heated in air or oxidizing atmospheres. The depth of this contamination is often marked by an excess of oxygen stabilized alpha grains near the surface. This alpha case is easily recognized in alpha-beta and beta alloys, but may be difficult to detect metallographically in unalloyed titanium or alpha alloys containing little beta phase. Figure 30 shows an alpha case on an alpha-beta alloy and Figure 31 an alpha case on a beta alloy.

Since the rate of diffusion of oxygen in titanium is a function of both time and temperature, it is generally desirable to employ minimum heating times and hot working temperatures.

**Figure 30** **75X**
RMI 6Al-4V Plate
2000F/2 Hrs.;
Air Cool
Alpha case approximately 0.012" deep, balance acicular alpha + beta and prior beta grain boundaries
Etchant:
2%HF-4%$HNO_3$

**Figure 31** **100X**
RMI 13V-11Cr-3Al Bar
1800F/4 Hrs.;
Air Cool
Alpha case approximately 0.007" deep in an annealed beta matrix
Etchant:
2%HF-4%$HNO_3$

## Matrix

In titanium metallography the continuous phase is usually referred to as the matrix. Either alpha or beta can be the matrix phase, depending on the alloy composition and thermal treatment. Alpha is usually the matrix in alpha alloys and in weakly beta-stabilized systems, whereas beta is the matrix in strongly beta-stabilized alloy systems. Figure 29 represents an alpha-beta alloy in which alpha is the matrix and Figure 32 shows an alpha-beta alloy having a beta matrix.

## Intermetallic Compound

In addition to alpha and beta phases, intermetallic compounds are occasionally present in titanium alloys. Intermetallic compounds form when solid solubility limits are exceeded. Figure 33 illustrates intermetallic compound in a Titanium 5% Nickel alloy. The compound (dark phase) was identified by X-ray diffraction as $Ti_2$, Ni. Figure 34 shows a fine dispersion of a silicide compound $(TiZr)_5 Si_3$) in the Titanium-679 alloy. The compound, evident both within the alpha grains and at the grain boundaries, enhances the strength of the alloy at elevated temperatures.

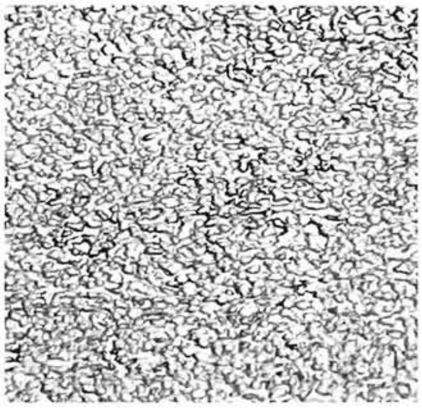


**Figure 32 500X**
RMI 8Mn Sheet
1200F/1 Hr.;
Furnace Cool to 900F
Air Cool
Alpha in a beta matrix
Etchant:
2%HF-4%$HNO_3$

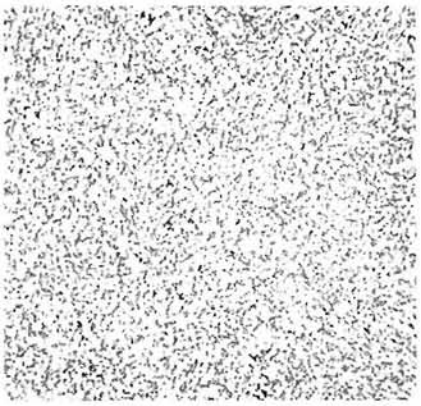


**Figure 33 500X**
RMI .5 Ni
Sheet 1350F/30 Min.;
Air Cool
Alpha and $Ti_2Ni$ (dark phase)
Etchant:
2%HF-4%$HNO_3$

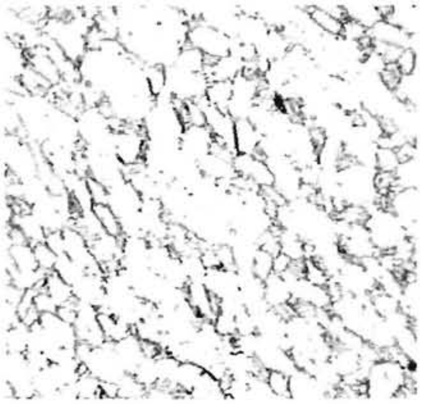


**Figure 34 1000X**
Ti-11Sn-5Zr-2.2Al-1Mo-.21Si-5/8" dia. Bar
1650F/1 Hr.;
Air Cool
930F/24 Hrs.;
Air Cool
Primary alpha, beta and fine dispersions of a silicide compound, $(TiZr)_5Si_3$
Etchant:
10%HF-5%$HNO_3$

## Beta Flecks

Beta flecks can be defined as a localized enrichment in beta-stabilizing elements which lowers the beta transus in the enriched area. Upon subsequent heat treatment near but below the beta-transus (in the $\alpha$ - $\beta$ phase field) the enriched area transforms to beta and is retained or transforms to an $\alpha + \beta$ structure when cooled to room temperature. The chemical variations are usually small but they have a significant effect on the microstructure. Alloy compositions that contain additions of the beta eutectoid stabilizing elements Fe, Cr, plus the other beta eutectoid elements are more prone to flecking than the alloys that contain the beta isomorphous stabilizing elements. Beta fleck can occur in both $\alpha - \beta$ (Ti-5Al-2Zr-2Sn-4Mo-4Cr) and beta (Ti-10V-2Fe-3Al) alloys. Figure 35 is an example of beta fleck in the Ti-10V-2Fe-3Al alloy which is due to local iron enrichment.

## Aluminides

Alloys based on the $\alpha_2$ ($Ti_3Al$) and $\gamma$ (TiAl) ordered structure are termed aluminides. Because of the attractive high temperature properties of these ordered structures, the $\alpha_2$ and $\gamma$ alloy systems are receiving a large amount of interest.

Metallographic examination of the $\alpha_2$ alloy system indicates that the microstructures obtained after heat treating can be predicted based on a knowledge of the more conventional titanium alloy systems. Typical microstructures of the Ti-14Al-21Nb alloy can be seen in Figure 36. As seen in this figure, the Ti-14Al-21Nb ($\alpha_2$ aluminide) is capable of obtaining an equiaxed $Ti_3Al$ phase and an acicular $Ti_3Al$ + beta phase when processed below but near its beta transus. This structure resembles that of Ti-6Al-4V when processed in a similar manner.

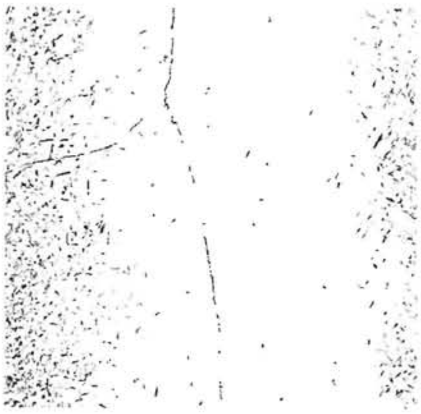


**Figure 35 100X**
RMI 10V-2Fe-3Al
Microstructure shows a beta fleck region (center) in an $\alpha + \beta$ matrix. The fleck was found in a 2 inch (5 cm) thick forging after heat treating at 1430F which is approximately 50F below the beta transus.

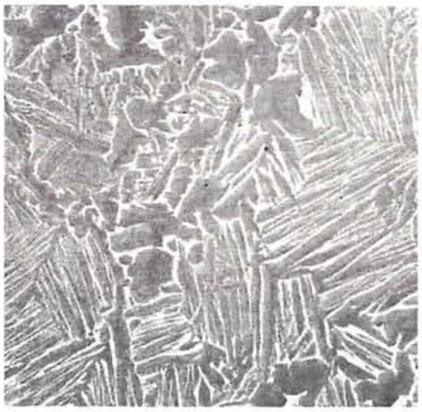


**Figure 36 1000X**
RMI 14Al-21Nb Bar
Scanning electron photomicrograph of an equiaxed $Ti_3Al$ phase and an acicular $Ti_3Al$ + beta phase when processed near but below the alloy's beta transus.
Etchant:
10%HF-5%$HNO_3$

## Ordering

Typical substitutional solid solutions have solute atoms randomly distributed at the lattice sites of the solvent. In certain alloy systems, this is true only at elevated temperature. As these systems are cooled to some critical temperature, the solute atoms take up an orderly periodic arrangement on the lattice sites of the solvent. This arrangement at first is inconsistent and does not occur throughout the entire crystal structure; a condition termed "short-range order." As the alloy is cooled further, the ordered arrangement may progress until it extends throughout the entire structure, producing "long-range order." Since ordered structures result in a definite ratio of solvent to solute atoms, their compositions can be expressed in a simple chemical formula. It should be noted, however, that the ordered structure is still a solid solution rather than an intermetallic compound. The basic difference is that intermetallic compounds *generally* melt at a constant temperature. On heating to a critical temperature, ordered structures will become disordered, and then melt — as alloys — over a range of temperatures.

The existence of an ordered phase in the titanium-aluminum system has been confirmed by both X-ray and electron diffraction techniques. This phase cannot be detected by light metallography. The ordered phase is based on $Ti_3Al$ and $Ti_3$ (Al, Sn) if tin is present. This phase is usually designated as Alpha 2.

Alpha 2 forms as uniformly distributed coherent precipitates. In general, Alpha 2 is deleterious in that it reduces ductility and increases the susceptibility to stress corrosion cracking. Alpha 2 can be controlled by reducing Al or Sn contents in the alloy. It appears that Alpha 2 can be suppressed by the addition of beta isomorphous elements like molybdenum.

## Typical Structures of Various Titanium Alloys

**Figure 37 250X**
RMI Pure Ti Tubing (525 ppm) hydrogen
Microstructure consists of alpha grains and titanium hydride.
Etchant: 2%HF-4%$HNO_3$

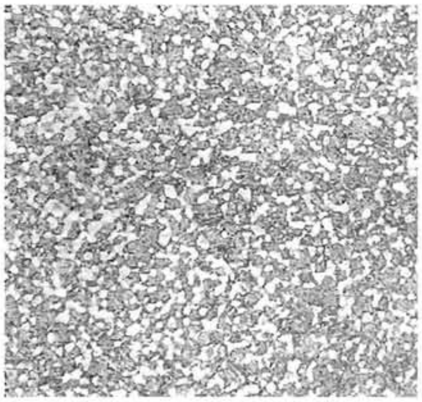


**Figure 38 250X**
RMI 6Al-6V-2Sn Bar
1300F/2 Hrs.; Air Cool
Primary alpha in a fine matrix of alpha and beta
Etchant: 2%HF-4%$HNO_3$

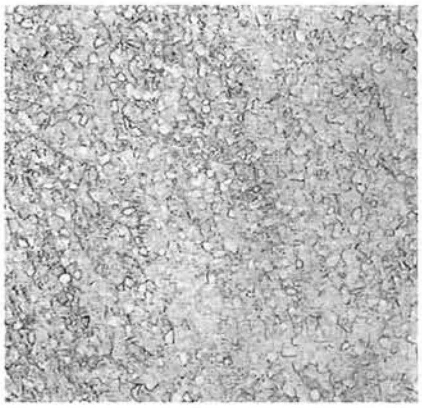


**Figure 39 250X**
RMI 6Al-6V-2Sn Bar
1625F/1 Hr.; Water Quench
1125F/4 Hrs.; Air Cool
Primary alpha in an aged matrix consisting of precipitated alpha and residual beta
Etchant: 2%HF-4%$HNO_3$

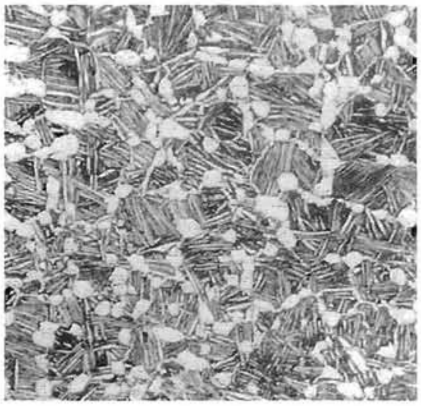
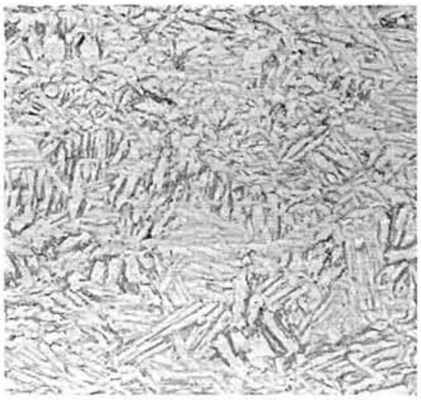


**Figure 40 250X**
RMI 6Al-2Sn-4Zr-2Mo Bar
1800F/1 Hr.; Air Cool
1100F/8 Hrs.; Air Cool
Primary alpha in a matrix of acicular alpha and beta
Etchant: 2%HF-4%$HNO_3$

**Figure 41 250X**
RMI 5Al-6Sn-2Zr-1Mo-0.25Si
Forged Product
1800F/1 Hr.;
Air Cool
1100F/2 Hrs.;
Air Cool
Plate-like alpha and intergranular beta
Etchant:
2%HF-4%$HNO_3$



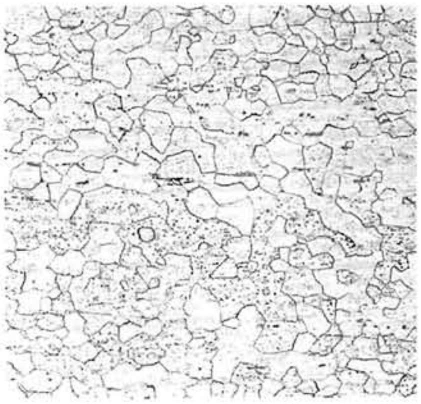
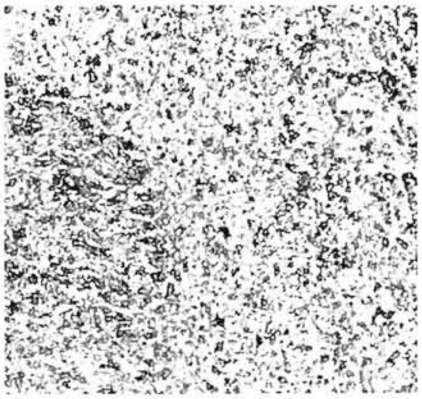


**Figure 45 100X**
RMI 3Al-8V-6Cr-4Mo-4Zr Sheet
Solution Treated
1500F/7 Min.; Air Cool
Equiaxed metastable beta and fine alpha precipitate
Etchant:
2%HF-4%$HNO_3$

**Figure 42 200X**
RMI 5Al-2Sn-2Zr-4Cr-4Mo
12" diameter Billet as forged
Primary alpha in a heavily worked alpha + beta matrix



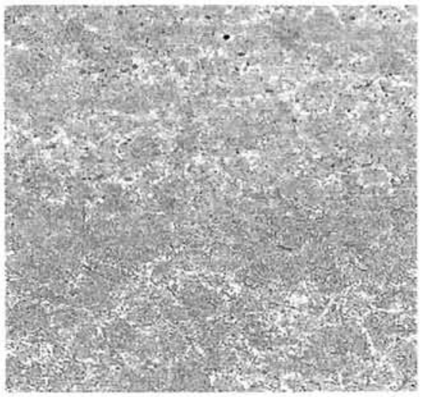
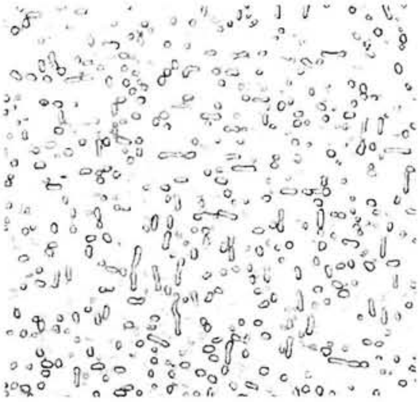


**Figure 46 100X**
RMI 3Al-8V-6Cr-4Mo-4Zr Sheet
Solution treated and aged 1500F/7 Min.;
Air Cool
950F/8 Hrs.;
Air Cool
Equiaxed prior beta grains containing beta and fine alpha precipitate
Etchant: 30ml Hydrogen Peroxide + 3 drops HF

**Figure 43 200X**
RMI 5Al-2Sn-2Zr-4Cr-4Mo
12" diameter Billet
Heat treated:
($B_t$-45F)/1 Hr.;
Fan Cool
+ 1150F/2 Hrs.;
Air Cool
Primary alpha in aged beta matrix (alpha + beta)



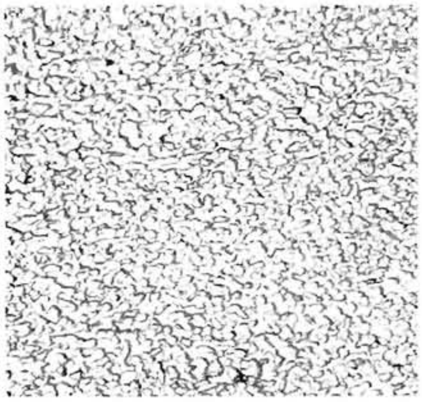


**Figure 47 500X**
RMI 8Mn Sheet
Alpha appears in a beta matrix after heating the sheet at 1200F, 1 hour and cooling in the furnace to 900F and then cooling in air
Etchant:
2%HF-4%$HNO_3$

**Figure 44 200X**
RMI 10V-2Fe-3Al
10" diameter Billet as forged
Very heavy worked transformed beta + beta
Large prior beta grains with grain boundary alpha

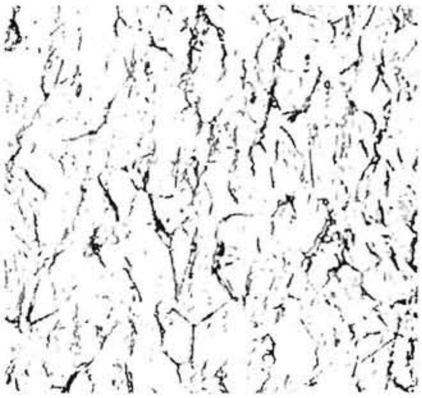


**Figure 48 500X**
RMI 5Al-2.5Sn
(655 ppm)
Alloy Alpha grains and titanium hydride appear in the microstructure after heating the alloy at 1500F, $^1/_2$ hour, and cooling in air followed by hydrogenating in a sodium hydride bath at 720F for 4 hours
Etchant:
10%HF-25%$HNO_3$
-45% Glycerine
-20% $H_2O$

## EFFECT OF PROCESSING ON MICROSTRUCTURE

Microstructural changes brought about through processing are numerous and varied, and are dependent on alloy content and working history. If working is initiated and completed at temperatures in the beta field, the resulting microstructure will be entirely transformed. The transformation product will consist of acicular or plate-like alpha, depending on section size and cooling rate. The structure will also show evidence of coarse equiaxed prior beta grains as shown in Figure 49. Structures developed in this manner are not changed significantly through the use of subsequent thermal treatments. Fine acicular structures can be coarsened somewhat by heating in the alpha-beta field, but the coarse prior beta structure can be altered only by further working at temperatures below the beta transus.

If working is initiated in the beta field and completed at some temperature in the alpha-beta field, the resulting structure will be predominately transformed beta. The prior beta grain boundaries will be distorted and partially broken up due to the lower finishing temperature as shown in Figure 52.

Work carried out entirely in the alpha-beta field, or in the alpha field in the case of an alpha alloy, generally yields a fine-grained structure with little or no evidence of transformation product.

Figures 49, 50 and 51 show the effect of a 50% forging reduction on the RMI 6Al-4V alloy at three different temperatures. Figures 52, 53 and 54 show the effect of a 75% forging reduction on this alloy at the same temperatures. In comparing Figures 49 and 52 it is seen that a greater reduction resulted in a partial breakup of the prior beta grains. Greater reduction at a lower temperature as shown in Figures 53 and 54 resulted in yet a finer-grained structure. Similar results are obtained with other alloy systems. Figures 55, 56 and 57 show the effect of a 50% forging reduction on the RMI 7Al-4Mo alloy at three temperatures. Figure 56 illustrates that a 50% reduction at 1800F is sufficient to break up the coarse prior beta structure shown in Figure 55. An equivalent reduction at a still lower temperature (1650F) yields an even finer alpha-beta structure. Figures 58, 59 and 60 show similar results on the RMI 8Al-1Mo-1V alloy.

**Figure 49 250X**
RMI 6Al-4V Bar
Forged 50% at 1950F
Annealed 1350F/2 Hrs.; Air Cool Acicular alpha + beta and prior beta grain boundaries

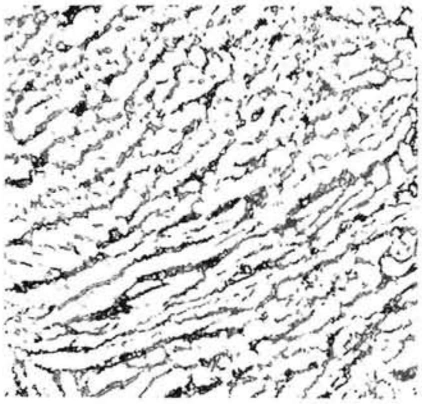


**Figure 50 250X**
RMI 6Al-4V Bar
Forged 50% at 1800F
Annealed 1350F/2 Hrs.; Air Cool
Plate-like and equiaxed alpha with a small amount of transformed beta present

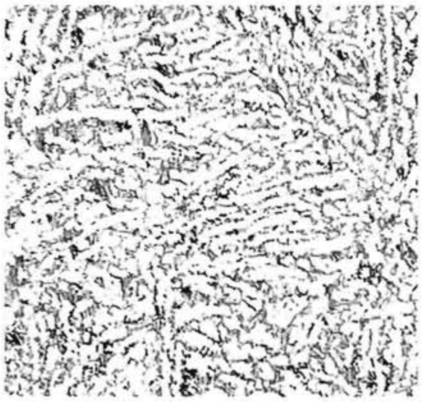
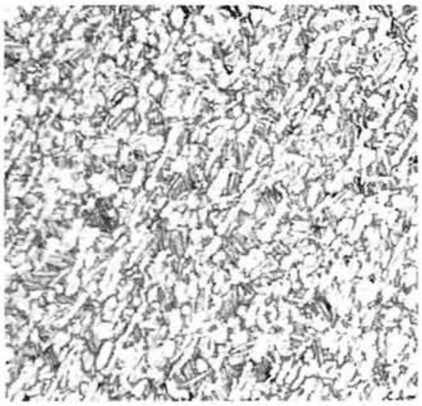


**Figure 51 250X**
RMI 6Al-4V Bar
Forged 50% at 1650F
Annealed 1350F/2 Hrs.; Air Cool
Plate-like alpha beta structure

Etchant:
$10\%HF-5\%HNO_3$

**Figure 52 250X**
RMI 6Al-4V Bar
Forged 75% at 1950F
Annealed 1350F/2 Hrs.; Air Cool
A worked beta structure consisting of partially deformed acicular alpha + beta and distorted prior beta grain boundaries

**Figure 53** **250X**
RMI 6Al-4V Bar
Forged 75% at 1800F
Annealed 1350F/2 Hrs.; Air Cool
Plate-like and equiaxed alpha with a small amount of beta



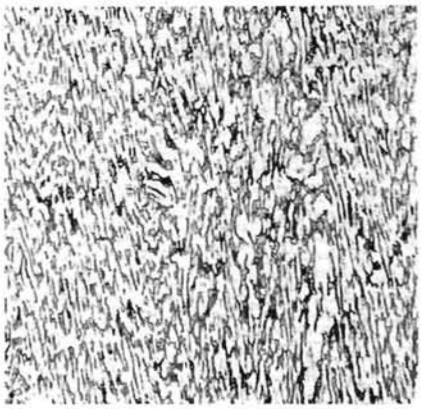


**Figure 57** **250X**
RMI 7Al-4Mo Bar
Forged 50% at 1650F
Annealed 1300F/1 Hr.; Air Cool
Fine slightly elongated alpha + beta
Etchant:
2%HF-4%$HNO_3$

**Figure 54** **250X**
RMI 6Al-4V Bar
Forged 75% at 1650F
Annealed 1350F/2 Hrs.; Air Cool
Fine elongated alpha + beta
Etchant:
10%HF-5%$HNO_3$

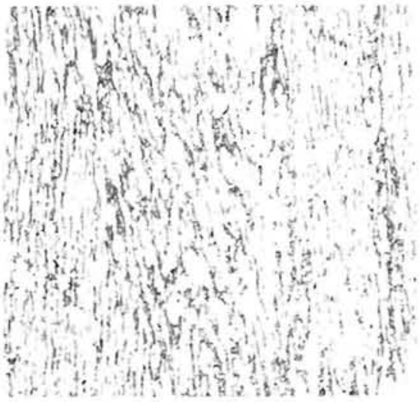
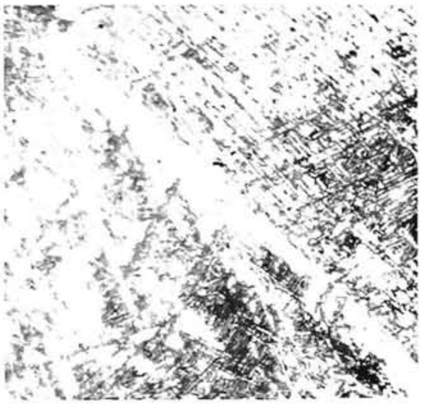


**Figure 58** **200X**
RMI 8Al-1Mo-1V Bar
Forged 70% at 2100F
Annealed 1450F/8 Hrs.; Furnace Cool
Acicular alpha + beta and prior beta grain boundaries

**Figure 55** **250X**
RMI 7Al-4Mo Bar
Forged 50% at 1950F
Annealed 1300F/1 Hr.; Air Cool
Acicular alpha + beta and prior beta grain boundaries



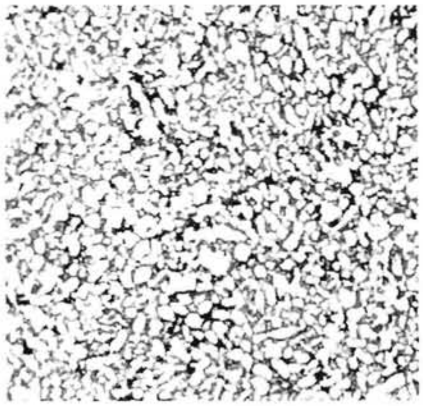
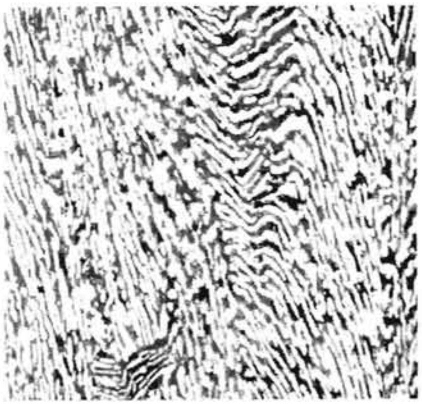


**Figure 59** **200X**
RMI 8Al-1Mo-1V Bar
Forged 70% at 1850F
Annealed 1450F/8 Hrs.; Furnace Cool
Equiaxed alpha and intergranular beta

**Figure 56** **250X**
RMI 7Al-4Mo Bar
Forged 50% at 1800F
Annealed 1300F/1 Hr.; Air Cool
Plate-like alpha + beta



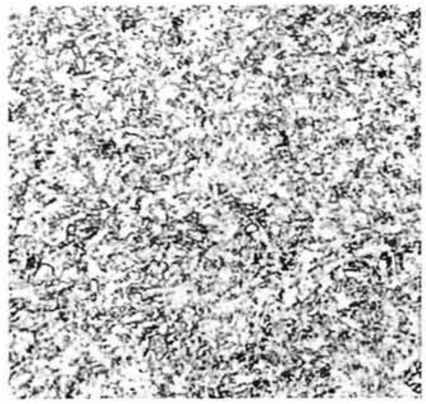


**Figure 60** **200X**
RMI 8Al-1Mo-1V Bar
Forged 70% at 1650F
Annealed 1450F/8 Hrs.; Furnace Cool
Fine alpha + beta
Etchant:
10%HF-5%$HNO_3$

## EFFECT OF THERMAL TREATMENT ON MICROSTRUCTURE

The microstructural changes that can be brought about through thermal treatment are also numerous. Figure 61 shows the effect of heating RMI 6Al-4V bar to four different temperatures and cooling at three different rates from each temperature. The tensile properties for each annealing treatment at 1000F are listed in Table 4. The aged properties indicate some information about the phases present. Little, if any, change in properties can be expected when phases are in a nearly equilibrium condition prior to aging. The presence of non-equilibrium phases, such as alpha-prime or metastable beta, results in substantial increases in ultimate tensile and yield strength properties following the aging. The tensile data in Table 4 shows that: (1) no response to aging occurs on furnace cooling from solution temperatures; (2) only a slight response occurs on air cooling; and (3) the greatest response is experienced with a water quench from the solution temperature. Good response to aging occurs on water quenching from the beta field; however, ductility values are quite low. The best combination of properties can be produced by solution treating at temperatures relatively high in the alpha-beta field.

TABLE 4 — Mechanical Properties of RMI 6Al-4V, 5/8" dia. Bar Following Various Heat Treatments

| Micro (figure 61) | Treatment* | UTS KSI | .2% YS KSI | Elongation % | RA % |
|---|---|---|---|---|---|
| A | 1950F/WQ<br>After Aging | 160.7<br>169.7 | 138.3<br>153.3 | 7.7<br>8.5 | 19.2<br>19.2 |
| B | 1750F/WQ<br>After Aging | 162.3<br>171.6 | 138.3<br>155.0 | 17.0<br>16.5 | 60.2<br>56.4 |
| C | 1650F/WQ<br>After Aging | 162.0<br>162.0 | 134.0<br>147.0 | 15.2<br>15.3 | 53.9<br>47.5 |
| D | 1550F/WQ<br>After Aging | 146.4<br>156.3 | 112.0<br>141.7 | 20.0<br>16.5 | 54.7<br>48.8 |
| E | 1950F/AC<br>After Aging | 153.7<br>153.7 | 137.0<br>136.3 | 7.0<br>9.8 | 10.3<br>16.0 |
| F | 1750F/AC<br>After Aging | 144.3<br>148.0 | 122.7<br>130.3 | 17.8<br>16.1 | 54.1<br>45.7 |
| G | 1650F/AC<br>After Aging | 145.3<br>149.3 | 126.0<br>136.0 | 17.5<br>17.3 | 54.7<br>50.2 |
| H | 1550F/AC<br>After Aging | 148.0<br>150.3 | 127.3<br>135.0 | 17.8<br>16.8 | 47.7<br>46.9 |
| I | 1950F/FC<br>After Aging | 151.0<br>146.6 | 136.0<br>136.0 | 10.5<br>9.5 | 15.6<br>15.4 |
| J | 1750F/FC<br>After Aging | 136.3<br>140.3 | 121.3<br>128.0 | 18.8<br>18.2 | 46.0<br>49.1 |
| K | 1650F/FC<br>After Aging | 139.6<br>139.6 | 124.0<br>127.0 | 16.5<br>16.8 | 43.3<br>48.3 |
| L | 1550F/FC<br>After Aging | 144.6<br>154.0 | 134.0<br>138.3 | 17.3<br>17.0 | 48.9<br>49.6 |

*Aging in all cases: 1000F/4 Hrs.; Air Cool

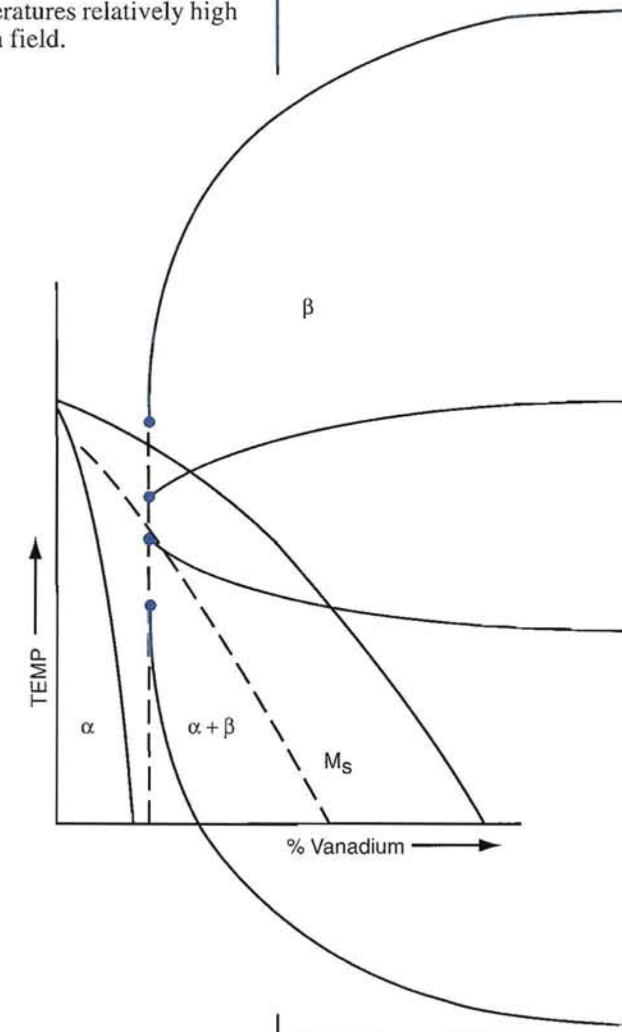
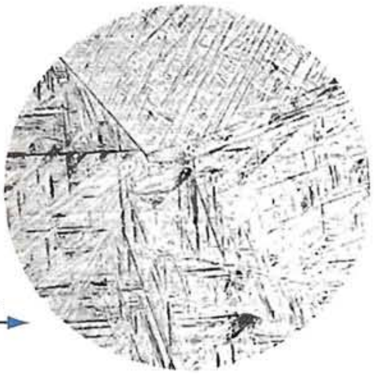


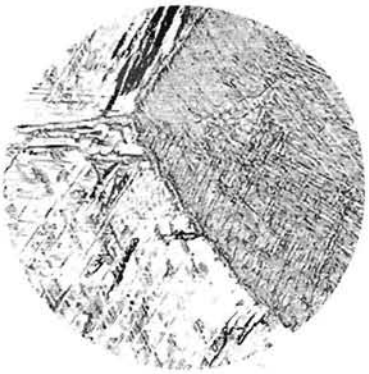

**Figure 61 250X (A-L)**
RMI 6Al-4V, 5/8" dia. Bar Microstructures resulting from various cooling rates from several temperatures.

**WATER QUENCHED** | **AIR COOLED** | **FURNACE COOLED**

1950F



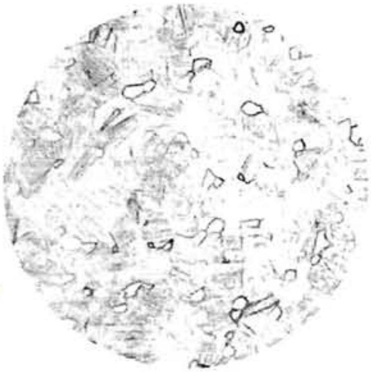
A ALPHA-PRIME + BETA AND PRIOR BETA GRAIN BOUNDARIES



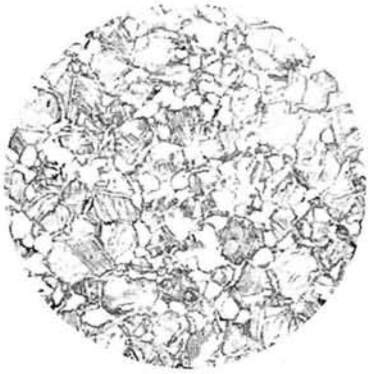
E ACICULAR ALPHA + BETA AND PRIOR BETA GRAIN BOUNDARIES

I PLATE-LIKE ALPHA + BETA AND PRIOR BETA GRAIN BOUNDARIES

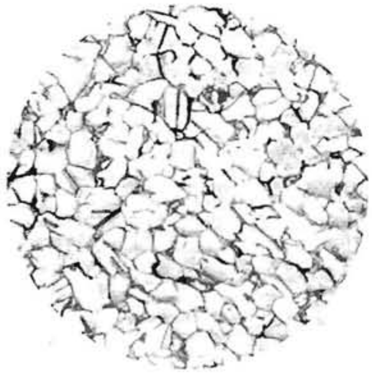
1750F



B PRIMARY ALPHA AND ALPHA-PRIME + BETA

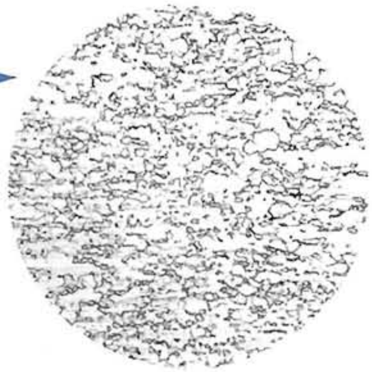


F PRIMARY ALPHA AND ACICULAR ALPHA + BETA



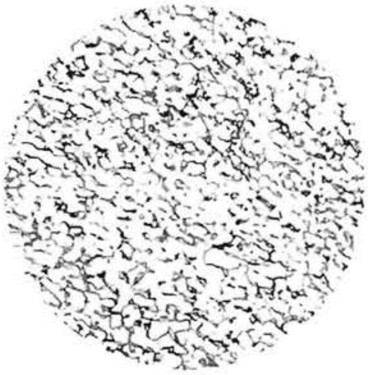
J EQUIAXED ALPHA AND INTERGRANULAR BETA

1650F



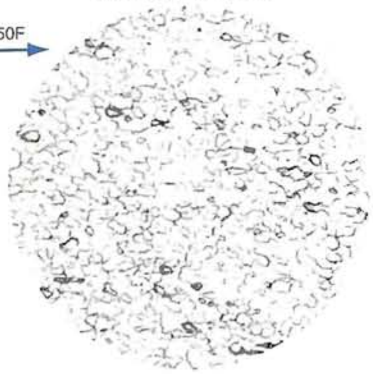
C PRIMARY ALPHA AND ALPHA-PRIME + BETA

G PRIMARY ALPHA AND ACICULAR ALPHA + BETA



K EQUIAXED ALPHA AND INTERGRANULAR BETA

1550F



D PRIMARY ALPHA AND METASTABLE BETA

H PRIMARY ALPHA AND BETA

L EQUIAXED ALPHA AND INTERGRANULAR BETA

Figure 62 shows the effect of thermal treatments on the microstructure of RMI 8Al-1Mo-1V, a high alpha alloy. Similar to Figure 61, four temperatures were selected and three cooling rates from each temperature. The higher aluminum (alpha stabilizer) and the lower molybdenum and vanadium (beta stabilizers) result in a higher beta transus temperature for RMI 8Al-1Mo-1V alloy.

The response to thermal treatments shows similar microstructures to those of other alpha beta alloys after treatment in similar areas as noted in the phase diagram. The alloy RMI 8Al-1Mo-1V will respond to strengthening by quenching and aging treatments, however, the increase in strength is minimal because of the lower beta content.

RMI 8Al-1Mo-1V is usually used in a solution treated and aged condition exhibiting the best creep and best room temperature properties.

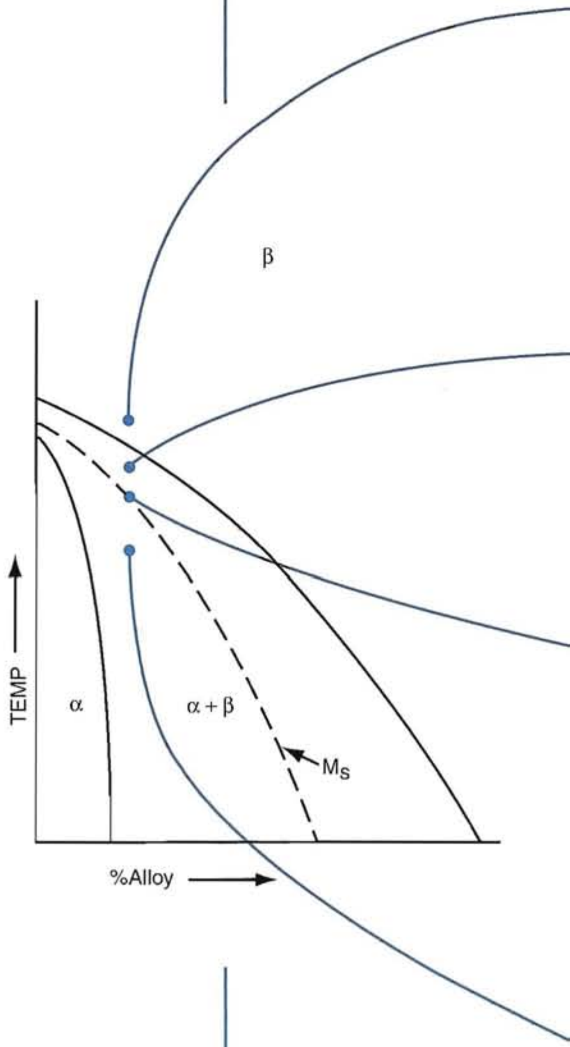
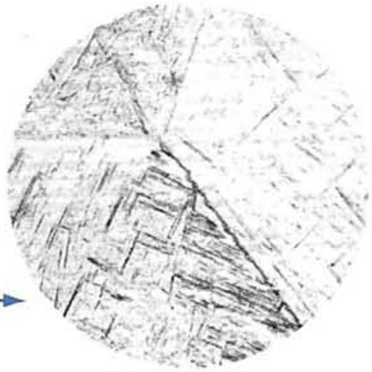



**Figure 62 250X (A-L)**
**RMI 8Al-1Mo-1V, 3/4" dia. Bar Microstructures resulting from various cooling rates from several temperatures.**

| WATER QUENCHED | AIR COOLED | FURNACE COOLED |
|---|---|---|

1950F

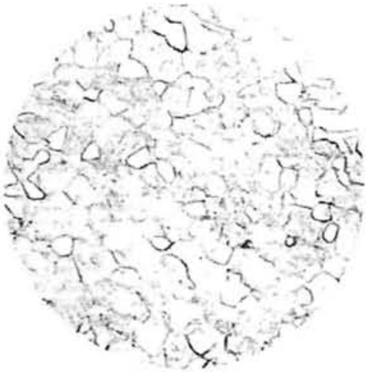


**A** ALPHA-PRIME + BETA AND PRIOR BETA GRAIN BOUNDARIES

**E** ACICULAR ALPHA + BETA AND PRIOR BETA GRAIN BOUNDARIES

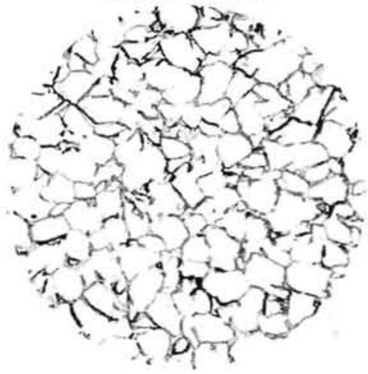
**I** PLATE-LIKE ALPHA + BETA AND ALPHA AT THE PRIOR BETA GRAIN BOUNDARIES

1850F



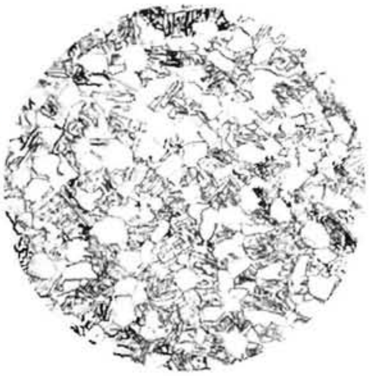
**B** PRIMARY ALPHA + ALPHA-PRIME + BETA

**F** PRIMARY ALPHA AND ACICULAR ALPHA + BETA



**J** EQUIAXED ALPHA AND INTERGRANULAR BETA

1750F

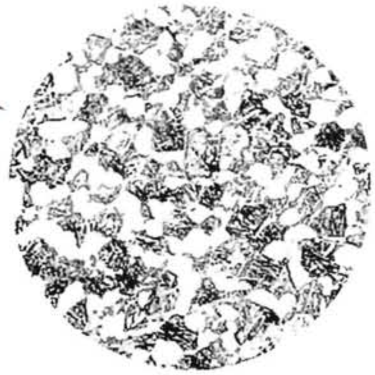


**C** PRIMARY ALPHA + ALPHA-PRIME + BETA

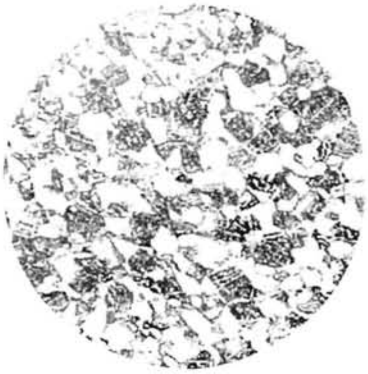
**G** PRIMARY ALPHA AND ACICULAR ALPHA + BETA

**K** EQUIAXED ALPHA AND ALPHA + BETA

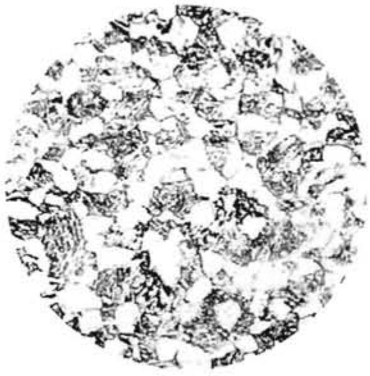
1650F



**D** PRIMARY ALPHA + ALPHA AND METASTABLE BETA



**H** PRIMARY ALPHA AND ALPHA + BETA



**L** EQUIAXED ALPHA AND ALPHA + BETA

# METALLOGRAPHIC PREPARATION

Procedures for the metallographic preparation of titanium vary somewhat from laboratory to laboratory. The preference of one procedure over another can usually be left to the discretion of the metallographer as long as care is exercised in avoiding conditions that may lead to misinterpretation.

Following is a brief outline of metallographic procedures used at RMI along with a list of suggested etchants.

## SECTIONING

Care should be exercised during the sectioning and cutting of metallographic samples. Abrasive cutting can be used if adequate coolant is provided during the cutting operation. Hack sawing or cutting on a diamond saw is recommended for small samples where heating effects can be a problem.

## MOUNTING

Titanium can be mounted in a number of molding materials. The most common are Bakelite, Transoptic and Diallyl Phthalate. Diallyl Phthalate is recommended when edge preservation is important. The temperatures encountered in using these materials are not generally a problem. If heating is of concern, samples can be mounted in Quick Mount, a room-temperature, self-curing, plastic material.

Specimens are usually left unmounted if electropolishing is to be used. However, if mounting is necessary, conductive mounting materials are available which allow subsequent electropolishing.

## GRINDING

Preliminary grinding of titanium is similar to that of other metals. Either silicon carbide or emery papers can be used. Specimens are ground on successive grades of paper, starting with No. 3 emery. Rotation of the specimen 90° to previous grind lines is recommended. Wet grinding is preferred; however, dry grinding can be used if care is exercised to avoid overheating of the specimen.

## POLISHING

Polishing can be by electrolytic, mechanical or vibratory methods. Electropolishing is carried out directly from the final grinding stage and is, therefore, considerably faster than mechanical or vibratory process. The electrolyte consists of 600 ml methyl alcohol, 360 ml ethylene glycol, 60 ml perchloric acid and 20 ml water. Polishing time is 15 to 25 seconds at a current density of 1 to 1 $^1/_2$ amps/sq cm, depending on specimen size and polishing area. The electrolyte, with a low concentration of perchloric acid, is non-explosive and can be stored safely for several weeks. However, care should be exercised in the handling of perchloric acid, since it can react explosively with organic materials.

Satisfactory results can also be achieved using mechanical polishing techniques. The mechanical polishing process is a two-step operation and is carried out as follows:

1. Preliminary polishing on red felt, billiard cloth or nylon using Linde C Alpha alumina (1.0 micron).
2. Final polishing on microcloth using .05 micron Linde B Gamma alumina.

Final polishing should consist of several sequences of polishing and etching to insure removal of disturbed metal. Adding 1/2% HF to the polishing lubricant is sometimes helpful in the final polishing stage.

Vibratory polishing, although a slower process than electrolytic or mechanical polishing, produces good results. The vibratory process is also a two-step operation and is carried out as follows:

1. Preliminary polishing on canvas cloth (for 2 to 4 hours), using a 5.0 micron slurry of levigated alumina.
2. Final polishing on microcloth (for 2 to 4 hours), using a .05 micron slurry of levigated alumina.

Unalloyed titanium has a tendency to smear in the vibratory process, so several short polishing and etching sequences should be used to remove disturbed metal.

# ETCHING

Etching can be accomplished by swabbing or immersing, with swabbing being preferred when mechanical or vibratory polish is used. Etching times are usually short; from 3 to 20 seconds depending on the alloy and the etchant.

The following table lists a number of etchants for titanium and titanium alloys. Nearly all etchants contain some hydrofluoric acid and an oxidizing agent. The 10%HF-5%$HNO_3$-85%$H_2O$ etchant is most widely used for revealing general structure.

| ETCHANTS FOR TITANIUM AND TITANIUM ALLOYS | | |
|---|---|---|
| **Material** | **Etchants** | **Remarks** |
| Unalloyed Titanium and most Titanium Alloys | 10ml HF<br>5ml $HNO_3$<br>85ml $H_2O$ | Reveals general structure |
| | **Kroll Etch**<br>10ml HF<br>30ml $HNO_3$<br>50ml $H_2O$ | Reveals general structure |
| RMI 8Mn<br>RMI 13V-11Cr-3Al (aged) | 2ml HF<br>4ml $HNO_3$<br>94ml $H_2O$ | Reveals general structure |
| All Titanium and Titanium Alloys | 1ml HF<br>2ml $HNO_3$<br>50ml $H_2O_2$ (30%)<br>47ml $H_2O$ | Removes stain |
| RMI 6Al-6V-2Sn | 10ml 40% KOH<br>5ml $H_2O_2$ (30%)<br>20ml $H_2O$ | Stains alpha and transformed beta Retained beta remains white |
| Ti-Al-Zr<br>Ti-Si<br>Alloys | 18.5 g Benzalkonium chloride<br>35ml Ethanol<br>40ml Glycerine<br>25ml HF | Reveals general structure |
| RMI 6Al-2Sn-4Zr 2Mo-0.08Si | 4% $HNO_3$<br>2% HF<br>Bal. $H_2O$ | Reveals general structure |
| Most Alloys | 2ml HF<br>98ml $H_2O$ | Reveals alpha case |
| RMI 5Al-2.5Sn | 10ml HF<br>25ml $HNO_3$<br>45ml Glycerine<br>20ml $H_2O$ | Reveals hydrides |
| Ti-Si Alloys | 2 drops HF<br>1 drop $HNO_3$<br>3ml HCl<br>25ml Glycerine | Reveals general structure |
| RMI 3Al-8V-6Cr-4Mo-4Zr | 30ml $H_2O_2$ (30%)<br>3 drops HF | Reveals general structure |
| Beta Alloys | 1g $KM_NO_4$<br>95ml $H_2O$<br>5ml $H_2SO_4$<br>5 drops HF | Reveals general structure |
| All Alloys | 47ml $H_2O_2$ (30%)<br>50ml $H_2O$<br>2ml $HNO_3$<br>1ml HF | Cleans stained specimens and rapidly etching alloys |

### Acicular Alpha

A fine, needle-like transformation product brought about through nucleation and growth.

### Alpha

The low temperature allotrope of titanium with a hexagonal, close-packed crystal structure.

### Alpha-Beta Structure

A microstructure which contains both alpha and beta as the principal phases.

### Alpha Case

The oxygen-enriched, alpha-stabilized surface which results from elevated temperature air exposure.

### Alpha-Prime (Martensitic Alpha)

A supersaturated, non-equilibrium phase formed by a diffusionless transformation of beta phase which is lean in solute.

### Alpha Stabilizer

An alloying element which dissolves preferentially in the alpha phase and raises the alpha-beta transformation temperature.

### Alpha Two ($\alpha_2$)

An ordered alpha structure, such as $Ti_3Al$ and $Ti_3$ (Al, Sn) found in highly stabilized alpha alloys.

### Alpha Transus

The temperature which designates the phase boundary between the alpha and alpha-plus-beta fields.

### Beta

The high temperature allotrope of titanium with a body-centered cubic crystal structure.

### Beta Eutectoid

Beta stabilizing alloying elements which result in the decomposition of beta to eutectoid products, such as alpha and intermetallic compounds.

### Beta Isomorphous

Beta stabilizing alloying elements which are completely miscible in the beta phase.

### Beta Stabilizer

An alloying element which dissolves preferentially in the beta phase and lowers the beta transformation temperature. Such elements promote the retention of beta at room temperature.

### Beta Transus

The temperature which designates the phase boundary between the alpha plus beta and beta fields.

### Elongated Alpha

A fibrous type of structure brought about by unidirectional fabrication.

### Equiaxed Structure

A polygonal structure having approximately equal dimensions in all directions.

### Hydride Phase

The phase TiH formed in titanium when the hydrogen content exceeds the solubility limit.

### Interstitial Element

An element with a relatively small atom which can assume position in the interstices of the titanium lattice.

### Intergranular Beta

Beta situated between alpha grains.

### Intermetallic Compound

An intermediate phase in an alloy system that has a narrow solubility range.

### Matrix

The constituent which forms the continuous phase of a two phase microstructure.

### Metastable Beta

A non-equilibrium phase that can be transformed to alpha or eutectoid products by heat or stress.

### $M_f$

The temperature at which the martensite reaction is complete.

### $M_s$

The maximum temperature at which alpha-prime begins to form from the beta phase on cooling.

### Omega

A non-equilibrium, submicroscopic phase that forms during the nucleation and growth transformation of beta to alpha.

### Ordered Structure

The orderly or periodic arrangement of solute atoms on the lattice sites of the solvent.

### Plate-like Alpha

Alpha grains which form along preferred planes of beta during transformation of beta to alpha. Plate-like alpha is characterized by relatively long and wide grains.

### Primary Alpha

Equilibrium alpha which remains untransformed on heating to temperature below and for short times above the beta transus.

### Prior Beta Grain Size

The grain size of the beta phase prior to transformation to alpha.

### Serrated Grain

Alpha grains which are characterized by irregular grain size and jagged grain boundaries.

### Spheroidal Structure

Grains with a circular or globular appearance.

### Substitutional Element

An alloying element with an atom size similar to the solvent which can replace or substitute for the solvent atoms in the lattice.

### Transformed Beta

Products of unstable beta after transformation, e.g., alpha, beta and eutectoid products.

### Widmanstätten Structure

A structure brought about by the formation of a new phase along preferred crystallographic planes of the prior phase. The Widmanstätten structure is a transformation product of the beta phase.