Figure 5
Schematic phase diagram showing the composition
dependence of the $M_s$ temperature, and the constitution
of alloys quenched from various solution treatment
temperatures

on properties of these alloys by affecting their con-
stitution in addition to affecting the strength of the
individual constituents.

In summary, the type and concentration of alloying
elements affects the equilibrium constitution of Ti
alloys by preferentially stabilizing one or the other
of the two allotropic forms. In addition, the alloying
elements partition selectively to one or the other
constituents and provide solid-solution strengthen-
ing. Aside from the effects of alloying on equilibrium
constitution, alloying also affects the kinetics of
decomposition of the elevated temperature $\beta$-phase.

resulting microstructures have a strong effect on
properties, so alloying also affects the properties
of Ti alloys by influencing the evolution of their
microstructure.

See also: Titanium Alloys: Powder Metallurgy; Titanium
Alloys: Thermomechanical Treatment; Titanium and
Titanium Alloys: Selection; Titanium: Properties

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Titanium Alloys: Powder Metallurgy

Powder metallurgy (PM) in general terms offers two
advantages over conventional cast and wrought ingot
metallurgy (IM): (a) the capability to produce net
shapes, which leads to cost savings; and (b) a fast
freezing rate, allowing unique alloy compositions
to be produced without the solute segregation that
occurs during slower freezing of large ingots (see
Powder Metallurgy).

Titanium is the initial design choice for many aero-
space and commercial applications because of its
low total cost (which includes both purchase and
maintenance). However, it often turns out that
titanium is not used in potentially attractive appli-
cations because of the high initial cost of component
procurement. As a result, net-shape or near-net-
shape technologies have been explored as methods
for reducing the cost of titanium alloy components.
The techniques evaluated have included isothermal
forging, casting, superplastic forming and powder
metallurgy. Titanium PM offers the potential of true
net-shape capability, combined with mechanical
properties that are equal to or even exceed cast and
wrought levels. These mechanical properties exist
because of a lack of texture and segregation, and a
fine uniform grain structure which is inherent to the
titanium PM product.

The possibility for making alloys that are difficult,
if not impossible, to make by conventional ingot
metallurgy practice arises because many potentially
useful alloying elements exhibit a strong tendency
for alloy segregation during freezing and cooling of
the ingot. In practice, PM has not been used to any
significant extent in the case of Ti alloys, because of
limitations connected with current Ti powder-making
methods, as will be described below. However, this
potential advantage may outweigh the net-shape
advantage in the long term if it can be brought to
fruition.

Titanium powder metallurgy can be separated into
the application of prealloyed powder and blended
elemental powders, which are alloyed by blending
with other elements before consolidation. High per-
formance is usually required from components made
from prealloyed powders, because such components are used in applications where there is direct competition between them and wrought products such as forgings, extrusions and plate. On the other hand, the applications intended for titanium powder metallurgy components that are made from “sponge fines,” the small (100 mesh, 0.149 mm) irregular granules of titanium produced as a by-product during conversion from ore to elemental titanium, blended with alloying elements and homogenized or partially homogenized during consolidation are considerably different. In general, these components compete with other titanium product forms such as castings, or with other alloys such as stainless steel or monel, in applications where the chemical properties of titanium such as its corrosion resistance make it attractive and where structural integrity is of secondary importance. The balance of this article discusses the methods used for powder making, consolidation of the powder, the general characteristics and properties of the two classes of powder products and powder-making capability and applications.

1. Powder Making

Because of the extremely high reactivity of liquid titanium, current methods for producing prealloyed titanium powder are restricted to local melting of the titanium (where the molten titanium does not contact any other material) or solid-state production of powder by comminution. Thus, prealloyed titanium powders are made by two basic techniques: (a) centrifugal atomization, using the rotating electrode process (REP) or its closely related companion process, plasma rotating electrode process (PREP); (b) comminution, of which the hydride–dehydride method is most common and may be particularly useful for making unalloyed titanium powder.

The centrifugal atomization processes produce small droplets of molten metal by rapidly rotating a solid bar which is being impinged by a high-intensity heat source. This is an arc from a tungsten electrode in REP and a plasma torch in PREP. The centrifugal force from the rotation of the bar causes ejection of the small droplets, which solidify within the atomizer chamber. The chamber is typically filled with argon in order to prevent significant oxidation or contamination of the molten titanium. A schematic of the rotating electrode process is shown in Fig. 1. The modification of REP leading to PREP has the basic benefit of minimizing the amount of tungsten that is included in the titanium powder because of the erosion or melting of the tungsten electrode. The PREP method combined with powder handling in strict clean-room conditions has resulted in material with all mechanical properties equivalent to those exhibited by IM material with a comparable microstructure. This is discussed in more detail later (see Sect. 4).

The reactivity of molten titanium is so high that a modest increase in interstitial content occurs even when the powder is prepared in argon. This increase is generally manageable and can be kept within the acceptable range established for wrought products. However, in such cases where very high toughness or large low-temperature tensile ductility is required, very careful powder production and handling is essential to achieve suitable values of these properties.

The commercially pure, common titanium alloys such as Ti-6Al-4V are generally quite ductile and therefore not readily amenable to comminution to fine powder. However, titanium is a hydride former and can easily be converted to a very brittle state by introduction of hydrogen, thus permitting efficient comminution to be carried out. The hydrogen is subsequently removed by vacuum annealing. This process is referred to as the hydride–dehydride (HDH) process. The difference between prealloyed HDH powder and centrifugally atomized powders is that the former are irregular in shape, whereas the latter are spherical. This difference is illustrated in Fig. 2a,b. The difference results in different flow characteristics and tap densities of the two powders. Also, the contamination level of HDH powder is generally relatively high.

In contrast to the production of Fe-, Ni- or Al-base prealloyed powders, no viable technique currently exists for the generation of a large molten mass of Ti and the subsequent atomization of a stream of molten metal. As a result, the existing powders are made from a homogeneous cast or wrought starting
of powder metallurgy parts vis-à-vis wrought products such as forgings.

The other method of obtaining Ti powder involves the use of sponge fines, as mentioned earlier. This PM technique is called blended elemental (BE) powder. In this approach titanium “sponge fines” and alloy additions are blended together before compaction.

2. Powder Consolidation

The consolidation of titanium powder to achieve fully dense compacts is carried out by several processes, including hot isostatic pressing (HIP), extrusion and forging in closed containers (see Powder Forging).

In the BE process, the blended “sponge fines” and alloy additions are cold compacted, under pressures up to $60 \times 10^5 \text{Nm}^{-2}$, to a “green” density of 85–90%. This can be carried out either isostatically or with a relatively simple mechanical press and a rigid die. The “green” compact is then typically vacuum sintered at 1260°C to increase density to 95–99.5% of the theoretical density, depending on the practice used, and to improve the chemical homogeneity by diffusion. A further increase in density can be achieved by hot isostatically pressing the article, which generally improves mechanical properties. This method can provide articles at lower cost than attainable from cast and wrought products. However, the porosity present (even after HIP), a consequence of the remnant chloride (sodium or magnesium, depending on whether the Hunter or Kroll process is used to produce the titanium sponge), results in degraded crack-initiation-related properties, making these products unsuitable for fatigue critical applications.

Four consolidation processes are currently under study for the prealloyed powder, all of which are capable of producing fully dense compacts. The technique most commonly used is HIP inside a heated pressure vessel or autoclave. By simultaneously applying increased temperature and pressure, full density in the part is attained by transmittal of the applied pressure. Press consolidation allows rapid (or lower-temperature) compaction of powder inside an evacuated shaped can. Powder can also be compacted by vacuum hot pressing (VHP), in which powder is hot compacted in a forge press adapted to a vacuum system. Dies can be designed which will produce the required shape and press the powder to 100% density. Finally extrusion is also used quite extensively as a compaction method. The trade-off between HIP and extrusion is that the former has considerably more flexibility with regard to shape making, whereas extrusion permits improved control of the microstructure, and hence mechanical properties, of the compact. In principle, closed-container forge consolidation combines the benefits of both processes.
3. Shape Making

Both the BE and prealloyed approaches allow net or near-net shapes to be produced. Generally, the prealloyed approach is capable of producing larger, more complex shapes, application of which should be realized in high-integrity aerospace components. For the prealloyed powder, wax patterns are coated with a ceramic material to produce a shell or envelope which closely resembles the final part. The wax is then removed by melting and the powder is introduced into the cavity which remains. Following compaction by one of the first three methods described in the last section, complex shapes such as the part shown in Fig. 3 can be produced.

![Image of a complex-shaped part](image)

**Figure 3**
Representative complex-shaped part made by HIP consolidation of REP powder

4. Properties of Powder Metallurgy Products

The properties of Ti alloys depend strongly on microstructure, as discussed previously in this article. Accordingly, it is sufficient here to comment that in Ti powder metallurgy products made from prealloyed powder, properties such as strength, ductility and toughness vary as a function of microstructure and oxygen content in much the same way as they do in wrought products. In the case of the BE material, the residual salt and associated porosity degrade mechanical properties such as fatigue crack initiation. Typical properties of powder products are shown in Table 1. Both equiaxed and acicular microstructures can be obtained in consolidated powder products. The microstructure depends significantly on the consolidation method. HIP consolidated prod-

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile yield stress (MPa)</th>
<th>Ultimate tensile stress (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM blended elemental</td>
<td>868</td>
<td>951</td>
<td>15</td>
</tr>
<tr>
<td>PM prealloyed</td>
<td>937</td>
<td>985</td>
<td>17</td>
</tr>
<tr>
<td>IM (typical)</td>
<td>923</td>
<td>978</td>
<td>17</td>
</tr>
</tbody>
</table>

*a* Annealed condition

ucts usually have an acicular microstructure, whereas powder compacts consolidated by extrusion or forging can have either an equiaxed or acicular microstructure, depending on the consolidation temperature. Examples of these are shown in Fig. 4.

![Light micrographs of Ti-6Al-4V](image)

**Figure 4**
Light micrographs of Ti-6Al-4V produced by extruding REP powder: (a) α + β extruded; (b) β extruded
The reactivity of Ti at elevated temperatures makes it to react with impurity particles if they are present. An example of a reaction zone between an Fe-rich impurity and the Ti powder is shown in Fig. 5. The large number of particles even in small parts creates a constant opportunity for such reaction sites.

![Image](image_url)

**Figure 5**
Light micrograph showing reaction zone associated with Fe-rich impurity in Ti–6Al–4V powder compact

The solution to this potential problem appears to be both adoption of clean powder making and handling methods and also the selection of microstructural conditions and alloys that are less sensitive to the presence of small microstructural defects. Clean-room handling and the use of PREP in lieu of REP have led to considerable improvement in microstructural homogeneity. In fact, by using clean powder making and handling procedures, fatigue properties of prealloyed PM products comparable to those of IM products with the same microstructure can be achieved (Fig. 6a). The width of the scatterband for the PM material in Fig. 6a is largely due to variations in impurity content. The effect on fatigue life of reducing the levels of contaminant is shown in Fig. 6b. Another extreme example of inhomogeneity related fatigue life reduction is seen in BE material. Because of the residual salt/porosity, the BE material exhibits fatigue behavior below the IM level (Fig. 6a).

5. Applications
Parts made using the BE approach are relatively cheap but exhibit mechanical behavior, particularly fatigue, inferior to that of parts fabricated using the IM approach. Thus, the situation here is relatively simple. For prealloyed parts the requirement is for both lower cost and mechanical properties at least equivalent to IM levels, including fatigue. Generally, the PM approach is most attractive for large, complex parts where the weight of the in-coming mill product compared with the weight of the final component is high when fabricated by conventional means. However, at present, since the largest autoclave available is 120 cm in diameter × 240 cm high, an upper size limit exists unless approaches such as subsequent welding to form large components are applied. Present estimates indicate that cost savings by the PM route over forged parts can range between 20% and 50% depending on the size and complexity of the part and quantity of parts produced; high-volume runs result in higher savings. An additional advantage, which assumes even greater importance in times of materials shortage, is that lead time can be reduced by 50% or more for PM parts over equivalent forged parts.

See also: Titanium: Properties; Titanium: Alloying; Titanium and Titanium Alloys: Selection
Titanium Alloys: Thermomechanical Treatment

Thermomechanical treatment (TMT) is commonly used to manipulate the microstructure and properties of titanium alloys. The principles of TMT are general in nature, though the detailed effects may vary from alloy to alloy. The effects of TMT on the properties of titanium alloys are especially pronounced in the case of fracture resistance. The influence of microstructure on toughness and tensile ductility tends to be inverse. This is illustrated by a representative set of data (Table 1) for Ti-6%Al-2%Sn-4%Zr-6%Mo, a high-strength titanium alloy in which this inverse trend is quite pronounced.

Although this article is largely concerned with the techniques and mechanisms of microstructural alteration by TMT, it is essential to emphasize that the principal motive for TMT is manipulation of properties. The particular processing route selected depends heavily on the intended application. For example, fracture-critical structures perform most efficiently when fabricated from materials processed to achieve high fracture toughness. Fatigue-limited structures, on the other hand, are more sensitive to crack initiation and crack growth rate. Other considerations may include the ductility required for applications involving forming or installation, in which case tensile ductility may dominate the processing selection. In general, it is not possible to optimize all these properties simultaneously.

Table 1: Typical properties of Ti-6%Al-2%Sn-4%Zr-6%Mo alloy

<table>
<thead>
<tr>
<th>Condition</th>
<th>Yield (MPa)</th>
<th>Ultimate (MPa)</th>
<th>Elongation (%)</th>
<th>Fracture toughness $K_{IC}$ (MPa mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$ block, $\beta$ finish, STA</td>
<td>1050</td>
<td>1200</td>
<td>7</td>
<td>1770</td>
</tr>
<tr>
<td>$\beta$ block, high $\alpha + \beta$ finish, STA</td>
<td>1100</td>
<td>1210</td>
<td>10</td>
<td>1420</td>
</tr>
<tr>
<td>$\alpha + \beta$ block, $\alpha + \beta$ finish, STA</td>
<td>1120</td>
<td>1210</td>
<td>13</td>
<td>1040</td>
</tr>
<tr>
<td>$\alpha + \beta$ block, $\alpha + \beta$ finish, STOA</td>
<td>1070</td>
<td>1140</td>
<td>14</td>
<td>800</td>
</tr>
</tbody>
</table>

Most commercially important titanium alloys contained varying amounts of the body-centered-cube (bcc) $\beta$ phase. The mechanisms and kinetics of transformation of the $\beta$ phase during cooling dominate the development of titanium microstructure. The principal effect of TMT is to perturb or alter these transformation mechanisms. As a result, TMT provides an additional degree of freedom in controlling or manipulating the microstructure of this class of alloys.

It is important to understand the competition between the nucleation and growth of $\alpha$ phase and the martensitic decomposition of the $\beta$ phase. To illustrate this point, a schematic vertical section from a titanium–aluminum–X phase diagram is shown in Fig. 1. Here X can be any $\beta$ isomorphous alloying element such as vanadium, molybdenum, niobium or tantalum. If an alloy is heated above the $\beta$ transus, (so that it is 100% $\beta$ phase) and then cooled, the transformation product which is formed depends on the cooling rate. If it is cooled rapidly enough, the $\beta$ phase transforms by nucleation and shear to a hexagonal-close-packed (hcp) martensitic product which is designated $\alpha'$. If it is cooled somewhat more slowly, it transforms by nucleation and growth to a colony microstructure comprising hcp $\alpha$ phase and $\beta$ phase. These two microstructures are shown in Figs. 2a and 2b. If the alloy is heated into the two-phase $\alpha + \beta$ region and then cooled at different rates, the transformation products which form depend not only on cooling rate but also on the solution treatment temperature. The typical range of products which