Breakthrough claimed for titanium PM

Using powder metal technology to produce large titanium parts has long been a major goal for the PM industry. But while small, expensive, parts have been produced, large, affordable, titanium PM parts have hitherto been consigned to the realms of wishful thinking. Now Massachusetts – based Dynamet Technology is claiming an advance that could see PM titanium products being used to substitute for wrought titanium airframe components on commercial aircraft. The company expects its work to significantly increase the volume of PM titanium product and provide a major breakthrough at the intersection of the titanium, aerospace and powder metal industries.

Conventional titanium PM is perceived as a method of producing relatively expensive, small parts. In contrast Dynamet’s advanced PM processing produces large, affordable, near net-shape components or starting stock for further processing. The process can be integrated with mill processing to produce affordable mill products and wrought components. Novel alloys with enhanced properties can be produced that would be difficult or expensive to produce by ingot melt (IM) processing. Affordability and enhanced properties by PM will increase titanium’s competitive position versus other materials. It will also expand the use of titanium and provide a new supply base to meet customers’ increasing demands for titanium product at lower cost and shorter lead-times.

Recent literature has focused on the limitations of PM titanium processes compared to other PM materials [1]. The major limitation cited is the high cost of PM titanium processing relative to other PM materials. There is no question that PM titanium is more expensive than ferrous and other nonferrous PM materials. But PM titanium competes effectively with conventional
methods of producing titanium components providing ample opportunity for growth. In addition PM titanium is increasingly viewed as an integral part of titanium processing where PM titanium forms, such as PM extrusion billet and PM forging preforms, are routes for reducing the cost of producing titanium components and for producing novel titanium alloys that cannot be produced by IM technology alone. Thus PM titanium is being viewed as an adjunct to conventional titanium processing and is gaining acceptance for aerospace, automotive, industrial and other commercial applications.

There is a growing acceptance of titanium PM processing because it is an affordable alternative to conventional IM technology that offers several important benefits to customers such as near net shape that reduces material buy-to-fly weight, shorter procurement lead times and the availability of alloys and metal matrix composites properties tailored to the customer’s needs. Dynamet Technology has manufactured a wide variety of commercial components including more than 100,000 titanium alloy near-net-shape missile housings and warheads, such as those shown in Figure 1, that have reduced customers’ costs by up to 70% over parts produced by machining from mill product bar or finish machining from forgings.

Table 1 shows the characteristics of the different types of titanium powders that are either available or under development today. This table is based in part on a recent review of powder production methods co-authored by McCracken [2]. The development of new titanium production methods such as the Armstrong, Frey and MER processes shown in the table is aimed at lowering the cost of PM titanium powder. However, these powders will not be available for some time and their relative cost and processing characteristics are yet to be established.

The blended element PM technology using hydride dehydride (HDH) titanium powder produced from Kroll sponge is the key to the commercial success of Dynamet’s PM process. This process is producing a wide range of affordable PM mill product forms and components. Dynamet has developed critical specifications for its titanium and master alloy powders that controls morphology, particle size, particle distribution and chemistry. The properties of the PM materials can be adjusted by modifications in these process parameters. The new powders that are under development may provide an opportunity for further reducing the costs of PM product when they become available, that is, if they can be processed to the necessary density levels with properties equivalent or superior to baseline PM and wrought titanium. Finally, the cost of producing components from those powders must be competitive.

### Table 1: Characteristics of different types of titanium powders

<table>
<thead>
<tr>
<th>Type/Process</th>
<th>Elemental or Prealloyed</th>
<th>Advantages</th>
<th>Status/Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hunter Process (pure sodium)</td>
<td>Elemental</td>
<td>Low cost Excellent cold compactibility</td>
<td>Limited availability High chloride</td>
</tr>
<tr>
<td>HDH* Kroll Process (pure magnesium)</td>
<td>Elemental</td>
<td>Lower cost Good compactibility Readily available Low chloride</td>
<td></td>
</tr>
<tr>
<td>HDH powder produced from ingot, sheet or scrap</td>
<td>Prealloyed</td>
<td>Readily available</td>
<td>High cost Fair compactibility</td>
</tr>
<tr>
<td>Atomized</td>
<td>Prealloyed</td>
<td>High purity Available</td>
<td>High cost Not cold compactable</td>
</tr>
<tr>
<td>REP/REP**</td>
<td>Prealloyed</td>
<td>High purity</td>
<td>High cost Not cold compactable</td>
</tr>
<tr>
<td>Armstrong</td>
<td>Both</td>
<td>Compactable Potential for low cost</td>
<td>Processibility/Quality Production Scale-up</td>
</tr>
<tr>
<td>Fray</td>
<td>Both?</td>
<td>TBD</td>
<td>Developmental</td>
</tr>
<tr>
<td>MER***</td>
<td>Both?</td>
<td>TBD</td>
<td>Developmental</td>
</tr>
</tbody>
</table>

*Hydride-Dehydride
**Rotating Electrode Powder/Plasma Rotating Electrode Powder
***MER Corp., Tucson, AZ

The CHIP PM process

Dynamet has developed the CIP-Sinter-HIP (CHIP) process, shown in Figure 2, as a
green manufacturing technology [3] that has proved to be an acceptable process for producing military, industrial and medical components. This advanced PM process uses titanium powder, typically Kroll process HDH powder, blended with master alloy powder such as aluminium-vanadium master alloy powder. The blended powder is compacted to shape by cold isostatic pressing (CIP) in elastomeric tooling. With proper selection of powders, well designed CIP tooling and appropriate pressing conditions a shaped powder compact can be produced and readily extracted from the PM tooling with sufficient green strength for handling. It must also have sufficient uniformity and intimate contact of the powder particles for densification and homogenous alloying in the subsequent sintering process.

The CHIP process is used to produce near net-shape parts for finish machining to high tolerance configurations. These processes can also be used to make forging preforms or mill product shapes for subsequent processing such as billet for casting, extrusion or hot rolling. In the case of as-sintered material full density is achieved during subsequent processing.

A wide range of shapes has been produced with size only limited by the capacity of the equipment. The size of the CIP is usually the limiting factor since vacuum furnaces and HIP units are available in larger sizes than high pressure CIP units. Size capability also depends on the powder fill characteristics, product configuration and tooling parameters. Successful products can range from a few grams to hundreds of kilos.

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lamellar structure of Ti-6Al-4V. In general the microstructure and phase composition is typical of Ti-6Al-4V. Figure 5 shows that the there is virtually no porosity in the CHIP structure.

If desired, hot isostatically pressing (HIP) can be employed to further densify the sintered part. HIP closes the residual fine porosity in the sintered shape by a combination of argon gas pressure and temperature. The result is a fully dense titanium alloy component with properties that are comparable to wrought material.

Table 2 compares the minimum tensile properties of wrought Ti-6Al-4V as specified in AMS 4928 and the typical tensile properties of wrought Ti-6Al-4V compared to the Ti-6Al-4V produced by the PM CHIP process. As shown in Table 2, PM CHIP meets the minimum tensile properties of AMS 4928 and can equal the typical tensile properties of wrought Ti-6Al-4V.

Titanium MMCs

Dynamet Technology has applied the PM CHIP process to the production of its CermeTi® family of titanium metal matrix composites (Ti MMCs). These MMCs consist of a titanium alloy matrix reinforced with a uniform dispersion of ceramic particulates. The ceramic particulate dispersions significantly improve the elastic modulus and wear resistance of titanium. Dynamet produces Ti MMCs reinforced with titanium carbide (TiC) or titanium diboride (TiB₂) particulates. The particulates are added to a blend of titanium and master alloy and then processed by PM CHIP to produce fully dense, high quality discontinuously reinforced CermeTi® Ti-based MMCs. The microstructure of the resulting MMC material is shown in Figure 6. The structure consists of a Ti-6Al-4V alloy matrix reinforced with particles of TiC. The density of TiC is very close to that of the titanium alloy matrix therefore the density of this Ti MMC is virtually the same as the density of Ti-6Al-4V. Therefore the stiffness to weight ratio of the Ti MMCs is significantly better than the matrix alloy.

The particulate addition results in a metal matrix composite with excellent wear resistance, increased strength and elastic modulus with useful ductility as shown in Table 3. Dynamet has considerable experience in the production of blended elemental Ti alloy and MMC billet and the extrusion of these billets for high quality commercial products.

Table 3: Typical properties of CermeTi® vs. Ti-6Al-4V

<table>
<thead>
<tr>
<th></th>
<th>Ultimate Tensile Strength MPa (ksi)</th>
<th>Yield Strength MPa (ksi)</th>
<th>Elongation (%)</th>
<th>Elastic Modulus GPa (msi)</th>
<th>Hardness (Rc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V PM</td>
<td>965 (140)</td>
<td>896 (130)</td>
<td>14</td>
<td>110 (16.0)</td>
<td>36</td>
</tr>
<tr>
<td>CermeTi®-C MMC</td>
<td>1034 (150)</td>
<td>965 (140)</td>
<td>3</td>
<td>130 (19.3)</td>
<td>42</td>
</tr>
</tbody>
</table>

‡ Ti has a density of 4.5 g/cm³ and melts at 1670°C while Ta has a density of 16.6 g/cm³ and melts at 3020°C
§ This work was conducted in part under a National Science Foundation SBIR grant, award number: IIP-0724433

Novel compositions

Titanium-Tantalum alloys for implantable medical devices

Titanium-tantalum (Ti-Ta) alloys offer a range of desirable properties that make them of interest for implantable medical devices. However, Ti-Ta alloys are not produced commercially because they are very difficult to prepare as homogeneous...
alloys by conventional IM due to the disparity in melting point and density between Ti and Ta.‡ Dynamet Technology has developed a radically different PM method of producing these alloys. The properties and wire drawing characteristics of these PM Ti-Ta alloys are now being investigated in the range of 30% to 95% Ta.§ Several compositions have been found to be of interest for medical devices. Specific alloys possess a unique combination of properties that makes them promising for a variety of implant applications including medical wire, orthopaedic implants and stents.

Titanium alloys containing tungsten

Tungsten (W) has been avoided as an alloying element due to the high disparity in melting point and density making it undesirable for traditional melt processing. Dynamet has investigated the use of tungsten as an alloy element by PM titanium processing and has developed a series of W-containing alloys (Abkolloy® compositions) that improve upon the properties of CP Ti and Ti-6Al-4V.

The tensile properties shown in Table 4 results from PM processing and through subsequent hot working and heat treatment. The

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate Tensile Strength MPa (ksi)</th>
<th>Yield Strength (psi)</th>
<th>Elongation (%)</th>
<th>Reduction in Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP Ti</td>
<td>517 (75)</td>
<td>414 (60)</td>
<td>24</td>
<td>46</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>951 (138)</td>
<td>862 (125)</td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>Alloy 1</td>
<td>910 (132)</td>
<td>855 (124)</td>
<td>27</td>
<td>58</td>
</tr>
<tr>
<td>Alloy 2</td>
<td>951 (138)</td>
<td>862 (125)</td>
<td>24</td>
<td>46</td>
</tr>
<tr>
<td>Alloy 3</td>
<td>1462 (212)</td>
<td>1351 (196)</td>
<td>5</td>
<td>24</td>
</tr>
</tbody>
</table>

‡ Ti has a density of 4.5 g/cm³ and melts at 1670˚C while Ta has a density of 16.6 g/cm³ and melts at 3020˚C
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Applications for tungsten-containing materials include medical implants, munitions, ballistic armour and automotive powertrain components. Examples of products under development for various Abkolloy materials are shown in Figures 7 and 8 below.

Commercial products

Shot sleeve liners for aluminium die castings

One of the most successful applications of CermeTi® is as shot sleeve liners for aluminium die-casting. In aluminium die-casting, molten aluminium is forced under high pressure into a die cavity through a shot sleeve. A “shot” of molten aluminium is laddled into the shot sleeve typically made from H-13 tool steel. A plunger then forces the shot of molten aluminium through the shot sleeve into the die cavity. Shot sleeves are subject to severe conditions and must be higher strength than annealed Ti-6Al-4V with similar ductility. Alloy 3 reaches yield strength levels on the order of 1350 MPa (200ksi) with useful (5%) ductility. The W-containing alloys also have improved wear resistance and high temperature strength compared with Ti-6Al-4V. These properties continue to be investigated.

** This application earned the 2002 Grand Prize in Advanced Particulate Materials at the International P/M Design Competition sponsored by the Metal Powder Industries Foundation.
Artificial articulating replacement disc

The wear resistance of CermeTi® is far superior to that of commercial titanium alloys. This material combines high wear resistance with the excellent imaging characteristics of titanium. This permits titanium to be used for metal-on-metal wear surfaces. This material is being used by a major medical device manufacturer for an artificial cervical disc eliminating the less desirable use of steel. The use of steel is less desirable due to its poor imaging characteristics, making X-ray difficult to read and causing distortion in MRI or CT scans. The device is in commercial use outside of the United States and is undergoing clinical trials in the US.

Automotive components

Dynamet has recently been awarded a National Science Foundation Phase I SBIR grant [4] to demonstrate the technical and economic viability of its Ti alloy and MMCs for lightweight titanium pow-ertrain components. The use of advanced titanium-based metal matrix composite materials can significantly improve automo-tive fuel efficiency and reduce greenhouse gas emissions. Reduction in vehicle weight results from the substitution of lighter weight titanium for steel and also from the significantly reduced vibration management system needed for reciprocating engines. The major barriers to the adoption of titanium for automobile engine components has been its poor wear resistance and high cost. Through PM processing, titanium components can be produced at lower cost than by conventional methods. Dynamet’s novel alloys and metal matrix composites retain the benefits of titanium (lightweight, high specific strength and corrosion resistance) while overcoming other major barriers to the use of titanium.

The PM near-net shape capability and the good forgeability of Dynamet’s titanium alloy and MMCs has been demonstrated in the manufacture of prototype forged Ti MMCs connecting rods for high-performance automotive engines. Conventional titanium alloys are lighter weight and have less rotating mass than steel but they do not have the desired wear resistance, stiffness, and creep resistance for optimal performance. CermeTi MMC preforms in the as-CIP’d condition, as-sintered condition and an as-forged connecting rod are shown in Figure 11.

PM and aircraft hydraulic tubing

Dynamet’s novel alloys combined with its advanced powder metal technology offer the potential for producing affordable, higher strength, damage resistant, damage tolerant and cold formable tita-nium alloys. These alloys hold promise for producing improved titanium thin-wall high pressure hydraulic tubing that could operate at the higher pressures required for future aircraft.

Aerospace applications

Dynamet has produced and supplied its PM processed Ti-6Al-4V alloy mate-rials to a commercial aerospace manufacturer for extensive property analysis. Results of thousands of data points generated to date show that the static properties of CIP-Sinter and CHIP product data are consistently above the minimum allowable developed for wrought Ti-6Al-4V. Additional information and data was presented at the AeroMat2011 Conference [5]. It is anticipated that this work will soon lead to Dynamet’s PM titanium products being used to substitute for wrought titanium airframe components on commercial aircraft. This is expected to significantly increase the volume of PM titanium product and provide a major breakthrough at the intersection of the titanium industry, the aerospace industry and the powder metal industry.

Affordability and enhanced properties by PM will increase titanium’s competitive position versus other materials, expand the use of titanium and provide a new supply base to meet customers’ increasing demands for titanium product at lower cost and shorter lead-times.

References

[4] NSF SBIR Phase I Grant; Award Number IIP-1045207.

The authors

This feature is based on Affordable PM Titanium – Microstructures, Properties and Products, a paper by S.M. Abkowitz, S. Abkowitz, H. Fisher, and D.H. Main of Dynamet Technology, Inc. Burlington, MA 01803. It was given at PowderMet2011 in San Francisco.