Titanium Powder Metallurgy: A Review – Part 2

Titanium alloys offer improved performance in aerospace and terrestrial systems due to their excellent combinations of specific mechanical properties and outstanding corrosion behavior. However, the high cost of Ti alloys compared to competing materials limits their widespread use. Powder metallurgy (PM) techniques offer the possibility of lowering manufacturing costs. Part 1 of this article (September 2012 AM&P) as well as this second part review some of the developments in powder metallurgy as a cost effective approach to fabrication of titanium components under various aspects of the technology including the blended elemental (BE) approach, prealloyed (PA) methods, additive layer manufacturing (ALM), powder injection molding (PIM), and spray deposition (SD) processing.

Metal-matrix composites

Both continuously and discontinuously reinforced titanium components have been produced using PM approaches. Figure 1 shows a finished titanium metal-matrix composite (MMC) ring for spin pit testing fabricated by IMT Bodycote (Andover, Mass.) from HIP-densified plasma spray tapes. Dynamet Technologies Inc. (Burlington, Mass.) uses the blended elemental technique to fabricate MMCs using particulate and combined cold and hot isostatic pressing (CHIP) combination, or forging, extrusion, and rolling of the CHIP perform[1]. The CermeTi family of titanium alloy matrix composites incorporates TiC and TiB2 particulate ceramic TiAl intermetallic as reinforcements with minimal particle/matrix interaction. Table 1 compares the mechanical properties of CermeTi material with PM Ti-6Al-4V[1]. Dynamet made seven-layer armor and dual-hardness gears of CermeTi material.

Prealloyed approach

This method uses prealloyed powder (generally spherical in shape) produced by melting, either by plasma rotating electrode processing (PREP), plasma (either atomization or spheroidization), or gas atomization (GA), followed by hot consolidation typically by hot isostatic pressing[2]. Mechanical properties are superior to ingot material (because of the refined microstructure and lack of directionality). Powders contained a metal can (with metal inserts) or ceramic mold (sealed in a can filled with a secondary pressing media) are compacted by hot isostatic processing. The advantage of using the near-net shape PM approach for difficult to process alloys such as intermetallic Ti-Al type compositions has been recognized[3-5].

No parts are currently being produced using the ceramic mold process partly because of concerns that ceramic particles could get into the fabricated titanium parts. However, Figs. 2 and 3 show parts produced using a shaped metal can and removable mild steel inserts (removed by chemical dissolution) are production ready[6].

Despite the 30-35% volume shrinkage typical for HIPed PA powders, advanced process modeling allows “net surfaces” to be achieved with minimal machining stock on the near-net surfaces. Near-net-shape titanium parts can be made up to the size of existing HIP furnaces (up to 2 m), considerably larger than the capabilities of other technologies discussed in this article. Parts exhibit mechanical properties superior to those of conventional cast and wrought (ingot metallurgy) components (Fig. 4). Minimum values (used in design) for PM mate-

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<th>TABLE 1 — TYPICAL PROPERTIES OF CERMETI AND TI-6AL-4V</th>
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<td>Ultimate tensile strength, MPa (ksi)</td>
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<td>Ti-6Al-4V PM</td>
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<td>CermeTi-C MMC (Ti-64+TiC)</td>
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rial are greater than those for conventionally fabricated material\[4\]. Fracture toughness (KIC) of the PM product is superior to cast and wrought material (92.5-96.5 versus 55 MNm\(^{3/2}\)); data courtesy of Dr. Wayne Voice, Rolls-Royce, UK).

**Additive layer manufacturing**

In this approach, powder is laid down in successive layers and melted under the control of a computer to produce virtually any shape (Fig. 5). ALM Ti-6Al-4V has a tensile strength of 160 ksi (1104 MPa) with 5 to 6% elongation “as-formed,” and 140 ksi (965 MPa) after HIP with 15% elongation, properties equivalent to cast and wrought levels (data from B. Dutta, the POM Group Inc., Auburn Hills, Mich.).

S-N fatigue performance of parts made via ALM is equal to or slightly above that of conventional material levels. However, the main issue influencing growth in deployment of ALM for titanium alloys relates to raw material supply. Material cost is a major issue, with material cost typically 40 to 50% of total manufacturing cost for ALM titanium. Material supply chain is an issue for both powder and wire; sustainable sources are not always available, and supplies of certain alloys have limited availability\[7\]. ALM can be used to attach additional part features and can be used in part repair\[7\].

**Powder injection molding**

Metal powder-injection molding is based on injection molding of plastics; the process was developed for long production runs of small (normally <400 g) complex shaped titanium parts in a cost-effective manner. The technique involves melting and pelletization of a titanium powder-binder mixture that is injected into a die. The binder is chemically/thermally removed, and the part is sintered (Fig. 6)\[8-9\]. The method enables fabricating components with good mechanical properties provided the chemistry (particularly oxygen) is controlled\[10-11\]. Typical shapes are shown in Fig. 7. Incorporating a porous layer on the surface of body implant parts cause bone ingrowth and improved bonding between the implant and bone\[12\]. Currently, titanium PIM parts are up
to 1 ft long, but parts over 3 to 4 in. (about 50 g) are not common. Limiting factors are dimensional reproducibility and chemistry.

Worldwide titanium PIM part production is estimated at about 3-5 tons/month\[10\]. Market expansion requires low cost (<$20/lb, or $44/kg) powder of the right size (<40 μm) and good purity (which is maintained throughout the fabrication process). For nonaerospace applications, Ti-6Al-4V alloy purity level can be less stringent; for example, the oxygen level can be up to 0.3 wt% while still exhibiting acceptable ductility levels (aerospace requires a maximum oxygen level of 0.2 wt%\[13\]).

Oxygen levels can be even higher for CP grades (up to at least 0.4 wt%). Grade 4 CP titanium has a specification limit of 0.4 wt%\[13\]. While the ultimate tensile strength of Grade 4 CP titanium (80 ksi, or 550 MPa) is lower than that of regular Ti-6Al-4V (135 ksi, or 930 MPa), it may well be a better choice for many potential PIM parts where cost is of great concern. Grade 4 enables using a lower cost starting stock and a higher oxygen content in the final part. In the future, beta alloys with their inherent good ductility (bcc structure) and intermetallics with attractive elevated temperature capability are potential candidates for fabrication via PIM. The science, technology, and cost of Ti PIM appear to be ready for significant growth.

**Spray forming**

This technique can involve either molten metal\[14\] or solid powder. The challenges associated with molten metal spraying of titanium are considerable because of its very high reactivity. However, both spray forming in an inert environment and under reactive conditions were achieved using appropriately designed equipment\[15\]. A segmented cold-wall crucible combined with induction heating and an induction-heated graphite nozzle was used to produce a stream of molten metal suitable for either atomization, to produce powder, or spray forming.

There is increased interest in cold spray forming involving solid powder particles\[16\]. Cold spray (<500°C) can produce both monolithic “chunky” shapes and coated components. In the process, solid powder is introduced into a deLaval-type nozzle and expanded to achieve supersonic flow. The density of the sprayed region is less than full density, but can be increased to 100% density by a subsequent HIP. Examples of cold sprayed parts are shown in Fig. 8. The technique is also very useful to bond together normally difficult-to-bond metals such as titanium and steel.

**Future considerations**

Over the past 30 years, a great deal of money (much of it from federal funding), was spent in attempting to circumvent the high cost of titanium components for aerospace and terrestrial applications. However, despite successes with lower integrity BE parts and recent advances in PIM, the overall market is small; perhaps 20,000 lb total per year worldwide.

However, a variety of high-quality, low-cost powders should be available soon. A number of developments should lead to reasonable growth of products produced using PM. Three areas where significant growth can occur are small parts (<1 lb) by PIM, larger parts using BE and PA techniques, and larger parts using additive layer manufacturing.

Blended elemental applications are likely to grow especially with innovative approaches such as use of hydrogenated powder to produce uniform high densities\[17,18\] including large armored vehicle parts (Fig. 9).

Barriers to overcome using the PA approach are competition with critical components produced by “tried and true” cast-and-wrought or direct casting approaches. Recent developments suggest that immediate applications for PA titanium is in complex parts, very difficult to fabricate TiAl intermetallic alloys, and in metal matrix composites\[3,4\]. Additive layer manufacturing should also see significant growth in competition with the BE and PA techniques.

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References

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