Developments in Titanium P/M

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ABSTRACT
Recently there has been renewed interest in titanium powder metallurgy (P/M) as a cost-effective way of fabricating components from this expensive metal. In this paper, titanium P/M is reviewed dividing the technology into the categories of laserforming, powder injection molding, spraying, near net shapes (blended elemental and prealloyed), metal matrix composites, and far from equilibrium processing (rapid solidification, mechanical alloying and vapor deposition). It is proposed that with the availability of cost-affordable powders, and advances in fabrication techniques, the powder injection molding and blended elemental approaches in particular should see significant growth.

INTRODUCTION
Titanium alloys are amongst the most important of the advanced materials which are key to improved performance in aerospace and terrestrial systems (1,2). This is because of the excellent combinations of specific mechanical properties (properties normalized by density) and outstanding corrosion behavior [3-8] exhibited by titanium alloys. However, negating widespread use is the high cost of titanium alloys compared to competing materials. This has led to numerous investigation of various potentially lower cost processes [3], including powder metallurgy (P/M) techniques [3-7, 9, 10]. The titanium P/M scenario will be reviewed dividing the various technologies into the categories shown in Table I. An indication of where P/M fits into the broad scenario of fabrication techniques is shown in Figure 1.
Figure 1. Diagram showing where powder metallurgy (P/M) in general and powder injection molding (PIM) in particular, fit in with other fabrication processes. (Courtesy of Krebsôge, Radevormwald).

<table>
<thead>
<tr>
<th>Category</th>
<th>Features</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lasforming</td>
<td>Powder feed melted with a laser</td>
<td>Pilot Production</td>
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<tr>
<td>Powder Injection Molding</td>
<td>Use of a binder to produce complex small parts</td>
<td>Production</td>
</tr>
<tr>
<td>Spraying</td>
<td>Solid or potentially liquid</td>
<td>Research Base</td>
</tr>
<tr>
<td>Near Net Shapes</td>
<td>Prealloyed and blended elemental</td>
<td>Commercial</td>
</tr>
<tr>
<td>Far from Equilibrium Processes</td>
<td>Rapid solidification, mechanical alloying and vapor deposition.</td>
<td>Research Base</td>
</tr>
</tbody>
</table>
TITANIUM POWDER METALLURGY

Powders
Titanium powders which are currently available are shown in Table II. The atomized powders are generally prealloyed and spherical (Figure 2a), while the hydride-dehydride powders which are generally also prealloyed are angular in nature, (Figure 2b) and sponge fines (a by-product of sponge production) are “sponge-like” in nature and contain remnant salt (which prevents achievement of full density and adversely affects weldability) (Figure 2c). A new type of powder produced by a reverse electrolysis process is shown in Figure 2d.

Figure 2a. SEM photomicrograph of a gas atomized prealloyed spherical Ti-6Al-4V (Courtesy of Affinity International)

Figure 2b. SEM photomicrograph of the powder produced from Ti sponge fines.

Figure 2c. Al Ti process sponge.

Figure 2d. SEM photomicrograph of titanium powder produced by the Fray reverse electrolytic process. (Courtesy G. Chen, Cambridge University)
A listing of the titanium powders which are currently available are shown in Table II.

Table II: Titanium Powder Availability

<table>
<thead>
<tr>
<th>ORGANIZATION</th>
<th>TYPE</th>
<th>SIZE ((\mu)m)</th>
<th>PRICE ($/ lb)</th>
<th>MARKET ACTIVITY</th>
<th>GENERAL COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYROGENESIS</td>
<td>Various</td>
<td>-45</td>
<td>~180</td>
<td>Powder available</td>
<td>High quality (low O(_2)) PIM grade is &lt; 45 microns</td>
</tr>
<tr>
<td>(Plasma Atomization)</td>
<td></td>
<td>&gt;45</td>
<td>35-75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STARMET (PREP/REP)</td>
<td>Various</td>
<td>Average 150</td>
<td>50-100</td>
<td>Powder available</td>
<td>Sales of powder &quot;healthy&quot; with increasing PIM inquiries</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-500 +45</td>
<td>~45(6/4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-250</td>
<td>~45</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>-250</td>
<td>155 (1000 lbs)</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>-134</td>
<td>134 (5000 lbs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRUCIBLE RESEARCH (GA)</td>
<td>CP</td>
<td>-45</td>
<td>40-50</td>
<td>1-3 Tons/month</td>
<td>&quot;Tilop&quot; (Ti low oxygen powder) capability to 15 ton/month formerly Osaka Ti</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-150</td>
<td>20-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-250</td>
<td>20-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-250</td>
<td>20-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUMITOMO (ingot drip/GA)</td>
<td>CP</td>
<td>1 to 15</td>
<td>60</td>
<td>R &amp; D Stage</td>
<td>Produced on custom order basis</td>
</tr>
<tr>
<td></td>
<td>6-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TiAl</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MER (Plasma Discharge)</td>
<td>CP</td>
<td>1 to 15</td>
<td>60</td>
<td>R &amp; D Stage</td>
<td>Produced on custom order basis</td>
</tr>
<tr>
<td></td>
<td>Alloys</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Affinity (Gas Atomized)</td>
<td>CP</td>
<td>Various size fractions from – 230 to +43</td>
<td>20-48</td>
<td>Powder available with O(_2), Fe lower than ASTM, B-265 requirement</td>
<td>Containerless process 200MT/year capability 1000MT in 2001</td>
</tr>
<tr>
<td></td>
<td>6-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Affinity (Hydride-Dehydride)</td>
<td>CP</td>
<td>Various size fractions from -140 to +25</td>
<td>8-12</td>
<td>R &amp; D Stage</td>
<td>Low O(_2) 200mt/year capability</td>
</tr>
<tr>
<td>Metamorphic Metals Ltd.</td>
<td>CP Ti,</td>
<td>-250</td>
<td>20-50</td>
<td>Capacity @ 2 ton/month Custom lots/blends and low O(_2) powders available</td>
<td>Focus is on the development of new applications for P/S and PIM technology</td>
</tr>
<tr>
<td>(Hydride-Dehydride)</td>
<td>Ti-3Al-2.5V</td>
<td>Press/Sinter (P/S)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ti-6Al-4V</td>
<td>-74 and -44 for PIM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyper Industries (Hydride)</td>
<td>6-4</td>
<td>-200</td>
<td>20-25</td>
<td>Powder available</td>
<td>Produced on order basis</td>
</tr>
<tr>
<td>ADMA Chips (Hydride-Dehydride)</td>
<td>CP</td>
<td>-45</td>
<td>10</td>
<td>Samples available</td>
<td>Samples available</td>
</tr>
<tr>
<td>ADMA Fines</td>
<td>CP</td>
<td>-45</td>
<td>10</td>
<td>Powder available</td>
<td>Samples available</td>
</tr>
<tr>
<td>Reading Alloys (Hydride-Dehydride)</td>
<td>CP -300 + 50</td>
<td>20-50</td>
<td>20-50</td>
<td>Powder available</td>
<td>Powder available</td>
</tr>
<tr>
<td>Fray (Reverse Electrolytic)</td>
<td>Various</td>
<td>To be defined</td>
<td>To be defined</td>
<td>Research base</td>
<td>Oxygen 0.3wt % max. - Angular Oxygen 0.25wt % max. – Angular</td>
</tr>
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</table>

1. Further details on any of these powders can be obtained by contacting the company indicated directly.
2. The powder passing through a mesh is designated by a – sign and that retained by a + sign.
Laserforming
AeroMet Corporation’s Lasform technique (Figure 3a & Figure 3b) features shorter lead times and greatly reduced buy-to-fly ratios (minimal machining required). This P/M fabrication approach is being studied by Boeing to produce large 10 foot x 3 foot substrates, which would then be built-up (11).

Figure 3a. Schematic of the Lasforming System (Courtesy AeroMet Corp.).

Figure 3b. Examples of Lasform Shapes. (Courtesy AeroMet Corp.)
Powder Injection Molding
Metal powder injection molding (PIM) is based upon the injection molding of plastics, a process developed for long production runs of small (normally below 400 gm.) complex shaped parts in a cost-effective manner. By increasing the metal (or ceramic) particle content, the process evolved into a process for production of high density metal, intermetallic or ceramic components (Figure 4) [12,13].

Figure 4. Schematic of the steps involved in powder injection molding, in which a polymer binder and metal powder are mixed to form the feedstock which is molded, debound and sintered. The process relies on the thermoplastic binder for shaping at a moderately elevated temperature of about 150ºC [12,13].

The majority of the early work on developing a viable titanium PIM process was plagued by the unavailability of suitable powder, inadequate protection of the titanium during elevated temperature processing and less than optimum binders for a material as reactive as titanium [13]. However, some PIM practitioners have now learned what the titanium community has long known – that titanium is the universal solvent and must be treated accordingly [4-8, 14].

Titanium has a high capacity to readily form interstitial solutions with a wide range of commonly encountered elements including carbon, oxygen, and nitrogen, which has presented several challenges for titanium PIM development efforts. These interstitial solutions are undesirable since they significantly degrade the ductility of sintered titanium PIM parts. Therefore, it is advantageous to use a binder, which can be completely removed from the green PIM part without leaving these detrimental impurities behind. This is particularly true when fabricating structural aerospace and medical implant parts, which can require oxygen impurity levels below 300 ppm to meet ASTM F 167 Standards.
Unfortunately, unlike conventional ceramic and ferrous alloy PIM processing, there is a significantly narrower processing window between the debinding cycle and the temperature where impurity diffusion becomes significant within titanium. In general this requires that the Ti PIM binder be essentially removed from the green part at temperatures typically below 260°C to prevent introducing impurities into the sintered parts. Additionally, the binder must exhibit high chemical stability and not undergo catalytic decomposition in the presence of titanium metal powder surfaces during molding operations, even when held for long isothermal holds within the injection molding machine.

Attempts to adapt conventional ceramic and metal PIM binder systems for titanium processing have met with limited success. This is due to the fact that these systems often employ significant amounts of thermoplastic polymer within their formulations. Unfortunately, even some of the more well known polymer binders known for their ability to readily thermally unzip to their starting monomers (e.g. polymethylmethacrylate, polypropylene carbonate, poly-α-methylstyrene) still tend to introduce impurities into the sintered Ti PIM bodies because their depolymerization occurs close to those temperatures where impurity uptake initiates. Alternative binder systems based upon catalytic decomposition of polyacetals are promising but require expensive capital equipment to handle the acid vapor catalyst as well as suitable means of eliminating the formaldehyde oligomers that form as polymer decomposition by-products. However, there are a number of binder systems which appear to have the necessary characteristics to be compatible with titanium (14).

Currently titanium PIM parts run up to a foot in length, but parts over three or four inches (about 50 gm in weight) are not common. The limiting factors at this time are dimensional reproducibility and chemistry. Due to the shrinkage, large parts become dimensionally more difficult to make due to loss of shape during shrinkage. If the parts have flat surfaces to rest on the setter they come out fairly consistently. But parts with multiple surfaces that require setters in complex shapes become less practical as the size goes up. Further, large overhanging areas become difficult to control dimensionally due to gravity. With increasing experience, the packing density of titanium powder mixes will be increased, especially with new binders become available and the shrinkage can be decreased making the dimensional problems less of a factor. Typical parts produced by Titanium Products Inc. are shown in Figure 5 & 6.

![Figure 5. Titanium PIM knife handles.](Gr. 4 Titanium MIM Knife Handles. 9.6cm long, weighing 33g. Photo courtesy Titanium Products Inc.)

![Figure 6. Titanium PIM Parts. 7cm long, weighing 8g. Photo courtesy Titanium Products Inc.](Gr. 4 Titanium MIM Parts. 7cm long, weighing 8g. Photo courtesy Titanium Products Inc.)
The current estimate is that the world-wide titanium PIM part production is currently at about the 3 to 5 ton per month level. This market is poised for expansion. What is needed is low cost (less than $20/lb or $44/kg) powder of the right size (less than about 40 microns) and good purity (which is maintained throughout the fabrication process). For non-aerospace applications, the purity level of the Ti-6Al-4V alloy can be less stringent; for example, the oxygen level can be up to 0.3 wt% while still exhibiting acceptable ductility levels (the aerospace requires a maximum oxygen level of 0.2 wt% [8]). For the CP grades, oxygen levels can be even higher; up to at least 0.4 wt.% (Grade 4 CP titanium has a spec. limit of 0.4 wt% [8]). In fact, the Grade 4 CP titanium (UTS 550 MPa [80 ksi]) while lower strength than regular Ti-6AL-4V (UTS 930 MPa [135 ksi]) may well be a better choice for many potential PIM parts where cost is of great concern. The Grade 4 would allow use of a lower cost starting stock and a higher oxygen content in the final part. Further into the future, the beta alloys with their inherent good ductility (bcc structure) and the intermetallics with attractive elevated temperature capability are potential candidates for fabrication via PIM. The science, technology and cost (Table II) now seem to be in the market for titanium PIM to show significant growth.

Spraying
Spray forming can involve either molten metal [15] or solid powder. Because of its very high reactivity the challenges associated with molten metal spraying of titanium are quite considerable. However, both spray forming in an inert environment and under reactive conditions have been achieved with appropriately designed equipment (10). 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 (Fig. 7).

Recently there has been increased interest in cold spray forming involving solid powder particles [16]. In this process, solid powder is introduced into a deLaval-type nozzle and expanded to achieve supersonic flow (Figure 8). Powders are in the range of 1-50μm, at relative low temperatures (<500°C) with a velocity in the range of 300-1,200 m/s. Both monolithic “chunky” shapes and coated components can be produced (Figure 9); and the coatings can be applied even to the inside of tubular components. The density of the sprayed region is less than full density, but this can be increased to 100% density by a subsequent HIP’ing operation.

![Figure 7. (a) Cold-wall induction bottom-pour (CWIBP) crucible installed in a plasma cold hearth furnace, (b) Schematic of the CWIBP system.](image-url)
Fig. 8. Temperature/velocity regimes for common thermal spray processes compared to temperature and velocity in the cold spray technology.

Figure 9. Examples of cold-gas sprayed articles (top) monolithic shapes and (bottom) coated materials of a variety of shapes.
This technique is also very useful in bonding together normally difficult to bond metals such as titanium and steel (Figure 10).

**Figure 10.** Optical photomicrograph showing the excellent bonding of titanium to steel (Courtesy Ktech).

**Near Net Shapes**
Aside from PIM, many of the techniques generally available for production of near net shapes (NNS) are amenable for use with various types of titanium powders; these include conventional press-and-sinter, elastomeric bag cold isostatic pressing (CIP’ing), and ceramic mold or metal can hot isostatic pressing (HIP’ing). For convenience, NNS will be divided into those produced using blended elemental (BE) powders and those produced from prealloyed (PA) powders.

**Blended Elemental:**
The blended elemental approach is potentially the lowest cost titanium P/M process, especially if any secondary compaction step (e.g. HIP’ing) can be avoided (17). In the BE approach, sponge fines and master alloy, generally the 60:40 Al:V variety to produce the Ti-6Al-4V composition, are blended together, pressed and sintered to near full density.

Examples of how the BE approach has been used to produce valves for production models, the Toyota Altezza family automobile, golf club heads, and softball bats are shown in Figures 11-13 respectively.
Figure 11. The Toyota Altezza, 1998 Japanese Car of the Year, the first family automobile in the world to feature titanium valves. Ti-6Al-4V intake valve (left) and TiB/Ti-Al-Zr-Sn-Nb-Mo-Si exhaust valve (right). (Courtesy Toyota Central R & D Labs, Inc.).

Figure 12. Titanium metal matrix composite golf club head (reinforced with TiB). (Courtesy Toyota Central R & D Labs, Inc.).

Figure 13. Susan Abkowitz of Dynamet Technology, Inc. holds a softball bat with a powder metallurgy titanium alloy outer shell.
A very recent development using the BE approach has been the achievement of close to 100% density, using a simple cost-effective press-and-sinter technique, in complex parts (17). In this work, hydrided powder was utilized along with 60:40 Al:V master alloy to produce components comprised of the Ti-6Al-4V alloy. The press-and-sinter densities achieved using this novel fabrication technique are shown in Figure 14. The associated microstructure and typical mechanical properties are shown in Figure 15 and Table III respectively. The mechanical properties compare well with those exhibited by cast-and-wrought product. The low cost of this process in combination with the attractive mechanical properties make this approach well suited to the cost-obsessed automobile industry. Already the parts shown in Figure 16 have been fabricated, and a cost estimate of less than $3.00 for an 0.32kg (0.705lb)gm connection link has been made (18).

Table I. Tensile Properties * of a Ti-6Al-4V Compact Produced from Hydrogenated Powder

<table>
<thead>
<tr>
<th>Molding Pressure, MPa</th>
<th>Relative density, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>84</td>
</tr>
<tr>
<td>400</td>
<td>86</td>
</tr>
<tr>
<td>500</td>
<td>88</td>
</tr>
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<td>600</td>
<td>90</td>
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<td>700</td>
<td>92</td>
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<td>800</td>
<td>94</td>
</tr>
<tr>
<td>900</td>
<td>96</td>
</tr>
<tr>
<td>1000</td>
<td>98</td>
</tr>
</tbody>
</table>

*after dehydrogenation
Figure 16. Ti-6Al-4V parts produced using a press-and-sinter approach and titanium hydride: 1) Connecting rod with big end cap, 2) Saddles of inlet and exhaust valves, 3) Plate of valve spring, 4) Driving pulley of distributing shaft, 5) Roller of strap tension gear, 6) Screw nut, 7) Embedding filter, fuel pump, and 8) Embedding filter (Courtesy Ukraine Academy of Science).

A comparison of the S-N fatigue behavior of BE and prealloyed material with cast-and-wrought product is shown in Figure 17.

Figure 17. Fatigue data scatterbands of conventional BE, low chloride BE, treated low chloride BE, and PA, compared with wrought annealed material.
Prealloy:
The PA approach involves use of prealloyed powder, generally spherical in shape which has been produced by melting, either by a technique such as the plasma rotating electrode processing (PREP) or gas atomization (GA).

Powders are poured into either a metal can or ceramic mold and sealed in a can filled with a secondary pressing media, and compacted in a hot isostatic processing (HIP’ing) unit.

The mechanical properties of PA compacts, for example the Ti-6Al-4V alloy, are at cast and wrought (ingot metallurgy) levels, including fatigue behavior, Figure 17.

The PA approach has been used to produce large and complex parts such as the impeller and arrestor hook support fitting shown in Figure 18.

Figure 18. Ti-6Al-4V components produced from prealloyed Ti-6Al-4V powder, using HIP’ing and the ceramic mold process; (a) a nacelle frame for F14A Ti-6Al-6V-2Sn, (b) radial impeller for F107 cruise missile engine Ti-6Al-4V. (Courtesy Crucible Materials Corporation).
More recently, the advantage to be gained by the near net shape P/M approach for difficult to process alloys such as the intermetallic Ti-Al-type compositions has been recognized [19,20]. Components produced from this type of alloy include the shapes shown in Figure 19. The shapes are demonstration parts, the links, which demonstrate the amenability of the process to production of composite concepts, are actually in production. Another item produced from gamma-material is sheet produced from powder via a pack-rolling approach [21], which has been produced for systems such as the X series of NASA vehicles (Figure 20).

Figure 19. (Left photo) (left to right) Gamma titanium aluminide shapes made using prealloyed gas atomized powder followed by HIP’ing, (a) billet for subsequent forging, (b) forging or to be machined, (c) a near net sonic shape for an engine application and (right photo) Exhaust nozzle compression links for the F110 engine (power system for the F-16 Falcon), consisting of continuous SiC fibers in a Ti-6Al-2Sn-4Zr-2Mo matrix [20].

Figure 20. P/M Titanium Aluminide Sheet (Courtesy Plansee Aktiengesellschaft).

**Metal Matrix Composites**

Both continuously and discontinuously reinforced titanium components have been produced using P/M approaches. Figure 21 shows a finished titanium MMC ring for spin pit testing fabricated from HIP densified plasma sprayed tapes (Courtesy IMT-Bodycote).
The blended elemental technique has also been used for fabrication of MMCs utilizing particulate and a combined cold and hot isostatic pressing (CHIP) combination or forging, extrusion and rolling of the CHIP preform [26, 179-181]. The CermeTi family of titanium alloy matrix composites incorporates particulate ceramic (TiC or TiB2) (Fig. 30) or intermetallic (TiAl) as a reinforcement with minimal particle/matrix interaction. Seven layer armor and a dual hardness gear have been made from CermeTi material.

Figure 22. Microstructure of CermeTi material, TiC reinforcement.(Courtesy Dynamet Technology Inc.)

Research Based Processes
Rapid solidification (RS), mechanical alloying (MA) and vapor deposition (VD) all fall in the category of “far from equilibrium processes” [10]. Novel constitutional (such as extension of solubility levels) and microstructural (in particular microstructural refinement and production of very stable dispersions of second phase particles) effects can be obtained by all three processes, however commercial processes are not on the near horizon.
An example of the fine dispersion of second phase particles which can be obtained by RS is shown in Figure 23a and nanograined material produced by MA in Figure 23b. These nanograins show surprisingly good stability on exposure to elevated temperatures [22], especially when yttria particles are dispersed throughout the matrix [23].

![Figure 23. Titanium aluminide intermetallic alloys exhibiting (a) a fine dispersion of second phase erbia particles (Ti3Al based alloy) and (b) nanograins after HIP’ing at the temperatures indicated (TiAl based alloy).](image)

The VD approach can be used to alloy together normally virtually immiscible Mg with Ti to create low density alloys akin to Al-Li alloys, and fabricate layered structures at the nano-level (Figure 24).

![Figure 24. Schematic cross section of rotating collector used in vapor deposition of layered nanostructured materials (top left) (A: rotating collector, B: shutter, C: crucible, D: heater, and E: radiation screen box) increase in hardness with decreasing layer spacing (bottom left), and layered nanostructured consisting of layers of Al and Fe (top right).](image)
Also, currently in the research base are thermohydrogen processing (THP) and porous structures [10]. By intentionally adding hydrogen to a titanium alloy such as Ti-6Al-4V with a normal P/M microstructure, the microstructure can be refined in the dehydrogenated conditions (Figure 25) with an enhancement in mechanical properties [10].

A novel type of porous low density titanium alloy can be produced by HIP consolidation of alloy powder in the presence of an inert gas such as argon (Fig. 26). The tensile strength decreases in a linear manner as the porosity level increases, following the “rule of mixtures” relationship at least up to 30% porosity level. This material exhibited excellent damping characteristics suggesting a generic area of application.

Figure 25. (a) Pseudo binary phase diagram for Ti-6Al-4V. X represents the hydride phase and CST (Constitutional Solution Treatment) is one possible thermohydrogen processing treatment, and (b) refinement of the microstructure of Ti-6Al-4V powder compact using the thermochemical processing technique, (left) as HIP’d coarse alpha laths, (center) hydrogenated then compacted, (right) hydrogenated in compacted state. The latter two conditions are after dehydrogenation, both showing a refined alpha microstructure, (center) equiaxed grains, (right) fine alpha laths.
Figure 26. (a) Optical micrograph of pores in HIP’d Ti-6Al-4V containing argon after annealing at 700°C (1290°F), and (b) SEM of sample containing up to 40% porosity after an anneal in excess of 1000°C (1830°F).

Porous structures with potential use in honeycomb structures or in sound attenuating or firewall applications are now possible with very precisely controlled porosity levels and architecture using a novel blended metal-plastic approach. (Figure 27) [24].

A       B

Figure 27. Micrographs of foams produced by die compaction (A) and extrusion (B) A - cross-section is perpendicular to the compaction direction; B – cross-section is parallel to the extrusion direction [21].

Future Thoughts
Over the past 30 years, a great deal of money, much of it from US government sources, has been spent in attempting to circumvent the high cost of titanium components for aerospace and terrestrial applications. However, despite a few successes with lower integrity, BE parts and recent advances in PIM the overall market is small; in total perhaps 20,000 pounds per year maximum world-wide.

However, Table II indicates that a variety of high quality, low cost powders are now available. These have also been a number of developments, which should lead to a reasonable growth of products produced by the P/M method. There appear to be two areas where significant growth
can occur: small parts by PIM, and automobile parts by the BE technique. Early entrants to the PIM market place naively largely ignored what every good titanium metallurgist knows – that titanium is the universal solvent. Hopefully this fact is clear to current titanium PIM practitioners, and growth should be healthy in this area.

Blended elemental applications are likely to grown especially with innovative approaches such as use of hydrogenated powder to produce uniformly high densities (17) and the loose sintering to produce components including armored vehicle parts, (Figure 28).

Figure 28. Armored vehicle component produced using the “loose sintering” approach (Bradley Fighting Vehicle Hatch).

There are larger barriers to overcome using the PA approach here products are higher integrity, but also higher cost that BE or PIM components. The competition here is with critical components produced by the (“tried and true”) cast-and-wrought or direct casting approach [25]. Recent developments suggest that immediate applications for PA titanium is in the very difficult to fabricate TiAl intermetallic alloys and in metal matrix composite concepts [19, 20].

The research-based techniques mentioned in this paper all show promise, but have yet to approach commercial fruition.

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