ABSTRACT

Because of its high strength to weight ratio, titanium is a desirable material for automotive applications. Titanium is particularly useful in reducing fuel consumption by lowering the reciprocating mass of moving parts such as connecting rods, turbine wheels, gears, sprockets, cams and valve train components. Titanium brake rotors have also been found to significantly reduce reciprocating mass as well as overall vehicle weight. Titanium usage for static components such as brackets, seat belt buckles and lug nuts could also help improve fuel economy by reducing vehicle weight without a strength penalty. Powder metal (PM) parts have a long history in the automotive industry. In fact, over 90% of engine connecting rods are made from ferrous powder alloys using the press and sinter process. While titanium has proven to improve engine efficiency, it is viewed as too expensive to replace heavier ferrous alloys. This paper discusses opportunities for replacing ferrous alloys with low cost titanium parts for automotive applications made by the press and sinter process.
I. TITANIUM POWDER PRODUCTION

Because of its affinity for hydrogen, titanium metal can be heated in the presence of hydrogen to form TiH$_2$. This compound is quite brittle making it easy to crush into powder. The resulting powder can be converted back to its original form by removing the hydrogen in a vacuum chamber. The process, commonly known as Hydride-Dehydride (HDH) is a relatively low cost method for making titanium powder from elemental titanium (sponge) or wrought form. Other methods such as plasma rotating electrode process (PREP), titanium gas atomization (TGA) or plasma atomization (PA) require more expensive feedstocks and are not as cost effective for automotive applications.

Titanium Blended Elemental (BE) - Commercially pure (CP) powders can be used directly or blended with other metallic elements to form alloys. Typical particle sizes range from 20um to 250um.

Titanium Pre-Alloyed (PA) – Alloy powders can be made directly from various forms of wrought feedstock such as processed and cleaned sheet, plate, bar or billet. Chemistries can be tightly controlled and alloy powders conforming to most ASTM specifications are readily available.

Titanium Sponge Fines (SF) - In its elemental form, titanium has a “sponge” like morphology. Sponge particles larger than 250um, referred to as “sponge fines” can be compacted into simple shapes without going through the HDH process. The cost of this feedstock is significantly less than that made by HDH. For larger automotive applications, net shapes made from titanium sponge fines can be quite economical.

II. PRESS AND SINTER PROCESS

In this process, metal powder is fed into a die and compacted into shapes under high pressure. In most cases, the powder is mixed with an organic lubricant to eliminate die wear. Shapes must be simple enough to allow ease of removal from the die without moving slides or cores. The resulting “green” part can be handled like a solid metal part then sintered at elevated temperature to vaporize the lubricant and form a metallurgical bond between the particles. A fully sintered shape can achieve 80 - 90% density with strength levels similar to solid billet or bar. Sintered shapes are fully machineable and can conform to very tight dimensional tolerances.

III. TITANIUM PRESS AND SINTER

Titanium powder or sponge fines can be pressed into shapes similar to other metal powders with or without lubricant. Because titanium is a reactive metal, caution must be taken to prevent flashing (burning) during compaction. Often, a shielding gas such as argon is used to create an inert atmosphere and prevent ignition. Otherwise, titanium compaction is similar to that of any other metal powder.

IV. VACUUM SINTERING

As a reactive metal, titanium quickly forms an oxide layer when heated in the presence of oxygen (air). Therefore, sintering of titanium powder compacts must be done in a vacuum at temperatures approaching 2,200°F. This is typically done as a batch process although continuous processing is possible through a series of lock valves that isolate the load/unload chambers from the working zone. Vacuum sintering is the single cost driver that differentiates titanium from its ferrous counterparts.

V. HOT ISOSTATIC PRESSING (HIP)

Further densification of sintered titanium parts can be achieved using Hot Isostatic Pressing (HIP). Titanium has the unique ability to diffusion bond to itself causing internal porosity to heal under isostatic pressure at elevated temperature. Titanium compacted parts can achieve 100% density using HIP after
sinter. By healing subsurface porosity, HIP improves fatigue life and structural strength. Although this is an added cost, HIP provides the assurance necessary to prevent failure of critical components such as connecting rods or other reciprocating parts found in automobiles.

VI. GREEN STRENGTH COMPARISONS

Titanium powder made from sponge by the HDH process has excellent compaction strength. In its pure form, the “sponge like” morphology of titanium powder is quite ductile. As a result, very high green strengths approaching 85% can be achieved. Particle size, compaction pressure and lubrication all play a part in the integrity of a compacted shape. Green density is important in achieving minimal porosity during sintering. The higher the initial (green) density, the more effective the sintering process will be to promote diffusion bonding of powder particles.

![Titanium Powder from Sponge using the HDH process](image)

VII. PROPERTIES OF TITANIUM POWDER ALLOYS

The following data shows how titanium PM properties line up with titanium wrought forms and typical properties for PM steels. Note that HIP increases density by healing subsurface porosity resulting in higher strength.

### Sinter Only Properties

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Sintered Density g/cc</th>
<th>% Density</th>
<th>UTS (KSI)</th>
<th>YS (KSI)</th>
<th>%E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gr.4</td>
<td>4.20</td>
<td>93%</td>
<td>74</td>
<td>57</td>
<td>12</td>
</tr>
<tr>
<td>Gr.9 M</td>
<td>4.10</td>
<td>91%</td>
<td>89</td>
<td>75</td>
<td>8</td>
</tr>
<tr>
<td>Gr.4 EHI</td>
<td>4.35</td>
<td>96%</td>
<td>106</td>
<td>95</td>
<td>3</td>
</tr>
</tbody>
</table>
Micrograph: As-Sintered; >90% Density

Sinter/HIP v.s. Wrought Properties

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Condition</th>
<th>% Density</th>
<th>UTS (KSI)</th>
<th>YS (KSI)</th>
<th>%E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gr.4</td>
<td>Sinter/HIP</td>
<td>99%</td>
<td>87</td>
<td>73</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Wrought/Annealed</td>
<td>100%</td>
<td>80</td>
<td>70</td>
<td>15</td>
</tr>
</tbody>
</table>

Sinter/HIP( Fully Dense) Wrought/Annealed
Typical Steel (PM) Properties

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Sintered Density g/cc</th>
<th>% Density</th>
<th>UTS (KSI)</th>
<th>YS (KSI)</th>
<th>%E</th>
</tr>
</thead>
<tbody>
<tr>
<td>P304L</td>
<td>6.80</td>
<td>87%</td>
<td>56</td>
<td>36</td>
<td>5</td>
</tr>
<tr>
<td>P316L</td>
<td>6.83</td>
<td>88%</td>
<td>58</td>
<td>45</td>
<td>6</td>
</tr>
<tr>
<td>P410L</td>
<td>6.67</td>
<td>86%</td>
<td>64</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>P430L</td>
<td>7.65</td>
<td>95%</td>
<td>80</td>
<td>65</td>
<td>6</td>
</tr>
</tbody>
</table>

VIII. COST COMPARISON OF TITANIUM FEEDSTOCKS

Raw material costs for press and sinter parts made from titanium HDH powder or titanium sponge fines compare favorably to that of ferrous alloys. A slight premium is required for titanium over low alloy steels while stainless steel powder is similar to that of titanium HDH powder. HIP adds additional cost whenever full density is required. However, the raw material cost is a minor component of part cost when using titanium HDH powder for press and sinter. Vacuum sintering and HIP remain as the only cost barrier to competing directly with parts made from ferrous materials. For high volume automotive parts where HIP is not required, vacuum sintering cost can be reduced by employing various types of automated vacuum sintering methods readily available in the marketplace.

IX. PARTICLE SIZE EFFECTS

Many automotive parts made by press and sinter are small (<6” length; <1/2: wall thickness). These parts require particle sizes below 250um to achieve maximum packing density in small cavity dies. Whenever a fine surface finish is required, particle sizes below 45um are often used. As parts get larger and thicker (>6” length; >1/2” wall thickness), particle sizes greater than 250um are required to provide better green strength and edge retention. Low cost sponge fines (840-250um) have already been used successfully for large, heavy walled reciprocating automotive components.

X. GREEN MACHINING

Because of the relatively high green density of titanium powder compacts, parts can be CNC machined prior to sintering. Green machining can achieve close tolerances with minimal tool wear. The shrink rate is very low (5 – 6%) for titanium powder parts made by press and sinter. Therefore, critical features machined to the high side of the tolerance in the “green state” will shrink to nominal after sintering.

XI. TOLERANCES

Typical tolerances of +/-0.007 inch per inch can be achieved on titanium press and sintered parts after sintering. For features requiring closer tolerances of +/-0.002 or smaller, post machining will be required after sintering. Whenever possible, the designer should relax tolerances on non-critical features to minimize post machining cost.
XII. APPLICATIONS

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...Research provided by Sam Froes “Developments of Titanium PM”.

XIII. COST COMPARISON OF FINISH PRODUCT

Press and Sinter provides the most cost effective method of production for net shape automotive parts. Considering that low cost titanium PM feedstock is readily available, the challenge for titanium to compete with conventional automotive PM alloys is simply to overcome the perception of high cost. To date, the titanium PM industry has not found a champion willing to validate the use of titanium PM for automotive applications.

GTI has looked at a variety of automotive applications made from its titanium powders. In every case, the GTI cost model showed the ability to meet target pricing for high volume applications in the aftermarket automotive sector. Further research is required to demonstrate our ability to meet target pricing for passenger car applications.

XIV. CONCLUSIONS

With stringent CAFÉ standards looming in 2025, there are many design challenges ahead for the automotive industry. Titanium PM offers solutions for reducing vehicle weight and fuel consumption. Over the past 30 years, automobile manufacturers have challenged the titanium industry to develop low cost alloys. The HDH process provides a cost effective method for making titanium powder at a price point competitive with ferrous alloys. Titanium powder diffusion bonds quite effectively and sinters to densities greater than 90%. High strength or fatigue critical applications that require 100% density are possible using HIP. Economical titanium alloy powders made by blended elemental (BE) or pre-alloyed (PA) feedstock can achieve properties similar to titanium wrought alloys. Green machining of net shapes from a near net powder compacts can further reduce the cost of titanium parts that require close tolerances. Various titanium PM parts have been prototyped for the auto industry but none have yet been used in production. The design advantage of titanium as an engineered material for lightweight vehicle applications is undisputable. In time, the benefits of low cost, press and sintered titanium parts will be fully utilized.
XV. REFERENCES


2011 DOE Hydrogen and Fuel Cells and Vehicle Technologies Programs Annual Merit Review

**Low Cost Titanium –Propulsion Applications**

Curt Lavender - Pacific Northwest National Laboratory
Dr. Yong-ChingChen - Cummins Inc.
Dr. Vladimir Moxson - ADMA Products Inc.