PM Light Alloys

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Outline

- Aluminium PM
  - Processing
  - Materials
  - Properties

- Titanium PM
  - Motivation
  - Powder Production
  - (Near)-Net Shape manufacturing techniques
Aluminium PM

Introduction

- NET SHAPE PART PRODUCTION
- COST EFFECTIVE PROCESSING
- ENERGY AND MATERIAL SAVING
- COMPETITIVE PROCESSING ROUTE

Aluminium PM

- LOW DENSITY (2.7 g/cm³)
- GOOD STRENGTH
- GOOD CORROSION RESISTANT
- HIGH ELECTRICAL AND THERMAL CONDUCTIVITY
- GOOD RECYCLING
Aluminium PM

Advantages by using P/M aluminium in automobiles

**Lightweight construction**
- reduction of the fuel consumption
  (10% weight savings result in 8-10% fuel savings, i.e.
   100 kg weight saving reduces the fuel consumption by 0.6-0.7 l/100 km)
- reduction of the CO₂-emission
- lower inertia and friction losses of rotating masses

**Additional system effects**
- lower efforts for balancing of masses
- reduction of noise and vibration emissions
Aluminium PM

Processes for P/M aluminium

Pressing  Pressing
Dewaxing  Dewaxing
Sintering  (Sintering)

Sizing  Forging

Heat treatment
Finishing

High precision
Al-parts

High performance

Metal melt

Powder/Powder blends

CIP  Spray compaction
(Canning)
Degassing
Hot extrusion
Forging/Rolling

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Aluminium PM

Traditional Manufacturing Process

- Mixing
- Compaction
- Dewaxing and Sintering
- Aging
- Sizing
- Quenching
- Homogenization

Al - 4.4Cu - 0.7Si - 0.5Mg - 1.5Lub

> 90 % density, > 200 MPa strength and > 80 HB hardness,
Aluminium PM

Modified Manufacturing Process

AI - 14Si - 2.5Cu - 0.5Mg - 1.5Lub

>98% density, >250 MPa strength, >130 HB hardness and very good wear resistance,
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The Surface Oxides

Aluminium powders exposed to oxygen are covered by an oxide film spontaneously due to the very high oxygen affinity of aluminium.

- Surface oxides: amorphous oxide layers may be hydrated and contain adsorbed moisture, crystallisation to γ-Al₂O₃ at ~350 °C [Jacobs1972, Shinohara1982, van Beck1984]

- oxide layers are barriers for sintering and prevent the solid state sintering
- liquid phase sintering is also impossible due to poor wettability of Al₂O₃ by most liquid metals
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The Surface Oxides

**Oxidation of aluminium:**

\[
\text{Me} + \text{O}_2 \rightleftharpoons \text{MeO}_2 \\
\Delta G = -RT \ln K_1; K_1 = (p_{O_2})^{-1}
\]

→ the reduction at 600 °C needs a partial pressure \( p_{O_2} < 10^{-50} \) atm!

**Reduction of the aluminium oxide by hydrogen:**

\[
\text{MeO} + \text{H}_2 \rightleftharpoons \text{Me} + \text{H}_2\text{O} \\
\Delta G = -RT \ln K_2; K_2 = p_{H_2O}/ p_{H_2}
\]

→ the reduction at 600 °C needs a dew point < -140 °C \( (<10^{-3} \) ppm H\(_2\)O!)

aluminium cannot be sintered in conventional atmospheres
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The Surface Oxides and the role of magnesium

Partial reduction von $\text{Al}_2\text{O}_3$ by magnesium:
- Spinell formation --> change in volume, crack formation in the oxide layer
- metal-metal contacts facilitate diffusion, wetting and therefore sintering

$4\text{Al}_2\text{O}_3 + 3\text{Mg} \rightarrow 3\text{MgAl}_2\text{O}_4 + 2\text{Al}$
(or $\text{Al}_2\text{O}_3 + 3\text{Mg} \rightarrow 3\text{MgO} + 2\text{Al}$)
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Typical aluminium P/M blend chemistries

1. Pure Al powder (ductile) and pure metal powders or binary Al-X powders 
   \((X=\text{Cu, Mg, Zn, Si})\)
2. Pure Al powder (ductile) and a master-alloy powder (supersolidus sintering !)

<table>
<thead>
<tr>
<th>Alloying element</th>
<th>Influence on sintering and properties</th>
<th>Content in wt.%</th>
</tr>
</thead>
</table>
| Cu               | liquid phase formation \((T_E=548\,^\circ\text{C})\) 
                  precipitation hardening, hot strength | 0,25 - 5       |
| Mg               | reduction of the oxide layers, liquid phase formation \((T_E=437\,^\circ\text{C})\) 
                  solution hardening and precipitation hardening with Si \((\text{Mg}_2\text{Si})\) | 0,2 - 2        |
| Si               | liquid phase formation \((T_E=577\,^\circ\text{C})\), lowering the thermal expansion 
                  increase of the wear resistance \((\text{Si}>7\%)\) | 0,5 - 25       |
| Zn               | liquid phase formation \((T_E=381\,^\circ\text{C}, T_s=419\,^\circ\text{C})\) 
                  precipitation hardening, high-strength alloys | 3 - 8          |
| Fe, Mn, Cr       | low solubilities 
                  stress concentration at precipitations | < 0,2          |
| Sn               | sintering aid during liquid phase sintering 
                  formation of a stationary liquid phase \((T_L(\text{Sn})=232\,^\circ\text{C})\) | 0,01 - 0,3     |
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Typical aluminium P/M blends

AlCu4,5MgSi

AlMg50

AlSi12

Al

Cu

AlSi14Cu2,5Mg

AlSi25CuMg
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Liquid phase sintering of AlSi14CuMg

green density = 92%th.D.

sintered density = 99.5%th.D.

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Aluminium PM

Examples of ready-to-press powder mixtures

<table>
<thead>
<tr>
<th>Trade name</th>
<th>Company</th>
<th>Alloying equivalent</th>
<th>Composition (in weight-%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumix 123</td>
<td>ECKA Granules</td>
<td>2014</td>
<td>Al-4,4Cu-0,7Si-0,5Mg-1,5Lub.</td>
</tr>
<tr>
<td>Alumix 231</td>
<td>ECKA Granules</td>
<td>40XX</td>
<td>Al-14Si-2,5Cu-0,5Mg-1,5Lub.</td>
</tr>
<tr>
<td>Alumix 321</td>
<td>ECKA Granules</td>
<td>6061</td>
<td>Al-1,0Mg-0,5Si-0,2Cu-1,5Lub.</td>
</tr>
<tr>
<td>Alumix 431</td>
<td>ECKA Granules</td>
<td>7075</td>
<td>Al-5,5Zn-1,5Mg-2,0Cu-1,5Lub.</td>
</tr>
<tr>
<td>AMB 2915</td>
<td>AMPAL Inc.</td>
<td>MMC</td>
<td>Al-3,0Cu-0,25Si-1,5Mg-0,6Sn-16%Al₂O₃-Lub.</td>
</tr>
</tbody>
</table>
### Aluminium PM

#### Heat Treatment of Al-Sinter Alloys

<table>
<thead>
<tr>
<th>Suffix</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₁</td>
<td>As-sintered</td>
</tr>
<tr>
<td>T₁a</td>
<td>like T₁, but naturally aged</td>
</tr>
<tr>
<td>T₄</td>
<td>Solution treated at 505-540°C, rapid quenching and naturally aged at room temperature for four days</td>
</tr>
<tr>
<td>T₅</td>
<td>Artificially aged only</td>
</tr>
<tr>
<td>T₆</td>
<td>Same as T₄ plus artificial ageing at elevated temperature 160-170°C for 18hours</td>
</tr>
<tr>
<td>T₈</td>
<td>Solution treated plus cold worked plus artificially aged</td>
</tr>
</tbody>
</table>
## Aluminium PM

### ECKA Alumix® - Mechanical properties

<table>
<thead>
<tr>
<th>Type</th>
<th>Sinter alloy</th>
<th>Compaction pressure (MPa)</th>
<th>Sintered density (g/cm³)</th>
<th>Size alteration (%)</th>
<th>Tensile strength (MPa)</th>
<th>Hardness HB</th>
<th>Elongation A (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>AlCuMgSi</td>
<td>250 400</td>
<td>2.52 2.59</td>
<td>-0.4 -0.2</td>
<td>T₁: 160  T₄: 210  T₆: 320</td>
<td>60 75 100</td>
<td>5 3 1</td>
</tr>
<tr>
<td>321</td>
<td>AlMgSiCu</td>
<td>250 400</td>
<td>2.47 2.51</td>
<td>-0.2 +0.2</td>
<td>T₁: 120  T₆: 230</td>
<td>40 75</td>
<td>5 3</td>
</tr>
<tr>
<td>431*</td>
<td>AlZnMgCu</td>
<td>620</td>
<td>2.8</td>
<td>-2.0</td>
<td>T₁: 270  T₆: 470</td>
<td>100 150</td>
<td>7 1</td>
</tr>
<tr>
<td>231</td>
<td>AlSiCuMg</td>
<td>620</td>
<td>2.67</td>
<td>-2.0</td>
<td>T₁: 240  T₆: 330</td>
<td>100 130</td>
<td>1 0.5</td>
</tr>
</tbody>
</table>

(431* new developed ready-to-press premix based on 7xxx series)
Aluminium PM

Surface quality of AlSi = f (purity of sintering atmosphere)

Nitrogen 5.8
(≤ 3ppm O₂, ≤ 5ppm H₂O)

Nitrogen 6.0
(≤ 0,3ppm O₂, ≤ 0,5ppm H₂O)

Surface porosity

Oxygen

No porosity

(Cross sections of sintered Alumix 231)
Aluminium PM

Role of sintering atmosphere – oxygen impurities

Industrial belt furnace

- Strong pick-up of residual oxygen by the green parts during sintering.

Schematic view of the used belt sinter furnace with a *local oxygen measurement*

Measured development of the local oxygen content of the flowing nitrogen atmosphere in the used belt furnace (“G” marks the passing of green parts).
Aluminium PM

Surface quality of AlSi = f (purity of sintering atmosphere)

- The master alloy produces a **liquid phase with a persistent character and a high sensitivity to oxidation** during sintering.
- Formed **oxide layers hamper locally the sintering process** resulting in porous surface layers with a reduced mechanical and wear behaviour.

Elemental distribution by Auger:

- MgO-formation at particle surfaces

- Sputter depth (nm)

- Atomic concentration (%)
Aluminium PM

Surface quality of AlSi = f (purity of sintering atmosphere)

- No strong oxidation effects at surface

- No segregation of Mg and no superficial porosity in case of purer sintering atmospheres.

(Elemental distribution by Auger)
Aluminium PM

Potential application of P/M sinter aluminium

**Engine components**
- cam shaft bearing cap
- belt pulleys / sprocket
- camphaser
- **conrod** (powder forged)

**Cam shaft bearing caps / GKN Sinter Metals**
28 Mio. parts/year since 1993, using 2014 equivalent in V4/V6 of GM, DC, Ford, Mitsubishi, casting replacement, reduced machining steps

**Suspension (Shock absorber)**
- piston
- rod guides

**Auxiliary equipment**
- oil pump gears
Aluminium PM

Aluminium camphaser in the cylinder head

The first series engine with a complete aluminium designed camphasing system is the BMW NGR6 engine presented at the Aachen Colloquium 2004. **This is the first camphaser with an sprocket, rotor (Alumix 231) and stator made of aluminium.** The weight advantage in comparison to a steel camphaser is about 50%.
Aluminium PM

Aluminium parts for hydraulic application

- The serial G-rotor set from PM steel was compared with a rotor set from PMET AlSi14E alloy
- Test conditions:
  - 2000 rpm
  - 5 bar

- The aluminium rotor set shows at operating temperature about 20% higher volumetric flow in comparison with a steel set
- After the test program up to 5000 rpm during 200 h, no significant wear of Al rotor set could be observed
- The price of an Al rotor set is about 15% higher compared to a steel set
Aluminium PM

Powder Forging Process

Compaction → Delubrication/Sintering → Forging → Quenching → Heat treatment → Secondary operations

AI7075E  Al - 5.5Zn - 2.5Mg - 1.5Cu - 1.5Lub
>99 % density, >500 MPa strength, >150 HB hardness, >2% elongation,
Aluminium PM

Processes for P/M aluminium

- Pressing
- Dewaxing
- Sintering
- Sizing

<table>
<thead>
<tr>
<th>Powder/Powder blends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressing</td>
</tr>
<tr>
<td>Dewaxing</td>
</tr>
<tr>
<td>(Sintering)</td>
</tr>
<tr>
<td>Forging</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Metal melt</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIP</td>
</tr>
<tr>
<td>Spray compaction</td>
</tr>
<tr>
<td>(Canning)</td>
</tr>
<tr>
<td>Degassing</td>
</tr>
<tr>
<td>Hot extrusion</td>
</tr>
<tr>
<td>Forging/Rolling</td>
</tr>
</tbody>
</table>

Heat treatment
Finishing

High precision
Al-parts

High performance
High Performance PM Aluminium

- Increased cooling rates
- Gas atomization
- Melt extraction
- Spray forming
- Melt spinning

Increased cooling rates

$10^7$ K/s
High Performance PM Aluminium

Rapidly solidified aluminium (RSA) fills the gap between conventional aluminium and titanium

780 MPa
620 MPa
High Performance PM Aluminium

Spray Forming
High Performance PM Aluminium

Spray Forming

Improved microstructure

Gravity die casting

Spray forming
High Performance PM Aluminium

Spray Forming

Improved properties

Higher alloying contents can be distributed homogeneously (up to 15wt.-%)

Additional alloying elements (e.g. Sc, Mn, Zr, Cr) can reduce grain growth and contribute to dispersion hardening

\[
\text{Rm} = 791 \text{ MPa}/ \text{R}p0,2 = 783 \text{ MPa}, \text{A5 }= 9,9\% \\
\text{(AA7075:)} \\
\text{Rm} = 572 \text{ MPa}/ \text{R}p0,2 = 513 \text{ MPa}, \text{A5 }=11\%
\]
High Performance PM Aluminium

Rapid Solidification and SPS

Raw materials → Short-time sintering → High-performance parts

Rapid solidification → Spark Plasma Sintering → Hot forging

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High Performance PM Aluminium

Rapid Solidification and SPS

Meltspinning, chopping

Precompaction by SPS

Hot deformation

- **Al-8,7Fe-1,8Si-1,3V (RSA 809)**
- **Al-2,5Fe-5Ni-2,5-1Cu-1Mn-0,8Mo-0,8Zr (RSA 905)** (supplied by RSP Technology, Netherlands)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>Vacuum / nitrogen</td>
</tr>
<tr>
<td>Pressing force</td>
<td>35 kN – 586 kN</td>
</tr>
<tr>
<td>Temperature of degassing</td>
<td>300°C – 400°C</td>
</tr>
<tr>
<td>Temperature of sintering</td>
<td>400°C – 550°C</td>
</tr>
<tr>
<td>Time for sintering</td>
<td>1 min – 30 min</td>
</tr>
<tr>
<td>Current</td>
<td>Pulsed / unpulsed</td>
</tr>
</tbody>
</table>

**Hot forging at 375°C with varied reduction ratio φ (0.6 to 1.0)**
Relative densities:
98%th.d. for RSA 809
100%th.d. for RSA 905
could be achieved at
450° C / 5min / 200MPa

Optical micrographs

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen content in ppm</th>
<th>Oxygen content in ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alloy</strong></td>
<td><strong>RSA 809</strong></td>
<td><strong>RSA 905</strong></td>
</tr>
<tr>
<td>Melt-spun flakes</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td>SPSed materials</td>
<td>17</td>
<td>13</td>
</tr>
</tbody>
</table>

During SPS process a degassing was achieved resulting in reduced hydrogen contents of the pre-compacts.
Although the hardness values of the **SPSed compacts** are comparable with extruded reference materials (HB = 130 of RSA 809 and HB = 200 of RSA 905), the *bending strengths and ductilities are significantly lower* due to some residual porosity and the weakness of the metallic bonding.
Obviously, the most important parameter is the total deformation of the billets during forging. A deformation of about 60% (corresponding to a reduction ratio of 1) are necessary to obtain sufficient ductility of both alloys.
High Performance PM Aluminium

Rapid Solidification and SPS + Extrusion

- Al grains vary in size from 0.2 – 0.3 µm.
- Intermetallics with diameters 100-200 nm
- Bands of coarser and finer microstructures

SEM

TEM
BMW S1000RR:
Valve spring retainer made of P/M aluminum

Advantages:
Mass reduction by about 46% compared to a steel part.
This corresponds to an increase of the revolution speed by 4% corresponding to 560 rpm.
Titanium PM

Introduction

- NET SHAPE PART PRODUCTION
- COST EFFECTIVE PROCESSING
- ENERGY AND MATERIAL SAVING
- COMPETITIVE PROCESSING ROUTE

Introduction:
- high melting point
- high strength
- corrosion resistant
- relatively low density (4.5 g/cm³)
PM Titanium

Worldwide Titanium Market

Aerospace 41%
Commercial 33%
Military 8%

Industrial
47%

New & Emerging 12%

World Shipments

<table>
<thead>
<tr>
<th>Year</th>
<th>Metric tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>48.000</td>
</tr>
<tr>
<td>2003</td>
<td>36.000</td>
</tr>
<tr>
<td>2005</td>
<td>68.500</td>
</tr>
<tr>
<td>2006</td>
<td>70.000</td>
</tr>
<tr>
<td>2010</td>
<td>100.000</td>
</tr>
</tbody>
</table>

Sources: QinetiQ, CPP

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PM Titanium - Why?

Cost of Conventional Titanium Mill Products

The cost of titanium mill products is roughly split between conversion from mineral to alloy ingot and hot working of ingot into finished mill product.

Quelle: Dr. David M. Bowden: Near-Net Shape Fabrication Using Low-Cost Titanium Alloy Powders, Final report, DOE Contract Number EE0003480, Boeing Company
PM Titanium

Why Titanium Powder?

**Powder Potential**
- Reduced component costs
- Near net shape technology
- Reduced material usage
- Reduced processing steps
- Reduced machining operations

**Powder Process Questions**
- What is the cost
- Can the process make alloys
- What are the powder`s characteristics
- Can the powder be consolidated by existing processes
- Can the process provide the purity
- What is the manufacturing capacity
PM Titanium

Powder Production (Gas Atomization)

- „skull melting“ and inert gas atomization
- Spherical powders with good flowability
- Tap density app. 65-70%
- High purity
- 10-20% of atomized powder <45µm
- Cp-Ti, α+β, β-alloys and TiAl
PM Titanium

Powder Production (EIGA)

- Combination of inert gas atomization and crucible free melting
- Electrodes are used as pre-material
- Different qualities available (e.g. grade 1, 2, 5)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Electrode diameter</th>
<th>Melt rate</th>
<th>Spec. gas consumption</th>
<th>Particle-size distribution</th>
<th>Oxygen content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>kg/h</td>
<td>m³/kg at STP</td>
<td>&lt;45 µm %</td>
<td>Electrode ppm</td>
</tr>
<tr>
<td>Ti</td>
<td>50</td>
<td>42</td>
<td>14.3</td>
<td>32</td>
<td>1116</td>
</tr>
<tr>
<td>Ti</td>
<td>40</td>
<td>36</td>
<td>15.3</td>
<td>58</td>
<td>1370</td>
</tr>
<tr>
<td>Ti 6Al 4V</td>
<td>45</td>
<td>23.5</td>
<td>25.3</td>
<td>71</td>
<td>1540</td>
</tr>
</tbody>
</table>

Fig. 2.17. Particle size distribution of EIGA-atomised alloys. Open circles: TiAl; solid circles: cp Ti; open squares: Ti 6Al 4V; solid squares: Zr.
PM Titanium

Powder Production (Plasma Atomization)

- High purity
- Excellent flowability

http://www.raymor.com/apc/processes/plasma/
# PM Titanium

## Powder Production

### Titanium Powder Suppliers

<table>
<thead>
<tr>
<th>Company</th>
<th>Country</th>
<th>Powder type</th>
<th>Approximate cost/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP&amp;C</td>
<td>Canada</td>
<td>Plasma</td>
<td>€500-1000</td>
</tr>
<tr>
<td>Bongen/Affinity</td>
<td>China/USA</td>
<td>GA</td>
<td>€150-200</td>
</tr>
<tr>
<td>Bongen/Affinity</td>
<td>China/USA</td>
<td>HDH</td>
<td>€25-150</td>
</tr>
<tr>
<td>Crucible</td>
<td>USA</td>
<td>GA</td>
<td>€150-200</td>
</tr>
<tr>
<td>International Titanium Powder</td>
<td>USA</td>
<td>Direct reduction</td>
<td></td>
</tr>
<tr>
<td>Pioneer Metals &amp; Technology</td>
<td>USA</td>
<td>PREP</td>
<td>€500-1000</td>
</tr>
<tr>
<td>PyroGenesis</td>
<td>Greece/Canada</td>
<td>Plasma</td>
<td>€500-1000</td>
</tr>
<tr>
<td>Reading Alloys</td>
<td>USA</td>
<td>HDH</td>
<td>€25-150</td>
</tr>
<tr>
<td>Se-Jong</td>
<td>Korea</td>
<td>HDH</td>
<td>€25-150</td>
</tr>
<tr>
<td>Starmet (formerly Nuclear Metals)</td>
<td>USA</td>
<td>PREP</td>
<td>€500-1000</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>Japan</td>
<td>GA</td>
<td>€150-200</td>
</tr>
<tr>
<td>TLS</td>
<td>Germany</td>
<td>GA</td>
<td>€150-200</td>
</tr>
<tr>
<td>TLS</td>
<td>Germany</td>
<td>HDH</td>
<td>€25-150</td>
</tr>
<tr>
<td>ToHo</td>
<td>Japan</td>
<td>HDH</td>
<td>€25-150</td>
</tr>
<tr>
<td>Zunyi Titanium</td>
<td>China</td>
<td>HDH</td>
<td>€25-150</td>
</tr>
</tbody>
</table>

# PM Titanium

## Technologies for Titanium Powder

<table>
<thead>
<tr>
<th>Process/Company</th>
<th>Raw Material</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Existing Technologies</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atomisation/ Crucible</td>
<td>Sponge/ scrap/ alloys</td>
<td>Skull melting</td>
</tr>
<tr>
<td>Atomisation/ ALD</td>
<td>Bar</td>
<td>Electron beam melting</td>
</tr>
<tr>
<td>Atomisation/ AP&amp;C</td>
<td>Wire</td>
<td>Plasma melting</td>
</tr>
<tr>
<td>Rotating Electrode/ ASM</td>
<td>Bar</td>
<td>Plasma melting</td>
</tr>
<tr>
<td>Hydride/Dehydride</td>
<td>Sponge/ scrap/ alloys</td>
<td>Thermal/ H₂</td>
</tr>
<tr>
<td><strong>Emerging Technologies – Low cost Ti powder?</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Armstrong (ITP)</td>
<td>TiCl₄</td>
<td>Chemical</td>
</tr>
<tr>
<td>SRI International</td>
<td>TiCl₄</td>
<td>Thermal/ H₂</td>
</tr>
<tr>
<td>DuPont</td>
<td>TiCl₄</td>
<td>Chemical</td>
</tr>
<tr>
<td>Idaho Ti Technologies</td>
<td>TiCl₄</td>
<td>Thermal/ H₂</td>
</tr>
<tr>
<td>FFC Cambridge/Metalysis</td>
<td>TiO₂</td>
<td>Electrolytic</td>
</tr>
<tr>
<td>MER</td>
<td>TiO₂</td>
<td>Electrolytic</td>
</tr>
<tr>
<td>BHP Billiton</td>
<td>TiO₂</td>
<td>Electrolytic</td>
</tr>
<tr>
<td>OS (Kyoto University)</td>
<td>TiO₂</td>
<td>Electrolytic</td>
</tr>
<tr>
<td>MIR-Chem</td>
<td>TiO₂</td>
<td>Chemical</td>
</tr>
<tr>
<td>CSIRO</td>
<td>TiO₂</td>
<td>Chemical</td>
</tr>
</tbody>
</table>

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PM Titanium

Titanium Powder – Armstrong Process

Schematic description of Armstrong Process

- Continuous process (in contrast to the „Hunter“ process)
- Electrochemical separation of NaCl and re-use of Na and Cl
- 2000 t/a (production unit is planned)


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## PM Titanium

### Powder Design

<table>
<thead>
<tr>
<th>CP Titanium (Na reduced TiCl₄)</th>
<th>Type</th>
<th>Oxygen ppm</th>
<th>Apparent Density %</th>
<th>Powder size d₅₀/µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Powder</td>
<td>1750</td>
<td>6.2</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Ball milled</td>
<td>2380</td>
<td>18</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Hybridizer dispersed</td>
<td>3360</td>
<td>41</td>
<td>13</td>
<td></td>
</tr>
</tbody>
</table>

Need to de-agglomerate the powder with lowest oxygen pick-up!
PM Titanium

Powder Design

Plasmaspherodisierung von ITP-Pulver durch Tekna, Canada (25g/min)

MIM Qualitäten

Quelle: ITP, PowderMet2007
PM Titanium

Powder Consolidation Processes

- Vacuum sintering (typically 1000-1250°C) 98% possible
- Hot pressing (typically 800-1000°C, 100 MPa) 100% density possible, full wrought alloy mechanical properties

- Press & Vacuum Sinter
- Metal injection moulding
- Hot pressing
- Hot isostatic pressing
- Direct Powder Rolling & Sinter
- Dynaforge
- Direct 3D deposition
  - laser
  - electron beam
PM Titanium

Press- and Sinter of Titanium

Powder

Alloying Concepts

<table>
<thead>
<tr>
<th>Alloy [wt%]</th>
<th>Masteralloy [wt%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V</td>
<td>Al-40V</td>
</tr>
<tr>
<td>Ti-6Al-1.7Fe-0.1Si</td>
<td>Al-21.8Fe-1.3Si</td>
</tr>
<tr>
<td>Ti-6Al-2Sn-4Zr-2Mo-0.2Si</td>
<td>Al-14Sn-28Zr-14Mo-1.4Si</td>
</tr>
<tr>
<td>Ti-4.3Fe-7Mo-1.4Al-1.4V</td>
<td>Al-50V + Fe-62Mo</td>
</tr>
<tr>
<td>Ti-3.5Al-1Fe, Ti-5Al-2.5Fe</td>
<td>Al-37Ti, Ti-53Fe</td>
</tr>
<tr>
<td>Ti-0.6Si-0.5Fe</td>
<td>Fe-33Si</td>
</tr>
<tr>
<td>Ti-2.5Cu</td>
<td></td>
</tr>
</tbody>
</table>

Powder Particle Size, Size Distribution
sintered density
homogeneity of material properties

Powder Particle Shape
flowability
compaction behaviour

Powder Purity
oxygen content
residual chlorides
other compounds
PM Titanium

Application

Figure 8. Ti-MMC automobile components (prototype) made by the blended elemental P/M process.

Table II. Comparison of Mechanical Properties of the Developed Ti-MMC and 21-4N Heat Resistant Steel

<table>
<thead>
<tr>
<th></th>
<th>Tensile Strength/MPa (R.T.)</th>
<th>0.2% Proof Strength/MPa (R.T.)</th>
<th>0.2% Proof Strength/MPa (1,073 K)</th>
<th>Fatigue* Strength/MPA (1,123 K)</th>
<th>Creep** Deflection/mm (1,073 K)</th>
<th>Density g/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-MMC</td>
<td>1,290</td>
<td>1,180</td>
<td>580</td>
<td>160</td>
<td>13.0</td>
<td>4.6</td>
</tr>
<tr>
<td>21-4N</td>
<td>880</td>
<td>560</td>
<td>380</td>
<td>150</td>
<td>18.3</td>
<td>7.9</td>
</tr>
</tbody>
</table>

* Rotating bending fatigue (R = -1)
** Bending creep = 50 MPa, 100 h

PM Titanium

Application (Dynamet Technology, Inc. (USA))

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 (Ti-64+TiC)</td>
<td>1034 (150)</td>
<td>965 (140)</td>
<td>3</td>
<td>130 (19.3)</td>
<td>42</td>
</tr>
</tbody>
</table>
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Application (Hot Isostatic Pressing)

Fig. 4 — Comparison of mechanical properties of prealloyed HIP, wrought, and cast material.

Quelle: QinetiQ
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Application (Metal Injection Moulding)

Artificial heart valve consisting of heart valve ring and three cusps.
weight: 2.3 g (ring 1.25 g, each cusp 0.35 g)
diameter: 23 mm
material: Ti Al6 Nb7
aortal valve prosthetic

Double threaded screw with cannulas
weight: 1.05 g
length: 41 mm
material: Ti Al6 Nb7
setting of fragmented bone pieces in fractures of the vertebrae of the cervical spine

http://www.mim-experten.de
PM Titanium

Application (Additive Manufacturing)

Additive layer manufacturing (ALM) processes

<table>
<thead>
<tr>
<th>Powder bed</th>
<th>Powder feed</th>
<th>Wire feed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser beam (IW-UK)</td>
<td>Laser beam (IW-UK)</td>
<td>Laser beam (IW-OTN)</td>
</tr>
<tr>
<td>+++++</td>
<td>+++++</td>
<td>+++++</td>
</tr>
<tr>
<td>Electron beam (IW-UK)</td>
<td>Laser</td>
<td>Plasma / arc beam (Norsk Hydro)</td>
</tr>
<tr>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Complexity of component: +++++, ++++, ++++, ++, +
Accuracy: +++++, ++, +
Size of component: +++++, ++, +
Building speed: +++++, ++, +
Material variety: +++++, ++, +
Material quality: +++++, ++, +
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Application (Additive Manufacturing)

Aerospace

Material: $\gamma$-TiAl
Size: 8 x 12 x 325 mm
Weight: 0,5 kg
Build time: 7 hours / blade

Turbine Blades

Courtesy of Avio S.p.A.
PM Titanium

Application (Additive Manufacturing)

Medical Engineering

CE-certified & FDA-cleared Implants

- CE-certified acetabular cups with integrated, engineered Trabecular Structures™ since 2007
- Implants with FDA clearance since 2010
- > 40,000 cups manufactured
- > 20,000 cups implanted

Adler Ortho, IT 2007
Lima-Lto, IT 2007
Exactech, US 2010
Thank you very much for your attention!

Thomas Weißgärber