P/M METAL MATRIX COMPOSITES

Dr. Vicente Amigó Borrás
Universitat Politècnica de València
Instituto de Tecnología de Materiales
Spain
Different techniques for processing MMCs

**Processing of the Powders**

- High Energy Ball Milling
- Atomization

**Processing of the Composites**

- Spray forming
- Conventional P/M
- Microwave Sintering
- HIP consolidation
- SPS Technique
- SHS Process
- Laser Processing
High Energy Ball Milling

Produce spherical particles including all elements. It’s depend **parameter’s process:**
- Rotation speed
- Ball diameter
- Relation ball/powder
- Time

![Images of Al – 0.5 Y₂O₃ 1h and Fe – 25 TaC – 25 WC 4 h]
Spray forming

MMCs manufactured by this method are made by the introduction of reinforced particles inside the atomizing beam for being incorporated into the solidified alloy. The contact time between the liquid metal and the reinforcing particles is short. This fact and the high cooling rate of the molten particles reduce the interfacial reaction possibilities.

The atomizing melting rate is close to 5 kg/min, and the obtained preform has a density of 95% of the theoretical value. After that, a finishing operation must be done (such as forging, extrusion or rolling) in order to obtain the full density.

This processing method gives the obtained parts a fine microstructure with a very homogeneous distribution of the reinforcing material, and they can retain a high amount of alloying elements in solution.
Conventional P/M route

All the properties of the MMCs obtained by P/M can be improved through liquid phase sintering with or without extra pressing, and usually through final steps such as extrusion, forging or rolling.
HIP consolidation

- Improved pressure distribution within the compact: Uniformity of properties.
- No problems of friction.
- It allows more complex forms, and more slenderness.
- Best green densities are achieved.
- HIP: Forming MMCs, superalloys, high speed steels, Ti alloys, advanced ceramics, etc., materials with high associated value.

Disadvantages
- Slow, low productivity.
- Low dimensional tolerances.
- Worse surface finish.
- Discontinuity of the process.
- In HIP: High cost of autoclave.

Bodycote-IMT in USA. 1,62 m diameter by 2,33 m height.

Layer matrix composite reinforced with SiC aluminum, bonded to an aluminum ring

Example encapsulation (F. Thümmler)
The solids are rigid (not flexible as CIP)
**SPS Process**

SPS used uniaxial pressure and a pulse of electrical current creates a discharge between the particles.

Outline of pulsed current path: a) through the machine, and, b) through the powder.

Simulation of rapid heating process (From left to right: the mold before and during the process)

AMC – Al/B₄C 20w/o
Microwave Sintering

Schematic Sketch of Microwave Sintering Setup

Mg-0.5%Y2O3, with Mg2Cu intermetallics
SHS Process

The commonly known example of in situ processing is the unidirectional eutectic solidification. However, the newly developing processes are based on two principles:

- controlled reaction between a molten alloy and a gas, and the subsequent forming of reinforces in the molten metal, and/or

- endothermic reactions between the components in order to produce the reinforcement.

The latter process is known as self-autopropagating high temperature synthesis (SHS). One example of controlled reactions in a liquid is the in situ oxidizing process, called the lanxide process [29,30]. In this process molten Al oxidizes to produce a mixture of Al and Al₂O₃ (Aluminum matrix composite obtained by in situ formation).
Laser Cladding

- With 15% TiC, there are virtually no primary particles. DISCARDED
- With 30% TiC, acceptable limit TRANSFER (D1/D2)
- With 60%, overdilution
  
  Activation convective flow

  Reduce, I, M / VD and increase t
Laser Cladding

- Continuous coatings without oxidation, bonded.
- TiC accumulation in the middle.
Different Materials for MMCs

- Iron Matrix Composites
- Hard Metals
- Aluminium Matrix Composites
- Magnesium Matrix Composites
- Titanium Matrix Composites
## Iron Matrix Composites

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Processing Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Speed Steel Base</strong></td>
<td>Blend elements/ High energy milling</td>
</tr>
<tr>
<td></td>
<td>Uniaxial compaction and sintering</td>
</tr>
<tr>
<td></td>
<td>HIP</td>
</tr>
<tr>
<td><strong>Fe-Cr-C Base Alloys</strong></td>
<td>High energy milling</td>
</tr>
<tr>
<td></td>
<td>Uniaxial compaction and sintering</td>
</tr>
<tr>
<td></td>
<td>Starch consolidation</td>
</tr>
<tr>
<td><strong>Stainless Steel Base</strong></td>
<td>Conventional mix</td>
</tr>
<tr>
<td></td>
<td>Uniaxial compaction and sintering</td>
</tr>
<tr>
<td><strong>Fe-NbC</strong></td>
<td>SHS (self-propagating high temperature synthesis)</td>
</tr>
<tr>
<td></td>
<td>Uniaxial compaction and sintering</td>
</tr>
<tr>
<td></td>
<td>CIP</td>
</tr>
<tr>
<td></td>
<td>Starch consolidation</td>
</tr>
</tbody>
</table>
Iron Matrix Composites

M3/2 System – TaC/NbC  (Molybdenum High Speed Tool Steel)
Conventional Mix
Uniaxial Compaction and sintering in vacuum

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.15-1.25</td>
</tr>
<tr>
<td>Cr</td>
<td>3.75-4.50</td>
</tr>
<tr>
<td>Ni</td>
<td>0.3</td>
</tr>
<tr>
<td>Mo</td>
<td>4.75-6.50</td>
</tr>
<tr>
<td>W</td>
<td>5.00-6.75</td>
</tr>
<tr>
<td>V</td>
<td>2.75-3.75</td>
</tr>
</tbody>
</table>

M3/2 + 10 %v TaC

M3/2 + 7,5 %v NbC
Iron Matrix Composites

M3/2 System – TaC/NbC
High Energy Mix

M3/2 + 8 %v NbC
Compaction on the matrix, and sintering in vacuum

M3/2 + 8 %v NbC
HIP

PM Summer School, Valencia 2016
www.upv.es/itm
Iron Matrix Composites

M3/2 System – 25 TaC – 25 WC
High Energy Mixing

Composite Powder

Uniaxial Compaction sintering in vacuum

Density 98% of theoretical at 1310 °C
Hardness 66 HRC
Homogeneous microstructure
Iron Matrix Composites

Fe System – 25 TaC – 25 WC
Mezcla alta energía

1280 °C
1350 °C
1330 °C

W, Fe carbides
Ta carbides
Iron Matrix Composites

316L Systems + AlCr₂, TiCr₂, SiC, VC (1,5 v% - 3 v%)
Conventional mix
Vacuum Sintering, H₂, N₂/H₂

- TiCr₂ additions improve tensile strength.
- AlCr₂, TiCr₂, SiC increases hardness.
- The addition of 3% SiC improve the wear behavior.
- The corrosion behavior improvement in all cases except with additions of 3% SiC and 1,5 % VC.
Hard Metals Matrix Composites

2-phase WC-Co (left) and 3-phase WC-TiC-TaC-Co (right)
Hard Metals Matrix Composites

4-phase cermet (left) and nano-scaled WC ($d_{50}=160$nm, right)
Aluminium Matrix Composites

Aluminum is a very reactive metal that it is passivated generating an oxide layer covering the particles.

Because of this, sintering is necessary to break the passive layer by plastic deformation (extrusion)

For composites one of the best ways to get pre-alloyed powders by mixing the components by high energy milling.

For the best conditions hardenable alloys for precipitation of second phases are used, mainly families Cu-Mg, Mg-Si and Mg-Zn. mainly families Cu-Mg, Mg-Si and Mg-Zn.
### Aluminium Matrix Composites

| 2xxx Base alloys (2014, 2124) | Conventional mix/High energy milling  
|                             | Compaction matrix  
|                             | Extrusion  
|                             | Sintering. Study of the liquid phase. |
| 6xxx Base alloys (6061)      | Conventional mix/High energy milling  
|                             | Compaction matrix  
|                             | Extrusion |
| Reinforcement                | Carbides: TiC, VC, SiC,...  
|                             | Nitrides: AlN, Si₃N₄  
|                             | Intermetallics: Ti-Al, Ni-Al  
|                             | Others: B₂Zr, TiCN... |
Aluminium Matrix Composites

AA6061 + 5 % ZrB₂

PM Summer School, Valencia 2016
www.upv.es/itm
Aluminium Matrix Composites

AA6061 + 5% AlN

![Graph showing apparent density vs milling time for AA6061 and AA6061 + 5% AlN.

![Graph showing apparent density vs milling time for 5% AlN and 15% AlN.

![Graph showing apparent density vs milling time for 5% AlN, 5% Si3N4, and 5% ZrB2.]}
Aluminium Matrix Composites

2014 + VC- 5h

2014 + VC- 7h

2014 + VC- 10h

PM Summer School, Valencia 2016
www.upv.es/itm
Aluminium Matrix Composites Process

- Ratio balls/powder: 6/1 - 20/1
- Balls diameter: 5 & 20.0 mm
- Rotation speed: 700 rpm
- Molling time: 1.5, 3, 4.5, 6, 8, 10h
- PCA: 1-1.5 % wt

Compaction pressure: 200 MPa
Lubricant: Zinc stearate

Extrusion Rate: 25/1
Extrusion Temperature: 500 °C
Lubricant: Grafite
Aluminium Matrix Composites

AA6061 + 5 % AlN

Blend Elements

Mechanical Alloying

AA6061 + 15 % AlN

Blend Elements

Mechanical Alloying
Aluminium Matrix Composites

Mechanical Properties

**AA6061 + 5 % AlN**

**Tensile Strength (MPa)**

**Hardness (HV)**

**Time (hours)**

**AA6061 + NbC**

**Yield Strength**

**Tensile Strength (MPa)**

**Base**

**NbC-1**

**NbC-2**

**NbC-3a**

**NbC-3b**

**NbC-4a**

**NbC-4b**

**NbC-4c**

**AA6061 + VC**

**Yield Strength**

**Tensile Strength (MPa)**

**Base**

**VC-1**

**VC-2**

**VC-3a**

**VC-3b**

**VC-4a**

**VC-4b**

**VC-4c**
Aluminium Matrix Composites

Other systems

(a) AA6061 +10% of TiAl composite. (b) AA6061+10% of TiB$_2$ composite.
(b) (c) AA6061 + 5% of SiC$_w$ composite.

Tensile strength of different composites
Aluminium Matrix Composites

Other systems

Scanning electron microscopy image of composites: (a) AA6061: + 10% de TiAl, (b) AA6061+ 10%TiN. (c) AA6061+ 10%de B₄C. (d) AA6061 + 10% TiB₂. (e) AA6061 + 5% de TiB₂
Magnesium Matrix Composites

Magnesium is a highly reactive metal not passive, so its surface oxide does not prevent sintering and allows use elemental powder mixture, but requires protective atmospheres.

Steps involved in the development of magnesium composites

Manoj Gupta Group, Department of Mechanical Engineering, National University of Singapore
Magnesium Matrix Composites

Properties of \textit{Mg/Al}_2\textit{O}_3\) hybrid composites reported by W. Wong and M. Gupta

<table>
<thead>
<tr>
<th>Material</th>
<th>Grain Size ((\mu\text{m}))</th>
<th>Micro-hardness ((H_v))</th>
<th>Tensile Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Tensile Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>27 ± 7</td>
<td>40 ± 1</td>
<td>116 ± 11</td>
<td>168 ± 10</td>
<td>6.1 ± 2.0</td>
</tr>
<tr>
<td>Mg/0.3Al_2O_3</td>
<td>-</td>
<td>48 ± 3</td>
<td>119 ± 7</td>
<td>175 ± 8</td>
<td>7.5 ± 0.2</td>
</tr>
<tr>
<td>Mg/0.6Al_2O_3</td>
<td>24 ± 4</td>
<td>54 ± 3</td>
<td>130 ± 5</td>
<td>180 ± 7</td>
<td>7.4 ± 0.3</td>
</tr>
<tr>
<td>Mg/1.0Al_2O_3</td>
<td>15 ± 3</td>
<td>60 ± 4</td>
<td>154 ± 5</td>
<td>213 ± 12</td>
<td>6.3 ± 0.4</td>
</tr>
<tr>
<td>Mg/1.5Al_2O_3</td>
<td>18 ± 1</td>
<td>68 ± 2</td>
<td>148 ± 10</td>
<td>209 ± 7</td>
<td>5.6 ± 0.3</td>
</tr>
</tbody>
</table>

Microstructure of a PM Magnesium-Silver-Rare Earth composite QE22/SiC\(_p\), parallel to the extrusion direction.

Main compounds

Properties of \textit{Mg/SiC} nanocomposites by W. E Wong and M. Gupta

<table>
<thead>
<tr>
<th>Material</th>
<th>CTE ((\mu/K))</th>
<th>Micro-hardness ((H_v))</th>
<th>Tensile Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Tensile Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>30.1</td>
<td>35 ± 1</td>
<td>106 ± 7</td>
<td>160 ± 8</td>
<td>5.8 ± 1.8</td>
</tr>
<tr>
<td>Mg/0.35SiC</td>
<td>29.3</td>
<td>38 ± 1</td>
<td>116 ± 7</td>
<td>169 ± 17</td>
<td>5.2 ± 1.4</td>
</tr>
<tr>
<td>Mg/0.5SiC</td>
<td>28.6</td>
<td>40 ± 1</td>
<td>107 ± 10</td>
<td>161 ± 11</td>
<td>6.5 ± 0.2</td>
</tr>
<tr>
<td>Mg/1.0SiC</td>
<td>28.5</td>
<td>41 ± 2</td>
<td>125 ± 2</td>
<td>181 ± 4</td>
<td>6.1 ± 0.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>CTE ((\mu/K))</th>
<th>Micro-hardness ((H_v))</th>
<th>Tensile Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Tensile Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>29.1</td>
<td>39 ± 1</td>
<td>125 ± 15</td>
<td>172 ± 12</td>
<td>5.8 ± 0.9</td>
</tr>
<tr>
<td>Mg/0.35SiC</td>
<td>28.3</td>
<td>40 ± 1</td>
<td>152 ± 14</td>
<td>194 ± 11</td>
<td>6.3 ± 1.8</td>
</tr>
<tr>
<td>Mg/0.5SiC</td>
<td>28.3</td>
<td>42 ± 1</td>
<td>144 ± 12</td>
<td>194 ± 10</td>
<td>7.0 ± 2.0</td>
</tr>
<tr>
<td>Mg/1.0SiC</td>
<td>28.1</td>
<td>43 ± 2</td>
<td>157 ± 22</td>
<td>203 ± 22</td>
<td>7.6 ± 1.5</td>
</tr>
</tbody>
</table>
Magnesium Matrix Composites

Properties of Mg/Y₂O₃ nanocomposites reported by Tun and Gupta

<table>
<thead>
<tr>
<th>Material</th>
<th>Grain Size (µm)</th>
<th>Microhardness (HV)</th>
<th>Tensile Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Tensile Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>20 ± 3</td>
<td>40 ± 1</td>
<td>134 ± 7</td>
<td>193 ± 2</td>
<td>7.5 ± 2.5</td>
</tr>
<tr>
<td>Mg/0.2Y₂O₃</td>
<td>19 ± 3</td>
<td>38 ± 0</td>
<td>144 ± 2</td>
<td>214 ± 4</td>
<td>8.0 ± 2.8</td>
</tr>
<tr>
<td>Mg/0.7Y₂O₃</td>
<td>18 ± 3</td>
<td>45 ± 2</td>
<td>157 ± 10</td>
<td>244 ± 1</td>
<td>8.6 ± 1.2</td>
</tr>
</tbody>
</table>

Mechanical properties of Mg/Y₂O₃ nanocomposites reported by Mallick et al.
# Magnesium Matrix Composites

<table>
<thead>
<tr>
<th>Material</th>
<th>Microhardness (HV)</th>
<th>Tensile Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Tensile Failure strain (%)</th>
<th>Compressive Yield Strength (MPa)</th>
<th>Ultimate Compressive Strength (MPa)</th>
<th>Compressive Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>45 ± 1</td>
<td>121 ± 5</td>
<td>179 ± 6</td>
<td>11 ± 1</td>
<td>103 ± 4</td>
<td>263 ± 5</td>
<td>22 ± 2</td>
</tr>
<tr>
<td>Mg/0.5ZnO</td>
<td>53 ± 0.4</td>
<td>119 ± 9</td>
<td>203 ± 17</td>
<td>16 ± 2</td>
<td>111 ± 8</td>
<td>344 ± 15</td>
<td>14 ± 2</td>
</tr>
<tr>
<td>Mg/1.0ZnO</td>
<td>62 ± 2</td>
<td>125 ± 4</td>
<td>231 ± 13</td>
<td>17 ± 2</td>
<td>106 ± 11</td>
<td>372 ± 15</td>
<td>13 ± 1</td>
</tr>
<tr>
<td>Mg/1.5ZnO</td>
<td>66 ± 2</td>
<td>125 ± 4</td>
<td>229 ± 4</td>
<td>17 ± 2</td>
<td>109 ± 3</td>
<td>368 ± 21</td>
<td>14 ± 1</td>
</tr>
</tbody>
</table>

Properties of Mg/ZnO nanocomposites reported by Tun et al.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Grain Size (μm)</th>
<th>Microhardness (HV)</th>
<th>Tensile Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Tensile Failure strain (%)</th>
<th>Compressive Yield Strength (MPa)</th>
<th>Ultimate Compressive Strength (MPa)</th>
<th>Compressive Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Mg</td>
<td>29 ± 6</td>
<td>48 ± 1</td>
<td>136 ± 8</td>
<td>170 ± 7</td>
<td>6.1 ± 1.2</td>
<td>70 ± 2</td>
<td>250 ± 7</td>
<td>24.5 ± 2.7</td>
</tr>
<tr>
<td>Mg/0.29BN</td>
<td>21 ± 3</td>
<td>51 ± 3</td>
<td>127 ± 6</td>
<td>192 ± 8</td>
<td>7.8 ± 0.9</td>
<td>88 ± 6</td>
<td>290 ± 9</td>
<td>20.9 ± 1.8</td>
</tr>
<tr>
<td>Mg/0.86BN</td>
<td>22 ± 2</td>
<td>55 ± 3</td>
<td>142 ± 4</td>
<td>200 ± 5</td>
<td>8.6 ± 0.5</td>
<td>108 ± 2</td>
<td>312 ± 8</td>
<td>19.9 ± 1.2</td>
</tr>
<tr>
<td>Mg/1.44BN</td>
<td>19 ± 3</td>
<td>57 ± 2</td>
<td>145 ± 3</td>
<td>217 ± 5</td>
<td>7.2 ± 0.8</td>
<td>115 ± 4</td>
<td>319 ± 4</td>
<td>19.7 ± 1.4</td>
</tr>
</tbody>
</table>

Properties of Mg/BN nanocomposites reported by Seetharaman et al.
Magnesium Matrix Composites

Properties of Mg/AlN nanocomposites, Sankaranarayanan et al.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Grain Size (μm)</th>
<th>Micro-hardness (HV)</th>
<th>Tensile Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Tensile Failure strain (%)</th>
<th>Compressive Yield Strength (MPa)</th>
<th>Ultimate Compressive Strength (MPa)</th>
<th>Compressive Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Mg</td>
<td>28.2 ± 7.7</td>
<td>41 ± 3</td>
<td>96 ± 6</td>
<td>137 ± 9</td>
<td>6.0 ± 3.0</td>
<td>51 ± 9</td>
<td>268 ± 16</td>
<td>18.9 ± 1.6</td>
</tr>
<tr>
<td>Mg/0.2AlN</td>
<td>23.8 ± 7.9</td>
<td>49 ± 3</td>
<td>102 ± 6</td>
<td>159 ± 8</td>
<td>11.0 ± 2.2</td>
<td>65 ± 1</td>
<td>284 ± 12</td>
<td>19.3 ± 1.5</td>
</tr>
<tr>
<td>Mg/0.4AlN</td>
<td>19.6 ± 6.2</td>
<td>55 ± 3</td>
<td>120 ± 1</td>
<td>164 ± 3</td>
<td>8.4 ± 0.9</td>
<td>72 ± 5</td>
<td>314 ± 20</td>
<td>17.5 ± 0.6</td>
</tr>
<tr>
<td>Mg/0.8AlN</td>
<td>19.4 ± 5.3</td>
<td>53 ± 8</td>
<td>129 ± 5</td>
<td>176 ± 3</td>
<td>6.3 ± 0.4</td>
<td>71 ± 3</td>
<td>307 ± 17</td>
<td>18.3 ± 2.3</td>
</tr>
</tbody>
</table>
## Magnesium Matrix Composites

Properties of amorphous particle reinforced Mg composites reported by Sankaranarayanan et al.

**Ni$_{50}$Ti$_{50}$**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Material</th>
<th>Microhardness ($H_v$)</th>
<th>Compressive Yield Strength (MPa)</th>
<th>Ultimate Compressive Strength (MPa)</th>
<th>Compressive Failure strain (%)</th>
<th>Tensile Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Tensile Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pure Mg</td>
<td>32 ± 6</td>
<td>58 ± 8</td>
<td>234 ± 8</td>
<td>16.4 ± 0.9</td>
<td>75 ± 9</td>
<td>119 ± 11</td>
<td>8.6 ± 2.1</td>
</tr>
<tr>
<td>2</td>
<td>Mg/3Ni$<em>{50}$Ti$</em>{50}$</td>
<td>49 ± 3</td>
<td>67 ± 9</td>
<td>291 ± 12</td>
<td>15.9 ± 0.7</td>
<td>94 ± 5</td>
<td>144 ± 6</td>
<td>8.8 ± 1.7</td>
</tr>
<tr>
<td>3</td>
<td>Mg/6Ni$<em>{50}$Ti$</em>{50}$</td>
<td>62 ± 4</td>
<td>89 ± 3</td>
<td>368 ± 8</td>
<td>15.1 ± 1.5</td>
<td>127 ± 4</td>
<td>183 ± 6</td>
<td>6.5 ± 0.9</td>
</tr>
<tr>
<td>4</td>
<td>Mg/10Ni$<em>{50}$Ti$</em>{50}$</td>
<td>66 ± 8</td>
<td>102 ± 4</td>
<td>417 ± 6</td>
<td>14.9 ± 2.0</td>
<td>148 ± 7</td>
<td>178 ± 9</td>
<td>2.0 ± 1.3</td>
</tr>
</tbody>
</table>

Properties of amorphous particle reinforced Mg composites reported by Jayalakshmi et al.37

**Ni$_{60}$Nb$_{40}$**

<table>
<thead>
<tr>
<th>Material</th>
<th>Microhardness ($H_v$)</th>
<th>Compressive Yield Strength (MPa)</th>
<th>Ultimate Compressive Strength (MPa)</th>
<th>Compressive Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Mg</td>
<td>13 ± 2</td>
<td>70 ± 6</td>
<td>265 ± 8</td>
<td>16.2 ± 0.8</td>
</tr>
<tr>
<td>Mg/3Ni$<em>{60}$Nb$</em>{40}$</td>
<td>62 ± 4</td>
<td>85 ± 4</td>
<td>283 ± 10</td>
<td>17.6 ± 1.1</td>
</tr>
<tr>
<td>Mg/5Ni$<em>{60}$Nb$</em>{40}$</td>
<td>84 ± 5</td>
<td>130 ± 11</td>
<td>320 ± 11</td>
<td>18.4 ± 1.3</td>
</tr>
<tr>
<td>Mg/10Ni$<em>{60}$Nb$</em>{40}$</td>
<td>95 ± 5</td>
<td>90 ± 7</td>
<td>322 ± 10</td>
<td>17.2 ± 1.6</td>
</tr>
</tbody>
</table>
Titanium Matrix Composites

Titanium is a very reactive metal, which is passivated by formation of surface oxide, but is capable of dissolving high amounts of oxygen so it can be sintered but requires controlled, or better, high vacuum atmosphere.

Its high reactive reactions makes virtually all elements and form intermetallic and solid solution phases. One of the compounds under development, by Toyota Central R&D Labs, is the Ti + TiB obtained by pressing and sintering techniques.
Titanium Matrix Composites

Other systems: TiC, TiN, TiSi₂

Titanium Carbide (TiC) Ti+5%TiC (1200°C)

General microstructure optical microscope

Detail particle, secondary electrons

Secondary electron image

Composición atómica resultado de análisis por EDX.
Titanium Matrix Composites

Titanium Carbide (TiC) Ti+10%TiC (1250°C)

- Color map of the Euler angles.
- Inverse polar figures.
- Polar and inverse pole figures of Ti-Hex. and TiC.

<table>
<thead>
<tr>
<th>Phase Name</th>
<th>Phase Fraction (%)</th>
<th>Phase Count</th>
<th>Mean Band Contrast</th>
<th>Standard Deviation Band Contrast</th>
<th>Min Band Contrast</th>
<th>Max Band Contrast</th>
<th>Mean MAD</th>
<th>Standard Deviation MAD</th>
<th>Min MAD</th>
<th>Max MAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-Hex</td>
<td>82.14</td>
<td>47325</td>
<td>116.95</td>
<td>12.80</td>
<td>17.00</td>
<td>168.00</td>
<td>0.48</td>
<td>0.14</td>
<td>0.12</td>
<td>1.99</td>
</tr>
<tr>
<td>TiC</td>
<td>14.04</td>
<td>8092</td>
<td>146.30</td>
<td>17.87</td>
<td>40.00</td>
<td>194.00</td>
<td>0.57</td>
<td>0.19</td>
<td>0.11</td>
<td>1.81</td>
</tr>
<tr>
<td>Zero Solutions</td>
<td>3.81</td>
<td>2198</td>
<td>73.27</td>
<td>36.40</td>
<td>0.00</td>
<td>252.00</td>
<td>1.04</td>
<td>0.64</td>
<td>1.51</td>
<td>2.72</td>
</tr>
</tbody>
</table>

The percentage of phases found and resolution
Titanium Matrix Composites

Titanium Carbide (TiC) Ti+10%TiC (1250°C)

Compositional backscattered electron image EBSD

Contrast bands image.

Color code
Titanium Matrix Composites

Titanium Nitride (TiN) Ti+TiN (1200°C)

Ti+5%TiN (1200°C)
Ti+10%TiN (1200°C)
Ti+15%TiN (1200°C)

Optical Microscopy

Color map of the Euler angles.

Image of crystalline phases found.

Images of scanning electron microscopy

Compositional map of EDS
Titanium Matrix Composites

Titanium disilicide (TiSi₂)

Ti+5%TiSi₂ (1200°C)

Ti+10%TiSi₂ (1200°C)

Optical Microscopy

Color map of the Euler angles.

Image of crystalline phases found.

Formation of Ti₂Si₃
Ti₂Si₃ Interface
Fe impurities in grain boundaries
Ti Matrix

Particle and grain boundary detail, BSEI.

PM Summer School, Valencia 2016
www.upv.es/itm
Titanium Matrix Composites
Comparison between SPS and HP sintering processes

Evolution of sintered density (Ø 100 mm) Ti6Al4V/15% SiC with temperature. The first reactions below 850 °C are observed.

Density distribution in Ti6Al4V / 15% SiC (Ø 200mm, Tsinter = 900°C) after process optimization
Titanium Matrix Composites by Laser Cladding  (TiC)

- Compatibility reinforcement-matrix
- partial dissolution of the primary TiC
- Precipitation of secondary TiC
- compositional differences
- E is the key parameter

Cross section and detail of the deposition with 30% TiC and $E = 22 \text{ J/mm}^2$

General backscattered image in the overlap between cords, coating 1.

Coatings obtained

<table>
<thead>
<tr>
<th>Coating</th>
<th>$P$ (W)</th>
<th>$V$ (m/min)</th>
<th>$M$ (g/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating 1</td>
<td>600</td>
<td>0,75</td>
<td>3</td>
</tr>
<tr>
<td>Coating 2</td>
<td>800</td>
<td>0,75</td>
<td>3</td>
</tr>
</tbody>
</table>

Cross section of cord $P = 600\text{W}; V=0,75\text{m/min}, M=3\text{g/min at 50X}.$
Titanium Matrix Composites by Laser Cladding (TiC)

SEM images of coating reinforced with 60% TiC for two different power inputs. a) 400W. b) 600W. A higher degree of TiC melting is observed in the 2nd case, with apparent dendrite formation.

<table>
<thead>
<tr>
<th></th>
<th>Ti</th>
<th>Al</th>
<th>V</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%wt</td>
<td>%at</td>
<td>%wt</td>
<td>%at</td>
</tr>
<tr>
<td>Spectrum 1</td>
<td>77.52</td>
<td>46.37</td>
<td></td>
<td>22.48</td>
</tr>
<tr>
<td>Spectrum 2</td>
<td>83.78</td>
<td>65.45</td>
<td>4.92</td>
<td>6.82</td>
</tr>
<tr>
<td>Spectrum 3</td>
<td>91.5</td>
<td>87.96</td>
<td>5.43</td>
<td>9.26</td>
</tr>
</tbody>
</table>

Partial dissolution TiC particle due to laser radiation.
Titanium Matrix Composites by Laser Cladding (TiC)

Hardness and modulus evolution in the coating between two reinforcement particles, for two different P/VD values with same reinforcement content. (Δ) Hardness, (o) Modulus. a), c) 30%TiC, 22 J/mm². b), d) 30% TiC, 29 J/mm²
Titanium Matrix Composites by Laser Cladding (TiC)
Two-layered coatings

**Ti6Al4V+30%TiC**
- Minor cracks problem
- Coating $E = 22 \text{ J/mm}^2$ like one layer
- Coating $E = 29 \text{ J/mm}^2$ excessive dissolution
- Strong bond, flawless

**Ti6Al4V+60%TiC**
- TiC homogeneous distribution.
- Defect with Low Intensity.
- With high I, more gradual transition.
Titanium Matrix Composites by Laser Cladding (Other systems)

Alternatives to TiC

- Grafite
- B₄C
- SiC
- Cr₃C₂
- WC
- TiB₂
- TiN