Advances In Injection Molding Of Metals

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Presentation Overview

- Metal parts molding technology alternatives discussed; past & present
  - Metal Injection Molding, also known as MIM or PIM
  - Amorphous metal molding, commonly called Liquidmetal or Bulk Metallic Glass (BMG)
- Process capability comparison, MIM/PIM and Amorphous Metal
- Advancements in plastic injection molding has enabled the molding of precision, high performance metal parts
- Commercial resources for process simulation software, materials and equipment
- Recognition of presentation resources
MIM/PIM Process

1. Metal powder
2. Binder
3. Dry mixing
4. Compounding (pelletizing is an option)
5. Feedstock
6. Injection molding
7. Green part
8. Solvent debind
9. Sintering
10. Debound/brown part
11. Thermal debind
12. Final part (~20% shrinkage)
MIM/PIM Origins

1970 Dr. Raymond E. Wiech Jr. develops the first MIM process

1972 Dr. Wiech cofounds Parmatech

1980 Dr. Wiech leaves Parmatech to form Witec, focused on licensing feedstock and sintering systems

1980’s Widespread commercial progress

1987 MIMA is formed as one of 6 trade associations under the MPIF

1990’s Significant growth and widespread adoption, along with an increase in production volumes.

1993 First MIMA Std. 35 published, including 6 materials

2000’s Increased focus on leveraging advanced plastic injection molding systems

2017 Nearly a $2 billion industry
MIM/PIM Makes Commercial Progress

• Around 1970 there was one other notable MIM process based on Cabot patents held by Ron Rivers
  • The only known licensee of the ”Rivers” process was New Industrial Techniques (NIT)
• During the 1980s several North American companies are known to have purchased license agreements from either Parmatech or Witec:
  
  Brunswick  
  DuPont (for ceramics)  
  IBM
  Millett Sights  
  Multi Material Molding  
  Remington Arms
  Rockwell International  
  Zulaf

  During this period of time a commercial technology began to emerge
• The process is now being used on automotive applications, cell phones, dental and medical devices, orthodontic appliances, industrial products, power hand tools, and sporting arms, among other markets
Metal Injection Molding Association (MIMA)

• International Membership

• Open to:
  • Parts producers (metals and ceramics)
  • Material suppliers
  • Equipment suppliers

• Principle focus:
  • To provide technical facts, data, and standards
  • To improve and promote the products of the industry
  • To promote investigation, research and interchange of ideas among its members
  • To promote education in the science, practice and application of injection molding of metals and other powder materials
MIM/PIM Current Status

- Global industry approaching $2 billion USD revenues
  - 45% Asia
    - Approaching 60% of global metal powder consumption for consumer electronics applications
  - 30% Europe
  - 25% North America
- Stainless steels dominate global production
  - 316L
  - 17-4 PH
  - 410
  - 420
### MIM/PIM Markets and Applications

#### Automotive
- **2012** Sealing Seat  
  By: SolidMicron Technologies Pte

#### Dental
- **2016** Mirror Cover, Base & Middle  
  By: Indo-US MIM Tec Pvt. Ltd.
- **2004** Carriere Distalizer  
  By: World Class Technologies
- **2013** Sensing Element, Port & Ring  
  By: Indo-US MIM Tec Pvt. Ltd.
- **2007** Ortho Bracket, Slider & Hook  
  By: FloMet LLC

#### Electronics
- **2016** Tungsten Electrode  
  By: FloMet LLC An Arc Group Worldwide Company
- **2016** Trigger  
  By: Parmatech Corporation
- **2014** Stainless Steel Shaft Assembly  
  By: Smith Metal Products
- **2006** Cell Phone Flip Slider & Barrel  
  By: Advanced Materials Technologies

#### Medical
- **2012** Ortho Bracket, Slider & Hook  
  By: FloMet LLC
- **2013** Sensing Element, Port & Ring  
  By: Indo-US MIM Tec Pvt. Ltd.
- **2014** Stainless Steel Shaft Assembly  
  By: Smith Metal Products
- **2006** High Speed Steel Tool Bit  
  By: Pacific Sintered Metals

#### Recreation

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MoldingConference.com
Amorphous Metals... A New Commercial Manufacturing Solution
Amorphous Metal Process
Amorphous Metal Origins

- **1962**: Amorphous alloys discovered by Caltech
- **1993**: NASA-sponsored Caltech formulates bulk metallic glass
- **2002**: Liquidmetal Technologies goes public, making millions of cell phone and golf parts
- **2011**: Large scale alloy production established. Commercial Liquidmetal injection molding machine becomes available
- **Present**: State-of-the-art manufacturing and technology development in CA and China, leveraging strategic manufacturing relationships
Alloy Chemistry is Key to Manageable Cooling Rates

\[ R_C \text{ (K/s)} \]

**Liquidmetal Alloys**

- 10 mm
- 10^0 → 10^3

**Pure Metals**

- 10^6 → 10^9 → 0.1 mm

*Early Metallic Glasses*
**LM105 Amorphous Alloy System**

<table>
<thead>
<tr>
<th>Element</th>
<th>Melting (°C)</th>
<th>Density (g/cm³)</th>
<th>LM105 Melting (°C)</th>
<th>LM105 Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr</td>
<td>1852</td>
<td>6.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>1453</td>
<td>8.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>660</td>
<td>2.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>1083</td>
<td>8.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>1668</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>785</td>
<td>6.57</td>
</tr>
</tbody>
</table>
Amorphous Metal Technology

Crystal (Greek – ‘ice’):
• After conventional alloys cool to a solid, they crystallize into geometric atomic structures and shrink.
• The boundaries between crystalline structures or grains are weak regions or break points that cause metals to permanently deform or break under stress.

Amorphous (Greek – ‘without form’)
• Liquidmetal alloys solidify in a dense non-crystalline atomic structure. Minimal shrinkage occurs (<0.4%), enabling precision molded parts that meet tolerances of the best machined parts.
• Liquidmetal parts are stronger and more elastic because they do not have grain boundaries that create weak regions or break points.
Early Molding Technology

• Modified vertical die-casting machines

• Alloy exposed to impurities such as oxygen

• Early production yields were poor and product quality varied
Today’s Bulk Amorphous Molding Technology

Standard injection molding machine platform and controls with cold crucible injection unit

Modified horizontal die-cast molding machine with a hot crucible injection unit
Amorphous Metal Molding Video
## Markets and Applications

<table>
<thead>
<tr>
<th>MARKETS</th>
<th>POTENTIAL APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>Engine timing systems, fuel injection, fuel rail component, small precision gears,</td>
</tr>
<tr>
<td></td>
<td>passenger safety devices, pumps, pressure sensors, ABS system components,</td>
</tr>
<tr>
<td></td>
<td>decorative interior and exterior components, severe duty connectors, ignition systems,</td>
</tr>
<tr>
<td></td>
<td>variable valve components</td>
</tr>
<tr>
<td>Medical</td>
<td>Broad range of device applications for actuation components, clamping, cutting,</td>
</tr>
<tr>
<td></td>
<td>piercing, sealing, stapling, suturing. Biocompatibility studies are underway to determine</td>
</tr>
<tr>
<td></td>
<td>the suitability of LM105 for implants</td>
</tr>
<tr>
<td>Sporting</td>
<td>Archery, bicycling, firearms, fishing reels, knives, recreational tools, scuba equipment</td>
</tr>
<tr>
<td>equipment</td>
<td></td>
</tr>
<tr>
<td>Industrial</td>
<td>Pressure sensors, compressor components, power tools, hand tools, small precision</td>
</tr>
<tr>
<td></td>
<td>gears, severe duty connectors, mechanical assemblies, poppets, valves, pumps</td>
</tr>
<tr>
<td>Dental</td>
<td>Tools, equipment, orthodontia brackets</td>
</tr>
</tbody>
</table>
Amorphous Metal and MIM/PIM...A Comparison
Design Characteristics...what can be made

**Amorphous Metal:**

**Cold Crucible** process
- Part weights up to 80 grams (100 gram max shot size)
- Maximum dimension of 100mm
- Wall thickness of 0.6mm to 4.0mm

**Hot Crucible** process
- Part weights up to 180 grams (300 gram max shot size)
- Maximum dimension of 200mm
- Wall thickness of 0.3mm to 3.0mm

**MIM/PIM:**

**Some Parts**
- Part weights above 100 grams
- Maximum dimension of 150mm
- Wall thickness of 0.5mm to 13mm

**Most Parts**
- Part weights under 50 grams
- Maximum dimension of 75mm
- Wall thickness of 1.0mm to 3.0mm
Material Property Comparisons

Liquidmetal has a substantially higher resilience* than other structural materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Resilience (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM105</td>
<td>12.5</td>
</tr>
<tr>
<td>Steel 1.7176</td>
<td>3.7</td>
</tr>
<tr>
<td>Ti-6-4</td>
<td>3.0</td>
</tr>
<tr>
<td>Al 7075</td>
<td>1.7</td>
</tr>
</tbody>
</table>

*Area under the elastic portion of the stress-strain curve
## Process Comparison

<table>
<thead>
<tr>
<th>Feature</th>
<th>Amorphous Metal</th>
<th>MIM/PIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensional precision (% of feature size)</td>
<td>± 0.08%</td>
<td>± 0.3%</td>
</tr>
<tr>
<td>Surface finish</td>
<td>0.025 – 0.05 Ra μm</td>
<td>0.4 to 1.6 Ra μm</td>
</tr>
<tr>
<td>Draft requirements for internal features</td>
<td>3°</td>
<td>0 to 0.5°</td>
</tr>
<tr>
<td>Low process scrap, material can be recycled</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Alloy availability</td>
<td>Narrow</td>
<td>Broad</td>
</tr>
<tr>
<td>High part complexity</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Corrosion Resistance</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Ability to insert mold</td>
<td>Excellent</td>
<td>Fair</td>
</tr>
<tr>
<td>Consumable cores for increased part complexity</td>
<td>Easy</td>
<td>Challenging</td>
</tr>
<tr>
<td>Material’s elastic limit</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Mold life</td>
<td>100,000 shots</td>
<td>1,000,000 shots</td>
</tr>
<tr>
<td>Material density</td>
<td>100%</td>
<td>96% – 98%</td>
</tr>
</tbody>
</table>
Borrowing Technology From Plastic Injection Molding
Plastics Molding Technologies Enable Precision Metal Parts

By the year 2000 the MIM/PIM industry was able to buy stable raw materials and debinding and sintering equipment. The industry broadly began to apply all of the advancements in injection molding and mold designs for plastics from the plastic industry and learned advance injection mold design techniques from plastics savvy customers in the automotive, consumer electronics and medical device markets.

MIM/PIM mold designs began regularly including:

• Hot-runner systems
• Unscrewing cores
• 3-plate molds
• Sophisticated hydraulic and mechanical slides
• Replaceable mold inserts for high volume production
Plastics Molding Technologies Enable Precision Metal Parts

Molds for amorphous metal molding are also similar to those used for plastics, but have a few distinctly different characteristics:

- Mold cavities must be able to withstand material temperatures of 1000°C.
- Amorphous alloys have very low shrinkage (<0.4%), but reach full physical properties before ejection, thus requiring draft on internal and some external features.
- All molds operated under a vacuum of 0.003 torr.
- O-rings required between plates.
- Replaceable mold inserts for high-wear areas are critical for high volume production.
- Since this is a one-step metal forming process, high cavitation molds drive part price economics.

Mold designs/systems that do not work with amorphous metal:

- Hot-runner systems.
- Unscrewing cores.
Plastics Molding Technologies Enable Precision Metal Parts

Today, a range of injection molding technologies for plastics are being leveraged for metal part production.

Quick screw change designs are critical for rapid material changes and eliminating cross-contamination of different metal alloys.

Closed-loop microprocessor controls have demonstrated improved shot-to-shot metal part quality.

Process automation has improved cycle efficiencies and product quality, while eliminating labor content.
Resources for Commercial Amorphous Metal and MIM/PIM
Injection Molding Simulation Software

Offers advanced MIM/PIM molding simulation software developed for BASF and other commercial feedstocks.

Liquidmetal and NASA provided material characterization necessary to develop molding simulation software for amorphous metal molding.
Amorphous Metal Simulation Software

- Injection Stroke Parameter Influences
  - Runner design
  - Gate design
  - Part volume
  - Part geometry
  - Cavitation

- Simulation Output
  - Flow front types
  - Knit/weld line placement
  - Surface defect density
  - Short shot prediction
Material Suppliers & Developers

MIM/PIM feedstocks are available globally for various debinding processes from catalytic, to thermal and chemical. There are other suppliers not listed.

Amorphous metal alloys are being developed and are commercially available.
MIM/PIM Injection Molding Machine Suppliers

The most notable in the MIM/PIM industry is Arburg:
• Separate business unit focused on the MIM/PIM industry
• MIM/PIM specific injection units and non-return valves built for high wear materials
• Dedicated MIM/PIM research & development lab
• Application development services

But many other machines are making MIM/PIM production parts successfully:
• Cincinatti Milicron
• ENGEL
• Haitain
• Wittmann Battenfeld
• and others
Amorphous Metal Injection Molding Machines

The only globally deployable and serviced machine is a cold crucible machine produced by ENGEL.

Liquidmetal’s technology partner, EONTEC, has developed a hot-crucible machine that is not currently available on the open market.
Post-molding Equipment for MIM/PIM

Debinding and Sintering equipment are available from a large number of global suppliers:

- CM Furnaces
- Centorr/Vacuum Industries
- Elnik
- Elino
- Hiper
- Kramer
- Sinterzone
- Tisoma
- and others
Presentation Resources

ENGEL
• Injection molding of amorphous alloys

EONTEC
• Amorphous alloys and processes

Liquidmetal Technologies, Inc.

Metal Powder Industries Federation (MPFI)
• MIM application examples from Annual Design Competitions

Metal Injection Molding Association (MIMA)
• MIM historical inputs

Dr. Peng Yu
Department of Materials Science and Engineering, University of Science and Technology of China, Shenzhen, China
• Chinese MIM market
Thank You