Semi-Solid Materials
Outline

1. Introduction
2. Semi-solid metal (SSM) characteristic
3. Alloy characteristics
4. Semi-solid processing techniques
5. Advantages and Limitation
6. Commercial applications
7. Future development
Introduction

• Semi-solid processing originated from work by researchers at MIT in 1971 experimenting on the rheological behaviour of Sn-15Pb alloy [Spencer et al. 1972, Flemings 1991].

• The semisolid slurry with a spheroidal microstructure of 0.4-0.6 weight fraction solid suspended in liquid had a very low value of flow resistance and that it would be possible to use this in developing new forming processes.
SSM=Near-net shaping process

• Near net shaping process is a process that fabricate products close to the final shape resulting in reduction of subsequent machining process.

Near net shaping process such as
  – Fine casting
  – Spray forming
  – Injection molding
  – Superplastic forming (Sheet metals)
  – Semisolid forming ect.
Semi-solid metal (SSM) characteristic

- Semisolid process is the process shaping materials during semisolid state (called slurry).
- Operation temperature is at a temperature that between its \textit{liquidus} and \textit{solidus} temperature (red area).
- Ideally, the slurry should be appx 30 to 65% solid.
The weight of solid fraction at a given processing temperature $T$ is given by:

$$f_s^{Sch} = 1 - \left( \frac{T_M - T}{T_M - T_L} \right)^{1-k}$$

Schel equation for fast cooling:

$$f_s = \frac{(T_M - T) - m_L c_0}{(T_M - T)(1 - k)}$$

- wide solidification range;
- large temperature processing interval (40-60% of solid fraction);
- the volume of solid fraction must be not sensitive to temperature
Why semi-solid?

- SSM process combines advantages of casting (Liquid) and forming (solid) processes.
- The microstructure of the semi-solid alloy is non-dendritic consisting of spheroidal solid phase suspended in the liquid phase before and during forming.
Thixotropy

- A non-dendritic structure behaves as a ‘thixotropic’ slurry.
- **Thixotropic** means the viscosity of semi-solid slurry is both time and shear rate dependent.
  - Viscosity decreases with increasing shear rate
  - At constant shear rate the viscosity decreases with increasing time
- A pseudo-plastic fluid (or shear thinning) at shear rates as low as $10^{-5}$ s$^{-1}$
- The alloys are stable when no shear stress is applied
(a) The slurry was solidified to a given fraction solid before shearing. Shear stress increases rapidly after 0.15 fraction solid due to dendritic structure.
(b) The alloy was stirred continuously from above the liquidus. Here the stress at a given fraction solid was approximately three orders of magnitude lower than (a) due to the spheroidal grain structure.

[After Spencer et al., 1972].
Structural evaluation during cooling

- Initial dendritic fragment
- Dendritic growth
- Rosette
- Ripened rosette
- Spheroid

[Diagram showing the structural changes and their corresponding labels (a) to (e).]
The viscosity reduces with increasing shear rate and decreasing cooling rate.
shear thinning
Figure 6 Average viscosity against average shear rate of the 7075 deformed at different fraction liquids. The viscosity is calculated from equation (3) and the shear rate is calculated from equation (4).
\[ \eta = m \dot{\gamma}^{n-1} \rightarrow \log_{10} \eta = (n-1) \log_{10} \dot{\gamma} + \log_{10} m \]

Plots of the calculated instantaneous viscosity (\( \eta \)) against average shear rate (\( \dot{\gamma} \))

- \( y = -0.844x + 5.613 \) \( 605^\circ C, f_I = 0.20 \)
- \( y = -1.2655x + 4.8494 \) \( 615^\circ C, f_I = 0.32 \)
- \( y = -1.8953x + 4.7816 \) \( 620^\circ C, f_I = 0.42 \)
How to get semi-solid slurry?

1. **Solid state method (Thixo-route)**
   - RAP: Recrystallisation and Partially Melting
   - SIMA: Stress-Induced Melt Activating Process
• The alloy is warm worked below the recrystallisation temperature. Subsequent heating induces recrystallisation followed by partial melting.

• The liquid penetrates grain boundaries and the result is a spheroidal structure suspended in the liquid phase.

RAP
Worm worked (extruded) → Rex → Partial melting

620 °C (2 min)

475 °C (1 min), 600 °C (1 min), 620 °C (20 sec)

630 °C (2 min)
\[ \frac{1}{t} = Ae^{-Q_r/RT} \]
In the SIMA process, the billet is hot worked above the recrystallisation temperature (for a given percentage transformation e.g. 50 percent), and then lightly or moderately cold worked to induce grain boundary migration. Subsequent partial melting at high angle boundaries causes fragmentation and transformation into the spheroidal structure.
2. Liquid state method (Rheo-route)

- the MHD (MagnetoHydroDynamically stirred)

(MHD technology is based on a fundamental law of electromagnetism: When a magnetic field and an electric current intersect in a liquid, their repulsive intersection propels the liquid in a direction perpendicular to both the field and the current)
MHD *(paper mhd semi)*

- In this process a dynamic electromagnetic field is applied to the metal near freezing in the mould in order to generate high local shear.
- As a result, fine uniformly sized (typically 30 µm) and uniformly distributed solid particles are produced with very small amounts of contamination.
Alloy characteristics

1. Solidification range
2. Low melting point phase/eutectic phase
3. Cooling rate/Castability
4. Potential for aging
MTDATA of AA7075 by CALPHAD

- Low melting point phase/eutectic phase
- Solidification range
Extruded Al wrought consists of elongated grains with small amount of recrystallised grains at grain boundaries reduce stored energy for recrystallisation.

Various types of precipitates retard the recrystallisation.

Intermetallic compounds effects partial remelting.
DSC trace and fraction liquid of 7075D
Suitable % liquid for forming

- **7075D-2 step heating**
- **7075D-single step heating**

Suitable temperature range
SSM techniques for products

1. Rheocasting
2. Thixoforming
3. Thixomoulding
4. Rheomoulding etc.
Three main routes for semi-solid metal processing:

1. Rheocasting
2. Thixocasting
3. Thixoforming
1. Rheocasting
   - Non-dendritic ally slurry obtained from shearing (such as stirring) while cooling from liquid state
2. Rheomoulding

- Vigorous shearing of liquid alloy using screw type drive while cooling
- Similar to Injection moulding
- Twin Screw Rheomoulding (TSRM) process is an upgradation
3. Thixoforming

- slugs are cut from a bar of non-dendritic material, then re-heated and partially melted into the semi-solid condition. Finally, slugs are shaped into the die.
Thixoforming

1. Graphite die
2. Tool steel heated die
4. Thixomolding®
Simultaneous heating and shearing of solid feedstock in a chamber by rotating barrel. Similar to injection molding.
Commercial Magnesium Thixomolding application

- Process

- Advantage
  http://www.parkwayproducts.com/enterprise/capabilities/thixomolded_magnesium_injection/process_advantages.htm
Advantages

In comparison to fully liquid operation (Casting ect.)
1. Semisolid slurries provide laminar flow in a cavity leading to less gas entrapment, high density and higher dimensional tolerances
2. Reduce solidification shrinkage and the tendency to hot tearing
3. Lower operating temperatures
4. Shorter solidification times lead to shorter production times
5. Light weight and near net shape process
6. Reduce thermal shock the die lead to longer die life
Advantages

In comparison to solid-state operations (forging, rolling, extrusion etc.),

1. semisolid slurries fill the die more evenly under pressure
2. Complicated shapes can be made more easily using lower loads
3. The operation requires lower energy, resulting in lower overall production costs
## Semi Solid Molding

A Comparison of Aluminum Casting Methods

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Sand</th>
<th>Permanent Mold</th>
<th>Low Pressure</th>
<th>High Pressure</th>
<th>Semi Solid Molding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die Composition</td>
<td>Metal &amp; Plastic</td>
<td>Iron &amp; Treated Steel</td>
<td>Treated steel</td>
<td>Treated steel</td>
<td>Treated steel</td>
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<tr>
<td>Die Cost</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
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<tr>
<td>Die Life</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>Highest</td>
</tr>
<tr>
<td>Die Development Time (P.O. to sample)</td>
<td>2-8 wks</td>
<td>4-10 wks</td>
<td>5-12 wks</td>
<td>10-18 wks</td>
<td>10-18 wks</td>
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<tr>
<td>Die Modification Costs ($)</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Section Thickness</td>
<td>.125 min</td>
<td>.167 min</td>
<td>.167 min</td>
<td>.080 min</td>
<td>.070 min</td>
</tr>
<tr>
<td>Casting Temp. F</td>
<td>1300-1350</td>
<td>1250-1300</td>
<td>1225-1250</td>
<td>1200-1225</td>
<td>1000</td>
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<tr>
<td>Surface Finish</td>
<td>Fair</td>
<td>Good</td>
<td>Very good</td>
<td>Excellent</td>
<td>Best</td>
</tr>
<tr>
<td>Alloy Selectivity</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Limited</td>
<td>Limited</td>
</tr>
<tr>
<td>Density</td>
<td>Fair</td>
<td>Good</td>
<td>Very good</td>
<td>Fair</td>
<td>Best</td>
</tr>
<tr>
<td>Heat Treatable</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Dimensional Stability</td>
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<td>Good</td>
<td>Very good</td>
<td>Excellent</td>
<td>Excellent</td>
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<tr>
<td>Insert Capable</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Net Shape Capability</td>
<td>Fair</td>
<td>Good</td>
<td>Better</td>
<td>Best</td>
<td>Best</td>
</tr>
<tr>
<td>High Volume Production Capability</td>
<td>Good</td>
<td>Fair</td>
<td>Better</td>
<td>Best</td>
<td>Best</td>
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</table>

Source: http://www.cast-it.com/ssm_al_chart.html
### Semi Solid Molding
A Comparison of Brass Casting Methods

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Green Sand Casting</th>
<th>No Bake</th>
<th>Die Cast</th>
<th>SSM</th>
<th>Permanent Mold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die Composition</td>
<td>Wood, Metal &amp; Plastic</td>
<td>Wood, Metal &amp; Plastic</td>
<td>Tool Steel</td>
<td>Tool Steel</td>
<td>Tool Steel</td>
</tr>
<tr>
<td>Die Cost</td>
<td>Low</td>
<td>Lowest</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Die Life</td>
<td>High</td>
<td>Lowest</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Die Development Time (P.O. to sample)</td>
<td>6-10 wks</td>
<td>4-10 wks</td>
<td>10-18 wks</td>
<td>10-18 wks</td>
<td>6-10 wks</td>
</tr>
<tr>
<td>Die Modification Costs ($)</td>
<td>Low</td>
<td>Low</td>
<td>Highest</td>
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<td>Moderate</td>
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<tr>
<td>Section Thickness (Minimum)</td>
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<tr>
<td>Surface Finish</td>
<td>Good</td>
<td>Very good</td>
<td>Good</td>
<td>Best</td>
<td>Best</td>
</tr>
<tr>
<td>Alloy Selectivity</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Limited</td>
<td>Limited</td>
<td>Limited</td>
</tr>
<tr>
<td>Density</td>
<td>Good</td>
<td>Very good</td>
<td>Good</td>
<td>Best</td>
<td>Best</td>
</tr>
<tr>
<td>Heat Treatable</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Dimensional Stability</td>
<td>Fair</td>
<td>Good</td>
<td>Very good</td>
<td>Excellent</td>
<td>Excellent</td>
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<tr>
<td>Insert Capable</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Net Shape Capability</td>
<td>Good</td>
<td>Good</td>
<td>Best</td>
<td>Best</td>
<td>Very good</td>
</tr>
<tr>
<td>High Volume Production Capability</td>
<td>Good</td>
<td>Limited</td>
<td>Best</td>
<td>Best</td>
<td>Very good</td>
</tr>
</tbody>
</table>

Source: http://www.cast-it.com/ssm_al_chart.html
## Properties of Semi-solid metals

<table>
<thead>
<tr>
<th>Alloys</th>
<th>Condition</th>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
<th>E%</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061</td>
<td>RAP, Thixoformed</td>
<td>265</td>
<td>219</td>
<td>9</td>
<td>Pitts H., 1998</td>
</tr>
<tr>
<td>6082</td>
<td>RAP, Thixoformed</td>
<td>296</td>
<td>264</td>
<td>8.2</td>
<td>Modd, 2001</td>
</tr>
<tr>
<td>6082, modified with 0.2Ba</td>
<td>MHD, Backward extrusion</td>
<td>320</td>
<td>284</td>
<td>7</td>
<td>Gullo et al., 2000</td>
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<tr>
<td>6082 with grain refinement</td>
<td>Thixoformed (Central area)</td>
<td>249</td>
<td>201</td>
<td>16</td>
<td>Tausig, 2000</td>
</tr>
<tr>
<td>AlMgSi1 6xxx series</td>
<td>Thixoformed (Central area)</td>
<td>300</td>
<td>275</td>
<td>2.5</td>
<td>Bremer et al., 1996</td>
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<tr>
<td></td>
<td>Arm area</td>
<td>355</td>
<td>330</td>
<td>5.8</td>
<td></td>
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<tr>
<td>2024 (AlCu4MgI)</td>
<td>Wrought</td>
<td>476</td>
<td>393</td>
<td>10</td>
<td>Metals Handbook®, 1984</td>
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<tr>
<td>2024</td>
<td>SSM</td>
<td>366</td>
<td>277</td>
<td>9.2</td>
<td>Tietmann et al., 1992</td>
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<tr>
<td>2024 modified with grain refiner</td>
<td>EMC, press-formed</td>
<td>510</td>
<td>435</td>
<td>2.3</td>
<td>Rachmat et al., 2000</td>
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<td>Semisolid forming</td>
<td>Temper</td>
<td>UTS (MPa)</td>
<td>YS (MPa)</td>
<td>E%</td>
<td>Ref.</td>
</tr>
<tr>
<td>-------------------------------------------------------</td>
<td>--------</td>
<td>-----------</td>
<td>----------</td>
<td>-----</td>
<td>-------------------------------</td>
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<tr>
<td>As-wrought</td>
<td>T6</td>
<td>570</td>
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<td>Metals Handbook®, 1984</td>
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<tr>
<td>Semisolid forged</td>
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<td>405</td>
<td>361</td>
<td>6.6</td>
<td>Tietmann et al., 1992</td>
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<tr>
<td>LS casting, thixoforged (solid dominant part)</td>
<td>As-thixoforged</td>
<td>334</td>
<td>272</td>
<td>6</td>
<td>Tausig, 2000</td>
</tr>
<tr>
<td></td>
<td>T6</td>
<td>465</td>
<td>431</td>
<td>4</td>
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<tr>
<td>EMC, press formed</td>
<td>T6</td>
<td>546</td>
<td>518</td>
<td>11</td>
<td>Rachmat et al., 2000</td>
</tr>
</tbody>
</table>
Disadvantages

1. Relatively higher feedstock material cost
2. Precise control of operating condition is required.
3. Liquid segregation may occur as a result of non-uniform heating
1. Replacement of permanent mould parts to eliminate machining and finishing
2. Pressure tight parts such as master brake cylinders, fuel rails, air conditioner compressor housing etc.
3. High strength parts such as engine mounts, tie rods etc.
4. Wear resistant parts made from hypereutectic alloys such as compressor piston, brake drums, gear shift levers etc.
5. Forged parts requiring excessive tooling
Applications: Automotive, packaging, electronics, appliance etc.
Brake master Cylinder

Control arms for Steering

Automobile Wheels

Hydraulic Brake Valve
Future Developments

• Process development
• Mechanism of formation of non-dendritic structure
• Alloy development
• Simulation studies of process
• Viable process for steel and Cast Iron