SSM PROCESSING
R&D:
PROGRESS REPORT
D. Apelian and M. Makhlouf
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NADCA R&D Committee Meeting
October 16, 2002
ACRC Consortium Members

- Alcan International Ltd.
- Aluminum Company of America
- Aluminum Pechiney
- Amcast Industrial Corp.
- BMW AG
- Briggs & Stratton Corp.
- Buhler Inc.
- Chem-Trend Inc.
- Citation Corp.
- Consolidated Metco
- Daimler Chrysler Corp.
- Elkem Aluminum ANS
- Ford Motor Co.
- J. L. French International Ltd.
- General Aluminum Manufacturing Co.
- General Motors Corp.
- Harley-Davidson Motor Co.
- Hayes Lemmerz International, Inc.
- Heraeus Electro-Nite Co.
- Hitchcock Industries, Inc.
- Hydro Aluminum A.S. (VAW- Hydro Germany)
- IdraPrince Corp.
- Intermet Corp.
- Kennedy Die Castings, Inc.
- Leggett & Platt Aluminum Group
- Madison-Kipp Corp.
- Mercury Marine
- Metallurg Aluminum
- Montupet
- NEMAK
- North American Die Casting (NADCA)
- Ormet/Formcast, Inc.
- Palmer Foundry, Inc.
- Phillips Plastics
- Salzburger Aluminum AG
- Selee Corp.
- SPX Corp.
- Superior Industries International, Inc.
- Teksid Aluminum S.p.A.
- THT Presses
- TRW Automotive
- Visteon Chassis Systems

September 2002
Semi-Solid Processing Studies

Projects Completed  
(1998 - 2001)

1. Yield Stress Measurements and Quantitative Microstructure Characterization (WPI)
2. Modeling of Rheology in Semi-Solid Alloys (WPI)
4. Time Dependent Rheology of Semi-Solid Alloys (MIT)
5. Microstructural Evolution in Semi-Solid Alloys (MIT)
6. Development of Alternate Semi-Solid Aluminum Alloys (ORNL)
Semi-Solid Processing Studies

Current SSM Projects
Beginning January 2002

1. A Continuous Rheoconversion Process for Production of Semi-solid Slurries (WPI)
2. High-Temperature Rheological Measurements
3. AlB₂ Grain Refined Billet Route - SiBloy™ (WPI)
4. Modeling and Prediction of SSM Rheology (WPI)
DOE-Funded SSM Processing Projects

Yield Stress Measurements and Quantitative Microstructure Characterization
Q. Y. Pan and D. Apelian

• Establish yield stress vs temperature relationship for commercial semi-solid Al alloys
• Understand how processing method affects slurry yielding behavior
• Quantitatively characterize microstructural evolution of various semi-solid billets during commercial forming conditions
• Investigate the effects of semi-solid structure on the rheological behavior of commercial semi-solid billets
Yield Stress vs. Temperature (A356)
Yield Stress vs. Temperature (357)
Semi-solid Microstructure at 580°C

- MHD A356
- GR A356
- SiBloy
- MIT A356
- SIMA A357
- UBE (A356)
Image Analysis Results

Entrapped Liquid Content ($V_f$) vs. Temperature

- $V_f$ (GR) $>>$ $V_f$ (MHD)
- $V_f$(GR): 15-30%
  $V_f$(SIMA): 11-14%
  $V_f$(MHD): 8-10%
- $T \uparrow \Rightarrow V_f \downarrow$
- Little entrapped liquid in MIT and UBE billets
Image Analysis Results

Particle Size ($D_p$) vs. Temperature

- $T \Rightarrow D_p \uparrow$
- SIMA: 50-80 $\mu$m
- GR: 125-185 $\mu$m
- No effect on SiBloy
**Image Analysis Results**

**Shape Factor (SF) vs. Temperature**

- $\uparrow T \Rightarrow SF \downarrow$
- SF = 1 $\Rightarrow$ Spherical
- SIMA: 1.18 - 1.25
- SiBloy: 1.66 - 1.86
Modeling of SSM Processes
Andreas Alexandrou

Objectives:

• Perform numerical simulations of SSM mold filling operations and develop codes to predict and control mold filling instabilities

• Verify rheological models using experimental simulations
Flows in 2-D Expansions: Flow patterns and casting methods

![Graph showing flow patterns and casting methods](image)

- **Bi**
- **Re**
- **SQUEEZE CASTING**
- **SEMISOLID CASTING**
- **DIE CASTING**

- τ₀ = 70000Pa
- bubble
- mound
- shell
- disk
- transition
SSM Modeling: Flow Instabilities

Piston

Semi-solid aluminum

Cavity

Mold
Semisolid Aluminum Slurry: Flow Instabilities

Toothpaste Instability: experimental

Toothpaste Instability: FEM simulation results for (Re=1, Bi=3, L=10)

(Courtesy of Aluminum Pechiney)
Research Portfolio: DOE-Funded SSM Processing Projects

**Time-Dependent Rheology of Semi-Solid Alloys (MIT)**

A. Kato, A. M. de Figueredo, J. Yurko and M. C. Flemings

**Accomplishments**

- Obtained fundamental rheological data on microstructural evolution of semi-solid Al alloys
- Determined effects of semi-solid slurry structure on flow at shear rates typical of forming processes
- Carried out experimental simulations of SSM flow
SSM Transient Behavior (Hysteresis) in Rotational and Compression Experiments

- Agreement between experiments shows that complete break down of the slurry structure occurs in milliseconds
- Results show fully broken structures at shear rates below 1000 s\(^{-1}\)
SSM Rheology: Transient Behavior in Rotational Experiments

- Rapid shear deformation of SSM slurries leads to large decreases in viscosity.
- Viscosity recovery times are longer than typical mold cavity filling times.
- Once the SSM structure is fully broken, the resulting slurry becomes very fluid and remains so for relatively long times.
Microstructural Evolution in Semi-Solid Alloys (MIT)

R. Martinez, A. M. de Figueredo, J. Yurko and M. C. Flemings

Accomplishments

Developed a new method of forming semi-solid metal structures for slurry ready applications
Research Portfolio: DOE-Funded SSM Processing Projects

MIT New SSM Approach
Typical semi-solid structures obtained in A357 alloys by coupling forced convection with rapid heat extraction just below the liquidus temperature. Primary aluminum particles do not contain entrapped eutectic.

Processed Alloy, As cast

Re-heated to 585°C and quenched
A Continuous Rheoconversion Process (CRP) for Production of Semi-solid Slurries

M. Findon, A. M. de Figueredo, D. Apelian, and M. Makhlfouf

Objective

Develop novel, economic methods of continuously forming semisolid metal slurries for rheocasting and thixocasting applications
Research Portfolio: DOE-Funded SSM Processing Projects

Started January, 2002

CRP - Continuous Rheoconversion Process
CRP – Continuous Rheoconversion Process

- Continuous conversion of liquid to slurry
- Flexible
  - Thixocasting or slurry-ready
  - Not alloy specific
  - Allows for rapid adjustment of solid content
  - Recycling of scrap easy to incorporate
- Can be used with one melt as well – design flexibility
- Reasonable operating temperature range for slurry-ready processing
- Commercially viable – patent application submitted and in process
Research Portfolio: DOE-Funded SSM Processing Projects
Started January, 2002

CRP MICROSTRUCTURES: A356 ALLOYS

As-cast, $T_L=625°C$

Reheated to 585°C for 10min and quenched in water

As-cast, $T_L=660°C$
High Temperature Rheological Measurements
A. M. de Figueredo, Q. Y. Pan, and D. Apelian (WPI)
N. Tonmukayakul and Q. Dzuy Nguyen (University of Adelaide)

Objectives

• Investigate the flow behavior of semi-solid metals under transient flow conditions
• Determine shear stress-shear rate curves during rapid shear rate transients
• Correlate the viscosity of semi-solid metals with respective structures
• Develop instrumentation and techniques for rheological characterization of SSM slurries in the casting plant
Response of SSM 357 Alloy to Rapid Shear Deformation

Shear Rate Sweep

Viscosity Response

Shear Stress Response
A comprehensive program for the rheological characterization of SSM slurries has been established at MPI. This program is employing state of the art rheometry to characterize the flow behavior of SSM slurries under conditions of rapid deformation.
AlB₂ Grain Refined SSM Billet Route

Objectives

Investigate microstructural refinement in casting aluminum alloys by addition of Si-B master alloy (SiBloy® technology), and develop economic processes for the production of high-quality SSM feedstock.
Semi-solid Microstructures of SiBloy and GR A356 billets

SiBloy @ Billet Center

GR A356 @ Billet Center

580°C  582°C  585°C  590°C

580°C  582°C  585°C  590°C
Quantitative Data

Billet Center

Billet Edge

Entrapped Liquid (%) versus Temperature (°C)

A356
SiBloy
Quantitative Data

**Billet Center**

- A356
- SiBloy

**Billet Edge**

- A356
- SiBloy
Quantitative Data

Billet Center

Billet Edge

Shape Factor

Temperature (C)

A356
SiBloy
YS Measurement Results

Yield stress vs. temperature

Yield Stress (kPa) vs. Temperature (°C)

- Unmodified SiBloy
- Modified SiBloy
- GR A356

Logarithmic scale on Y-axis and linear scale on X-axis.
Modeling and Prediction of SSM Rheology

A. Alexandrou and Q.Y. Pan

Objectives

Develop simulation tools to understand and control SSM flow instabilities in mold filing operations
Methodology

**Constant Shear Rate**
- Temp.: 585°C
- Heating rate: 49°C/min.
- Shear Rate: $5 \times 10^{-3}$ s$^{-1}$; $8.33 \times 10^{-3}$ s$^{-1}$

**Constant Shear Force**
- Temp.: 585°C
- Heating rate: 49°C/min.
- Shear Force: 2N; 4N
Apparatus

\[ \Delta T: \leq 1^\circ C \]

LR: 0.001N
Flow Behavior of SSM A356 at Different Shear Strains

(T: 585°C; shear rate: 5.0×10^{-3}s^{-1}; Shear Strains: 0, 19.5, and 31.9)
Stress Distribution under Compression

Early Stage

Late Stage

(Bi=5, Re=1, F=-1.)
SSM processing of Hyper-eutectic Al-Si alloys

Deepak Saha, Babu Dasgupta* and D. Apelian
* SPX Contech, MI, USA

Objectives

Processing of 390 alloy via the Rheo-casting (Slurry-on-Demand) route having a consistent and uniform distribution of primary Si
Research Portfolio: Industrial Internship Funded SSM Processing Projects

Conceptual Framework: Diffusion Solidification

12.6% Si → L1 @ 760 °C
Al-25% Si Alloy

L2+S @ 550 °C
Sibloy® (Fraction solid ~ 85%)
Conceptual Framework

Control of uniformly distributed Si Phase is attained by heat balance

• Heat released

  (Cooling from Liquid temperature to Liquidus + Latent Heat from the nucleating and growing primary Si phase)

• Heat removal

  (The mixing of the Eutectic liquid + Dissolution of Primary Al)

Heat Released = Heat Absorbed
Research Portfolio: Industrial Internship Funded SSM Processing Projects

Example: Sibloy® at 550 °C mixed with 25% Al-Si at 760 °C (Final Temperature 590 °C)