# Semi-solid forming applications: high volume automotive products

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***Abstract***
*Efforts to improve fuel efficiency by the transportation industry have been directed in recent years toward the use of mass production capable, low-cost, aluminum castings as part of a weight reduction strategy. Die casting and permanent mold methods have been used extensively in the manufacture of light-weight castings to satisfy the need. However, quality limitations imposed by these casting methods such as porosity and the need for impregnation, trapped gas and the ability to heat treat the parts for improved strength, and non-uniform mechanical properties have restricted the range of applications available. In the last six years, a semi-solid forming (SSF) process has developed into a mature, high volume production method for light-weight, aluminum parts. The development of the SSF process depended upon the resolution of a number of critical technical issues: i) a reliable source of feedstock, ii) a robust forming technology capable of producing light-weight products capable of meeting automotive specifications, iii) alloys suitable for the SSF process of rapid cycling/high productivity manufacture, and iv) a joint customer/supplier 'design for manufacture' capability to enable the production of low-cost, functionally innovative products. In this paper, the products and mass production process used for high volume automotive applications will be described. The manufacturing experience described illustrates the benefits of joint supplier/customer development in the design and manufacture of critical parts. Tailoring of alloy, semi-solid viscosity, tool lubricants, press dynamics, and part design in order to optimize process/product characterize the engineering collaboration that took place. The advantages of the SSF process are described in terms of fundamentals of the forming process and the microstructural characteristics of the product. Robust methodology has been used throughout the development process and is currently being used in broadening SSF technology to include a semi-solid on demand process and a wider range of alloys.*

***Keywords***
*Semi-Solid, Forming, Automotive, Production.*

**Riassunto**
Recentemente gli sforzi indirizzati al miglioramento dell'efficienza nel consumo dei carburanti sono stati concentrati sull'impiego di getti di alluminio a basso costo e idonei alla produzione in serie, quale elemento di una strategia per la riduzione del peso. La pressofusione e la fusione in conchiglia sono stati largamente adoperate per la fabbricazione di getti di basso peso per rispondere a questo bisogno. Tuttavia le possibili applicazioni di questi metodi sono state limitate dalle problematiche qualitative, quale la porosità per intrappolamento dei gas che rende impraticabile il trattamento termico delle parti così ottenute per migliorarne la resistenza e le proprietà meccaniche. Negli ultimi sei anni il processo di formatura semisolida (SSF) si è sviluppato al punto di diventare un metodo maturo per la produzione in serie di componenti a basso peso in alluminio. Lo sviluppo dell' SSF ha richiesto la soluzione di alcune criticità tecniche: i) una fonte affidabile della materia prima; ii) una tecnologia robusta di formatura in grado di produrre elementi di basso peso conformi alle specifiche automobilistiche; iii) leghe idonee alla richiesta propria del processo SSF del ciclaggio rapido con alta produttività; iv) una capacità congiunta di "progettazione orientata alla fabbricazione" da parte del cliente e del fornitore tale da assicurare la produzione di prodotti funzionalmente innovativi a basso costo. L'articolo descrive i prodotti ed il processo di fabbricazione impiegati per applicazioni automobilistiche in grande serie. L'esperienza acquisita illustra i vantaggi dello sviluppo congiunto da parte del fornitore e del cliente nella progettazione e nella fabbricazione di parti critiche. La collaborazione ha curato la personalizzione della lega, la viscosità semisolida, i lubrificanti per gli stampi, la dinamica delle presse e la progettazione delle parti allo scopo di ottimizzare il processo ed il prodotto. Vengono descritti gli elementi fondamentali del processo di formatura e delle caratteristiche microstrutturali del prodotto. La metodologia è utililizata durante lo sviluppo del processo viene attualmente impiegata nella estensione della tecnologia SSF ad un processo semisolido "su richiesta" e ad una gamma di leghe più vasta.

**Parole chiave**
Semisolido, formatura, automobilistico, produzione.

## INTRODUCTION

### Comparison of semi-solid forming with other casting processes

Semi-solid forming (SSF) is an effective near-net-shape forming process in which the metal is formed in the semi-solid state [1]. The process combines a number of the advantages of both casting and forging. A comparison with conventional casting methods aids in understanding the origin of some of the advantages capable of producing complicated shapes at volume production rates. Mold-fill temperature, shrinkage, energy extraction, flow in mold filling, and solidification microstructure are critical features which influence the quality products manufactured by the methods.

High-pressure, die casting methods are used extensively for high volume automotive parts. However, the highly turbulent die fill in the process is responsible for porosity, oxide incorporation and blistering problems when heat treated and limits the application of this method for critical, structural applications. The slow laminar flow of SSF (20 to 50 cm/s) during die fill avoids the problems of gas and oxide entrapment and significantly reduces the shrinkage problems associated with solidification since SSF has about 70 % solid. In casting with a molten alloy, compensation for shrinkage is provided by a flow of liquid that can be significantly hindered by the permeability of a coherent dendritic structure. The result is generally the formation of macroscopic porosity. With SSF, solidification shrinkage is compensated by the compression of the semi-solid itself under the intensification pressure applied in the process. Any shrinkage porosity formed in this case will be micro-porosity that can occur if compressive force is not transferred to the shrinkage region while the semi-solid is still fluid. This topic will be considered further in the discussion of robustness.

Squeeze casting has the advantage of a relatively slow molten metal die fill and solidification under high pressure ( ~ 100 bars) which avoids many of the defect types noted for die casting. However, the extraction of heat in the solidification process extends the cycle time relative to that required in SSF where the energy extracted to solidify the product is only approximately 20% of that for the casting processes (pour temperatures assumed to be ~ 700°C). The high solid fraction (0.6 to 0.8) of the semi-solid material (SSM) feedstock accounts not only for reducing energy extracted and cycle time requirements but also accounts for the lower injection temperatures (~ 580°C) that extend tool life by a factor of ~ 4-5 times. Heat checking has not been experienced with the ferrous material used in SSF dies.

## CRITICAL SSF PROCESS REQUIREMENTS

### Reliable Feedstock Source

A highly consistent source of billet for the reheat process used in the SSF process is being produced by a magnetohydrodynamic (MHD) process described in the patent by Winter, et al.[2]. The process involves cooling a molten metal while it is mixed under the influence of a moving magnetic field across the full cross section of the mold and over the entire solidification zone. A semi-solid is formed with a magnetomotive stirring force sufficient to provide mixing during solidification. The casting produced by this process has a microstructure composed of clustered degenerate-dendritic particles in a matrix of second phase (eutectic for alloys A356 and A357). Each cast is examined for skin thickness (2 - 5 mm in thickness), porosity, oxides, and hydrogen which must meet rigid specifications. Composition and resistivity (40-42 %IACS) are closely controlled. The billets obtained by appropriately sectioning the cast logs when reheated provide a highly consistent feedstock for the SSF process.

### Robust Semi-Solid Forming Technology

A process flow cycle for the MHD billet reheat process consists of billet reheating, injection, and part stripping. Robust design methods were used to minimize the effects of variation in the manufacturing environment: (i) raw material and (ii) operating environment. With a parameter design method, the values (settings) of the process controllable factors are determined which involves the following:

- Determining the relationships between product/process parameters, noise factors, and quality characteristics; and
- Finding a combination of design controllable factors that gives the smallest variation in the value of the quality characteristic.

Often there is no additional product cost increase associated with changing the nominal value of control factors in the parameter design approach. With the parameter design approach, the focus is to identify the critical parameters in each of the processes using an understanding of the physics and metallurgical features of the process. The response functions are selected based on meaningful metallurgical parameters that are determined by the process conditions.

A list of SSF process elements and the current level of understanding of the relevant physical parameters is given in Table I. These physical parameters are used as aids in the selection of control parameters for multivariable test design (DOE) and as a basis for constructing control algorithms.

An experimental range based upon the Reynolds number, Re, and die fill velocity, V, and semi-solid apparent viscosity, (, namely, is used to assure laminar flow. An apparent viscosity/temperature relationship (exponential in nature) is found by adjusting simulation results to match interrupted-fill results with production parts. A closed-loop control system for MHD billet reheating has been developed using an algorithm developed on the basis of the forming press dynamics.

One of the unique metallurgical features of the SSF process is the microstructure developed within the formed part. Figure 1 illustrates the structures of a cast MHD billet, a reheated and quenched billet, and a solidified SSF part showing the divorced eutectic (the dark regions) structure with rounded primary aluminum particles and rosettes of entrapped eutectic.

**TABLE 1 - Quantitative Process Control Development**

| SSF Process Elements | Model Parameters | Control Parameters | Control Algorithm |
|---|---|---|---|
| MHD Billet | Solidification Rate (S)<br>Shearing rate ($\tau$) | Mold Temp. gradient<br>Feed rate | S $\propto$ f(mat'1; coolant; feed)<br>$\tau \propto$ f(stator input I) |
| Billet Reheat | Viscosity ($\eta$)<br>Liquid fraction as f(T) ($f_{liq}$)<br>Induction heating (Ind) | Coil location<br>Coil current balance<br>Coil frequency<br>Number of coils | $\eta \propto$ f($f_{liq}$; Ind; F-Ram-Pos; Ram en.) |
| Gate/Runner Design | Viscosity<br>Laminar flow | Geometry<br>SS viscosity<br>Fill velocity | $Re = DV\rho/\eta$ |
| Die Design | Viscosity<br>Laminar flow | Geometry<br>SS viscosity | $Re = DV\rho/\eta$ |
| Tool (heating/cooling) | Viscosity<br>Wall/SS friction | Mokon oil temp.<br>Oil flow rate | |
| Press Dynamics | Viscosity<br>Laminar flow | SS viscosity<br>Ram speed<br>Dwell time | Flow ($\eta$) $\propto$ f(FRP; Ram en.; Fill vel) |
| Tool Lubrication | Mold release<br>Tool cooling<br>T6 blistering | Spray location<br>% solids<br>Spray volume | |

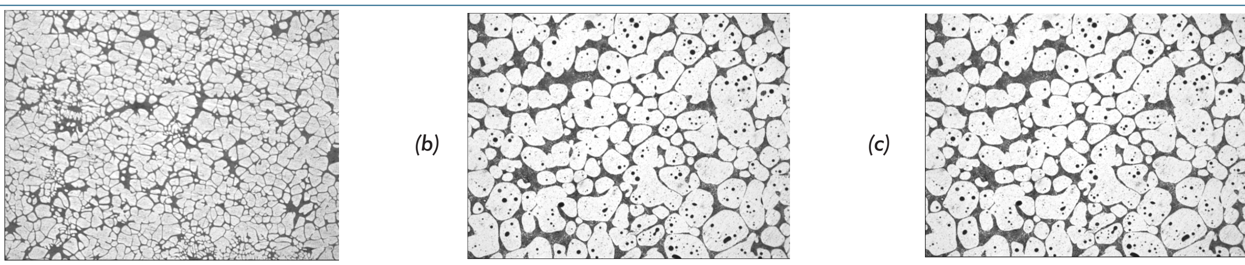


*Fig. 1: (a) As-Cast MHD billet microstructure; (b) reheated MHD billet structure; (c) SSF part structure (reheated MHD billet feedstock). The average particle size is ~ 100 $\mu$m. X100.*

If laminar flow conditions are maintained during die fill, then the microstructural similarity evident in Figures 3(b) and (c) occurs throughout the part. This unique forming property is due to the rheological behavior of the semi-solid formed from the reheated MHD billet. No deformation or evidence of texturing of the primary aluminum particles, or relative motion of the solid and liquid phases during die fill is noted unless strong shear gradients are present. This implies that under laminar flow conditions the semi-solid behaves as a Newtonian fluid where the shear stress is proportional to the shear strain rate. This proposal is also supported by the accuracy of single phase simulation models in predicting complex die fill.

## SSF Alloys

Many of the requirements for a useful casting alloy are modified when designing an SSF alloy. Viscosity is important but since the semi-solid is composed of solid particles with the remainder liquid, the particle size and shape and the fraction liquid are the controlling parameters. The smaller and more rounded the particles and the larger the fraction liquid the lower the viscosity. These same parameters are also assumed to be important in determining fluidity together with the benefits of a high latent heat of fusion of the liquid.

Resistance to hot tearing is usually related in aluminum alloys to a wide solidification temperature range, a large solidification shrinkage, and a low high temperature strength [3]. A definite advantage of SSF is that both the alloy solidification range and the shrinkage can be controlled by limiting the percent liquid in the semi-solid.

One of the processing requirements with the MHD billet is that the billet must retain its shape during the reheat process. In reaching solid fractions of 0.65 - 0.80 while retaining billet shape, castable Al-Si alloys have been found ideal. Alloys A356 and A357 are well adapted for the SSF process. Shape retention is improved by decreasing silicon concentrations with some loss in fluidity and strength. Magnesium additions (0.2 - 1.0 wt%) can be used to provide product strength through heat treatment. Eutectic modifications where necessary are accomplished with small additions of strontium (~0.02 wt%). Since, the 0.2% offset yield strength is reached in the early stage of dislocation motion, yield strength is only moderately affected by minor defects and grain size. This property is primarily a function of alloy composition and heat treatment.

A comparison of properties of alloy A357 semi-solid formed with squeeze cast and forged parts [4] is given in Table II to highlight the improvement in SSF properties. AEMP property (A357) averages from products are given in brackets [ ].

**TABLE 2 - Chiarmetta data (1996); AEMP data is bracketed [ ]**

| Process | Temper | Yield MPa (ksi) | UTS MPa (ksi) | Elongation % |
|---|---|---|---|---|
| SSF | As formed | 110 (16) [16] | 220 (32) [32] | 14 [13] |
| SSF | T4 | 130 (19) | 250 (36) | 20 |
| SSF | T5 | 180 (26) [33] | 255 (37) [40] | 5-10 [6-10] |
| SSF | T6 | 240 (35) [40] | 320 (46) [50] | 12 [8-12] |
| SSF | T7 | 260 (37) | 310 (45) | 9 |
| SC | T5 | 186 (27) | 262 (38) | 5 |
| SC | T51 | 138 (20) | 186 (27) | 2 |
| Forged | T6 | 280 (40) | 340 (49) | 9 |

The improvement in the properties of SSF parts relative to other casting methods is explained by microstructural features: reduced macro-porosity, less macro-segregation, lower level of entrained oxides, reduced levels of hot tears and feeding defects.

Fatigue property comparisons between SSF products and various cast products generally favor SSF and are indicative of sounder microstructures. Fully reversed fatigue tests of samples from SSF parts give fatigue strengths at 10 million cycles of 12 ksi (T5) and 15 ksi (T6).

### Design for Manufacturability (DFM)

Another important aspect of high volume production has to do with minimizing the time and cost of development - the problems occurring in the transition from development to production, the inspection required - while producing a product with a high level of quality and reliability. Parts are designed to meet customer requirements and to provide for ease of fabrication. Simulation software tools validated for accurate prediction of die-fill dynamics and shrinkage micro-porosity locations are very important in assuring ease of manufacture. Die-fill simulation is used to assure laminar flow conditions in the injection process and proper thermal conditions in the tool in order to avoid potential mend line, cold shut, and shrinkage porosity defects in the formed part. The development of a manufacturable part requires the joint efforts of both customer and supplier so that product functionality, weight minimization, and cost goals are met [5].

## HIGH VOLUME APPLICATIONS

### Master Brake Cylinders

| Mfg. Process | Annual Production million/year | Part Weight lbs. | Min. Wall Thickness mm | Leak Rate % | Machin. Steps |
|---|---|---|---|---|---|
| Perm. Mold | | 1.70 | 6.3 | 2 | 18 |
| SSF | 2.4 | 0.98 | 3.2 | 0 | 5 |

The master cylinder design converts the force of the brake pedal into hydraulic pressure to operate the wheel brakes. The MC body must maintain pressure integrity throughout the bore and with several mating components through high and low pressure bosses. Dimensional tolerance and seat geometry are important for o-ring squeeze and sealing. The mounting ears for external connection must provide a flat surface for interface to avoid side loading during MC operation (required machining to exacting tolerances with the permanent mold cast bodies). With the SSF design, the mounting ears including outer boot nose of the MC as well as the low-pressure reservoir ports are entirely as-formed. The high-pressure ports are net-shape externally and only material required for machining clean-up remains at the interior of the port. The interior bore was optimized through coring that allowed less metal removal than with permanent mold cast parts.
The only machining required with the SSF master cylinder is to ream and roller burnish the bore, punch and peen or drill the bypass, compensation and outlet holes, and drill and tap the high pressure outlets. An entire machine could be eliminated from the process. The SSF design not only reduced cost relative to the permanent mold part but reduced machining and lowered the cycle time, number of operators, and investment dollars required for manufacture.
Significant customer/supplier interactions occurred throughout the process/product development process. The 'design for manufacturability' process was performed while working closely with the customer to ensure that process modifications enhanced product performance. Typically a permanent mold master cylinder would be cast from alloy A356 (Iwt% Mg) with a T6 temper to meet the high strength and machinability requirements of the master cylinder body. With the SSF process the formed body with alloy A357 (1 wt% Mg) could meet the strength and machinability specifications with a T5 temper with significantly better dimensional control capability. Other design changes were made to improve product performance integrity while enhancing metal flow characteristics.

### Fuel Rails

| Mfg. Process | Annual Production million/year | Part Weight lbs. | Min. Wall Thickness mm | Leak Rate % | Machin. Steps |
|---|---|---|---|---|---|
| Solid Forging | | 1.500 | 5.1 | 4 | 82 |
| SSF | 1.0 | 0.735 | 3.8 | 0.1 | 26 |

Through customer/supplier collaboration a design was achieved that received the Ford 1997 Quality Excellence Award and the NADCA 1998 Die Casting Design Award.

### Engine/Transmission Brackets

Annual Production 1.0 million parts/year.

### Rocker Arm Pedestal

Annual Production 1.5 - 2.0 million parts/year.

### Timing Belt Bracket

Annual Production 0.2 million parts/year.

## CONTINUOUS IMPROVEMENT

### Semi-Solid on Demand

A significant cost factor in the MHD billet process is the casting of the MHD log, sectioning into billets, and reheating the billets to form the semi-solid feedstock for the SSF process. Several years ago, AEMP began development of a process to form semi-solid feedstock directly from a molten alloy without the MHD casting and reheating of billets. The process provides the additional benefit of 'semi-solid on demand' which solves the problem of billet loss during press operating interruptions in a continuous reheating process. This new process significantly lowers the cost of SSF products to the point where the process is competitive with die casting. Development of this new process provides three SSF process routes: (i) MHD billet process - current production; (ii) Semi-Solid on Demand process - in development; (iii) Alternate Semi-Solid on Demand process - automated process demonstrated.
New automotive products for engine components, powertrain brackets, brake and steering components, and suspension parts are currently being developed with the 'semi-solid on demand' (ii) process.

### Alloy Development

In addition to the cost benefits, the 'semi-solid on demand' process removes the alloy limitations of the MHD billet process where the semi-solid slug must retain its shape during handling. Alloy possibilities enabled with both MHD billet and slurry on demand types of SSF processing are listed in Table III to illustrate the scope of material and property variations of interest.

### Table 4 - Alloy possibilities for SSF processing

| Alloy Type | Property/Feature | SSF Process Route |
|---|---|---|
| Casting<br>A356, A357<br>319, 355, 390 | Strength and ductility balance<br>Wear | MHD billet<br>Slurry on demand |
| Wrought<br>6XXX, 2XXX, 7XXX | Improved strength and ductility | Slurry on demand |
| MMC | High modulus, Wear | MHD billet, Slurry on demand |

## CONCLUSIONS

Mass production applications of automotive products with SSF manufacturing methods are a reality. The applications illustrate the added value benefits of SSF of near-net-shape, short cycle times, improved properties, longer tool life, and weight reduction relative to other high volume casting processes. With supplier/customer joint development in part design a process in SSF has been developed that meets the stringent, mass production requirements for critical automotive applications. The process provides the potential for improving product functionality, reliability, and weight reduction at a cost competitive with other casting methods.

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