

SSM (semi-solid metal) technological alternatives for different applications

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Abstract

Since the original discoveries in the early 1970's, semi-solid processing has experienced all of the birth pangs of new technology. A wide array of patents and technological approaches has been proposed, many tried, but only a few have endured as manufacturing processes. This paper reviews the initial concepts first put forward by MIT, the diverse proposals entertained throughout the following 30 years and analyses the survivors. Semi-solid processing can now be broken down into three main categories; semi-solid processing, semi-liquid processing and slurry on demand processes. Each process variant is briefly analyzed, their attributes identified and an attempt made to suggest where each process is finding optimal performance. Practical examples are given for each process that provide insight to the process utility. Based upon this review, the key system features necessary to achieve success are discussed, the economic implications are identified and a projection is made regarding future developments.

Keywords

Technologies, Slurry, Mechanical properties, Applications.

Riassunto

Dalle prime scoperte agli inizi degli anni '70, la fabbricazione allo stato semisolido soffre di tutte le "malattie infantili" proprie di tutte le nuove tecnologie. Sono stati sviluppati molti fra i multipli brevetti ed approcci tecnologici proposti, ma ben pochi sono sopravvissuti e incorporati in processi produttivi. L'articolo passa in rassegna i concetti di base avanzati per la prima volta dall'MIT e le varie proposte esaminate durante i trenta anni successivi ed analizza i sopravvissuti. Oggi si possono distinguere tre categorie principali della fabbricazione allo stato semisolido, e precisamente i processi designati fabbricazione allo stato semisolido, fabbricazione allo stato semiliquido e SSF su richiesta. Segue una breve analisi di queste varianti e vengono individuati i loro attributi. Si cercano anche di suggerire i campi nei quali ogni processo sta realizzando le performances ottimali. L'utilità del singolo processo viene poi illustrata con l'aiuto di esempi della sua pratica applicazione. Alla luce delle considerazioni espresse vengono discusse le caratteristiche chiave del sistema necessarie al successo. Le implicazioni economiche vengono individuate ed una previsione dei futuri sviluppi viene prospettata.

Parole chiave

Tecnologie, impasto, proprietà meccaniche, applicazioni.

INTRODUCTION

When the initial discoveries of semi-solid processing were made at MIT in the early 1970's, Flemings and his team correctly identified them as revolutionary, with broad opportunity to impact metalworking across many alloy systems and processes. MIT proposed two basic variants for exploitation of the discoveries, utilising horizontal cold chamber diecasting machines as the critical device for shaping the material when semi-solid. These were called Rheocasting and Thixocasting (1), names which have since gone out of favor.

Both processes contemplated using mechanical stirring devices during freezing to create the special non-dendritic semi-solid microstructure. Perhaps not surprisingly, the early focus was on high temperature alloys, notably steels. Military production was a major activity and several projects were underway to perfect steel diecasting technology. The prospect of reducing effective casting temperature by utilizing semi-solid material was thought to offer a major contribution. Practically no mention was made of aluminum or magnesium alloys at that time, since the energy crises and result-

ing automotive market-pulls to save weight using high performance light metal parts were not yet a reality.

Rheocasting envisaged preparing semi-solid slurries directly beside a diecasting machine and casting the slurry into parts. Thixocasting included an additional step of casting ingots first. The ingots would later be sectioned into slugs or "charges", reheated to the semi-solid range and cast into parts. Thixocasting was seen as a means to consolidate material preparation into central locations as well as isolating material preparation issues from parts making: a problem in one area would not necessarily impact the other.

It is remarkable that these initial proposals differ only in degree from the practical reality of today, some 30 years later. During the early years, many alternative approaches to mechanical stirring were suggested to achieve the required microstructure. Partly, these explorations were a result of attempts to circumvent a strong MIT patent position, but almost certainly also a result of intense curiosity from the foundry world and perceived disadvantages of mechanical stirring. The suggested approaches included isothermal holding of dendritic material (coarsening), mixing of powders, passive stirring

(no active stirring at all, just flow through tortuous paths), electrical discharge through semi-solid dendritic material, inductive stirring, motor stirring via radial inductive fields, and extrusion and cold working(2). Of all of these suggestions however, really only electromagnetic motor or inductive stirring has become a widely accepted method for production of the so-called rheocast or SSM microstructure on a

CURRENT STATUS

Today there are three main variants of semi-solid processing which are achieving commercial attention and production. These comprise two alternative approaches to the original thixocasting procedure of MIT, namely semi-liquid processing and semi-solid processing, and a revival of the original rheocasting process now, sometimes, called “slurry on demand” processes.

Semi-liquid processing

The semi-liquid process has been perfected by Magneti-Marelli in Italy for the production of automotive fuel rails (Figure 1). It is characterized by the use of convection ovens to heat SSM slugs to relatively low fraction solid materials to aid flow into complex thin wall shapes(3).

Semi-liquid processing relies on a supply of specially prepared billet, pre-conditioned to generate the SSM microstructure upon reheating to the semi-solid temperature range. Typically these are cast using horizontal continuous casters and cold sheared to length, controlling shot weight. The sheared slugs are transferred by robot in an automated cell to steel boats coated with mold-wash, which transport them horizontally through a three-zone convection furnace.

Upon exiting the furnace at a temperature which can range

commercial scale, although small scale production via extrusion as well as variants of coarsening mechanisms are being used for some components today.

Also notable is that high temperature processing applications never achieved commercial success and the technology has been driven in recent years almost exclusively in the area of light metals for automotive applications.

from 580-615 degrees centigrade representing a fraction solid range for alloy 356 from approximately 55-60% to 35-40%, a separate robot is used to transfer the boat and slug to the shot sleeve, whereupon the boat is rotated, emptying the heated alloy through a slot into the sleeve. Since the material can be quite fluid at the time of casting, it is not always necessary to utilize powerful, real-time controlled machines in order to make high quality parts.

The semi-liquid process has been in full production since the early 1990's producing up to 9000 automotive fuel rails per day on five machines located in Italy and Brazil. Examples of a semi-liquid cast part are shown in a companion paper and elsewhere(3). Many similar parts are in production. These fuel rails are used in the as-cast condition exhibiting a high level of ductility and pressure tightness. Typical mechanical properties achieved are listed in table 1.

The use of convective heating improves the overall heating efficiency relative to induction heating and offers the possibility of using a range of fuel sources. Convective heating, however, as employed in the SSL process, does not seem to offer the same degree of heating control afforded by induction-based heaters which is also not required for the particular application.

The higher fluidity of the SSL process material allowed by the use of a boat to heat the slugs permits long, thin sections to be cast without porosity. The reduced thermal load and quiescent injection of the semi-solid slurry favors cores with draft angles of less than 0.5 degrees.

Semi-solid processing

Semi-solid processing (SSM) is a more direct development of the original MIT thixocasting technology. It is characterized by the use of induction heating to reheat slugs to the highest possible fraction solid in order to achieve the maximum mechanical performance. Also using SSM bar, semi-solid processing relies upon saw cutting as the norm for slug preparation since many systems rely upon the ability of the slugs to stand upright on ceramic pedestals during the reheating cycle. Since the slugs are heated to higher fractions solid, typically 55% for alloy 356, robots can be used to manipulate the slugs as soft solids and containers are not usual.

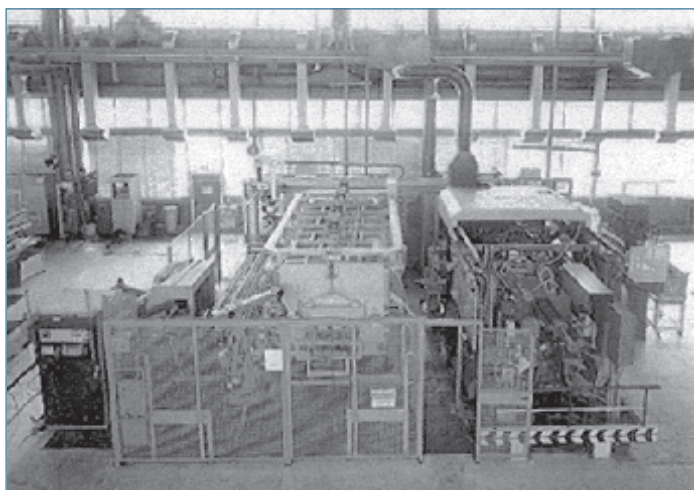


Fig. 1: Semi-Liquid (SSL) Installation at Magneti-Marelli, Italy

TABLE 1 - Mechanical properties achieved by SSM and SSL and competing casting processes
 (a) SSM, Squeeze cast and permanent mold comparison data from NADCA Standards for SSM and Squeeze cast Processes, 1999(b) SSL data from Magneti-Marelli S.p.A. 1998(c) SSM cast data from Aluminum-Pechiney, 1999

Alloy and Heat Treatment	Process	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation to fracture %	BHN
A356.0-T6(a)	SSM-cast	300	225	12	90
A356.0-T5(c)	SSM-cast	260	170	15	80
A356.0-T5(b)	SSL-cast	260		5.4	
A356.0-T6(a)	Squeeze Cast	300	225	12	90
A356.0-T6(a)	Permanent Mold cast	280	205	10	90

Recently, however, horizontal induction heating systems have also found utility. These horizontal systems heat slugs horizontally, in boats, much like the SSL process. This approach allows lower fraction solids to be achieved since the boats contain the heated material as it becomes soft and less viscous.

A disadvantage of the horizontal induction heating systems can be that transfer of the material, which may or may not be more fluid is less well controlled than with the higher fraction solid, vertical approach.

SSM installations are producing automotive and other structural components in Europe, North America and Asia, although none have yet achieved the production history of the SSL process.

An example of a part produced using a vertical heating system is shown in figure 5. This part currently in full production is heat treated to the full T6 condition after casting requiring no gas or lubricant entrapment beneath the surface. Typical mechanical properties are listed in Table 1.

Recycling

The high cost of SSM raw material has been a major hin-

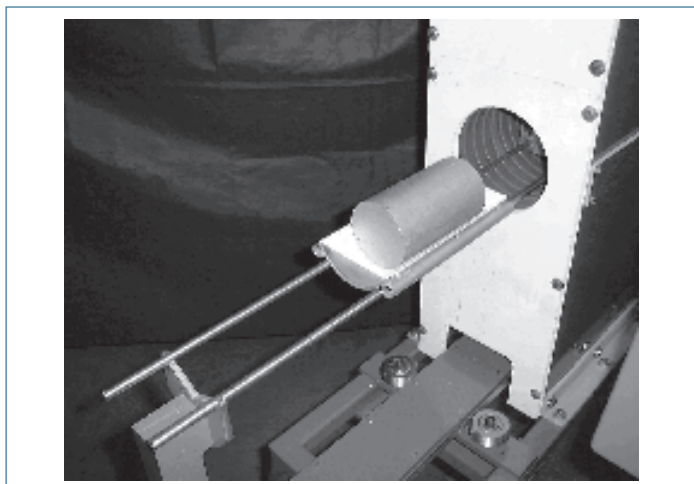


Fig. 3: Horizontal slug heating with boat

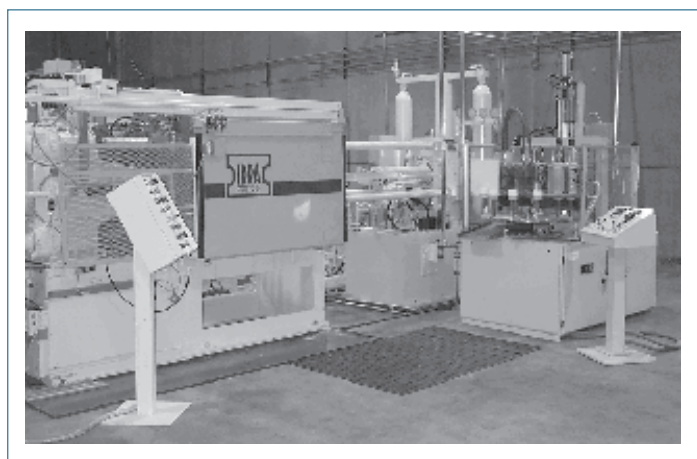


Fig. 2: Semi-Solid Metal (SSM) Installation at Vforge, Denver

drance to wider spread adoption of semi-solid processing and has re-ignited interest in slurry based systems, which are discussed below. Recently, however, small-scale horizontal continuous casting capability has been demonstrated as a viable means to recycle on-site(4). This topic is also the subject of an intense US Government funded research project located at Formcast, Inc., a subsidiary of Ormet Inc. one of three US

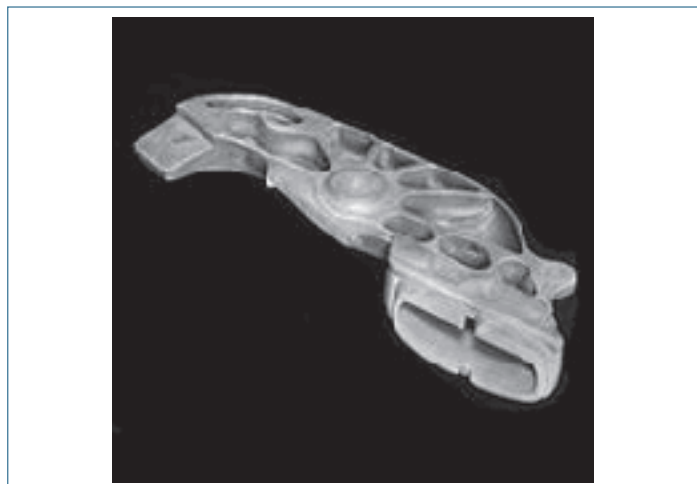


Fig. 4: SSM Motorcycle part T6

based producers of SSM raw material.

Horizontal continuous casting permits users not only to recycle scrap from SSM operations, it offers the potential to reduce raw material cost by purchase of lower cost melting scrap and/or the ability to produce custom-designed alloys. Potential recyclers however, must be prepared to deal with all the issues associated with liquid metal processing including chemical analysis, melt filtration, microstructure control and consistency. Recycling therefore offers potential reduced cost at the sacrifice of assuming many responsibilities which slug-based SSM processors today pass on to their raw material suppliers. Because of this scenario, it is likely that in-house recycled raw material will at least initially be applied on less critical components, competing perhaps for the same applications as slurry based systems.

Slurry on Demand

Slurry on demand, as we have chosen to call it in this article, is a relatively recent revival of the original MIT rheocasting process. Its resurgence can be attributed largely to the high initial cost of SSM raw material. A slurry on demand approach eliminates the need for special raw material and allows on-site recycling since the basis is liquid metal.

Slurry on demand describes a process whereby liquid alloy is transformed at the casting site to a semi-solid slurry. In the original MIT research, this was achieved with mechanical mixing systems and some of the latest versions would seem to retain this concept although electromagnetic stirring has also been suggested. Once formed, the slurry must be transferred to the shot sleeve of the casting machine. This transfer can presumably be identical to liquid based casting systems and can be via gravity, ladles, pumps or suction tubes. Use of this approach not only eliminates the high premium placed upon SSM billet by suppliers, but also solves a secondary recycling issue since scrap can be returned to the central melting furnace as in conventional foundries.

Since slurry on demand systems require a fluid slurry in order to function, it is probable that they will not achieve the same level of final part quality achievable with “best practice” slug-based systems. First, the material is more fluid and thereby more likely to experience turbulence during filling. Furthermore, the material is less solid and therefore likely to experience more solidification shrinkage issues. Economically, a disadvantage of slurry systems is that the alloy heat content of slurry is higher and therefore the die must extract more heat to generate a solidified part. This can impact cycle time and adversely affect die life.

However, by reducing the overall processing cost, slurry-based systems expand the market potential of SSM processing into pressure-tight parts such as air conditioner, brake and fuel system parts. Furthermore, because the material is very fluid, normal three phase injection system diecasting machines can be used, just as in the original MIT research work.

Figure 6 shows a part produced from a mechanical mixing system located at the casting machine. Fatigue life of this power steering pump housing was increased two fold relative to the die-cast conventional part and the need for impregnation was eliminated.

IMPLICATIONS FOR SSM SYSTEMS

As a candidate process for the new “High Integrity, High Performance” applications, process stability and control is a critical element for success. This means in a practical sense that incoming raw material, slug heating parameters (if relevant), shot injection profiles and post-forming heat treatment can be readily monitored, are stable and repeatable. In the case of slurry systems, slurry temperature or fraction solid, grain size and fluidity are important.

Incoming material inspection

For slug-based technology, an appropriate incoming material specification and acceptance procedure can ensure consistent performance. Parameters frequently specified include:

- Chemistry: Chemistry is important since it influences not only the final achievable mechanical properties, but also reheating behaviour and fraction solid versus temperature.

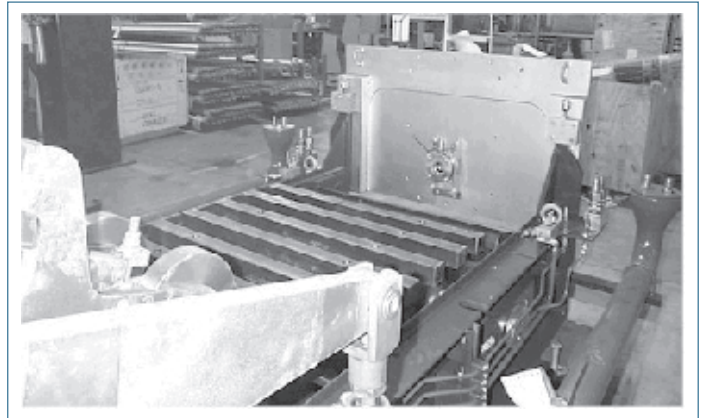


Fig. 5: Mini horizontal castee for SSM bar from Hertwich GmbH



Fig. 6: Power steering pump body cast from slurry on demand system

- Grain size: Grain size and shape impacts flow.
- Surface quality: Surface quality is not only important to limit the potential for defects to enter the parts, but it also impacts the radiation losses during reheating which can cause significant differentials in final fraction solid at forming.
- Inclusion content: Inclusion content limits the entrainment of harmful effects in the formed parts.
- Fluid behaviour: Fluid behaviour is often, but not always specified utilizing some proprietary test designed to mimic the actual part forming operation. Results in practice have been varied, however.

For slurry systems, chemistry and inclusion content would seem to be the only relevant parameters for incoming material inspection, since grain size, and fluid behaviour are generated on-site.

Heating Systems

Slug heating parameters depend upon the system employed, but frequently include frequency, electrical current and voltage combined with time exposure for induction equipment and zone temperatures and transfer time for convection furnaces. In-process monitoring for slug heating can include intermediate temperature measurement at some stage through the heating cycle (typically at the transition from solid to melt-start), as well as final temperature or indirect fraction solid sensing based upon inductive sensors.

Injection profiles

Both slug-based and slurry approaches require a stable, repeatable injection profile. While much has been made over the years about the necessity for real-time control, recent data suggests that many high quality parts can, in fact, be produced using simpler three-phase injection control, although more complex shapes still demand shot end flexibility and feedback loops. Perhaps more important is the need for high injection force, particularly for semi-solid systems and repeatability to ensure consistent performance and flow characteristics.

Typically, a rapid plunger approach velocity is used to move the slug from the load position to the entrance to the die cavity. Once at the gate, a slower preferred injection velocity typically in the range of 250 to 500 mm per second is applied to move the material as quickly as possible through the die without inducing turbulence. For simple cavities, this can be a single velocity, adequately achieved using a conventional machine. For more complex shapes, accelerations and decelerations are sometimes needed in order to fill quickly, but quiescently and these demand real-time control. However, perhaps as much as 50% or more of current applications can most likely be produced using simple injection velocity profiles. Machines which can offer both standard three-

phase injection as well as upgrade options for real-time control can therefore offer significant economic benefit for SSM manufacturers since this expensive option must not necessarily be purchased at the outset.

Given the lower viscosity of slurry based systems, injection velocities should generally be slower than with slug systems, but not so much as to impact cycle times. However, the use of slurry greatly improves the probability that conventional three-phase injection profiles can be effective for all applications reducing system cost even further.

SUMMARY

To summarize therefore, slug-based SSM forming requires the capital expenditure for not only the forming press but also the slug heater of whatever type and the associated robotics and sawing systems. The press system may have the additional cost of reinforced, high power injection and for some applications, may require real-time control. As trade-off for this added cost, slug systems have the greatest chance of producing the very highest quality, fully heat treatable components.

On the other hand, slurry approaches offer simpler systems, eliminating slug saws, slug heaters and much of the additional robotics in exchange for a slurry making machine interposed between the forming press and the liquid metal holder. As a general rule, the forming press can be simpler, with reduced requirement for reinforced shot-end and often eliminating the need for real-time control. Slurry based systems are therefore widening the potential market for semi-solid processing by reducing the manufacturing cost. This development should in turn increase pressure on raw material suppliers to reduce their costs and maintain market share in the face of this low cost competition. Overall, the outlook continues to be positive as more and more companies will evaluate and adopt semi-solid processing as one element of their metal part fabrication strategy.

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