Semi-solid forming: the process and the path forward

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SSM TODAY

"Semi-solid forming", also known as "Semi-solid metallurgy" (SSM), is now in its thirtieth year. The original experiment leading to the invention of SSM was performed in early 1971 by David Spencer as a part of his doctoral thesis. In that experiment, David discovered the essential rheological properties of vigorously agitated semi-solid metals.[1],[2] We immediately recognized the importance of the discovery and by the summer of that year had performed industrial trials demonstrating the feasibility of the two routes, which we termed "Rheocasting" and "Thixocasting".[3] Today, nearly thirty years later, with much production being carried on throughout the world, it is still not clear which of these two basic routes will be of the greatest long-term significance.
Whatever the route employed for semi-solid forming, several advantages of the process are clear. The most important of these, in the view of most technologists today, is the non-turbulent filling of the die, which results from the high and controllable viscosity of the semi-solid material. This smooth mold filling eliminates the air entrapment encountered in the conventional die-casting process and results in parts of high integrity with superior mechanical properties. For many alloys, heat treatment results in further property improvements. The semi-solid forming process produces parts with less shrinkage porosity than those produced by conventional die casting. Die filling temperature is lower and heat content of the metal less, resulting in less thermal shock and lower cycle times.
Over the last decade and more the primary driving force for development of semi-solid forming has been the energy efficient automobile. Aluminum usage in the automobile, primarily in cast form, has increased dramatically and with that increase has come the need for parts of higher strength and greater reliability. SSM is one of the important processes filling that niche. The major SSM route employed today is that of "Thixocasting"; that is, the manufacture of billets of the desired microstructure (usually by continuous casting), and the subsequent reheating and forming of the billets in the semi-solid state. The desired structure in the continuous castings is obtained in most cases by electromagnetic stirring. For small sections, the alternative "SIMA" process can be employed to obtain the desired structure. In this case, a conventional continuous casting is worked and reheated to obtain recrystallization in the solid state.
The main specific advantage of the Thixocasting route is that the forming facility is freed from having to deal with liquid metal, and the process can be highly automated using approaches similar to those employed in forging and stamping. This basic concept of completely separating the two main parts of the process (formation of the proper structure and forming of the parts) has been intuitively appealing, and much work has been done in developing this process route industrially. As time progresses, the disadvantages of the thixocasting route are also becoming apparent. It has been difficult to obtain fully homogeneous billets in electomagnetically stirred continuous castings. Typical billets have some degree of inhomogeneiety with respect to both structure and composition. There is metal loss on reheating the billets which may amount to as much as 10 percent of the total part weight. Gates and risers from formed parts cannot be recycled within the forming facility, but must be sent back to the ingot producer. Thus, the metal former pays a premium to the continuous caster, not only for the unique structure in the metal he sells to a customer but on that as well that he returns to the primary producer.
There is a modification of the thixocasting route that has become of commercial significance for forming of magnesium alloys: "Thixomolding". In this case, chips of fine structure are fed to a machine that has much in common with a plastic injection molding machine. The chips are partially melted, obtaining a structure suitable for semi-solid forming. A large number of such machines are now in operation for producing magnesium castings, particularly for electronic components. At the present time, the process appears to be limited to relatively low fractions solid and to magnesium or lower melting point alloys.
The search for low cost routes for producing parts by semi-solid forming directly from the liquid state (i.e. "Rheocasting") is now progressing in earnest. Processes being exploited today fall into two general categories. In one category liquid metal is poured into a container of approximately the size of the billet to be fed to the shot chamber of a forming machine. The desired structure is then obtained in the billet by some combination of cooling, grain refinement, and/or convection. At the proper temperature the billet is fed to the forming machine.
In the second route being exploited the desired slurry structure is obtained within a bath of some considerable size, that structure again being obtained by some combination of cooling, grain refinement, and stirring. Desired quantities of the semi-solid metal are then extracted from the bath and formed by one or another process.
Progress in semi-solid forming has been marked thus far by six biennial meetings. The first was held in Sophia-Antipolis, France in 1990[4]. The second at MIT in Cambridge in 1992[5], the third in Tokyo in 1994[6], the fourth in Sheffield in 1996[7], the fifth in Golden, Colorado in 1998,[8] and the sixth in Turin Italy in September 2000[ix]. Over these years, the meetings have been marked with steadily increasing attendance and numbers of papers presented, and also with steadily increasing conviction as to the commercial importance of the semi-solid forming process. At the recent meeting in Turin, there were near 300 attendees from 15 different countries, with 150 papers and posters presented.

We were privileged at the Turin meeting to have a large number of high quality papers on many aspects of the structure, processing, properties and performance of semi-solid alloys. Following are a few observations relating to some of the main categories of papers presented. Much progress has been made in the last two years in the modeling of semi-solid alloy structure, flow and filling. Models such as those presented here will find important industrial use in the coming years. Experimental work that was presented on structure-flow behavior relations provides necessary data for the mathematical model development. It is noteworthy that semi-solid forming of magnesium has come into its own industrially. Interest is obviously growing in a wide range of other metals and alloys, including even copper and steel. A number of interesting papers deal with production of the desired microstructure by other than the heretofore most widely followed route of electromagnetic casting. Examples of actual parts formed and cost comparisons of different routes provide useful case studies. Many of the advantages of semi-solid forming anticipated as long ago as the first SSM conference in Sophia-Antipolis have now been commercially realized.

In this issue of Metallurgical Science and Technology are reprinted a selection of papers presented at the Turin meeting.

Table 1 - Characteristics (of Semi-Solid Metals) for Future Exploitation

CHARACTERISTIC	POTENTIAL BENEFIT OR APPLICATION
Lower hear content than liquid metal	Higher speed part forming Higher speed continuous casting Lower mold erosion Ferrous part forming Forming of other high-melting-point materials Forming of reactive metals
Solid present at time of mold filling	Less shrinkage voids Less feeding required Less macrosegregation Fine grain structure
Viscosity higher than in liquid metals, and controllable	Less entrapped mold gases Reduced oxides – improved machinability Less mold attack Higher speed part forming Improved surface finish Automation New processes
Flow stress lower than for solid metals	Forming of intricate parts High speed part forming Lower cost part forming High speed forming of continu ous shapes (e.g. extrusion) New processes
Ability to incorporate other materials	Composites
Ability to separate liquid and solid	Purification

These papers demonstrate the breadth, scientific depth, commercial practice and potential of the SSM of today. They also reflect the high level of excitement and optimism for the future that pervaded the Turin meeting. I cannot close without also adding that the conference attendees were impressed and delighted with the efficiency, hospitality and grace of the Turin organizers of the meeting

THE PATH FORWARD FOR SSM

What of the future? It seems clear that in the near future the primary market for semi-solid formed parts will be the light alloys aluminum and magnesium, and to a limited extent composites, with these metals as matrices. Market applications will be for high-end automotive and electronic components. Process routes will continue to evolve, with emphasis in the coming few years on direct production of slurry from the liquid (i.e. the Rheocasting route). We need, and will find, better, more economical ways of producing the original slurry structure and transferring that structure to a forming machine. Aside from the major efforts that will certainly take place in overall process development, three research directions will be key. One of these will be the formulation of a better understanding than we now have of the mechanism whereby the desired "Rheocast" structure forms. Second will be the development and full application of mathematical models for overall part production. Third will be development of alloys specially tailored for SSM, and with that development, the forming of parts at higher fractions solid and faster speeds.

Some of us, who have been with this process since its beginning may think that thirty years is a long time to bring a new process to maturity, but many things have had to fall into place to make it happen, not least among them the development of a clearly defined market. Today, the key factors seem to be present for a large-scale expansion of the production and utilization of semi-solid formed parts.

REFERENCES

1 D.B. Spencer: PhD Thesis, Massachusetts Institute of Technology, Cambridge, MA 1971.

2 D. B. Spencer, R. Mehrabian, and M.C. Flemings, "Theological Behavior of Sn-15%Pct Pb in the Crystallization Range," Met. Trans., 3 (1972) 1925-1932.

3 R. Mehrabian and M.C. Flemings, "Die Casting of Partially Solidified Alloys," *Trans; of the A.F.S.*, 80 (1972) 173-182; *Die Casting Engineer* (July-Aug. 1973) 173-182.

4 Abstracts Book, Semi-Solid Processing of Alloys and Composites, Ecole Nationale Superieure des Mines de Paris, Societe Francaise de Metallurgie, Cemef, Sophia-Antipolis, France, 1990.

5 Proceedings of the Second International Conference on the Semi-Solid Processing of Alloys and Composites, (eds. Stuart B. Brown, Merton C. Flemings), Massachusetts Institute of Technology, Cambridge, Massachusetts, 1992.

6 Proceedings of the Third International Conference on Processing of Semi-Solid Alloys and Composites, (ed. M. Kiuchi), Institute of Industrial Science, University of Tokyo, Tokyo, Japan, 1994.

7 Conference Proceedings, 4th International Conference on Semi-Solid processing of Alloys and Composites (eds. D.H. Kirkwood, P. Kapranos), The University of Sheffield, England, 1996.

8 Proceedings 5th International Conference on Semi-Solid Processing of Alloys and Composites, (eds. A. K. Bhasin, J. J. Moore, K. P. Young, S. Midson), Colorado School of Mines, Golden, Colorado, 1998.

9 Proceedings 6th International Conference on Semi-Solid Processing of Alloys and Composites, (eds. G.L. Chiarmetta, M. Rosso), Turin Italy, 2000.