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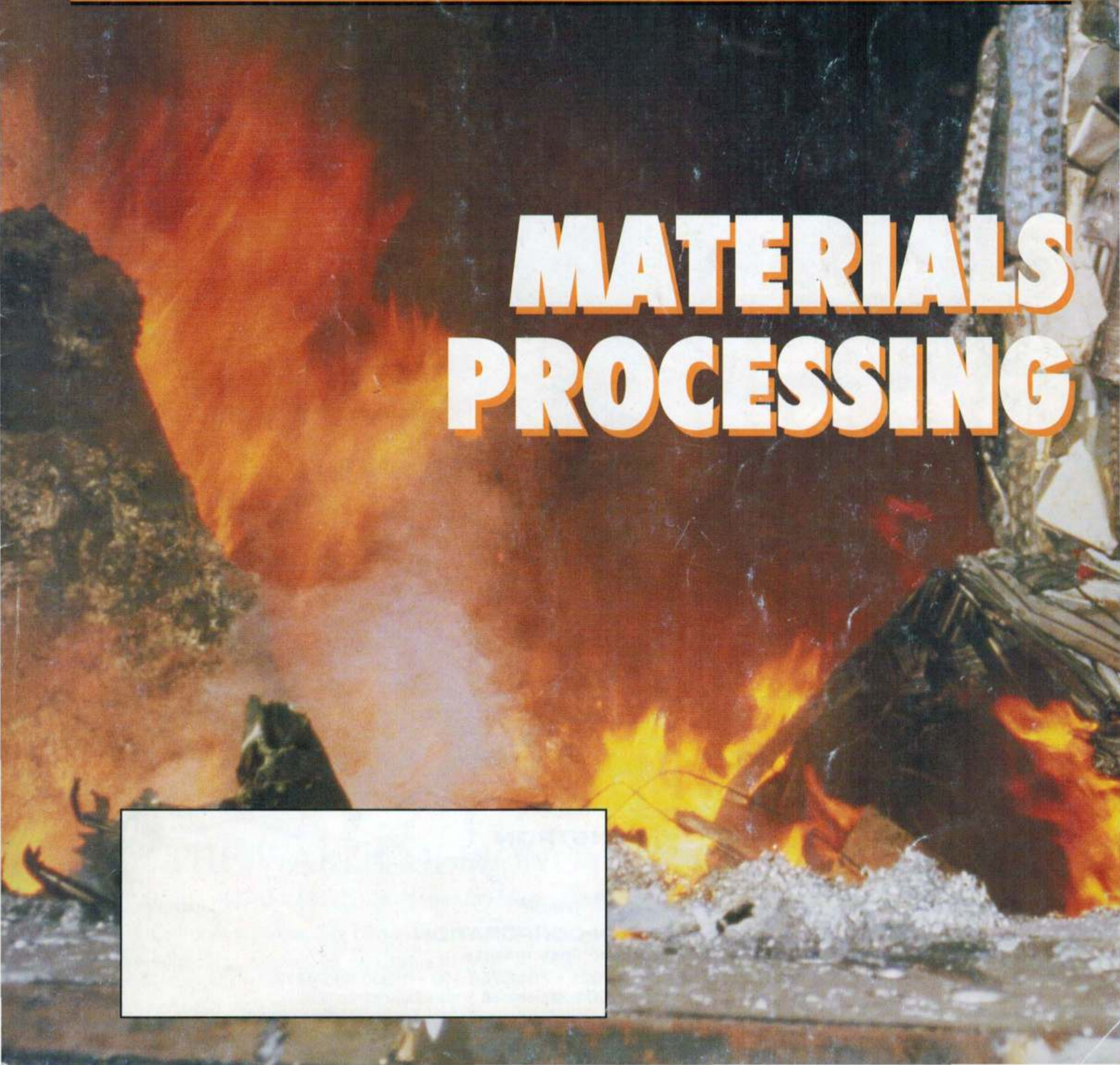

MATERIALS PROCESSING

Alloy Compositions for SEMISOLID FORMING

Semi-solid forming produces excellent surface quality and precise finished part geometry, high strength, and good plastic properties, but the alloy composition must be very carefully selected.

*Alexander A. Kazakov**
St. Petersburg State Technical University
St. Petersburg, Russia

Semi-solid forming is a production method that combines the elements of casting and forging. The process consists of three sequential stages: rheocasting, reheating, and forming.

The rheocasting stage involves magneto-hydrodynamic stirring of the alloy at the solidification front; this yields billets with nondendritic (thixotropic) microstructures (Fig. 1a). During the reheating stage, the slugs from the thixotropic billet are heated in an induction furnace. When they reach the semi-solid state temperature, they contain equal amounts of liquid and solid. Also at this temperature, alpha solid-solution grains become increasingly spheroidized, a process that begins in the first stage (Fig. 1b). In the third stage, forming, the mold is filled with the semi-solid material (SSM) and the finished part is produced.

The technical and economical advantages of SSF technology enable production of a variety of automotive and aerospace components. However, not all alloy compositions can be formed in the semi-solid state.

The advantages of the process and the principles of alloy composition selection for semi-solid forming technology are presented in this article.

Advantages of semi-solid forming

Advantages of SSF technology over conventional casting procedures are many and well known:

- The thixotropic structure of alloys in the semi-solid state provides excellent filling of the mold, even for geometrically complex parts (thin-section and hollow) under the applied forces, which are significantly less than those needed for conventional forging.
- Laminar filling of the mold eliminates the capture of gases during forming.
- Excellent surface quality and precise finished part geometry are produced.
- Defects such as pores, shrinkage cavities, and hot cracks are significantly reduced.
- High strength and good plastic properties can be produced by simple heat treatments because the forming process itself provides strengthening.
- SSM with thixotropic structures can be processed by automated equipment. This allows con-

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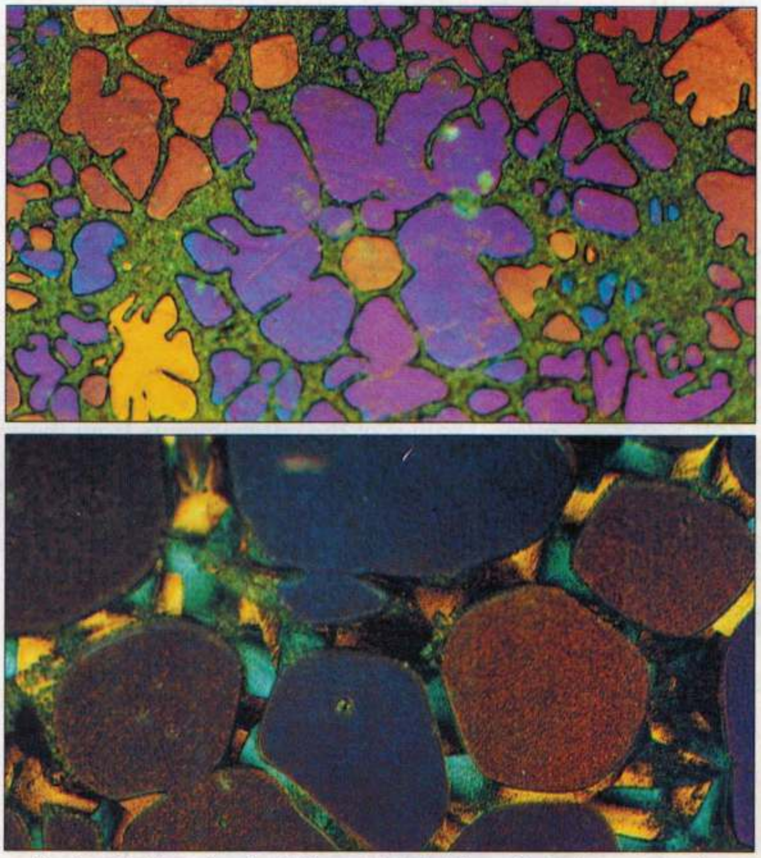

Fig. 1 — Test bar of semi-solid formed A356 with anodized microstructure in polarized light. a: as-cast, magnified 250X; b: as reheated, magnified 500X.

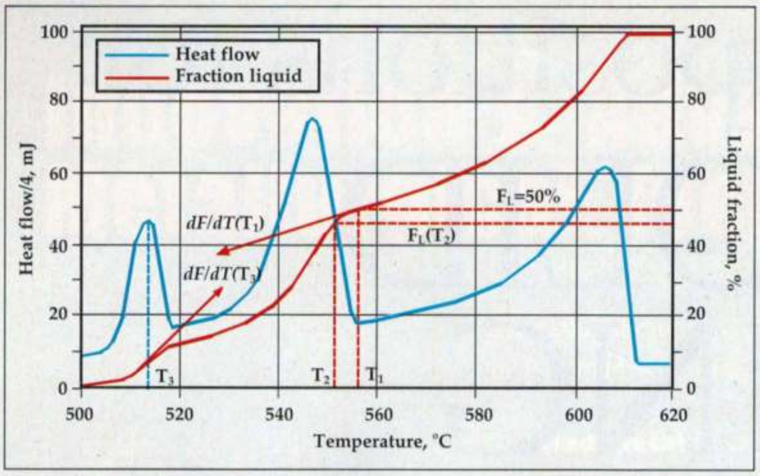

Fig. 2 — Results of the differential scanning calorimetry and parameters that are important for semi-solid forming. The graph shows an Al-5Si-5Cu alloy.

The physicochemical composition selection criteria for SSF alloys have been developed.

struction of high capacity, fully automated production lines, with reduced power consumption and cost savings.

Alloy selection

The physicochemical composition selection criteria for alloys produced by SSF technology have been developed, and the database of critical points for the fraction-liquid / temperature curves for the commercially important aluminum alloys has been created on the basis of thermodynamic modeling and scanning calorimetry experiments. The numerical values of the critical points from these curves can help optimize the chemical composition of the alloys produced for semi-solid forming technology.

The fraction-liquid / temperature relationship provides the fundamental basis for the design of alloy compositions for SSF technology. Therefore, a search for new SSM compositions, as well as physicochemical understanding of the process, is impossible without analysis of the temperature-dependent nature of the liquid fraction.

Beginning with the classic investigations of SSM by Mert Flemings and his colleagues, primary attention has been focused on rheological behavior and microstructural evolution at all stages of this technology, including rheocasting, reheating, and forming. Nevertheless, the importance of the fraction-liquid / temperature curve cannot be overestimated for proper understanding of rheological behavior and special features of the alloys in the semi-solid state. Also, the curve helps understanding of the microstructural evolution in these alloys during production. Therefore, this curve is the fundamental basis for a search of potential alloy compositions for SSF technology.

Our SSF investigation defines advanced SSM compositions based on analysis of the fraction-liquid / temperature curve. This information is based on differential scanning calorimetry aided by thermodynamic modeling.

The heat-flow / temperature curve can be based on differential scanning calorimetry methods to study the candidate alloys. An example for an Al-5Si-5Cu alloy is illustrated as the blue line in Fig. 2. This curve exhibits three peaks that correspond to the heat flow during the sequential crystallization of the alpha solid-solution of the base aluminum, then the binary eutectic, and finally the ternary eutectic. The area under the curve represents the fraction liquid (F_L) in the solidifying alloy, and is shown in red. Analysis of current SSF technology indicates that the following parameters are very important if we are to realize the advantages of this technology:

- *The temperature at which the slurry contains 50% liquid, T_1:* To minimize the problem of pressure welding between the steel tooling and the liquid aluminum alloy, this temperature must be <585°C (1085°F), and preferably lower.
- *The slope of the curve at fraction liquid F_L=50%, $dF/dT(T_1)$:* To minimize reheating temperature sensitivity, this slope should be as flat as possible. The slope of the curve, $dF/dT(T_1)$, should be minimal to permit overheating of the slug during the reheating process. Overheating produces a technological reserve, ensuring a sufficient quantity of fraction liquid for the following stage of SSM production. For example, for aluminum alloy 357, widely applied in SSF technology, $|dF/dT(T_1)| = 0.005/°C$.
- *The temperature of the beginning of alpha solid-solution melting, T_2:* This is the most important parameter of the curve. At this point, $[F_L(T_2), T_2]$, eutectic melting is completed and the alpha solid-solution grains start to dissolve. The difference $T_1 - T_2 \geq 0$ determines the kinetics of dendrites spheroidizing during reheating.
- *The slope of the curve in the region where the solidification process is completed, $dF/dT(T_3)$:* This slope should be relatively flat to avoid hot-shortness problems. For example, for alloy 357, $|dF/dT(T_3)| = 0.02/°C$

Thermodynamic effects

The fraction-liquid / temperature curve can be generated by thermodynamic modeling, which can minimize prolonged and expensive experimental investigations. The estimated results in the current study were generated by the commercial program ChemSage 4.1 and the thermodynamic database SGTE.

The most important parameter is the position of the point $[F_L(T_2), T_2]$. At this point, eutectic melting is completed and the alpha solid-solution grains start to dissolve. To ensure successful rheocasting and reheating operations, the new SSM should be selected in such a way that the point $[F_L(T_2), T_2]$ is located close to where the ratio of the liquid to the solid fraction is 50:50 With this reason as the basis for modeling, the binary Al – (5-7)Si system was selected, with a third alloying element added.

The ternary system was created by selecting the third element based on binary aluminum alloys in which the phase diagram predicts that the chosen third element and aluminum exhibit a eutectic transformation. Further, addition of this third element should increase the strength. Consequently, the following candidate third alloying elements were selected: lithium, magnesium, zinc, copper, manganese, cerium, and nickel. The concentration range studied was based on the usual content of these elements in commercial aluminum alloys.

The fraction-liquid curves were plotted by thermodynamic modeling methods for the solidification temperature range of the ternary systems Al – (5-7)Si – X, where X can be magnesium, lithium, copper, zinc, manganese, cerium, or nickel. Curves were also plotted for the quaternary aluminum-silicon-copper-magnesium system. Calculations revealed the following:

- *With increasing lithium content* from 0 to 6%, the position of the $[F_L(T_2), T_2]$ point is reduced by 48 to 42°C (86 to 75°F) in temperature, and increased by 0.22 to 0.26 in the fraction liquid, respectively.
- *With increasing magnesium concentration* from 0 to 1%, the $[F_L(T_2), T_2]$ point is reduced by 13 to 10°C (23 to 18°F) in temperature and decreased by 0.02 to 0.03 in the fraction liquid, respectively.
- *With increasing zinc concentration* from 0 to 8%, the $[F_L(T_2), T_2]$ point is reduced by 11 to 9°C (20 to 16°F) in temperature and raised by 0.08 to 0.09 in fraction liquid, respectively.
- *With increasing copper concentration* from 0 to 5%, the $[F_L(T_2), T_2]$ point is reduced by 21 to 14°C (38 to 25°F) in temperature and raised by 0.08 to 0.09 in fraction liquid, respectively.
- *The effect of manganese additions* on the position of the $[F_L(T_2), T_2]$ point is not significant; while additions of cerium and nickel have almost no influence on its location.

Therefore, out of all the elements considered, only additions of silicon, copper, magnesium, lithium, and zinc substantially change the position of the $[F_L(T_2), T_2]$ point, thus considerably affecting the technological properties of the semi-solid material.

Because of the known technological problems in the melting and casting of aluminum alloys containing zinc and/or lithium, the quaternary system Al – (5-7)Si – (3-4)Cu – (0-1)Mg was selected for subsequent studies.

Modeling results for this system at different alloying element concentrations are shown in Fig. 3. Changing the concentration of alloying elements in a rather narrow range provides a means to control the position of the $[F_L(T_2), T_2]$ point: 550 to 570°C (1020 to 1060°F) in temperature and 0.31 to 0.53 in fraction liquid. At the same time, other important characteristics of the fraction-liquid/temperature curve also change. This knowledge permits selection of compositions of new SSM while providing the required technological and mechanical properties.

The same calculations were made for some industrial alloys close in composition to the alloys studied. This suggested that commercial aluminum alloys 308, 319, and 343 should be tested for the SSF technology. The first two have fraction-liquid/temperature curve parameters that are more preferable for semi-solid forming than the commercial aluminum 356/357 alloys. In fact, the French alloy AS7U3G (Al - Si - 7Cu - 3Mg), which has approximately the same composition as the above-mentioned alloys, has been successfully produced by SSF technology. The tensile strength of this alloy in the as-formed condition with a T6 temper heat treatment, was 440 MPa (64 ksi), which is distinctly higher than that achieved by 356/357 alloys, which are widely applied in SSF technology.

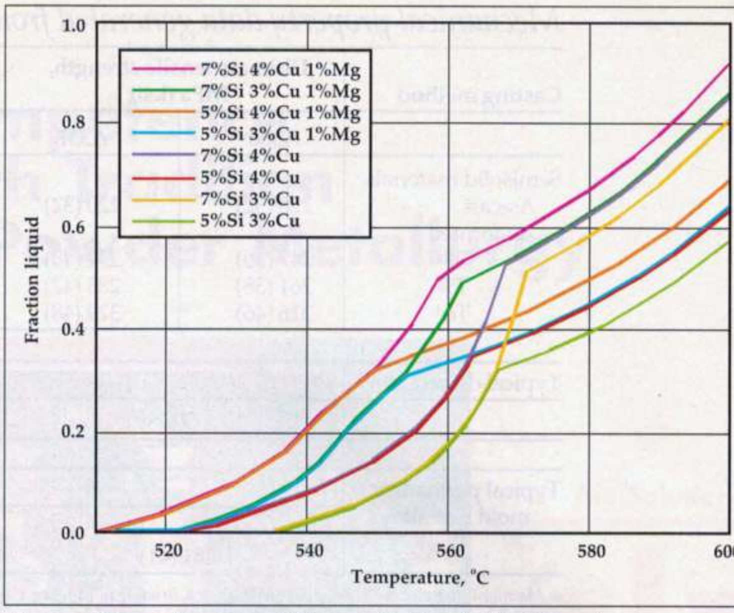

Fig. 3 — Thermodynamic modeling results of an AlSiCuMg system.

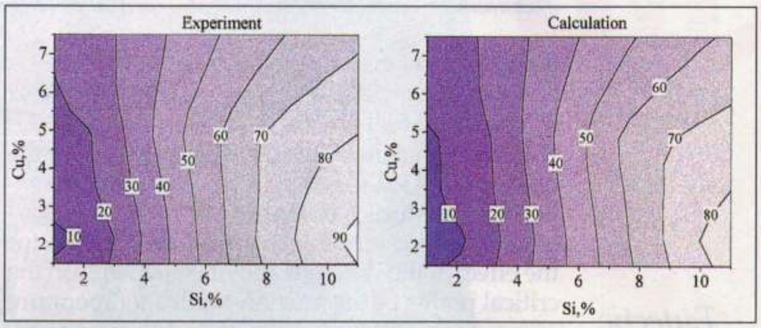

Fig. 4 — These graphs show the experimental and calculated values of the fraction-liquid isolines at the temperature of the beginning of alpha-solution melting of AlSiCu alloys.

Knowledge of the fraction-liquid vs. temperature curve permits selection of optimal compositions of Al-Si alloys.

Experimental investigation

To check the correlation between calculations and real process results in solidifying alloys, eleven alloys from the Al – (2-11)Si – (2-8)Cu system and sixteen alloys from the Al – (5-7)Si – (3-4)Cu – (0-1)Mg system were studied experimentally by differential scanning calorimetry. The alloys were melted in an induction furnace. The starting materials consisted of grade A8 aluminum (0.126-0.142Fe), monocrystalline silicon (total impurities <0.001%), cathodic copper (total impurities < 0.05%) and an Al-Mg master alloy.

The samples for calorimetric studies were cut from templates from ingots in the form of disks weighing about 125 mg. These samples were tested on a Setaram DSC111 calorimeter system at heating and cooling rates of 5°C/min and 1°C/min (9°F/min and 2°F/min). For each alloy studied, three replicate tests were carried out. The experimental results showing the dependence of heat flow versus temperature were received in digital array form. The fraction-liquid/temperature curves were

Mechanical property data generated from test bars[a]

Casting method	Ultimate tensile strength, MPa (ksi)		Yield strength, MPa (ksi)		Elongation, %	
	A356	A357	A356	A357	A356	A357
Semisolid materials						
As-cast	220 (32)	220 (32)	110 (16)	117 (17)	14	7
As-formed						
T4[b]	247 (36)	274 (40)	130 (19)	151 (22)	20	15
T5[c]	261 (38)	288 (42)	185 (27)	199 (29)	10	5
T6[d]	316 (46)	329 (48)	240 (35)	261 (38)	12	9
Typical diecast alloy	Alloy 380					
	329 (48)		165 (24)		3	
Typical permanent mold cast alloy	A356 T61					
	281 (41)		206 (30)		10	

a: Machined from cast parts. From S.P. Midson & K.Brissing in Modern Casting, *2, 41-3, 1997. b: 520°C, 2 hr water quench, 4 days at room temperature; c: 180°C, 2 hr air cool; d: 520°C, 2 hr water quench, 160°C for 7 hr.*

Note: The yield strength of semi-solid formed castings is higher than die castings because the porosity in die castings limits elongation and precludes the possibility of heat treatment to increase strength. The faster cooling rate of SSF castings produces a fine microstructure that results in higher yield and tensile strengths.

developed by digital integration of these data.

Figure 4 shows the comparison of calculated and experimental $F_L(T_2)$ results characteristic for the Al-Si-Cu system. Similar results were acquired for the quaternary Al-Si-Cu-Mg system. Results of the experimental studies demonstrated that the calculated data give absolutely correct estimations for the effect of the different alloying elements on the critical points of the fraction-liquid / temperature curves for aluminum alloys, thus permitting prediction of the ways to optimize compositions of these alloys for semi-solid forming.

Eutectic silumins are impractical for SSF technology.

One result showed that eutectic silumins are impractical for SSF technology. The comparative results of the experimental fraction-liquid / temperature curves for this alloy, and also for alloy 357 (which is widely used as a SSM), are illustrated in Fig. 5. As this figure demonstrates, the critical points of the curves for eutectic silumin do not satisfy the above-enumerated criteria for semi-solid materials. In particular, at the 50:50 ratio of liquid-to-solid fraction, the slope $dF/dT(T_1)$ is too steep, and the width of the mushy zone will be too narrow for rheocasting and will not provide a sufficient extent of destroyed dendrites.

Further, the high value of $dF/dT(T_1)$ will cause problems during reheating, because small temperature fluctuations will cause the slug to considerably change its liquid / solid ratio. This may result either in flowing out of eutectic from the slug (causing an "elephant foot" defect), or in freezing of the slug and resulting hot-shortness during the forming stage. By contrast, a flat portion of the fraction-liquid / temperature curve for the commercial aluminum 357 alloy in the neighborhood of the 50:50 liquid / solid fraction permits attainment of SSF technology parameters during rheocasting and during reheating. The result of these experiments is a database of critical points for the fraction-liquid / temperature curve. The numerical values of these critical points can become the basis for optimizing alloy composition. ■

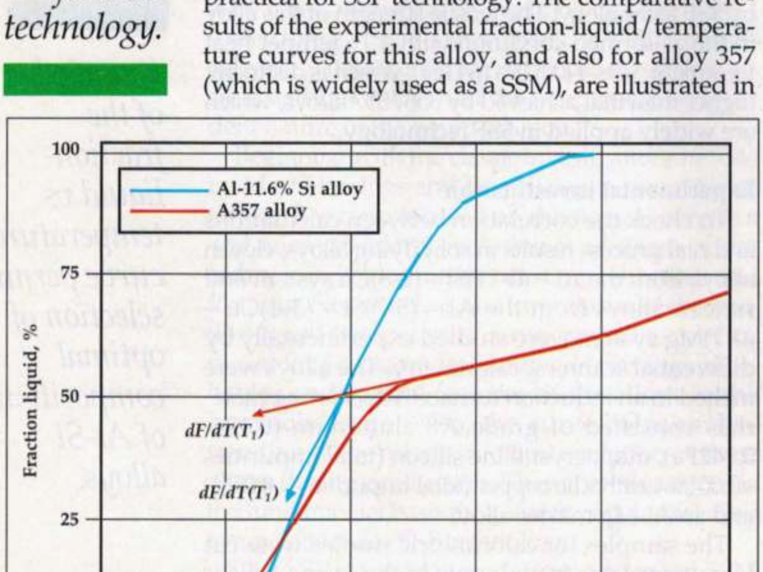

Fig. 5 — These experimental curves show the fraction-liquid/temperature relationship of AlSi alloys that are suitable for SSF.

For more information: Alexander A. Kazakov, St. Petersburg State Technical University, St. Petersburg, Russia; e-mail: kazakov@lb.csa.ru.

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