New foundry process for the production of light metals in the semi-liquid, doughy state

P.L. ANTONA and R. MOSCHINI, Centro Ricerche Fiat, Orbassano (Turin), Italy.

Abstract
Subjecting a metal alloy at the time of solidification to an elevated shear rate it is possible, upon solidification, to verify a microstructure very different from the conventional ones; the effect of the shear forces induced is, indeed, to destroy the solid network of dendritic interconnections developed during solidification of the liquid. In the absence of such a structure the dendrite fragments remain separate, and tend to assume spheroidal shapes by continual mutual mechanical collisions.
The Fiat Research Centre has patented and developed a process that makes it possible to confer on the metallic alloy such globular structures based on the use of a capillary type static mixer.
The present work describes the pilot plant able to produce semiliquid metal continuously, and illustrates the operating technique for producing a casting in the doughy state.
Moreover, the microstructural characteristics of an Al-Si-Cu alloy cast in the semi-liquid state underline the inherent fluid-dynamic peculiarities possessed by such an alloy in the solidification range which allow it to be used easily in forming processes.

Riassunto
Nuovo processo di fonderia per la produzione di leghe metalliche allo stato semiliquido pastoso
Sottoponendo una lega metallica in fase di solidificazione ad un elevato gradiente di scorrimento è possibile riscontrare, a solidificazione avvenuta, una microstruttura che si differenzia in modo molto evidente da quelle convenzionali; l'effetto degli sforzi di taglio indotti è infatti quello di distruggere la rete solida di interconnessione dendritica che si sviluppa durante la solidificazione del liquido: in assenza di tale struttura i frammenti dendritici restano indipendenti e tendono ad assumere forme sferoidali per i continui mutui urti meccanici.
Il Centro Ricerche Fiat ha brevettato e sviluppato un processo che consente di conferire alle leghe metalliche tali strutture globulari basato sull'impiego di un miscelatore statico di tipo capillare.
Nel presente lavoro viene descritto l'impianto pilota in grado di produrre semiliquido metallico in regime continuo e sono illustrate le modalità operative per l'esecuzione di una colata allo stato pastoso.
Viene inoltre presentata la caratterizzazione microstrutturale di una lega Al-Si-Cu colata allo stato semiliquido, sottolineando le peculiari proprietà fluidodinamiche possedute da tale lega nell'intervallo di solidificazione che ne consentono un agevole impiego in processi di formatura.

Introduction

The transformation processes usually employed in industrial practice for the forming of metallic materials make use of alloys in the completely solid state (as in the case of cold pressing, drop forging, extrusion, etc.), or the completely liquid state (as in the various foundry processes — sand casting, die casting, lost-wax process, etc).
Alloys only partially solidified (semi-liquid state) are not used individually in forming processes as their structure, derived from traditional solidification, is made up of an interlacing network of dendrites in a liquid matrix, that cause it to stiffen, with low percentages of solid phase (20-25%). It therefore appears impossible to use them in casting. Also, attempts to deform such a structure lead to the formation of hot cracks and zones of elevated segregation which inhibit the obtaining of a sound part having the desired characteristics.
At the start of the '70s, research at M.I.T. nevertheless demonstrated that, with partial solidification, it is possible to obtain a non-dendritic, but globular, solid-phase structure, provided that the bath is maintained in vigorous agitation during the actual solidification, thus rendering dendritic growth impossible. An alloy having this kind of structure (non-dendritic and only partially solidified) possesses pseudo-plastic and thixotropic properties. That is to say, its viscosity diminishes with increasing agitation and, the shear rate being equal, with increasing time.
This structure can be subjected to forming operations, either by means of deformation processes or by conventional die casting processes, because the semi-liquid material subjected to slip preserves the characteristic properties of liquids.
The main advantages deriving from the use of a semi-liquid alloy in die casting can be summarized as follows:
a) Less trapping of air, as a consequence of the increased viscosity of the slurry (about three orders of magnitude or more), making it possible to fill the mould with laminar flow.
b) Less solidification shrinkage, the alloy being already partly solid during injection, and therefore less prone to defects.
c) Less thermal shock to the mould, attributable either to the lower injection temperature (within the liquid/solid range) or to the method of filling, which determines a low coefficient of heat-transfer between semi-liquid and mould.
d) Shorter solidification time, the alloy being already partly solid.
The present work reports the results of an experimental research run at the Centro Ricerche Fiat with the aim of developing a continuous production process for doughy semi-liquids, with high fractions of primary solid, to be utilised either in die casting or in forging.

Method of obtaining the doughy semi-liquid

In order to produce an alloy in the doughy, semi-liquid state (i.e. characterized by a globular form in the solid phase) it is necessary to create a vigorous agitation between the various solid particles in the mixture. In such a mode, the formation of the dendritic interconnections that develop during solidification in the absence of agitation is inhibited. The dendritic fragments remain separate, and tend to assume spheroidal shapes under the action of mutual mechanical collisions.

Various techniques can be employed for keeping the bath in vigorous agitation during solidification, provided that they allow, at the same time, cooling of the alloy so as to withdraw the latent heat of solidification.
The first of the methods used is that of M.I.T., which consists in making the metal alloy, in the solidification phase, pass through an annular channel, arranged by means of a tubular shaped container, appropriately cooled, in which a "drag" rotor of cylindrical shape (1) wheels co-axially with the same container. The slurry produced in this way is then poured directly into the feed chamber of a die casting plant (Rheocasting), or cast into billets for subsequent utilisation (Thixocasting, Thixoforging, etc). In Fig. 1 the scheme of the Thixocasting process is reproduced.
An alternative method, patented by Centro Ricerche Fiat (2) for generating elevated shear rates, is making the alloy in the solidification phase pass through a static mixer device. The geometrical configuration of the mixer is arranged so as to generate high shear forces in the metallic alloy. In this way it is possible to keep the viscosity of the semiliquid relatively low, also with very high solid fractions, hard to attain in practice with other mixer systems.

Description of the Centro Ricerche Fiat plant

On the basis of results obtained with laboratory-scale plants for verification of the feasibility of the process, a semi-industrial plant for the continuous casting of aluminium alloys in the semi-liquid, doughy state, according to the Centro Ricerche Fiat patent, was planned and built.
Fig. 3 shows a block diagram of the scheme and Figs. 4 and 5 are photos of the actual plant. Casting, by the continuous system, is done with the use of an electromagnetically driven pump, suitably redesigned and manufactured at Centro Ricerche Fiat. This endows the liquid alloy with the necessary pressure energy to pass through the static mixer in the solidification state. As shown in the scheme in Fig. 3, the plant comprises the following equipment:
1) Melting furnace
2) Static mixer
3) System for drawing the liquid alloy into the mixer
4) Collecting system
5) Ancillary equipment.

Melting furnace

A resistance furnace is employed, with a capacity of 150 kg of aluminium alloy; the crucible is of silicon carbide; the furnace is equipped with a turn-over system controlled from an oleodynamic central console.

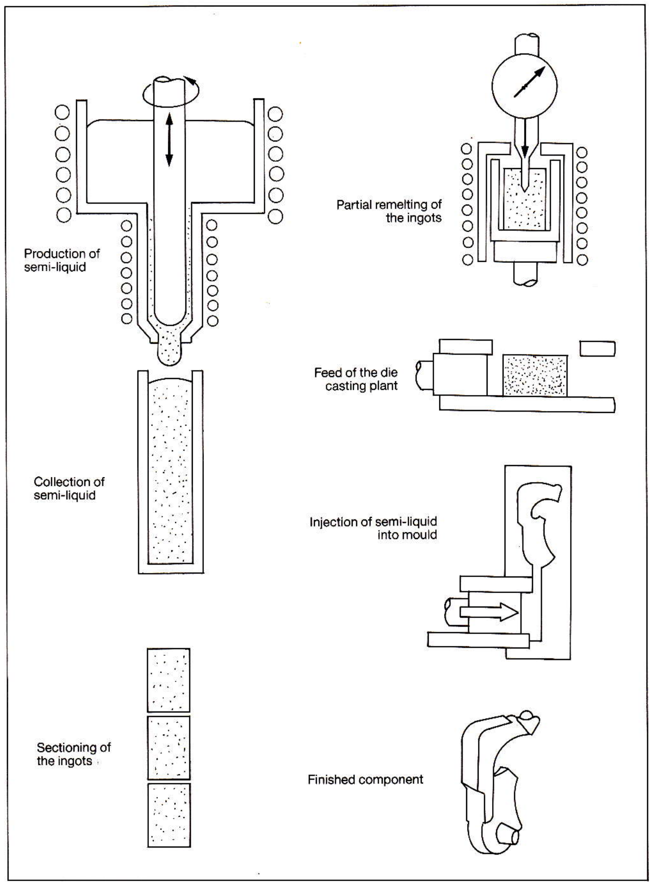


Fig. 1 - The thixocasting process [1].

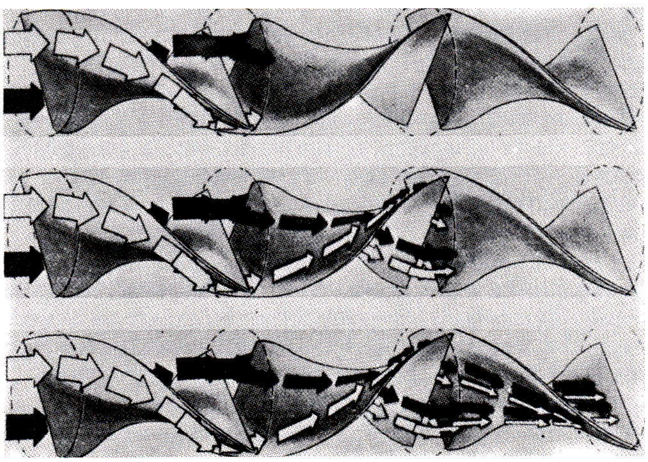


Fig. 2 - Phases of the mixing process [2].

System for drawing the liquid alloy into the mixer

The system that permits feeding the static mixer with

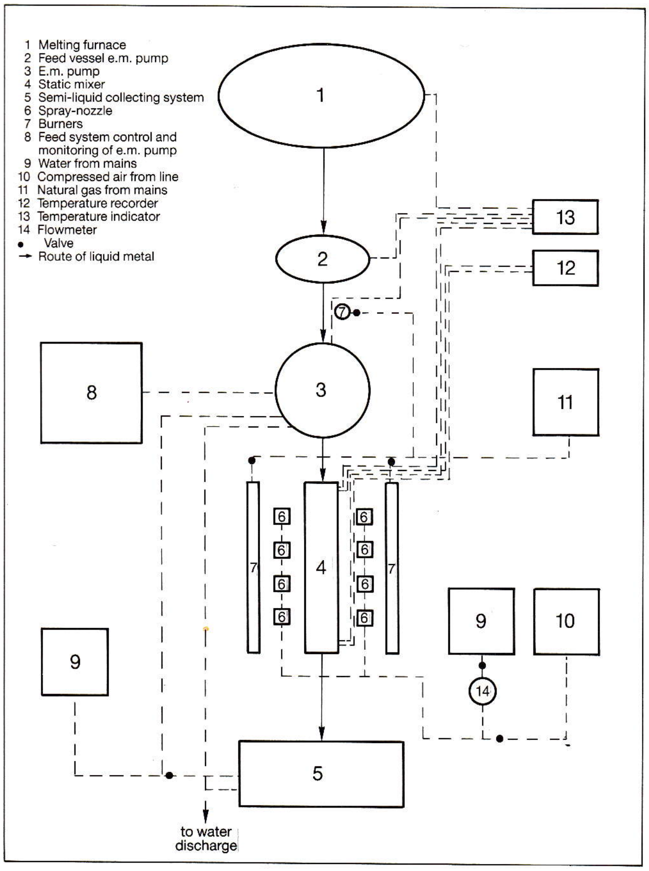
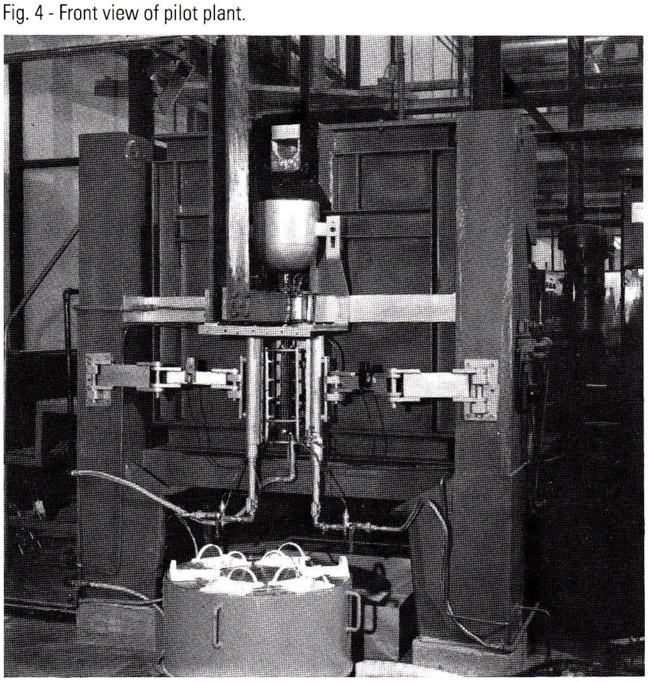


Fig. 3 - Pilot plant for the production of metallic semi-liquid light alloys in the doughy state, in a continuous process.

Fig. 4 - Front view of pilot plant.

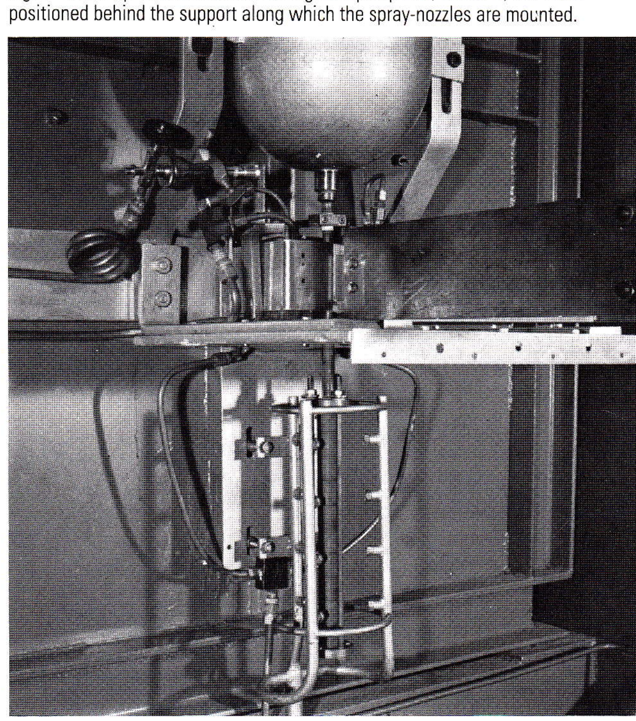


liquid alloy consists of an electromagnetic linear drive pump, fed with direct current from a transformer rectifier, able to provide a maximum current strength of 3000 amperes at low tension. The equipment was planned and built starting with an electromagnetic pump used to circulate sodium in nuclear reactors.
The new pump was designed to handle aluminium alloys at temperatures up to 700 °C. As can be seen in Fig. 6, the liquid metal flows through a duct with thin walls, on which are brazed two copper electrodes.
The whole is placed between the poles of a permanent magnet. The electric current, through the walls of the duct, passes into the liquid metal, developing in it a force perpendicular either to the magnetic field or to the current itself (Lorenz's force).
The characteristic curves of the pump (functional dependence between prevalence and capacity) depend on the current strength, the magnetic field and the geometry of the duct. Such curves are represented by the hatched outlines in Fig. 7 calculated for different current strengths.

Static mixer

The equipment is of modular type, and consists of a series of small elements shaped as alternated left-hand and right-hand helicals.
The single elements are welded in such a way that the sharp corners of two successive elements are perpendicular to one another (Fig. 2). The modular

Fig. 5 - Close-up view of the electromagnetic pump and, below it, the mixer positioned behind the support along which the spray-nozzles are mounted.



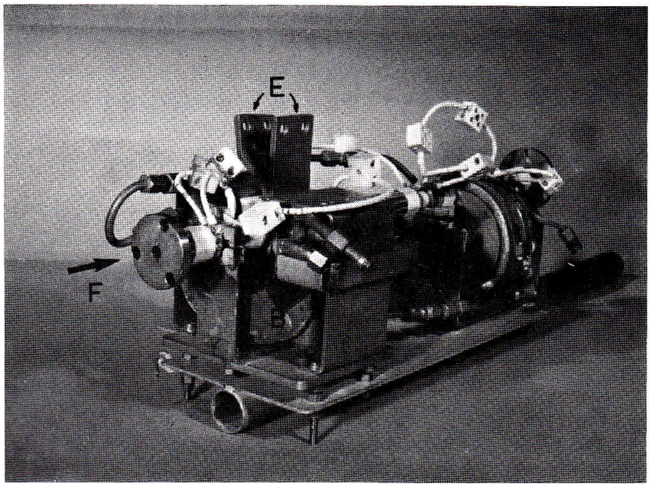


Fig. 6 - Direct-current electromagnetic pump (and electromagnetic flowmeter). The conductive fluid F is contained in a tube connected to the electrodes E, and which is located between the poles of the permanent magnet B: the passing of current creates a force (Lorentz's force) applied to the fluid and parallel to the axis of the duct.

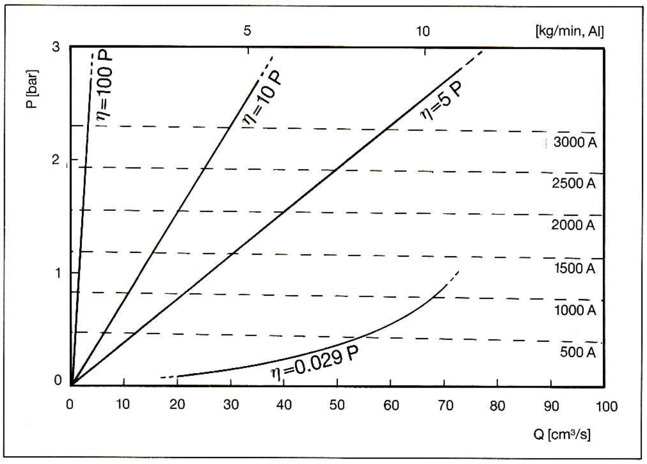


Fig. 7 - Representation of the characteristic curves of the electro-magnetic pump at different current strengths, and of the characteristic curves of the mixer with 10 modules for different viscosities of the semi-liquid metal.

design of the equipment makes it possible to vary the length suitably, as a way of increasing the degree of mixing and the possibility of withdrawing the heat of solidification of the treated alloy.
The static mixer acts in the following way: when the fluid enters the mixer, the first element begins to divide the flow into two parallel streams; the torsion of the helical element imparts a degree of rotation to these currents culminating in their edges being perpendicular to that of the following element, and thus throughout the whole length of the mixer, obtaining a mixing effectiveness such that in every element each of the two currents further divides into two parts. For example, the two flows occuring in the first element become four separate flows, two for each side of the second element, which are further rotated and guided to the following element. The mixing action is accentuated by the clockwise and anti-clockwise twisted elements, which tend to create in the fluid radial, direct and reverse flows.
It will be pointed out here, that unlike what occurs in similar mixing equipments, the mixing action is independent of the flow velocity, being the degree of mixing the result of repeated stratifications and not of turbulent transport phenomena.
The characteristic curves of the static mixer (i.e. the functional dependence between prevalence and capacity) were obtained by tests carried out with fluids having different viscosities.
These curves are reproduced as graphs in Fig. 7 for different values of viscosity, and can be represented by an equation of the type:

$$P = P\,[Q, f\,(Re)]$$

where P is the prevalence, Q the capacity, f the coefficient of friction, function of the Reynolds number Re. The intersection of the characteristic curve of the pump with the characteristic curve of the mixer gives the point of work of the plant.
It will be observed that the viscosity of the alloy in the solidification phase varies progressively up to stabilization at a constant value, to reach steady conditions of heat exchange. Correspondingly, the work point moves along the characteristic curve of the pump. It is possible, therefore, measuring the capacity and knowing the strength of the current fed to the pump, to also determine the average viscosity of the semi-liquid in formation.

Mixer cooling system

The cooling of the mixer is of fundamental importance for obtaining high productivity, since the withdrawal of the heat of solidification must occur while the alloy is flowing through the mixer.
The method adopted consists of a series of spray nozzles with a water-atomizing capacity of about 20 l/min, and disposed in such a way as to cover the whole surface of the mixer (Fig. 5).

Collecting system

The collecting system comprises a series of metal containers positioned on a turntable, integral with a water forced circulation tank.
Each container holds 8 kg of aluminium. The system is mounted on a plane able to move vertically if necessary, by means of an oleodynamic equipment (Fig. 4).

Ancillary equipment

The basic plant is completed by a series of auxiliary apparatus and control devices, among which are:

a) linear burners able to provide heating of the mixer in the first stage of casting, mounted on articulated mechanical arms;
b) flowmeter for checking the capacity of coolant;
c) cooling system for the permanent magnets, consisting of a series of copper jackets attached to the same magnets, through which water is circulated by forced convection;
d) electromagnetic flowmeter (based on the same magneto-dynamic principles that work the e.m. pump);
e) temperature readout and continuous recording system by means of thermo-couples located at different points on the plant.

Method of operation

The alloy is initially melted inside the furnace, and held there at a constant temperature. Operating the upsetting of the furnace, the liquid metal is poured into an ogival container (connected by means of a conical joint to the supporting tube) having the function of feeding the electromagnetic pump continuously. Under the effect of the pressure exerted by this last, the liquid metal is driven through the static mixer, in which it undergoes simultaneous actions by shearing and cooling until it reaches a temperature within the solidification range.
At the exit from the mixer, the alloy therefore consists of a solid phase (primary solid) and a liquid phase, in proportions depending on the quantity of the exchanged heat.
The semi-liquid is then collected in metal containers, where solidification is thus completed. In the described process, the independent variables which have to be considered, are as follows:

a) temperature of finale mixture;
b) average cooling rate during mixing;
c) cooling rate from the moment of ceasing mixing up to complete solidification.
These variables, together with the rheological conditions determined by the mixer (share rate and its time of application), affect the microstructure of the alloy produced, which is characterized by:
1) Fraction of primary solid (globular phase).
2) Average dimensions of globules.
3) Factor of shape of the globules.
4) Morphology of interglobular phases.

Characteristics of an alloy produced in the semi-liquid, doughy state

For the purpose of evaluating the characteristics of an alloy cast in the semi-liquid, doughy state, using the plant decribed, a casting was produced in an Al-Si-Cu (G-AlSi 6 Cu 2-UNI) alloy commonly used for making motor-vehicle components. The composition of this alloy is given in Table 1.
In Fig. 8 are shown typical microstructures of the alloy cast by the traditional method (Fig. 8a), and flow-cast (Fig. 8b). The characteristics of the material produced provided the results described below.

Fraction of primary solid

Three different ingots were examined once attained the steady state of plant operation, and from each of them five metallographic specimens were extracted, from different zones.
Quantitative analyses were made of all the specimens, by means of an Omnicon image analyser, examining 100 fields for each specimen. Table 2 reports the

TABLE 1 - Chemical composition of the alloy G-AlSi 6 Cu 2 - UNI (alloy in ingot and liquid charge of first melt)

Element		%
Si		5.50 - 6.50
Cu		1.75 - 2.25
Mg		0.30 - 0.50
Ti		0.10 - 0.20
Al		rest
Fe	Impurity	0.50 max
Mn	Impurity	0.10 max
Zn	Impurity	0.05 max
Ni	Impurity	0.05 max
Pb	Impurity	—
Sn	Impurity	—
Total other impurities		0.10

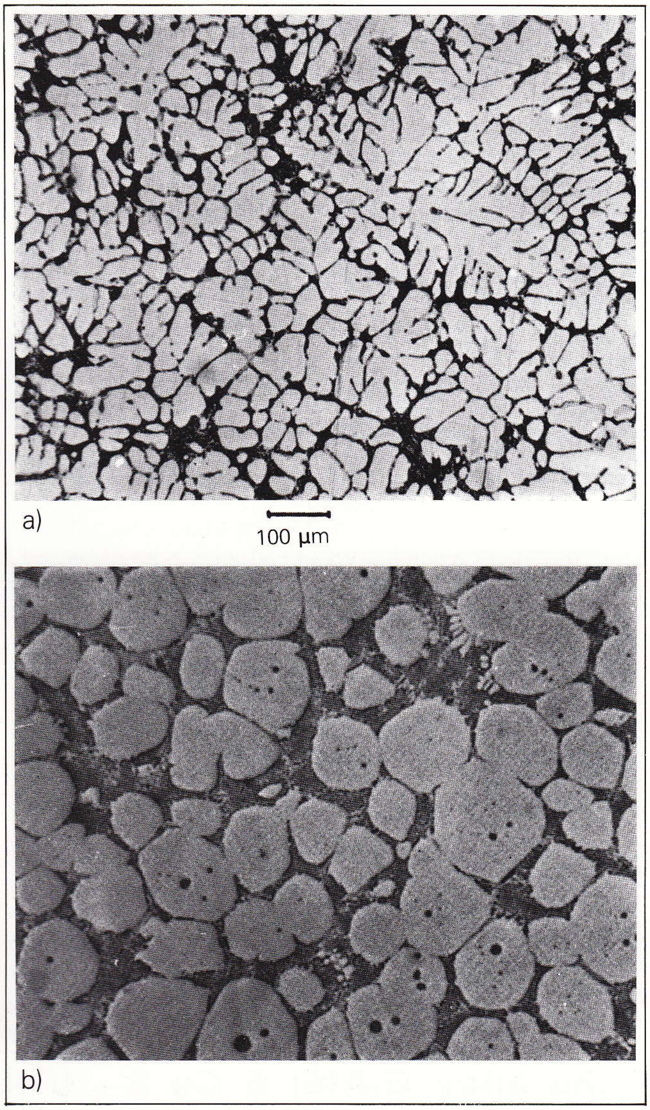


Fig. 8 - Microstructure of the alloy (G-AlSi 6 Cu - UNI): a) conventional; b) flow-cast.

TABLE 2 - Average values of the volume fraction of primary spheroidal particles (g_s) for each ingot

Ingot	(g_s)	$\sqrt{\frac{\Sigma_i (x_i-\bar{x})^2}{n-1}}$
A	0.79	2.8
B	0.82	1.9
C	0.79	2.6

average values of the volume fraction of primary spheroidal solid particles (g_s) for each ingot.

Average dimensions of globules

The measurement was taken on a micrograph representative of the structure of Ingot B, using the planimetric method normally employed for the evaluation of average grain dimension in the case of equi-axed crystals.
This measurement gave an average value of 100 μm.

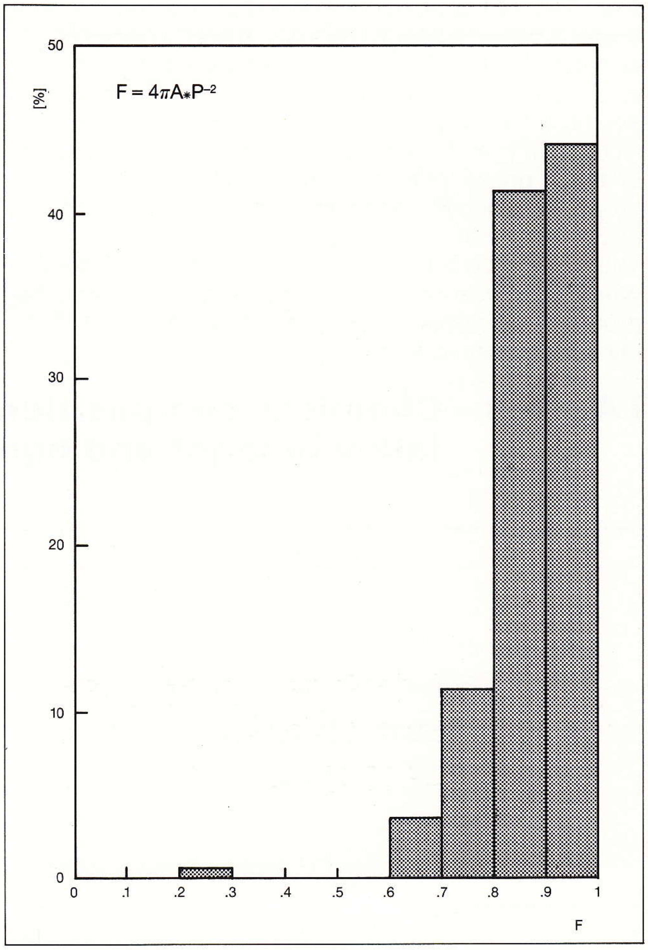
Factor of shape of globules

This factor is defined by the relation:

$$F = \frac{4 \pi A}{P^2}$$

where A is the area of the globule and P is its perimeter. The measurements of A and P were taken with a semi-automatic apparatus for quantitative image evaluation circumscribing single globules by means of

Fig. 9 - Distribution probability relating to the shape factor of globules of primary solid present in a flow-cast ingot of AlSi62.



an electronic pen. The examination made on five micrographs relating to different zones of Ingot C, yielded the results given in the histogram in Fig. 9.

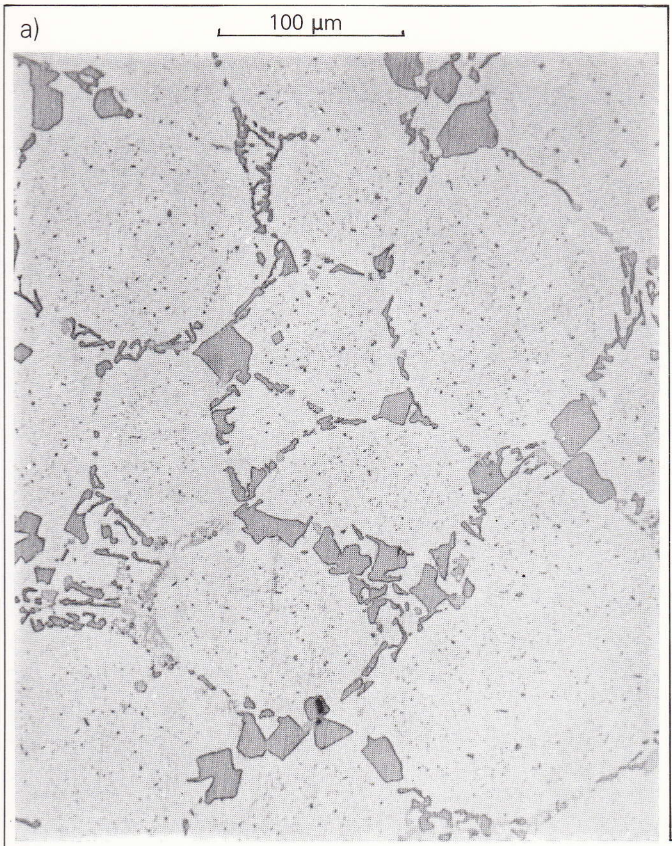
Morphology of the interglobular phases

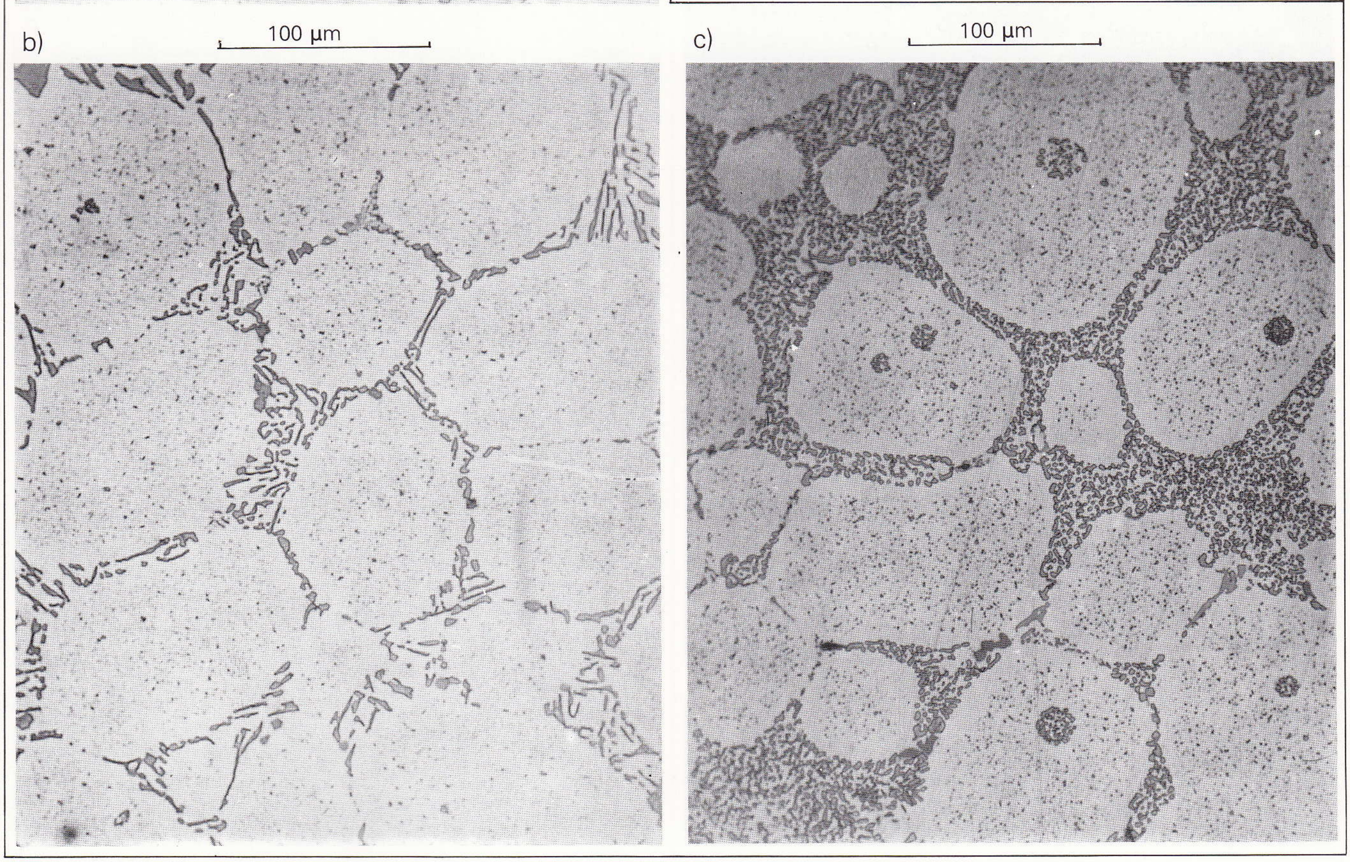
Fig. 10 shows the micrographs relating to three specimens extracted from, respectively, the centre (Fig. 10a), near the surface (Fig. 10c) and the zone between (Fig. 10b), of an ingot. The difference in the cooling rate, which is determined in the three zones by a simple effect of mass, does not influence the morphology of the globular phase, but only that of the eutectic phase, which is obviously improved with the increase in cooling rate.

Microsegregation in the globular phase

Fig. 11 shows the appearance of a primary globule (solid solution Al-Si-Cu) by scanning electron-microscope, and the x-ray map of the distribution of the principal alloy elements.
Fig. 12, on the other hand, shows the results of microanalysis done by a laser sampling technique, coupled with spectro-chemical emission analysis.

Fig. 10 - Microstructure of flow-cast AlSi62 alloy showing the globular structure of the Al-Si-Cu solid solution and the variations in the morphology of the eutectic corresponding to an increase in the cooling rate from (a) to (c).





Mechanical characteristics

The values of the mechanical characteristics of a flow-cast ingot have a purely indicative value, dealing with a technically transitory form. Indeed, use in forming processes (pressure die casting or moulding) involve a reheating to bring back, at melting, the eutectic matrix that surrounds the globules of primary solid.

Fig. 11 - Appearance of a grain of solid solution Al-Si by scanning electron microscope (S.E.M.) and map X of distribution of the principal alloying elements.

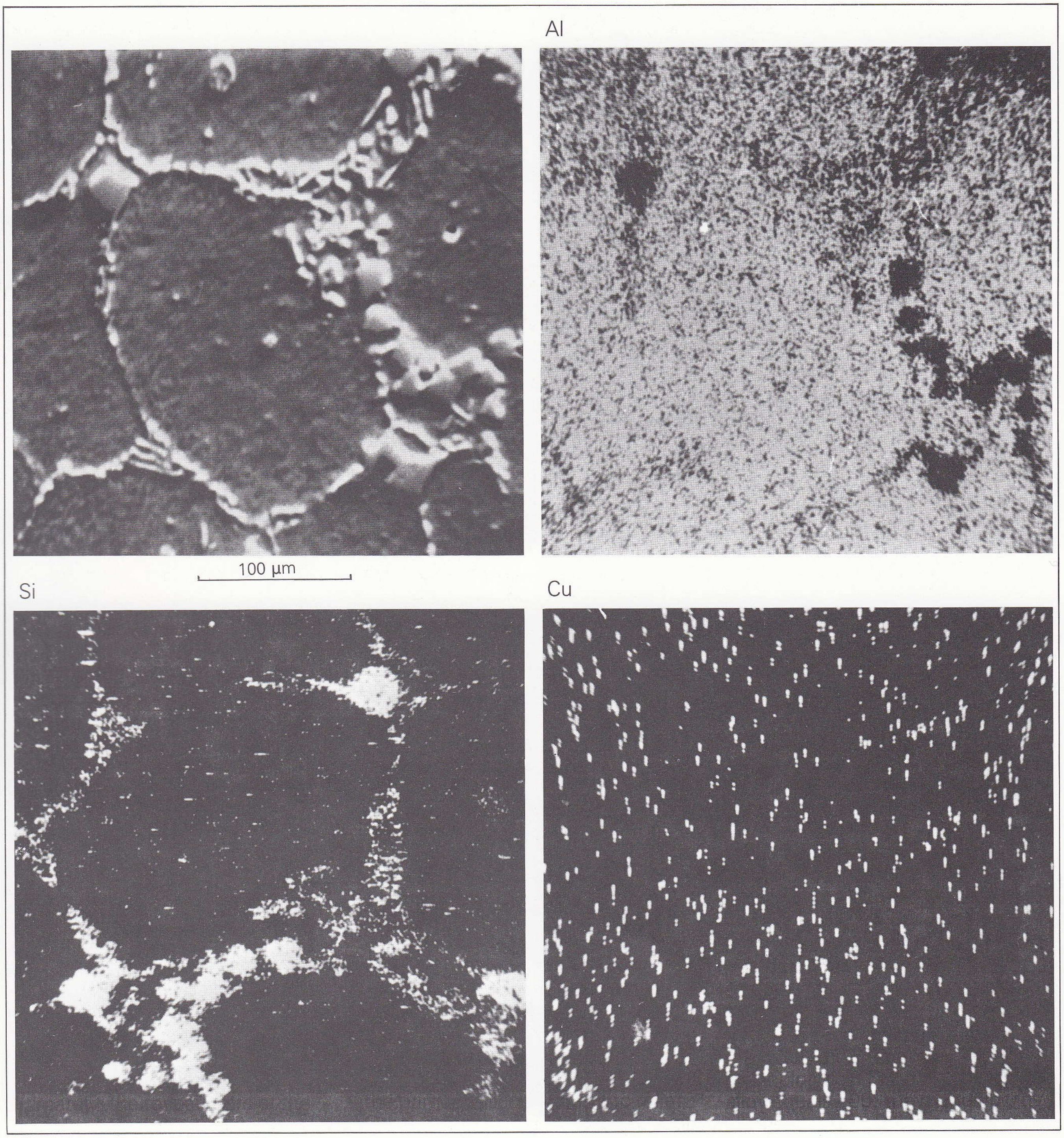
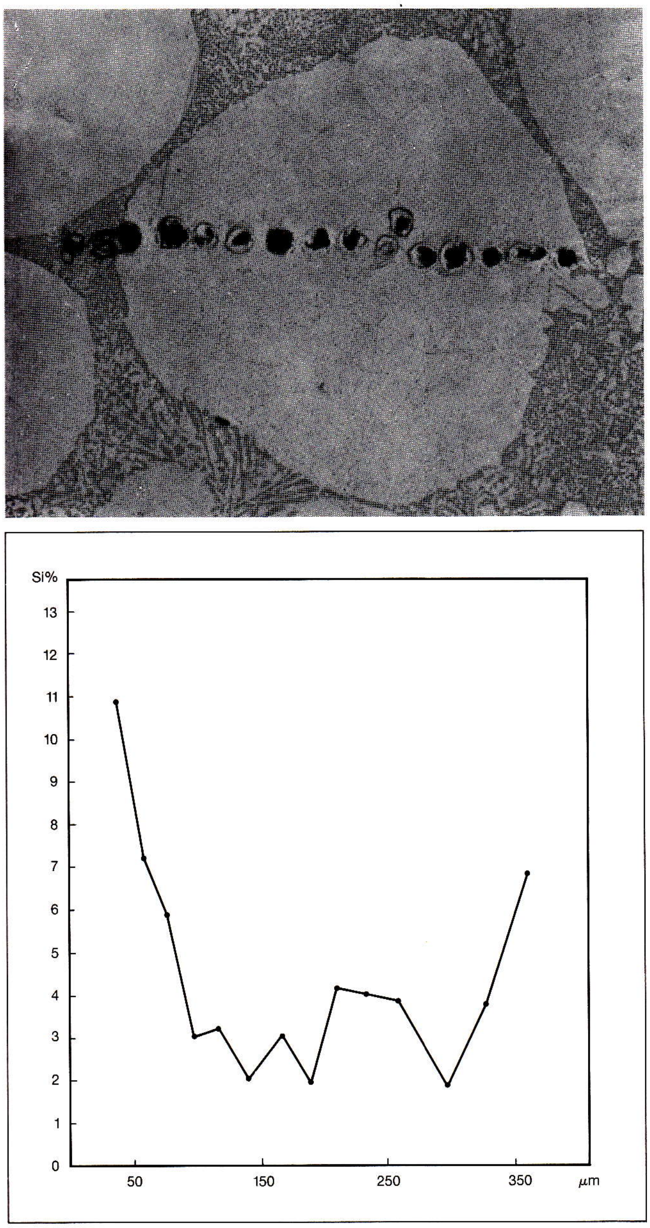


Fig. 12 - Variation of Si concentration inside a globule of primary solid.



The mechanical characteristics of the ingot, given in Fig. 13, for various temperatures, do not have, however, any correlation with those of the final product, and represent only an indicative strength.

Discussion of the results

The elevated values of the shear rate induced by the mixing system adopted, have made it possible to reach very high (80%) solid fractions, by maintaining a relatively low viscosity (10 poise), thus still permitting the flow of semi-liquid into the collecting system.

The advantage of using a semi-liquid with a high solid fraction in a moulding process consists, among others, in minimizing the time and the solidification shrinkage, and in adopting temperatures of moulding tangibly below those traditionally used (for an aluminium alloy, die cast as semi-liquid, by 120 K at least).

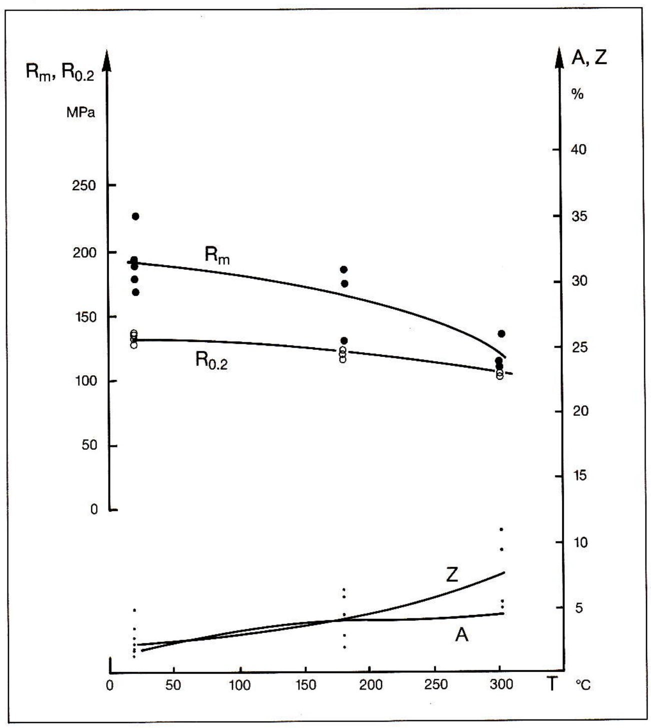
The viscosity of a metallic semi-liquid, besides the solid fraction, depends on the morphology of the globules and is much lower the more these tend to assume spheroidal shapes. This spheroidization increases with the shear rate, which in our case reaches values so elevated ($10^3 \div 10^4\ s^{-1}$) as to confer on the solid-phase factors of shape very close to unity. As far as the dimensions of the globules are concerned, it is well known from the literature (3) that these are notably influenced by the shear rate, only in the case of a cooling rate below 1 K/min.

Since in our process the average cooling rate in the mixer is of the order of 10^2 K/s, the dimensions of the globules do not depend on the extent of mixing, and are therefore comparable with those of a traditional solidification with the same rate of cooling.

With reference to the chemical heterogeneity encountered, by means of micro-analysis of the primary solid globules, the following is observed.

Homogenisation of the liquid during the formation and growth of primary solid globules is assured almost

Fig. 13 - AlSi62 alloy, flow-cast: progress of R_m; $R_{0.2}$, A, Z as a function of the test temperature.



instantaneously by strong agitation. In such a case, and on the hypothesis that the coefficient of partition at equilibrium is constant, that equilibrium is maintained at the interface and that the speed of diffusion in the solid is negligible, then Scheil's equation (non-equilibrium lever rule) applies (4):

$$C_s = K_o C_o (1 - g_s)^{K_o - 1}$$

This equation gives the progress of the concentration (C_s) of solute in the solid next to the interface, as a function of the coefficient of partition (K_o), of the volumetric fraction of solidified alloy (g_s) and of the concentration of solute (C_o) in the starting liquid alloy. The progress of the concentration of silicon encountered inside the globules following this rule confirms the fact that solidification occurs in non-equilibrium conditions.

Conclusions

The process of continuous casting in the semi-liquid, doughy state, put into operation according to the Centro Ricerche Fiat patent, has made it possible to obtain a metallic semi-liquid with a high primary solid fraction and pronounced globularisation, such as to maintain a relatively low viscosity, indispensable for facilitating use in a moulding process. The most strategic approach in utilising flow-cast alloys is, in our view, the use of the technology in specific cases where it is not possible, or in any case economically inconvenient, to mould an alloy by the traditional technology. In other words, the great potential of a flow-cast alloy lies, not in the mechanical characteristics obtainable (which are substantially the same as those derived from the traditional processes), rather, this potential lies in the unique fluid-dynamic properties. In the case, for example, of filling under pressure a mould with thin walls and/or large dimensions, with the imminent danger of shrinkage cavities or gas bubbles, an alloy in the doughy state will be able to show its appropriateness for the task, demonstrating that it possesses a double identity and combines in a perfect synergism the intrinsic advantages of the liquid and solid states.

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