# Improved Methods for the Lump Casting of Ferroalloys

M. B. Cortie, I. J. Barker, D. Knight and F. Levey

Mintek, Private Bag X3015, Randburg 2125, South Africa

## Abstract

Molten ferroalloys are generally 'bed-cast' into large moulds which are allowed to solidify slowly before being broken up, crushed, and screened. There are some disadvantages to this system, and alternative methods such as ingot casting or water granulation are also used. A new process, termed 'blobulation', which can produce lumps of ferroalloy directly from a melt, has now been introduced. The process involves the passing of molten material down a battery of parallel channels, which are simultaneously swept by a strong flow of water. The size and shape of the lumps can be tailored, within broad limits, to the user's requirements. The application of this process to certain ferroalloys is considered. It is found that the physical properties of the liquid ferroalloys have an important bearing on the outcome. The technique has been successfully piloted for pig iron, steel, ferrochromium and stainless steel.

## Introduction

Ferroalloys are examples of 'intermediate metallic products', defined here as metallic materials produced for the specific purpose of being re-melted later. These intermediate metallic products are usually consumed long distances from where they were produced and, in addition, they are often stockpiled for some time before being used.

The physical form in which the products are transported is determined by a combination of factors such as the processing technology of the producer, the mechanical and chemical properties of the product, the intrinsic economic value of the material, and the needs of the end-user. Therefore, there are a variety of physical forms in which these products are shipped: materials such as aluminium, lead, copper and zinc are usually transported as ingots with an individual mass of several tens of kilograms each, while materials such as ferromanganese, ferrochromium and ferroniobium are usually sold to the end user as lumps, produced by the crushing and screening of solidified masses of the ferroalloy. A few of the ferroalloys, such as ferroniobium and some ferromanganese [1] are first cast into small ingots, then broken up further by crushing. Increasingly, a number of materials are granulated in water, and supplied in the 2 to 10 mm size range [2-7]. However, granulated product is often considered to be too small for convenient use. This paper describes a recently developed unit operation that is also capable of converting liquid metal directly into lumps, but in this case the lumps are significantly larger than those produced by granulation. The new process has been termed 'blobulation'.

## The blobulator lump caster

### Apparatus

Some information concerning the design and operation of the Blobulator has been previously published [1], and only a relatively brief summary will be offered here. The principle of the Blobulator, which has been patented in several countries, is to gently unite a co-current stream of cooling fluid and liquid metal. Careful management of the contrasting effects of the surface tension of the molten metal and the acceleration induced by both the water stream and gravity cause the metal stream to break up into large blobs, which are then swept down a flume. The blobs solidify during their passage down the flume and are ejected solid but still hot at the end. A water-metal separator then draws off the water, allowing a stream of hot, dry ferroalloy to fall into a skip or onto a materials handling belt. One of the design variations is shown in Figure 1 below. The ladle and tundish are at position *a*, a bank of parallel water-filled flumes at *b*, a water-metal separator at *c*, a materials handling system ending at *d*, and a water tank and cooling tower at *e*.

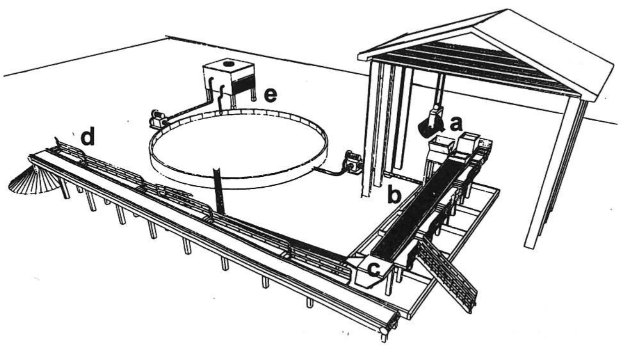


Fig. 1. Schematic design of a Blobulator. The individual items are identified in the text.

The experimental results described in this paper were obtained with a 12 m long pilot plant, equipped with two channels. Melts varying in size from 50 kg to over a ton were processed through this unit, in order to provide process and product information. The melts were prepared in induction furnaces, and transferred to the tundish of the Blobulator in a preheated ladle. The temperature of the liquid metal was measured with a dip thermocouple prior to blobulating.

**Mechanism of the blobulation process**

The key process in the Blobulator is the gentle separation of a metal stream into molten globules of the desired mass. These globules must then be allowed to solidify with the minimum of further disruption to their shape. The optimum operation of the process requires a careful control of several physical parameters. Obviously, larger blobs have a lower ratio of surface area to mass than small blobs. Therefore an important feature of the blobulating process is to limit the creation of new surface area in the liquid metal stream as much as possible. While the intrinsic design of the blobulating equipment goes a long way towards ensuring the break-up of the stream into liquid globules of the desired mass, the shape obtained on solidification of the globules depends also on the physical properties of the liquid ferroalloy. In particular, the surface tension of the ferroalloy, its viscosity, and the melting point of both the alloy and its oxides have been found to exert a very important influence on the blobulation process. These parameters will be briefly reviewed below.

*Effect of surface tension*

Surface tension might certainly be expected to be an important property, since it is responsible for pulling the globule together, and preventing its further break-up. It is reported that the surface tension of pure iron is around 1.8 $N.m^{-1}$, but that the addition of elements such as carbon, manganese and silicon reduce this value somewhat so, for example, it is about 1.5 $N.m^{-1}$ for a 4% carbon melt with normal residual values of manganese and silicon [8]. However, sulphur and oxygen are reported have a profound effect on the surface tension of iron, and as little as 0.06% of either can reduce the surface tension of iron-based melts further, to about 0.9 $N.m^{-1}$ [8,9]. The surface tension of binary Fe-Cr melts is slightly lower than that of pure iron, and can be lowered further by nitrogen contamination to a minimum of about 1.2 $N.m^{-1}$ [10]. On the other hand, additions of Ni to iron or iron-chromium melts have little effect on the surface tension [11]. Surface tension varies somewhat with temperature, and for iron-based melts seems to peak at a superheat of about 75 to 100 °C [8].

Unfortunately, reliable surface tension measurements for the other ferroalloys are hard to find. Nevertheless, it is known that the materials that contain large amounts of carbon, such as charge chromium and high carbon ferromanganese, have surface tensions of about 1.1 to 1.3 $N.m^{-1}$. Even lower values of surface tension may be associated with materials, such as intermediate carbon charge chrome, which have raised sulphur levels, and the surface tension of such materials could be as low as 0.8 $N.m^{-1}$.

One practical effect of the surface tension is the that it controls the thickness of the flattened 'biscuits' produced in the blobulator. It can be shown that the thickness of a blob of molten metal resting on the floor of a water-filled flume is given by

$$h \approx \sqrt{\frac{4\gamma}{(\rho_m - \rho_f)g}}$$

where $\gamma$ is the surface tension of the molten metal, $g$ is the acceleration due to gravity, and $\rho_m$ and $\rho_f$ are, respectively, the density of the molten metal and the cooling fluid around it. Therefore, under equilibrium conditions, the thickness of a blob of low carbon ferrochromium or mild steel will be of the order of 0.011 m, whereas that of a material with a relatively low surface tension might be no greater than 0.004 or 0.005 m. However, viscosity is also an important parameter, and a very viscous material can be converted into thick blobs even if its surface tension is low.

*Surface-tension stability criterion*

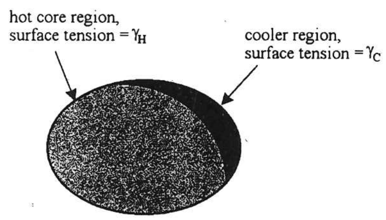


Fig. 2. Effect of a variable surface tension on the shape of a blob.

Consider a molten globule in the process of cooling down by means of a loss of heat from its surface. Assume that, for whatever reason, a slightly cooler region develops somewhere on its surface, as shown schematically in Figure 2. If the surface tension of this cooler region, $\gamma_C$, is less than that of the hot region, $\gamma_H$, then material from the surface of the cooler region will be pulled around onto the hot region. By this mechanism, the entire surface of the drop will tend towards assuming a uniform temperature. However, if the surface tension of the cooler region, $\gamma_C$, is greater than that of the hot region, $\gamma_H$, then material from the surface of the hot region will be pulled around into the cold region. This will expose new hot material on the surface of the hot region while accentuating the formation of the cooler region, and so the process will continue until the material finally all solidifies.

From the above consideration, we hypothesize that if the surface tension increases with temperature, then the drop should take on a smooth rounded form, while if the surface tension decreases with rise in temperature, then the drop is likely to form a crinkled surface or even, the extreme, the undesirable morphology sometimes described as "corn flakes". This same criterion should apply to both blobs and granules. In most cases, one would prefer a smooth rounded form.

We believe that this dependence of the surface tension on temperature is an important criterion in determining the morphology of blobs and granules. The difficulty comes in trying to predict *a priori* how the surface tension will vary with temperature, and what to do about the problem if the material has the wrong characteristic for the purpose required. However, as a general observation, it would seem that the surface tensions of many metals and alloys exhibit a non-linear variation with temperature, as shown in Figure 3.

The fact that the characteristic reaches a peak and then drops off with increasing temperature could explain the rather qualitative observation often reported by operators of both granulators and Blobulators that a large superheat sometimes leads to a crinkled morphology.

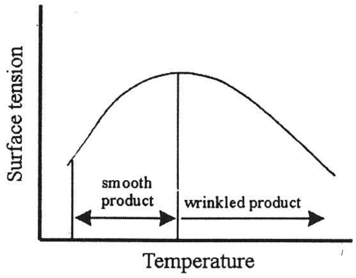


Fig. 3. Typical variation of surface tension with temperature, and the effect on the shape of the lumps produced.

*Viscosity*

The viscosity of the molten metal also has an influence on the shape of the blobs. This parameter varies markedly, with the less viscous metals, such as magnesium or tin, having an absolute viscosity, η, about half that of iron. In turn, the viscosity of iron, which is about 0.006 $kg.m^{-1}s^{-1}$ [12], is about an order of magnitude lower than that of molten slags, which have absolute viscosity's in the range 0.05 to 2 $kg.m^{-1}.s^{-1}$ [12]. A liquid with high viscosity will be comparatively resistant to deformation. This is taken into account in the design of the blobulator, since the metal stream is usually somewhat deformed or flattened on impact with the moving water, and the production of an appropriately-shaped product relies upon the action of surface tension on the molten globule to pull it together into an evenly-shaped biscuit before its surface solidifies. The time available for this final adjustment in product shape to take place depends on both the superheat of the material and the particular heat transfer characteristics of the cooling fluid. However, once a solid skin has formed on the globule, it becomes effectively rigid, and little further change in shape will normally occur.

Viscosity is decreased by an increase in temperature and is also effected by the composition of the melt. For example, Kozlov [13] reports that additions of nitrogen and oxygen to molten iron strongly increase the value of this parameter, while chromium, nickel and sulphur do so to a lesser degree. Conversely, additions of manganese, silicon, carbon and phosphorus lower the viscosity. However, the elemental pairs carbon and oxygen, and nitrogen and chromium, interact in a non-linear fashion in the melt. In particular, when they are present singly (as opposed to together) they lower the viscosity of the melt [14]. The effect of adding large amounts of chromium and nickel, as for example would be present in an austenitic stainless steel composition, is to increase the absolute viscosity to about 0.008 $kg.m^{-1}.s^{-1}$ [15]. This increase in viscosity has an effect when blobulating austenitic stainless steel. In contrast, large additions of carbon have a curiously non-linear effect on the viscosity of iron (Figure 4), but tend overall to depress it very strongly. It is interesting to note that the curve for viscosity's determined at a constant superheat shows a very similar trend to that for compositions at 1600°C, indicating that the effect of chemical composition outweighs the effect of temperature in these alloys.

This effect of carbon holds good in the Fe-Cr-C system too and, for example, at 1600°C the composition 30%Cr, 5%C, 1.3%Si has a viscosity about half that of pure iron [17]. However, higher levels of carbon may precipitate in the melt as carbides or graphite and will raise the viscosity again. Carbon-saturated ferrochromium, which has a liquidus of about 1600°C [18] and the composition 53%Cr,7.9%C, 1%Si, has viscosity more than double that of pure iron [17]. This effect also applies more generally to any other alloy system with an appreciable difference between liquidus and solidus temperatures. It is reported that a volume fraction of solids of about 20% causes the viscosity to double, and a volume fraction of 50% solids will induce a ten-fold increase in viscosity [19]. This may be the explanation for the marked rise in viscosity that occurs when several percent silicon is added to the Fe-Cr-C system [20].

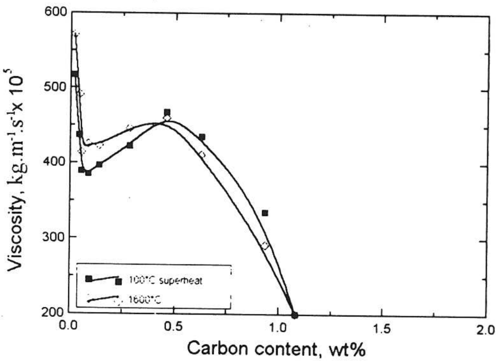


Fig. 4. Effect of carbon on the viscosity of binary Fe-C melts. The solid symbols are for melts located 100°C above their respective liquidus lines. (Data from [16]).

*Effect of fluid temperatures*

The effect of the temperature of the cooling water and of the liquid alloy on the surface temperature of a blob of liquid ferroalloy is shown in Figure 5. This purely illustrative calculation addresses the case for a large, flat blob of charge chrome 8 mm thick. The material and thermodynamic properties used for this calculation are listed in Table 1. The temperature at which this type of material becomes rigid depends on composition, but for the purposes of the present discussion can be taken as approximately 1530°C. It is evident that an increase in the pouring temperature of the ferroalloy from 1600 to 1700°C can lengthen the estimated time to form a solid skin from about 0.1 second to about 0.7 seconds. On the other hand, a decrease in the heat transfer coefficient of the water from 1500 to 750 $W/m^2/K$ (such as might be obtained by raising the temperature of the cooling water from 15 to 50°C) can lengthen the time taken to solidify to over 2½ seconds. These factors are taken into account in the design of the blobulating plant to ensure that a product of the desired morphology is consistently produced.

Table 1. Material and other properties used in the heat transfer calculations

| Property | Value | Units |
|---|---|---|
| Heat capacity | 838 | J/kg/K |
| Thermal conductivity of FeCr | 30 | W/m/K |
| Emissivity | 0.24 | - |
| Density | 6600 | $kg/m^3$ |

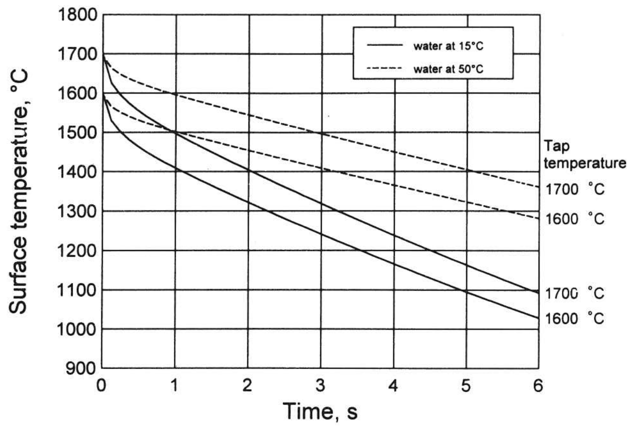


Fig. 5. Calculated surface temperatures of a large, flat blob of charge chrome 8 mm thick, introduced into hot and cold water.

*Melting point*
Finally, yet another factor that has an effect on the morphology of the product is the mechanical and physical properties of its oxide phase. If a solid brittle oxide is formed on the surface of a molten globule, then the surface-area minimising effects of the metal's surface tension will be counteracted. This can be inconvenient since the brittle oxide film will not only act to prevent any surface area minimisation due to surface tension, but worse, it may rupture readily before the metal within has become rigid, thereby allowing the metal within to run out in the form of a ribbon or other extrusion.

## Results of pilot plant trials

A number of materials have been the object of development work at Mintek, and the process parameters required to produce acceptable blobs have been determined for, among others, pig iron, mild steel, austenitic stainless steel, ferritic stainless steel, low-carbon ferrochromium, charge chrome and Fe-75% silicon. Development work is continuing on these and certain other materials.

### Effect of carbon content

The carbon content of binary iron-carbon and ternary iron-chromium-carbon alloys has a significant effect on the physical properties of the relevant melts, and hence also on the nature of material produced in the Blobulator. Considering first the binary system, the addition of carbon depresses the liquidus point considerably, from 1538°C to about 1150°C. The amount of superheat present in the liquid to be blobulated has a strong effect on the time taken to solidify in the flume, and it is obvious that, at a given temperature, there will be more superheat in a binary material of higher carbon content. However, this effect can be compensated for by blobulating such metal at a lower temperature. A series of experiments in which the carbon contents were varied but superheats held constant are indicated on Figure 6. It is interesting that the product of blobulating the low-carbon materials is normally a relatively solid and thick 'blob' (Figure 7a). However, as the carbon content rises the product becomes significantly porous, with the effect being manifested in its most extreme form for carbon contents of about 3% (Figure 7b). A further rise in the carbon content to values closer to those of pig iron causes the 'blobs' to change further into small, flattened pebbles (Figure 7c). The reason for these changes is not yet understood.

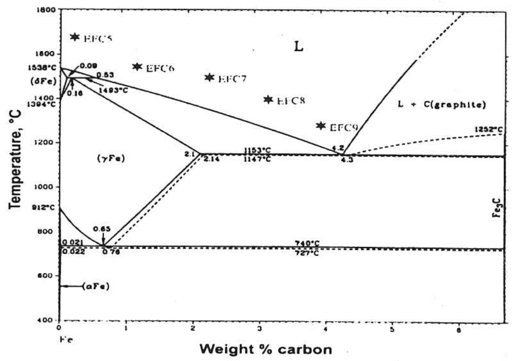


Fig.6. Series of melts to show the effect of carbon at a constant amount of superheat.

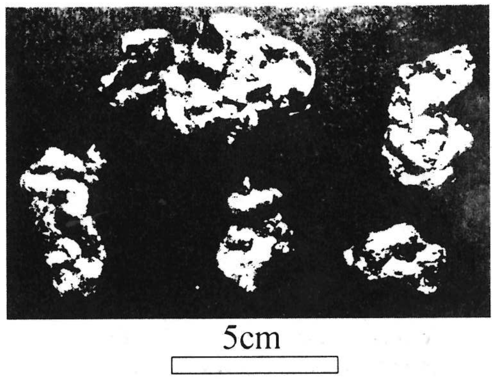


Fig.7a. Sample of blobs produced from mild steel. The average mass of the blobs shown is 34.6 g.

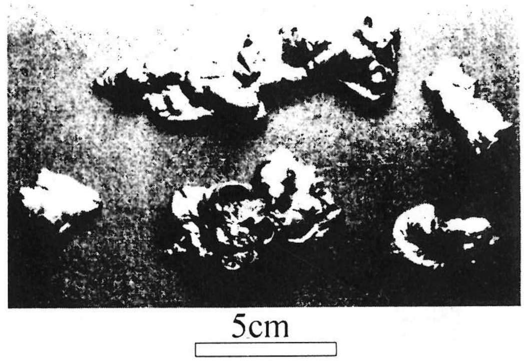


Fig.7b. Sample of hollow blobs produced from iron containing 3.1% carbon. The average mass of the blobs is 50.6 g.

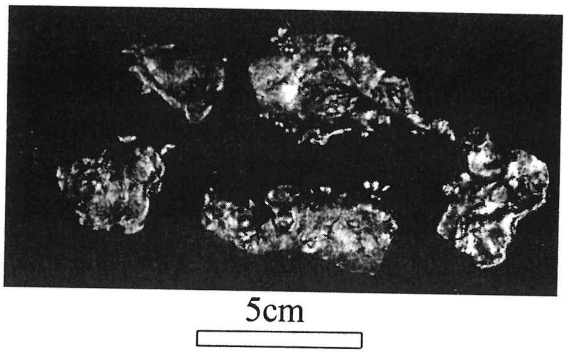


Fig.7c. Sample of blobs produced from pig iron. The average mass is 43g.

**Other materials**

A variety of other materials have been successfully processed during pilot plant operation of the Blobulator. These include ferritic and austenitic stainless steel, charge chrome (Figure 8), and low-carbon ferrochrome (Figure 9). Materials which have not yet been successfully processed to large blobs, either because they are too friable or because they generate too much hydrogen when contacted with water, are silico-ferrochrome, ferrovanadium, silico-ferromanganese and ferromanganese. The product obtained by blobulating these latter materials is apparently similar to that obtained by a conventional granulation process.

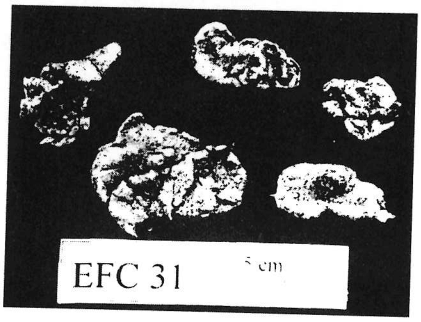


Fig. 8. Sample of blobs produced from low-carbon ferrochromium. The average mass is 44.8 g.

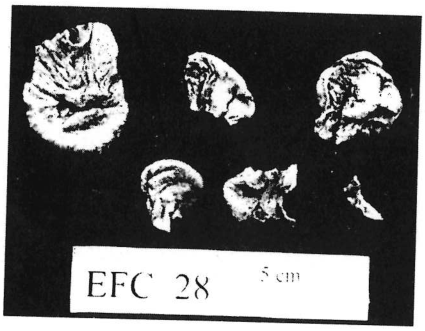


Fig. 9. Sample of blobs produced from charge chrome. The average mass is 35.4 g.

**Hydrogen content**

Hydrogen is generally regarded as an undesirable impurity in ferroalloys, and the extent to which the interaction of the molten ferroalloy with water would cause contamination with this element was investigated. It was observed that under some circumstances the water was decomposed by the molten metal according to the reaction $M + H_2O \Rightarrow MO + H_2$. This can occur for M= Fe, Cr, Mn and Si, since the oxides of each of these elements are more stable than water under the conditions applying in the flume. In many of these cases small flames caused by the combustion of hydrogen were visible above the water of the apparatus. However, in common with the industrial experience reported by others for granulators [21], this hydrogen generation has not proved to be a problem in practice, and does not lead to either a hazardous situation or to any excess hydrogen in the product. A low content of hydrogen in blobulated product is assured by the fact that the solid material is ejected dry and hot at the end of the unit operation. In this respect the Blobulator is significantly different to a granulator, which inevitably delivers wet product to its material handling system.

## Discussion

**Effect of the Eötvös number**

Clift, Grace and Weber [22] classify the behaviour of drops in terms of the Reynolds number, $N_{Re}$, and what they call the Eötvös number, $N_{Eo}$, which is also called the Bond number. These numbers are defined by:

$$N_{Re} = \frac{\rho . d_e . v}{\mu}$$

$$N_{Eo} = \frac{g . \Delta\rho . d_e^2}{\gamma}$$

where these variables have the following meanings, and the following approximate values for blobulator blobs:

$\rho$ = density of material ≈ 7000 kg.m$^{-3}$

$d_e$ = the diameter of the sphere with the equivalent volume to the particle, ≈ 0.03 metres

$v$ = the velocity of the particles ≈ 2.0 m.s$^{-1}$

$\mu$ = viscosity of the material ≈ 0.06 kg.m$^{-1}$.s$^{-1}$ for iron

$g$ = the acceleration due to gravity ≈ 9.8 m.s$^{-1}$

$\Delta\rho$ = the absolute value of the difference in density between the material and the surrounding fluid ≈ 6000 kg.m$^{-3}$

$\gamma$ = the interfacial tension of the material with the surrounding fluid ≈ 1.0 N. m$^{-1}$

With these values, the Reynolds and Eötvös numbers during the blobulation of molten ferrous alloys are

$$N_{Re} \approx 7000$$

$$N_{Eo} \approx 53$$

These values locate the behaviour of the blobs as being between 'wobbling' and 'spherical-cap', according to the classification of Clift, Grace, and Weber (pages 26 - 28 of reference [22]). Around this operating point the behaviour is more sensitive to the Eötvös number than to the Reynolds number, because the Reynolds number is well into the turbulent region. Unfortunately, it has been our experience that there is not much published on the subject of the formation and behaviour of drops and bubbles in this region of operation. Note that the Eötvös number depends on the square of the particle diameter, so we should expect the particle size to be a significant factor in determining the morphology. The Eötvös number (but not the Reynolds number) depends on the surface tension, but surface tension can vary widely and rather unpredictably. Since Reynolds number is into the turbulent region by about two orders of magnitude, we should expect the viscosity to be relatively unimportant in terms of the formation and behaviour of the blobs under normal circumstances, but the viscosity could become important if its value rose by two orders of magnitude or more (i.e. to at least 6.0 $kg.m^{-3}.s^{-1}$).

**Optimum product shape**

Currently, one of the economic characteristics of the intermediate metallic products is that the market that they are sold into is very competitive. Consequently, they are normally sold at low profit margins, with the basic price being largely determined by the cost of mining the ore, the cost of the energy required for the smelting process, and the necessity to account for the capital cost of the plant. There is therefore great interest both in reducing the cost of producing the products, and in optimizing the physical form in which they are presented to the market.

Most ferroalloys are currently supplied as lumps, produced by crushing and screening. Mintek has conducted a survey of the preferences of the market regarding the most desirable size and shape of these lumps and has found that while there is no absolute consensus, the various traders and end-users generally agree that

- lumps with maximum dimensions in the 20 to 80 mm range are suitable for addition to furnaces of capacities ranging upwards of 20 t
- lumps of 5 to 50 mm are suitable for smaller furnaces
- additions to a mould or ladle are often in the size range 2 to 8 mm.

Users agree that the ferroalloy intended for addition to the larger type of furnace should generally be substantially free of 'fines', usually defined as material smaller than 3 mm. This is because the 'fines' and dust do not sink speedily through any slag layer on top of the furnace, and may instead be transferred into the stream of gases coming off the furnace. Secondly, it is desired that the product should be readily transportable on conveyor systems. A spherical shape would, for example, be most inconvenient since the ferroalloy would then roll off the belt. Also, the product should not 'hang-up' in bins and hoppers, particularly in steel plants which have semi-automated materials handling systems. Finally, the shape of the product should be such as to ensure an efficient recovery of the desired alloying element in the melt. Material that is too fine may oxidize or blow off before becoming incorporated in the melt, whereas very large lumps may take too long to dissolve in the charge. The best product will have a size and shape that allows it to sink rapidly through whatever slag layer covers the bath of molten metal, while still being small enough to allow the addition to dissolve quickly and reproducibly [23,24].

Regarding the last factor, the mechanism by which the ferroalloys dissolve in the molten charge of the furnace has been studied [24,25]. The process has been divided into two rather different classes. In the first the ferroalloy or other addition has a lower melting point that the charge in which it has been placed, and in the second its melting point is much higher. Additions such as ferromanganese and ferrosilicon are examples of the first class, whereas ferrovanadium or low carbon ferrochromium are examples of the second. However, in either case, it seems that speedy and reproducible recovery will be obtained provided that one dimension of the product added is between 3 and 20 mm[ 24,25].

All the above considerations point strongly to the optimum product being a flattened ellipsoid, measuring between 20 and 50 mm in one plane, and between 5 and 15 mm in the other. Unfortunately, such a product cannot be produced simply by crushing a mass of ferroalloy, and it is also too big to be produced by conventional water granulation techniques. However, it is possible in many cases to produce such a product with the Blobulator.

## Conclusions

The Blobulator technology is able to produce a product suitable for sale, directly from a ladle of molten ferroalloy, iron, or steel. Although the addition of molten metal to water results in the rapid release of energy, it can be safely conducted in equipment of the appropriate design. A unique feature of the Blobulator is that a larger-sized product can be safely made than was hitherto possible. However, intrinsic material properties such as viscosity and surface tension place a limit on the variety of product shapes that can be produced. Large blobules of charge chrome, low carbon ferrochrome, stainless steel, mild steel and pig iron have now been routinely produced during pilot plant trials of the Blobulator. A product of smaller size has been produced for silico-ferrochrome and silico-ferromanganese.

## Acknowledgement

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