

ALLOYING OF MOLTEN ALUMINUM : OPTIMIZING THE PRESENT AND PREPARING THE FUTURE

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Abstract

Alloying is a very essential step in the global cast house process which has been comparatively little studied in recent years. Optimization of the alloying process would allow a more rapid adjustment of the composition in order to obtain the best quality of molten metal and an improvement of the productivity of the casting pits.

The improvement of the alloying process can be achieved by :

- i) Firstly, optimizing the existing technique where stirring is achieved by moving a blade-shaped tool back and forth in the molten metal.

Experiments were undertaken in a lab-scale furnace, simulating spreading of insoluble particles and dissolution of soluble particles in water.

The mathematical modelling of the stirring process has enabled a qualitative assessment to be made of how the stirring parameters influence the dissolution of alloying elements.

- ii) Secondly, developing a new process which consists in pre-alloying the metal in the transfer crucibles taking benefit of the high turbulence generated by a turbine and the high temperature of the metal.

Again, lab-scale experiments were conducted in water and aluminum to evaluate the influence of specific parameters, such as rotor diameters, speed ...

Introduction

In response to growing demand for high-quality foundry products, the Pechiney Group has for some years directed part of its research effort at the alloying process.

The objectives are twofold, i.e. :

- i) to systematise and minimise the time required of the process on average and hence increase productivity in the casthouse ;
- ii) to enable alloys to be produced to tighter compositional specifications.

This paper discusses work done to advance our understanding, and arrive in the molten metal at a mathematical description of the dissolution of the alloying elements during stirring operation.

In the first instance, the effects of stirring parameters on the dissolution of alloying elements were investigated in the laboratory, via tests using water as the liquid medium and substances chosen to simulate alloying elements. Two means of stirring were investigated (i) the commonly-used method, employing stirring blade, and (ii) a more sophisticated technology employing a rotor.

At present, most casthouses are equipped to use method (i), stirring being carried out in the alloying furnace by moving the blade back and forth over the heap of alloying elements. Simple though it is, this technique yields good results.

Another method consists in dissolving the alloying elements by means of a suitably sized rotor operated in the ladle used to convey the primary metal tapped from the reduction pots. The geometry of this transport ladle (tall and narrow) is ideally suited to generate an effective and uniform pattern of turbulence, while the temperature of the liquid metal also assists the process of dissolution.

The second phase of the investigation, carried out on the plant, using the normal industrial facilities, confirmed the representativeness of the data obtained in the experiments in water.

General principles governing the process of dissolution of alloying elements in a bath of liquid aluminum

Where two or more phases are in contact in a closed system, an exchange of matter will occur and continue until such time as thermodynamic equilibrium is attained.

In a solid/liquid system of the kind with which we are concerned here, two cases have to be distinguished, i.e. :

- a) If the melting point of the solid is lower than that of the liquid, the solid matter will simply melt and the two phases will mix.
- b) If the melting point of the solid is higher than that of the liquid, a process of dissolution will take place, whereby atoms or molecules pass from the solid into the liquid phase via a boundary layer connecting the liquid and the surface of the solid. This boundary layer, the size of which will vary as solution progresses, is the seat of the highest concentration gradients.

In what follows, we shall consider only the case of the dissolution of a solid material (an alloying element) in a bath of liquid aluminum.

Mass transfer equation

As long as a concentration gradient exists in the boundary layer, which is time-dependent, matter will be transported through this layer at a rate expressed by the equation :

$$\frac{dM}{dt} = -kS(C - C_i) \tag{1}$$

- Where : S denotes the exchange surface area (m²)
- k the solid/liquid exchange coefficient (m/s)
- C_i the mean concentration at the solid/liquid interface (Kg/m³)
- C the concentration of alloying element in the liquid (Kg/m³)
- M the mass of alloying element in solution (Kg)

At the solid/liquid interface :

$$\frac{dM}{dt} = S(C_s - C_i) \frac{dx}{dt} \tag{2}$$

- Where : dx/dt is the rate of displacement of the interface (m/s)
- C_s is the alloying element content of the solid (Kg/m³)

Combining equations 1 and 2 :

$$\frac{dx}{dt} = kh$$

$$\text{Where : } h = \frac{C - C_i}{C_i - C_s} \tag{3}$$

In the case of a plane interface (splatters), x is the thickness, z. In the case of a spherical particle (powder), x is the radius, r.

Resolution of the equation 3 requires a knowledge of the exchange coefficient, k, the value of which depends on the mode of mass transfer.

If the value of k is known, dissolution times can be estimated for the two extreme cases such that :

- a) the alloying elements are spread out evenly, forming a layer covering the bottom of the furnace ;
- b) the alloying elements are in suspension in the melt.

Dissolution of a layer of alloying elements

If the melt is only mildly agitated, the alloying elements will form a layer on the bottom of the furnace.

The time required for dissolution can be calculated if certain simplifying assumptions are made, viz :

- the surface area, S, of the layer is constant with respect to time ;
- the mean concentration, C, in the melt is constant during the process of dissolution and equal to the desired final concentration, C_f (the variation in the value of C over the range 0 to C_f is assumed to be negligible with respect to C_i).

The dissolution of a layer of thickness z₀ then obeys the equation :

$$\frac{dz}{dt} = kh$$

$$\text{Where : } h = \frac{C_f - C_i}{C_i - C_s}$$

The value of k depends on the mass transfer mode, which is in turn determined from the Schmidt number, S_c, where :

$$S_c = \frac{v}{D_m} = \frac{\text{kinematic viscosity}}{\text{molecular diffusivity}}$$

Either of two cases can occur, as determined by the value of S_c , viz :

$S_c \ll 1$: The diffusion sublayer will be thicker than the viscous sublayer, with a commensurate reduction in the effectiveness of the turbulence. This is because the small energy-dissipating vortices are localised in the viscous sublayer.

$S_c \gg 1$: The diffusion sublayer is thinner than the viscous sublayer.

In the case at issue, we have :

$$D_m = 10^{-8} \text{ to } 10^{-9} \text{ m}^2\text{s}^{-1}$$

$$v = 10^{-6} \text{ m}^2\text{s}^{-1}$$

Whence : $S_c = 100 \text{ to } 1000 \gg 1$

i.e. a state of **turbulent forced diffusion**.

Dissolution time, T_d , defined as the time required for complete dissolution of all the alloying elements introduced, is then given [1] by :

$$T_d = \frac{z_0}{h k}$$

Where : $k = \frac{u^*}{5 S_c}$

u^* is the turbulent velocity (m/s), generally taken as approximately equal to one-tenth of U , the mean linear velocity of the fluid (m/s).

Calculation of the value of k requires a knowledge of variations in the value of u^* .

Numerical example : Approximately 2 hours would be required for the dissolution in an aluminum melt at 750°C of a 5 cm thick layer of grains of manganese.

Dissolution of alloying elements in suspension

The assumptions made are the same as for the dissolution of a layer of alloying elements. The solids are further assumed to be powdered materials consisting of spherical particles. Turbulence in the liquid metal is assumed to be uniform, so that the solid particles are well dispersed and do not interact with each other.

Dissolution time, T_d , can then be calculated [2] using the approximation :

$$T_d \approx \frac{r_0^{5/3}}{0.6 D_m h \left(\frac{10 u^*}{D_m}\right)^{1/3}}$$

and $k = \frac{2r}{D_m} (2 + 0.42 \left(\frac{2r}{D_m} (2.25 U^2 + 1.82 r^2 \varepsilon)\right)^{5/3})^{1/3}$

r_0 is the initial radius of the solid particles (m)

r is the radius at time t (m)

ε is the rate of turbulent energy dissipation (W/m^3)

Numerical example : Dissolution time for 1 % manganese introduced as grains of diameter averaging 1.5 mm and in suspension in an aluminum melt at 750°C would be less than 5 minutes assuming uniform agitation of the melt by a stirrer operating at a speed averaging 0.5 m/s.

Influence of temperature

Temperature enters into the calculation via its effect on the interfacial concentration, C_i . This concentration is determined via the phase diagram for the chemical species in solution in the liquid. The higher the temperature and the higher the saturation concentration of the solid in the liquid, the greater the value of the coefficient h .

Influence of the solid/liquid exchange surface

The greater the area of the surface over which the exchange takes place, the higher the rate of transfer of matter from the solid to the liquid. The coefficient of exchange is a function both of time and of the particle size of the solid. For example, several hours may be required to dissolve a heap of powdered manganese dumped on the furnace bottom, as against only a few minutes if the powder is in suspension.

Influence of turbulence

Dissolution time varies with the velocity of turbulent flow, u^* , of the liquid around the solid particles, since this determines the value of the exchange coefficient k . If the melt is only mildly agitated, an approximate value for dissolution time, T_d , can be calculated thus :

$$T_d \approx z_0 u_*^{-1}$$

If the particles are in suspension, the approximate equation is :

$$T_d \approx r_0^{5/3} u_*^{-1/3}$$

In both events, dissolution will be assisted by increases in the mean linear velocity, U , of the liquid, particularly in direct proximity to the particles to be dissolved. However, once the velocity required to bring the solid completely into suspension has been attained, dissolution time will not reduce significantly in response to more powerful stirring, i.e. an increase in the value of u_* .

Industrial application

Rapid and effective dissolution of the alloying elements requires a stirring system with a performance close to that of a perfectly agitated reactor. Turbulence must be uniform throughout the melt to achieve good distribution of the solid particles in the liquid and bring the materials of highest density into suspension, thus maximising the area of contact between solid and liquid.

In actual industrial operation, however, it is not easy to evaluate with any accuracy the range of fluid velocities in the liquid metal and hence determine a value for the exchange coefficient k , especially where the stirring blade is employed. This being so, a model of this method of stirring, but substituting water as the liquid medium, was investigated in order to elucidate the mechanism of dissolution.

The first experiments in water were directed at determining the influence of stirring parameters on the horizontal dispersal of insoluble powders, on the assumption that the greater the dispersal, and hence the increase in the solid/liquid exchange surface, the more effective the dissolution of an alloying element in aluminum.

The second phase was to investigate, by conductometric measurements, the process of dissolution of powdered sodium chloride in water .

Stirring by blade-shaped tool

The experimental data obtained using water as the liquid medium was used to construct a mathematical model of the influence of stirring parameters on the process dissolution. The predictions of the model were then tested by experiments conducted in aluminum on actual industrial installations.

The parameters investigated were :

- the rate of travel and size of the stirring blade ;
- the stirring mode ;
- the mode of introduction of alloying elements.

Experimental apparatus for tests in water

The experimental apparatus (Fig. 1) consisted of a plexiglas tank, a replica of an industrial alloying furnace in a Pechiney Group casthouse, fitted with a stirring blade and containing water. A microcomputer was employed to control the operation of the stirrer. The tank, stirrer and height of water were all on the scale 1/10 as compared to industrial dimensions.

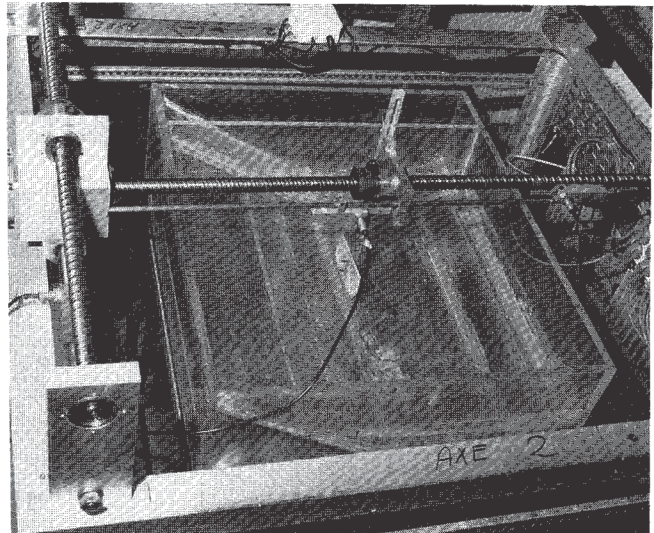


Figure 1
Experimental tank and stirring system

Measurement of the dispersal of insoluble powders

Powdered silicon carbide was used to simulate powdered manganese.

The experimental procedure was as follows : the tank was filled with water and one or more heaps of the insoluble powder deposited on the bottom. The stirrer was then operated to spread the powder over the tank bottom.

Photographs of the tank bottom were taken before and after stirring and subsequently processed by image analysis to convert the digitised image of the tank bottom post-stirring to an analysis in terms of levels of grey. The results were used to define (i) initial surface area, i.e. the area covered by the silicon carbide powder before stirring, and (ii) final surface area, i.e. the area covered after stirring.

A study was then made of how the ratio (ii)/(i), denoted E , varied with the different stirring parameters.

Measurement of variation of salt concentration in water

The grain size of the powdered salt (NaCl) was 50 to 300 microns. Four probes, located respectively at the four angles of the tank, were employed to measure the resistivity of the aqueous medium in the neighbourhood of the probes. This enabled variations in average concentration over time to be determined.

Experimental results

Certain parameters were found to have a particularly significant influence on the dispersal of insoluble powdered material over the tank bottom and on the dissolution of salt in water.

Speed of travel of the stirring blade

Tests in water

It was found from the preliminary dispersal experiments with silicon carbide powders (Fig. 2) that, whatever the grain size and mode of stirring employed, the dispersal of the insoluble powder increased significantly with the speed of travel of the stirring blade.

The extent of dispersal, E, of silicon carbide powders was found to vary with the rate of travel (U), as follows :

$$E \propto U^{2.2}$$

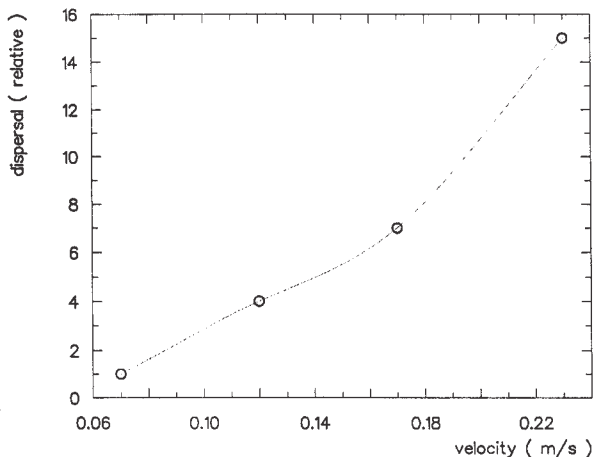


Figure 2
Effect of rate of travel of stirring blade on dispersal of powdered silicon carbide

This finding was confirmed by the experimental data on the dissolution of soluble powdered materials. Fig. 3 is a plot of variations in mean sodium chloride concentrations, expressed as ratios of final concentrations on completion of stirring.

Dissolution time, T_d , defined as the time required to effect solution of 95 % of the powdered salt, was found to be inversely proportional to the rate of stirring, i.e. :

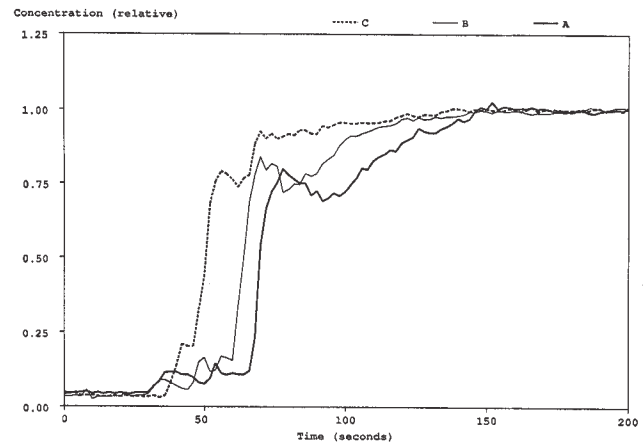
$$T_d \propto U^{-0.5}$$

The theoretical analysis concluded that dissolution time would be proportional to :

U^{-1} for particulate material tending to cover the furnace bottom

but $U^{-1/3}$ for particles in suspension.

The two series of experiments just described thus constitute an intermediate case in which the powdered material is not completely in suspension.



Test	A	B	C
Rate of travel (m/s)	0.12	0.17	0.30
T_d (s)	105	77	55

Figure 3
Effect of rate of travel on dissolution NaCl in water

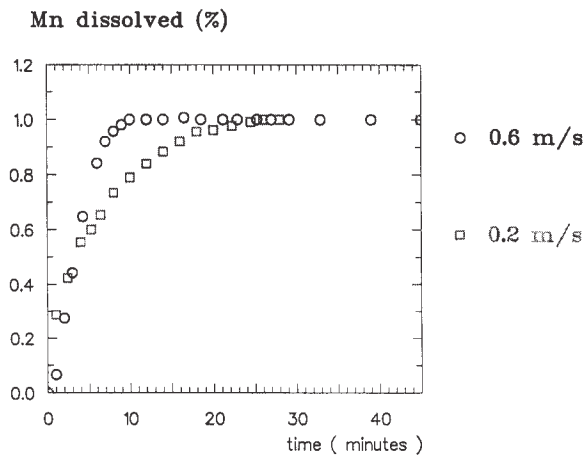
The model constructed from the data obtained in water thus enabled the direction and mathematical correlation of the influence of rate of stirring on dispersal and dissolution to be determined.

The representativeness of these findings was supported by the results of tests conducted on an actual industrial installation, in which the dissolution of manganese splatters in aluminum was monitored over time.

Tests on an industrial installation

Tests were conducted at two different rates of stirring, U1 (0.2 m/s) and U2 (0.6 m/s), but otherwise under rigorously identical experimental conditions.

Fig. 4 is a plot of manganese, expressed as percentages, dissolved with respect to time, from which it will be seen that dissolution time halved when the rate of stirring was increased by a factor of three. Dissolution time therefore varied approximately in inverse ratio to stirring speed raised to the power 0.7. This exponent is of the same order of magnitude as determined for the dissolution of sodium chloride in water.



U m/s	0.6	0.2
T_d, minutes	8	18

Figure 4
Effect of rate of travel determined on an industrial installation

Size of the stirring blade

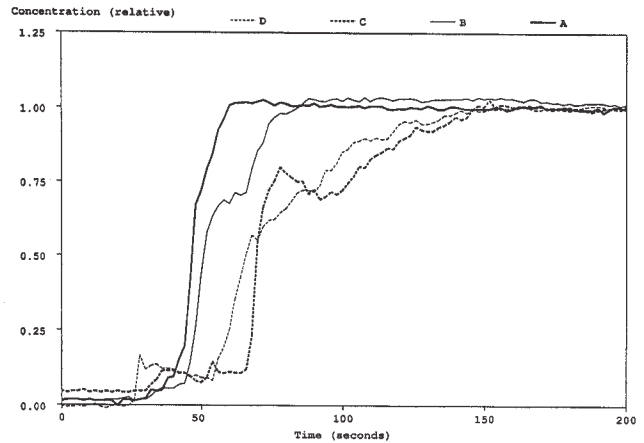
Tests in water

Four shapes of stirring tool, of the kinds in common use in foundries, but differing in surface area, were employed in comparative tests.

The powdered sodium chloride was introduced as a single heap initially positioned in proximity to the tank wall. The stirring mode employed consisted of moving the blade to-and-fro just above the heap.

Fig. 5 is a plot of salt, expressed as percentages, dissolved with respect to time for the four differently shaped stirring blades.

Stirrer blade	A	B	C	D
Area m ² .10 ⁻³	14.4	9.2	5.6	6.8
Shape				



Blade	A	B	C	D
T_d (s)	30	50	106	96

Figure 5
Effect of stirring blade size on dissolution of powdered salt in water

At constant stirring speed, it was found that dissolution times for salt in water varied with the surface area of the stirrer blade as follows :



$$T_d \propto S_b^{-3/2}$$

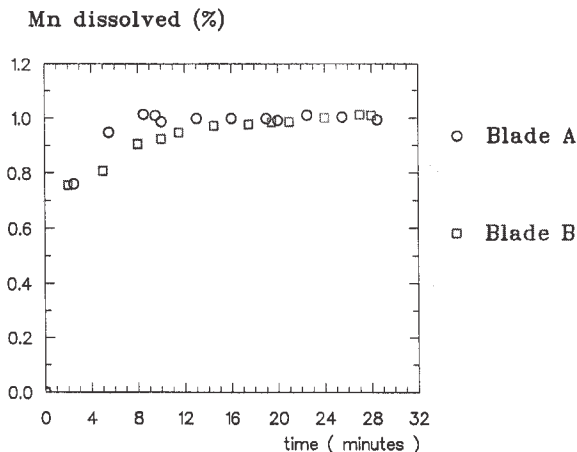
The larger the blade, the shorter the time required for dissolution, this because of the stronger eddies generated by the blade edges.

Tests in aluminum

Two sizes of stirrer blade were experimented. However, operational constraints on the plant made it impracticable to keep stirring speed constant from one test to the other. The rate of travel with the standard-size tool (A) was 1.5 times that with tool B.

In each test, rates of dissolution of 1 % of manganese in the aluminum were determined.

Test	A	B
Blade		
Surface area ratio	$\frac{S_{bA}}{S_{bB}} = 0.58$	
Rate of travel ratio	$\frac{U_A}{U_B} = 1.5$	



Blade	A	B
T _d , minutes	9	14

Figure 6
Effect of stirrer blade size determined on the industrial installation

It will be seen from Fig. 6 that rapid stirring with a small blade is more effective than slower stirring with a bigger blade.

This suggests that rate of travel has a greater influence than size on the process of dissolution.

Mode of introduction of powdered particles

Insoluble particles

A preliminary investigation was made of how the proximity of the walls affected the dispersal, on the bottom of the vessel, of an insoluble powder. Fig. 7 shows the number of times the stirrer had to be moved back and forth in order to disperse a heap of powder initially located close to the wall or at the centre of the vessel, respectively.

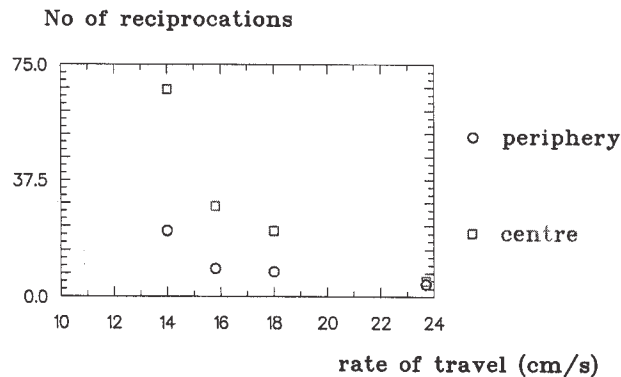


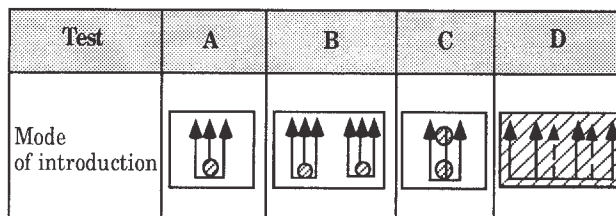
Figure 7
Effect of tank wall on dispersal of an insoluble powder

The number of reciprocations required to disperse a powder initially heaped near the wall was approximately half the number required for powder heaped at the centre of the vessel (except at maximum stirring speed, where dispersal was too rapid for any appreciable difference to be observed).

Where the powder is heaped near the wall, the turbulence generated by the motion of the stirrer is amplified by the additional instabilities due to circulation of the liquid in proximity to the wall.

Soluble particles

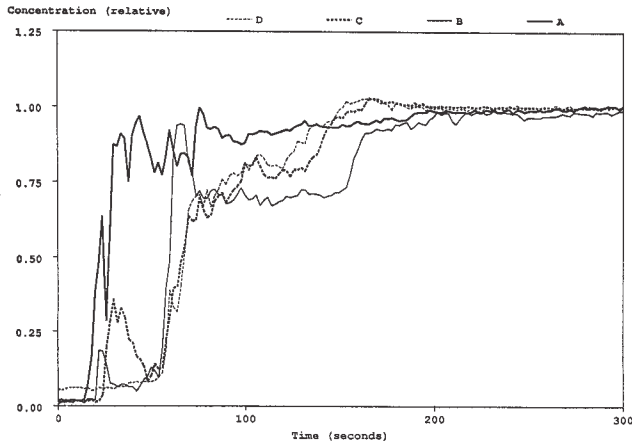
Four modes of introduction of the powdered salt were investigated, namely : in a single heap (A), in two heaps (B and C), and spread completely over the tank bottom (D).



In tests A and C, dissolution times were found to be of the same order of magnitude, indicating that there was no point in dispersing the powder as two heaps in order to speed up the process of dissolution.

Dissolution times for configurations B and D were found to be longer than for A and C.

Where the powder was introduced as a single heap, dissolution times were found to be shorter than where it was dispersed (Fig. 8). In the latter case, the turbulence generated by the two consecutive passes of the stirrer blade over the powder is only slight, so that the salt particles do not remain in suspension long enough to dissolve completely.



Mode of introduction	A	B	C	D
T _d , seconds	144	198	148	170

Figure 8

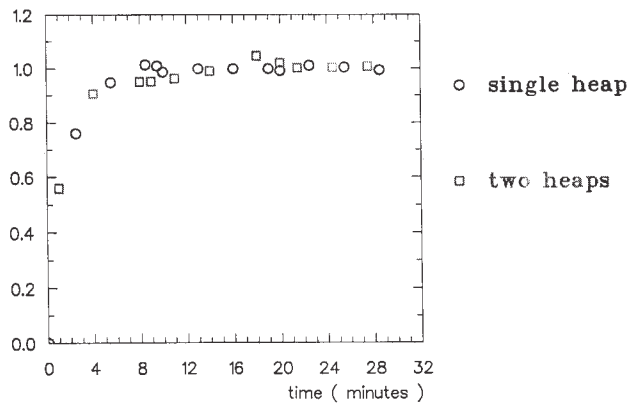
Effect of mode of introduction on dissolution of powdered salt in water

Tests in aluminum

Two modes of introduction of alloying elements were investigated : as a single heap and as two heaps, respectively.

The standard-size stirring tool was used and the mode of stirring was just above the heap.

Mn dissolved (%)



Test	Single heap	Two heaps
T _d , minutes	9	11

Figure 9

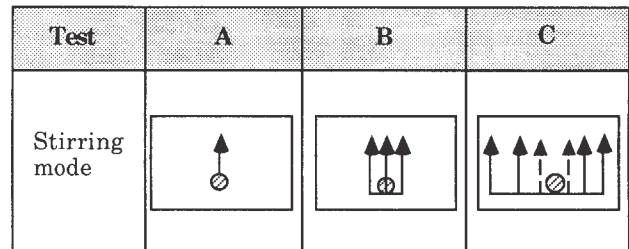
Experiments conducted in aluminum - Effects of mode of introduction of alloying elements

The results shown in Fig. 9 confirmed that there was nothing to be gained in terms of dissolution time by introducing the alloying elements as two heaps rather than one.

Stirring mode

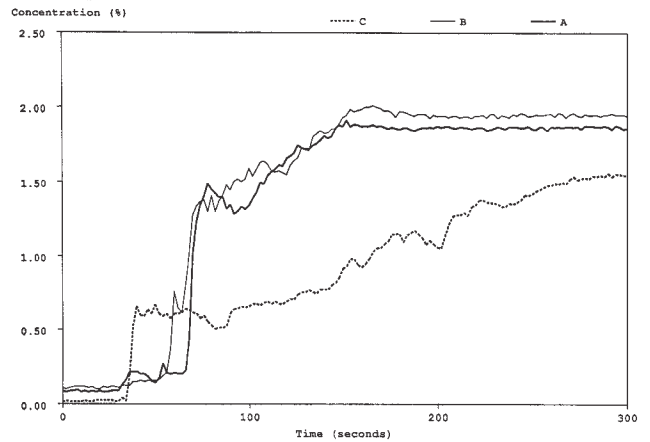
Tests in water

Three modes of stirring were compared experimentally : just above the heap (A and B) and over the whole of the tank cross-section (C).



In all three cases, the powder was introduced as a single heap near.

As will be seen from Fig. 10, it was not found necessary to stir over the whole of the tank section for the whole of the stirring time. To-and-fro motion over the heap of powder was sufficient to effect dissolution.



Stirring mode	A	B	C
T _d , seconds	145	144	228

Figure 10

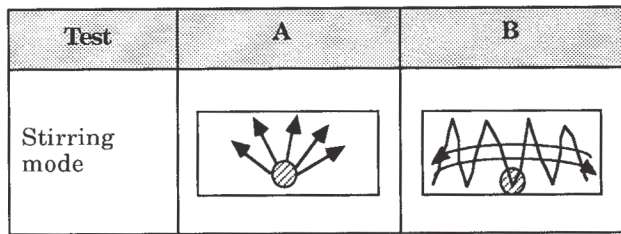
Effect of stirring mode on dissolution of powdered salt

Tests in aluminum

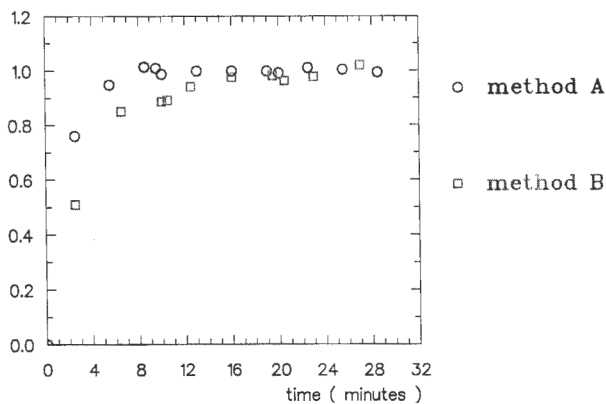
The two modes of stirring tested were : above the heap of alloying elements and over the entire cross-section of the furnace, respectively.

The materials were introduced as a single heap.

It will be seen from Fig. 11 that dissolution times for these two stirring modes differed by a factor of two. This confirmed the findings of the tests in water, i.e. that the most effective stirring mode was motion just above the heap of alloying elements.



Mn dissolved (%)



Test	A	B
T_d , minutes	9	19

Figure 11

Experiments conducted in aluminum / Effect of stirring mode

Stirring by rotor

A study was made of stirring in the ladle by means of a rotor, so as to take full advantage of the high temperature of the metal and of the fact that the geometry of the ladle (tall and narrow) lends itself well to effective stirring.

Experiments were carried out in water and in aluminum with a view to sizing the rotor for thorough mixing of the melt.

Sizing tests

Tests in water of the dispersal of insoluble powders (silicon carbide) by the action of a rotor enabled an evaluation to be made of the influence of various parameters on the diameter of action of the rotor, defined as the region below the rotor in which the strength of agitation is sufficient to lift the powdered material.

The parameters investigated were :

- rotor operating speed, N (300 to 1100 rpm) ;
- rotor diameter, D (20 to 30 mm) ;
- particle size, d_p (diameters 0.15 to 0.30 mm) ;
- depth of liquid in the tank, H (100 to 160 mm) ;
- distance of rotor from vessel bottom, h (3 to 11 mm) ;
- type of blades fitted to the rotor (vertical or inclined).

The experimental data obtained fitted an expression for the diameter of action, D_a , of a rotor over the range considered of the form :

$$D_a \propto \frac{ND^{5/2}}{D_p^{1/2}}$$

An increase in D_a would therefore require an increase in rotor rpm and, most importantly, in the diameter of the rotor.

The depth of liquid has no significant influence.

It was found that there is a limiting distance, h, between the rotor and vessel bottom over and above which the stirring action is insufficient to lift the particles.

A rotor with vertical blades generates strong turbulence and a powerful shearing action able to promote mixing of the currents in the fluid and the disintegration of large particles.

Tests to determine the rate of dissolution of manganese powder in liquid aluminum, conducted in a crucible with a capacity of 10 Kg and diameter of 180 mm, enabled the optimum value of the ratio of the diameters of the rotor and crucible, D/D_c to be determined.

A rotor fitted with four vertical blades was used.

It will be seen from Fig. 12 that the fastest possible agitation of the bath required a D/D_c ratio of between 1/3 and 1/2, which is consistent with standard reactor design data.

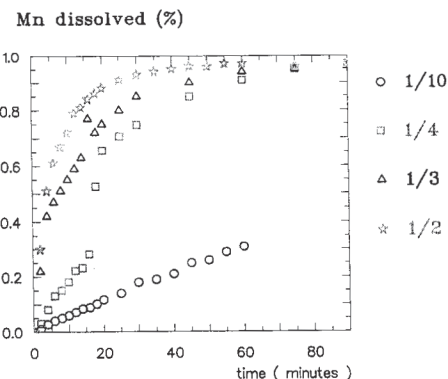


Figure 12

Determination of optimum D/D_c ratio

Industrial tests

Initial tests on an industrial prototype made it possible to determine :

- stirring time
- and turbine rpm

and optimise :

- penetration of alloying elements into the melt
- and the ability of the rotor to withstand the effects of the liquid metal at a temperature of 800°C

for all types of alloying elements.

Process operation

The system consisted of a motor-driven vertical shaft fitted at its lower extremity, immersed in the melt, with a rotor possessing six vertical blades.

The geometry of the rotor was optimised for the task of mixing a liquid with very high density metals tending to be not readily dissolved and to agglomerate at the base of the vessel.

The ladle was substantially cylindrical and contained a depth of liquid metal of 1 to 1.30 m. The rotor disc was 600 mm in diameter, one-third the diameter of the ladle, and was positioned approximately 20 cm from the base of the ladle.

Alloying elements were introduced via a feed hopper positioned above the melt and integral with the rotor assembly.

The full complement of alloying elements can be introduced in one or more ladles, i.e. the process can be operated to produce a "concentrate". For example, in the production of an alloy to contain 1.2 % manganese, the concentration in the ladle can be as high as 4 %.

Most alloys, especially those with high loadings of dense, hard to dissolve, elements like manganese, were investigated.

The alloying elements fed into the slight vortex depression at the surface of the melt were of several kinds :

- pure metals some with high melting points (powdered iron, manganese, copper, chromium, etc... ;
- master alloys introduced as ingots or splatters ;
- silicon, as lumps ;
- magnesium.

Dissolution efficiencies/times for alloying elements

Dissolution efficiencies and dissolution times were determined for manganese, silicon, copper and iron. The physical properties of these elements are set out in Table 1 below.

Element	Properties	Physical form
Mn, Fe	Rate of dissolution and solubility are both low	Mn : 96 % 0.5/3 mm powder Fe : 0.5/3 mm powder
Si, Cu	Rapidly soluble	Si : 10/100 mm lumps Cu : shot

Table 1

A series of tests was conducted on 3003 alloy to determine efficiencies for these alloying elements. Particulars of the tests are set out in Table 2 below.

Average weight. per ladle		5850 Kg
Weights introduced, Kg		Target concentration, %
Mn	250	3.9
Fe	70	1.3
Si	30	0.4
Cu	20	0.3

Table 2

Rotor operating speed was 120 rpm.

Element	Dissolution time, minutes	Efficiency, %
Mn	5	93 ± 2
Fe	4	99 ± 3
Si	< 5	100 ± 3
Cu	< 5	99 ± 3

It will be seen that less than 5 minutes was required to effect virtually complete solution of all alloying elements, particularly iron and manganese (Fig. 13).

This experimental result is of the same order of magnitude as predicted by the theoretical calculations.

Hence, the ladle and rotor stirrer assembly can be equated to a perfectly agitated reactor in which all the particulate matter is in suspension.

Mn dissolved (%)

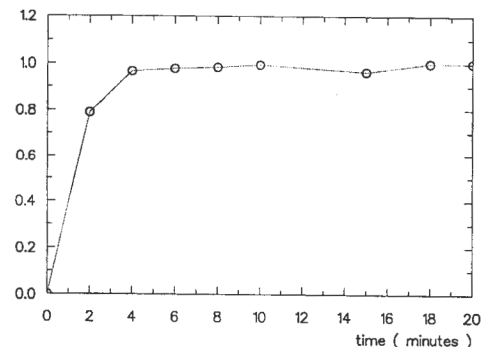


Figure 13

Dissolution of powdered manganese

Conclusion

Mathematical modelling of the stirring process, based on the results of experiments carried out in water with a blade-type stirring tool, has enabled a qualitative assessment to be made of how the stirring parameters influence the dissolution of powdered materials.

Although no direct and quantitative transposition from water to aluminum is possible, the data obtained does indicate the sense of the influence of the stirring parameters on dissolution, thus enabling these parameters to be optimised for any and all stirring systems.

The principal results yielded by the study in water with the blade-type stirrer concerns the major influence of the rate of travel of the stirrer blade ; dissolution time is inversely proportional to the rate of travel, as expressed by :

$$T_d \propto U^{-0.5}$$

Tests conducted on an industrial installation yielded analogous results, viz :

$$T_d \propto U^{-0.7}$$

The other results of significance obtained relate to :

- i) the size of the stirrer blade : in water, dissolution time is inversely proportional to blade size :

$$T_d \propto S_b^{-3/2}$$

- ii) the combination of positioning of the heap of alloying elements and stirrer travel : the optimum configuration has the stirrer reciprocating just above a heap introduced close to the furnace wall, a result confirmed by tests conducted on an industrial installation.
- iii) the furnace wall effect : dispersal of the powdered material over the furnace bottom was found to be improved by having the stirrer move over a heap positioned close to the wall.

This investigation of the mechanisms of dissolution has also enabled a process of stirring by means of a rotor to be sized which is capable of effecting solution of all alloying elements in a time comparable to that to be expected in a perfectly agitated reactor. In this case, the predictions of mathematical models of the dissolution process are in perfect agreement with the experimental data obtained on an industrial installation.

References

- [1] Burmeister L., 1982, "Convective Heat Transfer", J. Wiley, New York.
- [2] Batchelor G., 1980, "Mass Transfer from small particles suspended in turbulent fluid", J. Fluid Mech., vol. 98.

List of symbols

C_s	Alloying element content of the solid
C_f	Concentration in the melt on completion of dissolution
C	Concentration of alloying element in the liquid
H	Depth of liquid in the tank/ladle
D_a	Diameter of action of a rotor
D_c	Diameter of the crucible
T_d	Dissolution time
h	Distance of rotor from vessel bottom
S	Exchange surface area
r_0	Initial radius of a particle
z_0	Initial thickness of the layer of particles
ν	Kinematic viscosity
M	Mass of alloying element in solution
U	Mean linear velocity of the fluid
C_i	Mean concentration at the solid/liquid interface
D_m	Molecular diffusivity
d_p	Particle size
r	Radius of the spherical particle
ϵ	Rate of turbulent energy dissipation
N	Rotor operating speed
D	Rotor diameter
S_b	Size of the stirring blade
S_c	Schmidt number
k	Solid/liquid exchange coefficient
z	Thickness of the alloying element
u^*	Turbulent velocity