Essential Readings in Light Metals: Cast Shop for Aluminum Production.
Edited by John F. Grandfield and Dmitry G. Eskin.

REMOVAL OF INCLUSIONS - A SURVEY AND COMPARISON OF PRINCIPLES

F. Frisvold, T. A. Engh*, S. T. Johansen and T. Pedersen**

SINTEF Metallurgy, The Foundation for Scientific and Industrial
Research at The Norwegian Institute of Technology,
N-7034 Trondheim, NORWAY

*The Norwegian Institute of Technology, Division of Metallurgy,
N-7034 Trondheim, NORWAY

**Hydro Aluminium R&D Centre, N-6601 Sunndalsøra, NORWAY

Abstract

A number of melt refining unit operations for the removal of inclusions from aluminium exist. Examples are settling in holding furnaces, flotation in gas purging units, and settling and interception in filters.

The basic principles at our disposal for inclusion removal in the various units are few: blockage (sieving, cake-filtration), sedimentation (settling), interception, flotation, electromagnetic forces, and turbulent deposition. Also agglomeration prior to removal should be considered. A comparison of the principles is made on the basis of the particle size dependence of the mechanisms.

Introduction

Inclusions in aluminium may have an adverse effect on surface appearance, a severe effect on mechanical properties and may also influence the machining properties.

A number of methods for the removal of inclusions from melts exist and patents are plentiful. The basic mechanisms, ensuring the transfer of inclusions out of the melt are few on the other hand. Most of todays units are based on one or more of the principles: flotation, sedimentation, interception or electromagnetic forces.

In this paper a review of the basic principles for the removal of inclusions will be given. The physics of the deposition mechanisms will be highlighted. The question of adhesion and related subjects such as re-entrainment will only be briefly mentioned. The mechanisms deposit the inclusions in different manners. Re-entrainment will depend on the deposition mechanism and also on how the separation mechanism is implemented (f.ex: ceramic foam filters vs. deep-bed filters).

Mechanisms

An effective unit for inclusion removal must separate inclusions down to the smallest sizes from the melt (5 µm or even less). When comparing the efficiency of different units it is important to consider the number-size distribution (1). Using only total volume or mass in and out of the unit may give a biased picture of the efficiency. Large inclusions give significant contributions to both mass and volume. They are easily separated by a number of mechanisms. However if they happen to be present in the final product the effect on quality may be very detrimental.

As already mentioned only a limited number of mechanisms can be used to separate particles from fluids. Of these the inertial forces can be disregarded immediately since they are only of significance for gases i.e. where the density difference between particles and fluid is large.

Blockage

Inclusions may be removed by forcing the melt through a medium with pores smaller than the inclusion diameter. Pores smaller than the inclusions will then be blocked. This mechanism is utilized by cake-filtration. Obviously the capacity of such systems is low since the inclusions deposited give a very high pressure drop.

Sedimentation

Inclusions sinking in the gravitational field due to the density difference between inclusion and melt are said to be removed by sedimentation or settling. A single particle in a quiescent liquid will sink with a velocity given by a balance between buoyant forces and drag forces. The settling velocity is

$$U_s = \frac{\Delta\rho}{\rho}\frac{d^2 g}{18\nu} \qquad (1)$$

$\Delta\rho$ is the density difference between inclusion and melt, ρ is the melt density, d is the inclusion diameter, $g = 9.81$ m/s^2, and ν is the kinematic viscosity.

The equation is strictly valid only for single spherical inclusions settling in an infinite medium. Non-spherical particles or suspensions of particles will settle more slowly due to increased drag forces. Also close to surfaces the settling velocity will be reduced due to wall effects (2).

For rotating filters the "driving force" is still the density difference, but now the centripetal acceleration replaces the acceleration of gravity. Thus $\omega^2 r$ replaces gravity g in the various relations for removal, where ω is the rotational velocity and r is the distance from the axis of rotation.

Interception

Interception descibes the effect that the inclusion follows the streamlines and collides with the collector only due to its finite size. If the flow past the collector is taken to be potential flow the collision efficiency is

$$\eta = 3\frac{d}{d_c} \tag{2}$$

This is valid for:

$$\frac{d}{d_c}\sqrt{\frac{3}{2}Re_c} > 1 \tag{3}$$

Here d_c is collector diameter. The boundary layer around the collector was not taken into consideration in the above equation. An estimate of the boundary layer thickness is

$$\delta = \sqrt{\frac{\nu\, d_c}{6\, U_\infty}} = \frac{d_c}{\sqrt{6Re_c}} \tag{4}$$

where

$$Re_c = \frac{U_\infty\, d_c}{\nu} \tag{5}$$

If the boundary layer is considered, the number of particles moving near the collector surface is reduced. Then the collision efficiency becomes smaller (3). The relationship is given graphically as discrete points in (3). A conservative estimate based on the graph gives:

$$\eta = \frac{3}{2}\,\frac{d^2}{d_c^2}\sqrt{\frac{3}{2}Re_c} \tag{6}$$

This is valid for small Re_c:

$$\frac{d}{d_c}\sqrt{\frac{3}{2}Re_c} < 0.2 \tag{7}$$

Equation (6) applies to a smooth spherical collector. If the collector surface is "rough" and/or the collector has a number of protrusions, deposition may take place on the protrusions jutting outside the boundary layer. Then the additional collection efficiency due to the protrusions may be roughly estimated by Eq. (2) if d_c is replaced by the protrusion diameter d_p. The idea here is that the protrusion parts outside the collector boundary layer may be regarded as separate collectors. This means in practice that deposition rates of inclusions in a filter should increase with time due to a build up of "dendrite" protrusions (4). This mechanism is complex and modelling requires extensive numerical calculations.

Flotation

Flotation is not a single operation, but a combination of interception with a gas bubble and subsequent removal when bubbles and particles rise to the melt surface. Bubbles in aluminium may or may not be covered with a "stiff" oxide film. In the latter case the collision efficiency will be exactly the same as for an equivalent solid sphere surrounded by a boundary layer, i.e. Eq. (6).

In the former case the interface is a (free) gas-liquid interface, i.e. the gas inside the bubbles will move in two recirculating zones. As a consequence the bubble-melt interface is moving at a finite velocity. Also, now the inclusions have to penetrate the bubble-melt interface in order to be removed from the melt. For this to happen wetting properties must be such that the inclusions have the necessary surface energy potential to overcome the effects of shear from the melt and/or gravity and inertial forces. A particle is not retained if it barely touches the interface.

Frisvold and Engh (5) have taken the surface Gibbs energy into account and calculated the collection efficiency:

$$\eta = \frac{3d}{d_b}\sin^2\theta_c \tag{8}$$

Here θ_c is a critical polar angle for impaction of inclusion on the bubble. This angle is the largest angle that allows inclusions of size d to adhere to the bubble. At larger impaction angles the time of contact between bubble and inclusion is too small for the particle to penetrate deep enough through the interface. θ_c depends on bubble size, inclusion size, inclusion velocity, inclusion density, and on interfacial tensions in the system bubble/melt/inclusion.

Electromagnetic forces

Electromagnetic removal of inclusions has until now been utilized least of the mechanisms. Electro-magnetic forces are otherwise employed for stirring, casting, and pumping of metals.

Electromagnetic volume forces affect the (conducting) melt, but not the non-metallic inclusions (oxides and carbides). In a melt a pressure gradient will be generated by an electromagnetic field. An inclusion in the melt will feel the pressure gradient or volume force ("buoyancy") due to the inclusion not having the same conductivity as the melt. In principle inclusions may be driven in any direction by electric and magnetic fields.

The forces may be created by:

1. Use of an applied electric field in conjunction with a magnetic field.

2. By letting the magnetic field induce a current in the melt.

3. By sending a current through the melt thereby inducing a magnetic field that interacts with the current (6). This gives a pinch-effect.

Note that the efficiency of the electromagnetic forces depends on the orientation of non-spherical inclusions (6,7,8).

The electromagnetic force the melt experiences, $\mathbf{f}$, is expressed in terms of the current density $\mathbf{j}$ and the magnetic induction $\mathbf{B}$:

$$\mathbf{f} = \mathbf{j} \times \mathbf{B} \tag{9}$$

The current density is

$$\mathbf{j} = \sigma[\mathbf{E} + \mathbf{u} \times \mathbf{B}] \tag{10}$$

σ is the conductivity, $\mathbf{E}$ is the applied electric field, and $\mathbf{u}$ is the melt flow velocity.

Turbulent deposition

A relationship between the collision efficiency, η, and the mass transfer coefficient for deposition, k_t, is derived in a following section

$$k_t = \eta\, u\, b \tag{11}$$

b is equal to the ratio between projected area in the flow direction and the surface area, i.e. b = 1/4 for spherical collectors. u is the inclusion bulk velocity relative to the collectors.

In turbulent flow the inclusions are carried to the surface due to (turbulent) velocity fluctuations. The turbulent deposition rate for a smooth surface is (9):

$$k_t = 5.1 \times 10^{-4}\, u_\tau \left(\frac{d\, u_\tau}{\nu}\right)^2 \tag{12}$$

ν is the kinematic viscosity, u_τ is the shear velocity in the boundary layer, and d is inclusion diameter. Engh and Lindskog (10) have derived a formula for removal to the rough walls of a ladle where k_t is given as a function of stirring power.

Deposition at a rough surface is complex and one will need a further treatment to describe removal in molten aluminium. Deposition at a rough surface is more efficient than for a smooth surface. In this case k_t may possibly be proportional to the inclusion diameter (11).

Agglomeration

Levich (12) has discussed coagulation in suspensions consisting of mono-size particles (monodisperse systems). Possible mechanisms for agglomeration is:

1. Brownian (thermal) agglomeration - the particles agglomerate due to the fact that small macroscopic particles in a liquid always will be in chaotic movement. The movements are manifestations of statistical fluctuations in equilibrium.

2. Gradient agglomeration - if there are velocity gradients in a liquid, e.g. in the boundary layer near a wall, particles close to each other move at different velocities. They may collide if the distance is less than a particle diameter.

3. Turbulent agglomeration - small particles in turbulent vortices migrate through the liquid in a chaotic manner resembling Brownian movement.

4. Agglomeration in polydisperse systems, i.e. suspensions with a distribution of particle sizes and particle densities. Since the forces from the gravitational field and electromagnetic fields depend on size and density difference, this may lead to collisions between particles of different sizes and/or densities.

Agglomeration is not a mechanism for direct removal of inclusions but amplifies the effect of the other mechanisms. It can be shown that the time constant for agglomeration is (13):

$$\tau\,[s] \approx \frac{\sqrt{\nu/\varepsilon}}{0.309\, c_0} \tag{13}$$

where c_0 is volume fraction inclusions and ε is the dissipation rate of turbulent energy.

If agglomeration is to be important the time constant for agglomeration must be less than the residence time.

As an example we have calculated the time constant for agglomeration to be 3.8 minutes in an aluminium melt with a dissipation rate of 1 m^3/s^2 and an inclusion concentration of 10 ppm.

It is seen that the time constant for agglomeration is independent of inclusion size. It follows that for small inclusions agglomeration (the production of larger inclusions) will be the only mechanism that is efficient. Since all inclusions become larger this would seem to be detrimental. However, the larger inclusions are easier to remove. In this manner even small inclusions can be eliminated.

If the stirring is too powerful, agglomerates may be broken up. Therefore, there is an optimum stirring power when creating agglomerates in a melt with a particular kind of inclusions.

Under ordinary conditions in aluminium melts coagulation should be insignificant (14). With powerful stirring agglomeration may be important only in the parts of the melt where dissipation is high.

Comparison of various mechanisms

Centripetal force vs acceleration of gravity

If we consider a rotating filter the separation mechanism will be an amplified sedimentation. The amplification is given by the ratio

$$\phi_1 = \frac{\omega^2 r}{g} \tag{14}$$

Assuming a rotor diameter of 20 cm and a rotational velocity in the range 500 - 900 rpm, Eq. (14) gives

$$27.9 < \phi_1 < 90.5 \qquad \textbf{(15)}$$

Electromagnetic removal vs sedimentation

Electromagnetic removal depends on the inclusion diameter to the square similarly to sedimentation. A comparison between the two appears reasonable. The improvement of electromagnetic separation over sedimentation is given by the ratio between the settling velocities:

$$\phi_2 = \frac{J_0 B_0}{\Delta\rho g} \qquad \textbf{(16)}$$

Here it has been assumed that the electromagnetic field is due to crossed electric and magnetic fields. Also the inclusions are assumed to be spherical. The effect of the electromagnetic field is slightly overestimated. For oxide inclusions the density difference is about 1500 kg/m^3. Vives and Ricou (8) have used the following values for the electromagnetic force density

$$6875 < J_0 B_0 < 148.000\ N/m^3 \qquad \textbf{(17)}$$

The ratio then becomes

$$0.5 < \phi_2 < 10 \qquad \textbf{(18)}$$

Turbulent deposition vs sedimentation

Stirring is used in steelmaking to remove inclusions (10).

The turbulent deposition mechanism will dominate over sedimentation (15) when

$$\alpha = 9.2 \times 10^{-3}\ \frac{u_\tau^3}{g\nu}\ \frac{\rho_m}{\Delta\rho} > 1.0 \qquad \textbf{(19)}$$

It is seen that the influence of the turbulence increases when the density difference $\Delta\rho$ gets smaller. For aluminium oxide inclusions in aluminium the critical shear velocity becomes u_τ = 0.066 m/s. An estimate on the shear velocity is

$$u_\tau \approx \frac{U_{bulk}}{20} \qquad \textbf{(20)}$$

This gives a bulk velocity of 1.3 m/s. Velocities of this size are rare in metallurgical systems, expect when stirring. In traditional filters the velocities are on the order of 1 cm/s or less (16).

The above is valid for a smooth surface. If the surface is rough one may assume that the shear velocity is higher. This means that turbulent deposition may dominate over sedimentation at bulk flow velocities down to roughly 13 cm/s if we assume that the shear velocity is twice as high (17) as given by Eq. (20). This is still high compared to velocities in filters.

Size dependence of mechanisms

In order to compare the size dependence of the mechanisms, we summarize the collision efficiencies:

Interception (smooth surface):

$$\eta_{i,s} = \frac{3}{2}\ \frac{d^2}{d_c^2}\sqrt{\frac{3}{2}\frac{U_\infty\ d_c}{\nu}} \qquad \textbf{(21)}$$

Interception ("rough" surface):

$$\eta_{i,r} = \frac{3d}{d_c} \qquad \textbf{(22)}$$

Flotation ("stiff" interface):

$$\eta_{f,s} = \frac{3d^2}{2d_b^2}\sqrt{\frac{3}{2}\frac{v_b d_b}{\nu}} \qquad \textbf{(23)}$$

Flotation (free interface):

$$\eta_{f,f} = \frac{3d}{d_b}\ \sin^2\theta_c \qquad \textbf{(24)}$$

Sedimentation:

$$\eta_s = \frac{U_s}{U_s + U_\infty}\ ,\ U_s = \frac{\Delta\rho}{\rho}\ \frac{d^2 g}{18\nu} \qquad \textbf{(25)}$$

Centrifugal:

$$\eta_{centr} = \frac{\phi_1 U_s}{\phi_1 U_s + \tilde{U}_\infty} \approx \phi_1\ \eta_s \qquad \textbf{(26)}$$

Electromagnetic:

$$\eta_{em} = \frac{\phi_2 U_s}{\phi_2 U_s + U_\infty} \qquad \textbf{(27)}$$

Turbulent (smooth wall):

$$\eta_{turb,s} = 20.4 \times 10^{-4}\ \frac{u_\tau}{u}\ (\frac{d\ u_\tau}{\nu})^2 \qquad \textbf{(28)}$$

The size dependence of the mechanisms are shown graphically in Figures 1-8. In the figures also the influence of the other parameters are given. In the calculations we have used a kinematic viscosity of 0.5 X 10^{-6} m^2/s and a melt density of 2350 kg/m^3. The inclusions are assumed to be oxides with a density of 3850 kg/m^3, giving a density difference of 1500 kg/m^3.

Removal efficiency

So far we have discussed the collection efficiency, η, of single collectors but what is the removal efficiency, E, of a unit with a given collection efficiency per collector ?

It is assumed that removal is proportional to particle concentration and surface area. A coefficient for transfer of particles, k, is introduced by defining it so that the number of particles transferred to the collector surface A_s per unit time is k A_s c.

Another expression for the number of particles removed is obtained by multiplying the collection efficiency with cross sectional area A_s b of the collectors and with u. b is equal to the ratio between projected area in the flow

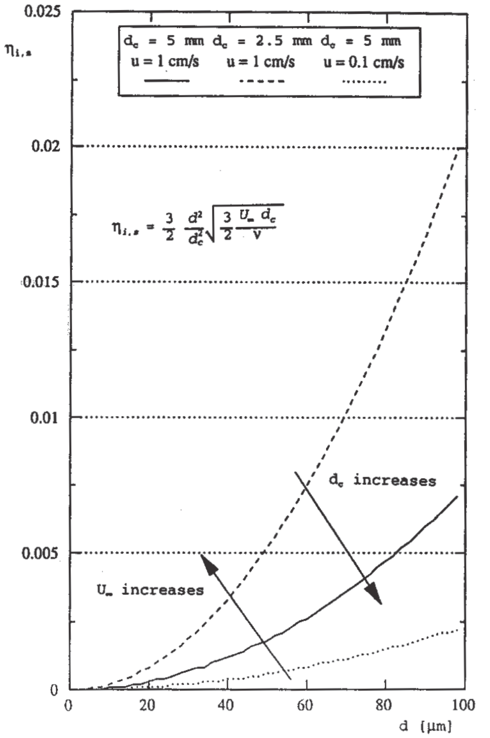

Figure 1. Collision efficiency due to interception at a smooth surface as a function of inclusion diameter.

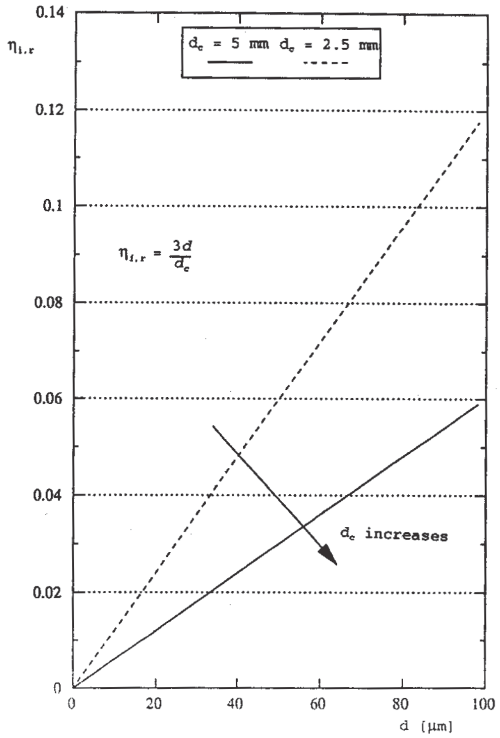

Figure 2. Collision efficiency due to interception at a rough surface as a function of inclusion diameter.

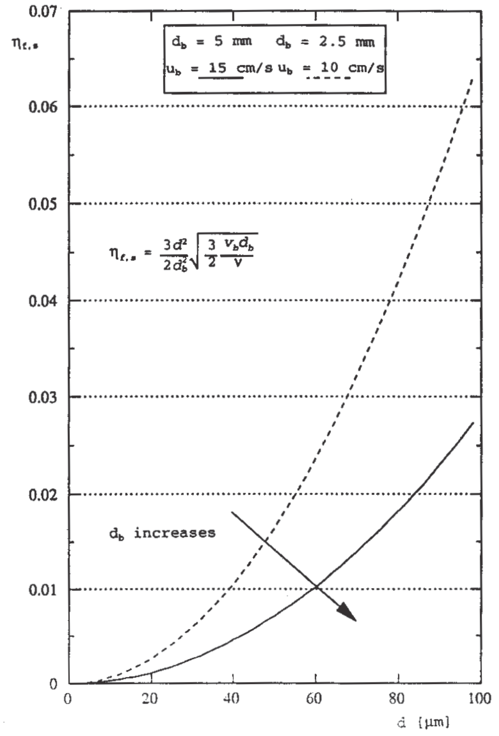

Figure 3. Collision efficiency due to flotation by a bubble with a "stiff" interface as a function of inclusion diameter.

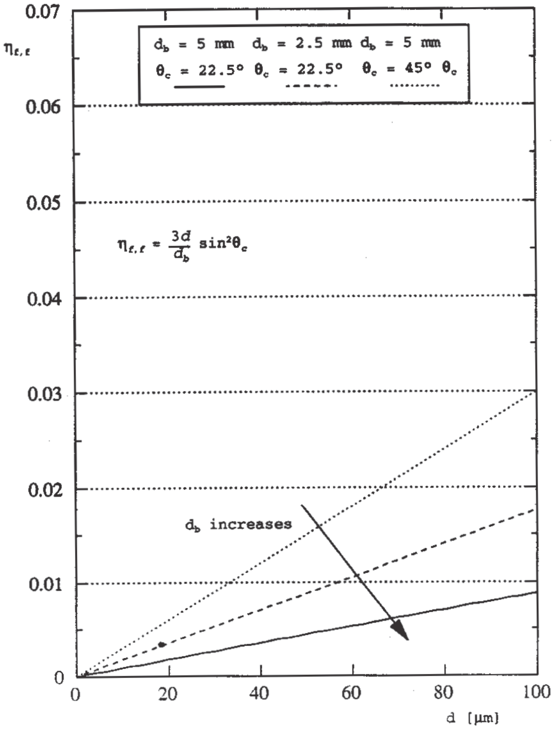

Figure 4. Collision efficiency due to flotation by a bubble with a free interface as a function of inclusion diameter.

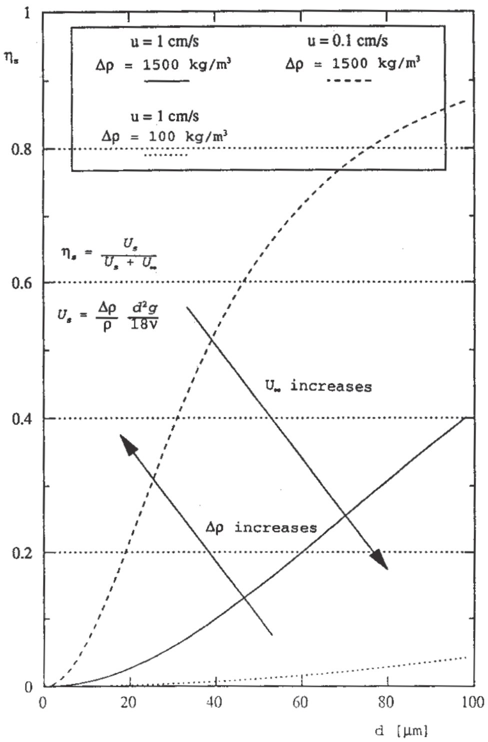

Figure 5. Collision efficiency due to sedimentation as a function of inclusion diameter.

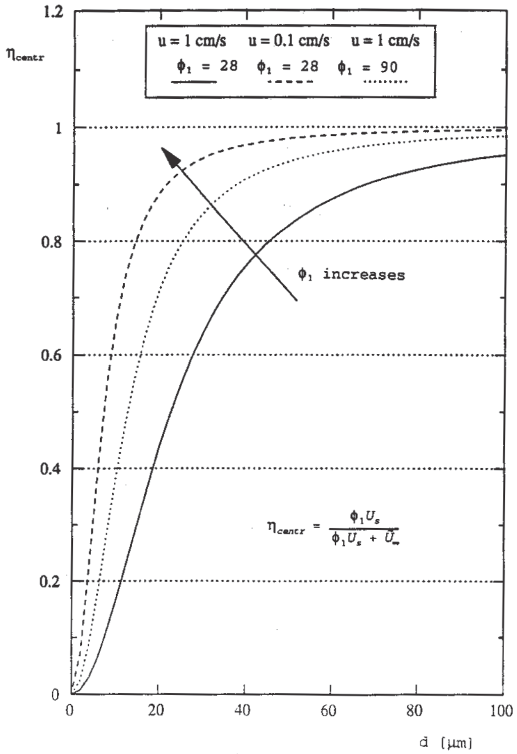

Figure 6. Collision efficiency due to centrifugal forces as a function of inclusion diameter.

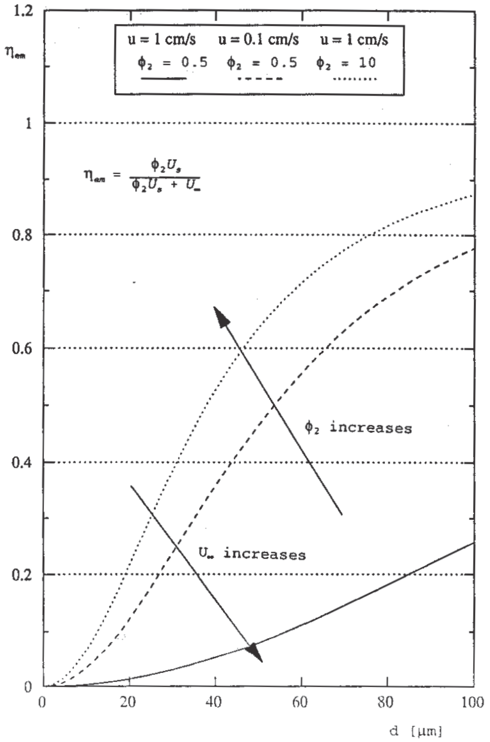

Figure 7. Collision efficiency due to electromagnetic forces as a function of inclusion diameter.

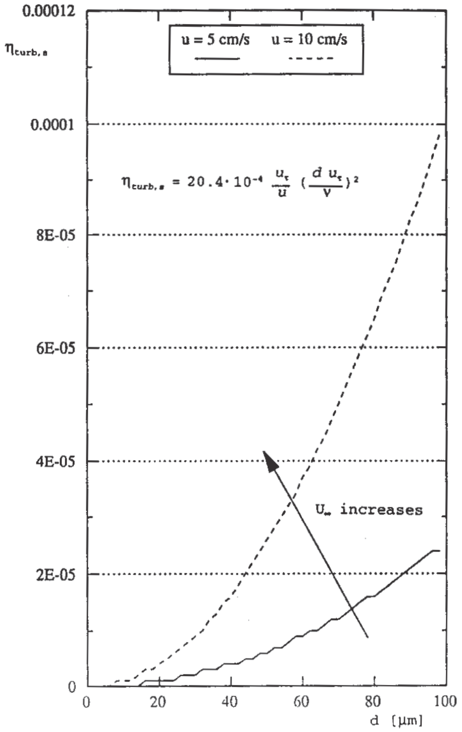

Figure 8. Collision efficiency due to turbulent deposition at a smooth wall as a function of inclusion diameter.

direction and the surface area. u is the particle bulk velocity relative to the collectors. Then $\eta\ A_s\ b\ u$ is the volume of melt cleaned up by the collectors. The number of particles removed is obtained by multiplying this expression with the number of inclusions per unit volume c. Comparison of the two expressions for the number of inclusions removed gives (18):

$$k = \eta\, u\, b \tag{29}$$

A number balance for particles gives:

accumulation of particles per unit time
= difference between convection in and out of the control volume
+ difference between flow in and out due to diffusion

Diffusion is assumed to be negligible. σ is the number of particles deposited per volume removal unit:

$$\frac{\partial}{\partial t}(\sigma+\varepsilon c) + \frac{\partial}{\partial x}(\varepsilon c u) = 0 \tag{30}$$

It is assumed that the number of particles deposited is much larger than the number of particles in the melt, i.e. the melt is regarded as a dilute suspension:

$$\sigma > \varepsilon\, c \tag{31}$$

From the above discussion it follows that the number of particles deposited per volume removal unit and unit time may be expressed as:

$$\frac{\partial \sigma}{\partial t} = k\, A_s\, c\, \varepsilon \tag{32}$$

Integration of Eq. (30) employing Eqs. (32) and (29) then gives:

$$\frac{c}{c_0} = e^{-\eta\, b\, A_s\, x} \tag{33}$$

The removal efficiency is defined as:

$$E = 1 - \frac{c}{c_0} = 1 - e^{-\eta\, b\, A_s\, x} \tag{34}$$

It is seen that a high removal efficiency may be obtained by having a large specific area, a deep unit with a large x, or a high collection efficiency, η. By assuming that the other parameters are the same for all units, we may compare units based solely on the collection efficiency as in the previous section.

Adhesion and re-entrainment

Particles are removed by transfer to a second phase, for example a solid wall in a filter or a gas bubble in a gas purging unit. Practical experience in the cast shop shows that there is sudden surges or releases of inclusions from filters.

Frisvold (3) have calculated the force pressing an inclusion towards a filter wall due to the surface tension of the melt. It was found that this force is much larger than the drag forces on the inclusion (diameter 10 μm). The industrial experience with particle releases must therefore be explained by particles using a long time to penetrate a film before they get stuck. In the mean time the particles are just 'floating' on this film and may be re-entrained by sudden filter surges due to flow and pressure variations.

The effect of time of contact on adhesion has not been measured for small particle adhesion. For a steel ball of 0.32 cm diameter on an indium block with 500 g load, Bowden and Tabor (19) report that full adhesion was reached in 2000 seconds. It is difficult to extrapolate these data to micron size particles where essentially no load is applied.

Conclusion

For most of the mechanisms, the removal of the smallest inclusions is proportional to the square of the diameter. The exceptions may be agglomeration and deposition on a rough surface.

In other words, removal of small inclusions is very difficult to attain. Therefor a solution to the problem of removal of the smaller inclusions may be agglomeration by powerful stirring as a first step. Theoretical studies indicate that the time constant for agglomeration is independent of inclusion diameter.

As much as possible of inclusions should be removed by sedimentation and/or flotation before eventual filtration, in order to increase the life time of the filter.

Acknowledgments

The authors wish to acknowledge the financial support of this work by the Royal Norwegian Council for Scientific and Industrial Research under the EXPOMAT program and by Hydro Aluminium a.s.

References

1. D. Apelian and S. Shivkumar, "Molten metal filtration - past, present and future trends" (Paper presented at the 2nd International Conference on Molten Aluminium Processing, Orlando, Florida, Nov 6-7, 1989), 14-1 -14-36

2. F. Durst and H. Raszillier, "Analysis of particle-wall interaction", Chemical Engineering Science, 44 (12)(1989), 2871-2879

3. F. Frisvold, "Filtration of aluminium. Theory, mechanisms, and experiments" (Dr.Ing.-Thesis, The Norwegian Institute of Technology, Trondheim, Norway, 1990)

4. S. T. Johansen and N. M. Anderson, "A mathematical model for large scale filtration of aluminium", EDP Congress '90, ed. D.R. Gaskell (Warrendale, PA: The Metallurgical Society, 1990), 441-451

5. F. Frisvold and T. A. Engh, "Flotation - a theory incorporating fluid flow and adhesion", To be published

6. E. I. Shilova, "Purification of liquid metals from nonconducting impurities in the magnetic field of a current in them", Magnetohydrodynamics, 1975, 250-251

7. P. Marty and A. Alemany, "Theoretical and experimental aspects of electromagnetic separation", Metallurgical Applications of Magnetohydrodynamics, Cambridge, England, 6-10 Sept. 1982, (Published by The Metals Society, 1984), 245-259

8. C. Vives and R. Ricou, "Liquid-solid separation in a molten metal by a stationary electromagnetic field", Liquid Metal Flows and Magnetohydrodynamics, Third International Seminar in the MHD Flows and Turbulence Series, Beer-Sheva, Israel 23-27 March 1981, 387-401

9. S. T. Johansen, "On the modelling of disperse two-phase flow", (Dr.Techn.-Thesis, The Norwegian Institute of Technology, Trondheim, Norway, 1990), chap. 9, page 11

10. T. A. Engh and N. Lindskog, "A fluid mechanical model of inclusion removal", Scand. J. Metallurgy 4 (1975), 49-58

11. T. A. Engh, Principles of Metal Refining, (Oxford University Press, Oxford, To be published), Chapter 5

12. V. G. Levich, Physicochemical Hydrodynamics, (Prentice-Hall, Inc., Englewood Cliffs, N.J., 1962)

13. K. Higashitani, K. Yamauchi, Y. Matsuno, and G. Hosokawa, "Turbulent coagulation of particles in a viscous fluid", J. Chem. Eng. Japan 16 (1983), 299-305

14. T. A. Engh, Principles of Metal Refining, (Oxford University Press, Oxford, To be published), Appendix 2

15. S. T. Johansen, F. Boysan, and T. A. Engh, "Numerical calculations of removal of inclusions and dissolution of refractory in a bubble stirred ladle", (Paper presented at The Fourth Japan-Nordic Countries Symposium of Science and Technology of Process Metallurgy, Nov. 17-18, 1986, The Iron and Steel Institute of Japan), 182-215

16. P. Netter and C. Conti, "Efficiency of industrial filters for molten metal treatment evaluation of a filtration process model", Light Metals 1986, ed. R. E. Miller (Warrendale, PA: The Metallurgical Society), 1986, 847-860

17. S. T. Johansen, "On the removal mechanisms for inclusions in a liquid metal", (SINTEF-Report STF34 F91071, The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology, 1991)

18. F. Frisvold and T. A. Engh, "Fundamentals of filtration", (Paper presented at the Second Australian Asian Pacific Course and Conference, Aluminium Melt Refining and Casting, 1-4 July 1991, Melbourne, Australia), 23:1-23:23

19. F. P. Bowden og D. Tabor, The friction and lubrication of solids, (Clarendon Press, Oxford, 1950), 307