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The Clifford Paterson Lecture, 1992: Magnetohydrodynamics in Material Processing

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The Clifford Paterson Lecture, 1992
Magnetohydrodynamics in material processing

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The need to increase quality and decrease manufacturing costs makes innovation in material processing more difficult. Magnetic fields, which can inject thermal or mechanical energy into electroconducting materials, are a very rich source of innovation. Industrial applications of research in magnetohydrodynamics have given rise to new technologies for melting, casting or shaping, not only useful for metallic materials but also for oxides, glasses or ceramics.

1. Introduction

During the first half of this century an original and independent discipline called magnetohydrodynamics (MHD) really started to be developed by astrophysicists, who pointed out the existence of magnetic fields in a set of astronomical objects. The main principles of the phenomena involved were clearly formulated at the end of this period by H. Alfvèn, who received the Nobel Prize in 1970. Original results obtained in astrophysics and in plasma physics initiated fundamental research dealing with interactions between magnetic fields and currents induced in electroconducting liquid volumes with a typical length scale much smaller than the astrophysical one. During the past 25 years a new field of research has developed out of the combination of material processing and magnetohydrodynamics. This new field, now called 'electromagnetic processing of liquid materials', was clearly revealed during the IUTAM Symposium on Metallurgical Applications of MHD held in Cambridge in 1982. Reviews of applications, and of the associated basic research, such as induction furnaces, electromagnetic stirring, electromagnetic shaping, levitation melting, were presented and showed how attractive and promising was this new research activity (Moffatt & Proctor 1984).

Two main classes of problems, and therefore of possible applications, are to be distinguished: whether the applied magnetic field is DC or AC.

2. DC magnetic field

The interaction between the local velocity of $\boldsymbol{V}$ of an electroconducting liquid and a constant magnetic field $\boldsymbol{B}$ gives rise to induced current $\boldsymbol{j}$ whose distribution is governed by Ohm's law, $\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B})$, where σ denotes the electrical conductivity of the liquid and $\boldsymbol{E}$ the electric field. When interacting with the applied magnetic field, the induced currents produce a pure braking force whose intensity is maximum when $\boldsymbol{V}$ and $\boldsymbol{B}$ are perpendicular, according to the anisotropy introduced by the

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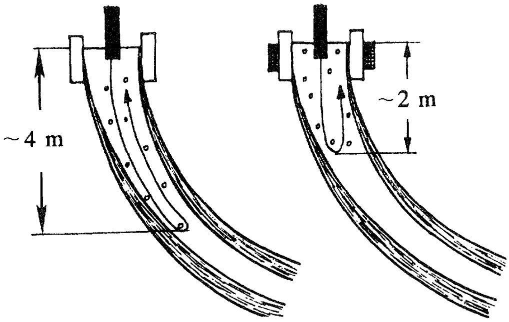

Figure 1. Reduction of flow velocity penetration into the strand due to EMBR.

$V \times B$ product. Such an anisotropy affects the velocity field (Sommeria 1988). Turbulence in liquid metals becomes two dimensional: vortices stretch along magnetic field lines and turbulent structures become columnar. This organization of flow in the chaotic behaviour of turbulence has an interesting influence on related transfer phenomena. In the direction of the magnetic field transfer which is governed by molecular diffusivity is very slow; on the contrary, in any plane perpendicular to this direction, transfer is governed by eddy diffusivity and is therefore very rapid and efficient. DC fields, through the modification of turbulence can therefore reduce transfer phenomena in one direction and promote them in any perpendicular direction. Such a property may find interesting applications in the doping of parallel separate layer during single crystal manufacturing, for example.

An interesting innovation using the damping effect produced by DC magnetic fields has been the result of a joint research project between ASEA Company and Kawasaki Steel Corp. This new technique is now referred as EMBR (electromagnetic brake). The aim of the research was to reduce the amount of slag inclusions which accumulate in the upper half of the strands when increasing casting speed in curved-type continuous casters. These phenomena occur because the velocity of the liquid steel flowing out the immersed nozzle is higher than the velocity of inclusions floating upward. A very interesting advantage has been taken from the electromagnetic braking effect induced by applied DC magnetic field to reduce velocity. A magnetic field is imposed in a direction perpendicular to the flow of metal jets (figure 1), which experience strong braking effect. This innovation is exemplary for several reasons: it is simple from a purely technological point of view since it only consists of four poles and associated windings, and two magnetic yokes; energy consumption is low because of the use of DC magnetic fields; and the mechanical effect is of first order importance compared with the Joule effect. The casting jets are not only braked but also split which results in a better mixing of the recently added hot steel with the surrounding cooler steel in the mould. This is of prime importance in preventing the slag inclusions from being entrapped in the newly formed shell immediately under the meniscus. Moreover, the braked jets erode much less the narrow faces of the shell whose thickness increases near the corners (figure 2).

Regarding material processing, DC magnetic fields cannot be limited to damping or suppression effects. Indeed the two media on both sides of the solidification front have a different thermoelectric power and a different electrical conductivity. Seebeck effect then arises along the dendritic non-isothermal interface and a voltage appears between tips and feet of the dendrite that is responsible for the presence of electric currents which flow roughly parallel to the surface of the dendrites from top to foot.

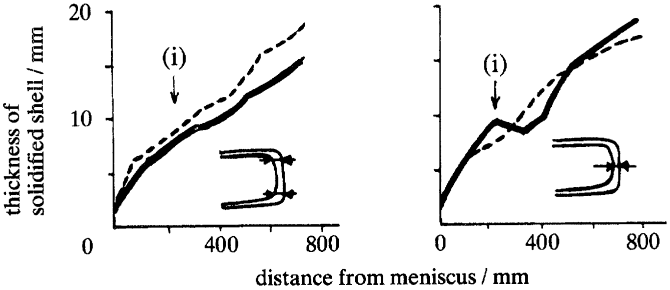

Figure 2. Influence of EMBR on solidification rate of narrow faces; (i) impinging point. ----, With EMBR; ———, without EMBR.

It is clear that the interaction of these currents with an external applied DC field produces motions within the interdendritic space. Modifications in solidification structure can then be easily obtained according to the relative direction of the magnetic field and the solidification front. Such modifications have been experimentally cleared up by Nippon Steel Corp. (Takeuchi *et al.* 1990) when submitting a Sn–Pb alloy undergoing solidification to a high intensity DC magnetic field produced by a superconducting magnet. When the magnetic field is parallel to the solidifying direction, the equi-axed structure without magnetic field becomes unidirectional and parallel to the magnetic field when applied with an intensity higher than 0.6T.

3. AC magnetic fields

When submitted to an external AC magnetic field $\boldsymbol{B}$, a given electroconducting medium experiences flux variations against which it reacts. This reaction results in the creation of electromotive forces and in induced currents $\boldsymbol{j}$ in opposition to the inducting currents. Induction heating applications are based on the existence of induced currents. MHD phenomena originate from the interaction between induced currents and applied magnetic fields which gives rise to mechanical effects through the Lorentz force $\boldsymbol{j}\times\boldsymbol{B}$. Note that since induced currents are the result of a reaction against the applied magnetic field, they flow perpendicular to the magnetic field lines, which is the most favourable direction for the generation of electromagnetic forces. These forces are pulsating at twice the frequency of the applied magnetic field. The r.m.s. value of the Lorentz force is a repulsive force between the inductor and the electroconducting material. This force can be split into an irrotational part, which results in magnetic pressure $\frac{1}{2}B^2/\mu$, and a rotational part, which is a driving force responsible for stirring motions in electroconducting liquid materials.

It is impossible to separate the thermal and mechanical effects when using AC magnetic fields. This is sometimes a disadvantage of AC magnetic fields for industrial applications, in comparison with DC fields, because of power losses due to the Joule effect and resulting reduction of the global efficiency when only mechanical effects are of interest. However, the frequency parameter f may vary over a wide range and offers interesting possibilities in the selection of induced effects Induced currents and electromagnetic forces are located within a boundary layer, because of the electromagnetic skin effect, whose thickness, proportional to $f^{-\frac{1}{2}}$, can be controlled. Moreover it is possible to select the frequency to promote a given induced effect. Indeed in the two asymptotic cases where frequency is zero or infinite, leading to zero skin depth, there are no induced currents resulting from the presence of the applied magnetic field and therefore induced effects are zero in these two cases. This implies that an optimum frequency exists, leading to the maximum intensity of a given effect.

Mechanical effects due to the rotational and irrotational parts of electromagnetic forces cannot exist separately except in purely two-dimensional geometries or in the asymptotic case with infinite frequency. For real configurations concerning industrial applications, electromagnetic forces have a rotational part which produces a turbulent velocity field.

With travelling or rotating magnetic fields the rotational part of the electromagnetic forces is predominant in any part of the material where the magnetic field exists. This is different with pure AC fields since rotational forces concentrate in regions where magnetic field intensity undergoes spatial variations in the direction of the applied magnetic field. The relative importance of rotational forces compared to irrotational forces is proportional to $R_\omega^{-\frac{1}{2}}$, where R_ω is the shield parameter $\mu\sigma\omega L^2$, where μ, σ, ω and L are the magnetic permeability, the electrical conductivity of the material, the frequency of the applied magnetic field and the typical length scale of the electroconducting medium; $R_\omega = 2(L/\delta)^2$, if δ denotes the electromagnetic skin depth. Then, when the frequency increases and the skin depth becomes very small compared to the typical length scale of the material volume, electromagnetic forces tend to become irrotational and the intensity of induced stirring motions decreases. The optimum frequency leading to the maximum intensity of stirring motion corresponds to $R_\omega = 40$.

4. Applications of irrotational forces in material processing

When R_ω increases, electromagnetic forces located in a very small skin depth tend to become perpendicular to the boundary of the material volume and are reduced mainly by pressure. The presence of such forces surrounding the electroconducting medium within a small layer gives the possibility of exerting mechanical effects similar to those exerted by the walls used to contain or to shape liquid materials. Such a possibility opens a very wide field of innovations in manufacturing processes of materials taking advantage of electromagnetic free surface control and stabilization, or of electromagnetic shaping of liquid materials.

5. Electromagnetic stabilization of liquid metal free surfaces

Some applications could be developed by using the stabilizing effect induced by high frequency magnetic fields. Magnetic field lines are confined within the electromagnetic skin depth: when a disturbance affects the free surface, the field lines have to be bent and the mechanical tension which affects them has to be overcome. This results in some rigidity of the free surface and possible suppression of waves. However, such an effect is anisotropic: only waves with an associated wave vector parallel to the applied magnetic field can be damped. Waves with wave vectors perpendicular to the magnetic field are unaffected (Garnier & Moreau 1983). DC fields induce a similar anisotropic stabilizing effect but a fundamental difference exists: effects induced by DC fields result from the interaction between velocity and applied magnetic field. The damping effect exists in the bulk of liquid material. Effects induced by AC fields only exist within the skin depth along the free surface and act against any geometrical deformation of the liquid material free surface. With suitable values of R_ω, AC magnetic fields are more efficient for stabilization of free surfaces than DC magnetic fields with same intensity (Garnier 1982).

The stabilizing effect induced by magnetic fields can bring solutions to surface quality products manufactured with new strip casting processes: single and twin roll processes, melt overflow or melt spinning processes may benefit from the use of magnetic fields. The stability problem of the meniscus also arises in continuous processes for the galvanization of steel plates. Local application of magnetic field may improve the process and suppress surface defects resulting from solidification of waves and ripples affecting the liquid zinc meniscus in contact with the travelling plate. AC fields are preferred to DC fields where only local effects are needed. Note that a good choice of frequency can promote mechanically induced effects compared to thermal effects which then remain limited and do not affect solidification.

Many demonstrations of electromagnetic shaping of liquid materials have been achieved whose aim was to suppress completely or partly the walls (Etay 1988). The principle of electromagnetic shaping of liquid is very simple. Repulsive electromagnetic forces induced within a very thin electromagnetic skin depth generate pressure in the liquid. With respect to the geometry of the inductor or to inducting current distribution, pressure may be non-uniform in the liquid. Through the balance between gravity, surface tension and fixed electromagnetic pressure an equilibrium shape is obtained. Various shapes are possible: local uniform magnetic fields impose rectilinear geometry and stagnation points lead to corners with smooth angles. From this simple principle and simple way to build a shaping inductor, two main difficulties are to be overcome to successfully suppress the walls. The first one comes from the precise determination of the equilibrium shape. A difficult free boundary problem is to be solved: the magnetic field distribution depends on the shape of the free surface, which is governed by electromagnetic pressure, i.e. the magnetic field distribution. Solution of this free boundary problem cannot be found without resorting to numerical modelling. The direct problem consists of the determination of the equilibrium free surface shape and can be solved for any shape of inductor (Gagnoud *et al.* 1988). However, the inverse problem, whose solution provides the geometry of the inductor able to impose a given shape to a liquid material volume, can be solved only in particular cases. The second problem arises from the requirement of the stability of the magnetically controlled free surface. Two conditions are to be verified: local and global stability. To get local stability, the anisotropic stabilizing effect induced by AC fields is to be used favourably. To impose global stability strong restoring forces are needed which cannot be generated by uniform magnetic fields and impose rapid spatial variations of magnetic field intensity near the free surface. These basic requirements, which are sometimes incompatible, are difficult to achieve. A particular solution, with possible application to strip casting process, have been found which verifies all these conditions (de Framond *et al.* 1985).

Possible free surface control and stabilization of liquid material volume limit industrial use of electromagnetic levitation melting process. With classical conical coils levitation melting is limited to loads whose mass cannot exceed 100 g; this limit is due to the magnetic field stagnation point which occurs at the bottom of the liquid charge. Important progress has been made by the use of the cold crucible technique, in which the mass of levitated liquid can reach 1 kg. The use of a cold crucible offers two main advantages. The first one results in the reduction of the weakness of magnetic forces at the bottom of the liquid charge: the stagnation point cannot be suppressed but at the bottom of the crucible the water-cooled sectors behave like a magnetic field concentrator which limits the negative effect of the stagnation point to the close neighbourhood of the vertical axis. The second one is due to the self-stabilization property of the system. Electric currents flowing along the internal face of the sectorized crucible have no imposed paths and adapt their distribution to the shape of the levitated load. When the liquid tends to come into contact with the crucible wall induced currents gather in the vicinity and a strong repulsive force occurs which prevents the liquid from touching the wall. Another advantage of this technique concerns safety conditions during use. If electrical power fails, the cold crucible behaves like an ingot mould in which liquid material falls and solidifies.

The cold crucible levitation melting process is an industrial tool for manufacturing alloys. High overheating can be reached since heat exchange is governed by radiation. To limit radiation heat transfer from the liquid to the crucible, the crucible can be coated with a very thin layer of reflecting material such as silver or chromium. Bottom pouring of the manufacturing material can be achieved, taking advantage of the magnetic field concentration produced by the sectors at the bottom of the crucible. A suitable geometry of the sectors allows flow out of the liquid without contact with the walls.

Industrial induction manufacturing of tungsten carbide powder is a good example of the use of the technique. In this application, developed by Technogenia, a mixture of tungsten and graphite powders compacted together with a particular organic material is introduced in a rod shape at the top of the crucible. High frequency magnetic field generated by the cold crucible enable the melting of the rod and promote chemical reaction between tungsten and carbon at a temperature close to 3000 °C. Liquid tungsten carbide flows at the bottom of the crucible on a watercooled rotating copper cylinder at the contact of which it solidifies into spherical droplets (Brunet 1983).

6. Electromagnetic control of liquid free surface

The most famous and the first example of metallurgical process using electromagnetic free surface control is the electromagnetic continuous caster invented by Getselev & Martynov (1975). A simple, single-turn inductor surrounding an aluminium ingot provides, in combination with a metallic shield, a magnetic field distribution suitable to control the shape of the meniscus of the liquid metal undergoing solidification. This technique is now industrial for aluminium and aluminium alloys which have well-adapted physical properties, such as low density and high thermal and electrical conductivity. Non-homogeneous distribution of electromagnetic forces within the skin depth along the meniscus leads to stirring motions which are beneficial for surface quality and solidification structure of the final ingot. This technique cannot be extended to other materials, such as steel, without major modifications.

This technique, full of promise, has not met with the predicted success because of difficulties in controlling the process and of some defects in the product. A very interesting compromise between conventional continuous casting and electromagnetic casting has resulted from a very fruitful collaboration between Pechiney and MHD Laboratory in Avignon (France). This technique, referred as the CREM process, combines the advantages of electromagnetic casting through free surface control and the advantages of classical continuous casting with electromagnetic

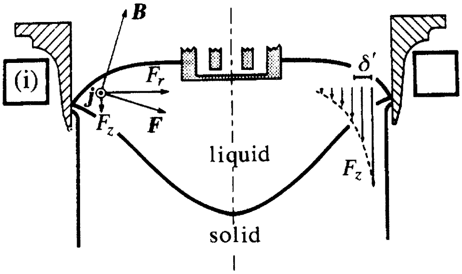

Figure 3. Schematic of the CREM process; (i) 50 Hz coil.

stirring and efficient heat extraction through the contact between melt and ingot mould (figure 3). In this device an inductor supplied with current at industrial frequency surrounds the ingot mould and the product undergoing solidification (Vives 1988). Because of induced electromagnetic pressure a pronounced free surface meniscus is formed in proximity to the mould. The height of the meniscus and the position of the line where liquid metal and mould are in contact can be precisely adjusted. The solidified zone in contact with the mould is then practically reduced to a line. In such conditions the surface quality of the ingot is improved with the suppression of exudation existing with conventional technique and the diminution of the thickness of the segregation zone. Moreover the rotational part of the electromagnetic forces produces turbulent stirring motions which promote the production of fine equi-axed solidified structure, leading to a significant reduction of grain refiner inoculated in classical casting process (Riquet & Meyer 1987).

Important studies are now underway in Japan to adapt the CREM process suitable for aluminium to continuous casting of steel with the aim of increasing casting speed without alteration in product quality. Together with higher casting speed, higher surface quality of steel cast products is required especially for the direct rolling process or for the near shape casting. Classically, the surface of the steel slab and billet produced in continuous casting is characterized by the presence of oscillation marks which are caused by mould oscillation through the flux channel between the solidified shell and the mould wall. Indeed the top of the shell is deformed periodically by the cyclic change of the pressure in the flux channel due to non-slipping conditions of the flux along the mould. The use of magnetic pressure at the early solidification region in a configuration similar to CREM process has been experimentally demonstrated by Nippon Steel Corp. to efficiently control the position of the initial solidification line and to improve quality of the ingot with the suppression of oscillation marks. However, the minimum thickness needed with steel for the copper mould is a major obstacle for the use industrial frequency, and work is underway to replace the ingot mould by a cold crucible. (Takeuchi *et al.* 1990).

A very similar approach has been adopted by Nippon Kokan K. to find new ways to control the initial solidification in continuous casters by the use of magnetic fields with high frequency to promote electromagnetic pressure. The control of initial solidification, through the control of stable position of the first solidification line is of prime importance in the new casting processes, such as strip casting or thin slab casting for steel, but also to solve problems encountered with horizontal continuous casting. In the experimental apparatus a high frequency coil is set up around the refractory tube placed in contact with the copper mould, either to feed the casting device with liquid metal in strip casting or used as a break ring in horizontal casting

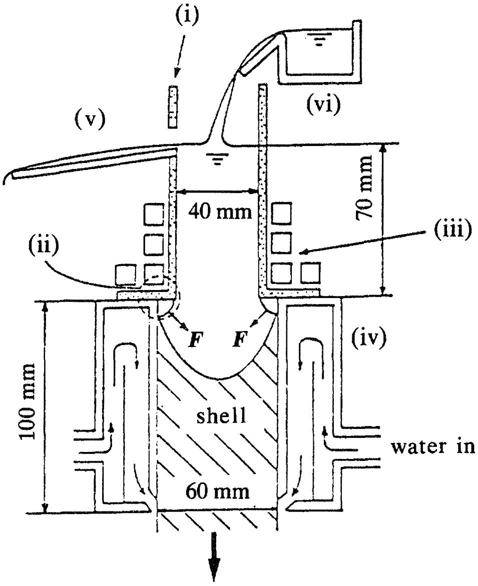

Figure 4. Experimental apparatus for controlling initial solidification. (i) Hot top refractory; (ii) 'triple point'; (iii) high frequency coil; (iv) water-cooled Cu mould; (v) overflow (for level control); (vi) Tundish.

(figure 4). Repulsive forces separate the molten metal from both refractory wall and copper mould and create a stable free surface. This results in a better surface quality of the produced ingot and an important reduction of subsurface defects (Nakada *et al.* 1990).

A very original innovation which takes advantage of electromagnetic free surface control is the electromagnetic valve for liquid metal flow control developed by ECRC (Lillicrap 1990). This valve concerns all the casting processes in which liquid metal has to be poured from a vessel into a mould, and makes possible automatic pouring which is difficult or impossible with conventional techniques. Nozzles with sliding gates or stoppers are widely used for controlling flows of liquid metals but suffer from a number of problems. For example, flow rates may have relatively large variations for relatively small displacements of the stopper and pouring conditions are difficult to reproduce. Moreover the stopper is constantly submerged in molten metal, and is submitted to erosion phenomena which result in pollution of the melt and modifications in the geometry of the stopper with serious consequences for the flow regulation. Electromagnetic forces induced in the liquid metal flowing from a nozzle may provide a simple and efficient contactless solution with no moving parts and offer the possibility of integrating into a computer controlled casting system.

Many experiments have been done in the past 20 years to provide an electromagnetic solution to the flow control problem. Two main ways have been explored. The first one used a travelling magnetic field to force a counter velocity and to reduce or stop the liquid metal flow. This was not successful because of relatively poor efficiency, prohibitive size of the inductors, strong stirring motions induced in the nozzle and instabilities in the flow which prevented regulation. The second way used the effect of electromagnetic pressure induced in the liquid to balance the hydrostatic pressure generating the flow. The device was a simple high frequency induction coil around the circular nozzle. Moreover because of the axisymetry of the

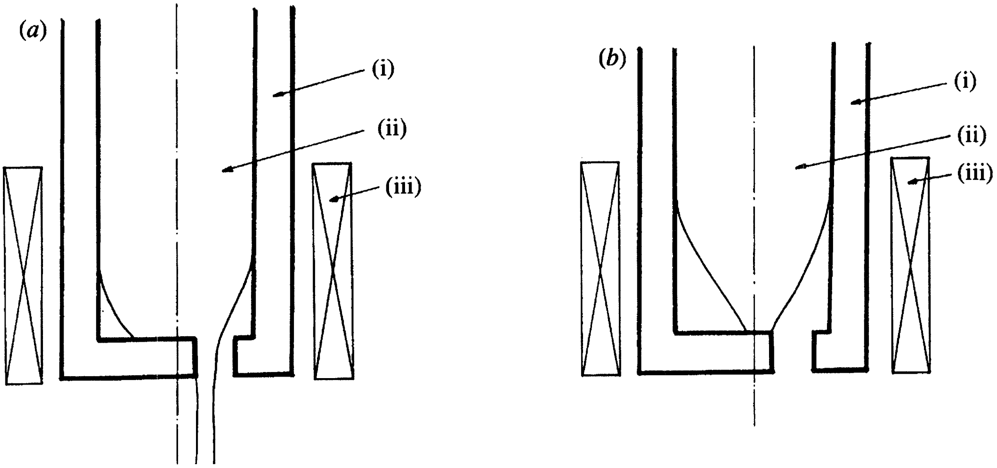

Figure 5. Electromagnetic nozzle: (*a*) low electrical power; (*b*) high electrical power. (i) Refractory nozzle; (ii) liquid metal; (iii) inductor.

system and the resulting presence of a stagnation point for the magnetic field, flow rate regulation was possible, but the device was unable to stop the flow. A very interesting solution to this problem was found by ECRC in England. This solution combines high frequency magnetic field and a new shape of nozzle – a classical refractory tube with a decentrated hole. When a magnetic field is applied electromagnetic forces repulse the liquid metal from the wall and reduce the flow rate (figure 5). Along the axis where electromagnetic force is zero, the refractory wall can contain the liquid metal and the flow can be interrupted. In this case magnetic energy is dissipated in the liquid metal by the Joule effect and prevents molten metal at rest from freezing. Thanks to the results obtained the dream of producing an electromagnetic tap for liquid metal has now become a reality: research in Capenhurst have clearly demonstrated that flows of molten aluminium or steel can be controlled and interrupted. For steel or high melting point metals nozzles made out special materials are to be used.

7. Application of rotational forces in material processing travelling and rotating magnetic fields

The use of magnetic fields to stir a given volume of liquid metal during its solidification is no doubt the oldest example of using MHD phenomena in material processing.

Electromagnetic stirring (EMS) has brought a significant contribution to the widening use of continuous casting in the steel industry. EMS is now commonly used and various stirrers are available whose purpose is to improve the quality of the product and raise the yield of cast strands. The stirrers in use have specific characteristics and provide complementary metallurgical improvements, even if, to some extent, they overlap each other. Mould stirrers (MEMS) remove slag inclusions, pinholes and blowholes; strand stirrers (SEMS) increase the quantity of equi-axed structures, reduce centreline quality, porosities and cracks; final stirrers (FEMS) always used in combination with EMS or SEMS, reduce still further centreline segregations and porosities.

Developments of EMS in ladle metallurgy, which began about 30 years ago, continue today. This technique has some advantages, such as gas bubbling. However, the efficiency is questionable especially for large size ladles. Various stirrers are used. Cylindrical coils imposing a main rotational motion in the ladle with secondary vertical recirculating flows; vertical coils generating travelling magnetic fields, upward or downward, alone or in combination to induce vertical flows with one or several vortices. The effect of a turbulent stirring motion is to accelerate dispersion of additive elements poured into the melt from the free surface, to renew very rapidly the melt–slag interface, to accelerate chemical reactions between the melt and these elements, and to enhance mass transfer through the melt–slag interface to reduce the entrapment time of non-metals. But generally the global refining process efficiency tends to a saturation limit when increasing intensity of turbulent stirring motions. The only way to increase efficiency is to increase the surface of exchange between slag and melt. It is not physically and economically realistic to modify the geometry of the ladle by decreasing the height and increasing the horizontal surface: heat losses during the refining process would be too high to be compensated. The use of low frequency AC fields may provide a solution by increasing the effective surface of exchange between melt and slag without any change in the ladle geometry (Galpin *et al.* 1990).

The electromagnetic force induced in a liquid metal by an alternating magnetic field may be split into a mean part F and an oscillating part $\tilde{\boldsymbol{F}}$. With industrial or higher frequencies, liquid metal because of its inertia cannot follow the oscillations of $\tilde{\boldsymbol{F}}$ and only the mean part is effective.

In the low frequency range, namely $f \leqslant 20$ Hz, $\tilde{\boldsymbol{F}}$ becomes predominant and induces fluctuating velocities both in the bulk and at the free surface. Free surface motions may reach large amplitude (some centimetres with mercury) when the frequency is less than 14 Hz. The motion of the surface consists of standing waves whose pattern depends both on the frequency and on the coil intensity, I, generating the applied magnetic field. Two kinds of standing waves may exist: concentric waves, which are directly forced by the oscillating part of electromagnetic forces, and azimuthal waves, which originate from the instability of the concentric waves system. The wavelength of the dominant modes depends on the frequency. When increasing intensity in the coil with frequencies typically ranging from 4 to 10 Hz the free surface deformation becomes strongly chaotic with small-scale intermittent bursts. There are four different types of free surface configurations (figure 6):

type I: free surface motion consisting of axisymmetric standing waves whose dominant frequency is $2f$;
type II: characterized by azimuthal waves superimposed on concentric waves; frequency is $2f$;
type III: large amplitude and small wavenumber azimuthal waves;
type IV: free surface geometry becomes chaotic.

In this case maximum efficiency in mass transfer between liquid metal and slag is obtained. Such an enhancement is the result of three combined phenomena: a large increase of the effective area of the disturbed interface; turbulent mixing of the liquid metal with the overlaying liquid layer; thermal and chemical homogenization.

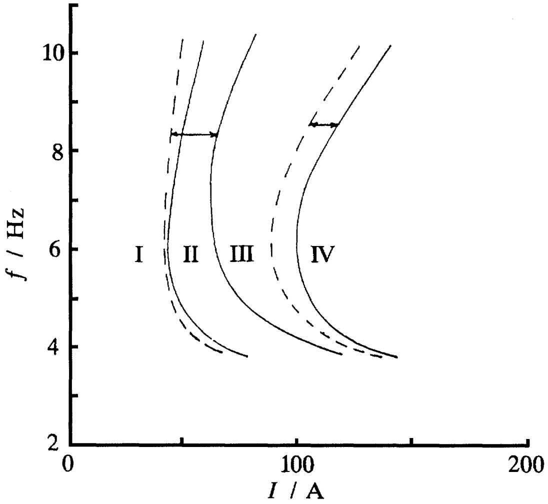

Figure 6. Typical diagram of the various flow régimes in the (I, f) plane: ———, boundary obtained with increasing values of 1; ----, boundary obtained with decreasing values of 1.

8. The '4C Process'

The 4C Process for 'cold crucible continuous casting' is a material manufacturing process which is exemplary since it combines in a single device all the possibilities offered by AC magnetic fields.

The principle of the inductive cold crucible technique was discovered very early in this century. The first important industrial applications were made by 1960 by the U.S. Bureau of Mines (Clites 1982). In the case of titanium two particular applications have been developed. In the first, 'inductoslag ingot melting', titanium turnings can be melted with continuous casting of billets (diameter 125 mm, length 1125 mm). In the second, called 'inductoslag casting', a titanium charge is melted before casting. In these two processes metal is melted by induction inside a water-cooled crucible lined with slag. An induction heating coil surrounds the copper crucible made of a number of vertical sectors. The effect of the gaps between the sectors is to prevent the shield effect of the electrically conducting crucible. For material processing a slag barrier is formed between the crucible and the melt to provide electrical and thermal insulation. The slag seals the gaps between the sectors and enables easy continuous withdrawing of an ingot from the bottom while scraps are fed into the top, for a continuous casting device. Slag was used essentially to prevent damage to the crucible from arcing between sectors and between crucible and melt. However, for titanium alloys (Ti–6Al–4V, for example) it was demonstrated that slag (CaF_2) reacted with liquid material. This was a major obstacle to the development of the inductoslag technique.

However, three main applications derived from this technique are used at an industrial scale. The first is a direct application of the 'inductorslag process' for the treatment of radioactive wastes, zircalloy, or stainless steel, for which purity or composition are not severe requirements. The second, developed by the Duriron Company, demonstrated that slag could be suppressed in 'inductoslag casting process' (figure 7) (Chronister 1988). The third, corresponding to a similar improvement of the 'inductoslag ingot melting' technique through suppression of slag, was developed in France by Madylam and Cezus.

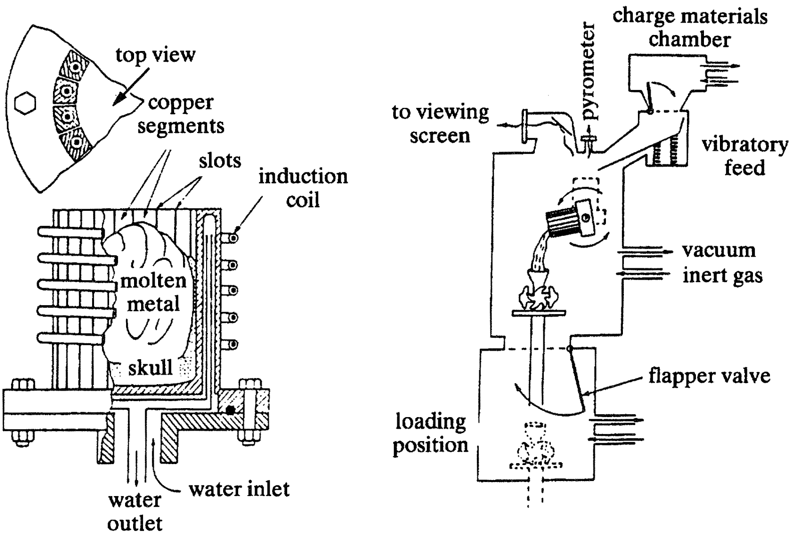

Figure 7. Induction skull melting (from Duriron Company).

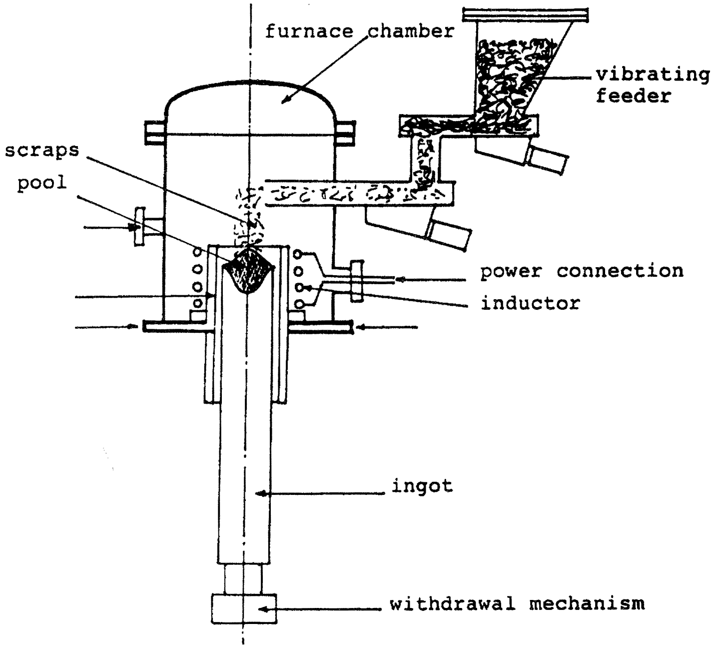

Figure 8. Cold crucible continuous casting device.

The process is schematically shown in figure 8 corresponding to the device used by Cezus in Ugine (France) for TA6V scrap melting and continuous casting of ingot. The device comprises the furnace chamber (water-cooled double-walled stainless steel vessel), a charging system consisting of a stainless steel hopper and vibrating feeders, a water-cooled segmented copper crucible, a multiturn water-cooled inductor, a mechanical billet withdrawal system.

The cold crucible which is an induction furnace, an ingot mould and an electromagnetic stirrer cannot be designed purely empirically. To allow continuous

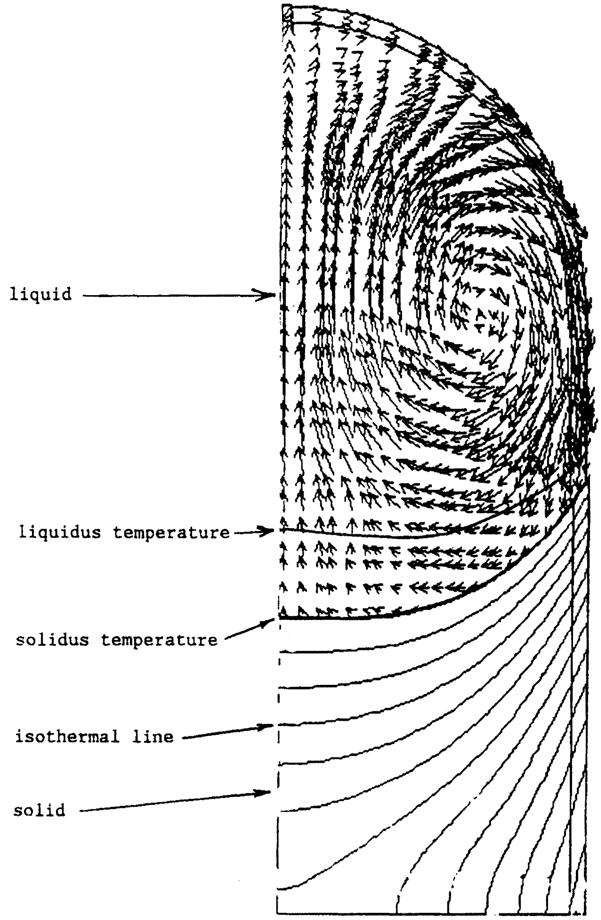

Figure 9. Velocity field and temperature field computation.

casting without slag, with direct contact between the electrically conducting material and the crucible wall, very precise numerical modelling must be used. Two main problems are to be solved.

1. The computation of the three-dimensional magnetic field resulting from the inductor, the sectorized crucible and the charge. The 'Socrate' computational code developed by Madylam (Gagnoud 1986) is able to give the local distribution of magnetic field and the induced currents for any frequency and given power. The method used is derived from boundary integrals which are very convenient because of the rather small skin depth in the electroconducting parts of the device. The voltage between two neighbouring sectors and between any sector and the charge can be arrived at as a function of operating parameters and the geometrical characteristics of the device. Thus, the number of sectors and the geometry of the splits suitable to prevent short circuiting of the crucible by the charge or arcing phenomena between the charge and the sectors can be determined for any material and any size of crucible.

2. There is a double free boundary problem to be solved.

Indeed liquid material is contained in a domain limited by two free boundaries: the free surface and the solidification front. The free surface shape is governed by a balance between electromagnetic pressure, hydrostatic pressure and surface tension. Since magnetic field distribution is strongly dependent on the shape of the free surface because of thin skin depth and since the free surface shape is fixed by local magnetic field distribution, a first free boundary problem arises. This problem is solved by using a method based on the minimization of global energy of the system (Leclerq 1990). Thermal field in the liquid material imposes the shape of solidification front. However, the temperature distribution in the liquid is governed by turbulent electromagnetic stirring motions which can only be computed if the magnetic field distribution in the liquid and the solidification front shape, as leading boundary condition, are known. This second free boundary problem is solved by using a computational code called NEPHTYS (Maestrali 1990). An example of computation is given on figure 9.

Another application has been developed by Osaka Titanium Corp. (Kaneko *et al.* 1990) for the casting of solar cell grade silicon. Solar cells made of wafers sliced from the produced ingot exhibited a high photovoltaic conversion efficiency up to 13.7%.

9. Direct inductive skull melting process

The principle in this technique is very simple. The inductor is a single-turn coil which forms the water-cooled wall of the crucible. The inductor is a copper cylinder with only one split between the edges of which an alternating voltage is applied. Skull melting in this crucible is only possible with materials whose electrical conductivity in a solid state is very low: oxides, refractory materials or ceramics can be manufactured. The optimum frequency to melt these materials corresponds to a shield parameter $R_\omega = 2$, which prevents electromagnetic stirring.

It is of interest to compare cold crucible and the direct inductive skull melting that can be used both for oxides manufacturing. The major difference between the two devices is the presence of a water-cooled crucible between inductor and charge in the cold crucible technique. This results in a lower efficiency: Joule losses in the crucible are about half the total power supplied to the inductor. With high resistivity materials the induction heating efficiency is very high: 98%. Then global efficiency of direct inductive skull melting is 98%, whereas it is 49% with a cold crucible. Therefore, except for particular applications with special constraints, like in the nuclear industry, direct inductive skull melting is to be preferred to a cold crucible for the processing of materials with high electrical resistivity.

10. Conclusion

Magnetohydrodynamics now plays a very important part in material processing through a new discipline of research and development – electromagnetic processing of liquid materials. The increasing interest of industrial companies and the increasing number of research programmes in which they are involved together with scientists are proof that electromagnetic fields are a source of improvement in the quality of manufacturing products, in the reduction of energy consumption and in the automation of industrial processes. Several electromagnetic techniques for material manufacturing now exist and are in use at industrial scale, and which are the result of the collaboration between research laboratories and industrial companies.

Electromagnetic fields are the cleanest way, since contactless, to inject mechanical and thermal energy into liquid materials. This property, unique in material processing, will give a growing importance to the part played by MHD in the research towards new materials and new methods of material processing.

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