Induction processing of liquid materials

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I. INTRODUCTION

The use of alternating magnetic fields is now widespread in metallurgical processes. AC magnetic field was initially used for heating and melting electrically conducting materials from metals to poorly conducting fluid such as plasma or oxides. However, it has been discovered that the magnetic field was able to achieve many other effects (desirable or undesirable), such as bulk and surface stirring, free surface control etc. A recent trend consists in either superimposing several effects or controlling accurately one effect with a single electromagnetic device. This may be possible by means of the use of complex AC magnetic fields generated by complex electric current sources. That possibility offers new prospects for Electromagnetic Processing of Materials [1].

II. FREE SURFACE UNDER ALTERNATING MAGNETIC FIELDS

AC magnetic fields may be used to shape, to levitate or to stir the free surface of a liquid metal pool.

1). Shaping of liquid metals. Axisymmetric dome-shaped free surfaces are often expected and observed in induction furnaces. But in some particular conditions especially small aspects ratio, electromagnetic instabilities may arise, and the shape of the pool looses its axial symmetry. This phenomenon has been evidenced by various recent experiments as well as theoretical analyses [2]-[4]. This is illustrated by the pictures shown in Figure 1. Such instabilities, the so-called "edge instability" [4] are similar to a kind of pinch effect, which has also been observed in liquid metal layer submitted to an AC magnetic field [3]. Note that that kind of instability is an issue which affects various devices such as the electromagnetic seals or levitation.

2) Levitation. By a suitable choice of the inductor shape it is possible to achieve complete levitation of the liquid metal [5], [6]. The usual shapes of the coil or the cold crucible are sketched in Figure 2. The electric currents must be more important beneath the liquid blob in order to counter-balance the gravity forces. This explains the cup-shape of the inductor (or the cold crucible) illustrated in Figure 2. The typical dimension of the liquid pool which may be levitated depends obviously on the force balance which involves the gravity and the electromagnetic forces but also on the real electric current distribution coming from the coupling with the melt, e.g., on the cold-crucible configuration (see Figure 2c for example).

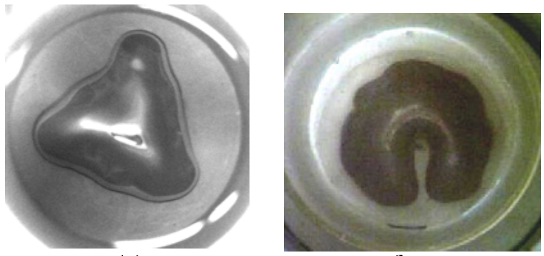


Fig. 1 Shape of liquid metal drops located in a coil supplied with middle frequency alternating currents, (a) gallium drop [2], f = 7.8kHz; B_{0max} = 20 mT; the drop is immersed in cold water (50°C); (b) f = 14kHz; B_{0max} = 66.4 mT, the drop temperature is close to 150°C and its surface is oxidised

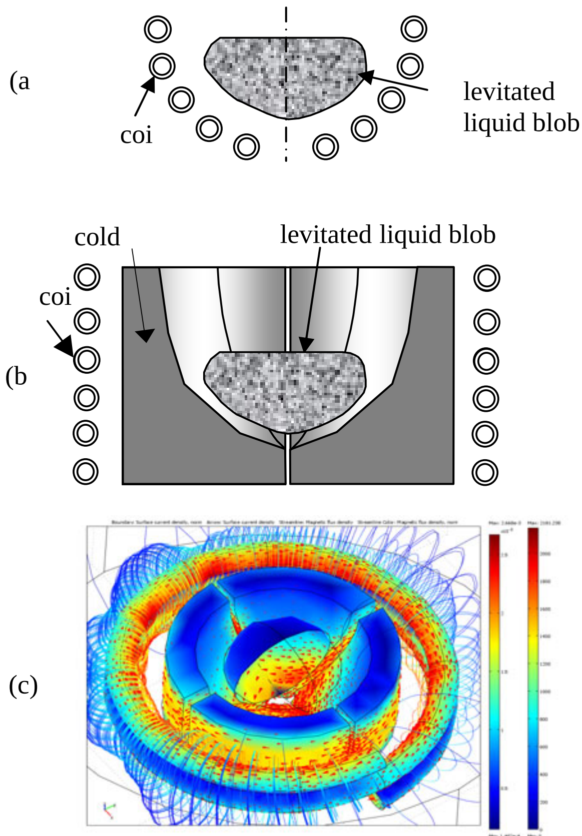


Fig. 2. sketch of typical levitation devices using AC magnetic fields, (a) simple-coil system, (b) cold-crucible system, (c) computation of levitated droplet in a 3D cold-cruclble

Levitation allows the use of aggressive materials although it is somewhat difficult to obtain a significant overheat of the melt because of the radiative cooling of the free surface. An example of special application is shown in Figure 3. Melting of titanium is difficult in refractory crucible due both to its high melting point (T_f = 1800°C) as well as its chemical aggressiveness, and levitation in cold crucible offers an alternative solution. Figure 3 shows a typical levitation device used to coat a carbon fibre [7]. Thanks to the gap between the crucible sectors, it is possible to immerse the moving fibre in the titanium blob.

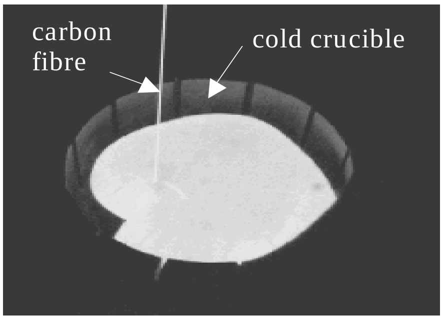


Fig. 3. levitation device used for coating carbon fibres with a titanium alloy; the pool diameter id 60mm; the electric current frequency is 275 kHz; the fibre velocity is of order of several meters per second.

2) Free surface under low frequency magnetic fields. Other types of phenomena occur when the coil frequency is very low in such a way that its order of magnitude is close to the natural frequencies of the free oscillation modes of the free surface (typically a few Hertz). In that case the alternating part of the Lorentz becomes predominant and generates a free surface agitation by resonance effects [8]. Strong free surface motion may be expected when the frequency of the applied magnetic field is tuned on the resonance frequency of the free surface [8], leading sometimes to emulsion formation (Figure 4a).

(a) (b)

Fig. 4. (a) Emulsification of a liquid gallium drop located in a coil supplied with low frequency electric currents; f = 6.22 Hz, B_0 = 0.24 T. (b) vertical oscillations at the free surface of a gallium located in a coil supplied with two-frequency electric currents (14kHz and 4.7Hz).

III. ACTION OF ALTERNATING MAGNETIC FIELDS ON SOLIDIFICATION

It is possible to control the solidification of a metallic alloy by a forced convection. Travelling or rotating magnetic fields are usually used to generate forced convection [9]. Initially it was aiming at promoting equiaxed solidification by increasing the fragmentation of the dendrite tips and increasing accordingly the number of nucleating particles [10]. However, drawbacks, e.g., segregations, were observed, for example the white bands in continuous casting of steel [9]. Thanks to the development of the numerical modelling coupled to experiments it is now possible to have a deeper understanding of the subtle effects of forced convection. For example macro-segregation in solidifying alloys which is a major drawback, originates from the washing effect of the liquid motion in the mushy zone. This leads to segregated channels which may be significantly enhanced by electromagnetic stirring [11], [12]. This is illustrated by Figure 5 below which shows the appearance of a large central segregation.

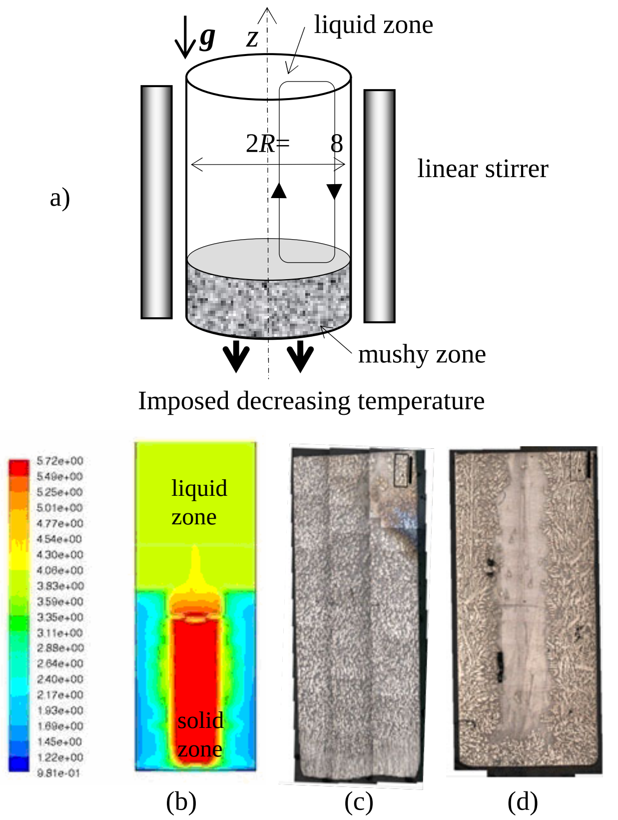
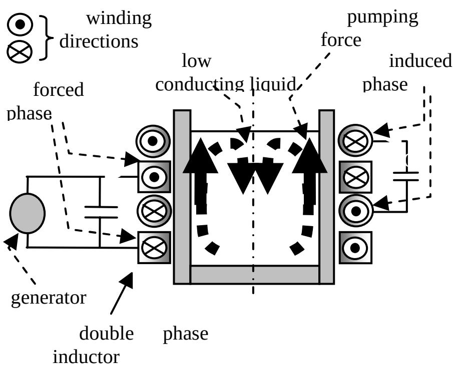


Fig. 5 Directional solidification of binary Al-3.5wt.%Ni alloys under the influence of a traveling magnetic field (TMF). a) sketch of the geometry. b) numerical modeling of the macrosegregations generated by a traveling field showing the significant variations of the alloy composition in the solid zone. c) and d) Representative metallographies on refined Al-3.5%wt Ni solidified with V = 10 µm.s^{-1} and G_L = 3 °K.mm^{-}The electromagnetically forced flow is upward along the axis. Cooling rate $\dot{T} = 0.03$K/s. b) without TMF. c) with TMF,B = 70mT.

IV. COMPLEX MAGNETIC FIELD AT HIGH FREQUENCY

Thanks to the flexibility of the high frequency electric power sources, it is possible to generate complex magnetic fields. A first example concerns the creation of multiphase magnetic fields by such type of power supply. This offers the possibility to design travelling magnetic fields at middle or high frequency. Such types of magnetic field are able to heat efficiently a material and also to stir the liquid. This is an issue especially for low conducting materials such as molten oxides, electrolytes or plasmas [13]. An example of stirring device is shown in Figure 6. Figure 6b shows an example of a middle frequency “inverse” stirring at the free surface of a liquid metal (i.e., flow directed toward the pool axis), which allows a more efficient melting of scraps during the feeding process.

(a)



(b)

Fig. 6. Polyphase stirring at high frequency. a) scheme of the principle of the device. b) top view of a stirring experiment of liquid tin which shows that the surface flow is directed toward the pool centre.

V. LOW CONDUCTING LIQUID MATERIALS

1). Induction plasma. Another application of induction to poorly conducting materials is induction plasma [14]. Rare gases like argon or helium become electrically conducting at high temperature. The electrical conductivity is less than the one of metals; nevertheless induction heating may be used thanks to higher frequency magnetic fields. Such a principle is used to build plasma torches. The quality of the generated plasma is good since it is not polluted by some vapours coming from the volatilisation of any electrodes like in arc plasmas. Plasma spraying and nano-powder synthesis are among the most interesting applications of induction torches in material processing [14]. The most common application remains the trace and ultra-trace chemical analysis: more than 20000 ICP-OES systems (Inductively Coupled Plasma Optical Emission Analysis) are today worldwide implemented. However, Figure 7 shows an example of a promising application which couples induction heating and stirring with treatment by plasma torch. The plasma torch is used to overheat the free surface of a silicon bath in order to volatilise the impurities contained in the silicon, thanks to the addition of reactive gases into the plasma.

2) Induction oxide melting. The vitrification process has been used for more than 35 years for the treatment of high activity nuclear waste. The Vitrification Unit in CEA Marcoule (France) and the storage facilities at La Hague (France) have demonstrated the potential of this process by vitrifying more than 4.5 thousand million curies [15]. More recently, CEA has developed a new vitrification process based on a cold crucible heated by direct induction (see Figure 8). This process is characterized by the cooling of all the walls and by currents directly induced inside the molten glass. In addition, a mechanical stirring device is used to homogenize the molten glass [16]. The advantages of the cold crucible are mainly related to the formation of a skull, i.e., a thin layer of solidified glass. This solidified glass forms a "skull melter" that insulates the cold melter walls from the molten glass. Thus, the crucible walls are not corroded by the molten glass and in turn the molten glass is not contaminated. Cold-crucible vitrification greatly extends the service life of the melter thereby decreasing the production of secondary technological waste. In addition, much higher temperatures can be used in comparison with temperatures conceivable with metal pots, making it possible to increase waste loading and implement liquid phase feed techniques. The direct feeding of liquids to the surface of the bath would result in as simple one-step process. Consequently, the size and maintenance requirements of the industrial process are considerably reduced along with the amounts of technological waste. Mechanical stirrers and bubblers can be added to thermally and chemically homogenize the molten glass.

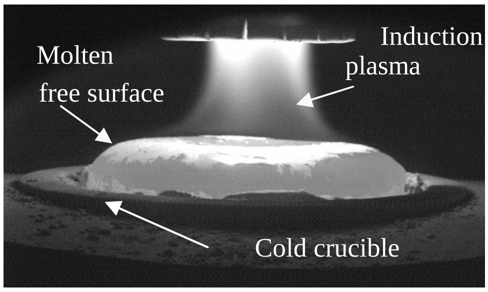


Fig. 7. Heating of the free surface of a silicon melt by an induction plasma torch; the frequency is 3.3 MHz; the silicon load itself is located in an induction furnace whose frequency is 12 kHz; the diameter of the silicon bath is 120 mm; the electromagnetic forces in the silicon melt generate a dome effect; the surface temperature of the silicon is approximately 1600°C.

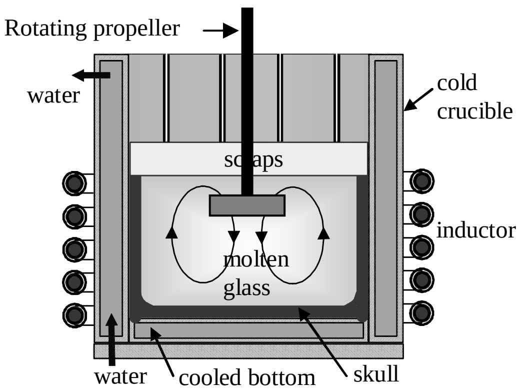


Fig. 8. Scheme of the vitrification reactor based on the cold crucible technique equipped with an additional mechanical stirrer.

VI. CONCLUSIONS

The present paper has shown various phenomena which may be applicable to improve the existing devices or to imagine new ones. We have illustrated the two main effects of induction, namely bulk heating and mechanical action.

Induction may be applied to electrically conducting liquid such as metal, but also to poorly conducting materials such as oxides, glasses or plasmas. The absence of any contact between the inductor and the load allows the clean processing of the materials, e.g., heating without any oxidation and stirring of the liquid metal.

It is still possible to discover new phenomena since the development of new electrical power sources allows the use of complex electric currents.

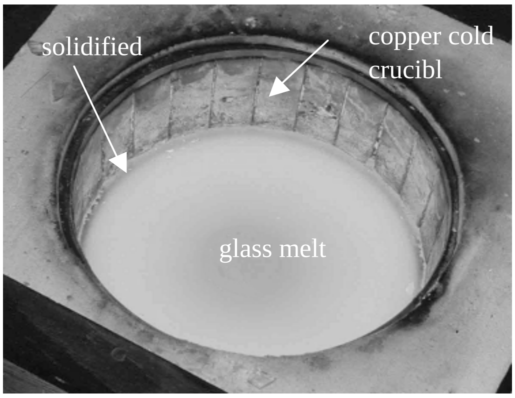


Fig. 9. view of a glass melting experiment without any stirrer. The diameter of the crucible is 300 mm, the working frequency is 300 kHz, the bath temperature is 1450°C corresponding to an electric power equal to 50 kW.

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