Part B:
Applications in Engineering and Metallurgy

Introduction: An Overview of Metallurgical Applications

1 The History of Electrometallurgy

> When Faraday first made public his remarkable discovery that a magnetic flux produces an emf, he was asked, 'What use is it?'. His answer was: 'What use is a new-born baby?' Yet think of the tremendous practical applications his discovery has led to... Modern electrical technology began with Faraday's discoveries. The useless baby developed into a prodigy and changed the face of the earth in ways its proud father could never have imagined.
>
> *R P Feynman (1964)*

There were two revolutions in the application of electricity to industrial metallurgy. The first, which occurred towards the end of the nineteenth century, was a direct consequence of Faraday's discoveries. The second took place around eighty years later. We start with Faraday.

The discovery of electromagnetic induction revolutionised almost all of 19th century industry, and none more so than the metallurgical industries. Until 1854, aluminium could be produced from alumina only in small batches by various chemical means. The arrival of the dynamo transformed everything, sweeping aside those inefficient, chemical processes. At last it was possible to produce aluminium continuously by electrolysis. Robert Bunsen (he of the 'burner' fame)[1] was the first to experiment with this method in 1854. By the 1880s the technique had been refined into a process which is little changed today (Figure I.1).

In the steel industry, electric furnaces for melting and alloying iron began to appear around 1900. There were two types: arc-furnaces and induction furnaces (Figure I.2). Industrial-scale arc furnaces made an appearance as early as 1903. (The first small-scale furnaces were designed by von Siemens in 1878.) These used an electric arc, which was made to play on the molten metal surface, as a means of heating the metal. Modern vacuum-arc remelting furnaces are a direct descendant of this

[1] Actually, it was Faraday who invented the burner!

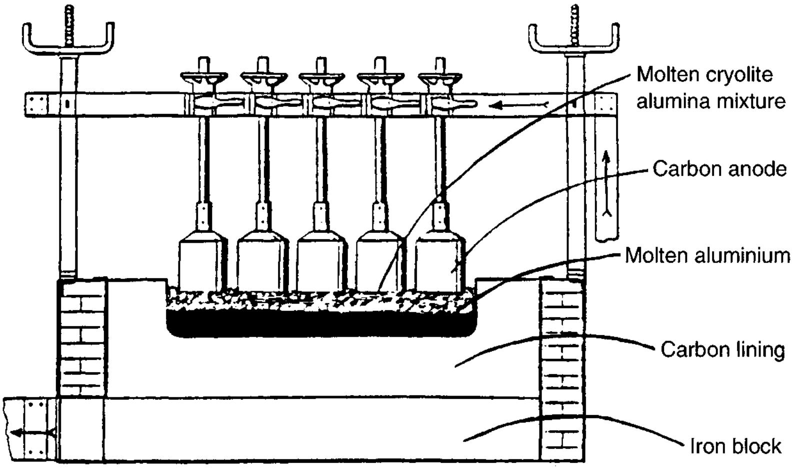

Figure I.1 Turn-of-the-century aluminium reduction cell.

technology (see Figure I.6). The first induction furnace, which used an AC magnetic field (rather than an arc) to heat the steel, was designed by Ferranti in 1887. Shortly thereafter, commercial induction furnaces became operational in the USA. Thus, by the turn of the century, electromagnetic fields were already an integral part of industrial metallurgy. However, their use was restricted essentially to heating and to electro-

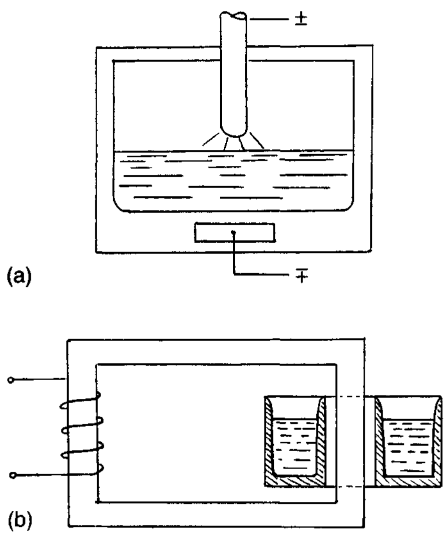

Figure I.2 (a) An early arc-furnace. (b) An early induction furnace.

lysis. The next big step, which was the application of electromagnetic fields to casting, was not to come for another eighty years or so.

The great flurry of activity and innovation in electrometallurgy which began at the end of the nineteenth century gave way to a process of consolidation throughout much of the twentieth. Things began to change, however, in the 1970s and 1980s. The steel industry was revolutionised by the concept of continuous casting, which displaced traditional batch-casting methods. Around the same time, the oil crisis focused attention on the cost of energy, while the worldwide growth in steelmaking, particularly in the East, increased international competition. Once again, the time was ripe for innovative technologies. It is no coincidence that around this time 'near-net-shape' casting began to make an appearance (Figure I.3a). Instead of casting large steel ingots, letting them cool, and then expending large amounts of energy reheating the ingots and rolling them into sheets, why not continuously cast sheet metal in the first place?

There was another reason for change. The aerospace industry was making increasing demands on quality. A single, microscopic, non-metallic particle trapped in, say, a turbine blade can lead to a fatigue crack and perhaps ultimately to the catastrophic failure of an aircraft engine. New techniques were needed to control and monitor the level of non-metallic inclusions in castings.

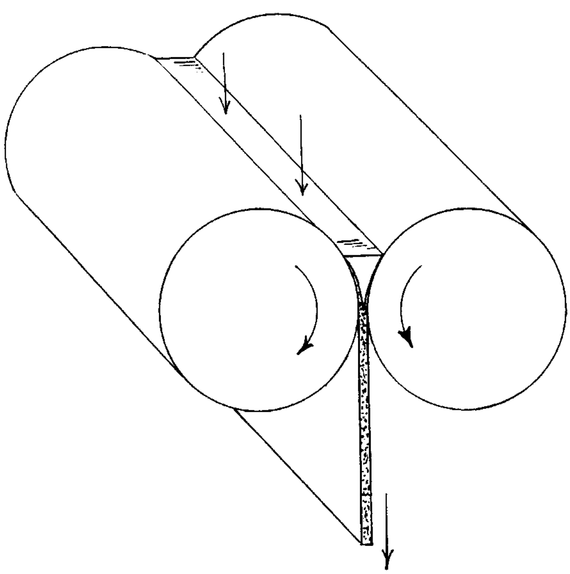

Figure I.3 (a) Twin-roll casting of steel.

Metallurgists set about rethinking and redesigning traditional casting and melting processes, but increasing demands on cost, purity and control meant that traditional methods and materials were no longer adequate. However, just like their predecessors a century earlier, they found an unexpected ally in the electromagnetic field, and a myriad of electromagnetic technologies evolved. Metallurgical MHD, which had been sitting in the wings since the turn of the century, suddenly found itself centre-stage.

Magnetic fields provide a versatile, non-intrusive, means of controlling the motion of liquid metals. They can repel liquid-metal surfaces, dampen unwanted motion and excite motion in otherwise still liquid. In the 1970s, metallurgists began to recognise the versatility of the Lorentz force, and magnetic fields are now routinely used to heat, pump, stir, stabilise, repel and levitate liquid metals.

Metallurgical applications of MHD represent a union of two very different technologies – industrial metallurgy and electrical engineering – and it is intriguing to note that Faraday was a major contributor to both. It will come as no surprise to learn that, on Christmas day 1821,

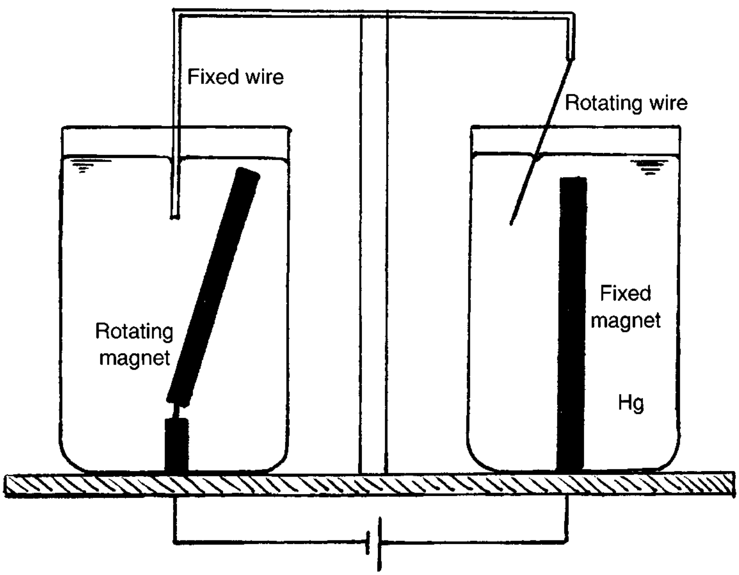

Figure I.3 (b) The first electric motor as devised by Faraday in 1921. A wire carrying a current can be made to rotate about a stationary magnet, and a magnet to rotate about a stationary wire.

Faraday built the first primitive electric motor (Figure I.3b) and of course his discovery of electromagnetic induction (in 1831) marked the beginning of modern electrical technology. However, Faraday's contributions to metallurgy are, perhaps, less well known. Not only did his researches into electrolysis help pave the way for modern aluminium production, but his work on alloy steels, which began in 1819, was well ahead of his time. In fact, as far back as 1820, he was making razors from a non-rusting platinum steel as gifts for his friends. As noted by Robert Hadfield: '*Faraday was undoubtedly the pioneer of research on special alloy steel; and had he not been so much in advance of his time in regard to general metallurgical knowledge and industrial requirements his work would almost certainly have led immediately to practical development*'. It is interesting to speculate how Faraday would have regarded the fusion of two of his favourite subjects – chemistry and electromagnetism – in a single endeavour.

In any event, that unlikely union of sciences has indeed occurred, and the application of magnetic fields to materials processing has acquired not one but two names! The term *electromagnetic processing of materials* (or EPM for short) has found favour in France and Japan. Elsewhere, the more traditional label of *metallurgical MHD* still holds sway: we shall stay with the latter. The phrase *metallurgical MHD* was coined at an IUTAM conference held in Cambridge in 1982 (Moffatt, 1984). In the years immediately preceding this conference, magnetic fields were beginning to make their mark in casting, but those applications which did exist seemed rather disparate. This conference forged a science from these diverse, embryonic technologies, and almost two decades later we have a reasonably complete picture of these complex processes. From both a technological and a scientific perspective, the subject has come of age.

Unfortunately, much of this research has yet to find its way into text books and monographs, but rather is scattered across various conference proceedings and journal papers. The purpose of Part B, therefore, is to give some sense of the breadth of the industrial developments and of our attempts to understand and quantify these complex flows.

2 The Scope of Part B

The content and style of Part B is quite different to that of Part A. It is not of an introductory nature, but rather provides a contemporary account of recent developments in metallurgical MHD.

We shall look at five applications of MHD. These are:

(i) *magnetic stirring* induced by a rotating magnetic field (Chapter 8);
(ii) *the magnetic damping* of jets, vortices and natural convection (Chapter 9);
(iii) motion arising from the *injection of current* into a liquid-metal pool (Chapter 10);
(iv) *interfacial instabilities* which arise when a current is passed between two conducting fluids (Chapter 11);
(v) *magnetic levitation and heating* induced by high-frequency magnetic fields (Chapter 12).

The hallmark of all these processes is that R_m is invariably very small. Consequently, Part B of this text rests heavily on the material of Chapter 5.

Although these five processes may be unfamiliar in the metallurgical context, they all have simple mechanical analogues, each of which would have been familiar to Faraday.

- *Magnetic stirring* (the first topic) is nothing more than a form of induction motor where the liquid metal takes the place of the rotor.
- *Magnetic damping* takes advantage of the fact that the relative motion between a conductor and a magnetic field tends to induce a current in the conductor whose Lorentz force opposes the relative motion. (As far back as the 1860s, designers were placing conducting circuits around magnets in order to dampen their vibration.) This is the second of our topics.
- *Current injected* into a conducting bar causes the bar to pinch in on itself (parallel currents attract each other), and the same is true if current passes through a liquid-metal pool. Sometimes the pinch forces caused by the injection of current can be balanced by fluid pressure; at other times it induces motion in the pool (topic (iii)).
- The *magnetic levitation* of small metallic objects is also quite familiar. It relies on the fact that an induction coil carrying a high-frequency current will tend to induce opposing currents in any adjacent conductor. Opposite currents repel each other and so the conductor is repelled by the induction coil. What is true of solids is also true of liquids. Thus a 'basket' composed of a high-frequency induction coil can be used to levitate liquid-metal droplets (topic (v)).

Let us now re-examine each of these processes in a little more detail, placing them in a metallurgical context. Magnetic stirring is the name given to the generation of swirling flows by a rotating magnetic field (Figure I.4). This is routinely used in casting operations to homogenise the liquid zone of a partially solidified ingot. In effect, the liquid metal acts as the rotor of an induction motor, and the resulting motion has a profound influence on the metallurgical structure of the ingot, producing a fine-grained product with little or no porosity. From the perspective of a fluid dynamicist, this turns out to be a study in Ekman pumping. That is, Ekman layers form on the boundaries, and the resulting Ekman pumping (a secondary, poloidal motion which is superimposed on the primary swirling flow) is the primary mechanism by which heat, chemical species and angular momentum are redistributed within the pool. Magnetic stirring is discussed in Chapter 8.

In contrast, magnetic fields are used in other casting operations to suppress unwanted motion. Here we take advantage of the ability of a static magnetic field to convert kinetic energy into heat via Joule dissipation. This is commonly used, for example, to suppress the motion of submerged jets which feed casting moulds. If unchecked, these jets can disrupt the free surface of the liquid, leading to the entrainment of oxides or other contaminants from the surface (Figure I.5). It turns out, however, that although the Lorentz force associated with a static magnetic field destroys kinetic energy, it cannot create or destroy linear or angular momentum. A study of magnetic damping, therefore, often comes down to the question: how does a flow manage to dissipate kinetic energy while preserving its linear and angular momentum? The answer to this question

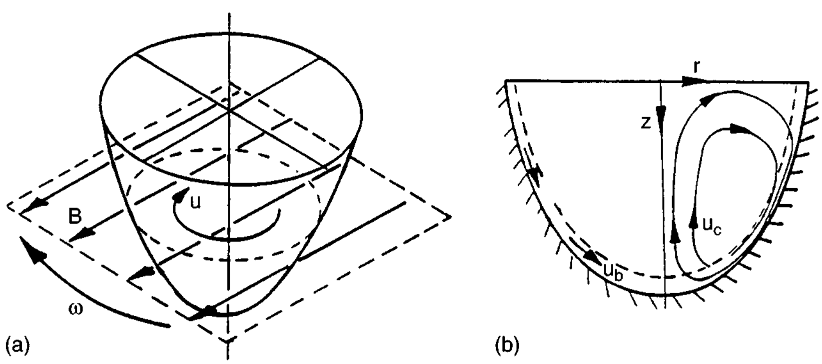

Figure I.4 (a) Electromagnetic stirring. (b) Ekman pumping.

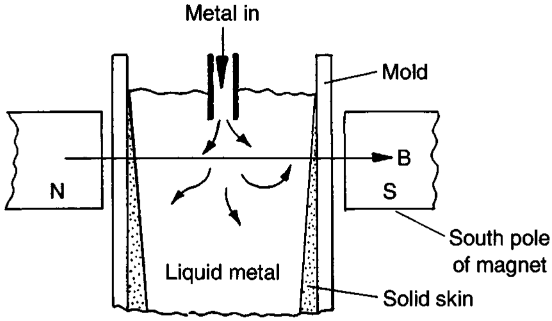

Figure I.5 Magnetic damping.

furnishes a great deal of useful information, and we look at the damping of jets and vortices in Chapter 9.

In yet other metallurgical processes, an intense DC current is used to fuse metal. An obvious (small-scale) example of this is electric welding. At a larger scale, intense currents are used to melt entire ingots! Here the intention is to improve the quality of the ingot by burning off impurities and eliminating porosity. This takes place in a large vacuum chamber and so is referred to as vacuum-arc remelting (VAR). In effect, VAR resembles a form of electric-arc welding, where an arc is struck between an electrode and an adjacent metal surface. The primary difference is one of scale. In VAR the electrode, which consists of the ingot which is to be melted and purified, is ~ 1 m in diameter. As in electric welding, a liquid pool builds up beneath the electrode as it melts, and this pool eventually solidifies to form a new, cleaner, ingot (Figure I.6(a)).

However, vigorous stirring is generated in the pool by buoyancy forces and by the interaction of the electric current with its self-magnetic field. This motion, which has a significant influence on the metallurgical structure of the recast material, is still poorly understood. It appears that there is delicate balance between the Lorentz forces, which tend to drive a poloidal flow which converges at the surface, and the buoyancy forces associated with the relatively hot upper surface. (The buoyancy-driven motion is opposite in direction to the Lorentz-driven flow.) Modest changes in current can transform the motion from a buoyancy-dominated flow to a Lorentz-dominated motion. This change in flow regime is accompanied by a dramatic change in temperature distribution and of ingot structure (Figure I.6(b)). This is discussed in Chapter 10.

Next, in Chapter 11, we give a brief account of an intriguing and unusual form of instability which has bedevilled the aluminium industry

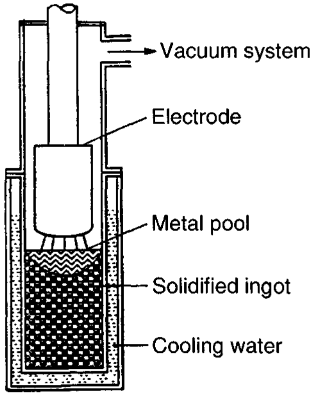

Figure I.6 (a) Vacuum-arc remelting.

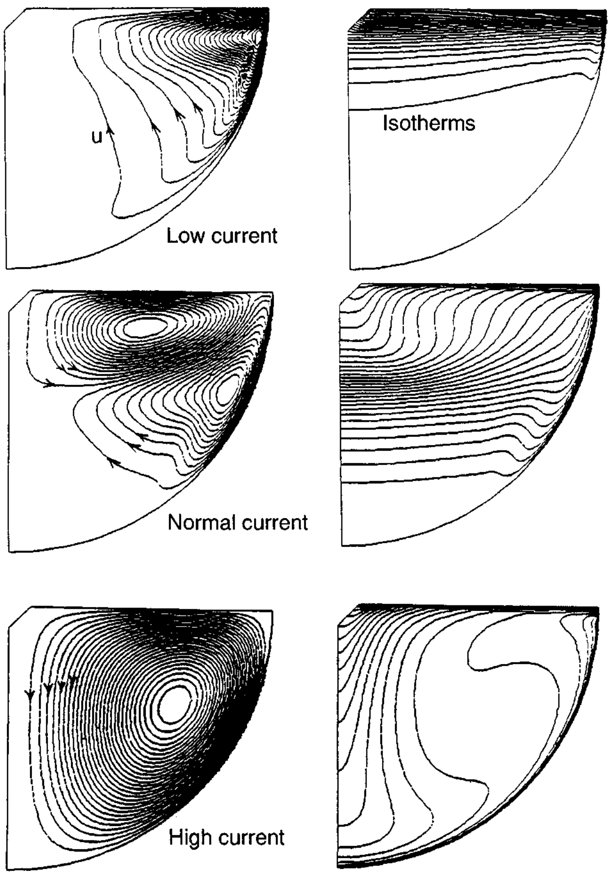

Figure I.6 (b) Changes in flow pattern and temperature field with current in VAR.

for several decades. As we shall see, the solution to this problem is finally in sight and the potential for savings is enormous.

The instability arises in electrolysis cells which are used to reduce alumina to aluminium. These cells consist of broad, but shallow, layers of electrolyte and liquid aluminium, with the electrolyte lying on top. A large current (perhaps 300 k Amps) passes vertically downward through the two layers, continually reducing the oxide to metal (Figure I.7). The process is highly energy-intensive, largely because of the high electrical resistance of the electrolyte. For example, in the USA, around 2% of all generated electricity is used for aluminium production. It has long been known that stray magnetic fields can destabilise the aluminium–electrolyte interface, in effect, by amplifying interfacial gravity waves. In order to avoid this instability, the electrolyte layer must be maintained at a thickness above some critical threshold, and this carries with it a severe energy penalty.

This instability has been the subject of intense research for over two decades. In the last few years, however, the underlying mechanisms have finally been identified and, of course, with hindsight they turn out to be simple. The instability depends on the fact that the interface can support interfacial gravity waves. A tilting of the interface causes a perturbation in current, **j**, as shown in Figure I.8. Excess current is drawn from the anode at points where the highly resistive layer of electrolyte thins, and less current is drawn where the layer thickens. The resulting perturbation in current shorts through the highly conducting aluminium layer, leading to a large horizontal current in the aluminium. This, in turn, interacts with the vertical component of the background magnetic field to produce a Lorentz force which is directed into the page. It is readily confirmed

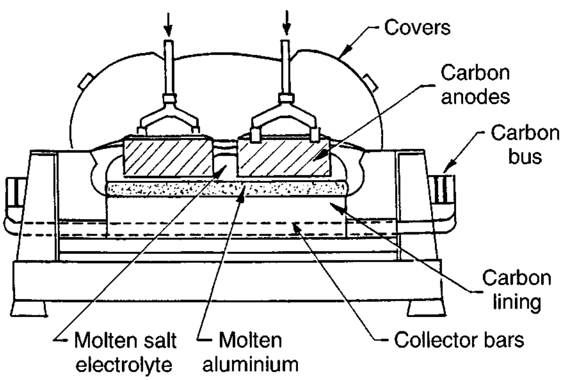

Figure I.7 A modern aluminium reduction cell.

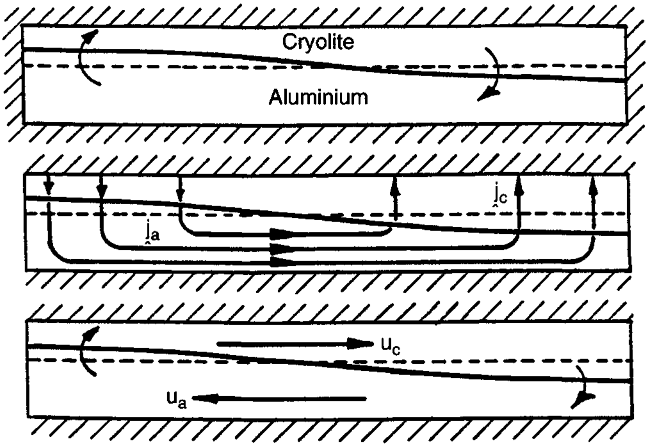

Figure I.8 Unstable waves in a reduction cell.

that two such sloshing motions, which are mutually perpendicular, can feed on each other, the Lorentz force from one driving the motion of the other. The result is an instability. This is discussed in Chapter 11.

A quite different application of MHD in metallurgy is magnetic levitation. This relies on the fact that a high-frequency induction coil will repel any adjacent conducting material by inducing opposing currents in the adjacent conductor (opposite currents repel each other). Thus a 'basket' formed from a high-frequency induction coil can be used to levitate and melt highly reactive metals (Figure I.9), or a high-frequency solenoid can be used to form a magnetic valve which modulates the flow of a liquid-metal jet (Figure I.10).

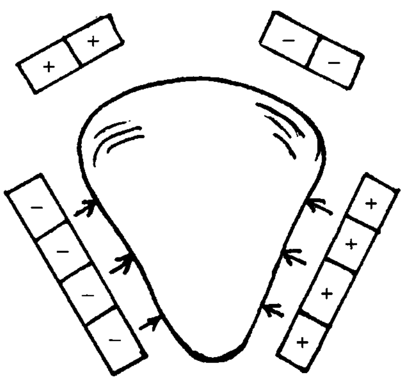

Figure I.9 Magnetic levitation.

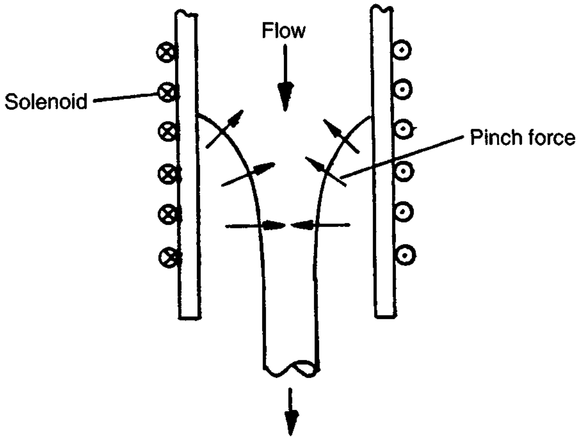

Figure I.10 An electromagnetic valve.

The use of high-frequency fields to support liquid-metal surfaces is now commonplace in industry. For example, in order to improve the surface quality of large aluminium ingots, some manufacturers have dispensed with the traditional, water-cooled mould and replaced it with a high-frequency induction coil. Thus ingots are cast by pouring the molten metal through free space, the sides of the ingot being supported by magnetic pressure (Figure I.11). Such applications are discussed in Chapter 12.

This concludes our brief overview of Part B of this textbook.

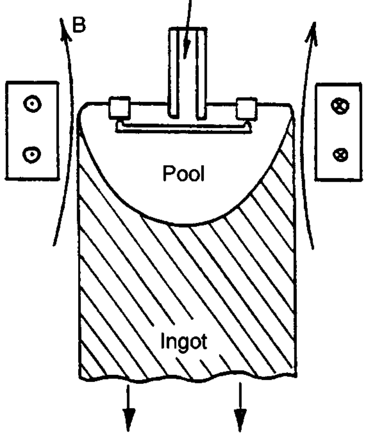

Figure I.11 Electromagnetic casting of aluminium.