

Figure 2
Pressing on the end cap of a high-voltage fuse: (a) before forming; (b) after forming

tion of capacitor energy makes it a simple matter to bend the edge of the cap without damaging the ceramic tube.

Figure 3 shows another application of electromagnetic forming. The stator laminations of a dc motor are held by an assembly mandrel. An aluminum tube is positioned over them and compressed over its whole length. The laminations are held together in this way. Seats for the two endshields are also produced by compressing the tube ends to the size of the mandrel.

Further applications of electromagnetic forming include the production of electrical connections, and

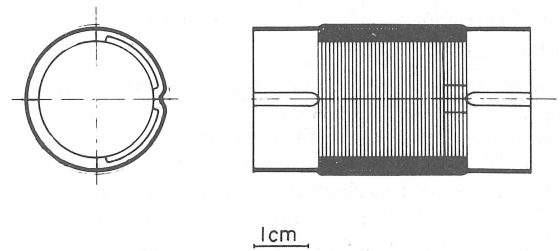


Figure 3
Contactless assembly of a dc motor stator

the assembly of maintenance-free ball joints and shock absorbers. The advantages and limitations of electromagnetic forming are summarized in Table 1.

See also: High-Energy-Rate Forming

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Table 1
Advantages and limitations of electromagnetic forming

(a) Advantages
Low costs per forming operation
Contactless forming (also through protective coverings)
Forming pressure acts equally on all sides
A controlled pressure can be directed to definite zones of the workpiece
High forming rate and extremely short forming times
Easy adaptation to different workpieces by suitably formed fieldshapers
No moving parts in the electromagnetic forming machine
Production can be easily automated
Assemblies and equipment can be joined without close tolerances being required at the joints
Pipes can be compressed or widened (sheet metal can be deep-drawn, but this process is rarely used in practice)
(b) Limitations
The materials to be formed must have a relatively high electrical conductivity (copper, aluminum, and their alloys)
The materials should be highly ductile
Wall thicknesses are limited to a few millimeters
The forming distances must be only a few millimeters

Electrometallurgy

Electrochemical processing is used both in the primary extraction of metals from their ores (electrowinning) and in the subsequent refining of metals to high purity (electrorefining). Both operations are accomplished in an electrolytic cell, a device that permits electrical energy to perform chemical work. This occurs by the transfer of electrical charge between two electrodes immersed in an ionically conducting liquid (electrolyte) containing metal dissolved as positive ions. At the negatively charged cathode the metal cations acquire electrons (are reduced), and deposit as neutral metal atoms. At the positively charged anode there are two possible reactions, depending upon the type of cell. In an electrowinning cell, nonmetal anions generally undergo oxidation at the anode to give gaseous products, whereas in an electrorefining cell the dissolution of the anode metal itself occurs. The more noble metals such as copper and zinc are electrolyzed from aqueous electrolytes, whereas reactive metals such as aluminum and magnesium are electrolyzed from electrolytes of their fused salts.

1. Aqueous or Hydrometallurgical Processes

1.1 Electrowinning

Although it is possible to extract the more noble metals by electrolysis of aqueous solutions of their salts, chemical reduction methods such as smelting are also feasible. The choice of process depends upon site conditions such as the composition of the ore and the relative costs of electrical energy versus other forms of energy. Copper and zinc are the main metals extracted by electrowinning from aqueous solutions (see *Copper Production; Zinc Production*).

Before electrolysis can take place there are many processing steps. Briefly, the concentrated ore is first converted to an acid-soluble form, followed by leaching in acid, commonly sulfuric, to produce an acidic solution of metal salts. This solution is purified to remove the more noble metal ions, which will electrodeposit more readily than the metal of interest. Purification techniques include cementation and solvent extraction or ion exchange. The purified solution is then fed to electrolysis cells.

The electrolysis cells are open concrete tanks lined with plastic or rubber, approximately 1 m across, 1 m deep and 5–15 m long. Electrodes measuring somewhat less than 1 m × 1 m hang vertically at intervals of about 5 cm in diaphragmless cells and about 10–15 cm when diaphragms are employed. The electrodes are arranged so that they are alternately anodic and cathodic, and all anodes and cathodes in a single tank are usually connected in parallel. The anodes are made of a lead alloy; the cathodes consist of the metal being produced and are prepared by prior electrolysis onto titanium or aluminum starter sheets. The cells operate at current densities of 100–500 A m⁻². During electrolysis the electrolyte is made to circulate slowly between tanks.

Table 1 shows the particulars for the main aqueous electrowinning operations.

1.2 Electrorefining

In contrast to electrowinning, which faces competition from other primary extraction processes, electrorefining is virtually unrivalled in its capability to produce metal of the highest purity. Copper is the predominant metal to be electrorefined, as this is the only process for preparing metal pure enough for electrical applications. Electrorefining is also becoming increasingly popular for recycling metals. Table 2 summarizes the operating conditions for electrorefining.

In the electrorefining of copper, nickel and lead, it is also possible to recover silver and gold from the anode slimes by first dissolving the less noble anode impurities in acid and then casting the remaining noble metals into anodes for subsequent electrorefining. In many cases the value of the noble metals so recovered exceeds the cost of the entire base-metal refining operation.

2. Fused-Salt Processes

2.1 Electrowinning

(a) *Aluminum*. All primary aluminum extraction is performed by fused-salt electrolysis (see *Aluminum Production*). In the Hall-Héroult process, alumina which has been converted from bauxite by the Bayer process is dissolved in molten cryolite (Na₃AlF₆). The electrolyte also contains CaF₂ and AlF₃. The electrolysis cell consists of a steel shell lined with refractory insulating bricks covered with graphite. The cathode is a pool of molten aluminum on the bottom of the cell. The anode is a carbon block

Table 1

Production of metals by electrolysis of aqueous solutions (after Robertson 1978)

Metal	Anode	Cathode	Electrolyte	Temperature (°C)	Cell voltage (V)	Cathode current density (kA m ⁻²)	Energy requirement (kWh kg ⁻¹)
Zn	Pb-Ag	Al	100–200 g l ⁻¹ Zn as sulfate	35	3.5	0.3	3.3
Cu	Pb-(6–15%)Sb-(0–1%)Ag	Cu	20–70 g l ⁻¹ Cu, 20–70 g l ⁻¹ H ₂ SO ₄	30–35	2.2	0.1	2.2
Mn	Pb-1%Ag	Hastelloy 316 stainless steel or Ti	30–40 g l ⁻¹ Mn as sulfate, 125–150 g l ⁻¹ ammonium sulfate, 0.1 g l ⁻¹ SO ₂ ^a		5.1	0.4–0.6	8–9
Co	Pb-Sb-Ag	stainless steel	15–50 g l ⁻¹ Co	50–65	5.0	0.035–0.04	4.5

a Added to prevent MnO₂ deposition

Table 2
Parameters for electrorefining processes (after Pletcher 1982)

Metal	Electrolyte (g l ⁻¹)	Current density (kA m ⁻²)	Cell voltage (V)	Temperature (°C)	Current efficiency	Impurity metals	
						Slime	Solution
Cu	CuSO ₄ (100–140), H ₂ SO ₄ (180–250)	0.1–0.2	0.15–0.30	60	95	Ag,Au,Ni,Pb,Sb	Ni,As,Fe,Co
Ni	NiSO ₄ (140–160), NaCl (90), H ₃ BO ₃ (10–20)	0.15–0.2	1.5–3.0	60	98	Ag,Au,Pt	Cu,Co
Co	CoSO ₄ (150–160), Na ₂ SO ₄ (120–140), NaCl (15–20), H ₃ BO ₃ (10–20)	0.15–0.2	1.5–3.0	60	75–85		Ni,Cu
Pb	Pb ²⁺ (60–80), H ₂ SiF ₆ (50–100)	0.15–0.25	0.3–0.6	30–50	95	Bi,Ag,Au,Sb	
Sn	Na ₂ SnO ₃ (40–80), NaOH (8–20)	0.05–0.15	0.3–0.6	20–60	65	Pb,Sb	

immersed in the electrolyte from the top of the cell. Molten aluminum is produced at the cathode; the anode, which is consumed in the process, produces carbon dioxide. The overall cell reaction is



At a typical cell operating temperature of 960 °C the thermodynamic minimum decomposition voltage is 1.18 V. To compensate for the resistances of the anode, cathode and electrolyte, as well as the anodic overvoltage, cells operate at the much higher applied potential of 4.0–4.5 V. Other cell performance characteristics are given in Table 3.

Aluminum is also produced industrially by the electrolysis of AlCl₃ in a solution of NaCl and LiCl. At 727 °C the thermodynamic voltage requirement is 1.75 V, compared to the operating voltage of 3.3 V.

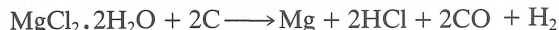
The electrolysis cells employ bipolar carbon electrodes charged so that chlorine is evolved on the bottom surface and aluminum is deposited on the top surface of each electrode. This improves the space-time yield over that of the Hall-Héroult cell. Furthermore, the higher electrical conductance of the chloride electrolyte, the smaller anode-cathode separation, and the lower voltage drop across the electrodes make the electrolysis of AlCl₃ more energy-efficient than the Hall-Héroult process.

(b) *Magnesium.* Electrolytic magnesium is produced at 700 °C by the electrolysis of MgCl₂ dissolved in CaCl₂-NaCl-KCl (see *Magnesium Production*). In the I G Farben process the cell feed is anhydrous MgCl₂, and in the Dow seawater process the cell feed is MgCl₂·1.7H₂O. The cells are made of steel and may be lined with refractory brick. At the steel

Table 3
Production of metals by electrolysis of fused salts (after Robertson 1978)

Metal process	Anode	Cathode	Melt (%)	Temperature (°C)	Cell voltage (V)	Cathode current density (kA m ⁻²)	Energy consumption (kW h kg ⁻¹)
Al (Hall-Héroult)	prebaked graphite	Al	Cryolite (80–85), CaF ₂ (5–7), AlF ₃ (5–7), Al ₂ O ₃ (2–8)	940–980	4.1	3–3.5	13–15
Al (Alcoa)	Söderberg graphite	Al graphite		NaCl (50), LiCl (45), AlCl ₃ (5)	700	~3.3	8–23
Na	graphite	steel	CaCl ₂ (58), NaCl (42)	580 ± 10	5.7–7	9.7	
Mg	graphite	steel	MgCl ₂ (20), CaCl ₂ (20), NaCl (60)	700–720			18.5

cathodes, molten magnesium is deposited and rises to the surface of the electrolyte. Chlorine evolves at the graphite anodes, which are consumed in the Dow cell for the in-situ removal of water from the cell feed. This dehydration can be viewed as an electrolytically assisted carbochlorination reaction, such as



The precise details are unclear; however, CO and HCl are found in the anode gas and H₂ is present in the cell gas. The thermodynamic voltage requirement is 2.52 V at 700 °C, in contrast to the typical operating voltage of 7 V.

(c) *Sodium*. Sodium is produced at 580 °C by the electrolysis of NaCl–CaCl₂ in the Downs cell, which features concentrically arranged graphite anodes and steel cathodes separated by a steel diaphragm (see *Sodium Production*). Both the molten sodium metal and chlorine gas rise to their respective compartments at the top of the cell.

(d) *Titanium*. Titanium can be produced by the electrolysis of TiCl₂ from a melt of KCl–LiCl at 520 °C (see *Titanium Production*). The cell has three electrodes: an anode, a deposition cathode and a feed cathode. A graphite anode is surrounded by a diaphragm of reinforced screen which has been electroless-plated with cobalt or nickel. The cathodes are made of steel round-bar stock. The cathode feed assembly is surrounded by a screen basket with which it makes electrical contact. TiCl₄ is added to the feed-cathode compartment where electroreduction to TiCl₂ occurs. At the deposition cathode, TiCl₂ is reduced to titanium metal. The anode gas consists of chlorine and TiCl₄, the latter being recovered, purified and recycled as cell feed.

(e) *Other metals*. There are fused-salt electrowinning processes for the other alkali and alkaline-earth metals, as well as for the rare earths.

2.2 Electrowinning

Aluminum is the only metal that is electrowinning to any great extent in fused salts. The cell consists of a steel shell with a graphite-lined lower section and an upper section coated with alumina frozen out of the electrolyte. For this purpose a "three-layer" cell is used. The lowest layer is the anode, which consists of impure molten aluminum alloyed with copper to increase the layer's density. The middle layer is the fused-salt electrolyte—a mixture of cryolite, BaF₂, and alumina. The uppermost layer is pure aluminum, with a purity exceeding 99.99%. Electrical contact is made by graphite cathodes which are immersed in the floating molten aluminum cathode and by the graphite lining on the cell bottom, which is covered by the molten aluminum–copper anode.

See also: Electroplating Plants: Prevention of Pollution in Effluents; Metals Production: An Overview

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Electron-Beam Perforation

The outstanding features of electron-beam perforation are: (a) the high drilling performance (up to several thousand holes per second, depending on material thickness), and (b) the accurate repeatability of the hole geometry, once adjusted. In contrast to mechanical drilling processes, the hardness of the material sets no limits, and the possibility of producing heavily inclined holes (at an angle down to 25° with reference to the surface) is of importance for many applications.

1. Processing

By appropriate adjustment of beam power, focus and pulse duration, various diameters and cross sections of holes (e.g., cylindrical, conical, barrel-shaped and trumpet-shaped) are obtained. The material to be perforated (e.g., sheet metal) is lined with an auxiliary material, which develops high vapor pressure upon impingement of the electron beam. During the perforation process, the electron beam first penetrates the material by producing a vapor channel surrounded by molten metal, and then penetrates the underlying auxiliary material, whereby a vapor eruption originates which ejects the molten metal.

Figure 1 shows the relationship between material thickness, hole diameter and drilling frequency (holes per second) for cylindrical holes.