Challenges in Light Metals Production

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ABSTRACT

Light metals have great potential for application in the automotive and aerospace industries because of their excellent physical properties. The usage of aluminium, titanium and magnesium is limited by relatively high costs of production, associated energy costs and large ecological footprint. The use of aluminium, significant improvement to the Hall-Héroult process is still achievable through advances in cell design, materials and process control. Alternative production processes, including carbothermic reduction and low temperature routes are also possible. Magnesium and titanium production are currently dominated by batch metallothermic processes and new process routes are required to develop these industries. Research at CSIRO, through the Light Metals Flagship, is currently focused on step change improvements in the production of light metals, aimed at lowering energy usage, increasing productivity and reducing the overall environmental impact. In this paper, the overall status of the existing technologies will be described, highlighting areas that are being developed around the world and at CSIRO.

INTRODUCTION

Light metals, such as aluminium, titanium and magnesium, have great potential for application in the automotive and aerospace industries because of their generally excellent physical properties compared to steel and plastics. For example, Lou (2000), comparing the bending stiffness of magnesium (AZ91 alloy) to steel, estimated a 61 per cent saving in weight through the use of magnesium. A comparable plastic component would save 35 per cent in weight compared to steel but would need to be twice the thickness of the equivalent magnesium component (Lou, 2000). Alloy development has also seen improvements in the performance of light metal alloys, for example, the development of creep resistant magnesium alloys (Song et al, 2005) and oxidation resistant titanium alloys for high temperature applications (Kosaka, Fox and Faller, 2005).

In the case of automobiles, the potential to substantially decrease the weight of cars without sacrificing strength could lead to lowering the overall environmental impact of transport through reduced fuel usage (Norgate, Rajakumar and Trang, 2004). Currently, the average aluminium and magnesium content of European automobiles is estimated to be only eight per cent and 0.2 per cent respectively of the total weight (Norgate, Rajakumar and Trang, 2004). In the case of magnesium, greater than ten per cent pa growth in consumption by the automotive industry has been experienced over the last decade, reflecting a drive towards lighter cars, alloy development and lower prices.

Outside of aerospace applications, titanium continues to be under-utilised compared with other metals. The potential applications for titanium are numerous with attractive attributes such as:

- the highest strength to weight ratio of any metal up to 500ºC,
- outstanding corrosion resistance in many common yet challenging environments,
- amenability to powder metallurgy, and
- recyclability.

From an environmental perspective, the prospect of a light yet strong metal that resists corrosion and is recyclable is particularly attractive. However, fifty years after the first commercial process was established, the annual production rate is still in the precious metal category, even though titanium is the ninth most abundant element and fourth most abundant structural metal on earth.

Though it is well known that aluminium, magnesium and titanium have excellent properties and great potential for application in many industries and products, their total combined production is an order of magnitude smaller than steel. As shown in Table 1, world metal production is dominated by steel and the recent rapid growth in China has fuelled an even greater discrepancy between steel and light metal production. For example, world steel production grew from 962 Mtpa from 1999 to 2003, compared to growth in aluminium from 23.6 to 27.7 Mtpa over the same period. Growth in magnesium production over the same period has been impressive, 0.34 Mtpa to 0.50 Mtpa, but this has been from a low base. Titanium production remains very low at less than 0.1 Mtpa.

There are many inter-related reasons for the large discrepancy between ferrous and light metal production but the dominant reason is that light metals are expensive to produce in comparison to steel. In particular, the production of light metals requires far greater energy compared to steel, which leads to greater environmental impact, particularly in terms of global warming through the release of carbon dioxide. For example, the cradle to gate energy required to produce titanium is over 16 times greater than required to make steel and over five times greater that required to produce copper. The relative energy requirements and values calculated from life cycle analysis for a number of major metals are provided in Table 1. The enormous variation between the energy requirements and environmental impacts of various metals reflects variations in the chemical stability of the major minerals, availability of valuable ores and process routes for production. This issue is explored in greater detail by one of the authors in an earlier paper (Brooks and Subagyo, 2002).

Significant reduction in energy requirements and environmental impact for light metals production would lead to a greater utilisation of light metals in transport applications, which could lead to lower fuel consumption. It must be acknowledged that the trend towards light weighting of cars is a complex economic and social issue (eg consumer demand for larger SUVs) and that lowering the cost of light metals production does not immediately equate to generally lighter cars and less fuel consumption. However, it is true to say that lowering the overall energy consumption and environmental impact of light metals production would facilitate any trend towards lightweighting of cars.

This drive to lower the cost and reduce the environmental impact of light metals production is one of the main drivers toward the creation of the CSIRO Light Metals Flagship in 2003. The Flagship has a series of ambitious goals, including reducing the energy required to produce light metals by 30 per cent, reducing the full life cycle environmental impact of light metals by 50 per cent and increasing asset productivity by 30 per cent. (Filmer, Johnson and Rajakumar, 2003) This paper will examine some of the specific issues relating to light metals production in the context of current research at CSIRO and around the world that is addressing these ambitious goals.
ALUMINIUM PRODUCTION

Hall-Héroult process

There is essentially only one process used for the commercial production of aluminium: the Hall-Héroult process. This electrolytic process was patented in 1886 and has remained fundamentally unchanged, except for the form of the carbon anodes. A modern aluminium smelter consists of several hundred Hall-Héroult cells (Figure 1) arranged in series, with an electric current of up to 350 kA. Cells are typically 10 - 14 m long and 3 - 4 m wide, containing up to 50 anodes arranged in two parallel lines. Over time, improvements in cell productivity and reduced emissions have been achieved through magnetic compensation allowing for larger cells, improved materials and advances in process control. These improvements have been underpinned by the application of advanced mathematical modelling techniques.

Alumina is regularly fed and dissolved into the molten electrolyte, consisting mainly of cryolite and aluminium fluoride at ~960°C. Carbon anodes are attached to aluminium rods and positioned in the electrolyte. Electric current is passed through the anodes and electrolyte to the carbon cathode. Aluminium is produced at the cathode and forms a pool of molten aluminium beneath the electrolyte. The oxide ions are oxidised at the carbon anodes and combine with the carbon to form CO2 and CO. The aluminium metal is removed (‘tapped’) from the cell about once per day. The carbon anodes are consumed and must be replaced every two to three weeks. The main reaction is:

\[ 2\text{Al}_2\text{O}_3 + 3\text{C} \rightarrow 4\text{Al} + 3\text{CO}_2 \]  

Although the Hall-Héroult process has been remarkably successful for over a century, it suffers from two key issues. Firstly, it requires significant energy to electrolytically produce aluminium from alumina. The best Hall-Héroult cells consume
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~13 kWh/kg of aluminium produced. Whilst this is a significant improvement over the ~20 kWh/kg aluminium in 1950 (Keniry, 2001), it is relatively high compared to other metals, as discussed previously. Secondly, electrolytic cells for producing aluminium have much higher capital cost per tonne of capacity than pyrometallurgical reactors such as basic oxygen steelmaking.

Although there are several factors that contribute to the relatively high energy consumption and high capital cost/tonne, most of them can be traced back to materials. The thermodynamic energy requirement for producing aluminium (6.3 kWh/kg) only represents ~50 per cent of the energy consumed in electrolysis of alumina. The remainder is lost as heat. The electrolyte is extremely corrosive at 960°C and inexpensive materials that are resistant to cryolite have not yet been developed. Currently, the only practical way to protect the sidewall is to form a frozen layer of electrolyte on the internal surface of the cell. This requires a high heat flux out of the sidewall and hence high energy consumption to maintain the heat balance (Welch and Keniry, 2000).

In addition, the carbon anodes are consumed in the reaction to produce aluminium and so must be replaced regularly. Thus the cell design must allow for easy replacement of anodes. Any such design is not well sealed and so there is also high heat loss from the top of the cell. The replacement of an anode also introduces a large temporary thermal imbalance to the cell, which makes process control more difficult.

An important reason for the high capital cost of the Hall-Héroult process is that the carbon cathode is not wetted by molten aluminium. Thus a relatively thick layer (several centimetres) of molten aluminium is required to produce interfacial stability between it and the electrolyte. This can only be achieved with a horizontal cathode and consequently the plant has a very large footprint. The cryolite and aluminium also attack the oxidation of carbon (that provides some of the energy input) and so as to provide a smooth transition from one anode to the next as they are consumed. VAW operated a potline of CPA cells at its Elbewerk smelter for many years (Scholemann and Wilkening, 2001). The cell was an old design and so never achieved superior performance comparable to a modern conventional cell. Significant challenges for the CPA concept include achieving low voltage drop through the anodes, ensuring good gluing between successive anodes and the positioning of alumina hoppers and feeders within the cell. Hydro now owns VAW and has announced the closure of the Elbewerk smelter (Knutzen, 2005). It is believed that no significant research into CPA is occurring.

It has long been the goal of the aluminium industry to develop an inert anode (Anon, 1999). Alcoa has concentrated on a nickel ferrite cermet anode and has tested such anodes in pilot scale cells. In 2000 Alcoa was reportedly close to commercialisation (van Leeuwen, 2000), but only limited information has been provided since that date. Moltech is developing a Ni-Fe alloy and has tested eight anodes in a 20 kA cell (McMinn and de Nora, 2004) and a 25 kA cell (Sekhar et al, 1998). This coating consists of three separate layers to balance the requirements of wetting by aluminium, wear resistance and adhesion to the cathode (Nguyen and McMinn, 2002). This coating has been tested in commercial cells (De Nora, 2005). Alcoa and Kaiser tested tiles of TiB2, TiB2/C and Ti3SiC2 in 23 kA pilot cells (Bruggeman et al, 2002). A cell was operated for 60 days and the results were sufficient to plan testing at commercial scale; however, the research was terminated when the Mead smelter was shut down.

It is apparent that several wettable cathode technologies have been tested with some success in commercial cells. It is therefore possible that at least one of these technologies could be commercialised in the next few years.

The continuous prebaked anode (CPA) is an approach to minimise the disturbance to the cell caused by anode replacement. Anodes are stacked on top of each other in the cell, and so as to provide a smooth transition from one anode to the next as they are consumed. CPA is a prebaked anode that drains to a tapping sump. Moltech have worked to develop a TiB2/cloisoidal anode for 12 years (Sekhar et al, 1998). This coating is only a thin metal layer on the cathode that drains to a tapping sump. Moltech have tested tiles of TiB2, TiB2/C and Ti3SiC2 in 23 kA pilot cells (Bruggeman et al, 2002). A cell was operated for 60 days and the results were sufficient to plan testing at commercial scale; however, the research was terminated when the Mead smelter was shut down.

Comalco has spent over 15 years developing a TiB2/carbon composite coating (Taylor et al, 2000), including the operation of more than 25 full-scale cells at two smelters. The cells ranged from applying a composite coating to a cathode in an existing cell design, to a fully drained cathode cell, where there is only a thin metal layer on the cathode that drains to a tapping sump. Moltech have worked to develop a TiB2/cloisoidal anode for 12 years (Sekhar et al, 1998). This coating consists of three separate layers to balance the requirements of wetting by aluminium, wear resistance and adhesion to the carbon cathode (Nguyen and McMinn, 2002). This coating has been tested in commercial cells (De Nora, 2005). Alcoa and Kaiser tested tiles of TiB2, TiB2/C and Ti3SiC2 in 23 kA pilot cells (Bruggeman et al, 2002). A cell was operated for 60 days and the results were sufficient to plan testing at commercial scale; however, the research was terminated when the Mead smelter was shut down.

Alternative processes
Another approach is to develop a new process for producing aluminium that bypasses many of the issues with the Hall-Héroult process. There is ongoing work into developing alternative electrolytes, including room temperature electrolytes, and a carbothermic production route.

Alcoa vigorously pursued the electrolysis of aluminium chloride in the 1960s and 70s. Lower energy consumption was achieved (9.5 kWh/kg aluminium), but Alcoa halted operation of these cells in the 1980s, reportedly due to difficulties with producing and handling aluminium chloride (Thonstad et al, 2001).
Ionic liquids are novel electrolytes that can dissolve a range of inorganic materials and are molten at relatively low temperatures (<100°C). Chloroaluminate ionic liquids have been intensively investigated in the past (Zhang, Kamavarn and Reddy, 2005); however, they contain anhydrous aluminium chloride, which renders them water and air sensitive. These electrolytes are likely to have the same handling issues as the electrolysis of aluminium chloride.

Carbothermic production of aluminium would have the advantage of lower capital cost and faster reaction kinetics. A critical issue is that high temperatures are required (∼2000°C) and the formation of aluminium carbides is favoured at these temperatures. Most of the large aluminium producers have researched carbothermic production over the last few decades (Thonstad et al, 2001), but only Alcoa is believed to be still active in the area (Johansen et al, 2003).

**CSIRO aluminium research**

In 2004, Comalco and CSIRO began a joint project to continue the development of drained cathode cells. CSIRO is using specialised microscopy tools to understand and improve the performance of the TiB2/carbon composite. Coating technologies are being developed to better protect the cathode during cell start-up. Computational fluid dynamics modelling and physical modelling are being used to predict metal, electrolyte and gas bubble movement in the drained cell. This knowledge is being used to improve cell and anode designs and operating strategies. The modelling expertise can also be applied to conventional reduction cells (Cooksey and Yang, in press).

CSIRO is undertaking projects in a number of other aspects of the Hall-Héroult process. These include alternative raw materials for carbon anodes, anode coatings for protection from airburn, development of new sidewall materials, detection of bath during metal tapping, welding in magnetic fields, low temperature electrolytes and automation of metal transfer in smelters.

**TITANIUM PRODUCTION**

**Kroll process**

The Kroll process, the only commercial route to titanium production, is a batch wise magnesiothermic reduction of titanium tetrachloride, according to Equation 2:

$$\text{TiCl}_4(l) + 2\text{Mg}(l) \rightarrow 2\text{MgCl}_2(l) + \text{Ti(s)}$$

(2)

Titanium tetrachloride is a volatile halide that can be fractionally distilled to produce a relatively pure feedstock. Produced in high volume as an intermediate in the pigment industry, TiCl4 is available at a relatively low cost. In the Kroll process (Anon, 1983), the TiCl4 is slowly trickled into a dry, argon blanketed stainless steel retort precharged with pure magnesium metal. While the retort is preheated at the start of the cycle, the reaction is sufficiently exothermic to maintain the contents in the target range between 800 and 900°C. Under these conditions the magnesium chloride by-product is in a liquid state and is periodically tapped off the retort. Provided it can be kept anhydrous, the recovered magnesium chloride can be converted back into magnesium metal and chloride gas via electrolysis.

After several days, the temperature inside the Kroll retort drops as the availability of unreduced magnesium drops, thus signifying the effective completion of the reaction. The process is usually conducted with a 15 - 30 per cent stoichiometric excess of magnesium. At this point, any free magnesium chloride is drained from the retort to leave a porous metallic structure consisting of metallic titanium, unreacted magnesium, impurities (from the feedstocks and picked up from the retort structure) plus trapped magnesium chloride. The retort is then heated to around 900 - 1000°C under vacuum (at 0.1 Pa.a) for around 85 hours to distill off the remaining magnesium chloride and magnesium. After the retort has cooled down, the ends are cut off and the porous titanium residue, referred to as sponge, is pressed or jack-hammered out. The lumps of sponge are then hand classified according to the degree of alloying with the steel retort. Up to 25 per cent (Habashi, 1997) of the recovered sponge is unsuitable for commercial purity (CP) titanium due to alloying and must be disposed of as ferrotitanium; a lower value product. The loss of materials to the alloying effect, combined with the aggressive nature of magnesium chloride, means that each retort only has a very limited cycle life, thus contributing to environmental impact.

The purer lumps of sponge (85 per cent) are pressed together with scrap to form a consumable vacuum arc furnace electrode. The molten metal from this labour intensive and expensive process eventually enters the metal tapping, welding in magnetic fields, low temperature electrolytes and automation of metal transfer in smelters.

**Manufacturing**

The costs associated with converting titanium ingots into semi-finished items like plate are dominated by mill processing costs. In the case of 1” thick titanium plate, 43 per cent of the cost relates to production to the ingot stage with the remaining 57 per cent associated with mill processing costs (Anon, 2005a).

The high melting point and the affinity of titanium for gases like oxygen and nitrogen continue to contribute greatly to high cost. In the process of going from ingot to finished product, a scrap rate of 40 per cent is typical. In high end applications like aerospace, often only ten per cent of the metal purchased ends up in service.

While titanium is technically amenable to lower cost manufacturing approaches like powder metallurgy, titanium powder that is produced in elaborate steps after vacuum arc refining is currently one of the most expensive forms of titanium. Until a low-cost powder can be produced, the benefits of powder metallurgy in the context of titanium will remain unrealised.

**Innovation**

Although there have been small gains in efficiency in the Kroll process, it is impossible to achieve the large cost reduction needed to fully develop the titanium business, using existing technology. In an analysis of the titanium business, Cariola (1999) made comparisons between the transition of aluminium from precious metal to commodity and identified the need for radical innovation. There have been hundreds of alternative process pathways proposed; however, none have yet come to commercial fruition.

Kraft (2005) classifies pathways to titanium metal according to the form in which it is produced; via either granule or liquid. Details of the main developments are given elsewhere (Anon, 2004); however, the most promising approaches involve producing titanium in an electrolytic cell in the manner of aluminium, or the direct production of titanium powder. Unlike the Kroll process, both these approaches are based on continuous or semi-continuous operation and are therefore amenable to optimisation and process control. The Fray-Farthing-Chen (FCC) process and the BHPB process are examples of the electrochemical approach. Good progress has recently been reported by the team at BHPB with development of their Polar™ process (Rigby et al, 2005). This approach is based on the reduction of TiO2 to Ti using molten salt (CaCl2 based) electrochemistry. Purity, scale-up and process economics are reported to be the biggest challenges associated with the electrochemical approach (Kraft, 2005).
On the direct powder side, the aim is to produce titanium powder for around the cost of sponge. In addition to higher yields, this approach facilitates low-cost powder metallurgy techniques. Armstrong/ITP have reported good progress with their approach (Kraft, 2005), which involves the injection of titanium tetrachloride into liquid sodium to produce finely divided titanium and sodium chloride. The TiRO™ process, developed by researchers within the CSIRO Light Metals Flagship, is also aiming to produce powder directly using the proven chemistry of the conventional Kroll process.

In contrast to the conventional Kroll process, the TiRO™ reaction takes place in an operating window that is conducive to a fluidised bed reactor. The mass and heat transfer and continuous operating efficiencies associated with gas-solid fluidisation have a significant impact on the size, capital and operating costs of the plant. A small scale TiRO™ reactor module is in operation (Figure 2) and the criteria for ‘proof of concept’ achieved. Plans for pilot plant testing of the system are well underway. Projected capital and operating costs are significantly lower than those of the conventional Kroll process. The CSIRO team is currently in the process of designing a larger scale pilot facility (Kraft, 2005). The broader CSIRO initiative also includes the direct production of alloy powders, plus development of powder metallurgy based processes to convert the titanium powders into semi-fabricated products at significantly lower cost (Anon, 2006).

In conclusion, if the full potential of titanium is to be realised, a new production-manufacturing process will be required. Research activity is strong and the development of an alternative approach means that realisation of the vision is within sight.

**MAGNESIUM PRODUCTION**

**Existing processes**

World magnesium production is currently dominated by the Pidgeon process, which uses silicon, in the form of ferrosilicon, to reduce magnesia produced from calcined dolomite under vacuum. The overall reaction of the process can be written as:

$$2\text{MgO(s)} + 2\text{CaO(s)} + (x\text{Fe})\text{Si(s)} = 2\text{Mg(g)} + \text{Ca}_2\text{SiO}_3(s) + x\text{Fe(s)}$$

The reaction is performed in batch mode within steel retorts that operate at approximately 1200°C and a vacuum of 10 - 20 Pa to produce approximately 20 kg of magnesium over an eight to ten hour period. A generalised flow sheet of the Pidgeon process is shown in Figure 3. In general, the process suffers from high energy usage and low productivity, but does have the advantages of low capital costs and process simplicity.

Large scale silicothermic processes have been developed, including the Magnetherm and Balzano processes (Oye, 1990). In the Magnetherm process, an electric arc furnace operates in batch mode between 1500 and 1600°C and under a vacuum of 4 - 9.3 kPa. Production rates of 12 t/day have been reported (Oye, 1990). Calcined dolomite and ferrosilicon are fed into a calcium silicate slag rich in alumina and the overall reaction is (Cameron *et al*, 1987):

$$2\text{MgO(s)} + 2\text{CaO(s)} + (x\text{Fe})\text{Si(s)} = 2\text{Mg(g)} + \text{Ca}_2\text{SiO}_3(s) + x\text{Fe(s)}$$

**Fig 2** - CSIRO’s TiRO™ reactor (rated at 200g Ti/h).

**Fig 3** - Schematic of Pidgeon process (after Kipouras and Sadoway, 1987).
Alternative processes

Four main options to the existing thermal routes for magnesium production are discussed in the literature, namely:

1. large-scale continuous silicothermic reduction;
2. aluminium reduction of magnesia or dolomite;
3. carbothermic reduction to produce a Mg/CO rich vapour that is subsequently quenched to avoid reversion (carbothermic quench route); and
4. carbothermic reduction in a metallic solvent to produce a magnesium rich liquid alloy that is subsequently exposed to a vacuum for magnesium removal and refining (carbothermic solvent route).

There has been significant previous work on all of these options, including large-scale pilot plants. In this section, the basic chemistry of the processes and previous work will be summarised.

Large-scale continuous silicothermic reduction

The Magnetherm and Bolzano processes represent an advance on the Pidgeon process in terms of scale and productivity, but suffer from the practical problems of running large-scale batch vacuum processes.

Mintek continued development of the silicothermic route in the 1980s and 90s using plasma technology and various condenser designs (Barcza and Schoukens, 1987; Schoukens, 1989; Barcza et al., 2000; Schoukens 2003). The important features of their process are:

1. use of dc furnaces with an open arc,
2. continuous operation, and
3. atmospheric pressure in the reduction stage.

A similar approach has been developed by Cameron and co-workers but with special emphasis on operating with a slag chemistry that allows the reactions to proceed at higher operating pressures (Cameron et al., 1990; Cameron, 1995; Cameron et al., 1997). Both the work by Mintek and Cameron et al have been carried out at pilot plant scale but are yet to be commercialised.

Aluminium reduction

A number of researchers have investigated the concept of using aluminium as a reductant (Emley, 1966; Wadsley, 2000; Capocchi and Rajakumar, 2000). The central reaction of the process can be written as:

\[
\text{MgO} + 2/3 \text{Al} \rightarrow \text{Mg(g)} + 1/3 \text{Al}_2\text{O}_3
\]

In the Heggie-Iolaire process, the reduction reaction is carried out between 1500 and 1600°C using a calcium aluminate slag in a thermal plasma arc furnace using aluminium scrap as the reductant (Wadsley, 2000). The reduction stage of the process was tested in an EAF with up to 120 kW power. A number of condenser designs were trialled and production rates of 10 kg/hr achieved.

Proposed aluminothermic routes suffer from the problem that aluminium is an expensive reductant compared to ferrosilicon and carbon, quite apart from the various problems associated with the smelting and condensation technology.

Carbothermic reduction

Carbothermic reduction is an alternative to both silicothermic and electrolytic processes for the production of magnesium. The main reaction of this route is:

\[
\text{MgO} + \text{C} \rightarrow \text{Mg(g)} + \text{CO(g)}
\]

This reaction is favoured above 1700°C and a total pressure of 1 atm provided by the product gases is achieved at 1764°C (Oye, 1990). The reaction can proceed at lower temperatures by either operating under reduced pressure and/or diluting the product gases with an inert gas. The equilibrium partial pressure of magnesium is shown in Figure 4, as a function of temperature.
including some large-scale industrial trials during the Second World War (Hansgirg, 1943; Duncan, 1944) and recent work at CSIRO (Brooks, Trang and Nagle, in press; Brooks et al, 2006) and by researchers in the USA (Odle and McClaine, 2004; Donaldson and Cordes, 2005).

These developments have concentrated on two process routes: the ‘quench’ route and the ‘solvent’ route. Schematics of these two routes are shown in Figures 5 and 6. In each route, magnesite feed is calcined to form MgO and then pelletised with a fixed carbon. In the case of the quench route, flux may be added to the pellets to promote removal of impurities during reduction. In the quench route, magnesium and CO vapours are generated in a reduction step, then rapidly quenched and collected. The collected condensate may then be further refined through a subsequent distillation step. The great majority of work in the last century concentrated on this approach, particularly focusing on avoiding ‘reversion’ reactions, that is, Mg(g) and CO (g) recombining during cooling to produce a metal heavily contaminated by MgO. In addition to the issue of reversion the product produced from such processes were also pyrophoric and difficult to handle and process.

In the solvent route, shown schematically in Figure 6, the agglomerated feed is fed into the reduction stage containing a molten metal solvent in which the magnesium formed by reduction dissolves and the CO produced is allowed to escape. The reaction can be written as (the square brackets denote that the magnesium is dissolved in a solvent):

\[ \text{MgO(s)} + \text{C(s)} = \left[ \text{Mg} \right] + \text{CO(g)} \]  

(7)

Associated with this reaction is the vaporisation of magnesium from the melt:

\[ [\text{Mg}] = \text{Mg(g)} \]  

(8)

Separating magnesium removal from CO removal is the great attraction of the solvent route, as it avoids the issue of reversion in the gas phase that has plagued the development of the quench route. The overall recovery of magnesium from the process will depend greatly on both the thermodynamics and kinetics of Equations 7 and 8, currently the subject of study at CSIRO.

There is very little information on the solvent process in the open literature (Andersen and Parlee, 1976; Eckert et al, 1983; Eckert et al, 1984; Brooks et al, 2006), though significant experimentation and theoretical assessment of the process was carried out by Rajakumar and co-workers at CSIRO in the 1990s. Current work at CSIRO has concentrated on identifying suitable solvents, process kinetics and the submergence of pellets (Brooks et al, 2006).

**CONCLUSIONS**

Significant technical and economic challenges face the light metals industry if the production of aluminium, titanium and magnesium is to grow to levels comparable to steel. Lowering the cost and environmental impact of light metals production would likely have very positive flow-on effects to the overall environmental impact of transport and aerospace. The technical challenges cover a wide range of issues related to physical chemistry, materials science, reactor optimisation and process development. The CSIRO Light Metals Flagship and other research groups around the world are meeting these challenges through concentrated research on the key issues outlined in this paper.

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