SILLIMANITE MINERALS

By Ted Dickson
TAK Industrial Mineral Consultancy, Gerrards Cross, UK

The sillimanite group consists of three minerals, andalusite, kyanite and sillimanite itself, all with the same chemical composition but with different crystal structures and physical properties. Both andalusite and sillimanite are orthorhombic, but kyanite is triclinic. Andalusite has a hardness of 7.5, sillimanite 6-7 and kyanite 5-7. Andalusite has the lowest density at 3.16-3.2, sillimanite is slightly higher at 3.23-3.27 but kyanite is significantly higher at 3.56-3.67. The chemical formula is normally written as $Al_2O_3.SiO_2$ with a theoretical composition of 62.93% alumina and 37.07% silica.

All of the sillimanite minerals convert to mullite (about 88%) and silica (about 12%) on calcining or heating at temperatures of 1,250°C to 1,500°C. Each of the minerals converts at a different temperature, with kyanite needing the least heat and sillimanite the most. Mullite is extremely refractory, has a small coefficient of expansion, is abrasion and slag resistant, and because it commonly forms intergrowths of needle-shaped crystals, products made from it have good creep resistance. Since mullite is the mineral component that is sought after by the refractory industry, the sillimanite minerals could almost be regarded as 'mullite ore'. Mullite, with a theoretical chemical formula of $3Al_2O_3.2SiO_2$, does occur in nature and takes its name from the type locality on the Island of Mull off the west coast of Scotland. In the case of andalusite, mullitisation begins at about 1,250ºC. About 50% of the andalusite is converted to mullite and glass as the temperature is raised to 1,350ºC. Only 10% andalusite is left at 1,400ºC and complete mullitisation occurs by about 1,600ºC. This is under test conditions where there is a rise in temperature of 120ºC per hour and two-hour soaking at various selected temperatures.

Sillimanite gave its name to the group mainly because a large portion of supply in the early years of the industry was sillimanite from India. It was also difficult until recent times to distinguish between sillimanite and mullite and it was believed that the product of calcination was sillimanite rather than mullite, which is now known not to be the case. In the US, kyanite was the predominant mineral produced and the term 'kyanite and related minerals' is commonly used to describe the group in that country.

While the three minerals that make up the group have the same chemical composition, their physical properties are different. Most importantly, sillimanite and andalusite increase irreversibly in volume by only about 4% and 6% respectively on calcining. They can be used directly in refractories without calcining because the small volume increase can be accommodated by the users and can be beneficial. The minerals are essentially being calcined during use and the expansion can result in very tight-fitting refractory linings. Kyanite, on the other hand, increases in volume by 16-18% on calcining. This expansion is used as an advantage in some instances where raw kyanite is added to a refractory mix to counteract the shrinkage on firing

of other components, notably clays. In other refractory applications, kyanite needs to be calcined prior to incorporation into refractory products. Conversion to mullite and silica usually takes place at temperatures of 1,250°C to 1,500°C and the mullite formed is then stable up to about 1,800°C.

Although the three minerals that make up this group have different properties, all of them are primarily used as refractories and depend on the steel industry for most of their demand. The health of the steel industry and changes in technology that affect the usage of refractories are by far the greatest influences on the consumption of these products and need to be assessed briefly to indicate market conditions.

Steel industry

Despite many predictions that there would be declines in the steel industry during 2002, world production of steel rose to 887 Mt according to figures from the International Iron and Steel Institute (IISI), an increase of 6.4% and was probably above 900 Mt if countries not included in the IISI survey are added. This was a reversal of the downward trend in 2001. There were considerable regional differences in the growth patterns. In the EU, there was virtually no growth, with an increase of a mere 0.1%. Within that figure there were some countries that performed better than others with growth of 5.6% in France and 0.4% in Germany contrasting with declines of 13.9% in the UK and 1.9% in Italy. Production in the rest of Europe grew by 4.7% with growth of 10% in Turkey. Production in the former CIS also grew but by a more modest 1.8%. Production in the US grew by 2.5% but by 26% when comparing the figures for December 2001 and December 2002. However, it should be remembered that production in the US fell significantly in 2001 and that the recovery is from low levels. Asia continued its strong growth, fuelled largely by the continuing surge in production in China. Growth in Asia as a whole amounted to 11.6%, bringing production up to 382 Mt. There was growth in all the major producing countries of the region, even in Japan where steel production grew by 4.7% following a 3.4% decline the previous year. However, no country can match the growth of over 20% in Chinese steel production.

Total volumes of steel production can indicate general trends, but there have also been changes in technology over the years that have resulted in lower consumption of refractories per tonne of steel produced, sometimes involving changes in the refractory raw materials used.

Mineral markets

Although all three of the sillimanite group of minerals have the same chemical composition, they have different physical characteristics and different regional availability. These differences are reflected in the markets served and because of this each of the minerals and high alumina calcines that have similar chemical compositions are dealt with separately below.

Andalusite

There was little change in the andalusite market during 2002, with some small declines, but a new supplier entered towards the end of the year with initial

shipments now reaching markets. Despite the fact that andalusite is a common mineral in geological terms, commercially viable deposits are very limited. All of the current production comes from South Africa, France and China. Outside China the world consumption of andalusite continued its recent declines to below 230,000 t in 2001. Production in China is estimated to have been only 10,000 t, all for local use, although the country reportedly has the capacity to produce 80,000 t/y.

The dominant world producer is Imerys through its subsidiary Damrec, with operations in both South Africa (through Samrec) and France. In terms of world trade, the company has been the sole supplier since the Hoogenoeg mine of Hernic was mothballed in 1999. Its current production is about 170,000 t/y in South Africa and a further 60,000 t/y in France. However, the company has considerably greater capacity and the Anref and Havercroft mines in South Africa remain mothballed.

There are significant regional differences in the market for andalusite. The largest markets continue to be Europe, with consumption of the order of 140,000 t/y, although this has been declining. There have also been some changes in patterns of consumption within Europe. The UK at one time was one of the largest single consumers of andalusite. However, with the decline of the UK steel industry and the transfer of some refractories production to Poland, its consumption has declined, although it is still a significant consumer. South Africa is the second largest consumer at about 45,000 t/y, based on the fact that it has local supply. However, at least some of the consumption may be exported in the form of finished refractory products. Asia, particularly Japan and to a lesser extent Korea and Taiwan, is the other major market accounting for about 40,000 t/y of demand. The US is notably a very small consumer of andalusite. The market is currently estimated to be less than 5,000 t/y. In the case of aluminosilicate refractories, the US industry has tended to use locally available, high-alumina calcines and calcined kyanite, as well as imported refractory bauxite from China or South America.

The new entrant to the andalusite market is Andalusite Resources of South Africa. Production started late in 2002, and a first shipment of 1,000 t was made to Europe in January 2003. The operation at Maroeloesfontein is in the Thabazimbi region of South Africa, which is well known as an andalusite-producing area and the new mine is very close to Samrec's Rhino mine. Initial production is based on a 57-58% alumina product with a size range of 0-3 mm although it is mainly in the range 0.5-3.0 mm that is being marketed under the name Marulsite 57. Iron content (as Fe_2O_3) is less than 1% and the company has pointed out that, although the alumina content is at the lower end of the range of commercially available material, there are low amounts of iron and silica-bearing minerals as distinct crystals giving good refractory properties. Initial production capacity is a relatively modest 30,000 t/y although it could be increased readily to 45,000 t/y depending on market requirements. The company may also be able to produce a higher alumina product or a larger grain-size product at some stage. Sales in Europe are being handled by Europe Minerals in the Netherlands, which in the past was the sales agent for Rhino Minerals.

The potential for greater andalusite production in China should not be ignored. While current production is estimated to be only 10,000 t/y, capacity has been cited as high as 80,000 t/y. Many of the deposits are in fairly remote areas and difficult to get to markets at competitive rates. Some of the products that have been produced were high in iron and unsuited to international markets. However, there may well be further developments and the huge Chinese steel industry could provide a ready market, although the country has a wealth of other refractory raw materials including refractory bauxite and flint clay.

In Peru, Refractarios Peruanos has been investigating a deposit near Peipa. From a pilot plant it has produced a product with an alumina content greater than 58% and a grain-size of 0.6-4 mm. There has been no indication yet whether the project will proceed to full production.

Kyanite

As in the case of andalusite, the kyanite market is dominated by a single producer. Kyanite Mining Corp. is by far the largest producer of kyanite from its operations in Virginia, US. The company is privately held and does not reveal production figures. Estimates have been made in recent years of production levels of the order of 90,000 t/y (100,000 short tons), but the company has indicated that current production levels are rather higher than that and may possibly be of the order of 100,000 t/y. Production capacity is considerably greater and could sustain higher production levels if markets were available. During 2002, markets were fairly flat with domestic US markets shrinking slightly and exports booming. About 35% of the company's production was exported during 2002, throughout the world, but with increased sales to Asia, and particularly China. The first quarter of 2003 looked more promising with improved sales both domestically and overseas.

For kyanite, there are essentially two market sectors. Raw kyanite is used primarily for its expansion characteristics where it counteracts the shrinkage of other refractory raw materials during firing, most notably clays and sales of this are worldwide. The other part of the market is for calcined kyanite, which tends to be stronger in the domestic US market, but is also traded internationally. The company has also been developing markets in non-traditional uses outside the refractory industry for its calcined products.

Production of kyanite outside the US is relatively small. Yet again, China has enormous potential, but relatively minor production. Current estimates are that production is of the order of 20,000 t/y, but it is known that the country is importing US kyanite. There is also about 10,000 t/y of production in India and Bajaj Associates now produces a calcined product referred to as sintered mullite from a 10,000 t/y capacity plant. There is also some by-product production from mineral sands operations, with a reported 15,000 t/y produced from operations in the Ukraine, and other mineral-sands producers have looked at the possibility of extracting a saleable product. There has also been some production in Zimbabwe, estimated to be a few thousand tonnes annually, and a deposit is being investigated in South Africa for which investors are being sought, but economic assessment is still at a relatively early stage.

Sillimanite

Although sillimanite gives its name to this group of minerals, its commercial production is now quite limited and international trade that once saw large quantities shipped from India to Europe is now very minor. It has been reported that production in China is about 20,000 t/y although the potential is far greater and capacity may be as high as 60,000 t/y. In India, about 15,000 t/y is produced, much of it as by product from mineral-sands operations. There is still some very minor production of sillimanite in Australia from a kaolinised deposit, where sillimanite is a by-product of clay operations.

Calcines and sinters

High-alumina calcines are not members of the sillimanite group of minerals as such, but a number are produced that have chemical compositions that are similar. They range from 47% alumina that is essentially pure calcined kaolin up to 70% alumina products blended to mimic the composition of pure mullite. In between these, blends of about 60% alumina are made to have compositions similar to a calcined kyanite, although Kyanite Mining Corp. points out that there are physical differences that differentiate the products.

C-E Minerals, part of the Imerys Group, is the largest supplier of these products to world markets. Three products, nominally with alumina contents of 47%, 60% and 70% alumina, are produced by carefully blending kaolin clay and bauxite or bauxitic kaolin from its deposits in southeastern US and calcining them in long rotary kilns. Patterns of usage have been very steady in recent years. In the US there was a small increase in consumption during 2002, balanced by some minor declines elsewhere. It is estimated that from a total production capacity of about 550,000 t/y the production of 60% alumina product is about 130,000 t/y with about 40,000 t/y of the 70% alumina grade, the balance being calcined kaolin at 47% alumina.

There has been production of similar grades in Brazil for many years, perhaps as much as 50,000 t/y for local markets. However, much of the focus on new sources has been in Asia and specifically China. In China, Aluref started full-scale production at its Datong operation in Shanxi province. The converted cement kiln it uses is expected to be able to produce up to 30,000 t/y. Nanchuan Minerals Group is also reported to have started production of two products labelled King Mountain Mullite 60 and Mullite 70 from a 25,000 t/y operation, the Chonggang Sintered Mullite Plant. Nanchuan is already a long-established producer of calcined bauxite and fused alumina, and raw material from the company's own deposits of bauxite will supply the new plant. Two other companies one in Hunan and the other in Henan province are reportedly offering high-alumina calcines.

The Chinese refractories industry is large as a result of its huge steel production, which is the largest in the world and now larger than production in the whole of the EU. However, much of the demand for high-alumina refractories is supplied by locally available cheap calcined bauxite and all of the producers or potential producers of high-alumina calcines in China are looking at export markets. Establishing these can be difficult as refractories consumers are slow to switch from a long-established, highly-regarded

consistent product such as the Mulcoa range to an untried product. That being said, there have been some positive responses to samples sent for evaluation from China, and Chinese refractory raw materials have traditionally been very competitive on price.

Fused and sintered mullite is more specialised and higher value products than the high-alumina calcines, although the calcines and calcined kyanite have been referred to as sintered mullite in some instances. Production of sintered mullite is very limited now, with Nabaltec the only remaining producer in Europe and production elsewhere minimal. Fused mullite production is considerably higher with several tens of thousands of tonnes produced in the US, Europe and Japan. However, this product is considerably more expensive than sillimanite minerals or high-alumina calcines and competes in very different markets.

Prices

None of the major suppliers reported any change in prices during the year, which is not uncommon in this industry, with sometimes several years between changes in list prices. The table below is therefore unchanged from last year's annual review. It should be noted that the price of South African andalusite cif North Europe is approximately €200/t and Andalusite Resources has stated that it does not intend to become involved in a price war with Damrec so its products are similarly priced.

Andalusite, 57-59% Al_2O_3 fob, South Africa, bulk, per tonne	€135-170
Andalusite, 58% Al_2O_3, fob, North France, bulk, per tonne	€210
Andalusite, 57% Al_2O_3, fob, North France, bulk, per tonne	€180
Kyanite, fob US, raw, per short ton	US$135-165
Kyanite, fob US, calcined, per short ton	US$238-268
Mulcoa 60, fob Georgia, per short ton	US$143
Mulcoa 70, fob Georgia, per short ton	US$220