The grate-kiln induration machine – history, advantages, and drawbacks, and outline for the future

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Synopsis

Iron ore pellets are a preferred feedstock for ironmaking. One method used for pelletizing is the grate-kiln process, first established in 1960. During the past decade, the establishment of new grate-kiln plants has increased rapidly, especially in China, and new constructors of pellet plants have started to operate in the market. It is well known that the grate-kiln method yields a superior and more consistent pellet quality compared with the straight-grate process. However, certain issues exist with the grate-kiln plant, which are discussed here, together with proposed practical solutions.

Keywords
grate-kiln, pelletizing, iron ore.

Introduction

In 2013, 1.600 Mt of steel were produced worldwide, approximately 77% of which was produced via ironmaking by the blast furnace (BF) and basic oxygen furnace (BOF) routes or by direct reduction (DR) and electric arc furnace (EAF), while direct melting of scrap by EAF accounted for approximately 23% (World Steel, 2014). Iron ore pellets are a preferred feedstock in ironmaking by both the BF and DR routes, and the demand for pellets is predicted to increase markedly until at least 2025 (Huerta *et al*., 2013). Of all the iron ore mined in 2012, 23% was converted into pellets (Ericsson *et al*., 2013).

Pelletizing is preferred because the chemical, physical, and metallurgical characteristics of pellets make them a more desirable feed for the ironmaking processes (Mbele, 2012). Moreover, because of their high strength and suitability for storage, pellets can be transported easily over long distances, with repeated transhipments if necessary. During pelletizing, iron ore is crushed and milled to a fine concentrate, mixed with additives and a binder, and balled into pellets prior to sintering and induration (hardening) in the furnace. In the past, the size and form of the pellets varied markedly. Figure 1a shows iron ore pellets produced in Persberg, Sweden, during the 1970s. Today, pellets are fabricated into a more uniform shape, with sizes typically 9–15 mm (Forsmo *et al*., 2008). Figure 1b shows iron ore pellets produced in Kiruna, Sweden, during the 2000s.

Magnetite is a preferred feed in pellet-making because of the exothermal energy released during oxidation. The most common method of pelletizing is the travelling-grate process (Huerta *et al*., 2013). This travelling grate uses a stationary bed of pellets, which are transported through the entire process, consisting of zones of drying, oxidation, sintering, and cooling (Potts, 1991). The travelling-grate process is often also used for pelletizing of haematite ores. The second most common pelletizing processes is the grate-kiln-cooler (GKC) or just grate-kiln process, which is often used for pelletizing magnetite ores. This process uses a shorter grate, with part of the oxidation (when using magnetite) and sintering taking place in the kiln, which is a rotating furnace that achieves more homogenous induration (Zhang *et al*., 2011). A third system used for pelletizing is the shaft furnace, the most traditional of the facilities. However, very few plants use this system today because of the limiting scale (Yamaguchi *et al*., 2010).

A pelletizing process consist of four consecutive steps (Yamaguchi *et al*., 2010):

- Reception of raw material
- Pre-treatment
- Balling
- Induration.

This paper deals with the fourth of these steps, the induration, as performed in the grate-kiln process. A short description and history is given, the benefits and drawbacks are discussed, typical problems are raised, and an outline for the future of the process is given.

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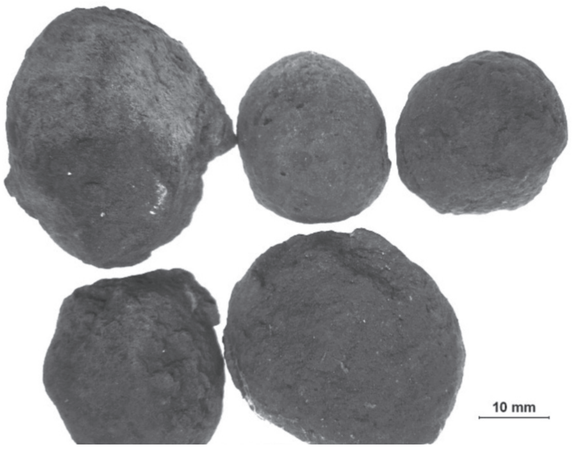
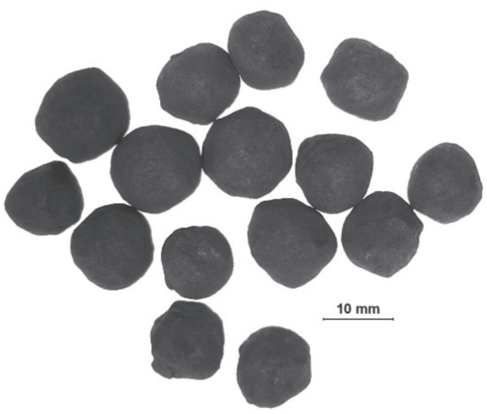


a)

Figure 1a—Indurated iron ore pellets, produced in Persberg, Sweden, during the 1970s



b)

Figure 1b—Indurated iron ore pellets, produced in Kiruna, Sweden, during the 2000s

The grate-kiln-cooler process

The main function of the grate (in the GKC process) is drying and pre-heating of the green pellets (Feng *et al.*, 2012). The grate is divided into three (Katsuyoshi *et al.*, 1984), four (Forsmo *et al.*, 2003), or five (Metso, 2014) different zones. These zones are normally: updraft drying (UDD), downdraft drying (DDD), temperature pre-heat (TPH), and pre-heat (PH). The typical length of a full grate furnace in the GKC is approximately 60 m, with a width of about 5 m.

A typical rotary kiln used in iron ore pellet production usually has a length between 30–50 m, and a diameter of 5–7.5 m (normally not more than 7.2 m, as difficulties with the refractory lining may occur at larger diameters), and is fired by coal or natural gas. The highest temperatures in the process are achieved in the kiln, up to about 1400°C. The refractory lining in the kiln normally comprises bricks based on Al_2O_3 and SiO_2. There are also kilns lined with castables.

A burner is located in the outlet of the kiln, where the pellets falls down in the cooler. In the case of pelletizing of haematite, burners are also located in the grate because of the lack of exothermal energy released by magnetite oxidation. The burner fuel is normally coal or gas, with fuel oil used as secondary fuel.

The annular cooler is functionally the same as the traveling grate, except for its annular configuration. The pellets fall from the kiln, down in the circular cooler carousel where they travel lying on the conveying elements (pallet grids). Ambient air is blown through the pallets and the temperature of the pellets drops from approximately 1200°C to 100°C during an orbit; the heated process gas is transported back to the grate for heat exchange. Cooled pellets discharge through the cooler's discharge hopper to a product load-out system. The typical outer diameter of an annular cooler is between 15 m and 30 m. There are also a few grate-kiln plants with straight coolers.

Figure 2 shows the outline of a modern GKC plant according to Metso's design (Metso, 2014).

Figure 3 shows the LKAB (Loussavaara Kiirunavaara Limited) kiln No. 4 in Kiruna, Sweden

History

Rotary kilns were originally developed in the late 19th century for Portland cement production, and the cement industry is still the largest user (Boateng, 2008). To improve energy efficiency in cement plants, a pre-heater in the form of a Lepol grate was used for the first time in 1927 (invented by Otto Lellep, marketed by Polysius), and it is from this system that the grate-kiln for iron ore pelletizing originated (Trescot *et al.*, 2000). Today, rotary kilns have been adopted for processing several different metal ores (besides iron ore), *e.g.* nickel (Tsuji and Tachino, 2012) and titanium (Folmo and Rierson, 1992), as well as for direct reduction of iron ore (Tsweleng, 2013).

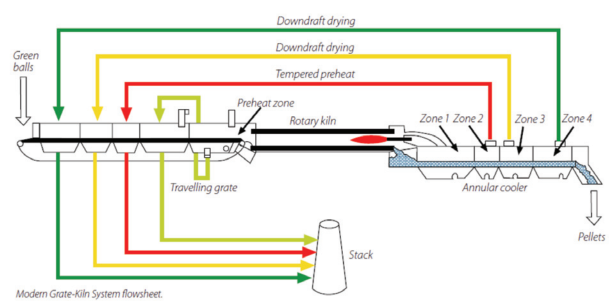


Figure 2—Outline of a grate-kiln plant

Figure 3—Kiln at the LKAB plant No. 4 in Kiruna, Sweden (view looking upstream)

Pelletizing of iron ore is a method of Swedish origin, patented in 1912 by A.G. Andersson (Yamaguchi *et al*., 2010). The process was developed in the USA in the 1940s, and the first commercial plant started operation in Babbitt, Minnesota in 1952 (Chernyshev, 1962). The first iron ore pellet plant of the grate-kiln type was established at Humboldt Mine, Michigan in 1960 (Sgouris and Oja, 2008). Allis-Chalmers (a predecessor company to Metso) have since built around 50 such plants. However, very few of the older plants built before 1975 are still in use. Another constructor of grate-kiln plants is Kobe Steel, who built their first plant in 1966 at Kobe Works, Nadahama, and have since then constructed more than ten plants, most of which are still in use (Yamaguchi *et al*., 2010).

Since 2000, the grate-kiln process developed by the Shougang Group has been rapidly adopted in China (Zhang and Yu, 2009). The establishment of new grate-kiln plants in China has been very prominent in the last decade (Zhang *et al*., 2011), with the rise of new fabricators such as Jiangsu Hongda and Citic.

Figure 4 shows the growth in grate-kiln plants for iron ore pelletizing since 1960, and their geographical distribution. An exponential increase can be seen since 2000, driven mainly by installations in China. Moreover, very few plants were built anywhere in the world between 1985 and 2000.

The grate-kiln process: benefits and drawbacks

The grate-kiln vs the travelling grate

The GKC process possesses both advantages and drawbacks compared with the travelling-grate process. A general comparison between the two (Sgouris and Oja, 2008; Zhang *et al*., 2011; Huerta *et al*., 2013) shows that:

- The grate-kiln yields a superior and more consistent pellet quality, and consumes less electrical energy. Since the speed of the grate, kiln, and cooler can be controlled independently, it provides process flexibility, allowing adjustment to changes in concentrate feed. The grate-kiln is more flexible regarding choice of fuel: cheaper fuels can be used. Moreover, less expensive high-temperature-resistant steel alloys are used in construction. Significant drawbacks are the low suitability for pelletizing of pure haematite feedstock, higher generation of fines in the process, and lower energy efficiency
- The travelling grate has a lower fuel consumption, as there is less radiated heat loss and a better heat exchange between the solids and the air because of the deeper bed of pellets. The maintenance and refractory costs are lower, and the cold start-up time is shorter. It is suitable for pelletizing of both magnetite and haematite burden (and magnetite-haematite mixtures), and fewer fines are formed in the final product. Significant drawbacks are the higher electricity consumption, and coal (or other solid fuels) cannot be used as primary fuel.

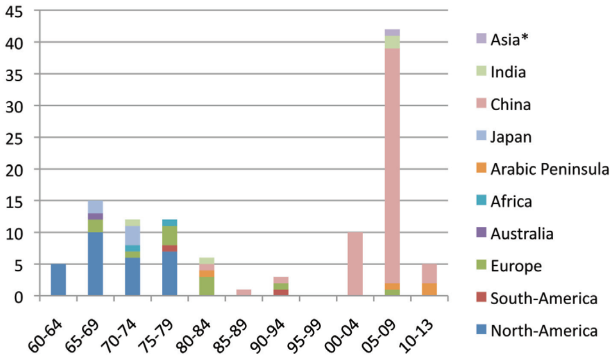


Figure 4—Grate-kiln plants for iron ore pelletizing built since 1960, and their geographical distribution. Asia* excludes India, China, Japan, and the Arabian Peninsula

Typical problem issues with the grate-kiln machine

There are some typical problem issues and symptoms that can arise with the grate-kiln, summarized here (based on the literature and drift-logs from LKAB).

Deposition of material on the refractory lining

Coal always contains inclusions of mineral matter that remain as fly-ash after combustion (Reid, 1984). Disintegrated pellets can, together with fly-ash from the coal burned to heat the kiln, form accretions on the lining, sometimes as ring-forms in the kiln (Jiang *et al*., 2009; Xu *et al*., 2009). This phenomenon is also common in lime kilns (Potgieter and Wirth, 1996) and cement kilns (Recio Dominguez *et al*., 2010). This material can also be deposited as stalagmite structures in the kiln (Figure 5) or as accretions in the transfer chute.

Air flows tend to be turbulent, especially in the transfer chute (Burström *et al*., 2010), as this is the geometrical bottleneck of the induration machine. A thin layer of deposit on the surface can act as protection for the lining, but when these deposits increase in thickness they contribute to mechanical strain. A fallout of such deposit causes a rapid increase in the temperature of the lining at the new hot face, which may lead to thermal shock and spalling (Stjernberg *et al*., 2012). The Allis-Chalmers Corporation investigated fuel

Figure 5—Accreted chunks in a rotary kiln (Svappavaara, Sweden) during a maintenance stop in 2013

combustion in grate-kiln plants in the 1970s (Cnare, 1977). It was observed that the key factor for deposition in the kiln was the presence of dust, and that deposition of fly ash on the lining could be minimized through correct selection of coal and optimization of overall process control. Tests with combustion of natural gas showed that in addition to the absence of fly ash deposits, another benefit was that the lining temperature could be maintained more than 50ºC lower, because the radiant heat of natural gas combustion is lower than that of coal or oil.

Kobe Steel noted in 1981 that when the burner fuel was changed from heavy oil to coal (because of the sharp increase in the price of fuel), adhesion of deposits on the lining was enhanced (Uenaka *et al*., 1983). Adhesion tests were carried out on a water-cooled specimen inserted through a hole situated at the end of the pre-heat chamber, just before the starting point of the process. Uenaka *et al*. investigated the amount of ash adhering to the detection bar, the density of the deposit, coal properties such as fine particle size, ash content, the proportion of pulverized ore in the pre-heated pellets, and operating conditions such as kiln off-gas temperature. It was observed that even if the same type of coal was fired, the amount of deposit varied with operating conditions. Similar tests with water-cooled probes were carried out at LKAB in Kiruna, Sweden (Jonsson *et al*., 2013; Stjernberg *et al*., 2013). It was found that inertial impaction was the dominant deposition mechanism, and that the flue-gas flow direction determines the texture and formation of the deposits. The deposits were mainly haematite particles embedded in a bonding phase, comprising mainly calcium-aluminium-iron silicate. In addition to haematite and the bonding phase, the minerals anorthite, mullite, cristobalite, quartz, forsterite, and apatite were also observed in the deposits after cooling to room temperature.

Lining problems in rotary kilns in Wuhan, China have been reported by Xu *et al*. (2009). These kilns also had problems with rapid accumulation of deposits on the lining that were hard to remove. One of the main reasons for this was the use of burner coal with a high fly-ash content and low ash melting temperature. Another important factor was the compressional strength of the iron ore pellets, which was observed to depend on the qualities of the ore and bentonite, mixing method, and moisture content during mixing. Pressure and air flow were observed to be important parameters in one of the plants, since these dictate where the fly ash falls, and also affect the extent of pellet disintegration, contributing to deposits on the lining.

At some production sites an additive based on magnesia (MgO) is added to the coal, mainly to increase the melting temperature of the slag phase in the deposits, in order to decrease the adhesiveness of particles on the lining. Another method is to add silicon carbide (SiC) or some other carbon-bonded phase to the lining, in order to decrease the wettability of the slag.

Refractory failures

The refractory lining in the grate and in the cooler seldom causes failures that lead to urgent shutdowns, as are caused by kiln failures. Upon heating, the lining in a rotary kiln expands with temperature in proportion to the coefficient of thermal expansion (CTE) of the refractory (Shubin, 2001a). This aids in securing the bricks, but stresses from the liners in the ring brickwork arise in the metal casing (Shubin, 2001b). Thermal shock induced by temperature gradients at starts and stops in the operation, together with mechanical strain, may cause urgent stops in production because of brick spallation or fallouts of bricks. Moreover, an even larger thermal stress acts on the lining at starts and stops during production, giving rise to several stress states in the form of longitudinal and lateral bending, brickwork twisting, vibration, and torsion (Shubin, 2001c, 2001d). The cold crushing strength of refractory bricks is often given in data-sheets However, it is more important that the material has a low Young's modulus at high temperatures, such that the lining becomes more flexible during operation. Otherwise the bricks suffer thermomechanical strains far above the cold or hot crushing strength (Saxena, 2009).

Even during steady-state conditions, the lining is exposed to temperature oscillations as it rotates (Shubin, 2001a). In rotary kilns used for iron ore pellet production the lining can be assumed to be exposed to different temperatures during each revolution of the kiln. When the pellet bed covers the lining, it is exposed to less radiation from the flame, but is exposed to heat from the energy liberated from the oxidation of the pellets (when using magnetite). If the kiln rotates at approximately 2 r/min (which is common for rotary kilns in this application) it revolves 3000 times a day, with a temperature oscillation during each revolution. The temperature oscillation range varies from kiln to kiln, depending on operating conditions, but the temperature variation can be as high as 100ºC in the lining, down to a depth of 30 to 40 mm beneath the hot face (Shubin, 2001a). This cycle gives rise to thermal fatigue. Kingery (1955) showed that thermal expansion hysteresis is associated with microcracks in ceramic materials.

A study carried out in a grate-kiln plant in Kiruna, Sweden (Stjernberg *et al*., 2012), showed that migration of potassium through the hot face of the lining caused the formation of feldspathoid minerals, leading to spallation. Moreover, haematite was found to migrate into the lining. This phenomenon was also found in rotary kilns for pellet production in China (Zhang *et al*., 2009). Although these are relatively slow phenomena, they contribute to the overall degradation of the lining. Zhu *et al*. (2003) reported lining problems in a rotary kiln in Qian'an, China. Urgent production stops caused by fallouts of bricks occurred only a few months apart. Different types of brickwork and lining material (*e.g.* chamotte, high alumina, and phosphate-bonded alumina) were tested in the kiln to avoid fallouts and rapid deterioration of the lining. In 2000 a mullite brick of an increased size was tested, which was still in service two years later.

Problems with fuel supply

Rapid changes in the fuel supply cause rapid thermal changes that affect the pellet quality, but more critically, cause thermal shocks in the refractory lining. Problems with coal quality at different production sites arise occasionally, and constitute a threat for uniform heat supply. This can arise from, for example, wet coal. Problems with sensors or automation may also disturb the fuel supply. Grate-kiln plants using coal as their primary fuel switch to a secondary fuel (oil or gas) when problems with the coal supply arise. Even if this transfer appears perfunctory, the temperature profile in the plant changes markedly. An even worse scenario is when the secondary fuel does not initiate. If the electricity supply to the production site is disrupted for any reason, it usually some time before the backup power comes into operation, causing unwanted temperature variations. The alignment of the burner is also important to avoid overheating of the lining. Some of these incidents can lead to serious failures of the lining.

Wear of grate plates

As the flue gas passes vertically through the pellet bed and the grate plates, it carries particles of iron oxide that have an abrasive effect on the grate plates, leading to deterioration of the plates. Figure 6a shows a plate as produced, and Figure 6b a worn-out plate. When the ribs wear down (as in Figure 6b), pellets may become stuck in the intermediate columns, affecting the air flow and the pellet quality, or pellets may even fall through the columns. The plates are usually made from a high nickel-chromium steel alloy (austenitic stainless steel), due to the requirement for refractoriness and resistance to wear and corrosion (Nilsson *et al*., 2013). Process parameters in the grate, such as the time of drying and pre-heating, air quantity, blast temperature, and blast velocity, affect the pellet temperature and strength. However, they may also cause burnout of the grate plate, shaft bending, chain breaking, and deviation of grate motion (Feng *et al*., 2012).

An investigation of a grate-link plate that had served in a grate-kiln plant for 8 months (Nilsson *et al*., 2013) showed that alkaline vapours from warmer parts of the indurator condense on the plates, forming chlorides and sulphates, which promote hot corrosion and intergranular attack (IGA) of the material along the grain boundaries.

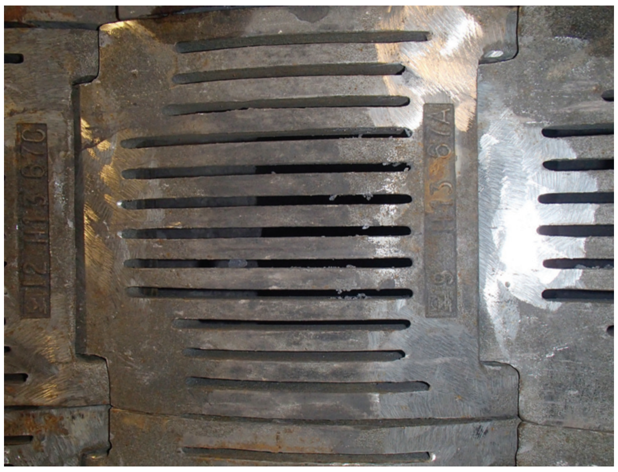


Figure 6a—Grate plate, as produced

Figure 6b—Grate plate, worn-out

Riding ring fatigue

The riding rings (tyres) of rotary kilns are subjected to static and dynamic stresses caused by mechanical forces and temperature gradients, of which only the stresses caused by mechanical forces can be influenced by the dimensions of the ring. The initiation of a crack can be caused by either the static strength or the fatigue strength being exceeded. Hertzian pressures between the ring and the rollers reach their maximum beneath the surface, and consequently cracks are usually not visible until they reach an advanced stage. Riding ring cracks are in general not a consequence of poor dimensioning, but of unfavourable running conditions and/or material defects (Bowen and Saxer, 1985).

Unfavourable running conditions are:

- High temperature gradients
- Inadequate guidance of the riding ring (wobbling)
- Insufficient contact area between riding ring and rollers
- Badly aligned kiln axis
- Badly adjusted rollers.

Structural material defects are:

- Cavities and/or nonmetallic inclusions
- Repair welding spots.

Riding cracks do not occur as frequently as some of other issues stated here. However, failures of the riding ring that necessitate replacement and the associated actions are time-consuming. A replacement of the riding ring involves cutting of the kiln on both sides of the ring, a heavy lift, and repair welding. It is therefore important that the riding ring satisfies the requirements of high rigidity or stiffness, high surface durability, and high static and fatigue strength, to achieve the longest possible lifetime (Bowen and Saxer, 1985). Figures 7a and 7b are from a riding ring replacement at LKAB's grate-kiln plant in Svappavaara, Sweden, in 2009.

Deformation of steel casing

The casing (shell) of the kiln deforms elastically owing to the pressure exerted by gravitational forces through the tyre towards the support rollers. This dynamic action can be detrimental to the refractory lining, especially if the kiln is rotated in a cooled state. However, there are other factors that create permanent deformation of the casing. At locations in the kiln where bricks have fallen out, and the kiln has not been cooled down quickly enough, permanent deformations may occur that are difficult to rectify. It is therefore important to monitor the casing with *e.g.* a kiln scanner, in order to

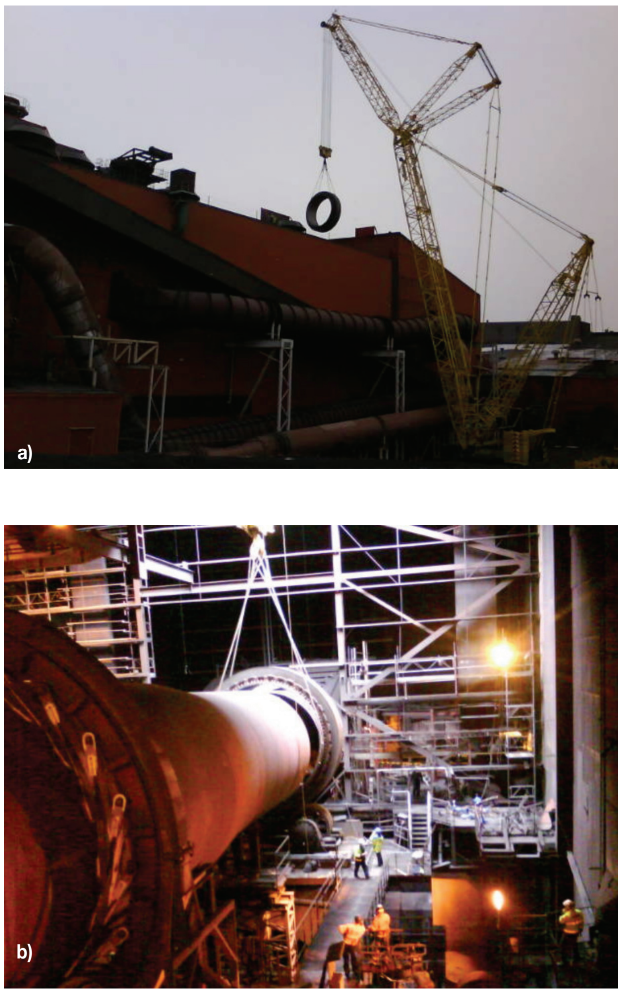


Figure 7—(a) Crane lifting a riding ring in Svappavarra, and (b) installation in the gap of the casing

identify heat abnormalities as soon as they occur (Zakharenko and Nikonenko, 2002). Permanent deformation can also result when the temperature is increased too rapidly and the riding ring does not expand as fast as the casing, leading to plastic deformation (Chapman and Yann, 1989).

Wear of mechanical parts

Gearboxes, sliding and rolling bearings, kiln girth gears, pinions *etc.* require continuous maintenance. In addition to the slow operating speeds of many of these parts, there are thermal, alignment, and cleanliness issues that need to be considered. Safe operation relies on a hydrodynamic oil film to avoid metal-to-metal contact (Singhal, 2008). Use of inadequate lubricants may decrease the service life of these mechanical parts markedly. Hankes (2013) reviewed the selection and application of lubricants for rotary kiln girth gears and pinions. He stressed the importance of not only using a correct lubricant, but also of using it correctly. Monitoring is the key to avoiding catastrophic tooth damage.

Lovas (2003) reported the performance of two identical cement kilns: one that ran without problems; the other that was plagued with drive-related failures. On the problem kiln, the pinion had to be replaced three times and the gear realigned three times over a five-year period. During this time the identical gear and pinions on the comparison kiln remained as good as new. Analysis of the problem showed that the uphill face of the thrust tyres comprised several noticeable discontinuities. When the tyre was cast there were probably voids in the cast, which were repair-welded and machined. The welded portions of the tyre were much harder than the surrounding areas, and high spots were developed at these locations. As the kiln revolved, these high spots on the side of the tyre created a sharp impact load towards the discharge end. This pressure caused pitting and wear of the pinion and gear. The problem was resolved by resurfacing the thrust tyre and eliminating the vertical load between the thrust rollers and tyres.

Cleveland Cliffs reported (Rosten, 1980) that they improved the lifetime of wear parts by using a nitriding hard surfacing process on chrome-type spare parts, and carburization of the surface of mild steels, used as fan wear liner applications.

Process fans

The fans that are used to transport flue gas through the system sometimes fail due to power failures, or when the blades become eroded by particles carried by the flue gas, if bearings are worn out, or due to problems with the frequency modulation. Failures of the fans can lead to the pellets not being sufficiently dried before they enter the warmer parts of the furnace, where the sintering usually takes part. Erosion of the blades of the fan can be prevented by installing electrostatic precipitators prior to the fan in the flue gas circuit.

Flue gas scrubbing

Flue gas scrubbing using *e.g.* electrostatic precipitators and NO_X and SO_X removers occasionally cause failures in pellet plants. There is the possibility to bypass such equipment; however, environmental regulations in many countries do not permit this. Moreover, more stringent regulations motivate companies to evaluate alternatives to current combustion technologies (Fredriksson *et al.* 2011).

Alternative methods

Several improvements have been made at different production sites, and other methods can be adopted from related processes.

Cooling system

In 2001 the Minntac division of US Steel introduced a ported kiln in their plant (Trescot *et al.*, 2004). It was a well-proven design that had been in use for more than ten years at the Tinfos direct reduction kiln for ilmenite in Norway. However, this was the first ported grate-kiln plant for iron ore pelletizing. This system injects air under the bed of pellets in the rotary kiln through slots in the joints between the specially designed refractory bricks. This design results in more rapid oxidation of the pellets. The company noticed several benefits. As the magnetite oxidizes more rapidly, a lower kiln temperature can be used. With more energy liberated in the kiln, the heat load in the annular cooler is reduced, and therefore a higher tonnage can be produced. An improved pellet quality was also observed.

Monolithic lining in the kiln

In the Tinfos direct reduction kiln for ilmenite in Norway, the lining consists of a monolithic castable applied by shotcreting (Folmo and Rierson, 1992). The air slots present for cooling complicate the installation of bricks, and shotcreting is a quick method. This could be the method of choice for the linings of rotary kilns for iron ore pelletizing in the future. Shotcreting is a fast installation method, and the lining does not have to be replaced as often as a brick lining. The drawback is that removal of the lining for maintenance is more complex.

Development of burners

Many burners used in the grate-kiln plants today are basically a lined steel pipe through which milled coal powder is blown. The combustion equipment used for the heat supply in rotary kilns for cement production is often far more complex than the burners used in the grate-kiln. The use of multi-channel burners for different fuels and different air channels allows adjustment of the flame shape during operation and ensures a stable flame front (Vaccaro, 2006).

Outlook for the grate-kiln process

Most of the grate-kiln plants for iron ore pelletizing built over the last 30 years have been built in China (around 40 plants over the last 10 years). China will likely continue to build grate-kiln plants; however, one significant characteristic of the Chinese growth cycle is the relatively direct influence of governmental policies (Becker, 2013).

The previous trend was to build larger plants (5–6 Mt/a), while most plants built in China today have a capacity below 3 Mt/a. Several plants with lower capacity are less dependent on the economic situation and access to raw material, compared with one large plant, when plants are used on an on-and-off basis. However, Metso has designed a plant with 7 Mt/a capacity and Kobelco an 8 Mt/a plant, and many existing plants are continuously being upgraded to cater for the increasing demand for iron ore pellets on the market.

Oxidation of magnetite in iron ore pellets occurs fastest between 1100°C and 1200°C. At higher temperatures the oxidation rate decreases as a result of increasing dissociation pressure and severe sintering in both the oxidized haematite shell (which becomes denser) and the magnetite core (Forsmo, 2008). As fully oxidized pellets already in the grate are desired when using magnetite (Niiniskorpi, 2002), a grate of increased length and increased dwell time in a zone where the temperature is optimal for oxidation, this, in combination with oxygen injection to further improve the oxidation rate, may be an alternative in the future. This could be combined with a shorter kiln in a machine comparable with a straight-grate plant completed with a short kiln, as the rotary kiln is the more sensitive part in the grate-kiln construction.

Coal will continue to be the major fossil energy source in China, at least in the coming decade (Zhou *et al*., 2013). However, with increasing energy prices, limited coal reserves, and environmental issues, biofuels (*e.g.* biogas and wood pellets) will in coming years be burned in pellet plants. With this innovation, new techniques may have to be developed, and plant outlines may have to change. A wood-based fuel has a lower energy density (heating value of approx. 20 MJ/kg compared with approx. 30 MJ/kg for coal), and therefore the feeding rate of fuel has to increase by some 50%. Moreover, wood-based fuels have in general higher friction coefficients (compared with coal) during transportation through pipes, which may cause bridging and hold-ups in the fuel feeding system. Co-combustion of blended coal (approx. 90%) and a wood-based fuel (approx. 10%) is realistic already today. Possibly, it might be beneficial to subject a wood-based fuel to pyrolysis prior to combustion. The advantages of wood-based fuels compared with coal are lower CO_2 emissions and a lower ash content (Nordgren, 2013). The use of waste material as an energy supply is required in cement production to make it economically possible, and burners are developed for this (Vaccaro, 2006). However, iron ore pellet makers can possibly be more selective in their choice of fuels, but will in the future need to use more alternative fuels.

The iron ore price has decreased rapidly over the last three years (2011–2014). However, the demand for iron is unlikely to decrease in the medium term, and predictions are that around 80 new pellet plants will need to be built in the coming decade (Huerta *et al*., 2013). Many are likely to be of the grate-kiln type.

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