

History and Evolution of Iron Ore Pelletization and Technological Developments

Malla Ganesh

Pellet Plant – Projects & Operations Head, Devki Steel Ltd., Kenya

Abstract

Iron ore pelletization has evolved significantly over more than a century, from early experimental agglomeration methods to a highly developed industrial process for producing high-quality iron ore pellets for blast furnace and direct reduction (DR) ironmaking. The development of pelletization has been closely associated with the increasing utilization of fine iron ore concentrates generated during mining and beneficiation, together with the need for consistent burden materials with controlled chemical, physical, and metallurgical properties. This review presents the historical development and technological evolution of iron ore pelletization, beginning with early pelletizing concepts and progressing through the establishment of commercial pelletizing processes and modern industrial technologies. The review examines the development of pelletizing and induration technologies and their evolution from experimental methods to established industrial processes. Attention is given to the development of major induration technologies, including shaft furnaces, straight-grate systems, and grate-kiln systems, and their influence on pellet quality. The evolution of pellet quality requirements for blast furnace and direct reduction applications is also discussed, including strength, reducibility, reduction degradation, swelling, porosity, and chemical composition.

Keywords: Iron ore pelletization, iron ore agglomeration, pelletizing technology, pellet induration, shaft furnace, straight-grate technology, grate-kiln technology, pellet quality, blast furnace, direct reduction.

1. Introduction

Iron is one of the most important metals in human history and has played a fundamental role in the development of human civilization. Although iron is abundant in the Earth's crust, metallic iron rarely occurs naturally because of its strong affinity for oxygen. It is therefore predominantly found in the form of iron-bearing minerals such as oxides, hydroxides, carbonates, and silicates [6]. The development of iron extraction from these minerals marked an important technological milestone, followed by continuous improvements in furnace design, fuel utilization, air supply, ore preparation, and metalworking practices. As iron production increased, the utilization of different grades and types of iron ore became increasingly important. The exploitation of lower-grade and finely disseminated iron ores requires crushing, grinding, and beneficiation to liberate the iron-bearing minerals from associated gangue. These processes generate large quantities of fine iron ore concentrates that cannot be directly charged into conventional blast furnaces because their fine particle size adversely affects burden permeability and gas flow [2,10]. The need to utilize these fine concentrates led to the development and progressive adoption of iron ore agglomeration technologies, particularly sintering and pelletization.

Iron ore pelletization developed as a process for converting fine iron ore concentrates into relatively uniform spherical agglomerates suitable for ironmaking. The fundamental concept of modern pelletization can be traced to the early twentieth century, including A. G. Andersson's 1912 patent for forming moist fine ore into balls followed by drying and firing [1,2]. Subsequent research and industrial development transformed this early concept into commercially viable pelletizing processes. The development of pelletization was particularly important for the utilization of fine concentrates generated during the beneficiation of low-grade iron ores.

Over the subsequent decades, pelletization underwent significant technological development involving raw-material preparation, grinding and beneficiation, concentrate filtration, binder addition, balling, drying, preheating, induration, cooling, and process control. Major induration technologies, including shaft furnaces, straight-grate systems, and grate-kiln systems [1–5], were developed and progressively improved to achieve higher productivity, better pellet quality, and improved energy efficiency. At the same time, developments in pellet binders and process control contributed to improvements in green-pellet and fired-pellet properties.

The requirements for iron ore pellets have also evolved with changes in ironmaking technology. Pellets became an important burden material for blast furnaces, while the growth of direct reduction (DR) technology created additional requirements for high-grade, low-gangue pellets with appropriate mechanical and metallurgical properties. Parameters such as green-pellet strength, cold crushing strength, reducibility, reduction degradation, swelling, porosity, and chemical composition have consequently become important considerations in pellet production [2,13–16]. More recently, the development of low-carbon and hydrogen-based ironmaking has increased the importance of producing high-quality pellets while reducing the energy consumption and environmental impact of pelletization.

This review presents an integrated examination of the history and evolution of iron ore pelletization, from its early development to modern industrial practice. Particular emphasis is placed on technological developments, process innovations, pellet-quality requirements, major pelletizing and induration technologies, and the changing requirements of blast furnace and direct reduction ironmaking. The review also examines developments in process control, energy efficiency, heat recovery, and environmental performance that have contributed to the evolution of modern pelletizing technology.

2. Historical Development of Iron Ore Pelletization

2.1. Early Use of Iron and Development of Iron Smelting

Iron has played an important role in human technological development for thousands of years. The earliest iron objects were not necessarily produced by smelting iron ore. Naturally occurring metallic iron, particularly iron of meteoritic origin, was available to ancient societies and could be shaped without the need for an extraction process. Archaeological investigations have confirmed meteoritic iron in several early artifacts, including iron beads from ancient Egypt [7,8]. Because meteoritic and terrestrial iron can have different compositions, particularly with respect to nickel, scientific analysis is important when determining the origin of early iron artifacts.

The development of extractive iron metallurgy, in which metallic iron was obtained from iron-bearing minerals, represented a major technological transition. Current archaeological evidence indicates that small-scale iron smelting was established in parts of Anatolia during the early second millennium BC [6], although the precise origins and subsequent development of iron metallurgy involved several regions and

remain subjects of continuing research. The wider adoption of iron occurred gradually and at different times in different societies rather than as a single technological event.

Early iron smelting commonly used iron oxide minerals together with charcoal as both a fuel and reducing agent. Air was supplied through natural draft or manually operated blowing systems to maintain the required furnace temperature. In bloomery-type furnaces, reduction occurred below the melting temperature of iron, producing a porous mass of metallic iron known as a bloom [6], together with slag and other furnace products. The bloom subsequently required consolidation and repeated forging to remove entrapped slag and produce usable wrought iron.

Over time, improvements in furnace construction, air supply, fuel utilization, ore preparation, and forging practices increased the efficiency and scale of iron production. These developments occurred independently or through technological exchange in different regions, leading to considerable diversity in early ironmaking practices [6]. The transition from small bloomery furnaces to larger and more efficient furnaces eventually enabled higher production rates and contributed to the development of later ironmaking technologies.

The evolution of early ironmaking established the fundamental relationship between iron ore characteristics, ore preparation, fuel, furnace conditions, and product quality that continued to influence subsequent developments in iron production [6]. As ironmaking expanded and increasingly diverse iron ore resources were exploited, the preparation and utilization of iron-bearing materials became progressively more important. This eventually led to the development of technologies for preparing and agglomerating fine iron-bearing materials, forming the technological background to the later development of iron ore sintering and pelletization.

2.2. Development of Iron Ore Agglomeration

During the extraction, crushing, and processing of iron ore, significant quantities of fine material are generated. Although these fines may contain substantial amounts of iron, their small particle size makes them unsuitable for direct charging into conventional blast furnaces, where excessive fines can adversely affect burden permeability and gas flow [1,2,10]. Historically, significant quantities of iron-rich fines were therefore stockpiled, discarded, or otherwise underutilized, representing a loss of potentially valuable iron resources.

The increasing generation of iron ore fines created a need for technologies capable of converting these fine particles into larger, stronger, and more permeable agglomerates suitable for ironmaking. Agglomeration consequently became an important development in iron ore preparation. Among the principal agglomeration routes, sintering emerged as one of the important methods for utilizing iron ore fines. In the sintering process, appropriately prepared iron ore fines are mixed with solid fuel, fluxes, and other materials and subjected to controlled thermal treatment to produce a porous agglomerate suitable for blast furnace charging [10].

The development and industrial adoption of sintering represented a major advancement in the utilization of iron ore fines. However, the continued exploitation of lower-grade and more finely disseminated iron ore resources created new challenges. Increasingly intensive crushing, grinding, and beneficiation were required to liberate iron-bearing minerals from associated gangue, resulting in concentrates with very fine particle sizes. Naturally fine materials such as blue dust also presented difficulties for direct utilization because of their fine granulometry and handling characteristics. Similarly, resources such as Banded Hematite Quartzite (BHQ) require extensive beneficiation to obtain iron-rich concentrates. These

developments increased the requirement for an agglomeration process capable of effectively treating very fine concentrates [1,2].

Although sintering could utilize a significant proportion of iron ore fines, the characteristics of very fine concentrates created limitations for their efficient incorporation into conventional sintering operations. In addition, sinter production is generally integrated with blast-furnace operations because sinter is produced as part of an integrated burden-preparation system and is not well suited to extensive long-distance transportation. This requirement for integrated sinter plants can limit its application where iron ore resources and ironmaking facilities are geographically separated or where the installation of a dedicated sinter plant is not economically or technically practical. These limitations encouraged the development and adoption of alternative agglomeration technologies capable of treating finely ground concentrates. Iron ore pelletization emerged as an important complementary agglomeration process, in which finely ground iron ore concentrates are formed into approximately spherical green pellets and subsequently hardened through thermal induration [1,2].

2.3. Early Development of Pelletization

The limitations associated with the utilization of very fine iron ore concentrates in conventional sintering encouraged the development of an alternative agglomeration method in which the fine concentrate could first be formed into individual spherical particles and subsequently hardened. This approach led to the early development of iron ore pelletization. Unlike sintering, where fine particles are agglomerated within a continuous bed through a high-temperature process, pelletization involves the formation of individual green pellets from finely ground iron ore concentrate, followed by drying and hardening through suitable induration or bonding mechanisms [1,2].

The early development of pelletization took place principally in Sweden and Germany [1,2], where finely ground magnetite concentrates created a need for improved methods of agglomeration. Early investigations demonstrated that fine concentrates could be mixed with water and suitable binders and mechanically formed into approximately spherical balls. The resulting green pellets could then be hardened to obtain sufficient mechanical strength for handling and subsequent use in ironmaking.

An important feature of these early investigations was the recognition that water and binders played a critical role in pellet formation. Moisture enabled the fine particles to adhere during ball formation, while binders could improve the strength and stability of the green and dried pellets. Early work considered several types of binding materials, including organic and inorganic substances, demonstrating that binder selection was already recognized as an important factor in the development of pelletizing technology [1,2,9,11].

The early pelletizing experiments also demonstrated the potential metallurgical advantages of producing spherical agglomerates from fine concentrates. In particular, early investigations reported favorable reduction behavior compared with some conventional agglomerated products produced from the same raw materials. These observations helped establish the concept that pelletization could produce not only a physically manageable material but also an ironmaking feed with useful metallurgical characteristics [1,2]. Although the early experiments established the fundamental principles of pellet formation and induration, the technology initially remained at an experimental stage and did not immediately achieve widespread industrial adoption. Further development was required in concentrate preparation, ball formation, binder selection, drying, induration, and process control before pelletization could become a reliable large-scale industrial process [1,2]. Nevertheless, the early work in Sweden and Germany established the technological foundation upon which subsequent developments in iron ore pelletization were built.

The early development of pelletization therefore represented an important transition in iron ore agglomeration: fine concentrates that were difficult to utilize efficiently through conventional sintering could be separately formed into green pellets and subsequently hardened to produce a stable ironmaking burden material. The historical development of one of the earliest foundational patents for iron ore pelletization and its contribution to the evolution of the process are discussed in the following section.

2.4. Andersson's 1912 Pelletization Patent

The development of iron ore pelletization reached an important milestone in 1912, when the Swedish inventor A. G. Andersson was granted Swedish Patent No. 35,124 [1,2] for a process for agglomerating fine iron ore. The patent is widely recognized in the technical literature as one of the earliest foundational patents for modern iron ore pelletization. It emerged from the need to find an alternative method for agglomerating very fine iron ore concentrates that were difficult to utilize efficiently through conventional sintering.

The basic principle described in the early pelletizing concept was to mix finely divided iron ore with water and form the moist material into approximately spherical balls. The resulting green pellets could subsequently be hardened either through the action of suitable binders or through thermal treatment.

This established the fundamental sequence that remains central to modern pellet production:

Fine concentrate preparation → moisture addition and ball formation → green-pellet strengthening → thermal induration [1,2].

The significance of Andersson's development was not simply the formation of spherical particles. It introduced a fundamentally different approach to fine-ore agglomeration in which the concentrate was individually formed into pellets before hardening, rather than being agglomerated as a continuous bed as in sintering [1,2]. This provided a potential route for utilizing very fine concentrates while producing a more uniform feed material for subsequent ironmaking operations.

However, the 1912 invention did not immediately result in widespread commercial adoption. Further development was required to establish reliable methods for controlling concentrate preparation, moisture, pellet formation, binder addition, drying, and thermal hardening. The early patent therefore represented an important technological starting point, rather than the completion of an industrial pelletizing process. Subsequent developments in Sweden, Germany, and later the United States transformed the basic concept into a practical large-scale technology [1–3].

The importance of the 1912 patent can therefore be understood in the broader evolution of iron ore agglomeration. Sintering provided an effective route for utilizing many types of iron ore fines, while Andersson's pelletizing concept provided a separate route for converting finely ground concentrates into individual green pellets that could subsequently be hardened. This distinction became increasingly important as beneficiation produced larger quantities of very fine concentrates from lower-grade and finely disseminated iron ore resources [1,2].

The 1912 Andersson patent thus established one of the fundamental technological principles of iron ore pelletization. The subsequent challenge was to demonstrate the technical and economic feasibility of the process at progressively larger scales. The following developments in experimental work, particularly those associated with fine-grained iron ores and the taconite resources of the United States, played a major role in transforming the early concept into an industrial process.

2.5. Early Industrial Development of Pelletization

The transition of iron ore pelletization from an experimental concept to an industrial technology was strongly influenced by the development of low-grade taconite ores in the United States. By the early

twentieth century, the high-grade direct-shipping iron ores of the Lake Superior region had been extensively exploited, increasing interest in the large quantities of lower-grade taconite resources. These ores contained iron minerals finely disseminated within a silicate-rich matrix and therefore required extensive crushing, grinding, and concentration. The resulting fine concentrates created a strong need for an effective agglomeration method [1–3].

A major centre of research was the Mines Experiment Station of the University of Minnesota, where E. W. Davis and his co-workers investigated the beneficiation of low-grade taconites of the Mesabi Range [1–3]. Their work combined crushing and grinding, magnetic concentration, and agglomeration of the resulting fine magnetite concentrates. This demonstrated that low-grade iron ore could be converted into a suitable ironmaking feed through beneficiation followed by pelletization.

Development also focused on establishing suitable methods for green-pellet formation and thermal hardening. During the 1940s, experimental work investigated pellet formation and induration, including shaft-furnace firing. In 1943, E. W. Davis and his co-workers demonstrated the firing of experimental pellets in a shaft furnace [2], providing an important step toward the practical production of indurated iron ore pellets.

The development of taconite processing demonstrated the complete technological sequence:

Low-grade ore → crushing and grinding → concentration → fine concentrate → pelletizing → induration → ironmaking feed [1–3]

The successful integration of these operations established the technical feasibility of pelletization on an industrial scale and created the basis for subsequent commercial development in the United States and other iron-producing regions.

2.6. Development of Commercial Pelletizing Plants

Following the successful demonstration of taconite beneficiation and pellet production, the technology progressed toward commercial-scale pelletizing plants. Pilot and preliminary plants established during the late 1940s provided important experience in handling fine concentrates, forming green pellets, and producing pellets with sufficient strength for transportation and ironmaking [1–3].

A significant development occurred at Ashland, Kentucky, where Reserve Mining Company's pelletizing development began in a pilot plant in 1949. The work, involving Armco Steel Corporation, Cleveland-Cliffs Iron Mining Company and Republic Steel Corporation, provided important experience in the beneficiation and pelletization of fine concentrates.

Commercial development accelerated in the early 1950s with the expansion of taconite processing in Minnesota. Reserve Mining developed the Peter Mitchell taconite operation and associated facilities at Silver Bay, where a large commercial pelletizing plant began operation in 1955 [3]. The plant demonstrated the ability to produce millions of tonnes of iron ore pellets annually and contributed significantly to the establishment of pelletization as an industrial method of preparing ironmaking burden. As production requirements increased, different induration technologies were developed and commercialized. Early plants used shaft furnaces, while travelling-grate and grate-kiln systems subsequently provided alternative arrangements for continuous large-scale pellet induration [3–5]. These technologies allowed better control of drying, preheating, firing, and cooling and supported the increasing production capacities required by the iron and steel industry.

The expansion of commercial pelletizing plants was also accompanied by improvements in concentrate grinding, filtration, mixing, binder addition, balling, green-pellet screening, induration, cooling, and

material handling. These developments improved pellet uniformity, mechanical strength, productivity, and process stability [1–5].

Thus, the commercial development period established the basic industrial configurations of pellet production and created the foundation for the subsequent technological improvements in process control, automation, energy efficiency, and environmental performance.

2.7. Transition to Modern Pelletizing Technologies

After pelletization had become an established industrial process, further development focused primarily on improving productivity, pellet quality, energy efficiency, process stability, and environmental performance [2,4,19,20] rather than establishing fundamentally new pelletizing principles.

Advances in ore beneficiation, grinding, classification, filtration, and concentrate handling enabled increasingly complex and finely disseminated iron ores to be processed. Improved grinding and classification systems provided better control of concentrate fineness and liberation, while improved filtration and handling systems provided more consistent feed conditions for pelletizing [2,17].

The technology of green-pellet formation also developed through improvements in disc and drum pelletizers, mixing, moisture control, and operating practices. The optimization of bentonite and other binders improved green-pellet strength and resistance to degradation during drying and induration [9,11,12,23–25]. Control of pellet size distribution became increasingly important because pellet size influences drying, heat transfer, induration behavior, and final pellet quality [2,17].

Induration technology subsequently benefited from improved temperature measurement, combustion control, gas-flow management, heat recovery, and instrumentation. The introduction of distributed control systems, online measurements, automated material handling, and process models enabled more stable operation and improved control of pellet quality [2,4,5].

At the same time, pellet specifications became increasingly dependent on the requirements of the downstream ironmaking process. Blast furnace pellets require appropriate mechanical and metallurgical properties, while direct reduction pellets generally require higher iron grades, lower gangue contents, and controlled reducibility and reduction behavior [16–18].

Environmental considerations have become an additional driver of technological development. Modern pelletizing plants increasingly incorporate heat recovery, improved combustion efficiency, reduced fuel consumption, dust control, and optimized gas handling [4,19,20]. The transition toward low-carbon ironmaking is further encouraging the development of energy-efficient induration and pellet production routes compatible with direct reduction and hydrogen-based ironmaking [21,22].

Therefore, the modern evolution of pelletization can be summarized as:

Established pelletizing process → improved raw-material preparation → improved pellet formation → advanced induration → automation and process control → energy and emission reduction → pellets for low-carbon ironmaking.

This transition has transformed pelletization from a technology primarily developed to agglomerate fine iron ore concentrates into an integrated, automated, quality-controlled, and increasingly energy-efficient process designed around the requirements of modern ironmaking.

3. Evolution of Induration Technology

The development of iron ore pelletization required not only a method for forming green pellets but also a reliable method for converting these relatively weak agglomerates into strong, metallurgically suitable pellets. Induration became the essential thermal treatment stage in which green pellets undergo controlled

drying, preheating, firing, and cooling. The development of induration technology therefore progressed alongside the development of pelletization itself.

The principal industrial induration technologies evolved through three major configurations: shaft furnaces, travelling-grate (straight-grate) systems, and grate-kiln systems. These technologies were not developed independently of earlier thermal-processing equipment. Existing furnace and thermal-treatment concepts used for mineral processing, sintering, cement production, and ore smelting were progressively adapted to the requirements of iron ore pellet induration. Historical literature identifies these three furnace types as the dominant approaches that emerged for hardening iron ore pellets.

3.1. Development of Shaft-Furnace Induration

The shaft furnace [1,2] was one of the earliest furnace configurations adapted for industrial iron ore pellet induration. Shaft furnaces had already been used for centuries in metallurgical operations and lime production, and their relatively high thermal efficiency and simple operating principle made them suitable for adaptation to pellet hardening. Both Sweden and the United States used shaft-furnace technology during the early development of industrial pelletization.

Major development of shaft-furnace pelletizing occurred in the United States during the 1940s and early 1950s, particularly in connection with the beneficiation of low-grade taconite ores. Research by the University of Minnesota Mines Experiment Station, together with industrial development by companies such as Armco Steel Corporation and Reserve Mining Company, demonstrated that fine magnetite concentrates could be formed into green pellets and subsequently hardened in shaft-type furnaces. Following earlier pilot-scale development at Ashland, Kentucky, large-scale pelletizing tests were conducted at the Armco pilot plant during 1950–1951 [1,2]. Following these developments, a four-shaft commercial-type plant was constructed at Babbitt, Minnesota, by Reserve Mining Company.

The shaft-furnace process involved charging green pellets at the top of the furnace and passing hot gases through the descending pellet bed. Drying, heating, firing, and cooling occurred progressively as the pellets travelled through the furnace. The process was particularly advantageous for magnetite pellets, because oxidation of magnetite to hematite is exothermic and can contribute substantially to the heat required for induration [2,4].

However, the shaft furnace had inherent limitations. The pellets continuously descended through the furnace, requiring relatively high green-pellet strength and resistance to thermal shock and abrasion. In addition, the close integration of drying, preheating, firing, and cooling within one furnace limited the ability to control individual process stages independently. As pellet production increased to several million tonnes per year at individual plants, the capacity and flexibility limitations of shaft furnaces encouraged the development of continuous travelling-grate systems [1,4].

3.2. Development of Straight-Grate Technology

The travelling-grate or straight-grate system represented a major development in pellet induration because it separated the thermal treatment into controlled zones while continuously transporting the pellets through the furnace.

The technology evolved in the United States during the early 1950s [3]. Development work involved the Mines Experiment Station, Arthur G. McKee & Company, and Allis-Chalmers [3], with the travelling-grate concept adapted from earlier sintering-machine designs. Pilot and test installations were operated at Carrollville and Babbitt between 1952 and 1954 [3].

A major milestone was reached in October 1955 [3], when the first commercial straight-grate pelletizing installation was started at Reserve Mining Company's Silver Bay operation in Minnesota, USA. Other

early commercial installations followed at International Nickel Company's Copper Cliff operation in Ontario, Canada, in 1956, and at Cleveland-Cliffs Iron Company's Ishpeming operation in Michigan in 1956.

In a straight-grate system, green pellets are transported on a continuous moving grate through successive zones for drying, preheating, firing, after-firing, and cooling. The process gases pass through the pellet bed through windboxes located below the grate. Later designs incorporated both updraft and downdraft sections to improve heat transfer and thermal efficiency [3].

An important advantage of the straight-grate system was that the pellets remained relatively stationary with respect to one another while being transported through the furnace. This reduced mechanical degradation compared with systems in which pellets were subjected to continuous movement through a shaft or rotary kiln. The separation of thermal zones also allowed better control of the pellet heating profile. The technology subsequently evolved through different engineering designs, including the McKee design and the Lurgi-Dravo design. Lurgi of Germany became an important supplier of travelling-grate pelletizing technology, contributing to its subsequent international adoption.

3.3. Development of Grate-Kiln Technology

The grate-kiln system represented another major development in pellet induration. Its technological origin can be traced to the Lepol process, developed for cement production in Europe. The Lepol concept used a travelling grate for drying and preheating followed by a rotary kiln for high-temperature treatment. This principle was subsequently adapted for iron ore pellet induration.

The feasibility of using the grate-kiln concept for iron ore pellets was investigated at the Allis-Chalmers pilot plant at Carrollville, near Milwaukee, Wisconsin, during the 1950s. The development involved the adaptation of the travelling grate and rotary kiln arrangement to the specific requirements of iron ore pellet induration.

The first commercial iron ore grate-kiln pellet plant was established at the Humboldt Mine in Michigan, USA, in 1960 [4,5]. The installation was associated with Allis-Chalmers, which subsequently became one of the major developers and suppliers of grate-kiln pelletizing systems.

The grate-kiln process separates the principal thermal stages between different pieces of equipment. The travelling grate performs drying and preheating, the rotary kiln provides high-temperature induration, and the cooler reduces the temperature of the fired pellets while allowing heat recovery. Modern grate-kiln systems therefore consist principally of a travelling grate, rotary kiln, and cooler, with independent control of the major process stages.

The rotary kiln provides continuous mixing and movement of the pellets during firing, allowing relatively uniform exposure to high temperature. This feature has contributed to the successful application of grate-kiln technology to both magnetite and hematite pellet feeds. The technology subsequently expanded beyond North America, including significant adoption in Japan and, more recently, China.

3.4. Historical Evolution and Comparison of Major Induration Technologies

The development of induration technology can therefore be viewed as a progression driven by increasing production requirements, ore characteristics, pellet quality requirements, and the need for improved thermal control.

Table 1: Comparison of Major Induration Technologies

Induration technology	Major development period	Main developers / organizations	Important historical location	Principal development
Shaft furnace	1940s–1950s	University of Minnesota Mines Experiment Station; Armco Steel; Reserve Mining and other industrial participants	Ashland, Kentucky; Babbitt, Minnesota, USA	Early large-scale induration of fine magnetite pellets [1,2,4]
Straight grate / travelling grate	Early–mid 1950s	Mines Experiment Station; Arthur G. McKee & Co.; Allis-Chalmers; later Lurgi–Dravo	Carrollville/Babbitt test facilities; Silver Bay, Minnesota	Continuous drying, preheating, firing and cooling on a travelling grate
Commercial straight grate	1955 onward	Allis-Chalmers, McKee, Lurgi and others	Silver Bay, Minnesota, USA	First major commercial travelling-grate installation in 1955 [3]
Grate-kiln	1950s–1960	Allis-Chalmers and industrial development partners	Carrollville, Wisconsin; Humboldt, Michigan, USA	Separation of drying/preheating, rotary-kiln firing and cooling [4,5]
Commercial grate-kiln	1960 onward	Allis-Chalmers; later Metso and other suppliers	Humboldt Mine, Michigan, USA	First commercial iron ore grate-kiln installation
Modern induration systems	Late 20th century–present	Multiple technology suppliers and iron ore producers	Worldwide	Automation, process modelling, heat recovery, advanced combustion and process control

The historical record should be interpreted carefully when identifying an individual "inventor." The development of these systems was generally collaborative and incremental, involving mining companies, steel companies, research institutions, and equipment manufacturers rather than a single inventor. The historical evidence supports identifying the principal organizations and milestone installations rather than assigning sole invention to one individual [1,3–5].

3.5. Modern Development of Induration Technology

The basic configurations established during the 1950s and 1960s remain the foundation of modern pellet induration, but their operation has changed substantially through improvements in instrumentation, automation, process modelling, combustion systems, and heat recovery.

Modern systems use temperature, pressure, gas-flow, moisture, bed-depth, and other measurements to control the thermal treatment of pellets. Advanced process-control systems can continuously adjust

process variables to maintain stable operating conditions, improve productivity, reduce energy consumption, and maintain consistent pellet quality [2,4,5]. Modern grate-kiln systems, for example, use process models and advanced control systems for optimization of temperature profiles, gas flow, fuel consumption, and pellet quality.

Energy efficiency has become an increasingly important objective. Heat recovered from fired pellets and exhaust gases can be reused within the induration process, reducing fuel requirements. Improvements in burner design, gas circulation, sealing, heat recovery, and combustion control have further reduced thermal losses and emissions. Modern systems are also increasingly designed to accommodate alternative fuels and the changing requirements of low-carbon ironmaking [4,19–22].

The evolution of induration technology therefore represents a transition from relatively simple thermal treatment in early shaft furnaces to highly integrated and controlled systems capable of processing millions of tonnes of pellets annually. Shaft furnaces established the early industrial foundation; straight-grate technology provided higher-capacity continuous processing; and grate-kiln technology introduced greater separation and control of the major thermal stages. Modern developments have subsequently focused on automation, energy efficiency, process optimization, emissions reduction, and adaptation to the changing requirements of blast furnace and direct reduction ironmaking.

4. Pelletization in Blast Furnace and Direct Reduction Ironmaking

Iron ore pelletization became increasingly important with the development of large-scale blast furnace and direct reduction (DR) ironmaking. Pelletization converts fine iron ore concentrates into relatively uniform, mechanically stable agglomerates [1,2] with controlled chemical and metallurgical properties. The resulting pellets can be transported, handled, and charged into ironmaking furnaces more effectively than untreated fine concentrates.

In blast furnace ironmaking, pellets are used as one of the principal iron-bearing burden materials, together with sinter and lump ore. Their relatively uniform size and shape can contribute to improved burden distribution and gas permeability within the furnace. Pellet quality is therefore influenced by properties such as iron grade, gangue content, cold crushing strength, abrasion resistance, reducibility, reduction degradation, swelling, porosity, and basicity [13–16]. Appropriate control of these properties is necessary to maintain stable furnace operation and efficient reduction.

The increasing utilization of beneficiated and finely disseminated iron ores further strengthened the role of pelletization in blast furnace feed preparation. Beneficiation produces fine concentrates that cannot normally be charged directly because of their adverse effect on burden permeability [1,2,10]. Pelletization provides a means of converting these concentrates into a suitable blast furnace burden while allowing greater utilization of fine and lower-grade iron ore resources.

The development of direct reduction ironmaking introduced more stringent requirements for pellet quality. Unlike blast furnace operation, where pellets form part of a mixed burden, many gas-based DR processes use pellets as the principal or exclusive iron-bearing feed. Consequently, DR-grade pellets generally require higher iron content, lower gangue levels, high reducibility, suitable porosity, and adequate mechanical strength [16–18]. The chemical and physical characteristics of the pellets directly influence reduction kinetics, metallization, productivity, and energy consumption in the DR furnace.

The growing importance of DR technology has therefore encouraged the production of specialized DR-grade pellets from high-quality concentrates. Beneficiation and grinding must be optimized to achieve high iron recovery while controlling silica, alumina, phosphorus, and other undesirable components [16–

18]. Pelletizing and induration conditions must then be controlled to obtain the required strength and pore structure without adversely affecting reducibility.

Thus, the evolution of pelletization has been closely linked to the changing requirements of ironmaking. For blast furnaces, pelletization provides a consistent and permeable burden material, whereas for direct reduction it provides a high-quality feedstock with the chemical and metallurgical properties required for efficient solid-state reduction. These increasingly demanding requirements are also relevant to the development of low-carbon and hydrogen-based direct reduction [21,22], where high-quality iron ore pellets with appropriate chemical, physical, and metallurgical properties are required.

Table 2: Representative chemical, physical and metallurgical characteristics of blast furnace (BF) and direct reduction (DR) iron ore pellets.

Parameter	BF-grade pellets	DR-grade pellets	Significance
Total Fe, wt.%	63–65 [16–18]	≥67 [16–18]	Higher Fe reduces gangue and increases iron-unit productivity
SiO ₂ , wt.%	2.5–5.3 [16–18]	1.0–3.0 [16–18]	Lower SiO ₂ is particularly important for DR because gangue remains with DRI
Al ₂ O ₃ , wt.%	~0.4 [16–18]	0.2–3.0 [16–18]	Influences slag formation, reducibility and pellet properties
MgO, wt.%	0.3–1.5 [16–18]	0.2–0.9 [16–18]	Affects basicity, slag chemistry and pellet microstructure
CaO, wt.%	0.6–3.6 [16–18]	0.4–1.2 [16–18]	Controlled according to required pellet basicity
Pellet size, mm	9–16 [13,16]	9–16[13,16]	Ensures suitable burden permeability and gas flow
(CCS), N/pellet	2,850–3,190 [13,16]	2,500–3,000 [13,16]	Resistance to handling and furnace charging degradation
Tumble Index, % +6.15 mm	95–96	92–95	Resistance to impact and generation of fines
Reducibility Index, %	91–97 [14,16]	92–95 [14,16]	Ability of pellets to undergo reduction
Porosity, %	Typically lower/controlled	Typically >20%, often ~25–35%	Influences reduction kinetics and gas penetration
Swelling	Controlled; typically ≤20%	Controlled; preferably low	Excessive swelling can impair burden permeability
Gangue content	Relatively higher acceptable	Low	Especially important for DR because there is no BF-type slag phase
Primary application	Blast furnace	Shaft-furnace DR / DRI production	Determines the required pellet chemistry and metallurgical properties

Values are representative ranges reported for commercial pellet qualities and should not be considered universal specifications. Actual pellet requirements vary with ore characteristics, pellet chemistry, induration conditions, furnace design, operating practice, and downstream ironmaking requirements.

5. Conclusions

Iron ore pelletization has evolved over more than a century from an early method of agglomerating fine iron ore into a highly developed industrial process that is closely integrated with modern ironmaking. The development of pelletization was driven primarily by the increasing generation of fine iron ore concentrates from mining and beneficiation and the need to convert these fines into a suitable, uniform, and mechanically stable ironmaking burden [1,2].

The early work of A. G. Andersson in 1912 [1,2] established an important foundation for pelletizing finely divided iron ore. Subsequent developments, particularly those associated with the beneficiation of low-grade taconite ores in the United States, demonstrated the industrial potential of pelletization. The development of shaft-furnace, straight-grate, and grate-kiln induration technologies [1–5] subsequently enabled large-scale production and progressively improved pellet quality, productivity, and thermal efficiency.

Over time, pelletization has developed beyond simple agglomeration. Advances in beneficiation, grinding, binder technology, balling, induration, automation, process control, and heat recovery [2,4,9–12] have enabled the production of pellets with increasingly controlled physical, chemical, and metallurgical properties. Pellet requirements have also evolved according to the needs of downstream ironmaking, particularly with the increasing importance of direct reduction.

The transition toward low-carbon and hydrogen-based ironmaking [20–22] is creating further opportunities and challenges for pelletization. High-grade, low-gangue, highly reducible pellets will become increasingly important for direct reduction processes. At the same time, reducing the energy consumption and greenhouse-gas emissions associated with pellet induration will be an important area of technological development.

Overall, the history of iron ore pelletization demonstrates a continuous relationship between changes in iron ore resources, beneficiation technology, agglomeration requirements, ironmaking processes, and environmental objectives. Future developments are expected to focus on high-quality DR-grade pellets, energy-efficient and lower-carbon induration, advanced process control, improved binders, heat recovery, and integration with hydrogen-based ironmaking [19–22]. Pelletization is therefore likely to remain an important technology in the continuing transformation of the iron and steel industry toward more efficient and sustainable production.

6. References

1. Meyer, K. Pelletizing of Iron Ores. Berlin: Springer-Verlag; 1980.
2. Moraes, S.L. de, Lima, J.R.B. de, Ribeiro, T.R. Iron Ore Pelletizing Process: An Overview. In: Shatokha, V., editor. Iron Ores and Iron Oxide Materials. IntechOpen; 2018. DOI: 10.5772/intechopen.73164.
3. English, A., Morgan, M.F. The Traveling Grate—Downdraft Hardening Taconite Pellets. Transactions of the American Institute of Mining, Metallurgical, and Petroleum Engineers. 1958;10:122–124.
4. Stjernberg, J., Isaksson, O., Ion, J.C. The grate-kiln induration machine – history, advantages, and drawbacks, and outline for the future. Journal of the Southern African Institute of Mining and Metallurgy. 2015;115(2):137–144. DOI: 10.17159/2411-9717/2015/v115n2a8.
5. Yamaguchi, S., Fujii, T., Yamamoto, N., Nomura, T. Grate-kiln pelletizing process. Kobe Steel Engineering Reports. 2010;60:12–21.

6. Erb-Satullo, N.L. The Innovation and Adoption of Iron in the Ancient Near East. *Journal of Archaeological Research*. 2019;27:557–607. DOI: 10.1007/s10814-019-09129-6.
7. Johnson, D., Tyldesley, J., Lowe, T., Withers, P.J., Grady, M.M. Analysis of a prehistoric Egyptian iron bead with implications for the use and perception of meteorite iron in ancient Egypt. *Meteoritics & Planetary Science*. 2013;48(6):997–1006. DOI: 10.1111/maps.12120.
8. Rehren, T., Belgia, T., Jambon, A., et al. 5,000 years old Egyptian iron beads made from hammered meteoritic iron. *Journal of Archaeological Science*. 2013;40(12):4785–4792. DOI: 10.1016/j.jas.2013.06.002.
9. Eisele, T.C., Kawatra, S.K. A review of binders in iron ore pelletization. *Mineral Processing and Extractive Metallurgy Review*. 2003;24(1):1–90. DOI: 10.1080/08827500306896.
10. Zhu, D., Pan, J., Lu, L., Holmes, R.J. Iron ore pelletization. In: *Iron Ore*. Elsevier; 2015. p. 435–473. DOI: 10.1016/B978-1-78242-156-6.00015-0.
11. Kawatra, S., Claremboux, V. Iron Ore Pelletization: Part I. Fundamentals. *Mineral Processing and Extractive Metallurgy Review*. 2022;43(4):529–544. DOI: 10.1080/08827508.2021.1897586.
12. Kawatra, S., Claremboux, V. Iron Ore Pelletization: Part II. Inorganic Binders. *Mineral Processing and Extractive Metallurgy Review*. 2022;43(7):813–832. DOI: 10.1080/08827508.2021.1947269.
13. International Organization for Standardization. ISO 4700:2015. Iron ore pellets for blast furnace and direct reduction feedstocks — Determination of the crushing strength. Geneva: ISO; 2015.
14. International Organization for Standardization. ISO 4695:2021. Iron ores for blast furnace feedstocks — Determination of the reducibility by the rate of reduction index. Geneva: ISO; 2021.
15. International Organization for Standardization. ISO 7992:2022. Iron ores for blast furnace feedstocks — Determination of reduction under load. Geneva: ISO; 2022.
16. Thaning, G. Pellets for Direct Reduction. Society for Mining, Metallurgy & Exploration; 1978.
17. Navaei, S., Ghorbani, M., Sheibani, S., Hosseini, L., Zare, M. A review on hematite concentrate pelletization: Effect of process parameters on iron ore pellet quality. *Journal of Materials Research and Technology*. 2025;38:4849–4859. DOI: 10.1016/j.jmrt.2025.08.295.
18. Pousette, H., Kojola, N. Factors influencing physical and mechanical properties of direct reduced iron ore pellets. *Ironmaking & Steelmaking*. 2026;53(2):405–414. DOI: 10.1177/03019233241277422.
19. Lv, W., Sun, Z., Su, Z. Life cycle energy consumption and greenhouse gas emissions of iron pelletizing process in China, a case study. *Journal of Cleaner Production*. 2019;233:1314–1321. DOI: 10.1016/j.jclepro.2019.06.180.
20. Pal, J. Sustainable Iron Ore Pelletizing for Reducing Energy Consumption and CO₂ Emissions – A Comprehensive Review. *Mineral Processing and Extractive Metallurgy Review*. 2026. DOI: 10.1080/08827508.2026.2731559.
21. Wang, Z., Xu, R., Liu, M. Towards a 100% hydrogen-driven direct reduction ironmaking future: A critical review on kinetics, bottlenecks, and research priorities. *Renewable and Sustainable Energy Reviews*. 2026;229:116620. DOI: 10.1016/j.rser.2025.116620.
22. Yang, C., Wei, L., Zhu, D., Pan, J., Xia, G., Qu, S. Hydrogen-based direct reduction behavior of iron ore pellets with iron grades ranging from 59% to 68%. *International Journal of Hydrogen Energy*. 2025;138:787–801. DOI: 10.1016/j.ijhydene.2025.04.006.
23. Zhao, H., Zhou, F., Zhao, H., Ma, C., Zhou, Y. A review on the effect of the mechanism of organic polymers on pellet properties for iron ore beneficiation. *Polymers*. 2022;14(22):4874. DOI: 10.3390/polym14224874.

24. Zhao, H., Zhou, F., Ma, C., Wei, Z., Long, W. Bonding Mechanism and Process Characteristics of Special Polymers Applied in Pelletizing Binders. *Coatings*. 2022;12(11):1618. DOI: 10.3390/coatings12111618.
25. Ma, Y., Li, Q., Chen, X., Zhang, Y., Yang, Y., Zhong, Q. Reducing bentonite usage in iron ore pelletization through a novel polymer-type binder: Impact on pellet induration and metallurgical properties. *Journal of Materials Research and Technology*. 2024;30:8019–8029. DOI: 10.1016/j.jmrt.2024.05.175.