metals

Article

Modernization and Optimization of Phosphoric Cast Iron Casting

Piotr Kurylo

Department of Mechanical Engineering, University of Zielona Gora, 65-246 Zielona Góra, Poland; P.Kurylo@ibem.uz.zgora.pl

Received: 2 September 2019; Accepted: 25 September 2019; Published: 29 September 2019

Abstract: The article presents a detailed analysis of technical and organizational problems of modernization of a phosphoric cast iron casting process. The paper indicates the need to optimize the process of phosphoric cast iron casting, and the analysis carried out in the article about the possibility of optimization of the casting process allowed us to determine the main direction of modernization of the process, oriented on a significant increase in the quality of the cast iron, as well as in the direction of a significant increase in the efficiency of the cast iron production process.

Keywords: phosphoric cast iron; casting; optimalizations; casting process

1. Introduction

Casting is one of the most common methods of producing semi-finished and finished products. Thanks to the technological progress in casting processes of iron alloys, gray iron castings, especially castings of nodular and vermicular cast iron, as well as ADI cast iron and phosphorus cast iron, play a special role, because these cast irons can be successfully produced in current technological processes on a mass scale.

The widespread use of iron castings results from its advantages, such as: Good casting properties, relatively simple casting technology, and various technological and mechanical properties depending on their types.Due to high mechanical and functional properties (e.g., damping factor), nodular cast iron and vermicular cast iron belong to the basic foundry alloys containing iron and carbon, and are widely used, primarily as a casting material for the automotive and machine (agriculture) industries, pipe casting and sanitary fittings, in the glass industry (molds and preforms) as well as steel castings, among others ingot molds, rollers, successfully replacing steel castings and steel products. Additionally, phosphoric cast iron characterized by, among others, high value and stability of the friction coefficient, regardless of the operating conditions, high resistance to wear under various operating conditions, high resistance to high temperature and high mechanical strength, are also applicable to the production of, among others, brake pads used in cars, military vehicles, and railways [1–3].

In the current decade, undoubtedly, the production of castings (including iron castings) is still dominated by China, the USA, and Japan (Figure 1).

Currently, a significant (40%) increase in production of castings is generated by the increase in production of gray cast iron and aluminum alloys for the automotive industry in the first place.

New technologies, cutting-edge machinery and production lines, co-financing for many investments, and above all, restructuring and privatization of the sector, create opportunities for iron foundries to compete with other foundries all around the world. Currently, the Polish foundry market is 15th in the world, with the annual production at the level of around 1.1 million tonnes. In terms of the amount of aluminum alloy casts, it ranks 10th in the world and third in Europe. Foundries export more than 50% of products, mainly to Western Europe. The vast majority of Polish casting products meet all expectations of recipients all over the world. Many companies from EuropeanUnion countries that have so far used foundries in China, India, Brazil, or Turkey, are transferring production to Poland. Continuous modernization and implementation of innovative technologies attract customers for long term periods. Foundries of non-ferrous metals, especially aluminum, which are developing technologically and are increasing production potentials, have their order books filled. Their situation is very good. Cast iron foundries are usually profitable, although this is not the same level of profitability as for the production of non-ferrous metal castings. Nevertheless, among Polish cast iron foundries, there are record holders, fully comparable with the best global companies [6].

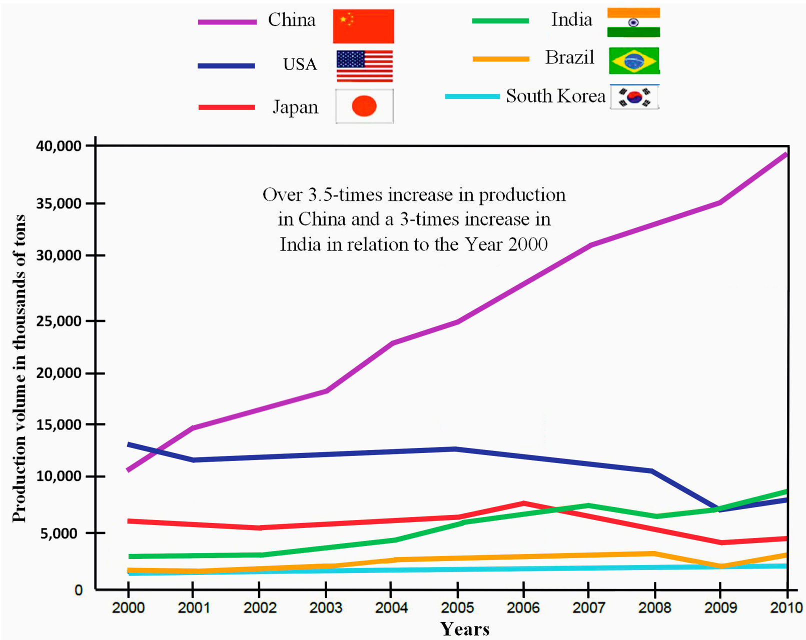

Figure 1. Global trend in the production of castings of major producers in the years 2002–2011 [4,5].

Maintaining the position and the competitiveness of castings made of spheroidal and vermicular cast iron, as well as of ADI and phosphoric cast iron, is conditioned by high quality, reduced production costs and shortening the lead time (launching the new production range). In modern technological processes, the aim is to obtain castings whose dimensions would be closest to the constructional dimensions of products, and allowances for removal machining would be reduced to a minimum. Lowering the allowance for removal machining (roughing and finishing) gives measurable material savings, thus significantly increasing the yield and reducing labor consumption. The favorable properties of spheroidal, vermicular cast iron, ADI cast iron, and phosphoric cast iron influence the fact that these types of cast iron are selected due to their functional characteristics. The possibility of increasing the strength of elements of machine parts by shaping the properties of their surface layers WW (from polish: Warstwa Wierzchnia) is one of the criteria for selecting a particular type of cast iron as a construction material, mainly in the engineering industry [7].

Operational tests and observations show that the basic condition determining the durability of components of machine parts is the condition of their surface layer (WW) [8–10].

Statistics indicate that the basic factor "causing" damage, cracks, or even destruction of parts of machines is insufficient strength of their surface layers. Therefore, it can be concluded with certainty that the condition of surface layers determines the usable properties of machine parts. The practical use of technological process parameters as effective reserves to increase the durability and reliability of machine parts is the subject of interest of many research centers around the world. These centers are usually grouped around large corporations and industrial factories [6], or [10–13].

Global industry produces about 80% of cast iron castings, where the remaining 20% are castings from other metals and their alloys (among others, aluminum alloys for the automotive industry) [4,6].

Such analyses were carried out at the Foundry Research Institute in Krakow. As a rule, they are subjected to mechanical treatment, hence the problem of machinability of various types of cast irons is a very important issue for production practice. Some product surfaces are not processed at all, while others are processed very precisely. Decreasing the allowances for machining results in material savings and the reduction of energy and labor consumption.

It is also very important to minimize these costs, e.g., by optimizing production yet in the design phase, e.g., while designing the required properties of the surface layer of a finished product.

On the basis of statistical surveys, it should also be stated that most machine failures are not due to structural errors, but due to insufficient strength of the surface layer of essential elements. Therefore, the operational strength of machine elements is closely conditioned by the properties of the surface layer itself.

It is estimated that 80–85% of damage to machine parts (tribologiacl damages, which means wear damages and mechanical damages such as cracks, chipping, surface fatigue) is due to the insufficient quality of the surface layer, which composes only a few percent of the entire element's volume. One of the effective ways to increase durability and reliability is to optimize the properties of the surface layers of machine elements [14–18].

The growing requirements for the engineering industry impose the necessity of using more and more modern technological processes, aimed at, among other things, obtaining castings whose further processing would be limited to a minimum or would be completely eliminated. To meet these requirements, machinability tests [19–22] have been performed. Of particular importance is the problem of machinability of cast iron castings and their surface layers in large-scale and mass production, since technological processes and complex single- and multi-tool operations require maintaining the constant work-cycle time.

2. Objectives of the Elaboration

The aim of this study is:

- to determine the direction of a possible technological modernization of grey phosphoric cast iron casting in a selected cast iron foundry,
- to conduct a detailed analysis of the possibilities of increasing the quality of phosphorus cast iron produced and increasing the production efficiency (of the foundry) by modernizing the casting process.

The proposed modernization should aim at indicating the possibilities of expanding sales markets, as well as the production increase to 8000 tons/year. It should be noted that the planned modernization should be implemented in such a way that supplies for existing customers would be maintained at the current level. The improvement in the quality of cast iron castings will enable the winning of new customers, whose future orders are conditional on the good quality of the cast iron, which, in turn, will contribute to attracting customers in new market segments (e.g., household appliances, automotive, machinery, etc.).

Scope of Research

The performed research consisted of four stages:

- The first stage resulted in developing the basic assumptions of the project.
- The second stage of the research included the analysis of the current state of the production process.
- The third stage of the research included the determination of the direction of modernization and the output parameters which should be achieved after the project completion.
- The fourth stage consisted in a detailed analysis of the economic viability of the investment and the determination of the scope of planned modernization with detailed stages of its implementation.
- In the last stage of the research, the effectiveness of the proposed modernization was assessed.

3. Analysis of the Current State

3.1. Scope of Research

The main product produced by the selected company, i.e., the iron foundry, are brake blocks for railway wagons. Four types of standard brake blocks are cast (Figure 2): DO 250 B, DOB 320 B, D2-B and DO 380 B.

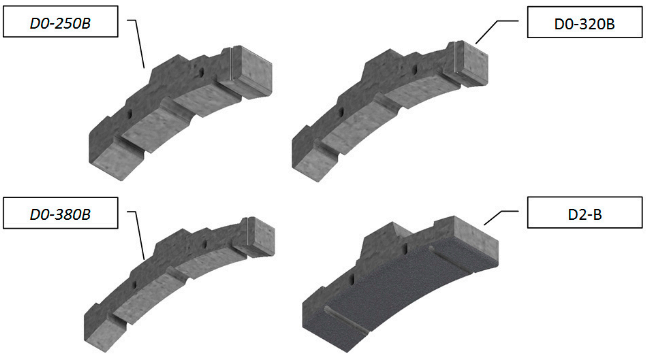

Figure 2. Exemplary castings made of phosphoric cast iron [23].

Where: D0-250B carriages and freight wagons; combustion engine vehicles; D0-320B electric locomotives D0-380B combustion locomotives; D2B electrical multiple traction units—chemical composition is shown in Table 1.

The foundry also produces products according to individual customer orders. The size of these additional orders is, on average, one tonne of finished casting a month. The condition for the acceptance of the order to be implemented is the delivery of a cast model by the ordering party. The foundry's production capacity is exploited at 50%. The maximum weight of a casting that is currently cast is 12.70 kg, and the dimensions of the molding box are 130 mm × 450 mm × 500 mm.

3.2. The Analysis of the Process

The castings are made of P 10 cast iron, whose chemical composition is shown in Table 1.

Table 1. Chemical composition is P 10 cast iron.

C [%]	Si [%]	P [%]	Mn [%]	S [%]
2.9–3.2	1.5–1.7	0.9–1.0% (allowable, 10%)	0.4–0.6	0.16% max

3.3. Preparation of Moulding Sand

The molding sand consists of: Circulating mass derived from knocked-out molds, fresh quartz sand, bentonite, coal dust, bentonite-cormix mixture, and water.

Figure 3 presents the scheme of the composition and the storage method of molding sand.

In order to mix and refresh the molding sand, a MK-060 mixer (supplied with a 750 kg loading bowl) is used. The components of the circulating molding sand are loaded into the bowl of the mixer with strictly measured batch sizes: Bentonite-circulation mixture, fresh sand, coal dust, and water. Mixing time 6–8 min for the primer and for 345 min for the filling mass.

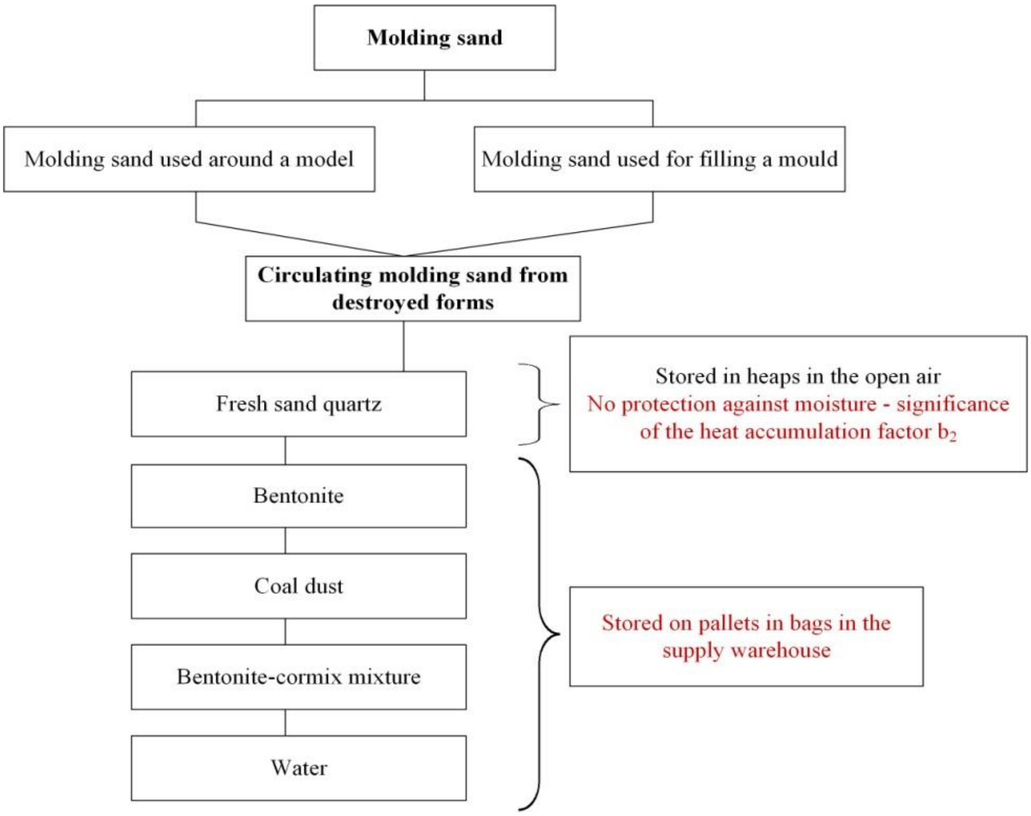

Figure 3. Diagram of the composition and the storage method of molding sand.

3.4. Formation of a Sand Casting Flask

The iron foundry where the modernization project was carried out uses a sand flask casting technology. There are around 720 sets of flasks in circulation, i.e., 720 lower and 720 upper halves of molding flasks. The casting flasks are stored in designated places in piles up to 1.5 m high, near the molders. Two types of flasks, differing in dimensions, are used: Smaller ones with dimensions of 12 mm × 450 mm × 500 mm and larger—with dimensions of 130 mm × 450 mm × 500 mm. The two-year durability of a flask is assumed (at the minimum).

The molding sand used to perform the mold is stored in molding machines. The facing sand, on the other hand, is stored in special containers, and the filling mass—on piles.

3.5. Core Sand and Cores

In non-reusable sand flasks for brake pads, cores made of varnish-based core sands are used. The core sand has a strictly defined recipe for one batch, i.e., per 100 kg of mass. The core sand is composed of: Dried quartz sand 94 kg, linseed varnish in the amount 2 kg, coal dust in the amount 2 kg, dextrin. The quartz sand was dried in a PP 05 type furnace. After drying, it is cooled to ambient temperature. The prepared dry ingredients of the core sand are transferred to the bowl of the MS-0075 B type blender and mixed for 5–8 min. In the final mixing phase, wet ingredients are added and then mixed for additional 3–5 min. If the core sand is too dry, water should be added.

Cores are made using core boxes according to the subsequent operations (Figure 4).

After preparing the core boxes according to the above-described technology, the core box should be spread, the core should be removed and then placed on a drying plate in dryers for 8 h at 180–220 °C. After drying and cooling, the cores should be removed from the dryer and transported to the storage location.

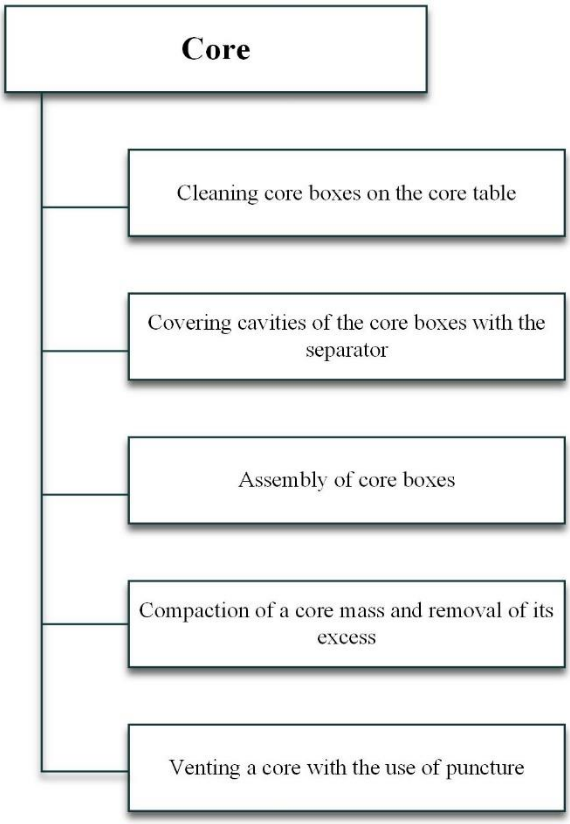

Figure 4. The order of making cores with the use of core boxes.

3.6. Preparation of Inserts

One of the main requirements posed by the recipient of the manufactured products is that the end product is durable and should withstand accidental cracks. To provide this, special inserts are added to the finished product, as soon as at the stage of the product construction. The process of inserts preparation consists of cutting the appropriate size of flat bars (the size and geometry of the flat bar depends on the type of the brake pad which is cast). The cut-to-size flat bars are subjected to a cleaning operation in a drum machine, until the scaling and corrosion are completely removed. The cleaned inserts are subjected to a plastic forming operation (on a press) to provide the appropriate radius for a given type of insert. The subsequent operation is covering the inserts with a colloidal suspension. The inserts are taken from transport containers and placed on a painting grill. After mixing the colloidal suspension, "DIMANOL" or "SILCOS2" in transporting containers, the inserts are placed on a painting grid. The formerly prepared angle beams are covered with a thin, even layer of suspension on each side. After the coating has dried up, the feet are deposited in containers (from which they are taken to form the mold).

3.7. Preparation of Liquid Cast Iron

Liquid cast iron is prepared in a coke-heated shaft furnace, the so-called cupola furnace, with a cold blast of 250–300 kg, with the use of process scrap (mixture of residual scrap) within the limits of 0–50 kg, air blow with a capacity of 350 kg, and the charge-ZZ8 scrap. The batch materials are stored on yards and storage areas located outside the foundry. Foundry coke and limestone are stored on the square in front of the foundry and are not protected against atmospheric factors. The square is in a considerable distance from the cupolas, which results in the lengthening of the supply routes of ingredients to the place of their use. Metal batch materials are stored near the cupola in special boxes, which perform the function of separators for the metal batch materials. The excess of these materials is stored near boxes on the square, with consideration for the type of metals. The metal charge is fragmented with the use of an acetylene-oxygen torch for steel scrap, and a pile driver for iron scrap breaking. The scrap pieces should not be longer than 250 mm, and weigh below 15 kg. Metal batch materials, placed in boxes, are taken according to the recipe. They are placed in a vertical lift tray, which is placed on an electronic movable scales during the loading time. After the tray has been loaded according to the recipe, it is hooked to a vertical lift and then transported to the upper charging platform of the cupola. After the cupola has been charged with metal batch materials, coke, limestone, and ferroalloys, the batch is heated to obtain liquid metal in the temperature range 1370–1390 °C (temperature is measured on the cupola tap hole). After the metal is heated to the required temperature, it is poured into the ladle.

3.8. Mold Filling Process

The key issue in the implementation of the modernization project was a detailed analysis of the mold filling process. The mold filling process begins when the casting ladle (dried and heated to temperatures of min. 200 °C) is placed below the cupola furnace drainpipe. After opening the tap hole of the furnace, the ladle is filled with liquid metal. During the discharge, the temperature of the liquid metal (should range 1390–1370 °C) is controlled on an ongoing basis. Additionally, a sample is taken for spectral analysis. If the chemical composition needs to be adjusted, granulated ferrosilicon is added, and if the liquid metal needs to be degassed, deslagged, or cooled down, it is poured into the drum ladle, which is preheated to temperature min. 200 °C. Next, in order to clean the surface of the liquid metal, slag coagulator is poured onto its surface and then the scum (formed on the surface) is collected. The slag is removed by a metal hoe, tilting the ladle in the direction opposite to the spout. After doing this, the ladle is transported (with the use of a gantry crane) to the potting station. The mold is filled by tilting the drum ladle and bringing it closer to the opening of the mold infusion. The filling process ends when the inlet system is completely filled. Special attention should be paid to ensure that slag and other solid contaminants did not enter the infusion system during the filling process. It is also necessary to constantly control the temperature of the liquid cast iron, which should range 1250–1190 °C. In case of a drop in the temperature or of an increase in the density-liquidity (density in the liquid state) of the liquid cast iron, the cast iron should be poured into the sink beam, and the ladle should be filled with "fresh" metal at a temperature above the upper limit of the filling range. After the mold has been filled, all protruding metallic surfaces should be covered with molding sand.

3.9. Mould Emptying

Molds are emptied manually by a trained employee. This operation is carried out after a minimum of 1 h since mold was filled. The period depends on the weight of the cast, and can take up to 3 h. The maximum temperature for mold emptying should not exceed 600 °C. The process of manual mold emptying takes place at the site where the filled molds are stored. First, the upper halves of the molds are removed with the use of steel hooks. With the use of the same hooks, the cast are removed from the mold halves. After the casts are removed from the molds, any excessive material (i.e., infusion systems, overflows, and traps) is broken off with the help of hammers. Empty casting flasks are placed in piles up to a height of 1.5 m in places designated for this purpose, close to the molders. The obtained hot castings (with removed infusion systems, overflows, and traps) are loaded into metal crates. The infusion systems, overflows, and trappings are also loaded into separate metal crates. Metal containers with castings are loaded onto carts and manually pushed to the casting cleaning hall. Crates with infusion systems, overflows, and traps are transported outside the foundry, to the gantry crane. Then they are unloaded into bins (containing iron scrap). The knocked-out molding sand is piled into long, low prisms, and poured with water. After its initial cooling, it is transported (with the use of the crane gripper) to the storage place for the circulating molding sand, near the mixers.

3.10. Cleaning of Castings

After the castings have been transported to the cleaning rooms, they are initially (visually) assessed and tested for hardness (197–255 HBW). Castings that do not meet the quality criteria are placed in containers marked "scrap" and eliminated from the cleaning operation. The remaining castings are loaded into the drum cleaner in an amount up to 70% of the chamber capacity. The temperature of the castings loaded into the chamber of the cleaner should be below 40 °C. The cleaning operation in drum machines takes minimum 1 h. After the tumbling operation has been completed, the castings are removed from the cleaner and again inspected visually. Castings that do not meet quality criteria are loaded into containers marked "scrap". Castings which may not meet quality criteria (according to the staff of the cleaning machine), are loaded into a container marked "suspended" and then transported with good products for further processing.

3.11. Grinding of Castings

Before starting the casting grinding operation (so-called "skinning"), a visual evaluation is repeated, the criteria are identical to those as before. Castings that do not meet the quality requirements are placed in containers marked "scrap", castings of dubious quality—in containers marked "suspended", and the remaining ones are subjected to grinding. The grinding process is performed to completely remove traps, growth, and any traces of the division of the mold. After these activities, finished castings are loaded onto carts and sent for further operations.

3.12. Segregation and Final Quality Control

The final (also visual) quality control is performed at the casting segregation stands. Castings classified as good are segregated by type. Castings are stacked and tagged with a green sheet of paper with the type of the product on it. Such arranged products undergo final acceptance and wait to be shipped to the recipient. Quality control is performed in the foundry laboratory, which is in the Factory Quality Control unit, which, in turn, is supervised by the control department, supervised by its manager. The foundry laboratory tests molding sand (in terms of its permeability, compressive strength, and its moisture) and cast iron (in terms of its chemical composition). Each portion of the mold sand produced is examined in terms of its physical and mechanical properties. The chemical composition of all the produced cast iron is tested on a sample taken from cupola drainpipe. The tests are carried out and the results recorded so that each product can be identified in terms of the chemical composition of the cast iron and the properties of the molding sand. The quality control department performs visual inspection of castings, statistical tests of the internal structure (destructive tests), and carries out casting hardness tests. The results of the tests performed are recorded, which enables the identification of test results with a controlled lot.

3.13. Employment

A total of 53 people are employed at the cast iron foundry, including one manager, two shift masters, and 50 people directly involved in production.

The employment structure is shown in Figure 5.

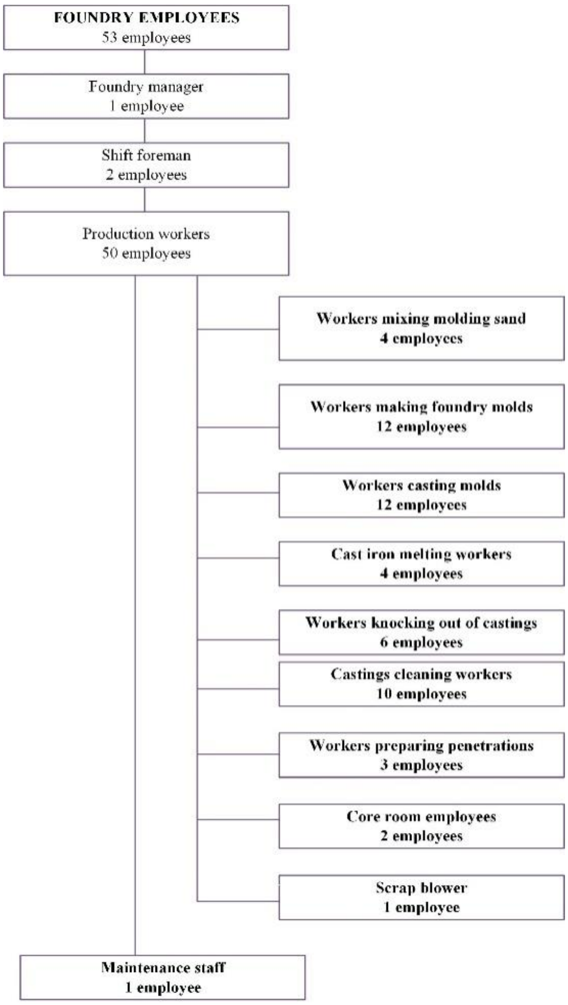

Figure 5. Foundry's employment structure.

4. Strengths and Weaknesses of the Functioning Production Process—SWOT Analysis

Weaknesses of the Process

The results of a detailed analysis of the weaknesses of the production process are presented in Table 2.

Table 2. Weaknesses of the process of casting cast iron products.

Molding Sand Storage	Coke Storage	Limestone Storage
The impact of the storage method on the molding sand: - increased moisture due to atmospheric precipitation, - pollution by leaves, branches, limestone, dusts, - altered temperature depending on the ambient temperature, - in winter, the molding sand may cake (freezing of wet molding sand).	The impact of the storage method on the coke: - increased moisture due to atmospheric precipitation, - mechanical damage and its fragmentation caused by multiple transportation, - in winter, the coke may cake (freezing of wet coke).	The impact of the storage method on the limestone: - increased moisture due to atmospheric precipitation, - no dimensional segregation

Table 2. *Cont.*

Logistics	Molding Sand Managing	Inter-operational Transport
The method of storage of batch components causes: - significant distance from the place of consumption, - manual, multiple reloading.	- lack of clear separation in the production process between molding sand ingredients, - considerable losses of circulating sand - no control of molding sand moisture, - lack of cooling of the molding sand, - no loosening of molding sand, - inaccurate purification and grinding of the return molding compound.	- all the activities of inter-operational transport are carried out manually, - storing the molding sand in heaps near molding machines results in considerable losses, - storing the molding sand (in a heap) in the middle of the hall after it has been removed from the molds, causes considerable losses, clutter in the hall, pollution and dust.
Melting Of Cast Iron	**Making a Mold**	**Removing Casts from Molds**
- the process of melting the cast iron in a cupola furnace is very inconvenient for the environment and employees, - liquid cast iron is immediately poured into the mold, it is not possible to store liquid cast iron, - the process of deslagging cast iron takes place in the sink ladle, and is not very precise.	- molds are performed with two kinds of molding sand - hand molding in casting flasks results in inaccuracies due to the process of fixing the flasks, and due to shifts between the lower and upper halves of the mold.	- removing casts manually from the flasks is very onerous for the employee, - no dust collection at workplaces where casts are removed from molds.
Cleaning of Castings		
- cleaning castings by tumbling causes mechanical damage and considerable noise, - the process of cast grinding causes dust and is harmful for grinder operators.		

The detailed analysis of the entire process also required an inventory of all resources, including the building facilities necessary to carry out the modernization of the iron casting process.

5. The Assumed Solution

The analysis of possible modernization of the process described above was based on the following assumptions: The annual production program was adopted at 7000 T of flawless castings, assuming a 3.5% level of defective products, and a 10% share of defective products in the mass of infusion systems and risers.

It was also assumed that the expected level of phosphoric cast iron production is approx. 8000 T of cast iron per year. As a result of a detailed analysis of the process, it was found that the foundry's production capacities after modernization depend on, among others, the performance of the DISA type flaskless molding line, and this yield is much higher, amounting to approx. 18,000 T.

As a result of a detailed analysis of the functioning production process, the following changes in the process have been suggested—Table 3.

As a result of a detailed analysis of the proposed changes, it was found that there is also a need for renovation and construction works. These modifications of the construction should include: Making new foundations for technological equipment, making a new floor in the facilities, hardening the floor of a warehouse of molding materials, making access roads to the warehouse, and performing a series of adaptation works for the needs of installing, e.g., an high frequency induction electric furnace with two crucibles (including the execution of channels for molding sand conveyors). On the other hand, a detailed cost analysis revealed that the estimated value of these works would amount to approx. 20% of expenditures on technological equipment. Therefore, it was proposed that the modernization of the foundry process should be implemented in stages.

The first stage, the implementation of the investment, is determined by the continuous work of the foundry. This calls for the need to split the task into stages. It was assumed the continuity of the process of production of the brake pads is to be maintained. It would be most appropriate to start work according to the following scheme (Figures 6–9).

Table 3. Areas and purposes of modernization.

Area of Modernization	Purpose of Modernization
Warehouse of molding materials	Quartz sand and a blend of bentonite with coal dust should be stored in tanks placed outside the production hall. The tanks must be adapted to rail and road tankers. Materials from external tanks should also be pneumatically transported to molding sand preparation stations
Station for molding sand preparation	The station should include: Buffer tanks for return mass, buffer tanks for quartz sand and bentonite mixture, a molding compound mixer, scales and dispensers, measuring and regulating systems, a belt conveyor for transporting the ready molding sand to the buffer tank, belt conveyors for transporting the removed molding sand (supplied with magnetic separators for metal parts), sieve chillers for sieving, dust collection and cooling of the return mass, bucket conveyors, a dust removal system for the mass preparation station, a sieve chiller, a vibration grate, and systems for controlling and visualization of the station operation.
Flaskless forming line	The flaskless molding line with vertical division of the mold should include: A buffer tank of the final molding sand, a belt conveyor, a DISA molding machine, a coring attachment, an automatic dispensing ladle ("PUROMAT" type), a pouring line, cooling line I, cooling line II, a vibration grate for knocking out castings, and a dust collection installation.
Castings cleaning line	The casting cleaning line includes a mesh conveyor, a tunnel cleaner, a belt conveyor, and a dust collection installation
Cast iron melting spot	**Variant I** The spot will consist of two existing modernized cupola furnaces, equipped with an installation for cleaning cupola dusts, so that the cleaning degree will be up to 95%. The spot is located in the place of the currently exploited cupola furnaces. **Variant II** The spot is designed to be equipped with a high frequency induction furnace with two crucibles with the batch capacity of 8 T each. In addition, the furnace will be equipped with a mechanized system of weighing the batch and loading the crucibles.

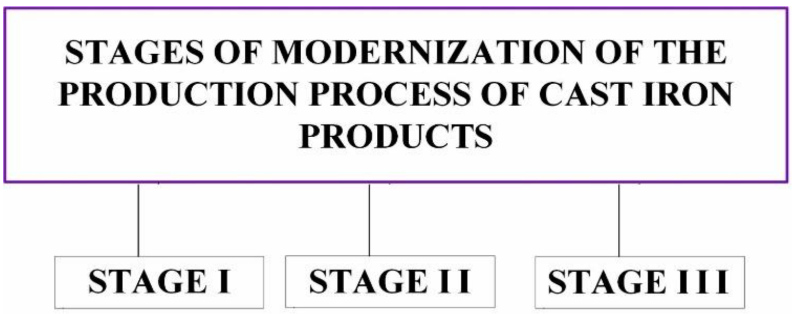

Figure 6. Schedule of modernization of the casting process.

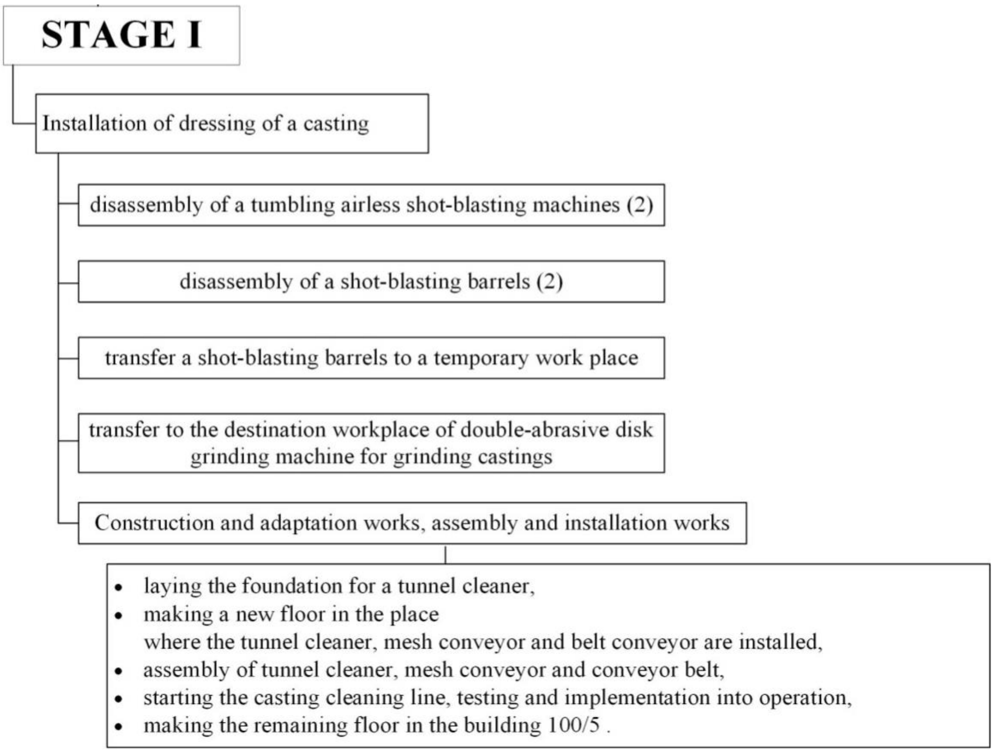

Figure 7. The first stage of modernization of the casting process.

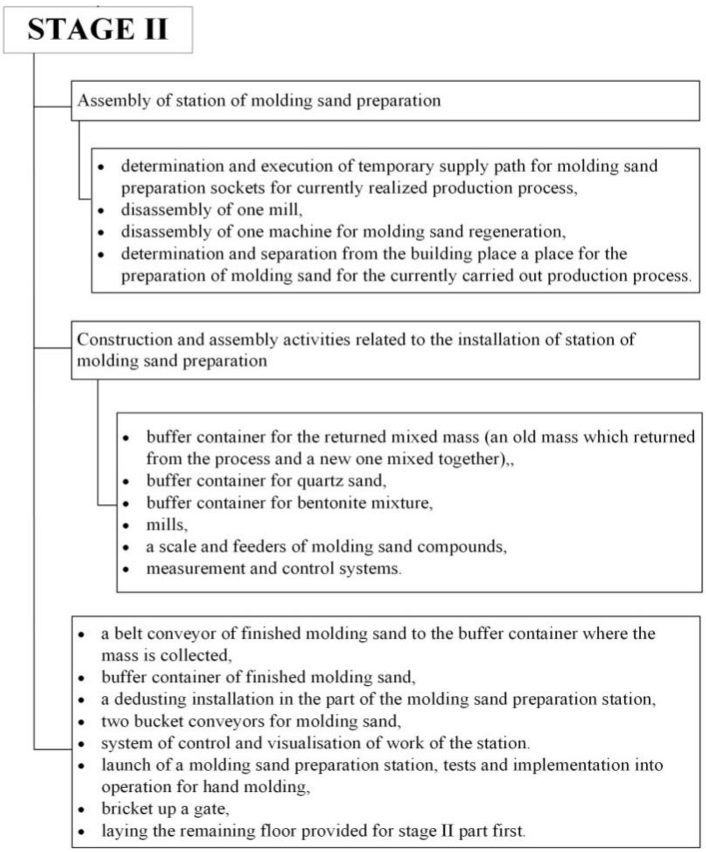

Figure 8. The second stage of modernization of the casting process.

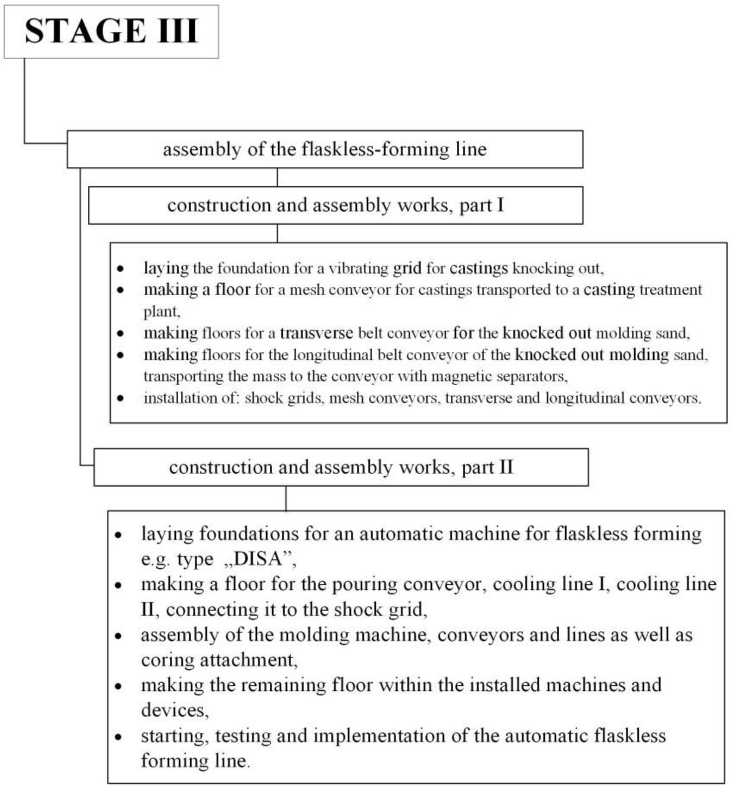

Figure 9. The third stage of modernization of the casting process.

The assumed effect of the first stage of modernization was mainly the improvement of the aesthetics of finished products, reduction of the number of flaw products (caused by mechanical damages), reduction in the number of transshipment and transport operations, and reduction of employment in the department of the cleaning of castings. The effect of the implementation of the second stage of modernization was to improve the quality of the molding sand, the reduction in the number of defects by improving the properties of the molding sand used. After the completion of this stage, molding sand will have better (but still not the target) properties. The effect of this stage of modernization was to obtain the target quality of molding sand, and to reduce employment through fully automating the work of the molding sand preparation station. The effect of the implementation of the third stage of modernization was, inter alia, ceasing of transport of the return circulating mass in an automatic cycle, closing of transport of castings in an automatic cycle, elimination of pollution (due to molding dust) of the foundry facilities, reduction of employment among workers removing castings from the molds, as well as the reduction of employment in the group of manual forming workers, reduction of molding sand losses, the possibility to carry out controls of all the prepared molding sand, reduction of losses due to the manual forming and assembling of casting flasks, eliminating the formation of casting flasks from the production process, increasing the production area thanks to storage area (casting flasks storage area and storage area for molds ready to fill-in), improving the foundry workers' working conditions, increasing the molding process efficiency (a 20 s automatic cycle), with the possibility of reducing it to 15 s.

It was assumed that the subsequent stages of modernization should also include modernization of the molding materials warehouse, modernization of the cast iron melting plant (two variants), and assembly of the mold pouring machine.

6. Conclusions

The common occurrence of cast iron castings requires, while implementation of new modified varieties, extensive operational tests in various branches of industry, namely:

- in the agricultural industry—cast iron for bodies of machines and devices working in field conditions with sand and artificial fertilizers, plant protection agents, in terms of surface wear;
- in the food industry, where resistance to cleaning agents is required—emulsifying and high smoothness requirements;
- in the machine tool industry, where vibration damping and vibration reduction are important factors, especially at currently used high cutting speeds;
- in the construction of road machines, where high resistance to local impacts is required.

In the era of the global market and very high competition, no manufacturing plant can afford inefficient, ineffective, and incorrect technology. The practical use of product properties (for example, the properties of the surface layer) by using the parameters of the already used technological process is one of the fundamental possibilities to increase the durability and reliability of each element of machine parts, including phosphoric castings.

Foundry processes are designed to form a semi-finished product in the shape of a finished product. These products must also have specific mechanical and operational properties.

In the case of foundry processes, the shape and the geometry of the casting must be consistent with structural requirements for free surfaces, while for functionally important surfaces (operating surfaces), due to increased requirements of shape and dimension accuracy, the grinding allowance is remained (grinding is the most commonly used finishing for castings) [24]. A characteristic feature of the foundry process being analyzed is the fact that, among all the features that the material possesses after a metallurgical process, the casting should have not only the same chemical composition, but also the same operating properties in its entire volume. In order to obtain the required geometrical shape of finished products on work surfaces, castings, as semi-finished products, can be subjected to machining processes.

Therefore, the foundry process, its quality, and efficiency are very important factors determining the position of the plant in the engineering industry. It is also necessary to constantly improve the efficiency of the foundry process, which in turn allows obtaining products of very good quality.

The expected effects of the proposed modernization of the foundry process should include:

- increase in the production of castings to min. 8000 T a year,
- improvement of the aesthetics of the castings produced,
- lowering the level of defective products by about 30%,
- reduction of employment in the group of production workers by about 25%,
- reduction of negative impact on the natural environment, reduction of pollutant emissions by about 25%
- improving the competitiveness of the production process, and thus the opportunity to acquire new customers,
- improving the working conditions for all production employees.

Funding: This research received no external funding.

Acknowledgments: M.R.D., K.K.D., W.W. acknowledge the financial support from the program of the Polish Minister of Science and Higher Education under the name "Regional Initiative of Excellence" in 2019–2022, project no. 003/RID/2018/19, funding amount 11 936 596.10 PLN.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Olofsson, J. Local microstructure-based material performance and damage in design and finite element simulations of cast components. *J. Comput. Des. Eng.* **2018**, *5*, 419–426. [CrossRef]
2. Pietrzak, K.; Klasik, A.; Kowalewski, Z.; Rudnik, D. Quantitative relationships between microstructural and mechanical parameters of steels with different carbon content. *Int. J. Mod. Phys. B* **2008**, *22*, 5819–5824. [CrossRef]

3. Rudnik, D.; Sobczak, N.; Gazda, A.; Homa, M.; Siewiorek, A.; Pietrzak, K.; Makowska, K. *Thermophysical Properties of Cast Iron Used in the Manufacture of Brake Discs*; Foundry Institute-Poland and World: Cracow, Poland, 2011; Volume 51, number 3; pp. 23–35.
4. Sobczak, J. *Forecasts and Development Trends in Global and Domestic Foundry*; Foundry Institute: Cracow, Poland, 2012. (In Polish)
5. Guzik, E. *Quality Evaluation of PE Method in the Productions of Modular and Vermicular Cast Iron*; Archives of foundry; Polish Science Academy (PAN): Katowice, Polish, 2006; Volume 6, book 19; pp. 131–140.
6. Brozio, M. Available online: https://polskiprzemysl.com.pl/wp-content/uploads/drawski-pp-w38.pdf/ (accessed on 29 August 2019).
7. Kuryło, P.; Frankovský, P.; Trebuňa, P.; Čižnár PKelemen, M. Modern Methods of Shaping the Surface Layer of Iron Casting. *Int. J. Appl. Eng. Res.* **2017**, *12*, 207–211.
8. Brodny, J. Friction modelling in mechanical systems. *J. Fac. Min. Saf. Eng. Ind. Autom.* **2010**, *5*, 7–17.
9. Płaza, S.; Margielewski, L.; Celichowski, G. *Wstęp do tribologii i tribochemia*; Wydawnictwo Uniwersytetu Łódzkiego: Łódź, Poland, 2005. (In Polish)
10. OliwiaŁupicka, O.; Warcholiński, B. Forming of the surface layer of 42CrMo4 steel in connected processes of shot peening and nitriding. *Surf. Eng.* **2011**, *16*, 43–49.
11. Starzyński, G.; Kucharski, S. Evolution of the Residual Stress State in the Surface Layer of the Elements under Torsion. In Proceedings of the AIMETA International Tribology Conference, LíAquilla, Italy, 20–22 September 2000.
12. Qiu, F.; Tong, H.-T.; Gao, Y.-Y.; Zou, Q.; Dong, B.-X.; Li, Q.; Chu, J.-G.; Chang, F.; Shu, S.-L.; Jiang, Q.-C. Microstructures and Compressive Properties of Al Matrix Composites Reinforced with Bimodal Hybrid In-Situ Nano-/Micro-Sized TiC Particles. *Materials* **2018**, *11*, 1284. [CrossRef]
13. Zhang, Z.; Dolbow, J.E. Remeshing strategies for large deformation problems with frictional contact and nearly incompressible materials. *Int. J. Numer. Methods Eng.* **2017**, *109*, 1289–1314. [CrossRef]
14. Kaźmierczak, A. *The Feasibility of the Titanium Nitride Coating on the Surface of the Piston Ring Engine Welding Technology Review Journal*; ZG SIMP Agenda Wydawnicza Przegląd Spawalnictwa: Warsaw, Poland, 2012; pp. 3–8.
15. Yang, S.; Li, W. Surface Quality and Finishing Technology. In *Surface Finishing Theory and New Technology*; Springer: Berlin/Heidelberg, Germany, 2018; ISBN 978-3-662-54131-9. [CrossRef]
16. Kurylo, P.; Janik, S. Criteria for selecting material for glass molds: New directions in production technology. In *V International Conferences*; Procedure: Presov, Slovakia, 2000; pp. 91–98. (In Slovakia)
17. Kurylo, P.; Janik, S.; Jenek, M. Taking advantages of the top layer properties of casts of the spheroidal cast iron 500-7. *Stud. Mater. (Mach. Technol.)* **2002**, *20*, 361–368. (In Polish)
18. Kurylo, P.; Janik, S. Choose method of formation of surface layer from cast-iron casts. In *Proizvodstvo: Technologija: Ekologija—PROTEK 2005*; Sborniknaucnychtrudov: Moskva, Russia; MGGU "Stankin": Moskva, Russia, 2005; Volume 1, pp. 24–43.
19. Musial, J.; Barycki, A.; Troszynski, A. *Forming Surface Layer Technological of the Rolling Elements Kinematic Pairs*; Logistyka vol. 4/2015; Logistic Journal by The Institute of Logistics and Warehousing (ILiM) in Poznan; The Institute of Logistics and Warehousing (ILiM): Bydgoszcz, Poland, 2015; pp. 2043–2049.
20. Gumienny, G. Wear resistance of cast iron. *Arch. Foundry Eng.* **2008**, *8*, 173–180.
21. Kurylo, P. Possibility of Taking Advantages of the Top Layer Properties of the Spheroidal Cast Iron Casts This Paper Is Not yet in Our Corpus. Ph.D. Thesis, The Publishing House of Poznan University of Technology, Poznan, Poland, 2003. (In Polish).
22. Canale, L.C.F.; Mesquita, R.A.; Totten, G.E. *Failure Analysis of Heat Treated Steel Components*; ASM International: Materials Park, OH, USA, 2008; pp. 204–586. ISBN1 13 978-0-87170-868-7. ISBN2 10 0-87170-868-X.
23. Odlewnia Spomel. Available online: http://spomel.com.pl/fosforowe.html (accessed on 23 September 2018).
24. Khan, S. Analysis of Tribological Applications of Functionally Graded Materials in Mobility Engineering. *Int. J. Sci. Eng. Res.* **2015**, *6*, 1150–1160.