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Technologies for high-temperature batch annealing of grain-oriented electrical steel: An overview

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Abstract: The production of grain-oriented, electrical steel consists of a series of processes that lead to a product with superior magnetic properties used in transformers due to the low core loss. The unique properties are gained during the process of secondary recrystallization and abnormal grain growth. The abnormal grain growth occurs during a process of special thermal treatment with careful control over the heating rate, pressure, and type of gas used as atmospheric pressure during the process. The process of thermal treatment is known as high-temperature annealing. Investigating of developing the process hardware is crucially important to sustain energy-efficient processes and to maintain excellent final product properties. This research presents an overview of the technology of high-temperature coil annealing (HTCA) furnaces used at Cogent Power Orb, UK. The research focuses on some specific details of running, managing, and controlling the operation of the HTCA furnaces during the annealing process. The research provides energy analysis of the annealing process at Cogent Power Orb. Different factors were examined to identify the main factors that contribute to the high energy consumption. Actual data were collected from the annealing furnace control system. The raw data were processed and analyzed carefully to examine different factors, namely, steel charge weight, furnace on-time, and furnace heating elements. The study focused then on one specific factor, namely, annealing cycle time, and investigated further the way that this factor affects the process energy consumption. It was found that one of the main reasons for the long cycle duration and the high energy consumption is the failure of the heating elements during the cycle. The research discussed the area of improvements in the process hardware with a particular focus on the furnace design and the potential of introducing convection currents to overcome failure in the heating elements and thus reduce the process on time.

Keywords: annealing furnaces, energy efficiency, electrical steel, grain-oriented, analysis of energy consumption

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1 Introduction

Grain oriented (GO) is a special type of electrical steel produced by cold-rolling and annealing hot-rolled silicon steel sheets to meet commercial standards for thickness. This process involves subjecting the steel to a series of treatments, resulting in a product with improved magnetic properties and reduced energy loss. The resulting GO steel is commonly used in the production of electrical transformers and motors, where its low energy loss and high magnetic permeability make it an ideal choice for efficient and effective electrical performance. The abnormal grain growth occurs when secondary recrystallization process is applied to the steel sheet of different thickness. This process includes decarburizing annealing in a wet hydrogen atmosphere. Then, the final annealing (high level of temperature) will be applied for the time period of more than 10 h under the level of temperature (greater than 1,100°C). Only a high level of secondary recrystallization can guarantee excellent electrical steel properties such as low core losses [1]. Steel sheets with a high magnetic flux density are those that have reached the right level of secondary recrystallization.

The magnetic properties are developed in the coil annealing at high temperatures. This is a critical stage in GO manufacturing, requiring accurate control over the gas composition and the rate of applied heating. After decarburizing, the high-temperature process of annealing is carried out. Decarburizing is performed to relieve the existing residual stresses due to the reduction in thickness of the steel strip and to enable recovery and recrystallization following changes in crystalline structure after the cold working [2,3].

The production process of GO electrical steel includes many different and multiple processes, starting from obtaining raw materials until reaching the final stages of production of thin steel sheets with abnormal grain growth structures. But one of the most important disadvantages of this process is the high energy use. One of the most general factors affecting the percentage of energy required is annealing, as an increase in the required temperature requires higher energy consumption. In fact, upon extensive and extensive research into the available adapters, it was found that there is very little research on energy analysis in the production of GO steel in Orb Cogent Power. The lack of research in this field creates a large research gap, and this gap requires comprehensive research efforts for studying, analyzing, and addressing the high energy consumption associated with the high-temperature annealing process. The primary objective of this study is to determine and analyze the energy of the high-temperature annealing process in the production of GO and find solutions, based on data collected from Orb Cogent Power, which is part of TATA Steel, based in the United Kingdom. Energy consumption patterns were studied in depth, and practical and fundamental solutions were presented to identify potential energy-saving areas. In addition, this study provided different insights to improve energy efficiency in the GO production cycle. The importance of these research results lies in finding solutions to reduce energy consumption, which will contribute to the development of this process device by identifying the main contributor to energy consumption and proposing some solutions. The results of this study can contribute to the development of devices used in the production of electrical steel.

2 High-temperature-level annealing process

During the high-temperature annealing process, the material undergoes purification, secondary recrystallization, and the formation of forsterite on the surface. The grain size and shape that are affected by temperature adjacent/or around the recrystallization temperature and the holding period at the specified temperature are what allow primary and secondary recrystallization to improve the mechanical properties of the strip. Glass film creation and strip purification are also accomplished during the procedure [4]. An accurate control system was applied to monitor and control the parameters of the process (heating rates, gas composition, and annealing time) according to the used weight.

License holders of high-permeability materials describe accurately the variation of heating rates during the process time. Any deviation above or under the specific value may lead to difficulties in generating an optimal Goss orientation [5]. A crucial factor in assessing the effectiveness of the annealing system is the variation in coil temperatures since it influences the necessary metallurgical modifications and results in uneven mechanical characteristics all the way down the steel strip. It can be considered that the coil temperature difference is the main key parameter when it is required to find the efficiency and performance of an annealing process. The required metallurgical transformations can be affected, and this leads to the steel strip having non-uniform mechanical characteristics. The glass film is formed during the heating phase (cycle), and secondary recrystallization occurs. It should reduce the temperature variation to the minimum level to ensure appearing uniform and optimal changes in the microstructure throughout the coil. In addition, the outer areas of the coil are annealing for a longer period due to the presence of a temperature gradient, which is ideally required. Excessive annealing will occur as a result of remaining for longer periods at the above-mentioned recrystallization temperature. On the other hand, sites that are slower to respond to heat are susceptible to under-annealed.

2.1 Annealing process procedures

The main elements of the batch annealing are the cooling and the heating steel coils in the transportable furnace. The main focus in the development field of batch annealing is on optimizing hardware performance and identifying the optimal cycle periods to obtain the required metallurgical characteristics.

Adopting hydrogen-based high convection batch annealing is one such hardware improvement [6,7] owing to the high magnitude of hydrogen's thermal conductivity, where the value of hydrogen's thermal conductivity is equal to seven times the nitrogen's thermal conductivity under the same temperature [8]. The hydrogen content also exerts an influence on the development of secondary recrystallization through its effect on oxidation processes [9]. Significant progress in the annealing process was observed when applied of 100% hydrogen gas, which, in turn, has reduced effectively the process duration [10].

The lowest/slowest heating and cooling rates occurred when using the ordinary batch annealing furnaces that used an NHx mixture of 90% nitrogen and 10% hydrogen as a shielding gas [10]. In order to penetrate the steel coil layers for the high-level convection batch annealing, a large volume flow rate of recirculating gas is needed. The high-temperature coil annealing (HTCA) furnaces are not like traditional batch annealing facilities in several ways, because they have special specifications such as high-level temperature (extreme level) and processing conditions. In the traditional batch system, during the time when the burner heats the charge, it was used a fan at the furnace base to circulate the ambient gas around. The electrical elements mounted on the walls of the HTCA furnace were used to heat up the steel charge. The main reasons to use a fan are the high level of temperature and large hydrogen gas content to distribute atmospheric gas, which is considered one of the challenges that facing engineers.

The typical steel coil charge consists of eight strip coils, each of which needs a lengthy time to be heated due to its average diameter of about 1,300 mm and weight of about 10 tones. When heating, the coil bore heats more slowly than the exterior [11]. The heating process will be stopped when the two main conditions are met: (1) the coil's temperature reaches a specified level according to the setup conditions, and (2) when the difference between high and low temperatures is less than 30 C in the coils [12].

3 High-temperature-level coil annealing furnace

Generally, in the HTCA furnaces, when it will be delivered an accurate thermal cycle, this will lead to reaching the product's mechanical and magnetic properties to the acquiring level. Two main two parts in the furnace are the base (hearth) and bell, in addition to the stacking components (including the separator plates and the inner covers). The bell is a movable part and is lowered over the base once the inner covers and coil charge are properly positioned, while the hearth part is fixed. Thermocouples placed at specified points throughout the bell and base provide temperature readings that are used by a process computer to manage the annealing cycle. During the cycle, the flow rates and the gas compositions are accurately monitored. The heating devices were distributed on the base and bell walls, as shown in Figure 1. Eight coils can normally be charged in the furnace, with a maximum weight of about 70 tons overall.

3.1 Hearth

It was designed the hearth to be around the steel frame and encased by the firebrick. A steel trough encircling the perimeter of the rectangular hearth is divided lengthwise by a steel plate. The inner area is filled with sand and the outer section with water to create an efficient seal when dropped the steel skirts that are connected to the bell into the two

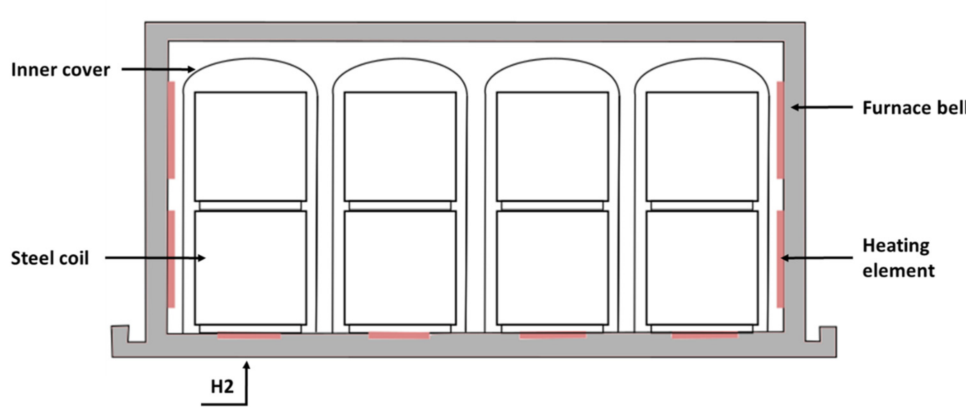

Figure 1: Schematic diagram of batch annealing furnace.

Figure 2: Furnace hearth at Orb electrical steel.

hearth troughs. This seal serves as the primary furnace seal, preventing air from entering or furnace gas from escaping, both of which increase the risk of an explosion [13].

Four circular recesses with electrical base heating components are located along the longitudinal axis of the hearth. To make coil loading easier, a steel base plate is set atop the recesses. As illustrated in Figure 2, the hearth is supplied with an emergency nitrogen purge intake and four inlet pipes for gas that are mounted in the four recesses.

3.2 Bell

Figure 3 illustrates a schematic of the suction caused by the bell of the furnace placed on the hearth without the separator plate and the charge. The four vertical walls in the removable furnace (Figure 1) are covered with electrical heating elements. Some coils therefore receive more energy from the furnace than others. The heating element radiation and convection through the process gas heat up the charge. These variations are not controllable because the furnace temperature is used to operate the control system. During cooling, a gas-filled cavity in the bell is removed from the furnace and circulated *via* a heat exchanger before being reinserted into the furnace. The inner cover is also shown in Figure 3. To prevent oxidation, the inner cover, which also serves as a radiation shield, is essential in keeping the ambient gas at a pressure greater than that of the furnace

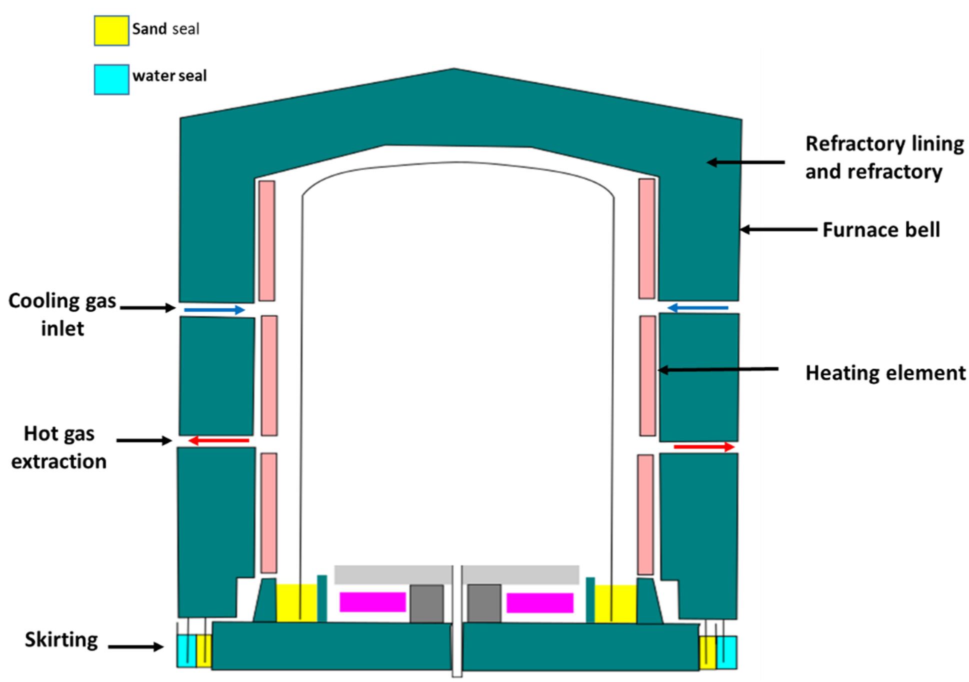

Figure 3: Schematic diagram of HTCA furnace bell.

bell. The bell's internal geometry is designed to reduce pressure losses and guarantee that the steel charge is heated and cooled uniformly.

HTCA furnaces and hearths require a high level of maintenance, due to the annealing process that takes place at a high temperature. Electrical failure occasionally happens because of a short circuit or, worse due to open circuit. In the case of an open circuit, the current cannot flow through the heating element, which might be caused by damage to the heating elements during the packing process.

4 Scheduling of the HTCA process

The steel charge is arranged in a specific sequence (started by the steel charge, separated plates, inner covers, and finally with the furnace bell), where the HTCA furnaces operate on a fixed base. A traveling overhead crane is used for every operation in the process. The procedure begins with the sequential stacking of separator plates and steel coils – two coils per stack – atop an empty base. The steel covers are added over the coil-laden stacks and sand-sealed at the base, completing the gas's protective atmosphere. In the next step, the deoxidizing gas flow is started to remove all of the air from the area beneath the cover. Three primary functions of the protective atmospheric gas are carbon removal, oxidation prevention, and carbon absorption. Therefore, the magnetic properties and the development of the grain structures are affected significantly by the gas composition [14,15]. The gas injection to the steel charge and the steel coil is depicted in Figure 4. After penetrating the sand seal, the gas enters the area beneath the furnace bell, where the furnace bell is moved to be lowered on the base. The pipes for the cooling system, thermocouple devices, and power supply connections are all made.

The initial step in the cycle is started by heating the coils bit-by-bit under the gas of working conditions that consists of a mixture of hydrogen and nitrogen. The charge is held at 750°C in the process of low soak temperature to allow lagging sections of the charge to reach the same temperature as warmer parts before progressing to higher temperatures. Then, the charge is maintained at a precisely regulated heating rate of about 1,200°C in a dry hydrogen atmosphere. According to the correlation between the holding time and the outer coil diameter, it was found that it needs 1 h for each inch in the section [16]. When the annealing conditions are met, the heating process ceases. A mixture of NHx ambient gas is used for cooling. During the cooling stage, the cooling fan is turned on and the furnace is shut off. After removing the furnace, the charge is allowed to cool naturally.

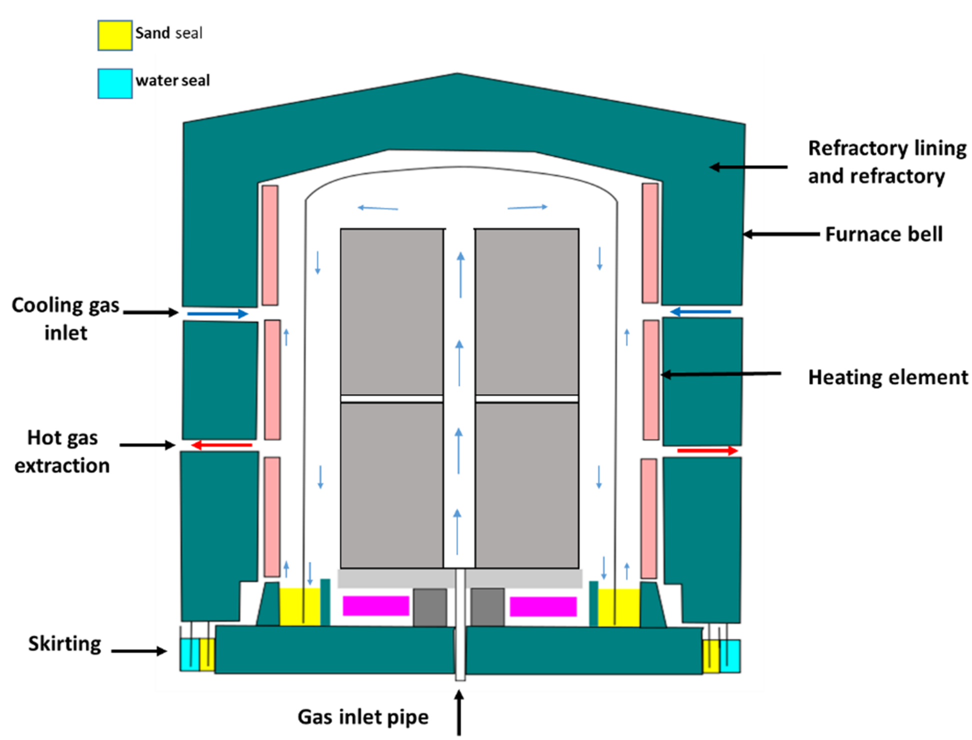

Figure 4: Coil stacks inside the HTCA furnace.

5 HTCA unit topology and monitoring

The battery system of the HTCA unit at Orb Electrical Steel is composed of eight batteries (denoted from A to H). All of these batteries have four bases (hearths), excluding the battery (C) that has two bases. The HTCA monitoring system closely observes the annealing cycle at each base. It assists the HTCA furnace operators by keeping them informed about the status of the process at each battery. The monitoring system provides the operators with detailed information about each charge such as product cycle number, segment type (heating or cooling), soak time, cycle duration, average temperature, gas type, and gas flow rate. Certain information, such as cycle number, soaking time, and cycle duration, is relevant to productivity and particularly important in energy consumption data. For that reason, this information is always noted and preserved in the charge history records.

Power supplies were indexed from each battery according to two terms: supply A and supply B. Every battery has four bases vying for two supplies, except for battery C, which is more productive than the others since it has as many supplies as hearths. The processes are scheduled based on the capacity of the batteries to ensure that all of the batteries in the HTCA unit are as productive as possible.

The HTCA unit uses several furnaces, and various bases can be used with different furnaces. When the cycle is finished and the furnace is lifted, it can be applied if there is any maintenance work is needed; otherwise, it can be applied. In order to heat up the furnace's structure, the main two factors are the time and energy, including the refractory and internal supports, to the working temperature that could be saved by using the furnace continuously before it cools down [17].

The monitoring system of the bases of an HTCA battery system provides the operators with information such as segment type (heating, cooling, or soaking), gas type, gas flow rate soaking, and cycle duration. All four bases function together; when two run, the other two are discharged from the steel coils or prepared for a new cycle. A new cycle can start as soon as the procedure ceases at one of the bases that are in use because the supply can be reconnected in a very short time to other bases.

6 Energy data collection

Data of the daily energy consumption was collected individually of the eight batteries from the Orb intranet to be the raw data of the present research. The range of date of collected data was started from 2014 to the 22nd week of 2017. This is to collect as many samples of energy

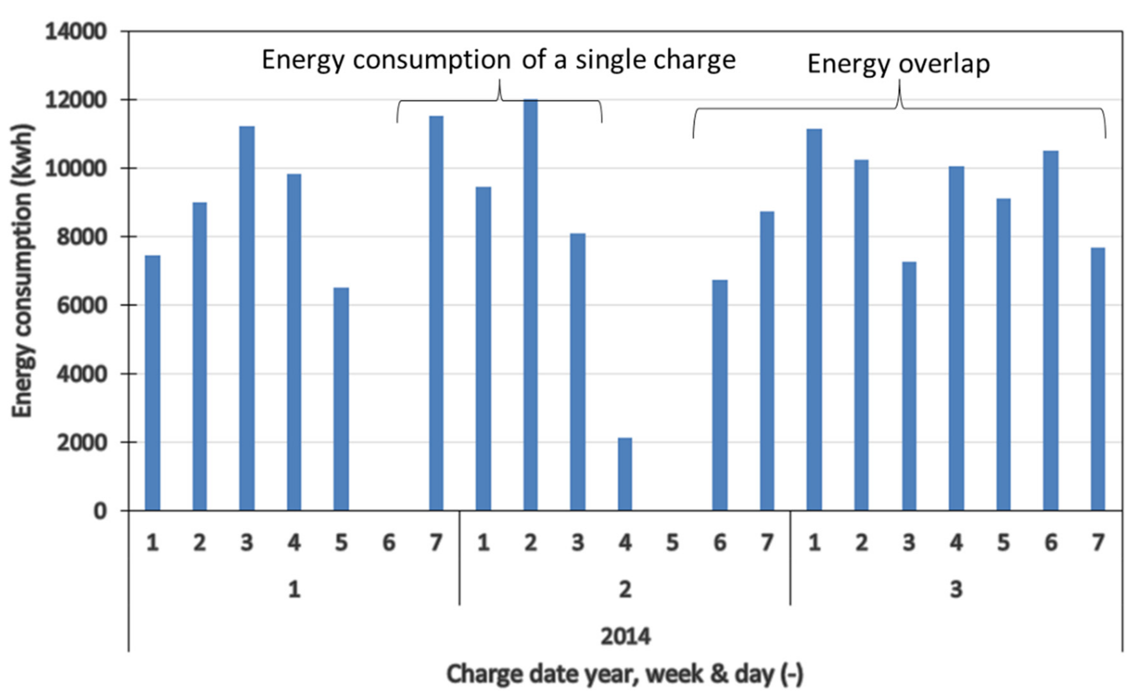

Figure 5: Daily records of the energy consumption of the steel charges.

consumption of annealing cycles as possible to analyze with a sufficient number of charges. Initially, a time interval during which only one steel coil charge is in process at the designated battery was determined by analyzing the daily energy usage records. The data have some energy overlap, making it difficult to determine the period for the single steel charge; therefore, this step required careful attention (Figure 5). The energy overlapping refers to a situation where multiple energy sources or systems are utilized simultaneously, resulting in an overlap or intersection of their functions or effects. In the case of the annealing furnaces, the energy overlap occurs due to the short time gap between two consecutive cycles on the same battery, as well as the simultaneous use of the same power supply on another base through the same day, as discussed in Section 5.

The normal annealing cycle duration of 4 to 6 days was the criterion used to verify the samples: records for time intervals longer or shorter than that were deemed to have energy overlap (Figure 5). Following the identification of the steel charge sample from the raw data, more data were gathered to obtain the specifics of each charge, including the number of charge number, number of the cycle, number of the furnace, mass, heating, and soaking times. In the period of collection data (2014–2017), around 300 samples for charges were collected and examined to assess the influence of the energy consumption for each contributor.

7 Energy consumption contributors

The initial step toward energy conservation is examining the various process parameters and determining which ones have the greatest impact on energy consumption. This section explored two potential energy consumers using data from Orb Intranet: (i) the weight of charge and (ii) the time of process. Figure 6 illustrates the consumption of energy (kW h) for HTCA charges from 2014 to 2017. Energy consumption of 24,000–28,000 kW h was excluded from further energy analysis as they were deemed outliers. They exhibit notable variations in values across a variety of samples and account for merely 1% of the charges that were gathered. Additionally, the exclusion of the outliers was predicated on their frequencies across the examined time period, during which comparable values did not appear.

Two distinct energy-consuming factors – the charge weight and cycle's on-time – will be examined in the following sections. To learn more about how dependent those contributors' variations are on energy usage, the coefficient of determination was employed. It can be considered that the correlation coefficient (R^2) is the main key of the regression analysis. It can be defined as the percentage of the variance in the independent variable (contributors) that can be predicted from the dependent variable (consumed energy).

According to the linear regression model that includes one independent variable, the following factor can be determined [18]:

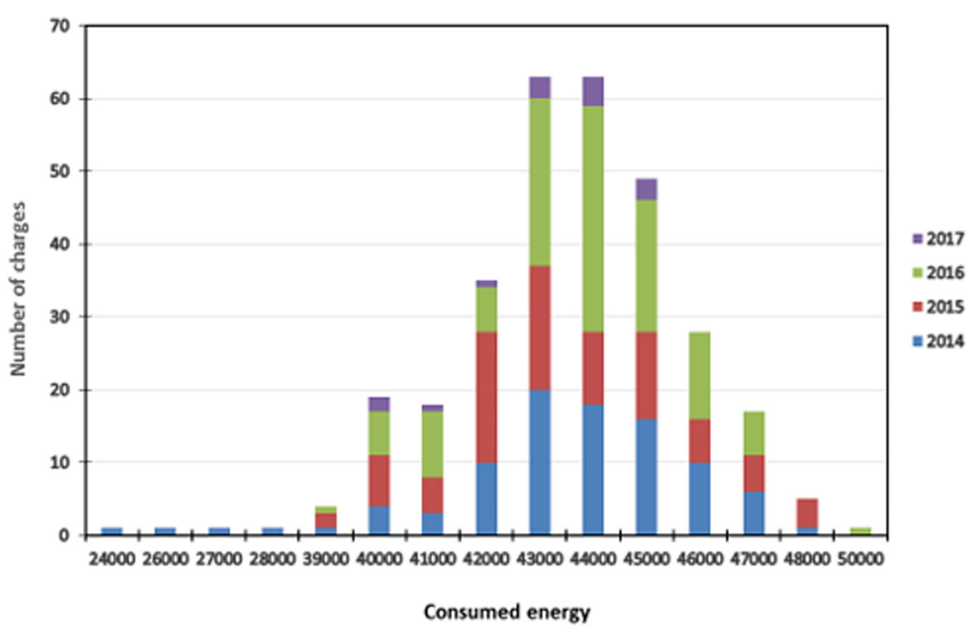

Figure 6: Distribution of energy consumed in HTCA charges.

$$R^2 = \left\{\left(\frac{1}{n}\right) \times \sum[(X_i - \bar{X}) \times (y_i - \bar{y})]/(\sigma_X - \sigma_y)\right\}, \quad (1)$$

where n is the number of observations of data, X_i is the observation of X value of data; $\bar{X}$ is the mean value, y_i is the observation of y value of data, ad σ_X and σ_y are the standard deviations of X and y.

A value between 0 and 1 indicates the extent to which the dependent variable is predictable when $R^2 = 0$, which means that the energy consumption cannot be predicted from the contributor, and vice versa for $R^2 = 1$.

7.1 The charge weight

Furnaces' fuel efficiency is often measured in terms of the amount of fuel or electrical energy used to heat a unit weight of load [19]. During the heat treatment process, the steel coils absorb a large quantity of heating energy to accomplish the necessary chemical changes. The heating energy is directly related to the weight of the charge. So, this useful energy can be determined as follows:

$$Q = \dot{m} \int_{T_{\text{initial}}}^{T_{\text{final}}} C_{\text{p}}(T)\text{d}T, \quad (2)$$

where C_{p} denotes the steel's specific heat and it is a function of temperature. Buckley [20] reported the variations in the values of electrical steels with a silica concentration of 3.15%. Equation (2) was used to compute the theoretical energy of 91.84 GJ needed to heat 70 tons of steel to the annealing temperature of 1,190°C. Throughout the procedure, the furnace is filled with specified flow rates of gases (H2, N2, and 3HN) at room temperature. As a result, more heat is needed to heat the injected gases. Using changes in gas enthalpies of the entrance and final states during the procedure, the theoretical energy was computed. It was found that approximately 1.9 GJ is the total energy used to heat the injected gases during the annealing process. Carefully selected steel charges were used to examine the true relationship between energy consumption and charge weight. When choosing the group, a possible factor – specifically an unusually long cycle time – was omitted to obtain reliable results. The cycle time was adjusted to correspond to a standard annealing procedure by limiting the soaking period to strictly 28 h.

Figure 7 illustrates the intricate relationship between consumed energy and charge weight during the steel coil annealing process. Contrary to expectations, the figure reveals that estimating energy requirements solely based on charge weight proves challenging. Notably, certain heavy-weight charges exhibit lower energy consumption than their lighter counterparts. This phenomenon primarily stems from the influence of process parameters and furnace efficiency during the annealing process. The R^2 coefficient value of 0.25 implies that 25% of the energy consumed can be accounted for by the charge weight, highlighting the need to consider other factors such as process parameters and furnace efficiency to accurately estimate energy requirements during the annealing process.

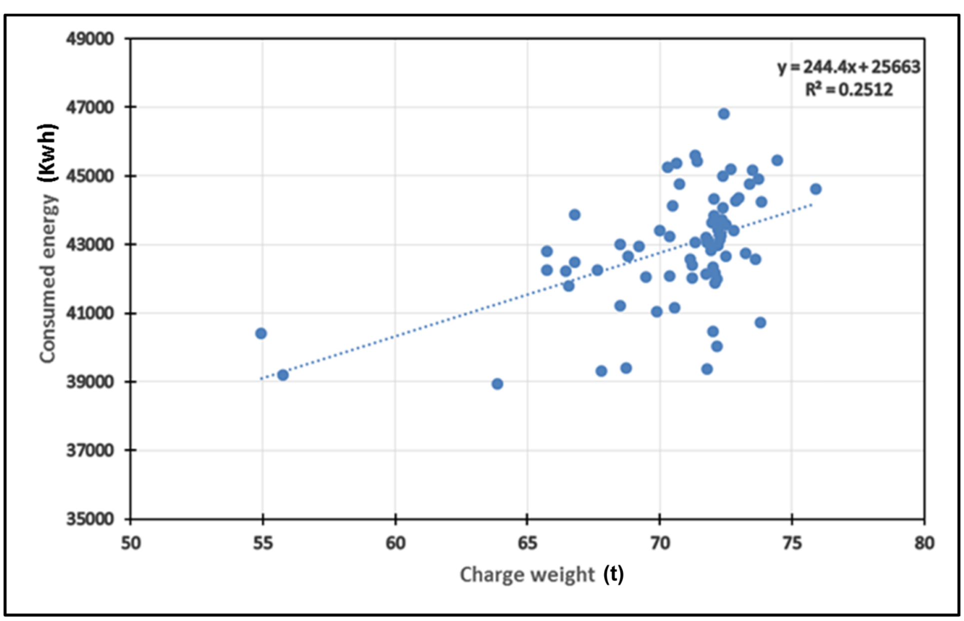

Figure 7: Relationship between energy consumption and charge weight.

7.2 Furnace on-time

The term “on-time” refers to the whole period (interval) of the furnace when it is running during a single cycle, including the heating and soaking phases but not cooling as the furnace during this segment is turned off. According to the process parameters, it will be changed, including the demands of a cycle, the furnace’s temperature, and any disruptive events that may arise. To determine how much of the charges’ energy consumption can be predicted from the process on time, a batch of charges weighing between 70 and 72 tons was chosen.

Any disruptive sources that lead to an increase in the cycle time were omitted. The amount of consumed electrical power (Q_{el}) is a function of the running time, where it can be used in Equation (3) to calculate the total amount of electrical power consumed:

$$Q_{el} = Pt_{total}, \tag{3}$$

where t_{total} is the on-time, and P is the power load (active).

It is noted that certain charges exhibit illogical discrepancies and disagreement with Equation (3). The cycles with low on-time consumed higher energy compared with cycles with high on-time. The coefficient of determination shows that the energy consumed over the cycle is only predicted to a very low degree (21%) (Figure 8). This again emphasizes the need to consider other factors such as process parameters and furnace efficiency to accurately estimate energy requirements during the annealing process. In the next section, the research examines one of the parameters that have a remarkable influence on the annealing time: the electrical failure of heating elements.

7.3 Furnace heating elements

Each base plate in the hearth of the furnace has electrical heating elements underneath it, and additional elements are fixed to the interior walls of the furnace. According to HTCA’s manufacturer, Almor Group, the HTCA furnaces installed at Cogent Orb Works provide a connected total thermal input of 770 kW gross. According to a typical electric resistance heating element efficiency of 97%, the total net capacity is 747 kW. However, the furnace hearth beneath each coil stack has a net input of 87 kW. The sole purposes of the base’s heating elements are to keep the refractory material at a certain temperature and slightly heat the product coils. The thermocouples are installed permanently at the furnace’s base and internal walls. They monitor the thermal profile. The thermocouples are used to measure the temperature of the baseplate and furnace atmosphere temperature in four zones.

Since the heating elements operate at the peak of their capabilities, careful observation is necessary to ensure their suitability for use. Throughout the annealing process, the HTCA monitoring system monitors the condition of each heating zone at the furnace walls as well as at the base to identify any sag or failure in the heating elements. The monitoring system identifies the heating element

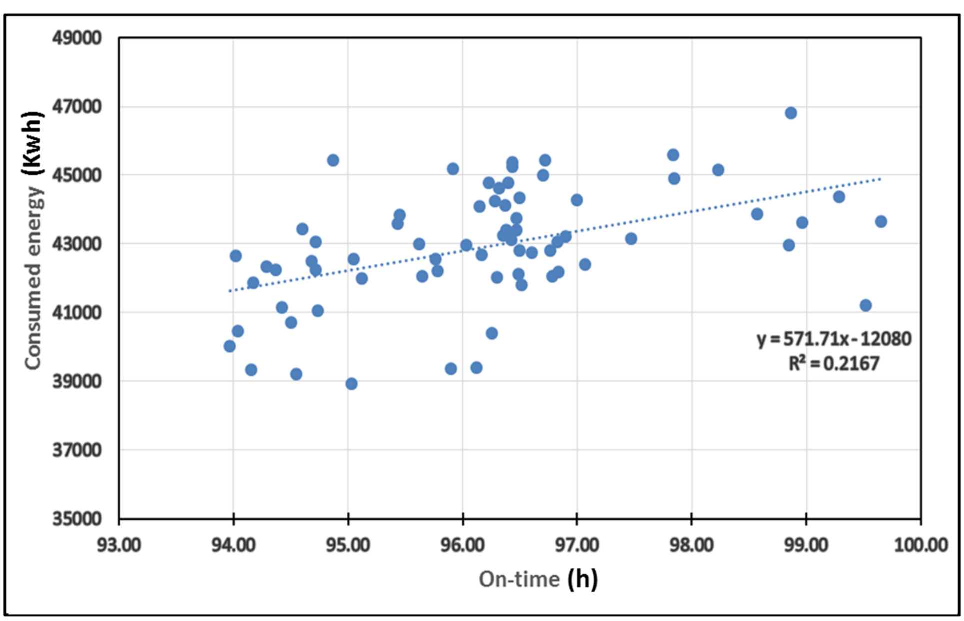

Figure 8: Relationship between energy consumption and furnace on-time.

experiencing a sag situation by labeling it as "fault" and as "off" when the heating element is in a short-circuit situation. The charge history records contain a report on every failure that occurs during the process. These records are kept for energy analysis purposes.

The elements occasionally sag or suffer short circuits when the current is unable to flow. Heat loss *via* the base material refractory makes an electrical failure in the hearth elements more problematic than in the wall components. This produces a zone where there is a lack of heat, which may indicate that the coils are not being properly heat-treated. This can have an impact on the qualities of the finished product, the length of the process, and the amount of energy used.

Figure 9 illustrates the energy consumption for steel charges that were annealed under typical annealing circumstances. The soaking time was 28 h, and the heating time was 67–72 h. HTCA set the weight of each charge at 70–72 tons.

Although the charges were handled in various furnaces with varying levels of efficiency, the average energy consumed – roughly 42,000 kW h – is considered to be normal for processing an annealing cycle. An energy benchmarking of the two most generated cycles is shown in Figure 10. The charges' samples were chosen carefully to highlight the impact of extended process durations on energy consumption and their connection to the events of electrical failure. The chosen charges were all between 70 and 72 tons in weight, had experienced some electrical failure in the wall and base heating elements, and required precisely 36 h to soak at 1,190°C.

Energy is still used throughout the soaking time to keep the temperature at 1,190°C and to enable some of the coils' lagging parts – which are near the inactive heating elements – to reach the same level of temperature as during the highly heated soak period. Certain charges utilized less energy than other charges with the same conditions, even with the heating elements failing. The strong possibility is that the charges were treated in a furnace that had low shell losses and exceptionally excellent performance.

8 Thermal efficiency of HTCA furnaces

This section presents an evaluation of the HTCA's performance based on reports conducted by Orb Works in 2013 regarding energy efficiency [21]. Three main reasons were identified for the high energy consumption by the HTCA unit: shell losses (losses from the outer shell of the furnace), losses due to maintenance, and long thermal cycling losses.

The furnace's almost 50-year-old design and the lining's materials caused a considerable amount of heat loss from the casing. As per the reports, the annual losses resulting from radiation and convection from the furnace's exterior surface during the heating and soaking stages of the annealing cycle were approximated to be more than

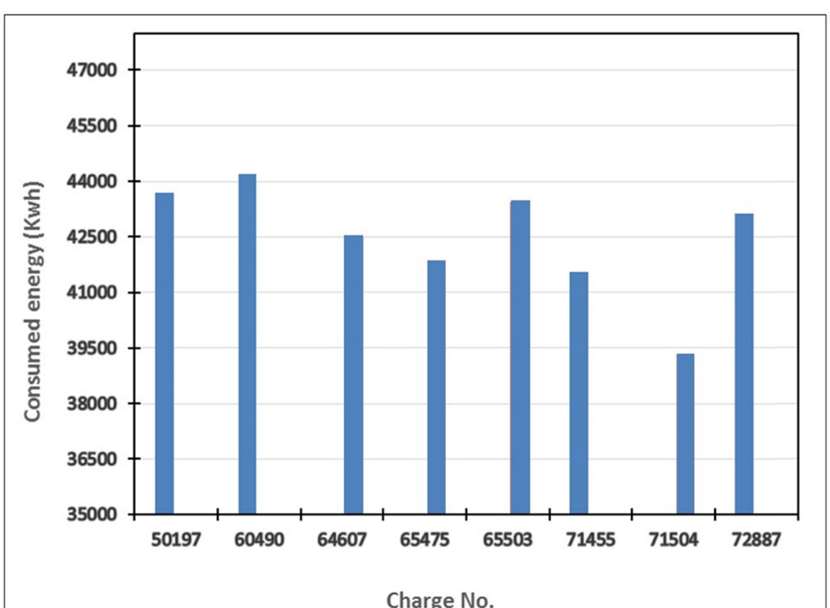

Figure 9: Energy consumption benchmarking of two cycles during a typical annealing process.

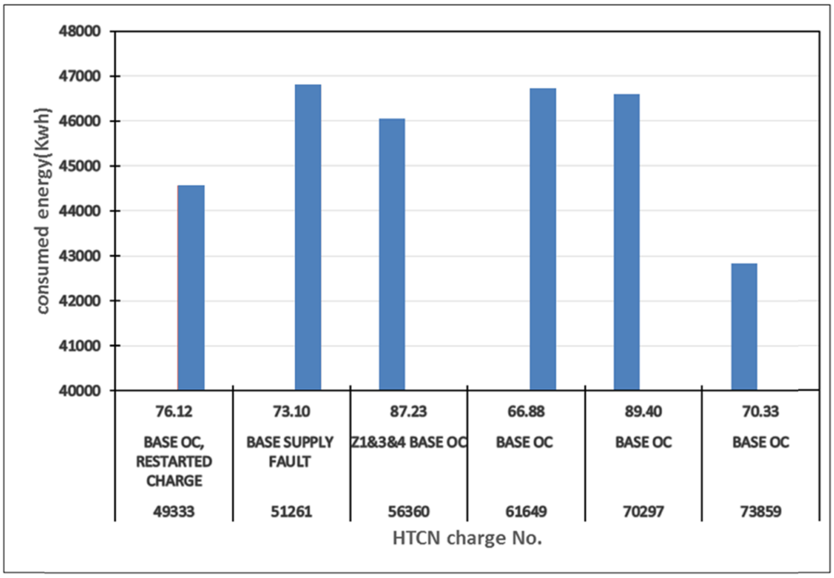

Figure 10: Energy consumption benchmarking during electrical failure.

7 GW h for all furnaces. This is equivalent to more than £400,000 in monetary terms, a sum that might rise in response to increases in energy prices. When a furnace is removed, its heat is lost since it needs to cool down to perform any required maintenance or inspection. According to reports, this amounts to more than 80 MW h annually for all of the annealing unit's furnaces.

Long thermal cycles result in losses because of the additional time and energy consumed when the heating cycle is prolonged as a result of open circuits. The annual total of these direct losses is more than £50,000. This results from the cycle being extended by 8 h for base open circuits and 2 h for zone open circuits.

Reducing cycle duration can reduce energy consumption. By reducing the effects of thermal cycling inefficiently and hotspot formation due to huge temperature variations across the furnace, a shorter cycle time can easily be achieved. Fluid recirculation is required to achieve this during the annealing process. Fluid recirculation helps in redistributing the heat within the furnace chamber, preventing hotspots.

9 Discussions

The main objectives of the industrial research activities are to enhance the performance and reduce the costs of manufacturing. This will be accomplished by enhancing processes, conserving energy and materials, maintaining market competitiveness, and adhering to environmental regulations. Considerable research and development work has been done to increase the productivity of GO electrical steel. All efforts were focused on enhancing the performance of hardware and optimizing the production cycle times.

For many years, the GO steel production companies have sought to reduce the cycle time and energy consumption of annealing furnaces during the forging process. To increase safety, lower maintenance costs, and prolong furnace life, manufacturers have also examined contemporary furnace building materials. Nevertheless, the development in the heating sector was not at the expected level. The reasons for this are many: the nature of the industry, the size of the companies that offer industrial heating systems, and the dependence of the whole plant on the heating system.

There have been attempts at Orb Steel Works to improve convection and optimize the annealing cycle time by developing the HTCA furnace. A new design was proposed to enhance the heat convection in the HTCA furnace and reduce the time of cycle [22]. Also, there is another suggestion for using rotation to advance turbulence behavior through the atmospheric gas's process [23]. In the case of electrical steel coils coated with MgO, convection heat transfer is preferable to radiation for materials with low surface emissivity. A proposed redesign of the furnace suggested the use of an impeller to increase convection within the furnace. The impeller circulates the gas around the charge, allowing heat from areas experiencing excessive temperatures to be scrubbed and transported by gas to cooler areas. Super-alloy fan/impellers are expensive and cannot cope with high annealing temperatures. It is also

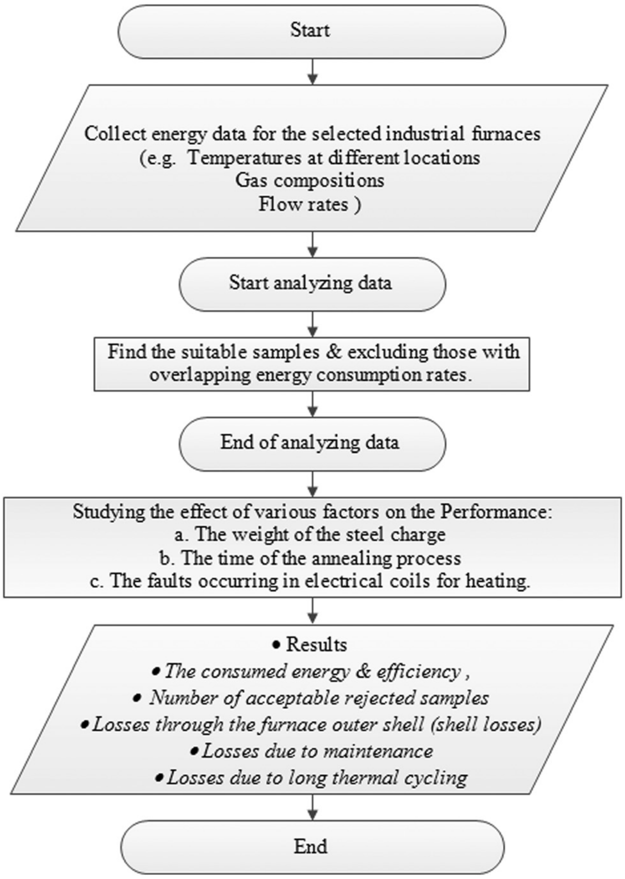

Figure 11: Flowchart of the energy analysis of the annealing process in the industrial furnace.

necessary to do engineering work to convert the base so that it can power and seal the fans perfectly. The HTCA furnace works under a hydrogen-based atmosphere. Redesigning and retrofitting existing HTA furnaces may not be a viable option. A radical new design with appropriate technologies installed may be the optimum solution as obsolete HTA assets are replaced. Figure 11 shows the main steps of the energy analysis of the annealing process in the industrial furnace.

10 Conclusions

This study has covered the energy analysis study of the annealing process of GO electrical steel. There is a lack of research in the literature to address the energy analysis of batch annealing furnaces and to investigate the possible options of optimizing the annealing cycle duration. The results of this study are summarized in the following points:

- Based on the energy analysis, it was found that 25% of the consumed energy is predictable from the charge weight. While the coefficient of determination shows a considerable degree of prediction (21%) of the consumed energy over the cycle on time, consider that this percentage is affected by other factors such as the charge weight, the furnace, and base conditions.
- The analysis proved that the major energy consumption is due to the long cycle time caused by the failure of some of the heating elements during the annealing process. The cycle is extended for more time to allow the lag parts of the coils to reach the desired temperature.
- The study explored the literature review for possible solutions to tackle the problem of long cycle duration and heating element failure. Promoting convection heat transfer mechanisms in an annealing furnace would shorten the annealing cycle and overcome the failure of the heating elements during the cycle. There has been a lack of research to investigate and address this challenge, and more attention should be given to improving the annealing furnace performance toward efficient usage of energy.
- Incorporating artificial intelligence (AI) technologies into the monitoring and predictive analysis of heating element failures would offer great improvement. AI algorithms can analyze data from sensors and historical performance records to identify patterns and correlations that may indicate impending failures. AI can predict the likelihood of a heating element failure, enabling proactive maintenance interventions. This predictive capability allows for the scheduling of maintenance activities at optimal times, minimizing downtime and reducing the risk of catastrophic failures. Additionally, AI-powered monitoring systems can provide real-time alerts, enabling operators to respond swiftly to potential issues before they escalate into major disruptions. By investing in AI technologies, manufacturers can enhance the reliability and efficiency of their heating element operations, leading to improved product quality, reduced production costs, and increased customer satisfaction [24].

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