International Journal of Minerals, Metallurgy and Materials
Volume 28, Number 8, August 2021, Page 1264
https://doi.org/10.1007/s12613-020-2246-2

Invited Review

Consideration of green intelligent steel processes and narrow window stability control technology on steel quality

Lu Lin and Jia-qing Zeng

Metallurgical Technology Institute, Central Iron and Steel Research Institute, Beijing 100081, China
(Received: 19 October 2020; revised: 23 December 2020; accepted: 29 December 2020)

Abstract: In order to promote the intelligent transformation and upgrading of the steel industry, intelligent technology features based on the current situation and challenges of the steel industry are discussed in this paper. Based on both domestic and global research, functional analysis, reasonable positioning, and process optimization of each aspect of steel making are expounded. The current state of molten steel quality and implementation under narrow window control is analyzed. A method for maintaining stability in the narrow window control technology of steel quality is proposed, controlled by factors including composition, temperature, time, cleanliness, and consumption (raw material). Important guidance is provided for the future development of a green and intelligent steel manufacturing process.

Keywords: steel manufacturing process; steelmaking; narrow window; brand value; green and intelligence; process function

1. Introduction

Several technical propositions regarding sustainable development currently exist in the steel industry. In addition to improving steel processing efficiency, such proposals have covered reducing energy consumption and emissions and effectively establishing a product brand to pay enough attention. To achieve this, intelligent technologies must be implemented in the steel manufacturing process. Furthermore, the stability of the production process and the accuracy of product performance standards must be improved. In the near future, the goals of improving energy efficiency, energy consumption reduction, and pollutant emissions reduction in steel processing can be achieved by improving the industry's green manufacturing processes. By developing more intelligent steel manufacturing processes, a narrow control window for the stable control of operational process parameters can be achieved, product quality (stability, reliability, and applicability) can be improved, and brand value can be added. By the combination of greener and more intelligent production, coordinated control and multi-objective optimization of the steel manufacturing process can be realized, thereby significantly improving the social responsibility and competitiveness of iron and steel enterprises.

The iron and steel industry plays an important role in maintaining the developmental momentum of China's national economy. Accordingly, it is necessary to solve the strategic proposition of green development, intelligent advancement, and significant improvement in industrial competitiveness in the iron and steel industry. The focus must be redirected from traditional development modes, such as using specific devices or local process optimization, to benchmarking to tap potential, and reducing the cost of the whole process. Also, new developmental ideas such as the cooperation of green and intelligent production are needed, which could represent a breakthrough in process, interface technology, and narrow window stability control of the whole process. In this way, the bottleneck that restricts the development of China's iron and steel industry can be addressed [1−5].

Improvements in steel quality and brand value largely depend on a narrow window in production processes, offering a means for ensuring the stability and control of molten steel quality. Improvements can be achieved through the coordination and coupling of material flow, energy flow, and information flow. This can be achieved using advanced methods of intelligent control. In this way, fragmented knowledge and experience can be transformed into a linkage control model, quantitative operation rules, a database, and standards that define the entire process. Accordingly, the steel process can be imbued with distinct technical characteristics of depth perception, intelligent decision-making, and accurate execution. Diverging and changeable input parameters can be

Corresponding author: Lu Lin E-mail: linlu_luke@sina.com

gradually optimized and adjusted to the upstream and downstream aspects of the manufacturing process. Output parameters can adopt a stable focus and acquire significant benefits to improve the level of accurate control of the entire steel production process. Thus, the personalized needs of different users can be achieved and the adaptability of large-scale production ensured [4–8].

In this paper, based on the operational situation and existing problems in the steel manufacturing process, technical characteristics of an intelligent steel manufacturing process are considered alongside a functional analysis to ascertain the reasonable positioning and optimization of each process function in steelmaking. This study aims to provide theoretical references for the innovative development of steel manufacturing in China.

2. Analysis of the operational status of iron and steel manufacturing processes

Over nearly 20 years of development, the equipment and technical level of China's steel manufacturing processes have made significant progress [9–10]. Research on steel processing technologies and equipment has been divided primarily into two areas, the first of which focuses on efficiency improvement, cost reduction, energy conservation, environmental protection, and other aspects of single processes. In doing so, individual challenges and aspects related to comprehensive problems within a single process have been resolved. For example, during the converter smelting process, the carbon and oxygen percentage content product ([%C]·[%O]) at the end of the full furnace service of a large converter in domestically dominant enterprises can be reduced to less than 0.0018 (reduced within 0.0015 by some top companies). Additionally, molten iron (slag) consumption is at a relatively low level for selected companies and the smelting cycle of the converter is shorter than before [11–13]. However, due to the lack of attention in the coordination and correlation of each process within steel manufacturing, local operations and the effect of individual processes, though improved, may be overshadowed by deterioration or changes in the operational quality of other processes, thus undermining overall improvements in the operational effectiveness of the entire process. For example, when high phosphate ore is used in a blast furnace, the cost of blast furnace ironmaking can be reduced. However, if the technical aspects of high-phosphorus molten iron smelting in the converter are insufficient, or if the relationship between the steelmaking process and the ironmaking process of high-phosphorus hot metal is not matched, the dephosphorization load of the converter may increase; this will render the process control more difficult (and give rise to a high probability of slag spillage). Furthermore, problems related to steel peroxidation and instability in the production rhythm will arise. Accordingly, the gains will outweigh the losses incurred.

Secondly, in the process of product research and quality improvement, the hit ratio of individual targets related to steel products (material composition, cleanliness, grain size, performance, and other indicators) is typically targeted. For example, impure elements (carbon, sulfur, phosphorous, nitrogen, hydrogen, total oxygen ([TO])) have been controlled at extremely low levels (Table 1) [12–14]. However, because process stability and production rhythm of the steel manufacturing process as a whole have been neglected, the stability of the entire process has not been improved by a specific quality index (including those mentioned above). For example, if control of the converter smelting endpoint is not precise, excessive dependence on the completion of the refining processes can arise, which will lengthen the refining time overall. Furthermore, refining costs will be increased and the quality of molten steel may frequently fluctuate, giving rise to uneven continuous casting; therefore, rather than advancing the entire manufacturing process, a negative impact will result. Observational perspectives must be changed to achieve collaborative control of individual process node indexes and, accordingly, implement comprehensive optimization of the entire steel manufacturing process.

Table 1. Development of the monomer control level of impure elements in steel 10^{-6}

Year	C	Si	Mn	P	S	[TO]
1960s	200	200	200	40	3	40
1970s	80	40	100	30	2	30
1980s	30	10	40	20	1	10
1990s	10	4	10	10	0.8	7
1996	5	2.5	10	10	<1.0	5
After 2000	4	0.6	3	6	0.5	2

The iron and steel industry is a typical process-based manufacturing industry with complicated operation laws, in which the technical difficulty of intelligent improvement is significantly higher than that in the discrete manufacturing industry. To date, no successful case of intelligent steel processing has been developed [15–23]. Different from the characteristics of existing single-process technology research, including individual and diverse development and quality improvement, intelligent improvement in the steel industry focuses on the overall operation of the steel manufacturing process. However, several contradictions and constraints exist regarding the intelligent development of the steel manufacturing process in China.

(1) For historical reasons, the unreasonable positioning of process functions is common within the production lines of existing steel processing facilities in several iron and steel enterprises. This can cause uneven removal efficiency, removal difficulties, and a hampering of the control precision of re-

lated impure elements, thereby rendering the steel manufacturing process as a whole complex and changeable. There remains significant room for improvement in the anticipated goal of smooth operations within the overall production process; this represents the "birth defects" of the steel manufacturing process physical system and the difficult aspects of realizing process intelligence.

(2) How to change the mechanism or operation, or both, of selected processes, devices, and process interfaces in the steel manufacturing process remains unclear. Meanwhile, a large number of multivariate heterogeneous input/output parameters between upstream and downstream processes have not yet fully realized mutual inductance and connection. Furthermore, data mining of cross-process or sectional collaborative correlation is inefficient, and there remain "isolated islands" of information that pose technical obstacles in realizing intelligent operation of the steel manufacturing process.

(3) The control parameters of key nodes during the steel manufacturing process still cannot be accurately measured, and an inability to promptly obtain process characterization data online remains. It is still necessary to conduct extensive personalized regulation based on human experience; however, blind spots remain in terms of the monitoring and correction of flow rules, causing a lack of normative and meticulous adjustment means. This frequently causes the output to fluctuate, thus affecting the convergence of an intelligent control model.

3. Technical characteristics of an intelligent steel manufacturing process

The input terminal of the steel manufacturing process comprises parameter groups related to material flow, energy flow, and information flow of the original fuel properties. After entering the time and space boundary of the steel manufacturing process, the process will affect different process nodes according to the flow of the network and based on specific rules of dynamic sequential execution. The material flow, energy flow, and information flow parameter groups constitute the output product attributes at the end of steel manufacturing process. Its goal is the multi-objective collaborative optimization of the entire process, which includes controllable operation rules, high efficiency, environmental protection, and batch-product quality stability.

Presently, a range of problems must be addressed to implement intelligent improvement processes in the steel industry. The input terminal of steel manufacturing processes may include a group of relatively divergent parameters that vary across a broad range and are not dependent on human will, e.g., the quality and price of raw fuel, supply factors related to raw fuel, market demand for a product, the skills and experience of different operators, and attention to the production line and process. For the output terminal of the steel manufacturing process, relatively narrow characteristic parameter groups are expected to be obtained continuously and stably (e.g., high production efficiency, energy savings, environmental protection, high product quality, and continuous stability). Objectively, regardless of the parameter groups included in the input terminal of the steel manufacturing process, people tend to subjectively prefer parameter groups (including those mentioned above) that change in a relatively narrow channel during actual process operations, because this renders procedures controllable within a narrow window as shown in Fig. 1. The intelligent steel manufacturing process has the functions of sensitive perception, intelligent decision-making, precise execution, and deep service, which covers specific technical characteristics such as self-perception, self-learning, self-decision-making, self-implementation, and self-adaptation.

In steel manufacturing engineering systems, the expected operational goal is to realize a multi-objective collaborative achievement that includes green and high efficiency processes and stable product quality, among others. Here the technical implications concern the intelligent operation of the steel manufacturing processes to create conditions for value-added brand products. The output quality is related to the op-

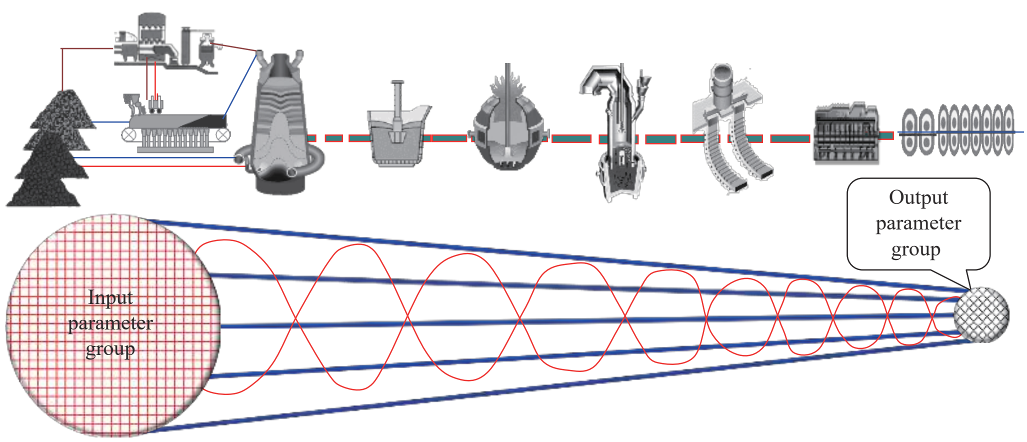

Fig. 1. Group control rules for input and output parameters in the steel manufacturing process.

erational status of each process within the overall process as a whole, considering the different working conditions and operational results. Therefore, the weight factors of each process and how they affect output quality are different. For example, by implementing relatively complete monitoring, situations in which the product quality may fluctuate, or where pollutants may be discharged, can be controlled. This is known as the self-perception stage of the steel manufacturing process. According to metallurgical mechanism analysis and big data analysis, these fluctuations (or abrupt changes) may be the result of an unstable drawing speed in continuous casting machines and inappropriate flue gas treatment of the sintering machine. This refers to the self-decision-making behavior stage within the steel manufacturing process. The stability of the molten steel superheating, the range within mold-level fluctuation, and the control parameters of the sintering machine represent the self-adaptive behavior stages of the steel manufacturing process. The regression of product quality and emissions, achieving a normal-value level index, represents improvements in the output quality process. The engineering system of the manufacturing steel process can realize closed-loop control as a result of identifying problems, analyze the causes of problems, and automatically push and control methods to realize closed-loop control. A causality diagram of input and output quality within the steel manufacturing process is shown in Fig. 2.

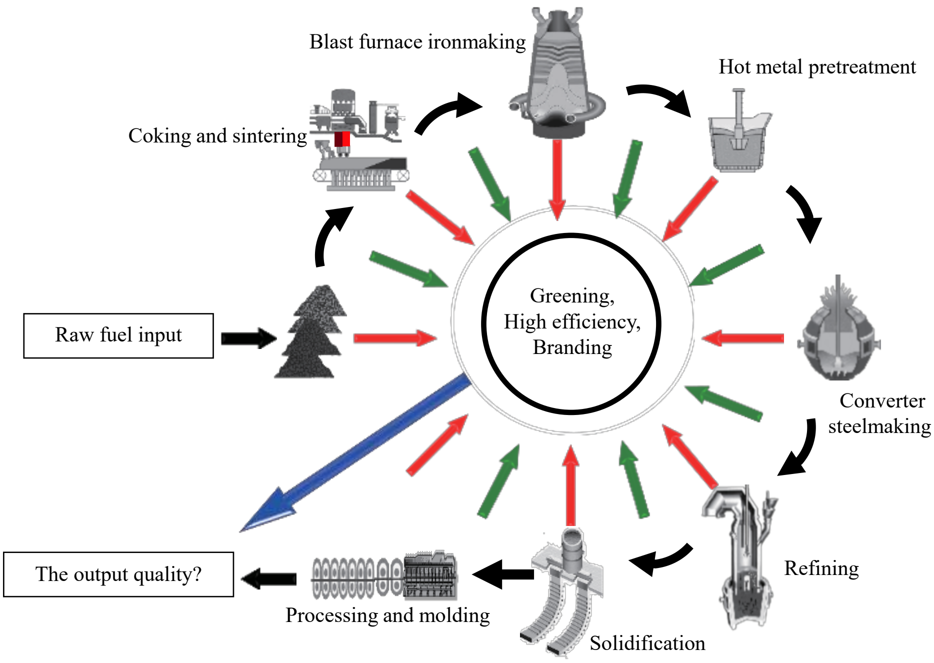

Fig. 2. Causality diagram of input and output quality within the steel manufacturing process.

Based on steel manufacturing process configuration and general operational rules, when one process receives different input conditions, automatic design and an optimized process path should be achieved, leading to a window parameter group for the dynamic and orderly operation of different procedures, thereby correctly guiding efficient, stable, and environment friendly and sustainable operation of the production process. Based on the differences between the output results of the steel manufacturing process, and considering the anticipated goals, the causes of these differences can be established through intelligent judgment and by effecting timely responses to accurately control the subsequent rounds in the input–output cycle. This will render the subsequent output run closer to the expected target, thereby achieving the expected goal of stable operation within a narrow window.

In the future, the steel manufacturing process should have a closed-loop control ability that includes both positive and reverse optimization. Intelligent prediction and an automatic iterative feedback loop are thus necessary aspects for the regulatory capacity of intelligent steel industrial processes.

4. Function analysis and optimization of each process in the steelmaking section

The steelmaking section is an important aspect of the high-temperature operation of the steel manufacturing process. The procedure has a connective function in the steel manufacturing process and is crucial for ensuring steel quality. The section affects the stable operation of blast furnace ironmaking (the procedure preceding steelmaking) and the stability and efficiency of product quality (the process after steelmaking). In the extensive process of advanced steel production, the steelmaking section includes four processes: hot metal pretreatment, converter steelmaking, molten steel refining, and continuous casting (see Fig. 3).

The steelmaking section has a major impact on the dynamic and orderly operation of the entire steel manufacturing process. The reasonable positioning of each process function in this section can realize multi-factor collaboration (including composition, temperature, production scheduling, multi-furnace continuous casting, product quality, cost-energy conservation, and emission reductions) in the steel manufacturing process and provide important support for integrated and intensive control [24–27]. Therefore, the reasonable positioning, optimization, and matching of each process function in the steelmaking section play an important role in improving the operational efficiency of steel manufacturing as a whole, thereby reducing costs and improving product quality. It is also the advance condition for realizing stability control technology for a narrow window of molten steel quality.

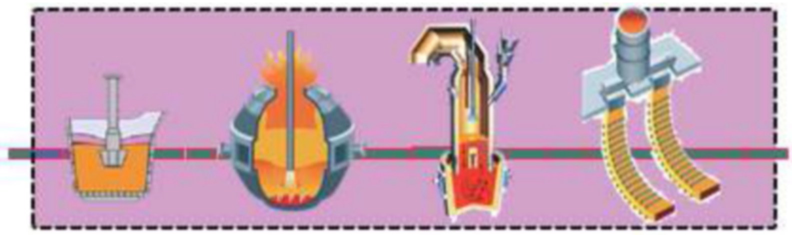

Fig. 3. Schematic of the steelmaking section in the typical long process of steel manufacturing process.

4.1. Analysis of the functional matching of each process in the steelmaking section

Through decades of development, China's iron and steel industry has made significant improvements in terms of technology and equipment. However, the development of several enterprises is completed in stages that form part of the process of expanding the scale of initial outdated production lines. The limitations of these production line conditions and the displacement caused by goals pursued in different transformation stages have led to several problems. These include unreasonable layout, weak system integration, uneven control of individual processes, and the unstable output of individual processes. In functional positioning and collaborative matching, all processes are extremely important, and the feedback among material flow, energy flow, and information flow cannot be adjusted in a timely, accurate, and collaborative manner.

In particular, the "four-in-one" technological framework (which includes hot metal pretreatment, converter steelmaking, molten steel refining, and continuous casting at a constant drawing speed and high efficiency) has not been established or improved in the steelmaking section. This represents an aspect of the advanced technological conceptualization and implementation required in the steel manufacturing industry. Although the steelmaking section of some enterprises already employs the above-noted equipment configuration, these enterprises have failed to achieve the functional positioning of individual devices and the division of metallurgical tasks. As a result, support for obtaining an efficient, stable, and accurate output of the entire process is considerably low as highlighted by the following aspects.

(1) In the steelmaking section, the hot metal pretreatment process can't take corresponding measures according to the change of input hot metal conditions. Such measures can be used to guide the hot metal pretreatment process to obtain accurate output parameters. The pretreatment function is limited to the desulfurization of hot metal; in this regard, the ideal degree of total disengagement for three aspects (desulfurization, desilication, and dephosphorization) has not been achieved. The current level of desulfurization and dephosphorization pretreatment is not sufficient, and some smelting tasks are not suitable for converter steelmaking processes, e.g., desulfurization (and controlling its reversion) and deep dephosphorization. Accordingly, these tasks will significantly increase the operational difficulty of subsequent steelmaking processes.

(2) In some instances, the converter steelmaking process has to accept hot metal following hot metal pretreatment with unsatisfactory conditions (related to chemical composition, temperature, supply timing, etc.). This substantially increases the task of removing impure elements in which the amount of smelting slag is significant, the phenomenon of primary molten steel peroxide is serious, precision control is difficult, and the output result is unstable. This increases the difficulty in promptly providing qualified molten steel for the subsequent refining process.

(3) When the parameters of molten steel after converter furnace processing are not ideal, the material flow input parameters in the refining process will deviate from the expected parameters (chemical composition, temperature, supply timing, etc.). Consequently, the refining process will be forced to passively accept converter molten steel with abnormal parameters, and the liquid steel refining process will become more complex, requiring more refining disposing time. Meanwhile, the difficulty in providing qualified molten steel in timely and continuous casting processes will increase, which, in turn, may increase the difficulty of the stable realization of multi-furnace continuous casting control in subsequent continuous casting processes.

(4) A continuous buildup of deviation from expected output parameters owing to the abnormal working state of the above-noted processes will lead to the inherent law of each process being irregular. This will further enlarge the gap between the passive input conditions and expected input conditions, thereby increasing the risk of the continuous casting process that causes unexpected fluctuations in output timing and the output quality of the slab. This will lead to disorder in the control parameter group connection among various processes, making the realization of a stable operation within a narrow window difficult.

4.2. Functional analysis, optimization and the reasonable positioning of each process in the steelmaking section

The optimization of iron and steel processes involves the analytical optimization of each individual process function, the coordination and optimization of each process with a matching relationship, as well as the reconstruction and optimization of each process set within the process. Presently, the links between different processes in the steel manufacturing process reflect simple but extensive linking phenomena. The goals pursued by independent processes are still not fully integrated within the processing system as a whole. An advanced steel manufacturing process should integrate the functional advantages of each process and avoid the shortfalls when meeting the function matching of each process. On the basis of the reasonable matching of each process function, the stability control target of each process parameter group can be achieved within a narrow window, thus achieving multiple goals such as high efficiency, low consumption, and stable product quality in the steel manufacturing process, while also providing technical support for product branding.

In recent decades, the equipment level of Kanbara reactor/pulverized desulfurization, converters, ladle/vacuum/Ruhrstahl Heraeus refining furnaces, as well as continuous casting has rapidly improved in China. However, the quality of molten steel and billet is generally poor or inconsistent, creating a bottleneck in steel brand value. In addition to influencing factors such as management philosophy, raw material quality differences, and the excessive pursuit of low cost in iron and steel enterprises, it is key that the overall ability of the industry to deeply excavate, integrate, and coordinate equipment functions among all processes within the entire steel production process be improved. This is mainly manifested with the following aspects.

The functional positioning of two processes, hot metal pretreatment and converter steelmaking, remains unclear. The crossover and dislocation of metallurgical task division directly affect the quality and stability of molten steel in the primary smelting furnace. Due to the fluctuation of molten steel quality in the converter, subsequent refining and continuous casting processes will be forced to accept the unstable molten steel. As a result, process problems that should have been effectively solved in the preceding process will make it difficult to control the output product quality in this section within a relatively narrow range.

Learning from the successful experience of foreign advanced iron and steel processes [28–30], the functional analysis and optimization of each process in the steelmaking section reflect the following three aspects: First, the desulfurization, desilication, and dephosphorization of hot metal are tasks that should be moved to the hot metal pretreatment process. This can provide support for achieving favorable conditions pertaining to thermodynamics and related aspects for improving treatment efficiency, thus reducing the workload of subsequent converter steelmaking. Second, the converter steelmaking process requires low sulfur and low phosphorus molten iron, which greatly reduces the slag quantity. The metallurgical function of the converter steelmaking process can be simplified into decarbonization and heating, which is conducive to a reduction in the degree of over-oxidation and endogenous inclusions and provides technical support for the subsequent rapid refining of steel at a steady rhythm and multi furnace continuous casting in continuous casting process. Finally, the smelting function of each process is supported, processing tasks are balanced and clear, treatment depth is explicit, process rules are easy to extract, and rhythm matching is controllable. Achieving these aspects will provide the conditions for stable operations within a narrow window in the steelmaking process.

4.3. Functional optimization and its realization in the steelmaking section

Dephosphorization in the steelmaking section is too reliant on a combination of parameters, such as the high basicity of the converter endpoint, large slag quantity, high-oxidizing slag, and over-oxidation. Although a high dephosphorization rate can be obtained, the high oxygen potential in the molten steel, high deoxidation costs, and a large number of endogenous inclusions make the subsequent refining task more intensive, controlling the purity of molten steel more difficult, and the division of metallurgical functions in the process before and after unfeasible.

In advanced iron and steel manufacturing processes, the potential for removing impure elements such as sulfur and phosphorus through molten iron pretreatment processes has been explored in depth. By transforming the function of efficient desulfurization and dephosphorization into the hot metal pretreatment process as much as possible, the focus of the subsequent converter steelmaking process will only be on the matching relationships between the carbon content and the temperature in the molten pool. Concurrently, the simultaneous hit ratios for composition, temperature, and treatment time in the molten pool will be significantly increased, control difficulty will be reduced, and operation time will be controllable. In this way, the difficulties associated with controlling the molten iron pretreatment and converter steelmaking processes can be balanced, and the stability of process output parameters can be significantly enhanced. In this context, the refining function will focus on adjusting the composition of the steel and removal of inclusions; this will effectively reduce the time required for removing impure elements and deoxidation. Process stability will be significantly increased and better adaptation to multi-furnace continuous casting. The different functions of the steelmaking section before and after improvement are shown in Fig. 4.

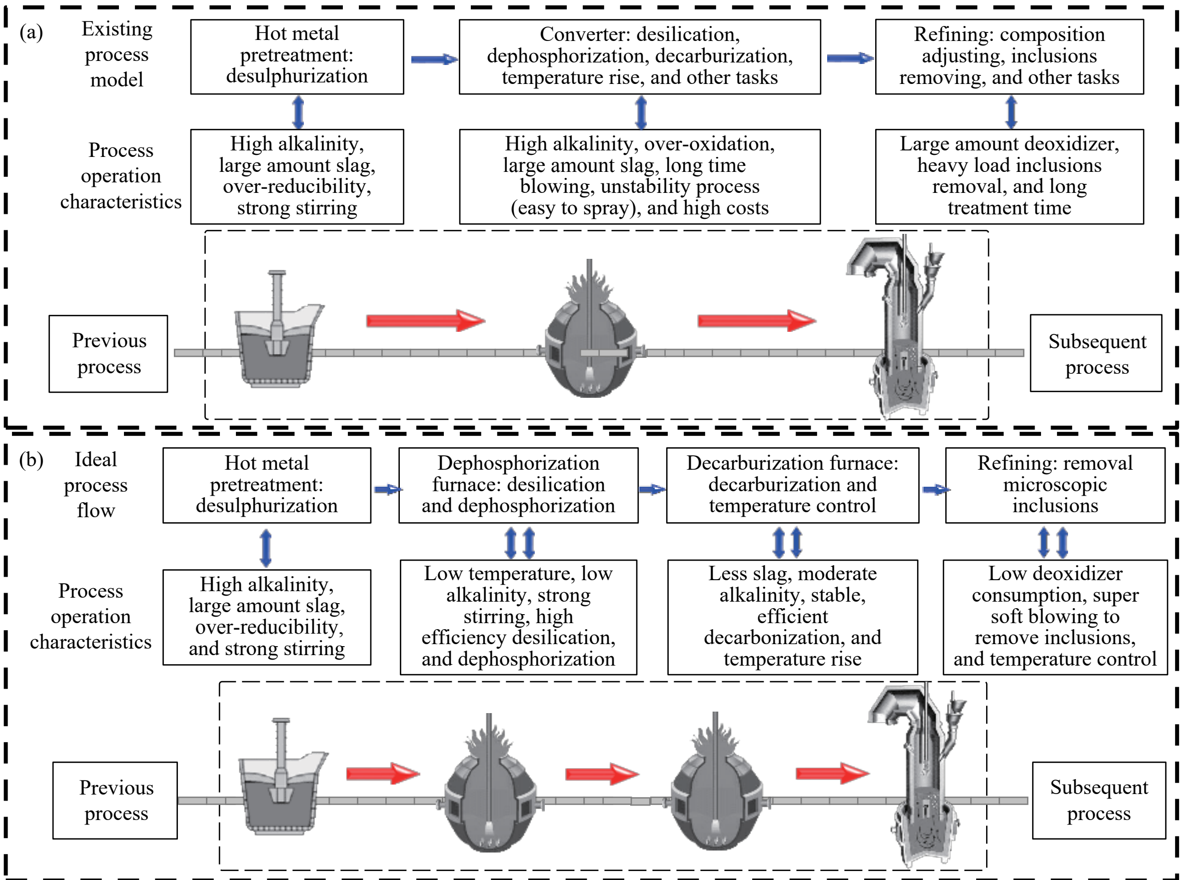

Fig. 4. Metallurgical function positioning of each process in the steelmaking section: (a) the existing steelmaking section; (b) the ideal steelmaking section.

5. Stability control technology for a narrow window and its influence on the molten steel quality

5.1. Current status of narrow window stability control technology on steel quality

Presently, the quality of the molten steel is not only limited to obtaining it with qualified composition; technically, it must also reflect low cost, high efficiency, and the prompt and stable supply of molten steel within a narrow fluctuation range as it relates to composition and temperature [31–32], with a dynamic input–output flow to ensure that the subsequent continuous casting process achieves a stable, smooth, high, and constant drawing speed. To achieve these goals, functional analysis optimization and the reasonable positioning of each process in the steelmaking section are extremely important and present the technical basis for success in this context.

From a perspective that includes the entire steel manufacturing process, the various processes in the steelmaking section require changes and interactions involving a series of parameter groups during normal operation. The molten iron pretreatment process may involve, among others, slag temperatures, composition, and production rhythm, whereas the converter steelmaking process includes oxygen lance position, oxygen supply intensity, converter bottom blowing strength, and smelting cycle. The molten steel refining process involves molten steel composition and temperature, refining time, soft-blowing and calming time, and molten steel purity, alongside numerous other factors. In the steelmaking section, the control parameter groups of the upstream and downstream processes are not only the relatively discretized parameter groups employed for adjusting related processes, each parameter group also has a degree of heritability and mutual correlation. Various possible fluctuations in process parameters (the above mentioned parameters) may exert different degrees of influence on the output quality of the steelmaking section.

The number of combinations in the above-noted range of parameter groups is significant, and their inherent laws are complex and flexible. It is extremely inefficient and costly to perform optimization of the entire process by trial and error. It is thus necessary to address the relationship between self-organization and the interrelationships among other organizations of functions of each process in the steelmaking section.

Establishing a reasonable cyber–physical system involving the steelmaking section with the help of the whole process monitoring system must be based on massive data and operating rules, use of mechanism models, and related optimization models and big data statistical models to input different parameters for different scenarios. Barring this, the change results, possibly caused by sudden interference events, are iterated in cycles. These include self-learning and predicting possible output results, performing dynamic comparisons with expected output results, and gradually narrowing the output results to automatically push out a reasonable execution path and a narrow window control parameter group of each node in the path. In this way, the development and execution of the intelligent optimization of the smelting process in the steelmaking sector can be achieved, alongside the goal of stable operation within a narrow window.

The quality of molten steel output in the steelmaking section is reflected in the stability of various indicators of the production process and the controllability of production costs, benefits, and environmental loads. It is expected that (regardless of the changes and conflicts that may be encountered at the input end of the steelmaking section or during its operation) by utilizing an intelligent control mechanism in the steelmaking section, the various parameter groups involved can be reasonably narrowed. Convergence changes should be affected in the data channel to ensure that the final output can achieve the multi-objective collaborative optimization (stable molten steel quality, matching production rhythm, as little environmental load as possible, etc.) as shown in Fig. 5.

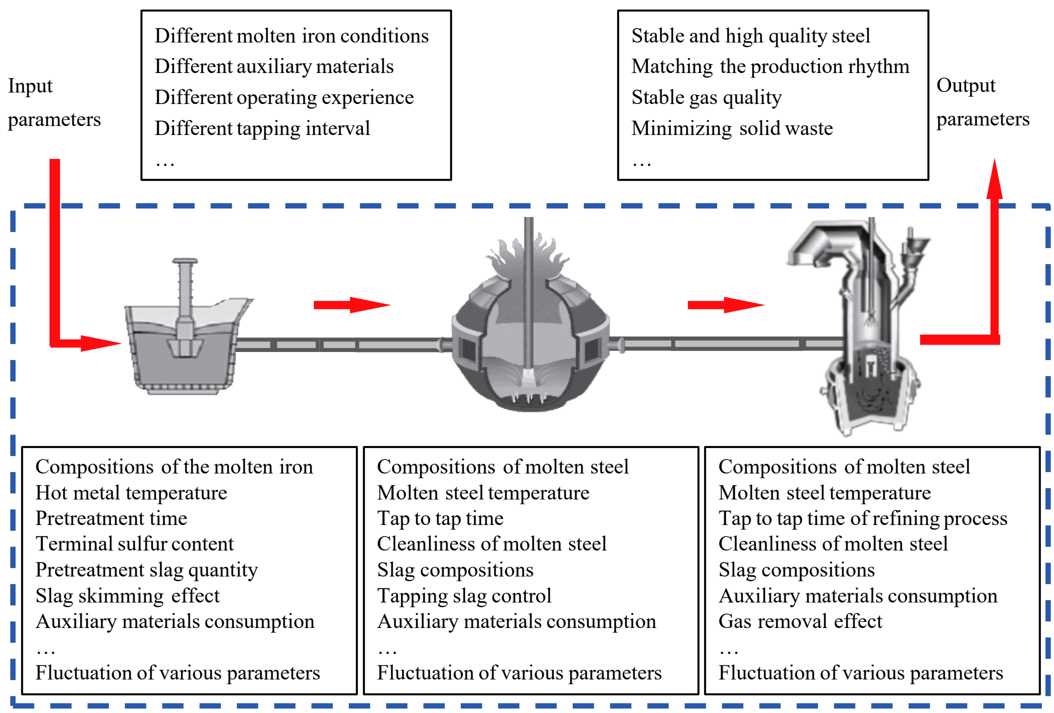

Fig. 5. Schematic of the parameter groups and output quality of each process in the steelmaking section.

5.2. Implementation path for the influence of narrow window stability control technology on steel quality

Based on the analysis of the influence of the control effect of each section within the entire steel manufacturing process, fluctuation in the control window parameters during the steelmaking section has a major impact on the final quality of the steel produced. It is also directly related to the rhythm of the entire process of production and operation and whether the connection is smooth.

Concerning the narrow window for stably controlling the molten steel quality in the steelmaking section, there are currently no successful cases to learn from in China. This narrow window aims to achieve intelligent optimization based on a vision that incorporates the steel manufacturing process as a whole. It is necessary to change the familiar traditional mode of over-focusing or pursuing the optimal operational effect of a single process, which neglects system-wide optimization. Optimization cannot be achieved by relying solely on the skills, experience, energy, and sense of responsibility of the operators responsible for different processes. The narrow window for stably controlling molten steel quality is based on having a reasonable layout of the physical framework required for the steelmaking section. Additionally, digital information systems must include comprehensive functional abilities and multi-objective collaborative optimization on the basis of the analysis and optimization of upstream and downstream process functions and the use of big data and mechanism analysis to ensure orderly interaction. The narrow window stability control of molten steel quality requires breakthroughs in key points, e.g., real-time online monitoring of process variables, closed-loop control of the process, collaborative optimization of processes/interfaces, and the control of process rules and parameter fluctuation ranges to establish an organic relationship between internal causal changes and externally controllable parameters. This will clarify the influence weights and control sequences to improve the effectiveness and accuracy of control in the steelmaking section, thereby achieving stable control of molten steel quality. By establishing an efficient, collaborative, and reliable implementation path between the divergent and multi-changing process inputs and by continuously focusing on and narrowing process outputs, multi-objective collaborative optimization of the entire process can be achieved alongside controllable operational rules, high efficiency, environmental protection, and batch-product quality stability.

Based on the rational positioning and optimization of the functions of each process in the steelmaking section and according to the individual requirements of different customers as it concerns the quality of molten steel, from multiple perspectives including molten steel composition, cleanliness, temperature, production rhythm matching, consumption and emissions, cost, etc., the limiting links and key control parameters that affect the molten steel quality in the steel manufacturing process will need analysis. An optimized matching database must be established, and an objective evaluation method of molten steel quality must be put forward. Corresponding molten steel quality control rules will require extraction and matching, and a process control model covering the linkage and convergence of each section of the entire process will need to be established. In addition, the functions of relevant process monomer technology (such as the development of high efficiency dephosphorization and the control of molten steel peroxidation of combined blowing converter bottom blowing oxygen and lime powder) must be developed and strengthened to solve the difficulties related to operational control before and after the process of the steelmaking section. This would circumvent bottleneck constraints. Furthermore, collaborative matching, control rules, and external control parameter groups within different processes must be transformed into databases and models. For example, construction of a narrow window model for stable control of molten steel quality in the steelmaking section.

Accordingly, through the reasonable positioning, analysis, and optimization of each process in the steelmaking section, a corresponding matching technology can be developed, process rules and monitoring methods among different processes can be improved, and a process rules database and model can be established. This can help realize the functional coupling matching and the dynamic and orderly operation of the steelmaking section process, as well as the stable control of molten steel quality (including molten steel composition, molten steel temperature, production rhythm, molten steel cleanliness, and process consumption and emissions). This will provide technical support for improving a product product's "three properties (product quality stability, reliability, and adaptability)," brand value-added aspects, and the intelligent upgrading of the steel manufacturing process as a whole.

6. Conclusion and prospect

Considering the development trends in both the domestic and abroad steel production technologies, the development of green and intelligent steel processes is a focus of concern for the next 20 years at least. Greening of steel manufacturing processes will help addressing the problems hampering the harmonious relationship of the steel industry and society, thereby supporting its persistence and sustainable development. Creating an intelligent steel manufacturing process is thus imperative. Green and intelligent steel processes must be system optimized according to a perspective that takes into consideration the entire system as a whole. Specific physical system support conditions will be required, and as such, a green and intelligent steel manufacturing process cannot be immediately achieved.

Based on improving the key technologies of existing green and intelligent steel manufacturing processes, we aim to further develop a stable technology-based narrow control window to ensure molten steel quality. This development will integrate multiple factors such as molten steel composition, molten steel temperature, production rhythm, molten steel cleanliness, process consumption, and emissions, and it will realize multi-objective collaborative optimization of the entire steel manufacturing process, including controllable operation rules, high efficiency, environmental protection, and molten steel quality stability. This will be one of the key development directions of a green and intelligent steel manufacturing process in the future and will play an important role in promoting the transformation and upgrading of China's steel industry toward green and intelligent manufacturing.

Acknowledgements

This work was financially supported by the National Key R&D Program of China (No. 2017YFB0304000), and the National Natural Science Foundation of China (Nos. 52074093, 51874102, 51704080, and 51674092).

References

[1] R.Y. Yin, A discussion on "smart" steel plant—View from physical system side, *Iron Steel*, 52(2017), No. 6, p. 1.
[2] J. Zhou, Intelligent manufacturing-main direction of "Made in China 2025", *Chin. Mech. Eng.*, 26(2015), No. 17, p. 2273.
[3] R.Y. Yin, "Flow", flow network and dissipative structure—Understanding of the physical system of manufacturing process of process manufacturing type, *Sci. Sin. Technol.*, 48(2018), No. 2, p. 136.
[4] Y.G. Sun, Development road map of digital. network and intelligent manufacturing technology of iron and steel industry, *China Steel Focus*, 2015, No. 9, p. 4.
[5] Q.S. Yuan, R.Y. Yin, X.H. Cao, and, P.C. Liu, Strategic research on the goals characteristics and paths of intelligentization of process manufacturing industry for 2035, *Strategic Study CAE*, 22(2020), No. 3, p. 148.
[6] R.Y. Yin, Process engineering and manufacturing process, *Iron Steel*, 49(2014), No. 7, p. 15.
[7] C.C. Qi, Big data management in the mining industry, *Int. J. Miner. Metall. Mater.*, 27(2020), No. 2, p. 131.
[8] Y.G. Sun, H.Y. Xu, Y.J. Zeng, and W.B. Li, Energy flow information model based dynamic multi-type energy scheduling in steel works, [in] *Baosteel BAC*, Shanghai, 2013, p. 266.
[9] R. Zhu, X.T. Wu, G.S. Wei, and B.H. Tian, Development of green and intelligent technologies in electric arc furnace steelmaking process, *Iron Steel*, 54(2019), No. 8, p. 9.
[10] J.H. Liu and H. Dong, Thoughts on continuous optimization of special steel production process, *Chin. Metall.*, 28(2018), No. 9, p. 1.
[11] L.B. Yang, J.Q. Zeng, Y. Deng, X.W. Xu, and L.P. Wu, Highly efficiency and long-life combined blowing technology of big converter, *Iron Steel*, 55(2020), No. 4, p. 45.
[12] R.Y. Yin, Integrated Technology of the platform for clean steel production-an important direction of the technology progress in steelmaking, *Iron Steel*, 44(2009), No. 7, p. 1.
[13] R.Y. Yin, Integration technology of high efficiency and low cost clean steel "prodoction platform" and its dynamic operation, *Iron Steel*, 47(2012), No. 1, p. 1.
[14] X.L. Pan, Z. Li, Y.H. Wang, and H.Z. Liang, Advanced technology of clean steel production at home and abroad, *Steelmaking*, 23(2007), No. 1, p. 59.
[15] X.C. Li, C.T. Shi, and F. Zhao, Industry 4.0 meets with China iron and steel industry, *Iron Steel*, 50(2015), No. 11, p. 1.
[16] C.H. Guo, Iron and steel industry and industry 4.0, *Metall. Ind. Autom.*, 39(2015), No. 4, p. 7.
[17] W.Z. Liu, Thinking on the intelligent manufacturing of steel industry in China, *Metall. Ind. Autom.*, 42(2018), No. 4, p. 1.
[18] W.Z. Liu, Current situation and thinking of intelligent manufacturing in China's iron and steel industry, *Chin. Metall.*, 30(2020), No. 6, p. 1.
[19] Y. Yu, Information architecture design of hesteel tangsteel industry for intelligent manufacturing, *Iron Steel*, 52(2017), No. 1, p. 1.
[20] H.F. Hu, Development and outlook of intelligent manufacturing technology in steel industry, *Baosteel Meishan*, 2014, No. 6, p. 1.
[21] K. Ohara, M. Tsugeno, Y. Sakiyama, K. Kitaqoh, J. Yanaqimoto, and H Imanari, Process optimization for the manufacturing of sheets with estimated balance between product quality and energy consumption, *CIRP Ann.-Manuf. Technol.*, 63(2014), No. 1, p. 257.
[22] E. Toshihiko, Optimizing steelmaking system for quality steel mass production for sustainable future of steel industry, *Steel Res. Int.*, 85(2014), No. 8, p. 1274.
[23] H.N. Zhang and S.Q. LI, Consideration about intelligent manufacturing of HBIS Shijiazhuang Iron and Steel Co., *Chin. Metall.*, 26(2016), No. 6, p. 1.
[24] R.Y. Yin, *Metallurgical Process Engineering*, 2nd ed., Metallurgical Industry Press, Beijing, 2009.
[25] R.Y. Yin, *Theory and Method of Metallurgical Process Integration*, Metallurgical Industry Press, Beijing, 2013.
[26] R.Y. Yin, *Theory and Methods of Metallurgical Process Integration*, Metallurgical Industry Press, Beijing, 2016.
[27] R.Y. Yin, Comment on behavior of energy flow and construction of energy flow network for steel manufacturing process, *Iron Steel*, 45(2010), No. 4, p. 1.
[28] S. Kawasaki, H. Hirahashi, M. Aoki, K. Hajika, and Y. Hunaoka, Improvement of the refining process around combined blowing converter in kobe works, *Tetsu-to-Hagané*, 76(1990), No. 11, p. 1900.
[29] O. Yamase, M. Ikeda, J. Fukumi, C. Taki, K. Yamada, and K. Iwasaki , Industrialization of a new steelmaking process utilizing hot metal pretreatment and smelting reduction, *Tetsu-to-Hagané*, 74(1988), No. 2, p. 270.
[30] E. Toshihiko, Steelmaking technology for the last 100 years: toward highly efficient mass production systems for high quality steels, *ISIJ Int.*, 55(2015), No. 1, p. 36.
[31] J.H. Liu, H. Cui, and Y.P. Bao, Key technologies for high grade pipeline refining, *J. Univ. Sci. Technol. Beijing*, 31(2009), No. S1, p. 1.
[32] Y. Fan, S.L. Li, X.C. Miao, G. Wang, and X.G. Ai, Application status and prospect of narrow window control and big data in direct rolling, *Chin. Metall.*, 28(2018), No. 9, p. 8.