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Key Intelligent Technology of Steel Strip Production through Process

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Received: 28 June 2018; Accepted: 28 July 2018; Published: 31 July 2018

Abstract: Because of the complexity of procedure interface and working conditions, the further improvement of steel strip quality and production efficiency is limited. Realizing the optimization of product quality and production process in multi-process, system-level through intelligent key technology is one of the strategic directions in steel strip production. (1) Collaborative intelligent optimization and dynamic scheduling technology for steel manufacturing supply chain oriented to customized production, reducing the cost of raw material purchase and production operations and improving production efficiency and precision service ability; (2) Online monitoring, diagnosis and optimization technology of product quality. Getting through the process information flow of product, the correlation analysis of process quality parameters, the tracing of quality anomalies, the reverse optimization of process parameters and the optimization of process route will be realized; (3) Multi-process coordination optimization and quality control based on CPS architecture. The precise control technology of process quality parameters will be developed; the structure of multi-process coordination optimization system is established and optimization of key quality parameters in the through process will be realized; and (4) Microstructure and mechanical property optimization and surface quality intelligent control technology in the hot strip rolling process. Intelligent prediction of microstructure and mechanical properties, rapid dynamic design and steel grade merging technology will be formed and green process design technology of oxide scale will be developed.

Keywords: steel strip; intelligent manufacturing; supply chain optimization; product quality improvement; through-process optimization

1. Introduction

Facing the new round of industrial revolution, "made in China 2025" was clearly put forward to focus on the upgrading of the manufacturing sector to improve innovation ability, integrate informatization and industrialization, focus on the development of fully-automated "smart" factories, pilot demonstrations and application promotion in areas such as process manufacturing, discrete manufacturing, intelligent equipment and products in industries with good infrastructure and urgent needs [1,2]. Meantime, countries around the world are actively taking action, the strategic initiative Industrial 4.0 developed by Germany [3], the Advanced Manufacturing Partnership launched by the United States [4,5], the UK Industry 2050 Strategy proposed by the United Kingdom [6], the New Industrial France program unveiled by France [7], the Super Intelligent Society 5.0 put forward by Japan [8], all of the programs take the development of intelligent manufacturing as the key measure to build the competitive advantage of the manufacturing industry. The main purpose of this article is a brief summary and perspective of intelligent technology carrying out in steel strip production.

The manufacturing process of steel strip production is a large and complex industrial process covering multi procedures and multi control levels and its product is called "general-purpose steel," which is an important support for the development of national economy. At present, the integrated control of the through process and the coordinated optimization of the various levels have not been formed in the manufacturing process of steel strip production, facing the problems of lower control stability of the product dimension and mechanical property, insufficient advanced supply capacity, lower labor productivity and so forth. On the other hand, personalized customization under conditions of large-scale and continuous production is urgently needed to be promoted [9]. Specifically, most of the production procedures are information isolated islands and the control levels do not interact well. Any change of parameters in the manufacturing process will cause a chain reaction of many other related parameters. The quality problems in upstream procedures will be inherited to downstream procedures and abnormal working conditions will not only affect the manufacturing process control but also affect production scheduling and decision-making. The research on the steel strip intelligent production has been the attentive focus around the world. The advanced scheduling technologies of continuous casting, hot rolling, have been preliminarily formed. However, the decision-making of purchasing, manufacturing and marketing still depends on human experience. The coordination and optimization of the multi-process scheduling have not been realized. The through process quality has been controlled consistently but the relationship between quality and process parameters is not structured, the on-line real-time monitoring and tracing of product quality and the reverse optimization of process is not realized. At the same time, the precision control and multi-process coordination optimization of the complex manufacturing process have become the bottleneck of product quality improvement. It is urgent to integrate the process mechanism with the production big data and realize multi-process coordination optimization through intelligent key technology. It is an important strategic direction to realize the optimization of product quality and manufacturing process of multi-process, system-level through the key technology of intelligence, which is an inevitable choice to solve the problems of complexity and quality stability in the manufacturing process of steel strip production.

In view of the future trend of steel development, the European Union has issued "European Steel Technology Platform (ESTEP)" and set up the "Integrated Intelligent Manufacturing (I^2M)" working Group. The priority development areas include through process control technology, integrated process monitoring and control technology management to further improve the quality of steel production [10,11]. The United States has released the "Smart Process Manufacturing (SPM)" roadmap to strengthen the application of advanced intelligent systems in petrochemical, building materials and metallurgy processes, the final target is to create an integrated, knowledge-based, modeled enterprise that speeds up new product development, responds dynamically to market demand and optimizes production and supply chain networks in real time. Amaral developed a new SPC tool and applied it to the ArcelorMittal Gent factory. The relationship between process parameters and product quality was established, the traceability analysis of quality anomaly was realized and the production process was optimized [12]. VDEh-Betriebsforschungsinstitut (BFI) and Primetals have collected the process data of several procedures, supported the user to analyze and mine multi-process data through the visualization module, established a quality prediction model of the through process and automatically tracked changes in equipment, technological process and product quality. Based on the prediction of intermediate product quality index, rolling process capability and customer requirement, the production route of stainless steel rolling process was optimized based on genetic algorithm [13–15]. Think of the hundreds of thousands of sensors, scanners and detectors, Big River Steel read, measured and reported all data from the processes, connecting every part of the complex steel manufacturing process to create a learning mill that is integrated at a level that was previously thought impossible and every point of steelmaking process from the furnace to the shipping bay can be analyzed and optimized for maximum quality and productivity [16]. Tata Steel, Northeastern University developed intelligent models to predict the mechanical properties such as yield strength (YS), ultimate tensile strength (UTS) and elongation (EL) of the hot rolled (HR) steel strips/coils [17,18]. ArcelorMittal and

other companies adopt "service-oriented architecture (SOA)" to develop an integrated intelligent manufacturing system for iron and steel industry. Semantic analysis technology is used to realize seamless cooperation and information exchange in the supply chain of the company [19,20].

This paper focuses on the complexity of the manufacturing process of steel strip, the uncertainty and diversity brought about by personalized customization and so forth. It is oriented to break through the key technology intelligent and improve the product quality and production efficiency. Develop intelligent decision system and intelligent production dynamic scheduling technology, through process quality on-line monitoring and diagnosis and optimization technology, multi-process coordination and matching and quality optimized intelligent control technology, the microstructure and mechanical properties matching of hot rolling process and the intelligent control technology of oxide scale. The ultimate goal is to form a through process intelligent control system of the steel strip production.

2. Collaborative Intelligent Optimization and Dynamic Scheduling Technology for Steel Manufacturing Supply Chain Oriented to Customized Production

Many steel enterprises have established complete Enterprise Resource Planning (ERP), Manufacturing Execution System (MES) and other information systems but the integrated decision-making of purchasing, manufacturing and marketing is still mainly based on the experience of engineers and managers, which has great limitations. At the same time, some advanced steel enterprises have realized modeling in single process scheduling but they still have not realized the coordination and optimization of the through process scheduling.

Through the deep analysis of various business problems in steel purchasing, manufacturing and marketing supply chain, combined with various technical means, such as process technology, supply chain theory and optimization method, a new theory of integrated and collaborative optimization of steel supply chain driven by both market and production process is proposed to realize the innovation of purchasing, manufacturing and marketing management mode. In the process of purchasing, a new idea of alloy purchase and inventory optimization based on the linkage mechanism of purchasing, manufacturing and marketing is put forward. The accurate calculation of alloy demand is realized based on order and metallurgical process and the stochastic optimization model of alloy inventory is established. The optimal alloy purchasing strategy is proposed, to enhance the rapid response to customer requirement and reduce the purchase and inventory costs of bulk materials such as alloys. In the process of manufacturing, a through-process supply chain planning method for eliminating load imbalances and logistics conflict between processes is proposed in the planning. Taking the resource allocation balance and the production rhythm coordinate of multiple procedures as object, the integrated optimization technology of the through process capacity balance planning is studied. Aiming at the contradiction between customer requirement and large-scale production of steel, the integrated optimization technology of the through process capacity balance planning is studied. The flexible production process is used as the driving force in the scheduling, a collaborative scheduling method is proposed from the view point of customer requirement and production process. The automatic scheduling optimization model of metallurgy and the rolling process and the semi-automatic scheduling model based on man-machine interactive mode are established and a fast dynamic adjustment strategy is put forward to deal with changes in the order and production environment. In the process of marketing, the intelligent decision-making technology of plate sales is proposed, the intelligent order combination, order and inventory optimization, supply chain simulation optimization and other decision support tools are developed. A new idea of strip predictive sales is put forward, which is precise docking with user production planning and collaborative manufacturing. Combined with stochastic multi-level inventory optimization and simulation technology, the co-optimization of manufacturing, sales and customer is realized. Collaborative intelligent optimization decision of steel strip purchasing, marketing and manufacturing supply chain is shown in Figure 1.

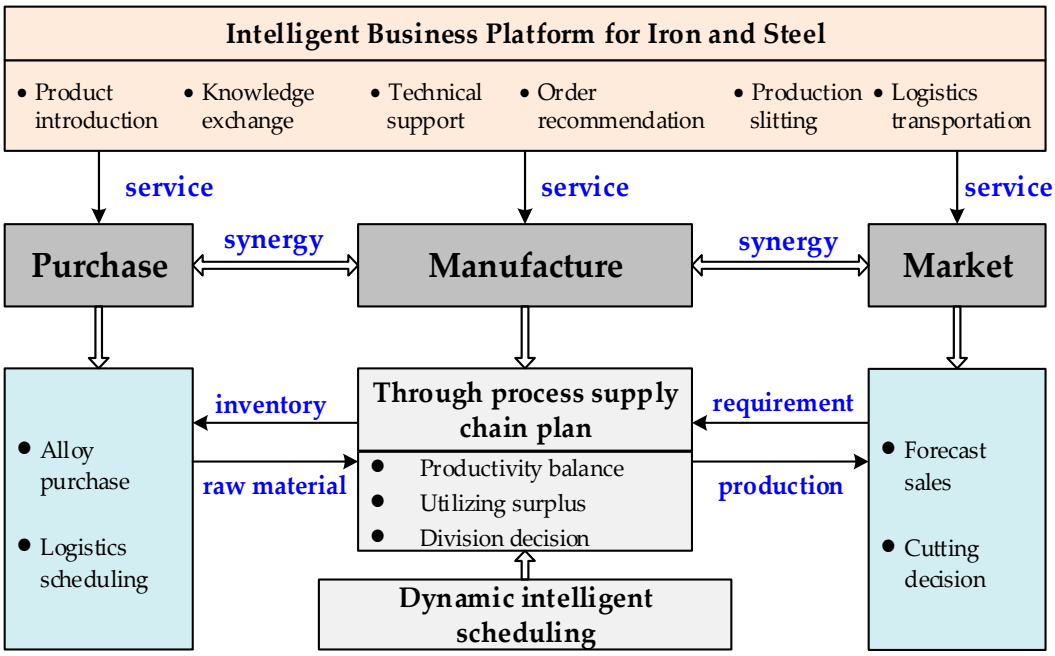

Figure 1. Collaborative intelligent optimization decision of steel strip purchasing, marketing and manufacturing supply chain.

Starting from improving the level of intellectualization in the steel industry, realizing the meticulous management of the through process and enhancing the actual demand of the overall operation efficiency of the supply chain, the basic theory, key technology and industrial application of collaborative intelligent optimization for purchasing, manufacturing, sales and electronic commerce are studied. The cooperation and sharing ability between the upstream and downstream enterprises of the supply chain and the through process of iron and steel are strengthened, to realize the purpose of reducing the purchasing cost of raw materials, the total inventory level of work in process and finished products, the operation cost of the through process production and improving production efficiency, precision service capability and shortening product manufacturing cycle.

3. On-Line Monitoring, Diagnosis and Optimization Technology of Product Quality in the Through Process

The on-line monitoring, diagnosis and optimization technology of product quality in the through process is the prerequisite for improving stability, reliability and applicability. Manufacturing process of steel strip is a complex industrial process composed of many procedures and the influence variables of product quality have the characteristics of high dimension and nonlinear and the quality characteristics among processes are heredity and coupling, resulting in the quality information of through process being difficult to monitor and optimize online.

The manufacturing process of steel has the characteristics of cascade integrated operation with multi-element, multi-phase and multi-level and the relationship between quality and process parameters is very complicated. The standardized specification of multi-source, heterogeneous and multi-resolution data acquisition is established. On the basis of data de-noising, time synchronization, data cleaning and data reorganization, the evaluation model of data quality is constructed. Product tracking model reflecting the evolution of material flow in the through process is used to realize the material flow correlation, hierarchical query and backtracking matching between different procedures. By adopting the technology of collecting data according to different temporal-spatial dimension in terms of product segment, time and event, the accurate matching of information flow and material flow data in through process can be realized. On-line monitoring and diagnosis of product

quality are carried out by using a classification method. In addition, according to the characteristics of product quality type and production state, an on-line quality monitoring model based on multiple methods, namely single variable and multidimensional variable process statistics and nonlinear prediction is established. The process monitoring method of each procedure is studied and the real-time quality fluctuation is monitored. The relationship model between key process variables and key product quality variables based on big data is developed and the evaluation standard of typical product quality index and the rule base of product quality comprehensive evaluation are established. The stability of quality is evaluated by the process capability index and the accurate diagnosis of quality anomalies is realized by the methods of pattern matching, association rules and cluster analysis. Through comprehensive application of the methods such as expert rule reasoning, case matching and reverse tracing to the source based on the inverse mapping model, a quality diagnosis model of product quality to process parameter is established and the multi-control level progressive quality anomaly tracing mechanism is formed. The on-line optimization of product quality can be divided into process optimization and parameter optimization. Combined with quality analysis and diagnosis conclusion, process parameters can be optimized by matching quality rule base and the manufacturing process can be optimized by querying the process optimization solution. On-line monitoring, diagnosis and optimization technology of product quality in the through process is shown in Figure 2.

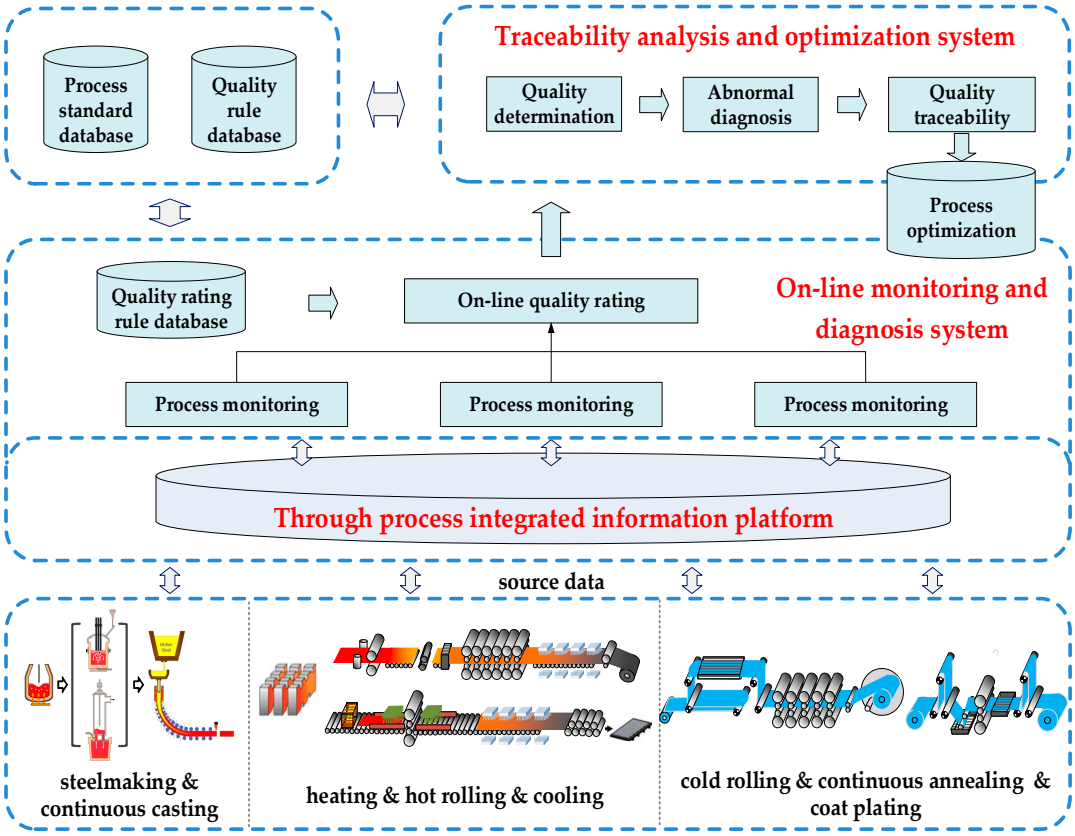

Figure 2. On-line monitoring, diagnosis and optimization technology of product quality in the through process.

Quality information of through process is captured and acquired to make the whole manufacturing cycle information of the product seamlessly connecting in space and precise docking in time. The on-line monitoring, diagnosis and optimization system of the full flow process quality is put forward. For the individual procedure, the functions of production process monitoring, process quality analysis and early warning, process quality diagnosis, on-line quality judgement and reverse optimization of process parameters are realized. For the through process, the functions of

correlation analysis of process parameters and quality indexes (including batch difference analysis, process capability analysis), tracing of quality anomalies, reverse optimization of process technology parameters, process route optimization are developed. Finally, the continuous improvement of manufacturing process level is realized.

4. Coordination and Optimization of Multi-Process and Precision Control of Product Based on CPS Architecture

The steel manufacturing process is long and complex, also with uncertain multi-interference. Normally, mechanism or statistical model and independent control of single process are usually used, which is difficult to ensure the quality accuracy in product-process state switching. At the same time, the multi mechanisms and multi procedures are separated from each other in the manufacturing process, it is difficult to realize the quality tracking and coordination control of multi procedures.

Aiming at the problems of frequent product specification switching and unstable product quality, the standard data interface is used to define the communication between procedures and the network structure and data platform for real-time interconnection of multiple procedures are designed based on the original control system. The Cyber-Physical Systems (CPS) system architecture for coordinated optimization control of the through process operation indexes and key process parameters is further established. Combining big data and process mechanism in the steel strip production process, the methods of big data reasoning and deep learning are employed to establish the intelligent perception technology in through process. The feeding and blowing operation of converter are controlled autonomously and the heat loss state database of lining in ladle turnover process is established. The temperature and composition perception model of refining process is constructed and heat transfer mechanism of continuous casting billet during solidification is studied. The fuzzy inference model of final stage of solidification is established by combining pressure feedback model. The control of smelting purification and billet homogenization based on big data is realized. Based on the thought of "procedure autonomy, process coordination", the intelligent setting and control technology of key quality parameters, such as component, three-dimensional dimension, temperature in the through process, are developed. The variable mesh and dynamic adaptive optimization are used to realize the optimization setting of specification variation. The methods of refined dimension control and fast temperature control for the unsteady process are proposed. The real-time coordination and optimization technology of multi mechanisms and multi procedures are broken through. Meanwhile, the real-time dynamic adjustment method of cooling path and multi-process temperature route is developed, the strip flatness and crown presetting and comprehensive matching control model during the multi procedures are established. Taking microstructure transformation and mechanical properties as object, integrated control of hot rolling-cold rolling-continuous annealing is realized. The complex CPS system is decomposed into several independent function modules by modularization method, which supports the application of the system. Coordination and optimization of multi-process and precision control of product quality is shown in Figure 3.

Key process model and parameter prediction technology are developed and high cleanliness, homogenized continuous casting billets without defects are prepared, as well as the control accuracy of the temperature and the 3-dimensional dimensions in the unsteady process are improved. In addition, the precise control of key process quality parameters under complex and changeable conditions, such as personalized customization, are realized, which provides support for the coordination and optimization of multiple procedures. The structure of multi-process coordinated and optimized control system is established and the technology rule base of each procedure interface is formed, which realizes the independent interaction of key parameters between procedures. From the view point of flat product quality in through process, the evaluation standard of the operation index is constructed, the key quality parameters of steel strip such as the temperature, the flatness and the mechanical properties are changed from the local optimization of the single procedure to the overall optimization of the through process.

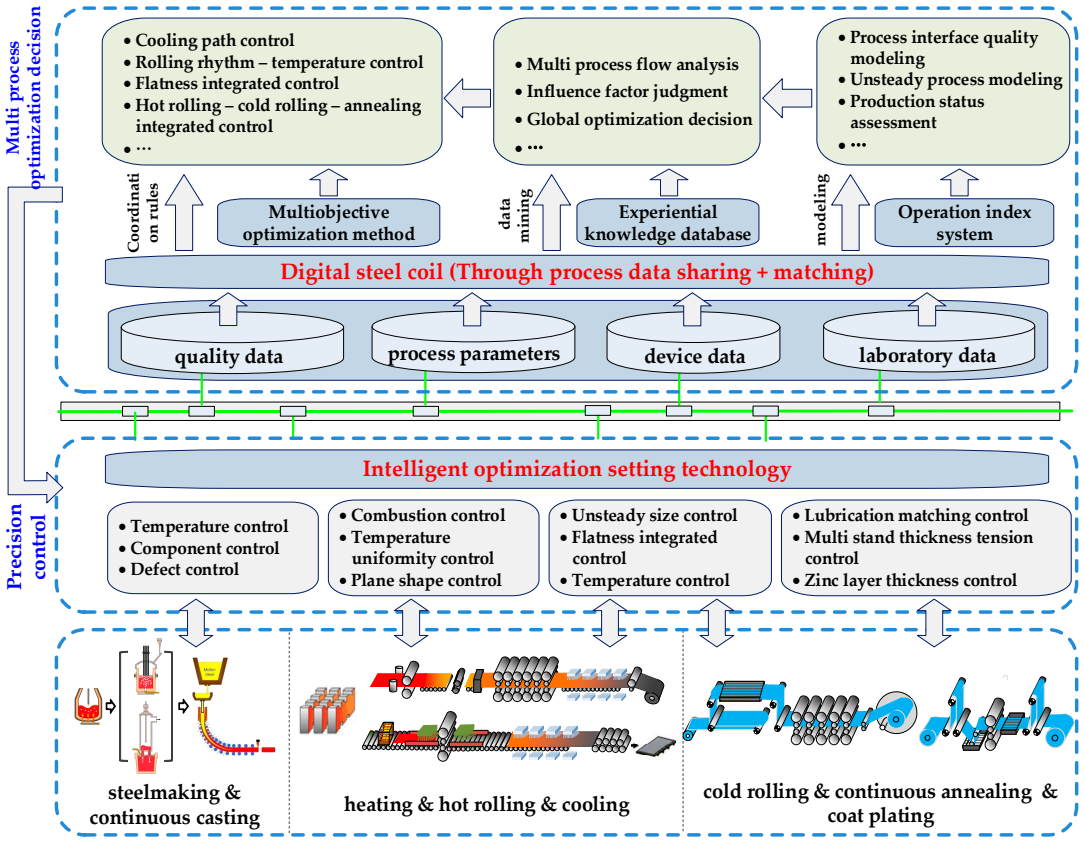

Figure 3. Coordination and optimization of multi-process and precision control of product quality.

5. Microstructure and Property Optimization and Surface Quality Intelligent Control Technology in Hot Rolling Process

During the steel manufacturing process, some problems such as imprecise control of chemical composition and unstable process control are often appear, which directly cause the mechanical property fluctuation and reduce the yield of finished product. The cooling path control and related simulation experiments with ultra-fast cooling and instant cooling technology are carried out. The corresponding relationship between microstructure and properties can be established by synthetically considering various strengthening mechanisms such as fine grain strengthening, phase transformation strengthening and so forth.

A database of chemical composition, process, microstructure and mechanical property is established by collecting industrial big data and combining with the recognition technology of microstructure images. Furthermore, based on multidimensional data mining technology for data screening, process clustering analysis and physical metallurgical rule determination of industrial big data, the Bayesian neural network (BNN) algorithm is developed. The prediction model of microstructure and mechanical properties based on neural network is established, combining with the locally weighted regression method under the condition of frequent variations of the manufacturing process. The multi-objective optimization function is set up according to the customer requirement and an efficient multi-objective Particle swarm optimization (PSO) algorithm combined with BNN is developed to establish the dynamic and rapid setting method of hot rolling process considering reasonable process constraints. By means of knowledge automation, the on-line, real-time and dynamic rolling process can be optimized rapidly, the process control ability of each procedure is evaluated in real time. On this basis, the potential of rolling and cooling process is fully utilized and the process parameters of downstream process are dynamically optimized in real time, which can guide the development of steel grades and realize the upgrade and downgrade rolling and the stability control

of product properties. Object library for steel grade merging is constructed, based on the big data of steel strip production, the influence weight of the chemical components on the mechanical properties of the product and the control margin of the mechanical property of the hot rolling products are analyzed and the technical guidance method for the steel composition lumping under the influence of multi-factors is established. Composition intensification for the steel grades with similar properties is proposed. The number of steelmaking grades is reduced, the full use of the remaining slab and strip is realized and the loss caused by the demotion or scrap of transition slab is reduced. Through the analysis of industrial big data, the database for composition of oxide scale, rolling process and surface quality is established and prediction module of structure and thickness of oxide scale and process optimization design module for hot rolled flat product are developed to realize the on-line recognition of the oxide scale defects and on-line process optimization for specific oxide scale structures. Temperature control-deformation coupling-property matching and intelligent control technology of surface quality in hot rolling process is shown in Figure 4.

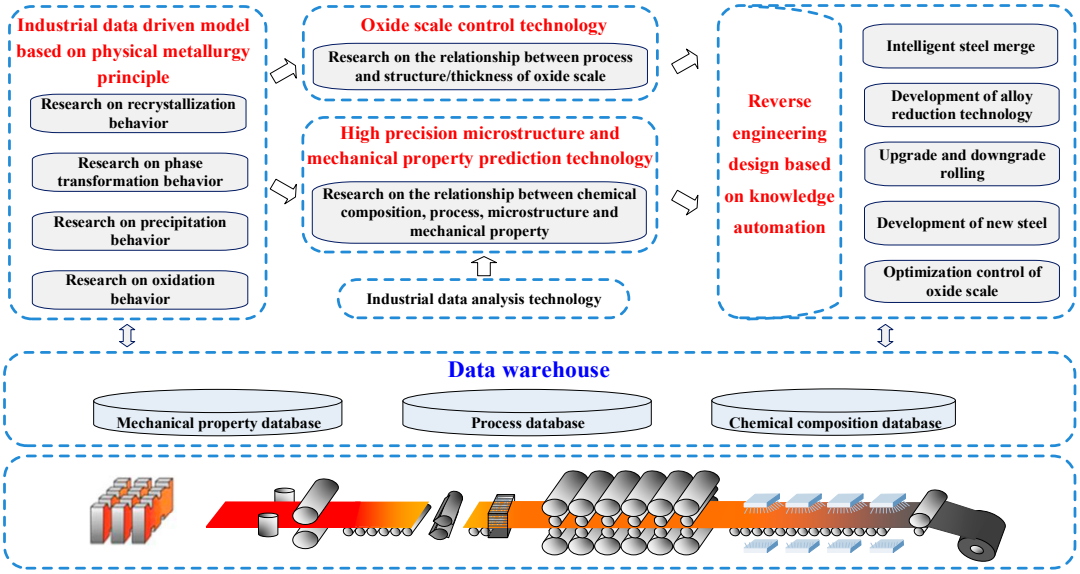

Figure 4. Temperature control-deformation coupling-property matching and intelligent control technology of surface quality in hot rolling process.

The corresponding relation between rolling technology and mechanical property in production process is confirmed, the intelligent prediction technology of microstructure and properties is developed and the high precision prediction of mechanical properties in accordance with the physical metallurgy is realized. The software package for dynamic rapid design of hot rolling process is also developed. In addition, the reverse engineering design of the process is carried out based on knowledge automation technology and the real-time adjustment of process parameters and the precise control of product quality are realized. Steel grade merging criterion under the influence of multiple factors is developed and the merging of steel grades of hot rolled products with "close mechanical properties cross series" or "adjacent mechanical properties with same series" is realized, steelmaking and continuous casting procedures are simplified. The surface quality control technology of hot rolled products is developed for realizing the soft measurement of the thickness and structure of oxide scale for hot rolled strip and the intelligent process design of the oxide scale for the special requirements of products with acid free and reducing acid pickling.

6. Conclusions

In this study, focus on field of the steel strip intelligent manufacturing, the complete theoretical system will be constructed, intelligent decision-making and production scheduling, on-line quality

monitoring and optimization, precision control and multi-process coordination, microstructure and mechanical properties control and other key common technologies will be formed and demonstrated, to improve production efficiency, product quality and flexible production capacity, expand the brand value of steel and meet the customer requirements of multiple varieties and small quantities. The complete process collaborative control of typical products such as automobile sheet, tinplate or other typical products will be formed. With the characteristics of information depth perception, intelligent optimization decision-making and precision control execution, an intelligent demonstration plant will be established, to realize the intelligent development of iron and steel industry.

Author Contributions: Conceptualization, D.Z.; Methodology, J.S., W.P., J.D. and D.Z.; Writing-Original Draft Preparation, J.S. and W.P.; Writing-Review & Editing, J.S., D.Z. and X.L.; Project Administration, D.Z.

Funding: This work was supported by National Key R&D Program of China (2017YFB0304100), National Natural Science Foundation of China (51704067, 51774084 and 51634002).

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

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