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Quality and Operation Management System for Steel Products through Multivariate Statistical Process Control

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***Abstract*—A new quality and operation management method is proposed for products in steel production processes. The proposed method is based on multivariate statistical process control, that is one of the applications of principal component analysis. The quality and operation management system using the proposed method was developed and has been applied to actual plants. The proposed method enables to detect the deviation from the normal correlation among the manufacturing conditions of the objective production processes. Significant effects on speedup of quality anomaly detection have been achieved in commercial production processes. The developed system has made contributions to reducing probability of occurring a large amount of product defects.**

***Index Terms*—quality management, operation management, steel products, multivariate statistical process control, principal component analysis**

I. Introduction

FOR early detection of the cause of quality anomaly and expedition of manufacturing process management, a quality and operation management system has been developed. The quality of steel products are built through a series of the following manufacturing processes; steel-making process, hot-rolling process, cold-rolling process and heat-treatment process. To build high quality products in demand, necessary processes increase, and then a great number of operation conditions of manufacturing processes affect the product quality. Conventionally, the general method called statistical process control has been carried out in quality and operation management. Because there are a large number of operation conditions to be managed, the load of observation was high in the conventional method, and there is the problem that the conventional method cannot detect abnormality easily if the process values of operation conditions are in control range. To solve these problems, the system has been developed for steel production processes based on multivariate statistical process control technique [1-5].

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To date, in steel industry, as an application using the technique, a monitoring system for continuous casting, i.e., one of steel production processes, to prevent breakouts has been reported [6]. It is a system for a single process. However, how to manage quality and operation conditions of multi processes has not been solved.

This paper proposes a method and a system for a series of steel production processes. Its application at JFE Steel's West Japan Works is also presented.

II. Object Process and Conventional Method

A. Production processes

A series of steel production processes shown in Fig. 1 are treated in this research. In the steelmaking process, the chemical composition of the material is adjusted and intermediate products called slabs are cast. In the hot-rolling process, these slabs are heated to the specified temperature in the reheating process; then they are subjected to plastic working in the rolling process to obtain the specified shape and dimensions. In the cooling process, the microstructure and mechanical properties of the steel material are built into the product by cooling it to the specified temperature. In the cold-rolling process and heat-treatment process, the microstructure and mechanical properties of the product are further adjusted.

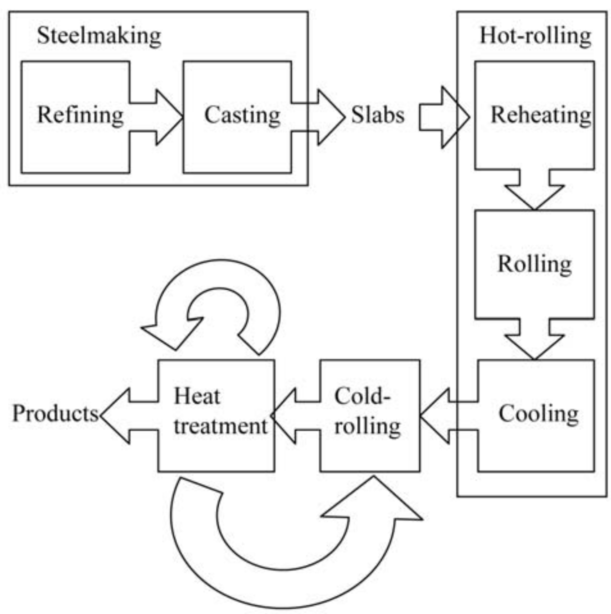

Fig. 1. Schematic diagram of production processes

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The product quality indices for steel products include mechanical properties such as strength, elongation, and toughness, electromagnetic property, i.e., iron loss and magnetic flux density, surface property, i.e., surface gloss and surface roughness, and dimensions, i.e., thickness, width, and length. A great number of operation conditions of manufacturing processes affect the product quality. In the application described in the following sections, the number of operation conditions is over 1,000. The conditions, which mainly affect quality indices, are the contents of alloying elements of the material which are adjusted in the steelmaking process, and the temperatures of the material in the production processes.

B. *Conventional monitoring method*

Based on the concept that the quality of products can be controlled at the target value if every operation condition is regulated at the target value, all the operation conditions of all the manufacturing processes are monitored by control charts as shown in Fig. 2. This quality control method is well known and it is called Univariate Statistical Process Control (USPC). Because there are a large number of operation conditions to be managed, the load of observation was high in this conventional method. In this case, the conventional method cannot detect abnormality easily if the process values of operation conditions are in control range.

III. Proposed Method and New System

To solve the problems mentioned above, the quality and operation management system using Multivariate Statistical Process Control (MSPC) has been developed.

A. *Multivariate Statistical Process Control*

Figure 3 shows difference between USPC and MSPC. To

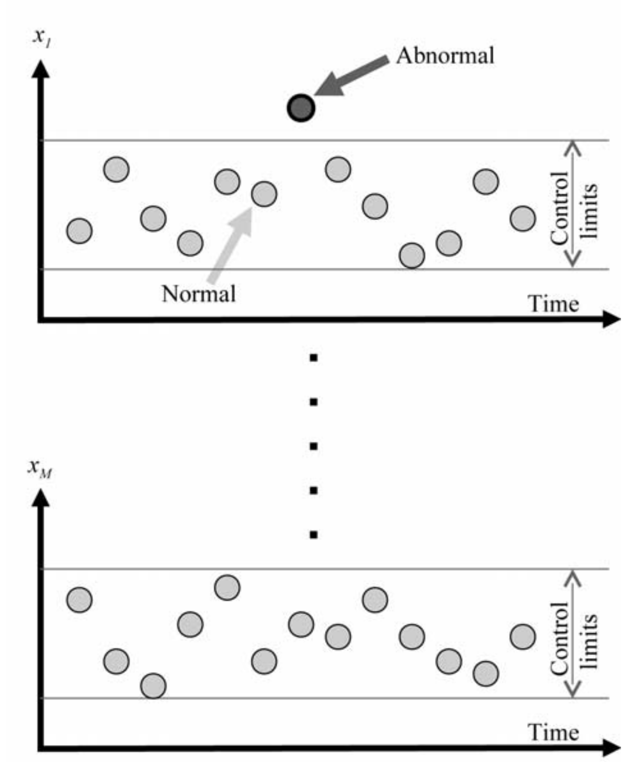

Fig. 2. Control charts of Univariate Statistical Process Control

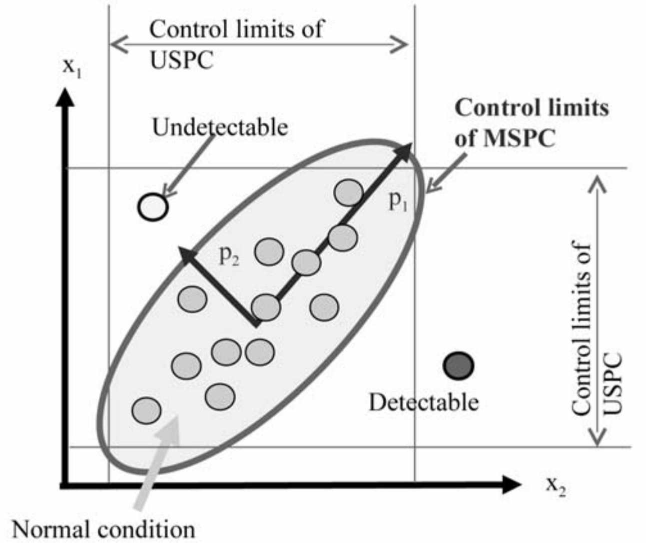

Fig. 3. Univariate Statistical Process Control and Multivariate Statistical Process Control

ease explanation, only two variables are used in this figure, although many variables can be treated in these methods.

The process values of operation conditions of production processes are generally linking with correlation. The control limits of USPC can be described as a rectangular as shown in the figure. An abnormal condition is detectable if the values are out of the rectangular, but another abnormal condition is undetectable if the values are inside the rectangular. Thus there is room for improvement on the abnormality detection performance.

The control limits of MSPC can be described as an ellipse, which fits to the data in normal condition, as shown in the figure. The control limits of MSPC are constructed by using principal component analysis. Because the process values of the operation conditions are linking with correlation, the space which expresses operation conditions are compressed using principal component analysis. Only 2 statistics are observed in the method. One is T^2 statistic which expresses essential change of the process. The other is Q statistic which expresses nonessential change caused by the reason such as the sensor abnormality [7].

B. *Improvements of MSPC for multi-processes*

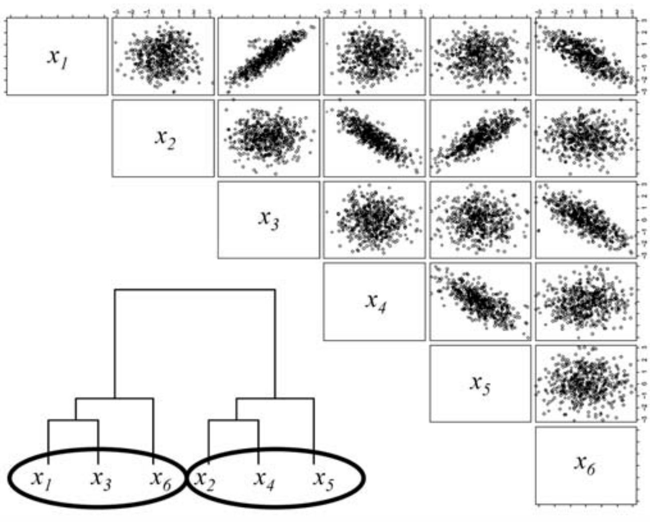

Fig. 4. Example of clustering variables based on their correlations

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Even if the technique mentioned above has been applied to the quality and operation management for the series of steel production processes, the following problem remains. It is that abnormal detection performance is not enough because there are a large number of operation conditions. Therefore we have improved the technique as shown below.

1) Clustering variables

It has been discovered that enough abnormality detection performance is not obtained when there are a great number of operation conditions which are linking weakly with correlation. Thus all the operation conditions have been divided into several groups based on the correlation of them, as shown in Fig. 4, so that every operation condition links strongly with other operation conditions in each group. Monitoring by MSPC is carried out in each group.

2) Parameter tuning

To decide easily and generally a tuning parameter, i.e., the degree of the principal components, we use a method that derive the value of the parameter from the singular value of standardized input data.

C. System Configuration

The system configuration of the quality and operation management system thorough Multivariate Statistical Process Control is shown in Fig. 5. It is a simple system constitution. It consists of a database in which the operation conditions of all the manufacturing processes and the quality index of the products are accumulated, and a general-purpose personal computer in which MSPC software is installed. They are connected to each other through LAN.

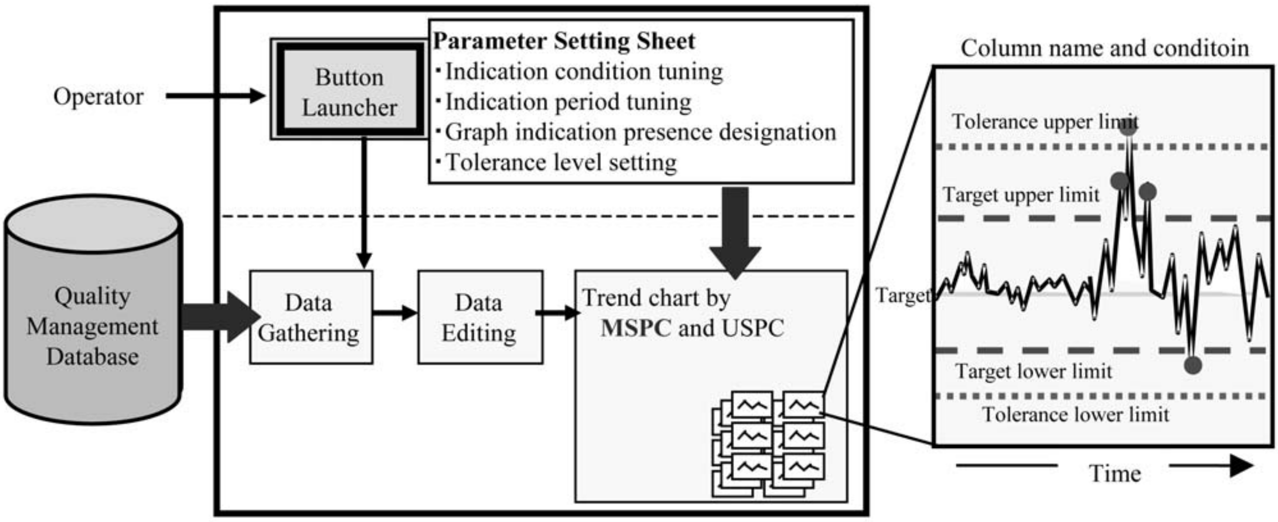

Fig. 5. System configuration of quality and operation management system through Multivariate Statistical Process Control

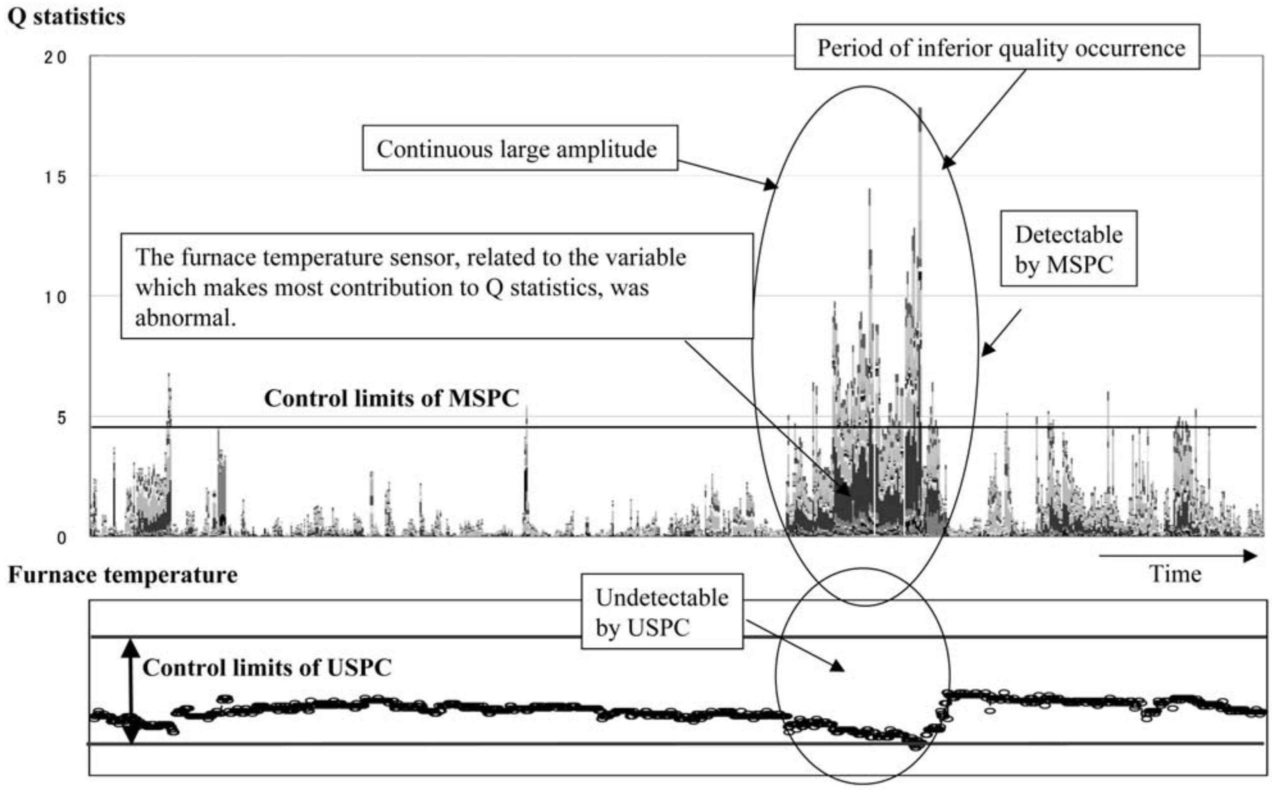

Fig. 6. Application result of case 1: control charts of a case of inferior quality caused by furnace temperature sensor abnormality.

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IV. Application Result

Two MSPC application examples are shown in this section. Application effects of MSPC are also introduced at the end of this section.

A. Case 1: Quality defects caused by furnace temperature sensor abnormality

This is one of the cases that inferior quality occurrence, which MSPC can detect but USPC cannot, in the commercial production processes as shown in Section II.

Control charts of this case are shown in Fig. 6. The upper one is Q statistic control chart with contributions of operation conditions introduced through MSPC. Continuous large amplitude over the control limit can be clearly detected with the Q statistic control chart through MSPC, although there are no control charts in which the process values exceed their control limits through USPC. The period of the continuous large amplitude is equal to that of the inferior quality occurrence. The most contribution to Q statistic is a furnace temperature of one of heat-treatment processes. By equipment inspection, it was revealed that the temperature sensor related to the variable was abnormal. The lower control chart is that of the variable related to the abnormal furnace temperature sensor. Because there are no process values, which exceed the control limits in the control chart, the abnormality cannot be detected by USPC.

A scatter plot is shown in Fig. 7. The horizontal axis shows the temperature related to the abnormal sensor. The vertical axis shows the other temperature of a furnace zone next to the zone of which the temperature measured with the abnormal sensor. The both process values are strongly linking with correlation. The abnormality cannot be detected by USPC because all the values are inside the control limits. However, the abnormality can be clearly detected by MSPC because the control limits fits to the data in normal condition as shown in Fig. 7.

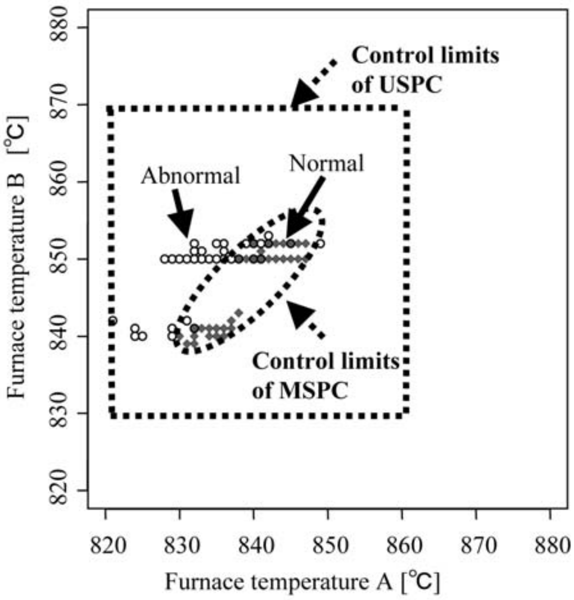

Fig. 7. Application result of case 1: scatter plot of a case of inferior quality caused by furnace temperature sensor abnormality.

B. Case 2: Quality defects caused by molten composition abnormality

This is another case that inferior quality occurrence, which MSPC can detect but USPC cannot, in the commercial production processes as shown in Section II.

Q statistic control chart of this case is shown in Fig. 8. Continuous large amplitude over the control limit can be clearly detected with the Q statistic control chart through MSPC, although there are no control charts in which the process values exceed their control limits through USPC. The period of the continuous large amplitude is equal to that of the inferior quality occurrence.

Figure 9 shows contribution plots for Q statistic. The 10 largest contribution variables among over 1,000 operation conditions are described in the figure.

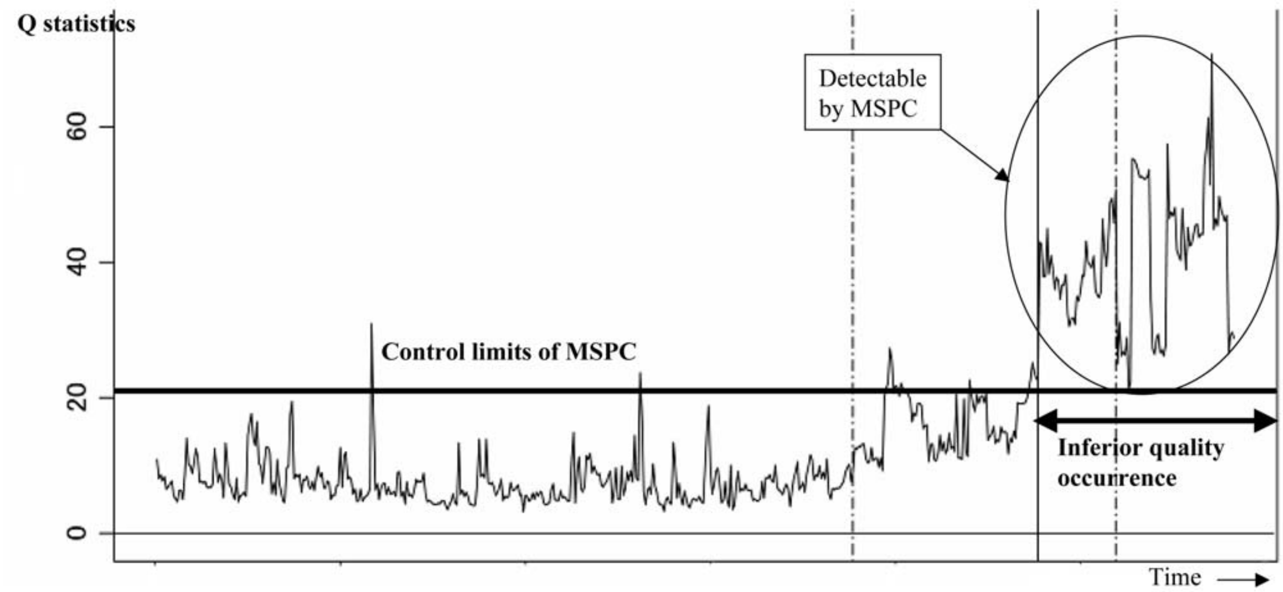

Fig. 8. Application result of case 2: Q statistic control chart of a case of inferior quality caused by molten steel composition abnormality.

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All of 10 variables shown in Fig.9 are refining operation conditions, i.e., molten steel compositions, slag compositions and converter blowing time. The most contribution to Q statistic is one of the molten steel compositions. By equipment inspection and product analysis, it was revealed that the composition of the auxiliary material thrown into the converter was abnormal, and the auxiliary material was related to the molten steel composition A, i.e., the largest contribution to Q statistic. Control charts, which describe the measurements, predictions and contributions to Q statistic of the molten steel composition A are shown in Fig. 10. The upper one shows the contributions to Q statistic, i.e., the squared prediction errors. The lower one shows the measurements and predictions. The predictions are derived through principal component analysis from the data in the normal condition as described in Section III. The predictions are equivalent to the estimations of the operation conditions based on the assumption that the quality of the products is in normal condition. During the period of inferior quality, it can be recognized that the predictions of the molten steel composition A deviates from its measurements. The range of the molten steel composition A during the period of inferior quality is as same as that in normal condition. Thus, the abnormality cannot be detected by USPC.

C. Application effects of Multivariate Statistical Process Control in the actual commercial plant

1) Monitoring load reduction

Monitoring load has been significantly reduced by MSPC because only 2 statistics (T^2 statistic and Q statistic) are observed although all the operation conditions have to be monitored by USPC.

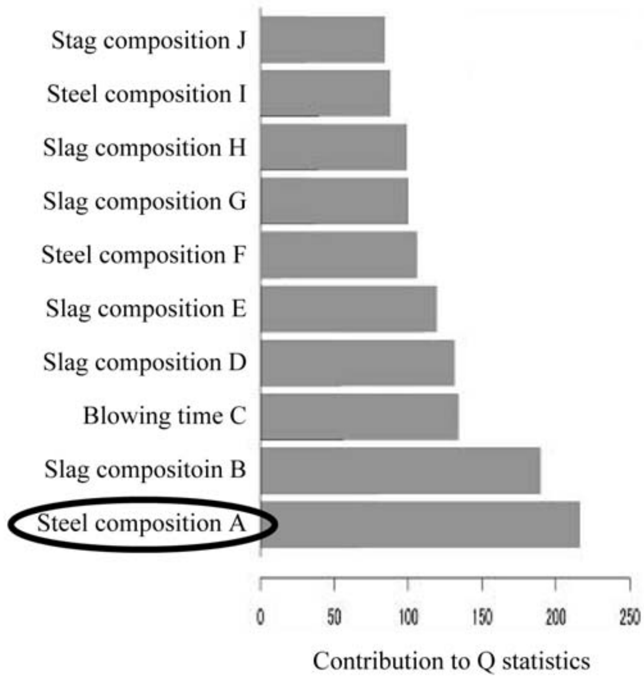
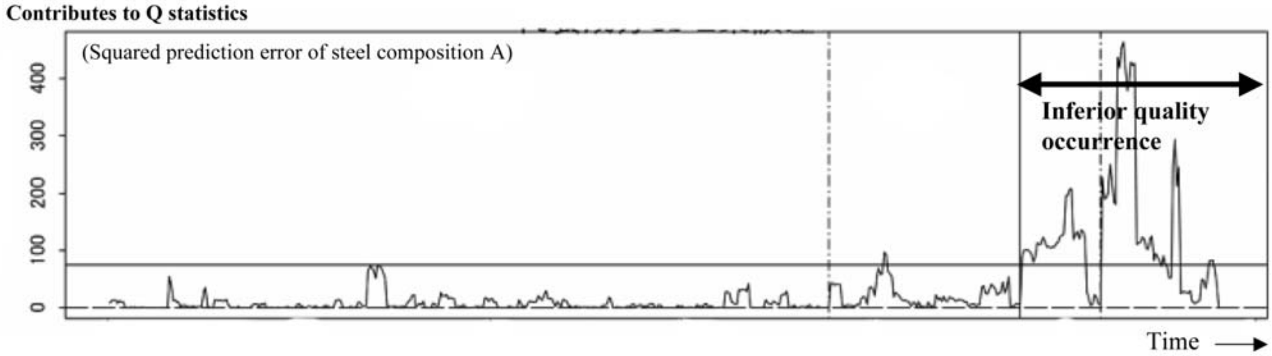


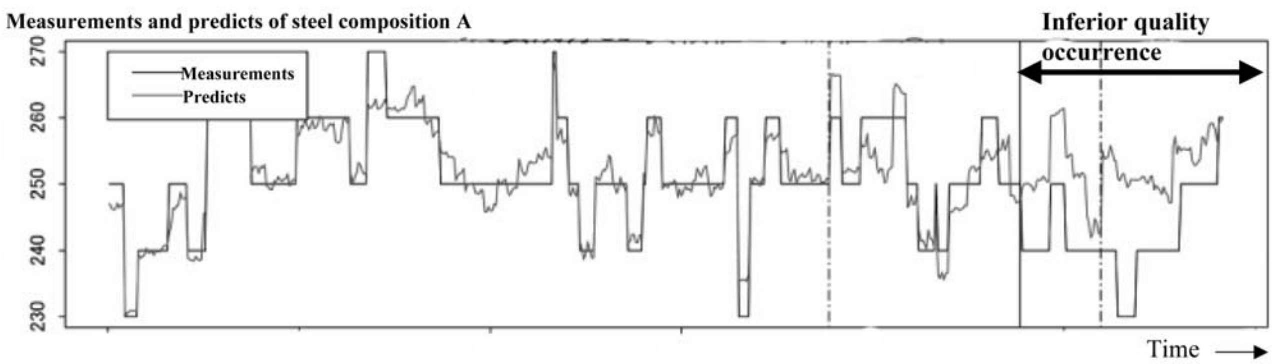
Fig. 9. Application result of case 2: Q statistic contribution plot of a case of inferior quality caused by molten steel composition abnormality.

2) Early detection of quality defects

Contribution of each operation condition to the statistic, which exceeds the control level, can be evaluated. In descending order of contribution ratio, making a hypothesis of mechanism of occurring of quality abnormality and search evidence by product analysis, whose workload are high, have been executed. The system enables to execute these works efficiently. Thus the system has been contributing to early detection of the cause of quality abnormality.



(a) Contribution to Q statistic, i.e., squared prediction error of steel composition A



(b) Measurements and predictions of steel composition A

Fig. 10. Application result of case 2: Q statistic control chart of a case of inferior quality caused by molten steel composition abnormality.

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3) *Effectiveness of proposed method*

By detecting the deviation of correlation of operation conditions in cases of chemical compositions in steel-making process, furnace temperatures in heat treatment process and so on, The system enables discovery and cause identification, which were difficult by the conventional method, Thus the effectiveness of the proposed method has been demonstrated.

V. Conclusion

A quality and operation management method for a series of steel production processes to detect abnormality of operation conditions sensitively in order to prevent leading to inferior quality was developed. The proposed method is based on multivariate statistical process control using principal component analysis and clustering technique. A system based on the proposed method was developed and applied to quality and operation management of various steel production processes. In this paper, the application result of the developed system for cold-rolled steel sheet, which is made through steel making, hot rolling, cold rolling and heat treatment processes, is reported.

This paper introduced a successful example in which modeling and management system development were performed efficiently by effectively utilizing the actual manufacturing conditions and quality indices data that are collected automatically and accumulated in large volume in a series of steel production processes, thereby contributing to early detection of the cause of quality anomaly and expedition of steel production process management.

In steel manufacturing plants, many quality and operation management system have been implemented since an early date, and the number of products and the operation conditions are continuing to increase. Because this is a general purpose technique, its scope of application is currently being expanded to quality and operation management in various other processes where the monitoring load is high and inferior quality need to be detected more sensitively due to environmental changes, i.e., more severe customer requirements and more diverse products.

The developed system for a series of steel production processes has been used at JFE Steel Corporation's West Japan Works since November 2010. It has functioned stably in spite of changes in manufacturing equipment and other environmental changes during this period. By detecting deviation from normal condition based on the proposed method, the product quality control accuracy was improved and the risk of quality defects was reduced.

The usefulness of the proposed system was confirmed through its industrial application; thus it is confidently expected that the system can be used for various purposes. Accordingly, the authors plan to expand the scope of application of this method to quality and operation management problems in various other processes in which it is necessary to reduce monitoring load or to detect faults more sensitively due to environmental changes.

This system has been contributing to improvement of quality abnormality detection and restraint of mass inferior quality outbreak greatly. The coverage of the proposed method and the system are going to be enlarged for various processes in the future.

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