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Development of Intelligent Monitoring and Prediction Technology for Ladle Operation

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The ladle is an important piece of equipment for loading molten steel in a steel mill. In the past, due to the lack of sensing equipment and prediction models, the ladle was managed by the number of times used and visual inspection by the operator. It is only to be expected that steel leakage incidents occur, resulting in losses and industrial safety hazards. In addition, the refractory quality of the ladle and the conditions of the stirring holes and filling sand at the bottom are also related to the maintenance of the molten steel temperature, the quality of refining and the smoothness of tapping. To meet the above-mentioned needs of the steelmaking plant, CSC has developed the intelligent monitoring and prediction technology for ladle operation and focus on the two main axes of preventing abnormal steel leakage and optimizing molten steel temperature control. In this paper, there are eight technologies being proposed and are divided into three application fields; equipment maintenance, process improvement, and management optimization. After the completion of off-line research in 2021, the online services of two technologies have been completed, the other technologies will be launched in 2022. It is expected that it will help steel mills dramatically reduce heating costs and maintenance fees.

Keywords: Ladle operation, Intelligent monitoring, Prediction, Steel leakage

1. INTRODUCTION

In a fully integrated iron and steel plant, after the molten iron is produced in the blast furnace, it is transported to the steelmaking plant using torpedo carts, and then the steelmaking plant uses a molten iron transfer ladle to take the molten iron from the torpedo cart and pour it into the basic-oxygen-furnace (BOF). As shown in Figure 1, the molten iron is converted into molten steel after being blown in the BOF, and then transported to the secondary refining station for refining by ladle, and finally transported to the continuous casting area for casting. It can be found from Figure 1 that there are two types of transport equipment for molten iron: torpedo

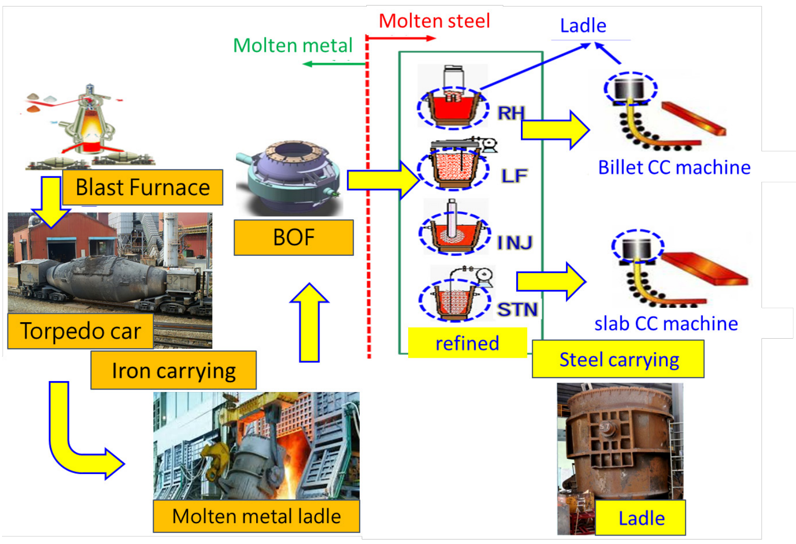

Fig.1. Steelmaking flow chart.

carts and molten iron ladles. But there is only one kind of transport equipment for molten steel: ladle. Therefore, it can be understood that the ladle is one of the most important piece of production equipment in the steelmaking plant, and is used in all procedures for processing molten steel, such as handling, refining and continuous casting procedures. Therefore, the maintenance and control of the health status of the ladle is a very important issue for the steelmaking process.

There are three problems to be solved for ladle operation in CSC. First, steelmaking plants all over the world will face a very serious problem, that is, "steel leakage". If the steel ladle is accidentally damaged during the hoisting or production process of the molten steel, it will lead to a steel leakage accident. The main equipment is damaged, the production schedule is delayed, the production capacity is reduced, and in severe cases, it will cause fatal accidents to personnel. Second, the ladle control method in CSC is all based on "visual inspection" and "number of times used", which lacks substantial data support. Third, there is a fracture in the information of the ladle operation, and the scheduling is still manually input, which is difficult to intelligently import. After the ladle is preheated and becomes a usable ladle, it needs to go through the scheduling of the turntable before it can enter the BOF, refining, continuous casting and other operations, and then it will go back to the turntable for the next scheduling use. However, because of the number of the ladle entering the turntable is keyed in manually, many pieces of data are mistakenly planted or misplaced, so that the inspection results of ladle status cannot be used for subsequent big data applications. Therefore, to improve the intelligent scope of the ladle operation, it is necessary to complete the ladle information automatically to provide intelligent model development, correct, and usable training data sets.

2. EXPERIMENTAL METHOD

In the research projects[1-4], there were three types of ladle thermal image monitoring systems being developed. This paper proposes intelligent analysis and diagnosis technology to upgrading former systems from "sensing level" to the "cognitive level", and then proposes prediction technology to upgrading to the "prediction level". To solve the above-mentioned problems, the developed applications can be divided into three facets: 1. Prevent abnormal steel leakage; 2. Optimize molten steel temperature control; 3. Develop an integrated ladle information service platform. According to the process of the ladle operation (Fig.2.), there are eight technologies being developed.

The main reason for the steel leakage in a ladle is that the refractory bricks have severe local erosion and brick drop, so that the ladle body is melted through by the high-temperature molten steel. In order to solve this problem, there were four core technologies being developed: 1. Slag line breakage warning[10], 2. Brick lining residual thickness prediction[5], 3. Prediction of abnormal use of main slag line bricks[5] and 4. Evaluation of refractory quality[5].

The temperature of molten steel when tapping, the number of times the ladle is used continuously, and whether the tapping is smooth during continuous casting after refining are the main factors that affect the temperature of molten steel. For the control of molten steel

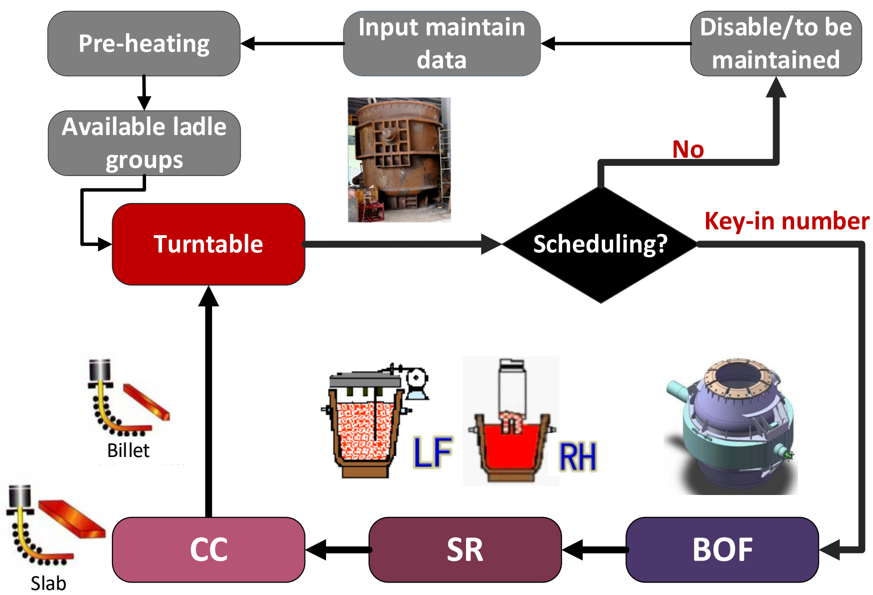

Fig.2. The process of the ladle operation.

temperature, there were three core technologies being developed: 1. Intelligent prediction of molten steel temperature before tapping(6), 2. Identification of ladle ID(6), and 3. Identification and analysis of stirring bricks and filling sand(10).

To provide more complete ladle information on site, an iLadle intelligent service platform(5) was established. In addition, the above-mentioned intelligent monitoring and forecasting service functions will also be gradually built on this platform to achieve the goal of comprehensive and intelligent operation and maintenance for ladle operation.

3. RESULTS AND DISCUSSION

The technologies aforementioned can be divided into three attributes, equipment application related, process improvement related and management optimization related. The corresponding indicators of each key technology are shown in Table 1. The eight technologies are descripted as follows.

3.1 Slag line breakage warning

The slag line early warning system has assisted many times on site to warn of steel leakage before the ladle failure. However, the identification method of the temperature threshold and the time threshold will cause false warnings due to the slag splashing and accumulating on the flange of the ladle during production. Therefore, the fuzzy state law was developed(4) and the warning method improved, which not only reduced the false warning time by 42%, but also accelerated the system response speed. The warning can be issued about 2 minutes earlier, to gain more response time for the personnel.

3.2 Brick lining residual thickness prediction

Lining in the ladle includes: wall, bottom and main slag line. After the analysis of this case, it was found that the residual thickness of the wall and bottom has a trend for linear erosion, and the residual thickness can be predicted by using the "number of times used " without importing an intelligent model. The main slag line brick has no relative trend with the number of times used. It is necessary to import production data and use a suitable intelligent model to predict the residual thickness. With the CatBoost algorithm(8), under the standard of error of ±25mm, the correct rate of model performance is over 80%. Overcoming the problem that the residual thickness cannot be measured when the ladle is used continuously on line. In the future, the real-time residual thickness prediction of an online ladle can assist personnel in determining and scheduling, preventing a ladle from being broken, and can also extend the total number of times used and reduce the number of major repairs per year.

3.3 Prediction of abnormal use of main slag line bricks

The ladle has a different initial thickness, safe thickness, and a target thickness for number of times in use for refractory brick lining in different parts. By bringing in the actual times in use and the final offline residual thickness value, the abnormal use data set can be found. The anomaly identification model established by using AutoEncoder (AE)(9) and has an accuracy rate of 92% and a recall rate of more than 90%. This technology can issue a warning for a ladle that may be being used abnormally, so that the operator can schedule to extend the times in use of the main slag line brick, so as to

Table 1 Key technology corresponding index table.

Key technology	Three facets			Class
	Steel leakage	Extend usage rounds	production intelligence	
1. Slag line breakage warning	◎	◎		Equipment
2. Identification of ladle ID		◎	◎	
3. Identification and analysis of stirring bricks and filling sand			◎	
4.Intelligent prediction of molten steel temperature after tapping			◎	Process
5. Evaluation of refractory quality	◎	◎		Management
6. Brick lining residual thickness prediction	◎	◎		
7. Prediction of abnormal use of main slag line bricks	◎	◎		
8. iLadle intelligent service platform		◎	◎	

reduce the number of minor repairs and achieve cost reduction benefits.

3.4 Evaluation of refractory quality

The quality of refractory used in a ladle can be evaluated at different facets: (i) company, through the usage of XAI[10], and considering the qualified ratio and erosion rate, it can be clearly pointed out that each manufacturer belongs to the forward or reverse thrust (Fig.3),

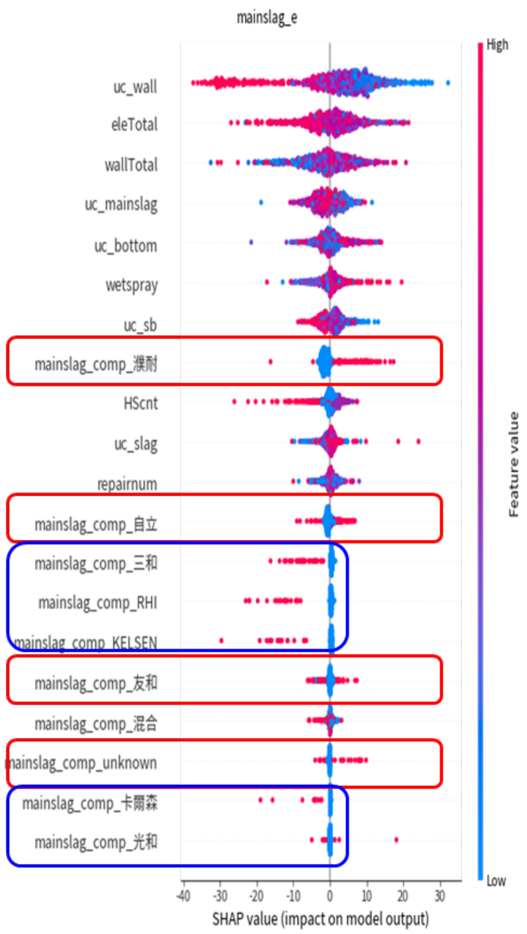

Fig.3. Use XAI to judge the pros and cons of manufacturers.

which is quite suitable for the maintenance unit as a basis for the quality control of the manufacturer. (ii) normal usage rate, calculating the normal usage rate of each manufacturer in each brick lining can make the maintenance unit clearly and quickly understand the durability performance of each manufacturer in each part and adjust the purchase of materials. As shown in Figure 4 and Figure 5, the normal usage rate in Figure 4 is low, and the distribution of points in the abnormal area is relatively scattered; especially in the north part. It can be found that the quality is not good, and it is prone to a low number of cycles and low residual thickness. In Figure 5, the normal usage rate is high and the points in the abnormal area are also quite close to the safety line, and the points in the abnormal area on the north side are concentrated and close to the safety line, that means the quality is good. (iii) qualifying frequency, as shown in Figure 6, which will compare the qualified frequency of each manufacturer used in the four directions of the main slag line brick, the horizontal axis is the manufacturer's times in use, and the vertical axis is the qualified ratio. In general, selected manufacturers that can provide a high pass rate the more they are used is the best policy. (iv) average erosion rate grouped by company, as shown in Figure 7, the horizontal axis is used rounds and the vertical axis is residual thickness. It can depict that in different rounds which manufacturer can have more residual thickness left. (v) average erosion rate grouped by part, the average erosion trend of refractory brick linings in different parts of the ladle is one of the more important indicators for maintenance and research units. This finding can provide research institutes to simulate the enthalpy of the online ladle, and then calculate the heat dissipation effect of the molten steel temperature due to the use of a ladle with different rounds, and then develop related technologies for stabilizing the molten steel temperature. (vi) average erosion trend under anomalous usage, Figure 8 is a graph of the residual thickness variation trend drawn by the four directions of the main slag line brick according to the normal use and abnormal use data points. It can be seen from the figure that the abnormal erosion curvature falls about 3.75mm/round in the three directions of east, west and south,

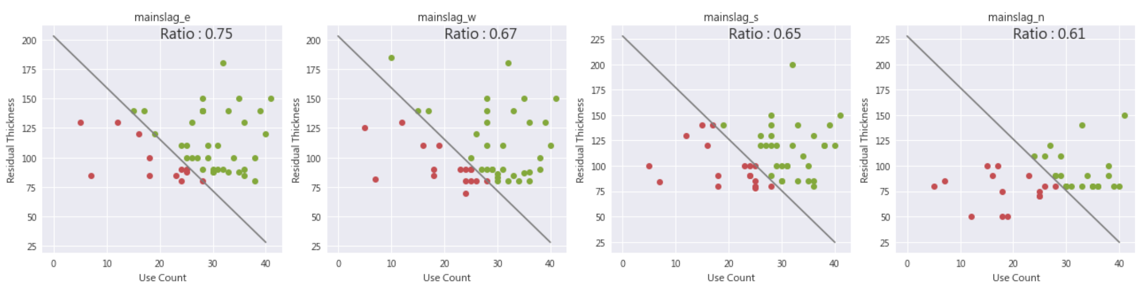

Fig.4. Example of low normal usage rate.

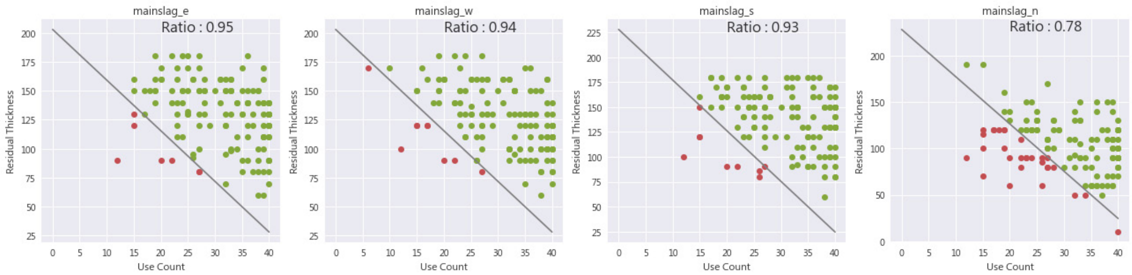

Fig.5. Example of high normal usage rate.

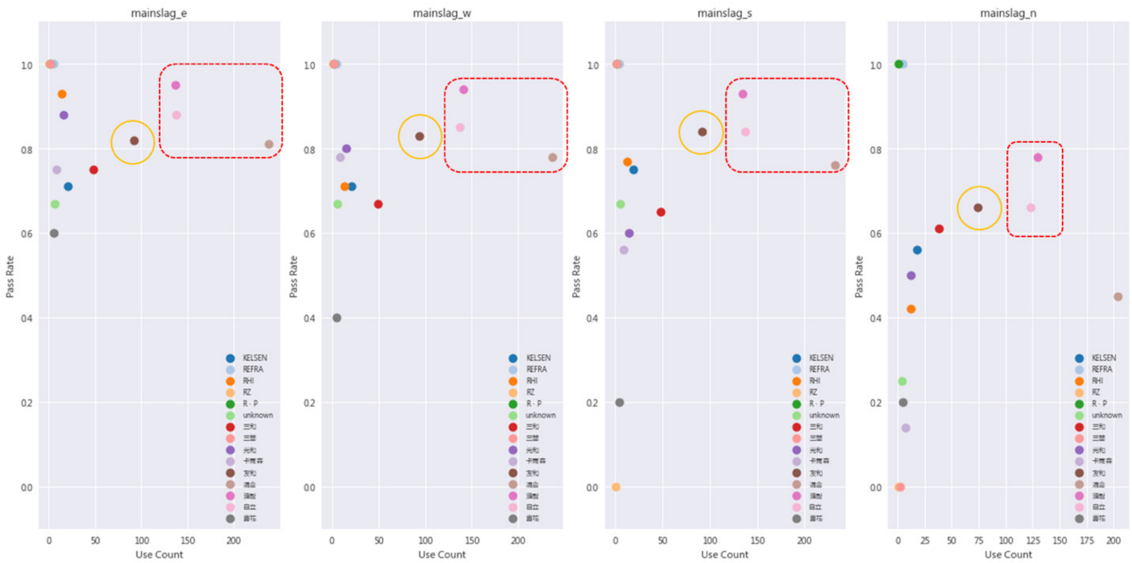

Fig.6. Qualified frequency comparison chart.

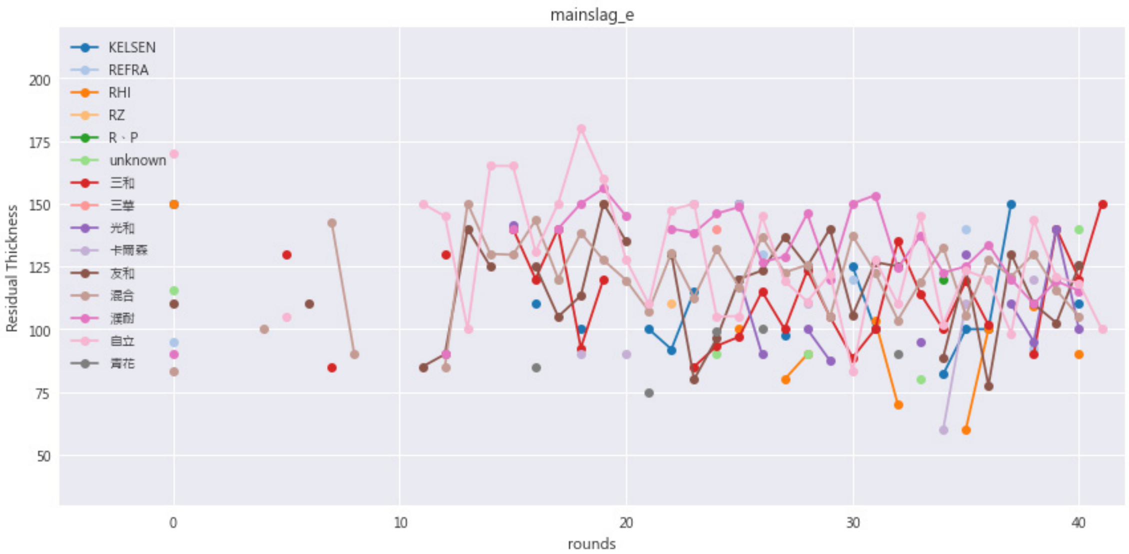

Fig.7. Average erosion rate grouped by company.

while the normal erosion curvature falls at 2.5mm/ round. The abnormal erosion curvature on the north side is also about 3.75mm/ cycle, but the normal erosion curvature increases to 3.33mm/cycle and changes more drastically. Therefore, it can be seen that there are special reasons on the north side, which makes the change of

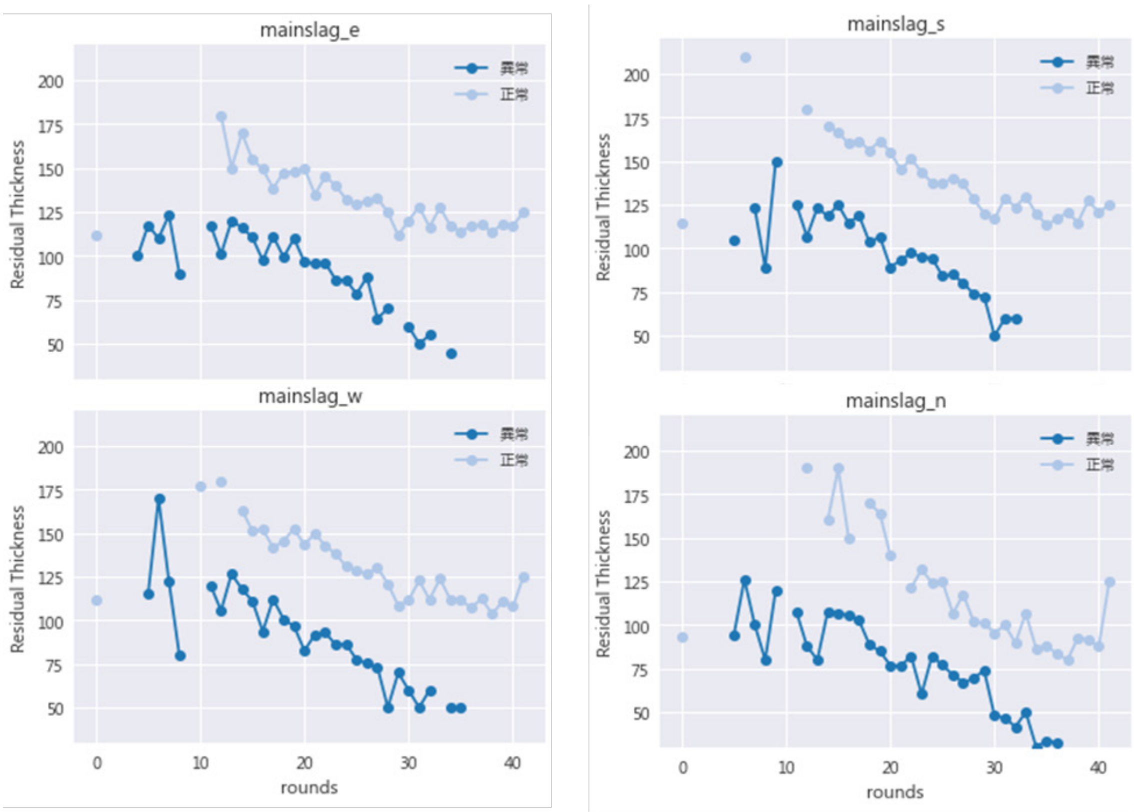

Fig.8. Average erosion trend under anomalous usage.

residual thickness from the other three sides significantly different. After tracking, it was found that the position of the electric shock rod of LF1 was closer to the north side. Therefore, through the analysis of the average erosion trend under normal and abnormal use, it will be able to assist on-site adjustment or detection of equipment abnormalities.

3.5 Intelligent prediction of molten steel temperature after tapping

Using the 108 available parameters in the BOF production data and the detection data of the ladle, the LightGBM[(11)] algorithm was combined with the integrated architecture to analyze the regression problem of the molten steel temperature after tapping, and the continuous prediction accuracy rate of the off-line model can reach more than 80%, successfully achieved the set goals. After going online, the predicted value of the molten steel temperature after tapping will be provided before the end-blow, allowing the operator to improve the temperature control accuracy and achieve the benefits of cost reduction, energy saving and carbon reduction.

3.6 Identification of ladle ID

Due to the influence of slag contamination and light changes, the ID recognition rate of the ladle number or the external label is undecipherable. Through self-developed high-temperature RFID tags[(7)], it breaks through the environmental temperature limitation. The reading distance can reach more than 3 meters at room temperature, and 1.5 meters at hot line operation. After 1014 production tests, it can still operate normally, becoming the most suitable for high temperature, low-cost ID identification solution in the environment of high-slag and high-dust steelmaking plants and can be expanded to other production lines in the future.

3.7 Identification and analysis of stirring bricks and filling sand

The high-low temperature dual model identification technology established by the YOLO[(12)] object identification algorithm can identify the positions of the "stirring hole" and "filling sand" inside the ladle. By linking the number of ladles without natural opening and abnormal stirring from the identification results, it can provide substantial data on the causes of abnormal stirring/opening, assisting personnel to analyze through the analysis results, improve operating conditions to reduce the incidence of abnormality.

3.8 iLadle intelligent service platform

iLadle intelligent service provides four major services: (i) ladle event inspection service: let the online scheduling unit master the online real-time status of the ladle; (ii) online thermal image inspection information service: users can directly check the inspection results of each site online; (iii) maintenance history digitization service: reduce data typo and provide correct training data for big data applications; (iv) use intelligent analysis service for brick lining: assist in evaluating the pros and cons of refractory manufacturers to stabilize production quality.

4. CONCLUSION

In CSC, the development of intelligent application technology for ladle operation was a field rarely involved in, in the past. It is necessary to provide highly customized solutions for on-site problems and characteristics, which is the key to improving the reliability, safety and efficiency of steelmaking plants. In the steelmaking process, the ladle not only affects the quality of molten steel, but also affects the safety of production and the cost of steelmaking. Aiming at the three major indicators of the steelmaking plant: equipment care, process improvement and management optimization, this paper proposed complete one-stop technical planning and development from online to offline. From online: safety monitoring, pre-judgment of refractory brick lining status, to offline: prediction of residual thickness of refractory materials, manufacturer evaluation, through the AIoT platform, the production unit has a more comprehensive grasp of the status of the ladle, to create energy savings, carbon reduction and, being cost-effective. In addition to assisting production units to save energy and reduce costs, the special technical achievements can also provide information required by research units for technological development such as molten steel temperature control, ladle preheating optimization and refractory development.

At present, two technical online services have been completed. Among them, the slag line hole breaking warning technology has been successfully warned for a total of 12 times, and the on-site evaluation benefit of up to NT$18 million. The hole position identification and analysis technology of the ladle will help to increase the natural opening rate by 0.5%, which is of positive help to the quality of the molten steel and the normal tapping rate. Other technologies are undergoing off-line verification and will be launched one after another after completion. It is estimated that it will help steel mills reduce heating costs and repair costs by more than NT$15 million.

In the future, through the deployment of the intelligent model on AIoT platform, the implementation of various key technologies will be completed. Achieving the above goal is only a phased achievement, CSC will continue to improve and expand the application to making the ladle operation intelligent. In addition, CSC will aim at smart factory transformation to maximize the benefits of energy saving and cost reduction.

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