A Shape Decision and Control Scheme for the Stainless Steel at the Skin Pass Mill

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(Received on October 17, 2008; accepted on February 19, 2009)

The objective of this paper is to build a shape decision and control system for the stainless steel and to ensure reducibility of workload for the next rolling process. The criterion of the shape quality is derived from the customer needs, and a shape decision system is implemented at the skin pass mill (SPM). The methods of shape decision are based on curve fitting and frequency analysis, and so on. A shape control system is also implemented with a programmable logic controller (PLC) using fuzzy logic. It receives process data from sensors such as shape meters, load cells, and pressure transducers. The field test with concerned customers is successful in the shape decision and control. The rate of the right decision is almost 99% and the claims from the customer have been largely reduced by annual 102 tons. The productivity of the rolling process is increased up to 38%.

KEY WORDS: shape decision and control system; stainless steel; fuzzy logic; PLC implementation.

1. Introduction

Stainless steel products are made from Cr, Ni, and alloy. Accordingly, stainless steels are better than the carbon steels with respect to the brightness, corrosion, and surface quality. The stainless coils may pass through a variety of the processes such as the annealing and pickling line (APL), sendzimir rolling mill (ZRM), brightness and annealing furnace (BAF), skin pass mill (SPM), and finally tension leveler line (TLL). While the stainless steels pass through the SPM, the mill gives the elongation and good surface, and it also determines the shape property. In some cases, the strip shape may be still bad after the SPM working, then it must go to the next process (TLL) for making a correction of the shape. However, the TLL has a few constraints. The TLL cannot correct the shape for the heavy thickness and severely bad shape steel as well. Therefore, for the heavy thickness steel and/or strict shape product, the shape should be corrected as much as possible at the SPM. Customers usually like to take products with the good shape quality, namely, products with the height of the edge wave below 4 to 7 mm.

There have been various conventional shape control methods. In the first method$^{2,3)}$ the shape is measured and recognized with neural networks and a fuzzy control is applied in real time. The shape recognition method is improved by using a curve fitting method for the edge wave compensation of the strip, and then a fuzzy control is performed in VME controller.$^{4)}$ And a shape is recognized as 4th order polynomial expression using neural network.$^{5)}$ A shape is recognized as polynomial model and then a decision is made for the shape and thickness of the strip.$^{7)}$ After plant identification by Elman network, a fuzzy control is shown by simulation.$^{8)}$ Generally, there are differences between the measured shapes under tension and the product shapes without tension. Hence, conventional shape decision methods have inherent problems from this point.

This paper proposes a method of shape decision and control for the stainless strip at the SPM in the stainless cold rolling process. The proposed method can improve efficiency of the rolling process and reduce process load by-passing the next process. In previous situations, as operators cannot reach precise decisions on the shape qualities of the products at the SPM processes, bad shape products may be transmitted to customers who file claims for compensation. Also good shape products may pass through the TLL, which has heavy workloads. Therefore, the shape meter is installed at the delivery side of the SPM as shown in Fig. 1. The shape is measured and the measured information is processed using techniques such as curve fitting and frequency analysis. Consequently, the shape decision system

Fig. 1. The shape meter of the SPM line.
applies to a reliable criterion which is derived from the customer needs and then makes a decision on the strip quality by the criterion. It is difficult for operators to make precise decisions about the strip shape because of high tension and rolling speed. And there is a gap between the measured shape (on line strip shape) and the free tension shape (off line strip shape).

Moreover, if the strip is judged to have bad shapes by the decision result, shape control is necessary to improve the shape quality. Interviews with customers are done to find problem of the stainless product. And then the shape deviation is selected as the quality improvement index by voices of customer. The control variables are deduced from the qualitative method such as the stratification and fish-bone chart and the statistical analysis such as the correlation and regression analysis. The shape control decreases the shape deviation using fuzzy logic, which is suitable for the nonlinear system and available informative knowledge. We have developed the shape control system using fuzzy logic implemented in a programmable logic controller (PLC). The strip shape is controlled by the shape control system composed of measuring instruments, a PLC, and a supervisory control computer (SCC). As a result, the shape quality of the stainless steel is guaranteed.

Table 1. Comparison between shape control methods at the SPM.

| Method             | Proposed method                  |
|--------------------|----------------------------------|
| Operation          | Maintain roll force without      |
|                    | shape deviation                  |
|                     | Control roll force with shape     |
|                    | deviation                        |
| Characteristics    | Work by experience,              |
|                    | No standard method,              |
|                    | Divergence between operators     |
|                    | Reproducibility & Repeatability  |
|                    | Accuracy                         |
|                    | Standardization                  |

Here ① means the case that the system decision is ‘a good shape’ and customer decision is the same. ② means the case that the system decision is ‘a good shape’ but customer decision is ‘a bad shape’. ③ means the case that the system decision is ‘a bad shape’ but customer decision is ‘a good shape’. ④ means the case that the system decision is ‘a bad shape’ and customer decision is the same.

If the system decision is ‘a good shape’, the products are delivered to the customer by skipping TLL. If the system decision is ‘a bad shape’, the products go to the next process (TLL). If a product seems to be ‘good’ by the system although it is determined to be ‘bad’ by the customer, the product is directly delivered to the customer. In this case, the customer files a claim for compensation. The claim induction ratio expresses unpleasant situations. If a product seems to be ‘good’ by the system although it is de-

2. The Shape Decision Method for the Stainless Steel

The measured shape data from the shape meter are analyzed using a curve fitting method. The right ratio of the shape decision with 181 stainless coils was about 70% for conventional methods based on the shape deviation and symmetry property.

Figure 2 shows the classification of the product flow. The criterion on the shape decision proposed in this paper is as follows.

- The right decision ratio=the number of the right decisions (①+④)/the number of total decisions (①+②+③+④).
- The claim induction ratio=the number of the wrong decisions (②)/the number of the bad shapes for customers (②+④).
- The process workload induction ratio=the number of the wrong decisions (③)/the number of the good shapes for customers (①+③).

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termined to be ‘good’ by the customer, the product is taken to the TLL. The process workload induction ratio shows an overload status of the next process. The performance index of the system decision is the right decision ratio. Unfortunately, the decision system usually has 70% right ratio. Accordingly, a conventional decision is not suitable for the shape decision online.

**Figure 3** shows extreme examples on a conventional decision method. The 2D and 3D strip shapes are shown in Fig. 3. As for 2D shapes, x-axis is the strip width from −900 to +900 mm. y-axis is the strip shape from −50 to 50 N/mm². As for 3D shapes, x-axis is the strip width shown by the load cell positioning number in the lateral direction. y-axis is the strip length and z-axis is the strip shape. In case of 1st and 4th rows in Fig. 3, the system decision satisfies customer’s requirement; however, 2nd and 3rd examples fail to reach a consensus. Though the system decision is ‘a good shape’ with respect to the symmetrical shape, customer decision is ‘a bad shape’ on the 2nd example. Besides, the system decision is ‘a bad shape’ with respect to the medium asymmetrical shape, while customer decision is ‘a good shape’ on the 3rd example. Consequently, an advanced decision method is necessary to reach an agreement with the customer. **Figure 4** shows the method of the frequency analysis for the stainless steel. The shape decision method was developed irrespective of tension. The edge waves of the strip shape are measured in the rolling direction. After a frequency analysis about the alternating current (AC) signal is carried out, the comparison between dominant frequency patterns of the edge wave is performed. The graphs of screen shots are FFT results of the strip edge wave. x-axis shows transformed discrete frequen-
cies of AC signal and y-axis is the amplitude of each frequency. The decision system compares the frequency pattern of the work side with that of the drive side from the strip edge wave.

Figure 5 shows the detailed procedure of the shape decision. The acquired shape data is processed for normalization and curve fitting. And then the shape grade is computed with respect to the symmetry and magnitude of the shape deviation. The shape grades have 9 levels from AAA (the highest level) to F (the lowest level). Moreover, the shape decision is done through the total shape analysis based on the similarity of the edge wave patterns on both sides. The shape decision has two procedures which depend upon ordinary and high grade products from the viewpoint of customer. The total shape analysis is the comprehensive analysis with the conventional and advanced procedure. The shape decision system applies a strict rule to high grade products. If the dominant frequency sequences of the both edge wave are different, the total shape analysis judges a bad shape prior to the conventional procedure. The decision result is also a bad strip shape. The shape decision system, meanwhile, applies a soft rule to ordinary grade products. If the conventional shape is over B (the middle level) grade with respect to the shape deviation, the total shape analysis judges a good shape prior to the frequency analysis procedure.

3. The Shape Control Method for the Stainless Steel

3.1. Control Output Selection

The SPM as a reversing mill has produced the strip through multi pass rolling. The shape deviation is a dominant factor which has influence on the final product quality and has a quite relation to the customer. Therefore, the shape deviation of the pass at the SPM working is selected as the control output. The strip is not flat in the horizontal and longitude of the strip. (Undoubtedly, good shape products have the excellent flatness in the longitude.) The shape deviation means the relative unbalance of the affected force in horizontal direction.

As shown in Fig. 6, the shape deviation (SD) means the cumulative value of the difference between a maximum and minimum shape.

- SD=maximum of the shape−minimum of the shape.

The shape deviation in the rolling direction (SDRD) is as follows.

- SDRD=\[\sum_{i=1}^{n} (max_i−min_i)\]/n for i=1, 2, ..., n and n is an integer. where n is the number of samples.

The shape meter consists of 54 load cells which are arranged in the direction of the column and horizontal. The load cells measure the relative distribution of the tension when the strip is rolling.

3.2. Control Input Selection

Minimum number of factors that have strong influence on the control output is selected for the control inputs. If the control inputs are not screened, the controller becomes complex and is not easy on tuning. Accordingly, the control inputs are deduced from the qualitative methods such as the stratification and fish-bone chart and the statistical analysis such as the correlation and regression analysis. As shown in Fig. 7, the fish-bone chart sorts out factors which have effect on the shape deviation by 4M1E (Man, Machine, Material, Method, and Environment).

The derived control parameters are the initial roll crown, elongation, strip width, material, actuator property (the response time and control range), roll force, thickness, tension, thermal crown and so on. The control inputs are selected from a few of parameters by the statistical analysis as below. The main elements which exert influence on the shape deviation as the control output are the roll force, actuator response time, and initial shape in the fish-bone chart.

Figure 8 shows an example of the correlation among parameters. The notation is as follows.

ShapeDev: shape deviation=maximum of the shape−minimum of the shape.
RFavgWs: roll force at work side.
RFavgDs: roll force at drive side.
Elongation: [increased length after rolling/material length before rolling] \cdot 10^5.
RF_Dev: roll force deviation between both sides.

The correlation coefficient depends on the linearity between compared parameters. If the graph is close to linearity, the correlation between parameters is large up to 1.0. If the graph is close to circle, the parameters are complete lack of the mutual relation. The correlation coefficient between the shape deviation and roll force is 0.4 and is bigger than any other factors.

**Figure 9** shows a result of the regression analysis. The boxed parts indicate statistic meanings. The VIF (variance inflation factors) means the independence among the inputs (X’s parameters). The P (value) means a significant statistical relation between Y (output parameter) and X (input parameters). R_sq (R squared) describes a statistical relational degree of X about Y. ANOVA (Analysis of Variance) results show a statistical meaning of P and F values. The result shows the independence among the inputs (X’s parameters) as VIF is less than 2 and P value is less than 0.05. Besides, the analysis shows the influence on the output (Y’s parameter) as R^2 is equal to 0.25.

Therefore, the shape deviation is selected as the control output. And the control inputs become the elongation and roll force on both sides of the work roll.

### 3.3. Shape Control Method

The shape control concept for the stainless product is shown in **Fig. 10**. First, the shape decision system is performed and decides the shape quality. Secondly, if the shape is bad and can be improved, the shape control system is operated. And lastly, the shape control system controls the roll force of the work roll and improves the strip shape.

The shape controller controls the difference between the roll force exerted on the work side and that exerted on the drive side. The shape control is implemented in a PLC which has been widely used in the industrial manufactory. The PLC can control in real time and communicate with the SCC and has been verified for operating actuators such as servo valves and cylinders. The controller outputs the roll force deviation and then operates the servo valves which drive the push up cylinders. The roll forces have an influence on the strip and finally affect the shape.

The proposed shape control method is as below. The shape deviation and symmetry are chosen as the control performance index. If the shape becomes severely asymmetrical, the strip leans to one way side. After all, the rolling operation becomes a bad state because of the terrible coiling and unstable working. The developed controller has a few constraints like any other controllers. The roll force deviation on both sides has to maintain less than 10 tons because of the stability of the rolling and working. Therefore, the controllable range is determined for this reason. The control output holds the roll force to the current value if the control performance is good, that is, the shape...
The deviation is symmetrically regulated and small. The main control objectives are the shape deviation and symmetry. And the control performance is affected by the actuator response, controller property (the response time and control period), implementation, simplification.

The relationship between the shape deviation (the control output) and roll force (the control input) is nonlinear. Moreover, the relationship between the actuators (the push up cylinders) and controller outputs is nonlinear, as well. Hence, it is difficult to obtain the excellent performance for the model based approach method such as the linear regression model. Consequently, the shape control makes use of fuzzy logic which is suitable for the nonlinear system and available informative knowledge.

Figure 11 shows the flow chart of the shape control. The output range of the fuzzy control is $-10$ to $+10$ V. A fuzzification method using singletons is employed because the measured data have high reliability. Fuzzy reasoning in this paper is based on Mamdani’s max-min method. A defuzzification method using the center of gravity (COG) is employed.

Figure 12 shows an example of the membership functions for the shape deviation and control output. The fuzzy rules are omitted here to save space.

The shape control procedure is shown in Fig. 13. The operators monitor the shape trend and then they select the automatic control mode mainly based on the shape deviation. If the shape deviation is less than 20 N/mm$^2$, the control system holds the initial roll force value. If the shape deviation is more than 20 N/mm$^2$, the automatic control is employed to decrease the shape deviation. The shape control has an influence on the roll force deviation on both sides of
the work roll under the control range. And then the shape control induces the shape to be symmetric. After the shape deviation is controlled very well, the roll force difference between the work side and drive side should be minimized to have the stability of the rolling mill.

4. Application Results

4.1. Shape Decision Results

The measured shape data from the shape meter are analyzed using a curve fitting method. A conventional approach about the shape deviation and symmetrical feature is performed. Besides, the decision method on the frequency pattern analysis of the edge wave is applied to the SPM line. Thus, as advanced test results for 200 stainless coils, the right ratio of the shape decision is increased by 90%.

Figure 14 shows some examples. Representative shapes imply the longitudinal average and display 2-dimensional shapes. The meanings of the frequency patterns are the fast Fourier transform (FFT) results on both sides. The vertical lines indicate the dominant frequencies. Classic grades are the results of conventional shape decision with the shape deviation and symmetry. Total analyses mean the results of the frequency patterns compared with the dominant frequencies on both sides. Customer decisions are the final judgements by customers. If the both frequencies have similar patterns, the shape decision result is a good strip shape. That means a decision consensus with customer.

Furthermore, the decision performance rises up to 99% due to the continuous system improvement. The final decision results have been offered to operators at the end of the rolling work with a man–machine interface (MMI). The shape decision system was installed at delivery side of the SPM and the operating room. Operators can monitor the decision results and watch the control status online.

4.2. Shape Control Results

The developed shape control has been applied to the SPM in POSCO. The developed controller composed of a PLC and a host computer. The PLC (Siemens S7-400 series) is used for data logging and control function. The control performance has been verified by off line simulation and in-line test. Also on line test is pursued carefully. The shape control system is tuned through the field test. The fuzzy rules are updated and also membership functions are modified continuously by the field test.

Figures 15 and 16 show on line test results. The shape control is applied in the 1st pass and 3rd pass. Test materials are the Cr steel. Strip thickness is 0.48 mm and width is 1254 mm. As for 2D shapes, x-axis is the strip width from 900 to 900 mm. y-axis is the strip shape from 50 to 50 N/mm². In statistical control chart of the shape deviation, x-axis is the time (s) and y-axis is the shape deviation from 0 to almost 200 N/mm². The logging period of the strip shape is 1 s. To compare the result of a manual operation with that of the automatic operation, manual operation is first applied from the strip head and then the automatic control is applied to the tail of the strip successively. As shown in Fig. 15, the big asymmetrical shape by manual changes to the small symmetrical shape by the shape control in the 1st pass. In the control chart of the 1st pass, the shape deviation has a big initial value for the manual operation and then is decreased step by step using the automatic control. As shown in Fig. 16, in the 3rd pass the large shape deviation caused by the manual operation is improved greatly using the automatic control. The shape deviation is reduced by 20 N/mm² with the shape control.
Another test results are shown in Figs. 17 and 18. The conditions of test materials are similar. As shown in Fig. 17, the big asymmetrical shape converges on the small symmetrical shape after the shape control in the 1st pass. In Fig. 18 in the 3rd pass, the large shape deviation for the manual operation has a big initial value over 110 N/mm² and then is improved significantly using the automatic control. The shape deviation is reduced from 110 to 20 N/mm².

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| Representative shape (2D) | Total shape (3D) | Control chart | Performance of Shape deviation |
|---------------------------|------------------|---------------|--------------------------------|
| ![Representative shape (2D)](image1) | ![Total shape (3D)](image2) | ![Control chart](image3) | Converge |
| ![Representative shape (2D)](image4) | ![Total shape (3D)](image5) | ![Control chart](image6) | Converge |
| ![Representative shape (2D)](image7) | ![Total shape (3D)](image8) | ![Control chart](image9) | Keep regulating |
| ![Representative shape (2D)](image10) | ![Total shape (3D)](image11) | ![Control chart](image12) | Converge |
| ![Representative shape (2D)](image13) | ![Total shape (3D)](image14) | ![Control chart](image15) | Converge |

Fig. 19. The advanced results of the shape control.
with the shape control. The on line results also exhibit symmetrical reduction on the shape deviation.

Figure 19 shows the shape control results with various material and size of the strip. Test materials are the Cr-Ni steel and Cr steel. Strip thickness is 0.75 to 1.43 mm. Two and three dimensional shapes and control charts of the shape deviation are shown in this figure. The big shape deviation decreases gradually and converges stably by the shape control.

5. Conclusions

This paper proposes a method of shape decision and control for the stainless strip at the SPM in POSCO. The proposed method improves efficiency of the rolling process and reduces a workload by omitting the next process. The shape decision system has made decision on the shape quality and has been installed at the SPM. The rate of the right decision at the final pass has been selected as the quality improvement index by customer needs. The performance factors of the shape decision are the shape deviation, symmetry, elongation, and frequency patterns of the edge wave. The shape decision method has been applied irrespective of tension through the total shape analysis. And the developed decision system has been operated at the SPM. The right ratio of the shape decision system is almost 99%. And the financial profit is about $1.1 million due to a productivity improvement and bypassing the TLL.

Moreover, the shape control method is necessary to improve the shape quality for the bad strip shape. The shape controller has decreased the shape deviation which is performance index from customer needs. The influence factors of the shape control are the roll force, elongation, and initial roll crown. They are deduced from the qualitative method and the statistical analysis. The shape control method achieves the symmetrical reduction in the shape deviation and improves significantly the bad shape of the strip. The shape control method makes use of fuzzy reasoning which is suitable for the non-model based approach and available informative knowledge. The strip shape control has been successfully done by the control system composed of the measuring instruments, PLC, SCC, and actuators.

The SPM as 2 high reversing mill has no conventional actuators such as benders and shift function, so that the shape control is almost impossible. However, in this paper the stable control system has been developed successfully and the shape quality of the stainless product is guaranteed. Besides, the productivity of the rolling process has been increased up to 38%.

REFERENCES

1) Y. G. Hur: Proc. of the Int. Conf. on Control, Automation and Systems, ICCAS, Muju, (2002), 1089.
2) Y. G. Hur and D. K. Lee: Proc. of the 9th Conf. on Int. Fuzzy System and Association, IFSA, Vancouver, (2001), 251.
3) Y. G. Hur and D. K. Lee: Proc. of the 16th Conf. on Int. Federation of Automatic Control, IFAC, Sydney, (2000), 1.
4) Y. G. Hur and Y. H. Lee: Proc. of the 6th Conf. on European Congress on Intelligent Techniques and Soft Computing, EUFIT, Aachen, 3 (1998), 1645.
5) Y. G. Hur: Korea Patent Registration Number 0851199, (2008).
6) Y. Peng, H. Liu and R. Du: J. Mater. Process. Technol., (2008), 54.
7) M. Jelali: J. Process Control, 17 (2007), 805.
8) C.-Y. Jia and H.-M. Liu: J. Iron Steel Res., Int., 13 (2006), 31.