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Characteristics of Continuous Wire Rod Rolling and Precision Rolling System

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Abstract

The demands of users for closer dimensional tolerances and improved metallurgical properties in wire rod products prompted the research and development of sophisticated dimensional and material temperature control technologies in continuous rolling. To cope with these problems, first, we have developed a nonlinear simulation model for calculating interstand tension, height, width, temperature, load and torque in steady state, transient state and influence coefficient of continuous rolling. The examples of simulation results were in good agreement with the measured values. As an example, material temperature of 2 block mill was simulated using this model. Second, as applications of the simulation model, we have developed multivariable control systems. Third, we have developed a precision rolling system (NT Block Mill Automatic Gauge Control).

1. Introduction

Recently, there is an increase in the demand among wire and steel rod users for: precision rolling materials that makes it possible to omit the drawing and peeling processes; finer order sizes (currently 1 mm to a future of 0.1 mm) with the objective of increasing the yield of the forging processes; steel material manufacturing that can shorten and omit heat treatment; and free-size rolling to realize shortened delivery times.

As a method for realizing precision rolling, there are the following methods: (1) Method using mill hardware and; (2) method adding control system to the existing 2 roll mill. As actual applications of the former method, the 3 roll mill[1,2] whose spread by rolling under light reduction is extremely small, the 4 roll mill[3] and the 2 roll sizing mill whose light reduction rolling spread was made smaller[4] have been reported. The latter method has had reports of the analysis of influence coefficients of the block mill with regard to the size control technology of the wire[5,6], of free tension control[7] in the 2 strand rolling and of the set-up of intermediate mill[8]. With regard to finishing block mills, currently manual operation is used to adjust the dimensions so it is difficult to roll with the dimensional tolerance of ≦ ±0.1 mm.

On the other hand, in order to realize material manufacturing, it is necessary to control the rolling temperature.

We created a simulation model[9] of the continuous wire rod rolling that calculates the deformation, load and temperature of the rolled steel to handle this problem and studied the rolling characteristics. Then we used a linear state equation, applied and extended the multivariable control theory to develop the multivariable control technology[10,11] that corresponds to the mill configuration. Also, with the objective of realizing less downtime by precision rolling through controlling absolute values of dimensions, reduced material for adjustment and automated operation, the wire precision rolling systems[12] for finishing block mills have been commercialized. This

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report describes an outline and calculation examples of the simulation models, block mill multivariable control technology and wire precision rolling systems.

2. Wire and Rod Single Stand Rolling Model

2.1 Deformation and load model

2.1.1 Deformation model

(1) Width spread model: Our influence coefficients of tension were added to the Shinokura's formula[13].

(2) Advanced model: Influence coefficients of tension were added to the Saito's formula[14].

(3) Area of projected contact model: The Shinokura's formula[13] was used.

2.1.2 Load model

(1) Flow stress model: The Shida's formula[15] was used.

(2) Load model: Influence coefficients of tension were added to the Saito's formula[14].

(3) Rolling torque model: The Saito's formula[14] was used for calculations of the torque arm coefficients.

2.2 Influence coefficients[16] of tension affecting deformation and load

Experiments at the hot continuous model mill found influence coefficients of front and back tension affecting the rolling characteristics.

2.3 Temperature model[17, 18]

The shape of a section of the material was converted to a roundness with the same area of cross section and approximating a one-dimensional thermal conduction in the radial direction. The processing heat supposedly uniform in the cross section was found from the processing energy (rolling torque). The roll shape approximated the cylindrical circumference of the material and the friction heat and contact thermal conductivity of the material and roll as well as the water cooling (roll cooling water and forced cooling water) between stands [strands?] and the air cooling were calculated. Moritaka et. al developed a similar model[19], too.

(1) Conversion of the material shape

Converting the material shape to the roundness with the same cross section area, the one dimensional thermal conductivity equation in the radial direction was differentiated and calculated. The amount of reduction of the surface area was corrected with the heat transfer rate so that there would be no change in heat flux by the conversion of the shape as the boundary condition between stands.

(2) Temperature calculations in the roll byte

The roll shape was approximated to the co-axial cylindrical shape contacting the circumference of the material and using the boundary conditions given, the thermal conductivity equation of the cylindrical coordinates were converted to the implicit difference equation and calculated[20].

(3) Calculations between stands

Using the given boundary conditions, the thermal conductivity equation of the cylindrical coordinates were converted to the explicit difference equation and calculated.

2.4 Heat transfer coefficient of water jet cooling in wire rolling[21]

(1) Current research

The development and cooling characteristics[22] of cooling tubes for steel rods has been reported. They found the average heat transfer rate using measured values of temperatures before and after cooling. But the local heat transfer coefficient and non-dimensional general formula noted in the water blast cooling[23] with steel sheets and the measured values of the heat transfer rate of the wire have not been reported.

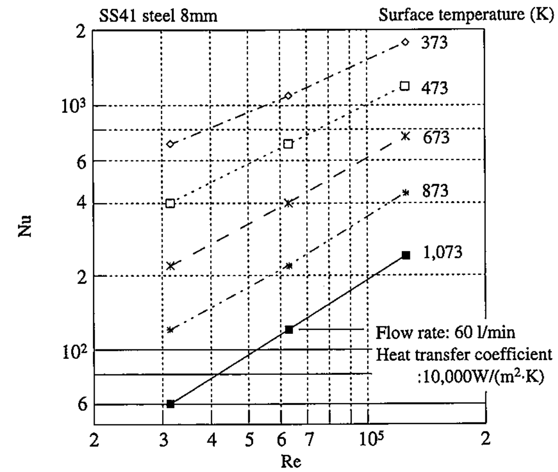


Fig. 1 Relation between Re number and Nu number in nozzle of water jet cooling for wire

(2) Experimental method of heat transfer in this research

In this experiment, a nozzle for actual steel wire mills was located in the model mill cooling trough. Steel wire was heated to 950°C in an electric furnace sealed with N_2 gas. After extraction and being carried to the trough, it was placed lengthwise in eachcooling tube and cooled with a water jet. The temperature history of the center of the wire was measured and the heat transfer rate was determined that the temperature values matched the calculated ones.

(3) Experimental results

This report describes the experimental results of heat transfer 50 mm downstream from the stagnation point. Using the wire diameter as the representative length, the water jet flow speed in the cooling tube as the representative speed and the 60°C water as the representative temperature, the Reynolds number Re and the Nusselt number Nu were defined using the kinetic viscosity and thermal conductivity for those representative values. **Fig. 1** shows the relationship between Re number and Nu number for each surface temperature when Re = 31,300 to 125,200 (nozzle flow rate was 30 to 120 l/min.). As the flow rate increased, the Nu number increased proportionately to it. The heat transfer coefficient was 10,000 W/(m^2·K) when Re number was 62,600 and the surface temperature was 1,073 K, and was 110,000 W/(m^2·K) when Re number was the same value and the temperature was 400 K. It was approximately 2 to 5 times higher than the value of steel sheets[23], and higher than the value of steel bars[22] at the same Re number.

3. Continuous Rolling Model of Steel Bar and Wire Rod

3.1 Calculation method of the steady state[24]

In the non-linear equation for unknown numbers of the tension, deformation, load and temperature of each stand [strand?], after solving the continuous equation with tension or roll speed as the unknown numbers, it is calculated in the order from upstream stand to downstream stand.

3.2 Method of calculation of the non-steady state[25]

The tension and rolling characteristics as functions were calculated in minute increments from the initial time to the final time while considering the moving delay of the material through the stands.

3.3 Method of calculation of the influence coefficient

Solving the non-linear equation, the rolling characteristics of the standard state and the minutely changed state were found and the change rate between those two states was calculated.

4. Comparison of the Calculated and the Measured Values in Continuous Rolling

4.1 Simulation of the actual wire mill steady state

SWRH62A material (cross sectional dimension of 120 mm × 120 mm) was rolled to a dimension of 5.5 mm ϕ at a finishing speed of 60 m/s. The calculated rolling load and the measured values are shown in **Fig. 2**. The accuracy of the calculations were mostly good. **Fig. 3** shows a comparison of the calculated values of the material temperature and the measured values. When the heat transfer coefficient of cooling water for the roll was hypothesized [α = 500 to 1000 kcal/(cm^2·h·°C)] as the nearly appropriate value, the calculated value of the material surface temperature matched well the measured value.

4.2 Simulation of the actual 2 rod block mills

Fig. 4 shows the calculated value of the material temperature when SWRH62A material (cross sectional dimension of 120 mm × 120 mm) was rolled to a product dimension of 5.5 mm ϕ at a finishing speed of 120 m/s setting the No. 2 block mill (reducing sizing mill, etc.) at the exit of the non-twist rod finishing block mill (NTM). In this case, the heat transfer coefficient of the forced cooling water was 9,300 W/(m^2·K), the cooling lengths were (water cooling length 3 m + air cooling length 3 m) × 2 boxes + air cooling length of 7 m at each exit of No. 13 and No. 15 before NTM, (water cooling length 5 m + air cooling length 5 m) × 6 boxes + air cooling length of 10 m between NTM and No. 2 block mill, and (water cooling length 5 m + air cooling length 5 m) × 4 boxes + air cooling length of 5 m at No. 2 block mill exit. Material surface, average and center temperatures were 777, 804 and 855°C respectively at No. 2 block mill entrance, and 857, 869 and 900°C respectively at the exit.

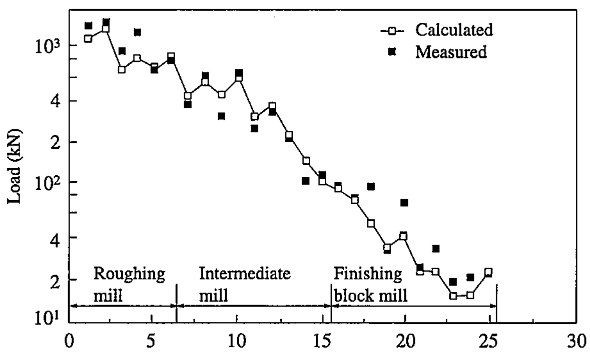


Fig. 2 Rolling load of wire rod mill

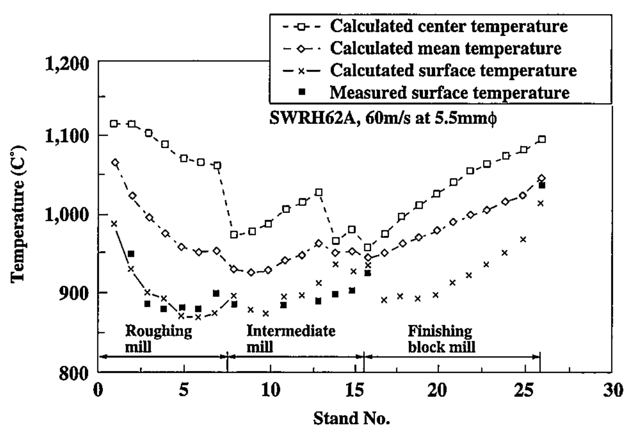


Fig. 3 Stock temperature of wire rod mill

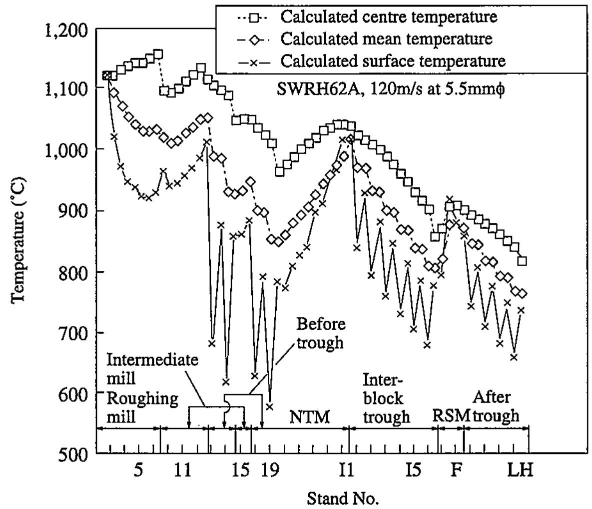


Fig. 4 Stock temperature of 2 block mills

5. Multivariable Control for Rod Finishing Block Mill

5.1 Control system design

We have extended the optimal regulator theory[11] that consists of the optimal control system. This optimal control system uses a feed-forward control that uses the measured values of the mill entrance dimensions and the temperature disturbance, and a feedback control that uses the measured values of the finished dimensions. This method is called block mill AGC (Automatic Gauge Control).

5.2 Experimental results with model mill

Using the experiment of block mill AGC with the hot model mill (the mill for experiment), it was verified that the short adjusting time for the finished height (diameter of the compressed direction) and the finished width (diameter of the vertical direction to the compression) corresponding to the material disturbance could be controlled, i.e. the diameter changes according to the step mode.

5.3 Actual 4 strand mill simulation

Using the measured dimensions of the entrance of the actual rod finishing block mill, a block mill AGC simulation was studied under the conditions of material H72B, finished dimension 5.5 mm ϕ, finish speed 60 m/s.

(1) Without control

Responses are shown in **Fig. 5**.

(2) With control

Figs. 6 and **7** show the responses of dimension measurement period of 0.5 s and 0.1 s with the control period of 0.1 s. With the dimension measurement period of 0.5 s, dimension precision was controlled within ±0.05 mm. With 0.1 s, higher dimension precision rolling is expected.

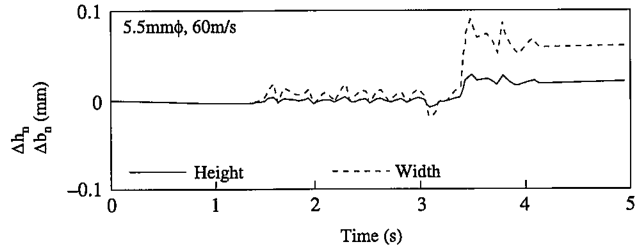


Fig. 5 Without control

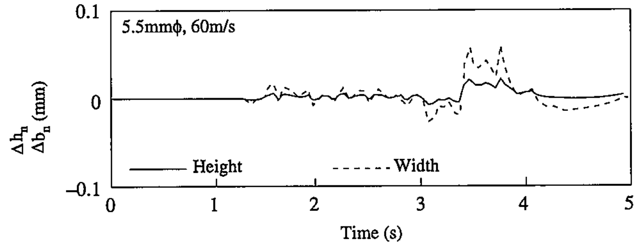


Fig. 6 With AGC (sampling period=0.5s)

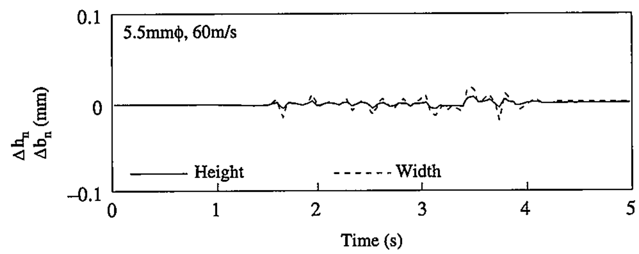


Fig. 7 With AGC (sampling period=0.1s)

6. Precision Rolling System of the Actual Finishing Block Mill

A precision rolling system comprising the mill housing for AGC and multivariable control technology has been commercialized at the Muroran Works Wire Mill (1 strand).

6.1 Mill housing for AGC

Fig. 8 shows the mill housing for AGC. The roll gap control system is driven by oil-hydraulic motors and backlash is reduced by pre-load springs.

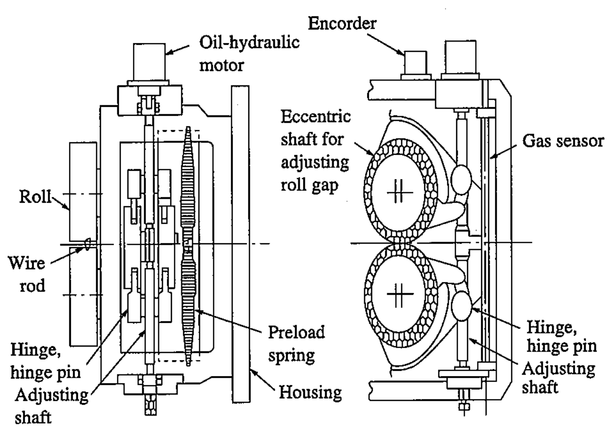


Fig. 8 Schematic drawing of the specially disigned No-twist rod finishing mill housing for AGC

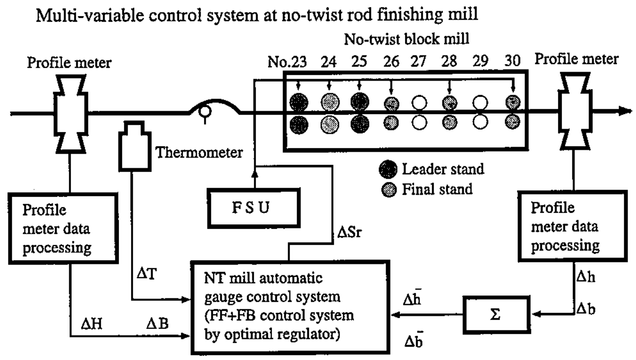
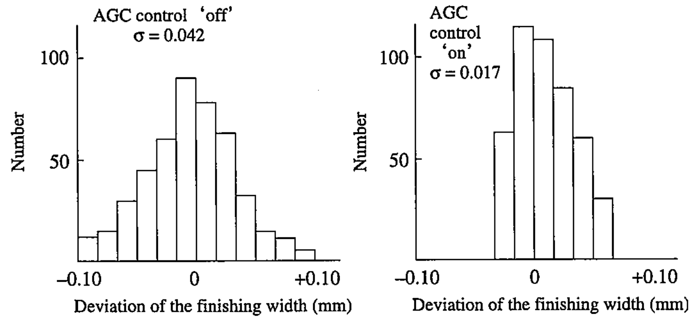


Fig. 9 Block Mill AGC Control System at Muroran Works



(a) With AGC (a) Without conrtol

Fig. 10 Effect of Block Mill AGC (18 mm diameter wire rod)

6.2 Control system

Fig. 9 shows the control system. This system has a mill housing for AGC, profile meters at the entrance and exit, a thermometer at the entrance and a process computer. The process computer control system is composed of a block mill AGC (control in billet) and finishing set-up (FSU, control between billets).

6.3 Control results

Fig. 10 shows the control results of material S45C, finish dimension 18 mm ϕ, finish rolling speed 16.7 m/s. Variations in finish width by the block mill AGC are reduced and it realizes dimension tolerance of ±0.1 mm.

7. Conclusion

Studying continuous wire rod rolling and precision rolling technology, we have developed the following technologies.

(1) A simulation model of continuous bar and wire rod rolling that efficiently calculates deformation, load and temperature was developed. The calculated values of the actual wire mill and the measured values were compared to verify that the model is appropriate.

(2) The heat transfer coefficient of the actual nozzle water cooling was measured at the model mill cooling trough. Superior heat transfer performance was verified.

(3) The relationship of the 2 block mill rolling conditions and the material temperature were estimated as the calculated example of the new mill.

(4) Multivariable control technology for the rod finishing block mill which controls finishing height and width (block mill AGC) was developed. Its validity was verified through experiments of the

model mill and through actual mill simulation.

(5) A precision wire rod rolling system was commercialized through mill housing for dynamic control of roll gap and block mill AGC. Precision rolling was realized at dimensional precision of ±0.1 mm, decreased dimension adjustments, decrease of downtime, automation of rolling and operations without relying on operatoris skill were achieved.

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