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Progress of Diagnosis Techniques for the Cold Strip Processing Line

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Progress of Diagnosis Techniques for the Cold Strip Processing Line*


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1 Introduction

In the processing line to manufacture cold strip for automotive and other uses (hereinafter called "cold strip processing lines"), the progress of high-grade product manufacturing techniques is indeed noticeable. In particular, the techniques for high speed and high response control have made a notable contribution to quality improvement. Meanwhile, the development of fully-automatic continuous strip rolling techniques and the continuous automatic inspection techniques has made it possible to reduce operators to the minimum.

What naturally follows such upgrading of manufacturing techniques and the advance of automation is a demand for expecting product quality as full affirmation of such advanced manufacturing equipment and techniques. Equipment abnormalities are accompanied by quality deterioration, and even by a risk of mass production of non-conformance. What are required to avoid this failure are an earliest detection of premonition or signs of quality decline or equipment deterioration, an establishment of equipment diagnosis techniques based on the cause and effect principles covering quality and equipment, and the development of on-line systems that will assure constant demonstration of these techniques.

Named "quality and machine diagnosis system (QMDS)" at Kawasaki Steel, this system has since 1983 been kept on developing in the cold strip processing

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line[1], with a great deal of contribution made to quality improvement and stable operation of the equipment.

This paper reports the development of the facility diagnosis techniques applied to QMDS of the cold strip processing line and results of research on diagnosis examples.

2 Development Status of Diagnosis Techniques in Cold Strip Processing Line and Their Features

2.1 Development Status of Diagnosis Techniques

Correlation between ① major quality and operational-control items of the cold strip processing line and ② major equipment performances is shown in **Table 1** in a matrix form, thereby indicating the development status of diagnosis techniques.

2.2 Features of the Diagnosis Techniques

It is not too much to say that the development of major diagnosis techniques for the cold strip processing line has been promoted by the verification using QMDS.

The overview of the hardware configuration of QMDS, and the diagnosis information network are shown in **Fig. 1**. The diagnosis items have been expanded from the mechanical elements such as bearings and gears to ① assembled machinery and equipment such as the universal joint of the mill drive system and journal bearings, ② control system such as the speed control and hydraulic gage control and further ③ to quality control items such as the thickness accuracy and surface scratches of the cold strip.

The authors have taken electrical and instrumentation control signals into the diagnosis system, and also incorporated a linkage with the process computer. Further, diagnosis information is sent to the total operating management analysis and support (TOMAS) system, which stores all the quality and operation information

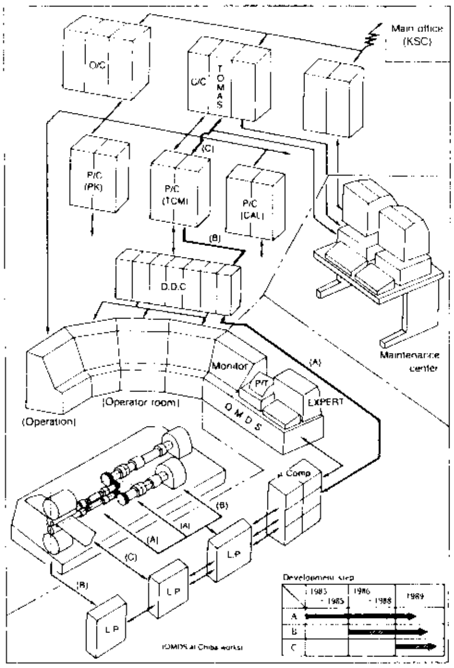


Fig. 1 Overview of a quality and machine diagnosis system (QMDS) and its information network at Chiba Works

Table 1 Correlation of equipment with quality and operation, and development of diagnosis technology

Section			Entry side				Middle part (main process)															Delivery side			
							PK			TCM							CAL								
Quality and operation control items		Equipment and devices	POR	Welder	Bridle roll	Looper	T/L	Mechanical descaler	Pickling tank	Driving system	Reduction system	WR/BUR	Bearing (WR/BUR)	Hydro static system	Roll cooling	Rolling lubrication	T/L	ECL	Furnaces	In-furnace rollers	Temper mill	Looper	Side trimmer	Shear (SH)	T/R
Quality		Off gage	—	—	—	—	—	—	○	○	●	○	○	⊙	○	○	—	—	—	—	○	—	—	—	—
	Shape	Surface defects	—	—	—	—	○	—	—	○	○	○	○	○	○	○	○	—	○	○	⊙	—	—	—	○
		Coil form	—	⊙	—	—	○	—	—	—	○	○	○	○	○	○	○	—	○	○	○	—	○	○	⊙
	Surface defects	Eccentric roll mark	—	—	—	—	—	—	—	—	—	●	—	—	○	○	—	—	—	○	○	—	—	—	—
		Chatter mark	—	—	—	—	⊙	—	—	⊙	○	○	○	—	○	○	⊙	—	—	—	○	—	—	—	—
		Slip mark	⊙	—	⊙	○	○	—	○	○	○	○	○	—	○	○	○	—	—	○	○	○	—	—	⊙
		Impression	○	⊙	○	—	—	○	—	—	—	—	—	—	—	○	—	○	○	—	○	—	—	○	○
		Rough edge	—	—	—	—	○	—	—	—	○	○	○	—	○	○	○	—	—	—	○	—	⊙	—	—
	Strength	Residual scale	—	—	—	—	○	●	○	—	—	—	—	—	○	○	—	○	—	—	—	—	—	—	—
		Mechanical properties	—	○	—	—	—	—	○	—	○	○	—	—	○	○	—	—	○	○	○	—	—	—	—
Operation		Rapture at the welds	—	●	—	—	—	—	—	○	○	○	○	○	○	○	○	—	○	○	○	—	—	—	—
		Rapture at the normal part	—	—	—	—	○	—	—	○	○	○	○	○	○	○	○	—	○	○	○	—	—	—	—
		Transverse displacement	—	⊙	○	⊙	○	○	○	—	○	○	○	○	○	○	○	—	○	○	○	○	—	—	—
		Chattering	—	—	—	—	—	—	—	○	●	○	○	—	○	○	—	—	—	—	⊙	—	—	—	—
		Nozzle clogging	—	—	—	—	—	—	—	—	—	—	—	—	—	⊙	—	○	—	—	—	—	—	—	—

	Correlation	Development of diagnosis techniques
●	Yes	Finished (QMDS)
⊙	Yes	Finished (off line)
○	Yes	Not yet
—	No	—

and supports analysis for various improvements, so that the caused and effect relation between the diagnosis information and on-line quality can also be analyzed.

On the other hand, the authors have developed the expert system for the rotating machine[2], thereby achieving functional reinforcement such as identification of causes and abnormal portions.

3 Diagnosis Techniques for Welder

3.1 Welder Configuration and Its Functions

An overview of the flush butt welder (FBW)[3] which is working at No. 6 continuous pickling line of Chiba Works, and an outline of the welding process are shown in **Fig. 2**. Major equipment configuration and functions of the welder consist of ① the side guide and cross adjust for centering the preceding and following strips, ② rotary shear (R/SH) for strip end cutting, ③ clamp cylinder after positioning steel strip height and clearance, ④ top and bottom electrodes, travelling carriage and welding cylinder which perform flush and upset, and ⑤ bead trimmer (B/T) for trimming post-welding beads.

3.2 Details of Development

The monitoring functions of the welding conditions and sequence of the welder were already installed. Therefore, the authors developed the diagnosis techniques placing emphasis on the cutting performance and flush-butt accuracy. For the cutting performance, attention was paid to the change of cutting power and sliding power, and for the flush-butt accuracy, attention was paid to the motions of the carriage during flush and upset processes.

3.3 Diagnosis Examples for Welder

3.3.1 Cutting performance diagnosis of rotary shear

Changes of sliding and cutting power before and after rotary shear trouble is shown in **Fig. 3**. The rotary shear transfers the rotary torque of the hydraulic motor through the chain to the saddle carriage as tention force, which causes the top and bottom disk-type shear blades to eat into the steel strip to cut it.

While this R/SH was travelling, it caused trouble of collision with the steel strip. The figure indicates the evaluation of damage caused by the trouble.

This figure indicates that an overload of 5 t was applied at the time of the collision and, according to the one-month data, sliding power gradually dropped, and conversely, cutting power was slowly enhanced.

The reasons for these phenomena were considered to be the following: ① As a result of the wear or cracking, due to the overload, of the linear bearing, which was incorporated in the saddle carriage, the pressure given by the bearing to the rail was lost and lowered the sliding force and ② the saddle carriage swayed during the steel strip cutting, thereby enhancing cutting force. When the saddle carriage was overhauled and checked, it was found that the bearing had cracked at two locations and flaking occurred at several locations. The linear bearing was replaced. As a result, both sliding power and cutting power became normal, stabilizing weld quality and saving the need of re-welding.

3.3.2 Upset performance diagnosis during welding

Configuration of upset mechanism and the relation between the travelling distance of the carriage and welding time are shown in **Fig. 4**. Operations of various

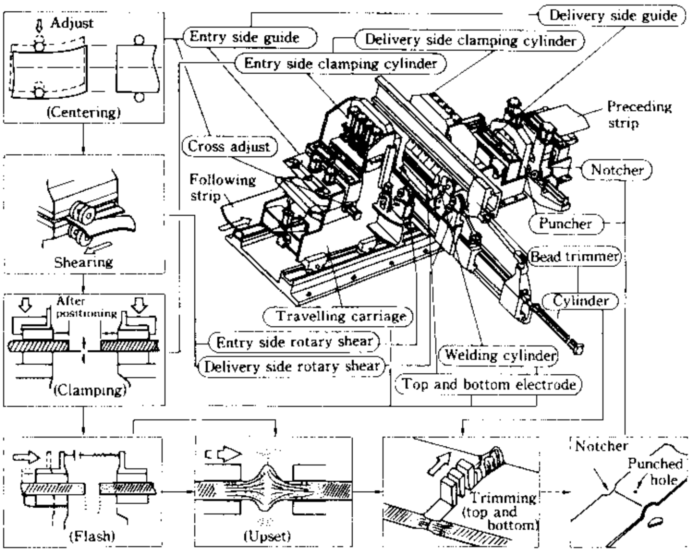


Fig. 2 Overview of flash butt welder (FBW) and schematic diagram of welding process flow

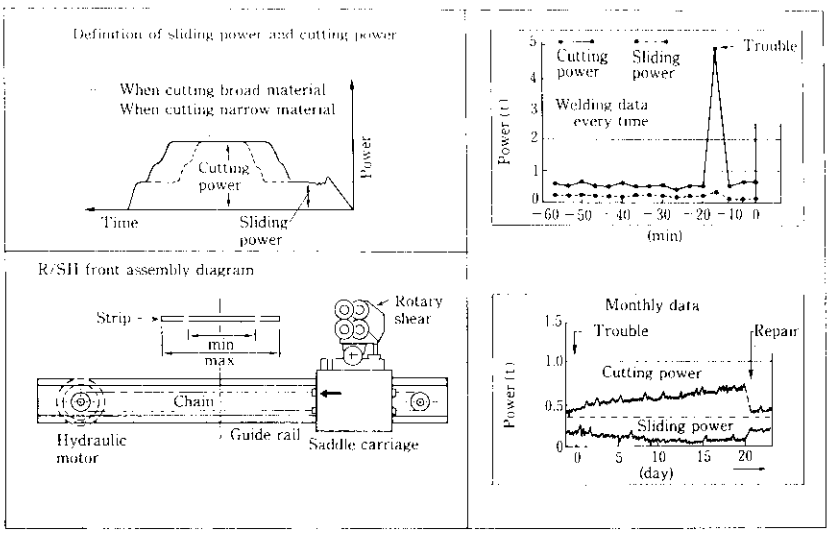
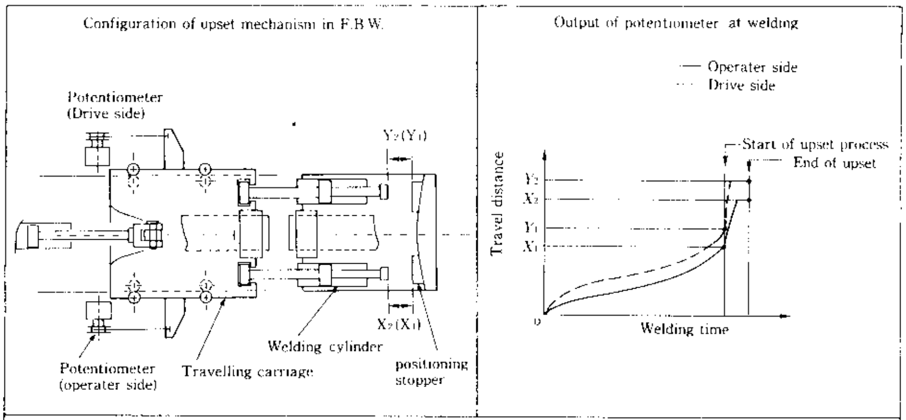


Fig. 3 Sliding and cutting power before and after rotary shear trouble



$\varDelta=(X_2-Y_2)-(X_1-Y_1)$

$\varDelta$: Difference of upset quantities

Fig. 4 Method to detect the difference of upset quantities

units are as follows: First, the trailing end of the preceding strip and the leading end of the following strip are clamped by electrodes. Next, the top of the welding cylinder rod is inserted into the spigot joint of the travelling carriage and fixed. Then the carriage is pulled toward the welding cylinder at the prescribed feed control pattern. The total travelling distance will be the distance between the end block of the cylinder and the fixed stopper. This travelling quantity can be known by the outputs of potentiometers at the operation-side and driving-side of the travelling carriage.

On the basis of the output signals of these potentiometers, the upset quantity difference $\varDelta$ was defined by the calculation formula shown in Fig. 4, and trend-value control was carried out.

This upset quantity difference showed exessive hunting at each time of welding. The condition in those days is shown in **Fig. 5**. In addition, the result of investigating the external appearance of the coil which exceeded the set value is also indicated in Fig. 5.

As a result, the weld joint protruded from the 20-mm

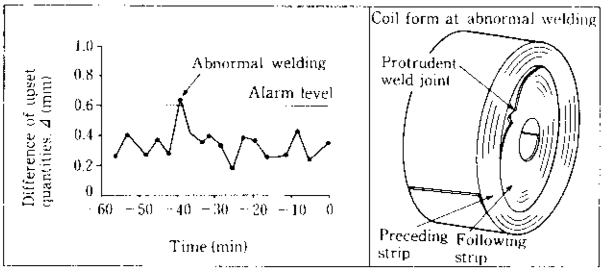


Fig. 5 Example of the difference of upset quantities and coil form at abnormal welding

wide coil edge and the joined steel strips were bent in the longitudinal direction in a "dog-leg" shape, thereby deteriorating the overall coiled shape.

As a result of analyzing the data of the aforesaid upset quantity difference and these phenomena combined, the authors considered that the reason was a drop in the centering performance. Finally, it was found that the light receiver of the steel strip edge position detector, which determined the adjust quantity was fouled by the deposition of grease. Judging this to be the cause, corrective measures were taken. Consequently, data hunting has disappeared and the coiled shape was restored to the normal.

4 Diagnosis Techniques for Mechanical Descaling Plunger Pump

4.1 Machine Configuration and Functions

Figure 6 shows ① an overview of the plunger pump for the mechanical descaler, which was introduced to No. 2 pickling line when the line and No. 1 cold rolling line were made cotinuous[4)] at Mizushima Works and ② schematic sectional diagram of suction and exhaust valves.

This plunger pump is of the high-power with a motor output of 3 000 kW, an exhaust pressure of 350 kg/cm^{2}G, and flow rate of 5 m^3/min and also having 13 pairs of plunger, suction valves and exhaust valves. Its compression mechanism is performed by the following sequence: ① First rotating, by the motor, the crank shaft directly-coupled to the speed reducer, ② elevating plunger pumps through the connecting rods which convert tension points of crank shaft, which is equally divided into 13 parts on the circumference, into elevating motions, and ③ using suction and compression accompanied by changes in displacement in the plunger chambers. Consequently, the positions of all plungers are determined by the positions of the tension points of crank shaft, thereby having the so-called "phase differences."

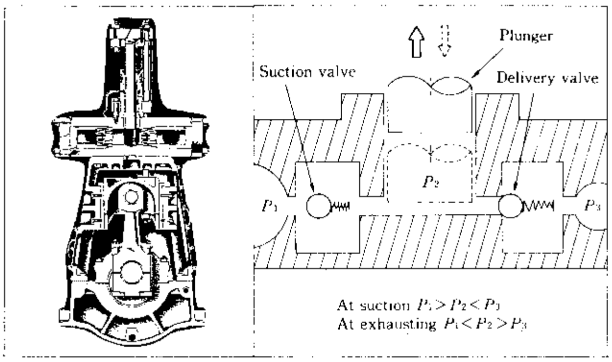


Fig. 6 Overview of plunger pump and schematic diagram of suction and exhaust valves

4.2 Contents of Development

In promoting the development, valve Nos. 1 to 5 were replaced with new ones, an acoustic emission (AE) sensor was installed to No. 3 plunger block and pressure and displacement in the plunger chamber were measured, in order to investigate what kind of AE is outputted and can be detected, at the time of operation of various normal valves, and when is the timing of these AE outputs. Measurements and results at this time are summarized in **Fig.** 7.

Facts which have been clarified as a result are: ① When the displacement of No. 3 plunger slightly passed the bottom dead point, pressure in the plunger chamber suddenly dropped, and simultaneously the AE output level rapidly rose, thereby generating pulse waveforms, ② the time difference between other pulse waveforms which were generated before and after the above-mentioned pulse waveforms is equal to the time equivalent to the phase difference between tension points of crank shaft, and ③ AE pulse waveforms occurred repeatedly five times in total and ④ there should be no other pulse waveforms.

From the above, the following have been clarified: When each exhaust valve in the same block closes, AE occurs; a single AE sensor is sufficient; and only pulse-shaped AE waveforms come out of the new valve.

Next, the detection method of the leaking valve is described. It is well known that when a pressure difference occurs between the front and rear in a high-pressure valve, and when the flow velocity during the leak exceeds Mach-number, the leak can be detected as elastic waves.[5)] Diagrams of potential ranges of AE outputs that occur when the suction or exhaust valve

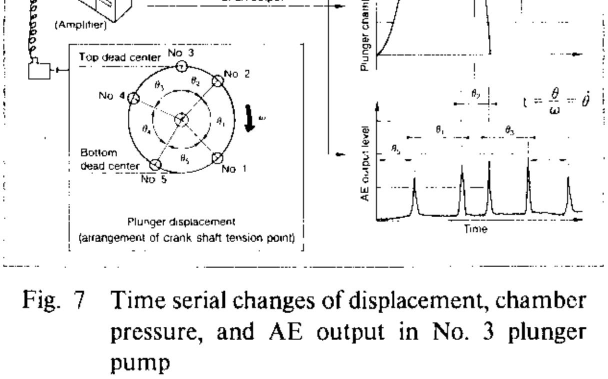


Fig. 7 Time serial changes of displacement, chamber pressure, and AE output in No. 3 plunger pump

makes a leak corresponding to the critical pressure difference of water are shown in **Fig. 8**.

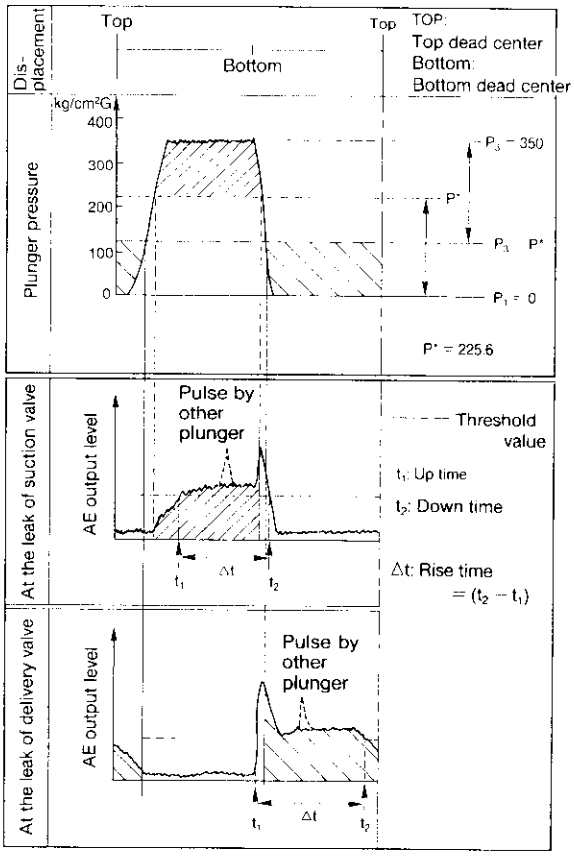


Fig. 8 Pressure difference in the plunger chamber and potential range of AE output

This figure indicates that it is possible to judge the identification of leaks of the suction and exhaust valves, by knowing at what particular time continuous AE is generated. Namely, when the suction valve leaks, continuous AE is generated during the process while plunger passes from the top dead point to the bottom dead point, and when the exhaust valve leaks, continuous AE is outputted, while plunger passes from the bottom dead point to the top dead point.

As mentioned above, the authors have constructed the diagnosis system so that these relations can be judged, processed and given a leak alarm or a manual precision analysis. Configuration of the hardware is shown in **Fig. 9**. Major contens of the hardware are as follows: Installation of an AE sensor at the center position of the 3-block cylinder, detection of the revolution-number signal of the crank shaft, and detection of the position of the No. 1 plunger pump bottom dead point.

4.3 Diagnosis Examples

After this system started working, the leak alarm of No. 7 suction valve was sounded. AE output waveforms per cycle at this time and after replacement of plunger block to be explained later are shown in **Fig. 10**. At the bottom part in the figure, top and bottom dead points of each plunger are printed. As a result, the AE output level rose from the top dead point of No. 7 plunger pump, and this condition continued until right after the bottom dead point of No. 7 plunger.

As a result, it was found that a leak had occurred at No. 7 valve. Upon investigation of No. 7 suction valve, it was found that the "O"-ring was broken and the cylinder block was also cracked. Therefore, the unified type block of Nos. 6, 7, and 8 valves was replaced. After

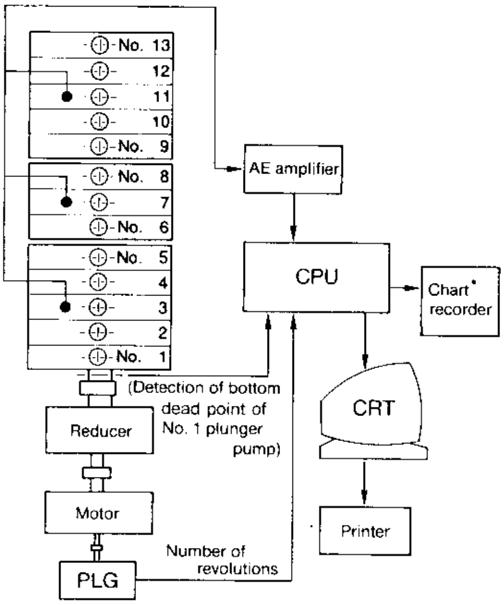


Fig. 9 Configuration of the diagnosis system of plunger pump

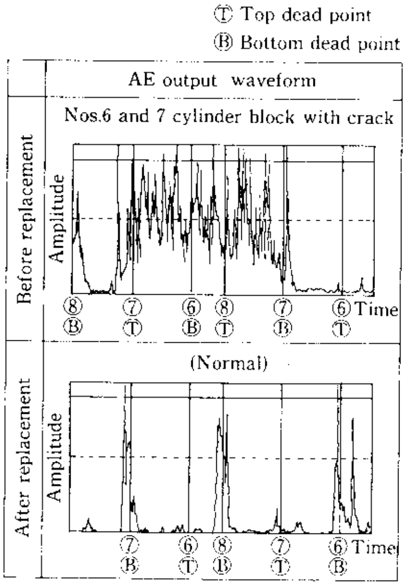


Fig. 10 Example of AE before and after replacement of plunger pump parts

replacement, it was found that only clear AE pulse waveforms were outputted at each plunger pump, thereby indicating normal restoration.

5 Diagnosis Techniques for Analyzing Thickness Fluctuation

5.1 Equipment Configuration and Functions

An overview of the hydraulic reduction equipment incorporated in the mill and the configuration example of detectors are shown in **Fig. 11**.

The configuration of the mill reduction equipment consists of work roll (WR) and backup roll (BUR), hydraulic cylinder, load cell for rolling load detection and the unified-type housing which holds all these units. Further, the hydraulic cylinder is operated by the hydraulic servo-valve located nearest to the mill and the position of this hydraulic cylinder is detected by the built-in-type Magnescaler (magnetic position detector).

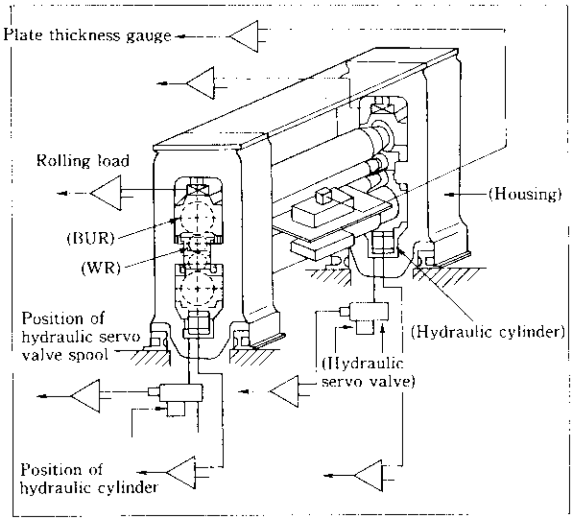


Fig. 11 Overview of hydraulic reduction equipment and configuration of detectors

On the other hand, the thickness meters arranged at the line center detect steel strip thickness, and this result is used as control information of the mill concerned and further of succeeding mills, and becomes product information at the delivery side of the final-stage mill.

5.2 Contents of Developments

As an example of performance diagnosis of hydraulic reduction equipment, first the detection method of the difference between the Op-side and the Dr-side (Op-Dr difference) is described on the basis of operation positions of various component units.

The diagram of the relation between time and positions of Op-side and Dr-side of the hydraulic cylinder as well as the Op-Dr difference detection logic are shown in **Fig. 12**.

This detection method is performed by ① simultaneously measuring the positions of Op-Dr at a sampling interval of several milliseconds, ② calculating the differences, and ③ reporting as abnormal when the magnitude and continuation time of the calculated differences exceed the respective set values.

On the other hand, these differences are added up cumulatively, with a mean value calculated. Then the value were transferred to TOMAS as a coil unit mean value and, further, as a daily mean value.

Next, techniques for automatically calculating and processing the identification of the eccentric quantity and eccentric portions of WR and BUR will be described below.

Steel strip thickness fluctuations caused by eccentricity of WR and BUR were generally obtained by using the frequency analysis method of FFT, etc., and from the magnitude of the strip thickness fluctuation quantity at specific frequency. It is empirically known that

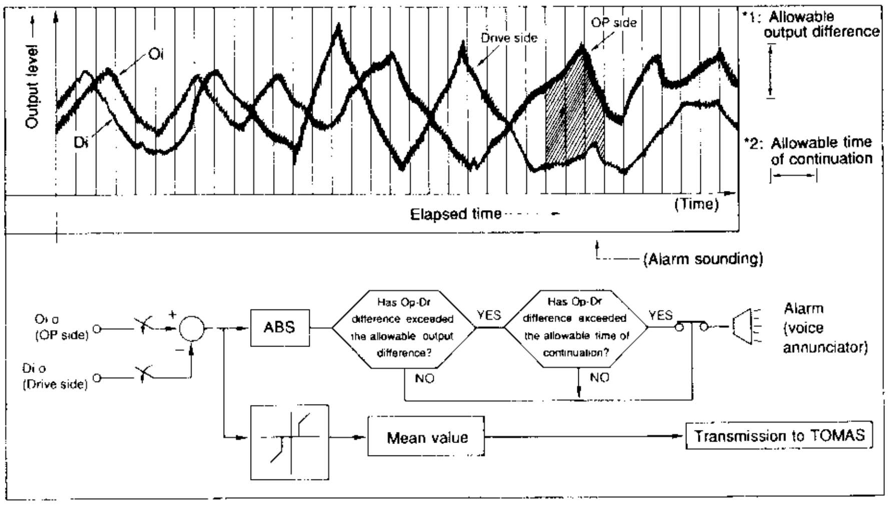


Fig. 12 Position of hydraulic cylinder and logic for Op/Dr-difference diagnosis

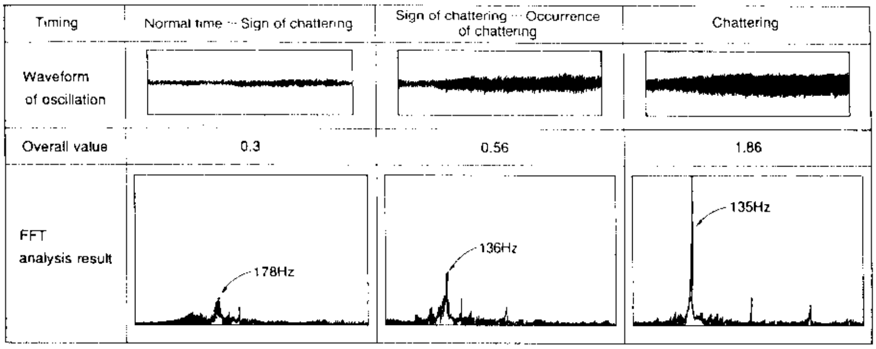


Fig. 13 Result of vibration analysis at chattering

this specific frequency can be approximated to roll revolution equivalent frequency (f_0) and double equivalent frequency ($2f_0$). Therefore, the authors have decided to perform a series of computations full-automatically ① by enhancing FFT resolution in order to specify f_0 and $2f_0$, thereby collecting strip thickness fluctuation quantities at high-accuracy and ② by setting line-speed fluctuation permissible values so that data collection can be temporarily suspended while these permissible values are exceeded.

The contents of development of the mill chattering diagnosis techniques are as follows: Out of vibration components of tension meter roll (TMR) bearing, which was installed between mill stands, vibration quantities at the chattering frequency band of the mill are extracted, and chattering diagnosis is made by the magnitudes and continuation time of the vibration quantities.

Vibration waveforms of the TMR bearing during chattering generation and the result of the FFT analysis are shown in **Fig. 13**, which indicates that vibration increases by about 2 min prior to chattering generation, and since the maximum peak frequency after the FFT analysis coincides with the second-mode resonance frequency of the mill, it is possible to predict the "forebodings." The authors have therefore developed condition diagnosis system which catches these forebodings and sends out an alarm.

Further, the chattering diagnosis techniques incorporate a system which memorizes the data from the time of predicting the forebodings until the chattering generates, thereby making the data useful in the chattering prevention analysis.

5.3 Diagnosis Examples

5.3.1 Hydraulic reduction performance diagnosis

In No. 3 cold rolling line at Chiba Works, there was an abnormal case in which the output of No. 1 stand delivery-side strip thickness meter went beyond the maximum deflection and the hydraulic reduction equipment became uncontrollable.

Therefore, the authors analyzed information recorded in TOMAS, namely, the long-term transitions of the strip thickness deviation mean value as well as Op-Dr differences of the rolling load, hydraulic cylinder position, and hydraulic servo-valve spool position. As a result, it was found that the Op-Dr difference of the hydraulic servo-valve spool position gradually increased two months prior to the occurrence of control-system abnormality, the Op-Dr difference of the rolling load and hydraulic cylinder position increased four hours earlier, and further accompanying this increase, the strip thickness deviation mean value increased.

The above analysis results indicated that the performance drop at the hydraulic servo-valve had become serious and became uncontrollable. Therefore, it was judged that an abnormality had occurred at this valve, and then both servo-valves at Op- and Dr-sides were replaced.

The analysis results before and after the replacement of the hydraulic servo-valves are shown in **Table 2**, indicating that everything was restored to normal after the replacing. Upon examining the performance of the dismantled servo-valves, it was found that the internal leak quantity on the Dr-side had increased three times the normal value, and dynamic characteristics deteriorated, thereby resulting in the identification of fundamental causes.

Table 2 Diagnostic results of servo-valve

No.	Item diagnosis	Result of judgement*¹	
		Befor replacement	After replacement
1	Deviation of #1 std plate thickness	△	○
2	Rolling load (Op−Dr difference)	△	○
3	Position of hydraulic cylinder (Op−Dr difference)	△	○
4	Position of servo valve spool (Op−Dr difference)	×	○

*¹ ○: Normal △: Attention required ×: Abnormal

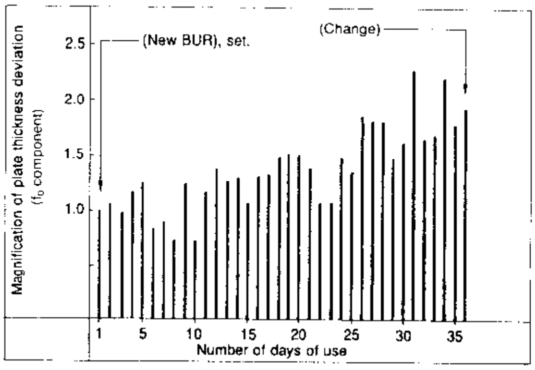


Fig. 14 Tendency values of plate thickness deviation

5.3.2 Diagnosis of backup roll eccentricity control performance

Trend values of strip thickness deviation owing to the roll eccentricity, which have been expressed in multiples of the initial values, after using #1 BUR for a certain period at No. 3 cold rolling line[6] of Chiba Works, are shown in **Fig. 14**.

These trend values sometimes drop below the initial values due to the difference in quality of strip thickness, but show a gradual-increase trend viewed macroscopically, and immediately before BUR replacement, the trend values reached about 2 times the initial values.

Further, at the time when this BUR was assembled, a normal values was shown, and it was difficult to consider the discrepancy as poor grinding, and was assumed to be the result of the failure of the roll eccentricity control in following the uneven wear of BUR.

6 Conclusions

The authors have described the development status of machine diagnosis techniques of cold rolling equipment and the features of these techniques, and further explained in detail the contents of development and diagnosis examples in respect of various development techniques which have been incorporated for effective use in the quality and machine diagnosis system (QMDS).

(1) Techniques for diagnosing the direct cause which leads to the performance deterioration of the flush butt-type welder. For instance, the increase in the clearance of the sliding portion and coarseness of the shear knife are diagnosed from changes in rotary shear travelling resistant force, thereby contributing to the prevention of welding defects and weld breaking trouble.

(2) Techniques have been developed for automatically judging the leaks of suction and exhaust valves of the high-pressure plunger pump using an AE sensor. Now, it has become possible to detect early and treat cracking of the cylinder block and the leak due to erosion of the valve body.

(3) Techniques have been developed for diagnosing the performance deterioration of the hydraulic reduction equipment in the cold rolling line. For instance, it has become possible to diagnose the performance deterioration of the hydraulic servo-valve from the difference in the feedback values on the Op-side and Dr-side, thereby permitting necessary treatment in good time.

(4) Techniques have been developed for giving an FFT analysis to the output values of the strip thickness meter on the delivery-side of the rolling mill and automatically diagnosing the deviation quantity of WR and BUR at each stand. As a result, it has become easier to detect early the defectively ground roll or to identify the roll eccentric control performance deterioration.

Techniques which have been developed so far still cover only a part of problems, and application of QMDS to all other lines have not yet been realized, thereby causing unsolved tasks to pile up. However, the outcome described in the diagnosis examples is being varified to be effective not only to the Maintenance Division but also to Production and Quality Control Divisions, and the authors would like to further disseminate and expand these diagnosis techniques.

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