Technical Report

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# Cost Reduction and Quality Improvement for Bar Inspection and Conditioning

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### Abstract

Special steel bars undergo secondary and tertiary work at users' plants and are converted into automotive critical safety parts, and as such, strict inspection and finishing are applied to them, piece by piece, after rolling before shipment. In view of the tough competition in the international market, however, , productivity improvement is urgently required. Against this background, Yawata Works of Nippon Steel & Sumitomo Metal Corporation modernized the product inspection and finishing facilities of the Bar Mill Plant to increase the processing speed and enhance the product quality assurance ability. In addition, a multistory automatic product warehouse was built to minimize product damage due to omissible handling. The technologies introduced at the revamp include those commercially applied as the first case in the world; they proved effective at markedly improving the speed and accuracy of product inspection.

### 1. Introduction

Through secondary and tertiary work at users' plants, special steel bars are formed into parts for automotive engines, drive systems, undercarriages and other critical safety parts. Every piece undergoes strict inspection throughout the entire process and conditioning, where necessary, before shipment from steelworks. However, the need for cost reduction and product quality enhancement has increased recently as a result of ever tougher competition in the international market.

In this situation, to improve product quality, the Bar Mill Plant of Yawata Works of Nippon Steel & Sumitomo Metal Corporation renewed the facilities of its bar inspection and finishing lines to raise the processing speed, enhance productivity and improve inspection accuracy. The present paper introduces the following principal aspects of the revamp: (1) renewal of two-roll straighteners; (2) introduction of new ultrasonic internal flaw detectors applying the synthetic aperture focusing technique; and (3) introduction of a multistory automatic product warehouse to minimize quality damage due to product handling.

### 2. Outlines of Bar Finishing Processes

The Bar Mill Plant started up in 1979 to produce straight bars

and bars in coil through a fully continuous single-strand rolling mill train. After rolling, straight bars are cooled at the pre-inspection storage, then inspected piece by piece through automatic inspection facilities, and conditioned as required. As seen in **Fig. 1**, bars are straightened through two-roll straighteners, automatically inspected in terms of surface defects through surface defect detectors and in terms of internal defects by ultrasonic testers (USTs), and the pieces approved as prime products are banded for shipment. The facilities for these processes are arranged in four lines according to the product size as given in **Table 1**.

### 3. Renewal of Two-roll Straighteners

#### 3.1 Features of new two-roll straighteners

To satisfy the product straightness requested by users, two-roll straighteners are provided to rectify the product bend arising during cooling after rolling by turning the bars between two rolls, one arranged on the other. **Table 2** lists the main specifications of the machines before and after the renewal. The new machines have the following two advantages:

- 1) Markedly higher processing speed; and
- 2) Guiding of bars according to diameter using two rotating guides of different inner diameters.

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Fig. 1 Special steel bar finishing lines

Table 1 Size ranges of automatic bar finishing lines

	Product size
No.1 line	Bar 40–120 mm $\phi$
No.2 line	Bar 18–50 mm $\phi$
No.3 line	Bar 25–80 mm $\phi$
No.4 line	Bar 18–44 mm $\phi$

Table 2 Main specifications of two-roll straighteners

	Before revamp	After revamp
Cross angle of rolls	15°	30°
Barrel length	700 mm	1 250 mm
Rotating guide	1 set	2 sets

At the straighteners, the two rolls hold and rotate a subject bar while applying bending to it to such an extent to cause plastic deformation. Applying bending plastic deformation during rotation means repetition of tensile and compressive plastic deformations, which cancels out the radial directionality of the residual strain in the material and thus initial bending, if any, is rectified. The axles of the two rolls are crossed with each other, and by this, the bar is driven in one direction, and the straightening work is applied continuously along the entire product length. To increase the processing speed, the cross angle of the new straighteners is increased from the previous 15 to 30° (see **Fig. 2**). When the cross angle is large, however, it is feared that the tensile and compressive plastic deformations are not sufficiently repeated and the straightening effect decreases.

As a countermeasure, the barrel lengths of the two rolls were increased from 700 to 1250 mm; consequently, a higher processing speed has been enabled with the same straightening effect. Since the bar turns at a high speed during the process, an end of it may be swung by centrifugal force, and the bar may sometimes veer off the line. To prevent this from occurring, a set of rotating guides had been used before the renewal, but they were insufficient for effectively harnessing small-diameter products. To solve the problem, two sets of rotating guides for different product sizes were provided at the revamp; they are arranged to shift into the position as shown in **Fig. 3**. Thanks to this, stable straightening operation has been enabled.

### 3.2 Introduction of new bend gauges

The products after the straightening were inspected in terms of residual bending using a bend gauge, which made the bar rotate for measurement, but as a result of the above improvements of the straighteners, the processing rate of the straighteners increased, and the processing speed of the entire line was restricted by the bend



Fig. 2 Two-roll straighteners before and after revamp



Fig. 3 Shiftable rotating guides after revamp

gauge. To remove this bottleneck, a new type of bend tester capable of measuring the bending during product travel was introduced.

Figure 4 compares the measurement principles before and after the renewal. The old bend gauge turned subject bars on turning rollers and defined the amount of bending from the bar dislocation at an end, but there were problems such as (1) the measurement cycle depended on the speed of the turning rollers, and (2) it was difficult to accurately measure large bending, which is not closely related to local bending near the ends.

The new bend gauge, in contrast, calculates the bending along the entire product length from the X-Y coordinates obtained during the product travel by three optical surveying devices provided at equal intervals along the line. This measurement method has effectively solved the problem of the bottleneck.

### Introduction of Ultrasonic Testers Incorporating Synthetic Aperture Focusing Technique Backgrounds

Ultrasonic testers (USTs) of the rotating probe type had been used for decades before the revamp. Bar mill plants of many competitors, however, already used USTs of the latest phased array type,



Fig. 4 Measurement principle of bend check

whereby many small emitter-receiver elements are arranged to form an arc-like array probe, and a plurality of such array probes are provided circumferentially at different positions. Thus, the old USTs paled in comparison with them in terms of the accuracy and speed of internal flaw detection. Since the UST flaw detection was expected to become a bottleneck after the renewal of the upstream processes described above, a new type of UST for bars using array probes and incorporating the synthetic aperture focusing technique (SAFT) has been developed and introduced to improve the flaw detection performance and the processing speed.

### 4.2 Methods of ultrasonic flaw detection

Figure 5 shows the methods of ultrasonic flaw detection for steel bars. By the conventional method (part (a)), a vertical emitter-receiver element (D) for scanning mainly the inside portion and oblique elements (L) for sub-surface portions rotates along the circumference of a subject product. For steel bars, usually two oblique elements (+L, -L) are provided to emit beams in the clockwise (CW) and the counter-clockwise (CCW) directions to reliably detect oblique planar defects in sub-surface portions. To cover a wide sectional area by this method, the beams are not focused, and the echoes, which tend to diffuse, are captured by the probes of a limited size, and as a result, it is difficult to improve the flaw detection ability. Moreover, the probe heads have to be driven along the product circumference at a high speed, and because of the speed limit of

the drive system, it is impossible to increase the inspection speed, and the drive system requires considerable time and labor for maintenance.

The ultrasonic flaw detection of the array probe type has been introduced lately at many bar mill plants to solve these problems. By the phased array method, a typical new practice, an entire sectional area is scanned by switching the beam emitting elements at different positions in array probes to change the incidence angles of the ultrasonic beams (electronic scanning). Here, it is necessary to repeat emitting ultrasonic beams several times for scanning a sectional area, but if the interval between the emissions is too short, the scattered echoes of a previous emission within the material are caught as noises (reverberated echoes). There is, therefore, a certain lower limit to the beam emission interval, and consequently, an upper limit to the rate of inspection.

To improve the performance and speed of the internal flaw detection, a new method called the synthetic aperture focusing has been devised, whereby, using array probes, the dispersion of emitted beams is controlled and synthetic aperture focusing is employed for beam receiving. At emission, beams are sent out by delayed control of the array probe so that they disperse beyond the prescribed position of the material. With beams thus dispersed, it is possible to cover a wider area and, because the dispersed beams have a vertical component and oblique components in +L and -L, it is possible to cover the three directions essential for defect inspection of steel bars at one cycle of beam emission and echo reception. This is a significant advantage over the phased array method, by which ultrasonic beams have to be emitted ten-odd times for each sectional area for increasing the inspection speed.

Because the echo from a flaw propagates cylindrically in the material, receiving it with an array probe having a large arc aperture means catching flaw signals of various waveforms by elements provided at different positions. It is possible to improve the defect detection ability and the signal/noise (S/N) ratio by analyzing the defect signals of various waveforms thus obtained applying synthetic aperture focusing, by which it is possible to focus on a selected position in the area to be detected. Although a very large calculation capacity is required for the synthetic aperture focusing, it has been made commercially viable in terms of performance and costs thanks to the latest development of electronic devices.

### 4.3 Technique of synthetic aperture focusing

The signal processing procedures of the synthetic aperture focusing are explained here. When the shape of the material in ques-



Fig. 5 Testing method of ultrasonic inspection

tion, the relative positions of vibrators and the sonic speeds in the transmitting media involved are given, it is possible to presume from which position of a subject material a certain flaw signal in waveforms received originates. For example, supposing that the number of the emitter-receiver elements of the array probe in **Fig. 6** is N, when the propagating time of all defect echoes received by the first element (given as 1CH in the figure) from an end is equal to T1 (s), the defect must lie somewhere on the orange arc in the right-hand top part of Fig. 6. Thus, in the grid presupposed for the sectional area to be scanned, the vibration amplitude of the defect echoes corresponding to T1 received by 1CH is added to each mesh of the grid on the arc. Then, as shown in the right-hand center part, the same procedure is applied to the defect echoes received by, say, the 16th element (16CH in the figure), and the defect must be somewhere on the red arc.

When the same procedure is followed for all the elements of the probe, and the results are added to all grid units, noises cancel each other because they come from randomly different positions, but defect signals add up at every addition. Eventually, the signal intensity increases at meshes where there are internal defects; this result can be expressed in a two-dimensional map. The above procedure brings about focusing effects at any position in any sectional area, and real-



Fig. 6 Synthetic aperture focusing technique

izes a high defect detection ability and high S/N ratio in wide areas. 4.4 Calibration of synthetic aperture focusing

As the acoustic pressure distribution of the ultrasonic waves propagated to disperse in a scanning space by the delayed control of the array probe is uneven, the echoes from defects of the same size may differ in intensity depending on their position. In the screen image obtained by the synthetic aperture focusing, therefore, the signal intensity of the pixels in areas where there are defects may be different depending on the position even when the defects are of the same size. In consideration of this, in order that, in flaw detection applying the synthetic aperture focusing, the echo intensity from the areas containing defects of the same size is equal regardless of their position, a new calibration method for two-dimensional distance-amplitude correlation (2DDAC) has been devised.

The calibration procedures according to the developed method are explained based on the illustration of Fig. 7. A bar specimen containing a plurality (four in part (a)) of artificial defects of the same size at radially and longitudinally different positions is turned about the axis, and the defects are probed at intervals of a prescribed angle of turn, while the position of the array probe is shifted longitudinally according to the defect positions. Part (b) shows the positions of the defect data eventually detected. By overlaying the echo images obtained at different rotational angles, an image of echo intensities for all artificial defects is synthesized as shown in part (c). The image thus obtained is a discrete intensity distribution map expressing only the signal intensity in the areas corresponding to the artificial defects. Assuming that the signal intensity changes continuously between neighboring defects, a two-dimensional continuous intensity distribution map is generated as given in part (d) by estimating the signal intensity in pixel areas outside those of the defects by two-dimensional interpolation.

The image of part (d) of Fig. 7 shows the signal intensity distribution by synthetic aperture focusing in the case where artificial defects of the same size are formed at given positions of a sectional area. Correction values (a gain to multiply and an offset to add to signal intensity) are calculated for each pixel such that the intensity distribution becomes even; the distribution of these two-dimensional corrective figures calculated for each pixel forms the 2DDAC. By applying 2DDAC thus obtained beforehand to the synthetic aperture



Fig. 7 Calibration method for synthetic aperture focusing technique

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focusing images of a subject product and detecting and identifying defects based on the aperture focusing image after the correction, the signal intensity fluctuation due to defect position, unstable probe performance, etc. are minimized, and thus stable flaw detection has been enabled.

### 4.5 Application result

Through commercial application, the above synthetic aperture focusing technique proved capable of identifying an internal cavity 0.3 mm in diameter at the center of a bar 50 mm in diameter at an S/N ratio of 11.9 or higher. The method is now employed stably for everyday production.

## 5. Introduction of Automatic Multistory Product Warehouse

Special steel bars after inspection and banding are stored inside the plant awaiting shipment according to the allocation of vessels. Before the revamp, the products were stacked on the plant floor by overhead cranes in the order of inspection and finishing. Consequently, when they were to be shipped it was often necessary to pick up correct products removing others stacked on them bundle by bundle, which sometimes caused bending and surface damage. To solve the problem, a multistory automatic product storage system has been introduced together with three stacker cranes (see **Fig. 8** and **Table 3**). With the new system, it is possible to pick up any desired bundle from a rack in a single crane operation, and the occurrence of product bending and surface damage has been markedly decreased.

### 6. Closing

An example of modernization of plant facilities aiming at improving the quality and productivity of steel bars was introduced. In



Fig. 8 Automatic bar warehouse

Fable 3	Main	specifications	of	automatic	bar	warehouse
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Item		Specification		
Product size	Diameter	18–120 mm		
	Length	3.5-8.0 m		
Number of racks		742		
Unit weight of bundles		Max. 2.3t (average 1.8t)		
Storage capacity		4006t		
Rate of handling		140 t/h (receiving and retrieving)		

the meantime, users' quality requirements are becoming increasingly stricter, and further improvements are requested on top of the improvements achieved through the revamp. We aim to strengthen the business of the Bar and Rod Division of the company through further technical developments in order to maintain the trust of users and differentiate the products from those of competitors.



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