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Artificial Intelligence and Wire Rods and Steel Bars

Manufacturing Techniques for Wire Rod and Bar Steel at Kawasaki Steel Corporation

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1 Introduction

Because wire rod and bar steel products enjoy a large market and are used in a wide range of industrial fields, the product quality requirements for respective applications are numerous and varied. In response, Kawasaki Steel has developed manufacturing technology and a quality assurance system suitable for high-end products such as automotive components, represented by tire cord and constant velocity joints, where product quality requirements are particularly strict. The basic rolling-plant equipment necessary for the production of high quality steels includes rolling equipment for the prevention of surface defects, such as the no-twist mill and slipless handling equipment, and the heavy-duty mill for rolling at low temperatures. In addition to this fundamental equipment, various techniques were also established: tension control aimed at improving dimensional accuracy, uniform reheating, and controlled cooling for the production of steels with which heat treatment is not required. With this equipment and the establishment of a quality assurance system based primarily on sensors, the production system for high quality steeels was substantially complete.

This report presents an outline of the equipment, describes quality assurance techniques, and gives examples of manufacturing technology for high-quality steel.

2 Product Types and Production Techniques

A breakdown of the functions required of Kawasaki Steel's wire rod and bar products is shown by application in **Table 1.**[1] Product quality requirements vary by application, but common requirements include minimal

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Table 1 Use and material quality

Use	Example	Required function	Center segregation	Inclusion	Structure	Machinability	Hardness, stiffness	Surface defect	Decarburization	Scale	End shape	Bar tollerance	Straightness
Drawing	Tire-code Piano-wire	Easy-drawing Easy-descaling	○	○	○			○	○	○			
Drawing Extraction	Machine parts Accel-shaft Cold-finished bar	Close tollerance Stiffness	○		○		○					○	○
Hot-forging	Crankshaft Connecting rod Bearing	Rolling life Wear resistance	○	○	○	○			○		○	○	
Semi-hot forging	Joint	Close tollerance		○				○	○			○	
Cold-forging	Joint High-tention bolt	Close tollerance Stiffness		○			○	○	○			○	
Machining	Drive-shaft	Close tollerance			○	○		○			○	○	○

inclusions, appropriate microstructure, freedom from surface defects, and dimensional accuracy. **Table 2** shows the technology developed and the equipment either developed or introduced by the company to meet these requirements and further improve the level of quality assurance.[2)] The following sections contain a detailed discussion of these techniques and equipment in Kawasaki Steel's Mizushima Works Wire Rod and Bar Mill.

Table 2 New equipment and technology and their purposes

	Equipment and technology	Purpose
'84/2	Reconstruction of billet mill · V-H mill installation	· Reconstruction of material supplying process · Improvement of billet quality
'84/9	Reconstruction of bar and rod mill · NT mill installation · Computer control · KS burner	· Improvement of surface quality · Data gathering for quality assurance · High productivity by automatic operation · Controlled reheating
'86/9	Installation of compact mill	· Mill power up for low temperature rolling
'87/4	Development of FTC	· Increase in dimention accuracy
'87/9	Installation of hot ECT for bar	· Assurance of surface quality
'88/3	Development of detecting surface defect system using special pyrometer	· Assurance of surface quality
'89/1	Reconstruction into automatic extraction system	· Preventing of surface defects · Automatic control
'89/12	Installation of billet UST equipment	· Establishment of quality assurance system for internal defect
'90	Development of continuous forging machine	· Elimination of center segregation

3 Rolling Facilities

3.1 Reheating Furnace

The main specifications of the reheating furnace are shown in **Table 3**; features of the improved equipment are discussed below.

3.1.1 Sliples handling of billets

Completely slipless handling of billets has been realized by the use of a charging roller table, walking beam handling in the furnace proper, extracting rollers, and an extractor. Product surface defects are held to a mini-

Table 3 Furnace specification

Type	Walking beam type
Capacity	150 t/h
Effective width and length	13.8 m × 17 m
Gas	Mixed gas 100%
Charging	By roller table
Discharging	By roller table in the furnace and extracter
Maker	Ishikawajima-Harima Heavy Industries

mum by use of these equipment.

3.1.2 Uniform reheating at comparatively low temperatures

Uniform reheating at the relatively low extraction temperature of 900–1 000°C was realized by (a) upgrading the reheating capacity of the heating zone by increasing the number of burners in the lower section. Further, (b) adoption of the KS burner (Kawatetsu sandwich burner) made it possible to ensure uniform heating in the longitudinal direction of billets even in low-load furnace operation. The advantage of the KS burner is that a constant flame length can be maintained regardless of load changes by adjusting the ratio of combustion air, which is supplied on both sides of the combustion gas. As a measure to reduce the "skid marks" caused by differences in temperature between the portion of the billet in contact with the skids and the rest of the billet, (c) hot skids were introduced in the soaking zone. This change has resulted in a lowering of the skid mark temperature by 40°C from the former 60°C. As a result of changes (a), (b), and (c), uniform heating at comparatively low temperatures has become possible, resulting in better dimensional accuracy and less surface layer decarburization.

3.1.3 One-man operation

Automation of the process covering billet charging, furnace operation, and extraction has been achieved by the introduction of furnace computer control (FCC), allowing operation of the furnace by a single monitoring person. FCC functions include (1) automatic handling of the billets from the charging table through extraction, (2) calculation of actual billet temperature and furnace temperature control based on a 3-dimensional difference equation, and (3) billet extraction control in consideration of reheating conditions and the status of mill operations.[3] The relations among the FCC functions are shown in detail in **Fig. 1**. These functions have made possible accurate temperature control, real-time collection of heating results, and on-line judgment of the shippability of products, and by ensuring that production conditions are appropriate, have made a major contribution to product quality assurance.

3.2 Bar Rolling Equipment

Rolling mills for high quality steel production were introduced during the original plant construction in 1972, and no-twist rolling was realized by adoption of a continuous HV arrangement. Thereafter, in response to the increasing need for high-power mills and appropriate tension control for the production of high-quality steels, including the production of steels which do not require heat treatment, various improvements were carried out, among the most important of which was the installation of a high-power compact mill. The following two subsections discuss the compact mill and the tension control system.

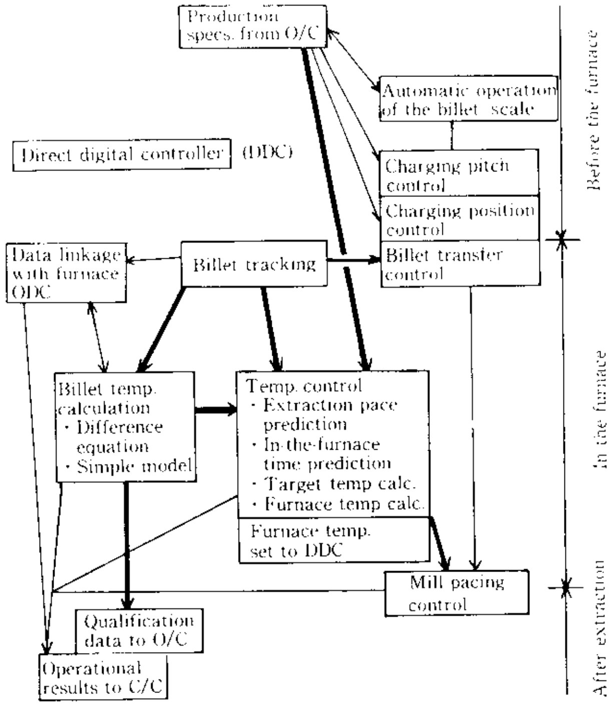


Fig. 1 Relations among the FCC functions

Table 4 Main specification of compact mill

Type	Compact mill locked flame			
Arrangement of stand	H-V-H-V stand			
	Stand AH	BV	1H	2V
Roll barrel length (mm)	320	320	320	320
Roll diameter (mm)	630	540	540	540
Motor (kW-DC)	450	800	1 100	900

3.2.1 Compact mill

The existing No. 1 and No. 2 stands were eliminated and a compact four-stand mill[4] was introduced. The main specifications of the compact mill are presented in **Table 4**; its features are described below.

(1) For the heavy reduction of low temperature materials from 150 mm section billets, the number of stands was increased and the motors were upgraded. In order to eliminate the effect of mill spring on dimensional accuracy, a heavy-duty mill was adopted.
(2) An electric screw-down device was installed, resulting in improvement of the process computer-based roll gap auto-control function and better setup accuracy.
(3) Automation of on-line roll changing makes it possible to change out the rolls at all four stands in the

short time of seven minutes.

The introduction of the compact mill not only responds to the needs of high quality steel production, but also made it possible to adopt low temperature rolling as a standard practice. This resulted in a decrease in yield loss to scale and reduced unit consumption of fuel, and thus made a significant contribution to cost reduction efforts at this plant.

3.2.2 Tension control

An indispensable condition for improved dimensional accuracy in products is tension-free rolling, which is realized by reducing the fluctuations in interstand tension caused by changes in the reheating temperature, changes in material dimensions, impact drop, and other factors. At the finishing train, where material cross-sections are small, the looper is the most effective means of eliminating tension, and loop control was introduced during the initial construction. At the rougher and intermediate mills, however, the material cross-section is large and the looper is difficult to use, since the bending rigidity of the material becomes a factor when the distance between stands is limited. A down looper was therefore installed between the No. 6 and No. 7 stands, where the interstand distance was relatively great, and a torque arm memory-type tension control system was introduced at the rougher and the intermediate stands.

Moreover, a combination of functions which include loss torque compensation for ensuring rolling torque accuracy, acceleration/deceleration control, and special control functions such as interference-free control and tension-increase control at the top and tail ends has resulted in the creation of a tension control system in which variations in product dimensions can be held to a minimum.

3.3 Wire Rod Rolling Equipment

With the aim of producing high-quality wire rod,[5] Kawasaki Steel replaced the 40-m/s twist type mill at its old wire rod plant, erected in 1965, with a state-of-the-art wire rod rolling mill, which went into commercial operation in October 1984.[6] The main specifications of the new mill are shown in **Table 5**. Notable features of the equipment are described below.

Table 5 Block mill line facilities

Water spray box ahead of block mill	
Type:	Cooling nozzle type (2 zones)
Capacity:	200 m³/h max
Maker:	SHI-Morgan
Block mill	
Type:	10 stands non-twist mill
Roll size:	#19~#20 stand 210 mmφ #21~#28 stand 158 mmφ
Maker:	SHI-Morgan
Main motor of block mill	
Capacity:	AC 6 000 kW (700/1 400 rpm) × 1
Control:	AC-VVVF, Digital ASR control
Maker:	Toshiba
Water spray box after block mill	
Type:	Cooling nozzle type × 4 zones
Capacity:	600 m³/h max
Maker:	SHI-Morgan
Laying head	
Type:	Inclined type (10°)
Ring diameter:	1 120 mm
Pipe:	1 piece pipe
Motor:	DC 185 kW (1 350 rpm)
Maker:	SHI-Morgan
Stelmor conveyer	
Type:	Roller conveyer × 8 zones (with retarded cover)
Blower:	250 mm Aq × 1 100 m³/min × 11
Control:	AC-VVVF
Maker:	SHI-Morgan

3.3.1 High-productivity no-twist mill

In spite of the fact that this is a one-strand mill, high-speed rolling is possible at 103 m/s with 5.5 mmφ material and at 130 t/h with materials 9 mmφ and over, giving the mill a capacity equivalent to that of a conventional two-strand mill.

3.3.2 Temperature control function

The use of water cooling zones before and after the block mill and between block mill stands allows strict control of rolling temperatures. Feed-forward control, based on temperatures at the delivery side of No. 12 stand, and setup control for the initial water supply, based on a temperature prediction model, were applied to the water cooling zone before the block mill. For the cooling zone after the block mill, feedback control based on coiling temperatures was adopted, making possible highly accurate cooling control.

3.3.3 Hydraulic screwdown device

A hydraulic screwdown unit was originally adopted for the block mill. Because the unit is equipped with remote roll pressure and roll gap control functions, it is contributing greatly to reductions in size-change time and manpower needs.

3.3.4 Retarded Stelmor

Because both a blower and a retarded cover are provided, a wide range of cooling rates is possible. Slow cooling times of as long as ten minutes can be obtained on-line, making direct softening treatment possible. In addition, uniform cooling in the conveyor width direction has been achieved by the adoption of an independently controlled three-section plenum chamber and a roller-type handling method.[7]

3.3.5 Coiling

At the time of construction, coiling by natural fall with a basic ring diameter of 1 170 mm was used, but with the aim of improving the coil package profile, the basic ring diameter was changed to 1 120 mm, rather than modifying the inner and outer diameters of the reforming tub. A ring-fall position control device was also introduced and subsequently improved. These changes have eliminated coil profile problems during transport and greatly improved the ease of debundling.

4 Quality Assurance

In view of progress in automation, labor saving, and inventory-free operation in processing and the pursuit of high reliability in finished products, the level of the quality assurance requirements applied to internal and surface defects in high-grade steels has become extremely strict. Moreover, these requirements will tend to become even more rigorous with the introduction of steels which allow users to eliminate processing steps. Kawasaki Steel has installed a full complement of quality assurance devices which will respond to these requirements.

4.1 Billet Inspection Equipment

4.1.1 Billet AUT

Kawasaki Steel put an automatic ultrasonic tester (AUT) into service at its production line in December 1989 with the aim of providing quality assurance for internal defects over the entire length of coil materials. The main specifications of the AUT are shown in **Table 6**; its features are discussed below.

(1) A deburring device is provided ahead of the AUT. Flaw detection is performed after complete removal of the burrs, and the untested zone at the head and tail ends is therefore short. In fact, the 50 mm untested portions fall entirely within the crops cut at the time of rolling, making perfect quality assurance possible.

(2) An optimum combination of vertical and slanted probes permits flaw detection over 100% of the cross-sectional area of square billets.

(3) When near-surface impurities are located, the position of detection is marked and the impurity is removed by a Magnaglow-equipped grinder in the subsequent process, thus maintaining quality assurance.

Table 6 Main specification of billet UST

Purpose of installation	· Perfect assurance of coil internal quality · Assurance of quality of hot scarfing
Accuracy	1 mmϕ × 10 mm$L$
Probe	6 ch × 4 = 24 ch
Cover ratio in the section	100%
Scope of detecting	Except 50 mm from top and bottom ends
Capacity	150 t/h
Maker	Mitsubishi Electric Corp.

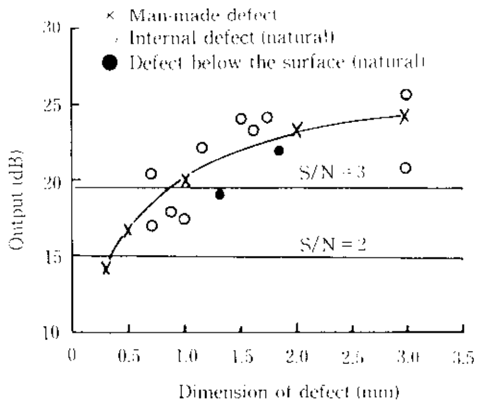


Fig. 2 Relationship between dimensions of defect and output at billet AUT

Figure 2 shows the results of flaw detection with artificial and natural defects. An excellent level of detectability of better than $S/N = 2$ is achieved even with the equivalent of 1 mmϕ natural flaws.

4.1.2 Magnaglow-equipped billet grinder

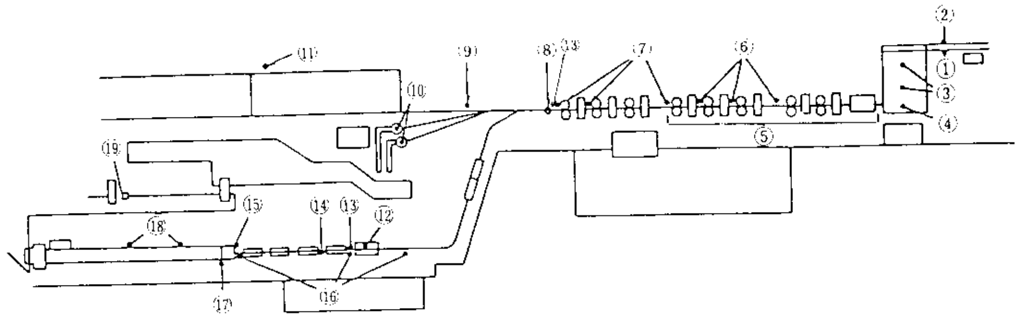
A Magnaglow flaw detector capable of detecting flaws at a depth of 0.3 mm or more is installed at the grinder which is used to eliminate billet surface defects. Immediately after conditioning, the operator confirms that there are no residual defects.

In response to the strict surface quality assurance requirements applied in recent years, it is necessary not only to control the pattern of trace marks from conditioning, but also to control the surface roughness of such marks. At Kawasaki Steel, standards have been established for grindstone grain size for each rolling ratio from the billet to the final product. Measures taken include the homogenization of grindstone grain size.

4.2 Rolling Line

4.2.1 Arrangement of sensors

A number of thermometers and load cells are used at the rolling line, as shown in **Fig. 3**. The values measured by these sensors are normally collected on a billet-by-billet basis for use in product quality analysis. An on-line computer automatically judges product



① Billet scale
② Charged billet thermometer
③ In-the-furnace billet pyrometer
④ Extracted billet pyrometer
⑤ Load cells
⑥ Bar line pyrometers (mono-color)
⑦ Bar line pyrometers (two-color)
⑧ Profile meter for bars
⑨ Straight bar pyrometer
⑩ BIC coiling pyrometer
⑪ Cold shear thermometer
⑫ Block mill metal thermometer
⑬ Eddy current flaw detector
⑭ Profile meter for rods
⑮ Machine vibration monitors
⑯ Rod line pyrometers
⑰ Rod coiling pyrometer
⑱ Stelmor pyrometers
⑲ Coil scale

Fig. 3 Locations of the sensors

cceptability for items within the control range.

4.2.2 Hot-state surface flaw detector

Eddy current flaw detectors for hot materials[8] were ntroduced at the wire rod line in September 1984 and t the bar line in September 1978. At the wire rod line, ull length inspection at the inspection line is difficult, .nd flaw detection of material in the hot state is of :rucial importance. Moreover, the improvement of letection accuracy is closely related to the improvement)f direct product quality assurance accuracy.

Formerly, flaw detection accuracy with the self-refer-:ntial type eddy current flaw detector was limited to ıbout 0.1 mm*d*,[9] and in some cases harmful defects vere not detected. In contrast, a quick response radia-ion pyrometer was installed at the delivery side of the vater cooling zone following the block mill as part of a 1ewly developed flaw detection technique based on the letection of minute changes in surface temperature. The location of the device is shown in **Fig. 4**, and the)rinciple of detection in **Fig. 5**. In the rapid cooling)rocess for wire rod, differences in the heat transmis-sion ratio caused by differences in surface condition are great, and the resultant temperature differences can be detected. The low temperature section is extremely short, however, and high-speed response (under 1 ms) is required. It is possible to detect inclusions using this method because the internal temperature of the material does not decrease uniformly when inclusions with a high heat content are present within the wire rod material, and such areas therefore have higher temperatures than normal portions.

This method is thus making an important contribution to quality assurance, and its use in tandem with the eddy current flaw detector has led to a major improvement in surface defect detection accuracy.

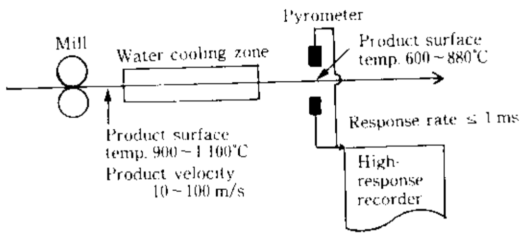


Fig. 4 Defect detector system by high-response pyrometer

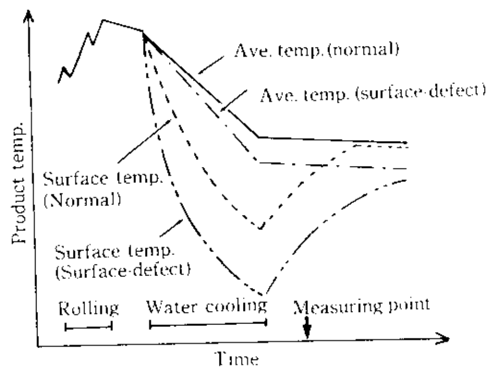


Fig. 5 Principle of detecting surface defect by high-response pyrometer

4.2.3 Dimensional measurement

The following measures were introduced to improve the measurement accuracy of the general-purpose rotary optical-type diameter gauge.

(1) The temperature of the material when it passes the diameter gauge is predicted using a temperature model on the basis of temperature values measured

by the thermometer at the exist side of No. 12 stand, and this predicted temperature is used as a initial value for the estimation model of cold dimmension. The initial temperature setting reflects the results of learning of the difference between the predicted value and the actual value of the material in the previous pass. By this means it is possible to estimate the cold dimensions of the material from the very head of the billet using accurate temperatures.

(2) Using a regressive formula which takes chemical composition into consideration in evaluating the shrinkage ratio, accurate estimation of cold dimensions is possible with a wide range of steel grades.

4.3 Bar Inspection Equipment

The specifications of inspection equipment for bars in the cold condition are shown in **Table 7**. As can be seen from the Table 7, the inspection equipment setup has been progressively upgraded. In the surface defect assurance process, the magnetic particle testing eqquipment with its current specifications already provides outstanding detection performance on the order of 0.1 mmϕ. For high grade steel products such as close tolerance bars, however, descaling and roughness adjustment are used as preconditioning practices for detection in order to improve detection accuracy to the 0.05 mmϕ level.

For internal defects, rotary ultrasonic testing (RUT)[10] was introduced in 1985, making possible quality assurance across the entire cross section of the material, including the subsurface region. However, the development of precision automatic magnetic testing (AMT) as a substitute for manual magnetic testing (MMT) remains an important task.

Table 7 Inspection equipment for bars

Equipment	Specification	Installation
RUT		
Method	Probe rotary type	
Frequency	5 MHz	'85/9
Number of probes	Normal 2, angle 4	
Inspection velocity	Max 75 m/min	
AMT		
Method	Probe rotary type	'76/7
Accuracy	0.3 mmϕ	
Inspection velocity	Max 90 m/min	
MMT		
Number	2	'73/4
Method	AC	
Accuracy	0.1 mm in diameter	

5 Manufacturing Techniques for High Grade Steels

This section will discuss the manufacturing techniques used in the production of high grade steels with which it is possible to omit post-processing, taking close tolerance bars and direct softened steel rods as examples.

5.1 Close Tolerance Bars

Numerous factors affect dimensional accuracy during rolling, the most important of which are shown in **Table 8**. Regarding the basic factor of groove design, prior to the introduction of conventional tension control, it was necessary to absorb tension fluctuations by groove release, and it was therefore difficult to use grooves with a high degree of roundness. Dimensional variations in the oval portion were reduced with the introduction of tension control, and it was thus no longer necessary to use the groove function to absorb fluctuations in oval dimensions. Groove roundness has thus been signifi-

Table 8 Factors to accuracy of dimension

		Factor	Dimension deviation	Countermeasure	Dimension deviation after countermeasure*1
Accuracy at rolling	In the section	· Caliver design · Caliver machining accuracy · Caliver wear · Roll thrust	±0.13 mm	· Development of FTC · Limitation of number of billets for one caliver · Development of accuracy of setting parting and roll location	±0.03 mm
	Longitudinal direction	· Deviation of tension · Deviation of temperature · Roll eccentricity	±0.16 mm	· Development of FTC · Controlled reheating · Reconstruction to new NC turning machine · Standard	±0.05 mm
Influence of off-line treatment	Straightening machine		−0.06 mm	· Establishment of rolling dimension aim considering decrease of dimension	−0.06 mm
	Shot blasting		−0.05 mm		−0.05 mm

*1 Deviation at 55 mmϕ rod

cantly upgraded.

In addition, as shown in the Table 8, a uniform heating technique was developed, as previously mentioned, and various measures have been implemented, including control of the number of billets rolled with a particular caliber based on estimated caliber wear, and the renovation of the NC lathe for better caliber machining accuracy. As a result, extremely good full-length dimensional accuracy of ±0.08 mm has been achieved in rolling.

One further notable point in connection with the production of close tolerance bars is the reduction of surface defects. Dimensional tolerances are narrow, and product surface defects must fall within the material allowance. Rolling practices which do not produce defects are thus a condition. A broad-scale decrease in surface defects was achieved by the adoption of slipless handling with all equipment downstream of the reheating furnace, supporting a first-class acceptance ratio of 98%.

5.2 Direct Softened Steel Rods

A Stelmor equipped with a retarded cover is used to achieve direct softening of low alloy wire rod. Although a bainite structure forms in ordinary air cooling, it is possible to obtain a ferrite–pearlite structure on-line by slow cooling. With SCM 435 grade, an appropriate cooling rate must be maintained from the beginning of transformation through its completion, but this condition has been satisfied by optimizing the rates of coiling and conveyor travel. At present, direct softening is possible with SCM 435 grade in sizes 11 mmϕ and over.

6 Conclusions

The Wire Rod and Bar Mill at Kawasaki Steel's Mizushima Works was modernized as a state-of-the-art facility for the stable production of high-grade steels. Its principal features are summarized below.

(1) At the reheating furnace, the development and introduction of completely slipless handling, a low temperature uniform reheting burner, and automatic combustion control have contributed to improved product quality in terms of surface defects, surface layer decarburization control, and dimensional accuracy.

(2) As rolling equipment, a combined mill for high-grade wire rod and bar steels was adopted based on the continuous HV no-twist mill. Controlled rolling has been realized by the introduction of a high-power compact mill as the rougher and all-stand full-length tension control. These rolling facilities have demonstrated their effectiveness in the manufacture of high-grade steels with improved dimensional accuracy.

(3) Quality assurance equipment including billet AUT and a hot-state surface flaw detector has been introduced to make possible full-cross section, full-length quality assurance, thus responding to the increasing sophistication of market needs.

(4) Computerized full-line automatic setting control has been applied to this equipment, making possible one-man operation and on-line acceptance of products.

(5) High-grade steels represented by close tolerance bar and direct softened alloy steel wire rod are now in stable production, and output is steadily increasing.

It appears certain that market needs, including delivery service, will become increasingly diverse and sophisticated in the coming years. Rolling plants which can respond flexibly to individual requirements while maintaining a high level of productivity will therefore be essential. From this perspective, the authors will pursue further technology development with the aim of establishing a high quality product rolling mill.

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