Reduction of Surface Defects on Steel Pieces That Occur in the Early Stages of Casting

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While scabs and longitudinal surface cracks of rolled products can occur during the rolling process, there are cases where surface cracks on billets do not disappear during the rolling process and remain. This article introduces efforts against the following surface cracks that appear during the continuous casting process, which occur at the initial casting stage at the bottom of oscillation valleys: (1) Short-stroke/high-cycle mold oscillation; (2) Optimization of mold dimple patterns; and (3) Improving responsiveness of mold level control.

Introduction

Mitsuboshi Metal Industry Co. Ltd. is an integrated steelmaking and rolling works located in Tsubame City, Niigata Prefecture, Japan. The product type is deformed steel bars of four JIS standard products: SD295, SD345, SD390 and SD490. The product sizes range from 10–41 mm in diameter, and 11 sizes are produced.

Due to the complicated shape of the steel bars, surface inspection with a flux leakage detector, where the probe follows the product surface, is difficult. Therefore, surface defects were detected by visual inspection by operators. In recent years, devices have been introduced that can visually detect defects based on the results of image processing and surface temperature measurement. In response to user requests, a device has also been introduced that measures the surface temperature of the product after rolling and detects abnormal areas based on the temperature difference. With the introduction of this device, the surface inspection of all products is now carried out mechanically to prevent the flow of defective products.

Although this has prevented the outflow of defective products, the extraction process reduces the production line utilization and yield. In order to not only prevent the outflow of defective products, but also to suppress the occurrence of fundamental surface abnormalities of deformed steel bars, the causes of the surface abnormalities were investigated and the casting defects that caused them were addressed.

Figure 1

Comparison of product defect detection images (a) and actual defects (b).

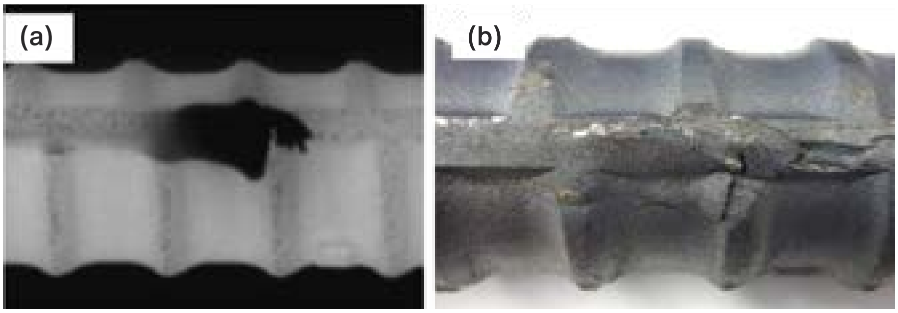


Table 1

Types and Causes of Surface Defects in Continuous Cast Billets

Type of defect	Causes
Surface vertical crack	Casting powder characteristics
	Intense cooling by spraying directly below the mold
	High sulfur in steel
Surface transverse crack	Tensile cracks due to inappropriate temperature during pinch roll straightening
	Pinch roll level deviation
	Solidification delays due to powder getting into oscillation
	Excessively deep oscillation marks
	Copper, niobium, carbon equivalent, sol. aluminum in steel
Hot shortness	Removing copper from the mold inner wall
	High-sodium powder
	Aluminum, copper, carbon in steel

Figure 2

Signs of peeling in the middle of rolling.

Figure 3

Billet corner crack.

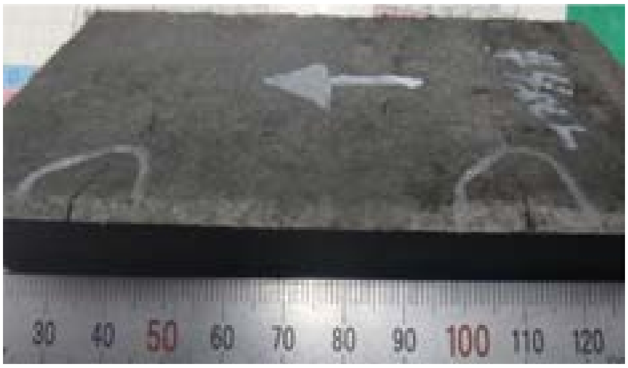
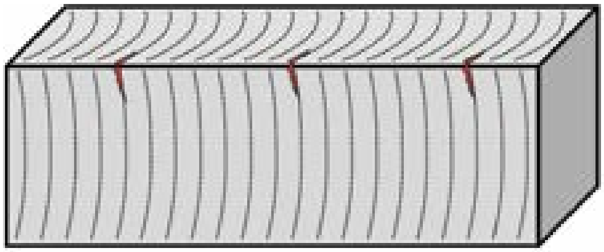


Figure 4

Image of transverse crack at billet corner.



Cause Investigation

According to Mori,[1] there are various types of surface defects on cast billets, each with a different cause (Table 1). The surface of the cast billet was observed and the target surface defects investigated.

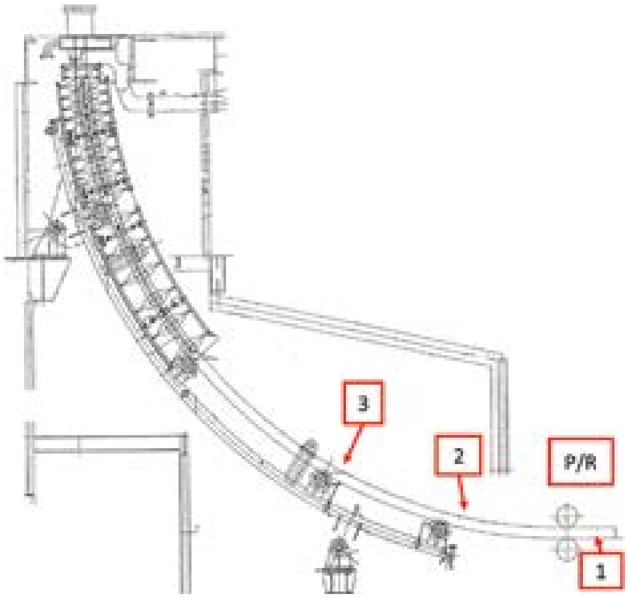
Approximately 99% of the defects found by product defect detection equipment were defects that looked like the surface of a deformed steel bar was beginning to peel off. In order to identify the location and timing of the occurrence of surface peeling defects, crop material was investigated in the rolling process and signs of peeling defects were found (Fig. 2). Furthermore, the location of the peeling defects was equivalent to the corners of the billet. Additionally, when the steel billet was inspected at the early stage of rolling, signs of peeling defects were already present. This led to the conclusion that the cause of the peeling defects was defects on the surface of the steel billet.

A detailed observation of the billet with a large number of peeling defects revealed that transverse corner cracks had occurred at the billet corners, shaped along the grooves of the oscillation marks (Fig. 3 and 4). When this billet was rolled, peeling defects occurred in the rolled deformed steel bar at the positions corresponding to the corner cracks of the billet.

One of the causes of transverse corner cracks in billets was thought to occur when the billet is straightened by the pinch rolls, and that they are affected by the molten steel components and the billet temperature when passing

Figure 5

Points where samples were taken on the continuous casting line.



through the pinch rolls. The spray flowrate and cooling position in the secondary cooling zone of the billet were adjusted, but the occurrence rate of peeling defects in deformed steel bars did not decrease. In order to confirm the occurrence location of transverse corner cracks, the billet was stopped during casting in the spray cooling zone before passing through the pinch rolls and samples were taken at the positions shown in Fig. 5. As a result, it was found that the cause of the transverse corner cracks had already occurred before the billet was straightened by the pinch rolls.

From the investigations up to this point, it was determined that the peeling defects on the surface of the deformed steel bars were caused by transverse cracks that occurred at the corners of the billet during the early stages of casting, and this was the target for efforts to improve the surface defects of the billet.

Efforts for Improvement

Reducing the Effects of Oscillation

The transverse cracks at the billet corners occurred along the bottom of the valley of the oscillation mark. Therefore, it was speculated that corner cracks would be less likely to occur if the effects of oscillation were suppressed. Kawakami et al.[2] reported that oscillation marks are formed by pushing and bending the tip of the solidification angle at the end of the negative strip time (the time when the mold descent speed exceeds the drawing speed due to mold vibration, hereafter referred to as tN). The larger the tN, the stronger the influence of pushing and bending, and the deeper the oscillation mark. Conversely, the shorter the tN, the shallower the oscillation mark, and it is said that the occurrence of transverse cracks in the billet can be suppressed. tN is calculated using the following formula, so it can be shortened by increasing the mold vibration frequency and reducing the mold vibration amplitude:

$$t = \frac{1}{\pi f} \times \cos^{-1} \frac{VR}{\pi fa} \quad \text{(Eq. 1)}$$

where

t = negative time,

f = frequency,

VR = casting speed and

a = stroke.

Based on this, the mold vibration conditions were changed as shown in Table 2. According to Kajitani

Figure 6

Transverse section sample (crack in yellow circle).

Table 2

Mold Vibration Condition

	Average Vc (m/min)	Amplitude (mm)	Frequency (rpm)	Negative strip time (s)
Before	2.00	11	118	0.162
After	2.00	8	163	0.124

Table 3

Oscillation Mark Status Before and After Changing Vibration Settings

	Oscillation mark span (mm)	Oscillation mark depth (mm)
Before	34	0.33
After	25	0.24

Figure 7

Changes in defect occurrence rate due to changes in mold vibration settings.

Figure 8

Cast piece with dimple marks remaining on the surface.

et al.,[3] short tN can cause restrictive B.O., and a criterion is to maintain tN of 0.1 second or more, so it was set so that tN would be 0.1 second or more, taking into account fluctuations in the pouring speed.

By changing the vibration settings, the depth of the oscillation marks became 30% shallower. In addition, after changing the vibration settings, the defect occurrence rate of surface peeling defects for the main sizes of deformed steel bars decreased by approximately 0.6 case/rolling ton.

Change in Mold Dimple Pattern

When a large amount of peeling defects occurred in deformed steel bars during hot direct rolling, the marks of the dimples on the inner surface of the mold were clearly visible on the billet surface. Therefore, the relationship between dimple marks and billet corner cracks was considered.

At the factory, a dimple mold is used to prevent the billet from deforming and causing internal cracks. On the inner surface of this mold, multiple dimples are machined below the meniscus (Fig. 9).

These dimples form an air gap between the shell in the early stages of solidification and the inner surface of the mold, suppressing heat conduction between the solidified shell. By suppressing the undercooling of the initial solidified shell, the amount of solidification shrinkage in the mold is reduced, and the occurrence of air gaps is suppressed. This allows the solidified shell to fit evenly to the four wall surfaces in the mold, so the four sides of the billet are cooled evenly and deformation of the billet is suppressed.

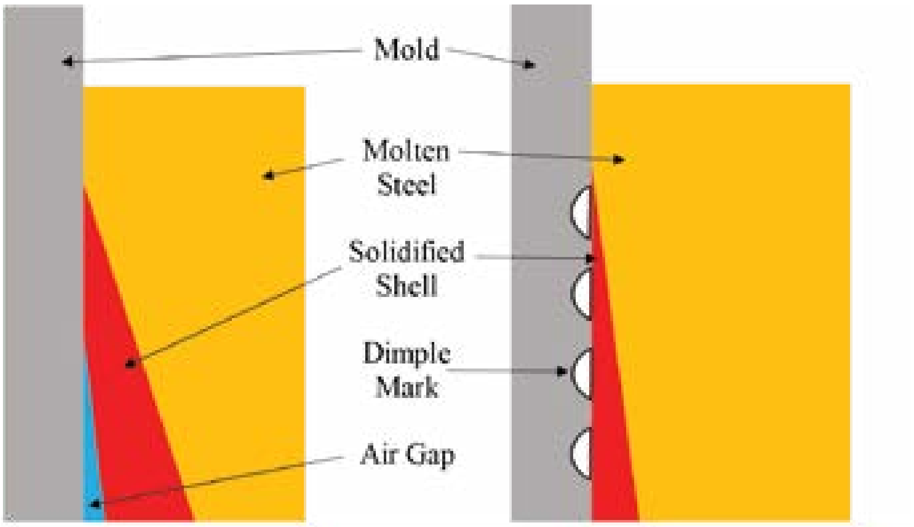
When the dimple processing position was moved closer to the meniscus, the cooling suppression effect was greater and the transferred dimple marks were clearer. The dimple mold had four rows of dimples, one with seven dimples from the top and one with six dimples from the bottom. When there was a dimple mark on the surface of the billet, it was always a seven-dimple mark. In order to confirm the effect of dimple marks on transverse cracks at the corners of billet, a mold test was conducted with different dimple processing.

Figure 9

Dimple mold image.

Figure 10

Dimple mold effect image.



The peeling defect detection rate is shown when a conventional mold and a mold with a changed dimple specification are used at the same time.

As a result, with a mold that did not have dimple marks, peeling defects were significantly reduced, but diamond-shaped deformation of the billet and associated internal cracks occurred. With a mold in which the top stage of dimple processing was lowered, it was possible to suppress the occurrence of peeling defects while also suppressing deformation of the billet.

Table 4

Operation Results of Mold With Changed Dimple Specifications

Mold type	Top dimple position	Peeling defect occurrence rate (※)	Diamond-shaped deformation/ internal cracks
Conventional specifications	±0 mm	100%	Almost none
No dimples	–	30%	Occurrence
Dimple position change	–5 mm	43%	Almost none

From this, it was speculated that when the very thin solidified shell passes through the top stage of dimples, dimple marks are generated on the billet surface due to thermal expansion, and that these get caught on the dimples during withdrawal, causing cracks in the billet corners along the oscillation marks.

Improved Responsiveness of Mold Level Control

By implementing the above two measures, the occurrence of transverse cracks at the corners of the billets was reduced, and the occurrence rate of peeling defects during rolling was greatly improved. However, even after that, there were sporadic cases where a large number of peeling defects occurred temporarily.

To investigate the cause, the records of the casting conditions of the billets that had a large number of defects during rolling were checked. As a result, it was found that the meniscus level of the mold changed significantly during the time period when the billets were being cast. Such billets often had clearly visible dimple marks remaining over a short range.

In the factory's continuous caster, the meniscus level is calculated using a thermocouple installed at the meniscus. When the amount of poured molten metal changes and the meniscus deviates from the set position, the mold level is stabilized by changing the withdrawal speed of the pinch rolls using proportional–integral–derivative (PID) control.

In the conventional control settings, the control coefficient was set small to suppress sudden fluctuations in the withdrawal speed. As a result, there were frequent situations where it took more than 10 seconds for the meniscus to return to the set mold level. For this reason, it was assumed that the effect of changing the dimple machining position was not being fully achieved.

As a countermeasure, the PID setting value was gradually adjusted and the control coefficient was increased so that the meniscus would return to the set mold level in the shortest possible time.

By increasing the control coefficient, the fluctuation in the casting speed became larger, but the fluctuation in the mold level was suppressed, and no problems occurred with casting. After that, operations were carried out using the settings in the second test stage in the table. By implementing change in mold dimple pattern and improving responsiveness of mold level control, the incidence rate of peeling defects decreased by approximately 0.3 cases/t of rolling (Fig. 11).

The investigations and countermeasures carried out so far have revealed the following:

1. In some cases, dimple marks from the top row remain on the surface of billets cast using dimpled molds.
2. Billets with strong dimple marks develop a large number of peeling defects during rolling, i.e., lateral cracks have occurred at the billet corners along the oscillation marks.
3. The dimple marks on the billet surface become thinner as the distance between the meniscus and the top dimple processing position increases, and corner cracks also decrease. This effect varies over a very narrow range (approximately 5 mm). Based on this, it was estimated that lateral cracks at the billet corners when a dimpled mold is used occur through the following mechanism:
   A. When a dimpled groove is installed directly below the meniscus, the very thin solidified shell in the very early stages of solidification is pressed against the mold wall by the internal pressure from the molten steel, and the dimple mark is transferred to the billet.
   B. When the transferred dimple mark passes through the dimpled groove, it gets caught and creates resistance in the drawing direction.
   C. The resistance in the drawing direction becomes tensile, and cracks occur in the valleys of the oscillation marks, resulting in horizontal corner cracks.

As mentioned in item 3, this condition is thought to occur in very thin shells in the very early stages of solidification. By stabilizing the mold level, the distance between the meniscus and the dimple processing position, which was adjusted to the appropriate position, was maintained, and it is assumed that horizontal corner cracks of the cast billet were also suppressed.

Table 5

Change of Proportional–Integral–Derivative Control Setting for Pulling Speed

	Pouring speed deviation m/min	Mold level deviation 10-second average value
Conventional settings	0.0344	1.65
Test stage 1	0.0573	0.95
Test stage 2	0.0918	0.74

Summary

In order to reduce the defect of horizontal corner cracks of the cast billet, which causes peeling defects on the surface of the deformed steel bar, the following was done:

1. The mold vibration setting was changed to high cycle and short stroke.

Figure 11

Changes in the number of defects detected during rolling of major size deformed steel bars.

2. The distance between the meniscus level and the top row of dimples on the inner surface of the mold was widened to 20 mm.
3. In order to stabilize the above distance, the responsiveness of the drawing speed was increased by changing the PID setting of the drawing speed control.

As a result, the defect occurrence rate of the main size deformed steel bar was reduced by 0.9 cases/rolled ton.

This article is available online at AIST.org for 30 days following publication.

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