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Improvement of Surface Quality of Austenitic Stainless Steel

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Abstract

The cause of scratched defects, occurred at edge area of austenitic stainless cold strip, is identified to be nickel segregation in the surface of continuous cast slabs. The mechanism of segregation occurrence is thought to be as follows. First, disordered oscillation marks in shallow gutters at edge area of slab wide face, induced by narrow face bulging, weakened strength of solidified shell, then cracks in weak solidified shell made segregations. Countermeasures to these problems are as follows. Steep taper of narrow side face in mold makes flat surface of slab wide face, and prevents disorder of oscillation mark. Strong cooling by use of high viscosity continuous casting powder in mold makes solidified shell strong, and depth of oscillation mark becomes shallow. Owing to these methods, segregations in slab surface become to be small, and slabs are transferred to hot rolling mill without surface conditioning by grind. The next subject is to make more shallow depth of oscillation mark by operation of high speed casting.

1. Introduction

The continuous slab caster of Nippon Steel Corporation's Hikari Works, put into operation in 1960, is presently producing more than 30,000 tons per month of stainless steel slabs, thanks to the technologies for casting JIS SUS 304 austenitic stainless steel and other steel grades developed ever since[1,2]. A significant cut in production costs has been brought about lately thanks to the production of conditioning-free slabs made viable by the development of a series of technologies for improving slab surface quality[3-5]. This paper describes the technologies of the conditioning-free slabs as a reference for further improvement.

2. Lamination Defects of Steel Sheets and Their Mechanism

Lamination defects occurred to SUS 304 austenitic stainless steel sheets produced from continuously cast slabs through hot and cold rolling. The authors examined the defects and the characteristics of slab surface layers for clarifying the mechanism of the occurrence of the defects.

2.1 Relation between lamination of steel sheets and slab surface layer characteristics

The lamination occurred mainly in the surface areas up to 300 mm from the edges. At the positions corresponding to the positions of the lamination of the sheet products, the slabs were found to have shallow gutters on the wide faces near the edges, bulging on short faces, deeper oscillation marks in and around the gutters on the wide faces and so forth, as shown in **Fig. 1**. The fact that the wide face surfaces were not smooth was suspected to be the cause of the lamination. This was confirmed through a test wherein the occurrence of the lamination was kept under control when slabs were cold-rolled after smoothing the wide face surfaces by grinding. Since such slab surface conditioning work caused an increase in production costs in

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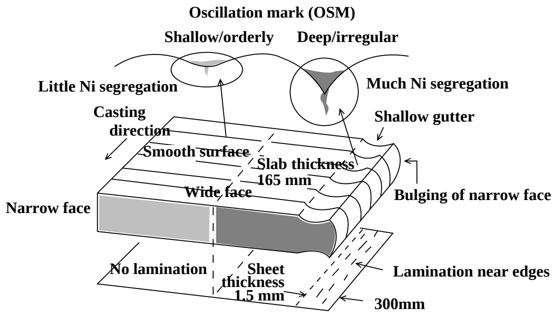

Fig. 1 Positional relationship of lamination between slab and product sheet

actual production practice, the conditions of slab surfaces and the characteristics of oscillation marks (OSMs) were examined and based on the result, technologies to improve slab surface quality were developed as a countermeasure.

2.2 Actual slab surface conditions

2.2.1 Shallow gutters on slab wide faces

An investigation of the surface conditions on slab wide faces made it clear that there were shallow gutters within 100 mm or so from the edges, as shown with conventional powder A (viscosity 0.08 Pa·s) of **Fig.2**, and their depth varied from about 0.5 to 3 mm, the average being 2 mm. **Fig. 3** shows the result of an examination of OSM depth of slab wide faces. As shown with conventional powder A in the figure, OSMs were found deeper at positions nearer the width center (500 mm from the edges), reaching a maximum depth of 500 μm.

2.2.2 OSM and Ni segregation

Fig. 4 shows a section of one of the deep OSMs occurring near the shallow gutter of the slab wide face. It was found out that there was a normal segregation of Ni at the bottom of an OSM[6,7]. The relationship between the depth of the Ni segregation and the depth of the OSM is as shown in **Fig. 5**[8)], when the depth of OSM is 500 to 600 μm, the depth of the Ni segregation is about 200 μm. It was also found out that the concentration of S was high in the Ni segregation portion, and it was suspected that cracks developed in these portions. The cause of the deep OSMs is a low strength of the solidification shell, and when the OSM depth is 300 μm or more the temperature at an OSM bottom is so high that the strength of the solidification shell is estimated at 1 kgf/mm^2 or less[8,9)].

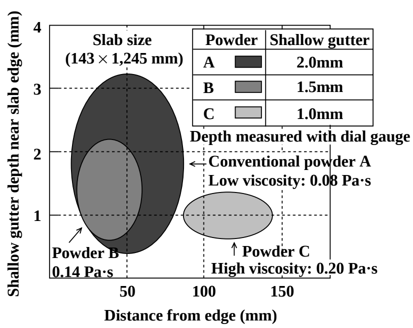

Fig. 2 Shallow gutters near slab edge

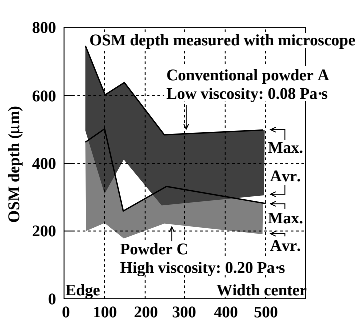

Fig. 3 Gutter depth and OSM depth

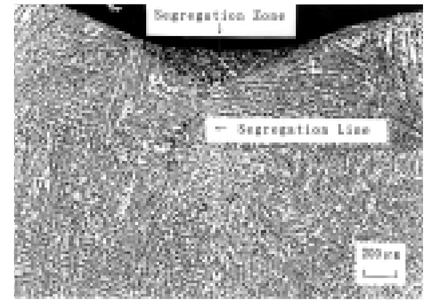

Fig. 4 Structure at OSM bottom

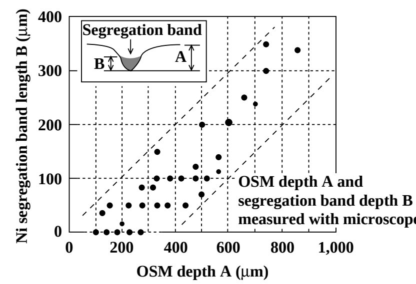

Fig. 5 Relationship of OSM depth and Ni segregation

2.3 Reasoning of lamination mechanism and countermeasures

Here, the mechanism of the occurrence of the lamination is reasoned on the basis of the actual slab surface conditions.

(1) Cracks occurring at the shallow gutter during hot rolling: When the taper of a mold narrow face is insufficient, the cooling of the slab through the mold becomes insufficient, the solidification shell does not have enough strength and as a result, the short face of a slab bulges. The shell at a slab corner where wide and narrow faces meet, on the other hand, has enough strength because the portion is cooled from both the faces and even when the narrow face bulges, the corner keeps its rectangularity. As a consequence, a shallow gutter is formed on a wide face of a slab near a corner, as shown in Fig. 2. When a slab having the gutters is hot-rolled, a tensile stress is created at each of the gutters, which causes small cracks to form on the surface layer, especially at OSM bottoms and then, the cracks develop into laminations during subsequent cold rolling.

(2) Precipitation-induced cracks at OSM bottoms: As seen in Fig. 3, OSMs are disturbed and become deeper near the shallow gutters under an influence of the steel flow in the mold, and shell strength is lowered at OSM bottoms, leading to formation of cracks. Then, molten steel having high concentrations of Ni and S oozes out through the cracks to the outer surface of the shell forming the segregation, as shown in Fig. 5. During the subsequent cold rolling, presumably, the lamination is formed owing to a difference in ductility between the segregation portion and normal portion. Therefore, it is necessary, with respect to (1) above, to rectify the wide face shallow gutters by intensifying the taper of the mold narrow face and with respect to (2) above, to strengthen the solidification shell by using a

high viscosity mold powder. The effects of these measures were then verified through field tests.

3. Prevention of Lamination by Elimination of Shallow Gutters

3.1 Elimination of shallow gutters by increasing taper of mold narrow face

The cause of the slab narrow face bulging, which leads to the occurrence of the shallow gutters on the wide faces, is an air gap between the slab and the mold narrow face owing to the taper of the mold narrow face not conforming to the contraction of the solidification shell from the meniscus downwards. With a one-step taper, in **Fig. 6**, the gap between the free contraction of the slab and the mold is large and the bulging of the slab narrow face occurs easily. With a two-step taper, in contrast, the gap is significantly decreased and the bulging can be suppressed.

It was verified that, with the two-step taper and the use of a high viscosity powder explained later, the bulging amount B of the slab narrow face was reduced to about 0 mm and the shallow gutter depth A of the wide face to about 1 mm, as shown in **Fig. 7**[10]. Next, the relationship between the depth of the gutter and the tensile stress forming at the portion was examined using the finite element method. In rolling a slab 1,330 mm in width and 165 mm in thickness, when the shallow gutter depth was decreased from about 2 - 3 mm to 1 - 0 mm, the tensile stress at the surface layer of the shallow gutter during hot rolling decreased from about 4 - 5 kgf/mm^2 to 2 - 1 kgf/mm^2, and the occurrence of the cracks during hot rolling was inhibited by reducing the shallow gutter depth to 1 mm or less.

3.2 Reduction of OSM depth by use of high viscosity powder

3.2.1 Philosophy of use of high viscosity powder

The philosophy of the use of the high viscosity powder is explained here referring to **Fig. 8**. With a low viscosity powder, the thickness of a molten powder film between the mold and the solidification shell is large and as a consequence, the heat transfer through the mold becomes small, the cooling of the slab slow, the temperature of the entire solidification shell high, and thus the shell strength is decreased. In this situation, the low strength shell bends significantly under a pressure from the molten powder layer imposed on the irregular surfaces of OSMs. This causes the OSM bottoms to become deeper, the shell strength to fall yet more and the segregation portion of Ni and S to grows larger. With a high viscosity powder, in contrast, the thickness of the molten powder film is small, the shell strength increases and as a consequence, the OSM bottoms are shallow, and the wide face surfaces become smoother, making it difficult for Ni and S to segregate.

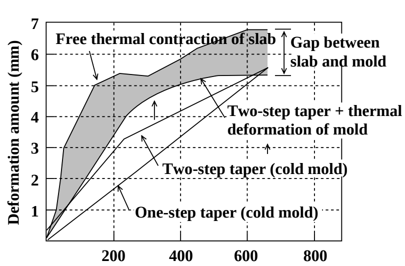

Fig. 6 Two-step taper of mold narrow face

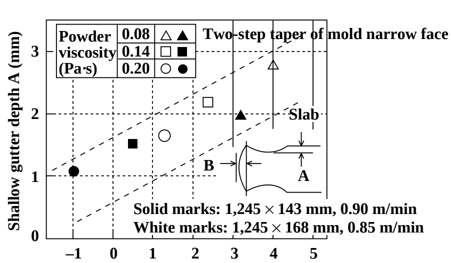

Fig. 7 Relationship of bulging amount and gutter depth

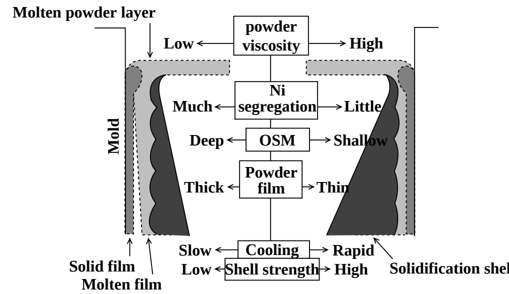

Fig. 8 Use of high viscosity powder

3.2.2 Reduction of OSM depth

For the purpose of reducing the OSM depth by the use of a high viscosity powder as stated above, slabs were cast under the conditions shown in **Table 1** and using powders of different values of viscosity. **Fig. 9** shows the influence of powder viscosity on the structure of a slab near a surface. The higher the powder viscosity, the less the OSM depth and the Ni segregation become. It is clear from the figure that the improvement effect is most noticeable, in particular, with a powder having a viscosity of 0.2 Pa·s[3].

3.2.3 Powder consumption and OSM depth[3,4]

As seen with A in **Fig. 10**, as the powder viscosity η becomes higher, the consumption of powder decreases, suggesting that the thickness of the molten powder film between the mold and the cast slab decrease. This agrees well with the fact that, the higher the powder viscosity is, the shallower OSM becomes, as seen with B of the figure, and also the fact that, the higher the powder viscosity, the higher the cooling rate of the solidification becomes, as seen with C of the figure. When the powder viscosity is 0.2 Pa·s, the average of OSM depth at the width center of a slab is 100 to 200 μm (measured with a profile meter).

3.2.4 Relationship between negative time and OSM depth

The relationship between negative time t_n and the OSM depth is as shown in **Fig. 11**. With the same powder viscosity, the OSM depth

Table 1 Casting conditions

Steel	Slab size		Casting	Mold oscillation		Negative strip
grade	Width	Thickness	speed	Stroke	Cycle	ratio
SUS 304	1,245mm	143mm	0.9m/min	6mm	2.5Hz	0.159s

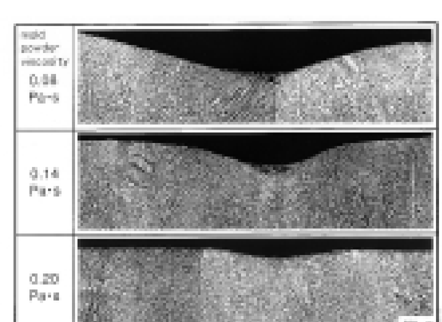

Fig. 9 Relationship of powder viscosity and OSM depth

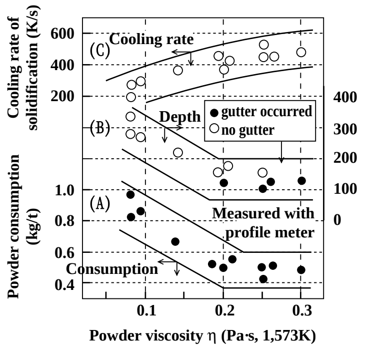

Fig. 10 Relationship of powder consumption and OSM depth

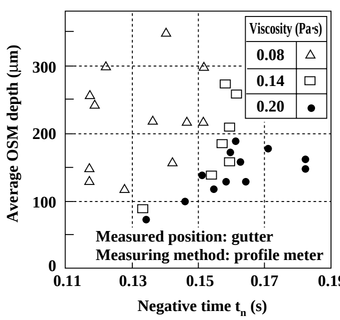

Fig. 11 Relationship of negative time and OSM depth

decreases as t_n becomes shorter. This agrees with the test result of a mold oscillation simulator, reported separately[11]. When the powder viscosity is increased from 0.08 to 0.2 Pa·s, the average of OSM depth is reduced to 100 - 200 μm (measured with a profile meter).

Here, negative time $t_n = (60/\pi f)*\cos - 1(V/\pi fS)$,
where, f is mold oscillation frequency (cycles/min.), V is casting speed (mm/min.), and S is mold oscillation stroke (mm). Note that the OSM depth in Figs. 10 and 11 was measured using a profile meter and, thus, the measurement is a little smaller than that in Figs. 3 and 5, which was measured with a microscope.

3.2.5 Cause of depressions and countermeasures

Depressions (over 2 mm in depth and over 50 mm in length) occurred along the OSM across the slab width at an interval of 200 mm in the direction of casting, when the powder having a high viscosity of 0.2 Pa·s was used. The depth of the transverse depressions and the cooling rate of solidification were found to change as shown in **Fig. 12**. The cooling rate of solidification of the subsurface layer at the depressions was slower than the other portions, and the thickness of the molten powder film was more than 10 times greater. It was found out that uneven powder influx occurred at the transverse depression portions[12], presumably because of the lower powder consumption owing to the higher viscosity, as seen in Fig. 10. For solving the problem, the characteristics of the powder were improved as follows.

Initially, for the purpose of preventing the transverse depressions through optimization of the viscosity and thermal conductivity of the powder, the notion of a thermal conductivity index α representing the temperature-dependency of the powder viscosity was introduced. As a result, even with the high viscosity powder, excessive powder influx was prevented by controlling the thermal conductivity index α to the zone below a critical line as shown in **Fig. 13** and as a result, it became possible to inhibit the occurrence of the transverse depressions. This is presumably because the powder influx was made even by optimizing the temperature gradient within the powder film in accordance with the viscosity[13]. Here, α is expressed as follows: $\alpha = 1.26 - 0.3(M_{Ca} + 0.5\,M_{Na} + M_{Mg})/(M_{Si} + M_{Al})$, where Mx is the molar percentage of the component element x.

In the second place, in order to homogenize the thickness of the molten powder film in the mold, the melting speed of the powder was increased by adding cellulose. As seen in **Fig. 14**, the transverse depressions were prevented from occurring when the addition amount of cellulose was increased. This is presumably because the cellulose burned, and the resultant carbon evenly dispersed in the molten powder prevented powder grains from sintering together, realizing a high melting speed.

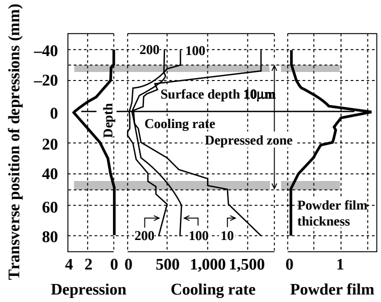

Fig. 12 Depression depth and cooling rate of solidification

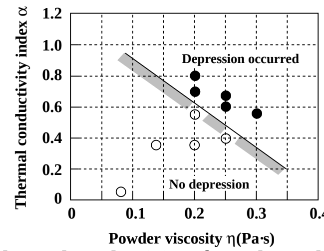

Fig. 13 Thermal conductivity of powder and depression

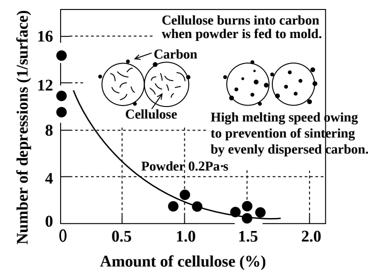

Fig. 14 Effect of cellulose addition

3.3 Reduction of OSM depth by elimination of shallow gutters and use of high viscosity powder

Fig. 7 shows that the depth A of the shallow gutters is reduced when the taper of the mold narrow face is increased and the viscosity

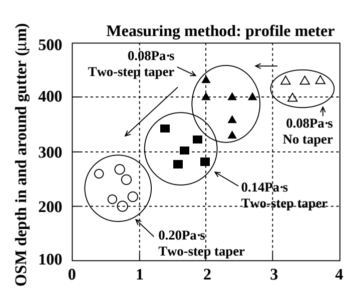

Fig. 15 Effects of powder viscosity and mold taper

of the powder is increased from 0.08 to 0.14 - 0.2 Pa·s, as stated in 3.1. This agrees with the fact shown in Fig. 2 that the depth of the shallow gutters was improved to 1 mm when a powder having a viscosity of 0.2 Pa·s was used. Thanks to the reduction of the shallow gutter depth and the effect of the high viscosity powder shown in Fig. 10, the OSM depth has been significantly reduced to an average of about 250 μm even in and around the shallow gutters, as shown in **Fig. 15**.

4. Conclusion

After the application of the two-step taper of the mold narrow face and the high viscosity powder introduced as explained above, the lamination of the cold-rolled sheet products decreased, and it became possible to reduce the conditioning ratio of austenitic SUS 304 slabs from 100% before the improvement to 25% (a cut in 75%). As seen in Fig. 11, when the negative time tn is made shorter, the OSM depth will be decreased yet more. Further optimization of the cycle, stroke and other mold oscillation conditions and increase in casting speed are required.

References

1) Takeda, M., Yanai, T., Komano, T., Hino, T.: Seitetsu Kenkyu. (294), 32-42 (1978)
2) Okimori, M.: History of Continuous Casting Technologies in Japan. ISIJ, p.138-144, p.427-431
3) Hojo, M., Tanaka, S., Fukuda, Y., Suzuki, N., Okimori, M.: Solidification Structure Forum, High Temperature Process Subcommittee, ISIJ, 1996, p.13-18
4) Fukuda, Y., Kawai, H., Hojo, M., Tanaka, S., Okimori, M.: Proc. 5th Int'l Conf. On Molten Slags, Fluxes & Salts., 1997, p.791-796
5) 104th Special Steel Subcommittee. ISIJ, Apr. 1998 (personal letter)
6) Hojo, M., Fukumoto, S., Suichi, I., Tanaka, S., Takeuchi, H.: CAMP-ISIJ. 5, 1256 (1992)
7) Miyazaki, M., Hojo, M., Tanaka, S.: CAMP-ISIJ. 6, 244 (1993)
8) Hojo, M., Tanaka, S., Fukuda, Y., Nakano, T., Okimori, M.: CAMP-ISIJ. 7, 1150 (1994)
9) Hojo, M., Suichi, I., Tanaka, S.: CAMP-ISIJ. 6, 1134 (1993)
10) Hojo, M., Okimori, M., Fukuda, Y., Tanaka, S., Suzuki, N.: CAMP-ISIJ. 11, 862 (1998)
11) Takeuchi, H., Matsumura, S., Hidaka, R., Nagano, H., Suzuki, Y.: Tetsu-to-Hagané. 69, p.62-67 (1983)
12) Hojo, M., Tanaka, S., Fukuda, Y., Okimori, M.: CAMP-ISIJ. 8, 288 (1995)
13) Fukuda, Y., Okimori, M., Hojo, M., Tanaka, S.: CAMP-ISIJ. 8, 1009 (1995)