NIPPON STEEL TECHNICAL REPORT No. 99 SEPTEMBER 2010

UDC 699 . 14 . 018 . 8 - 415

Technical Report

Development of Model for Formation of Surface Properties in Cold Rolling of Stainless Steels and Application to the Actual Mill

Fumio FUDANOKI* Jun ARAKI
Shuichi INOUE Kazuhiro YANAI

Abstract

The model "the rolling oil transudation model" by whom the decrease of the surface defect and smoothing the surface of the stainless steel cold-rolling was formed were constructed by applying Channel Jacking Mechanism. The surface of the sheet rolled with emulsion oil used this time is not smoothed easily when rolling on the same to neat oil condition, because this emulsion oil becomes a high viscosity under the high pressure, and is not moved easily under high-pressure in the roll byte. However the surface smoothness of the sheet rolled with emulsion oil is the same as one with neat oil with control of the rolling condition based on the rolling oil transudation model.

1. Introduction

The demand for cold-rolled stainless steel sheets has been rapidly increasing, mainly in the household appliance and building material fields. In those and other fields, user demand for stainless steel sheet surface properties, such as surface brightness and surface roughness, has become increasingly exacting. Therefore, there are many study subjects that need to be tackled regarding the influences of rolling and lubrication conditions on surface properties of cold-rolled stainless steel sheets. Recently, concerning the surface brightness of cold-rolled stainless steel sheets, various studies have been conducted from the standpoint of tribology[1-6].

In one of those studies, Kataoka, Kihara et al.[7-11] proposed what they call the Channel Jacking Mechanism (CJM) as their "micro-pool lubrication model" of the lubrication at the interface of friction between the material and the tool by the lubricant that is mechanically trapped in very small dents (micro-pits) in the material surface. This model applies when the lubricant is supplied to the interface of friction between the material and the tool not by the hydrodynamic-based effect but by the effect of the lubricant that is mechanically trapped in micro-pits in the material surface.

In the present study, referring to the above CJM model, we considered the transudation behavior of rolling oil which is trapped mechanically in micro-pits in the surface of steel material before cold rolling. Then, we proposed that the transudation behavior in each rolling pass should be evaluated based on the pass characteristic value (hereinafter called the F-value) that is calculated from the viscosity of the rolling oil used, rolling conditions and roll surface roughness using said model as a reference. We studied the relationship between the pass schedule using the F-value and the change in surface properties after rolling. The study results are described in this paper. In addition, we applied the F-value to smooth the steel surface in the cold rolling process using water-soluble emulsion oil (hereinafter called emulsion oil) which is generally considered inferior to neat oil from the standpoint of obtaining the desired steel surface properties. The results are also described in this paper.

2. Study of Transudation Phenomenon of Rolling Oil and Calculation of Pass Characteristic Value (F-Value)

First, we checked whether the rolling oil that was trapped mechanically in micro-pits in the stainless steel surface during cold rolling was transuding from the roll bite through a channel. The authors et al.[5] stopped cold rolling of SUS430 stainless steel halfway, obtained a sample of half-rolled steel, and measured the surface properties of the sample using a 3-D roughness gauge. The measurement

* Senior Manager, Automotive Stainless Steel Products Department, Nagoya Sales Office, Nippon Steel & Sumikin Stainless Steel Corporation
2-13-18, Meieki-Minami, Nakamura-ku, Nagoya, Aichi

results are shown in **Fig. 1**. In the surface of the sample before entering the roll bite, there were micro-pits in the form of streaks in the rolling direction. Those micro-pits decreased to such an extent that the sample surface roughness became almost equivalent to the roll surface roughness in the latter half of the roll bite. This indicates that the rolling oil trapped mechanically in micro-pits in the steel surface during cold rolling transudes toward the entry side and leaves the roll bite through a linear channel—a replica of the roll groove—under rolling pressure.

In the CJM model, the time, t, for which the rolling oil transudes from the micro-pool at the interface of friction between the material and the tool, through the channel, is formulated. It is expressed by the following equation[11].

$$t = 2\eta_0\gamma\left(\frac{L}{D}\right)^2$$

η_0 : viscosity coefficient of rolling oil under atmospheric pressure
γ : pressure coefficient of viscosity
L : channel length from micro-pool
D : diameter of micro-pool channel

Fig. 2 schematically shows the concept of the channel extending from a micro-pit in the rolled steel surface when the CJM model is applied to cold rolling of stainless steel. The maximum time by which the rolling oil trapped mechanically in the micro-pit in the rolled steel surface transudes through the channel is the time obtained on the assumption that the channel length is equal to the contact arc length. It is expressed by the following Equation (1). In contrast, the time by which the rolling oil moves inside the roll bite at the micro-pit in the rolled steel surface is expressed by the following Equation (2)[12].

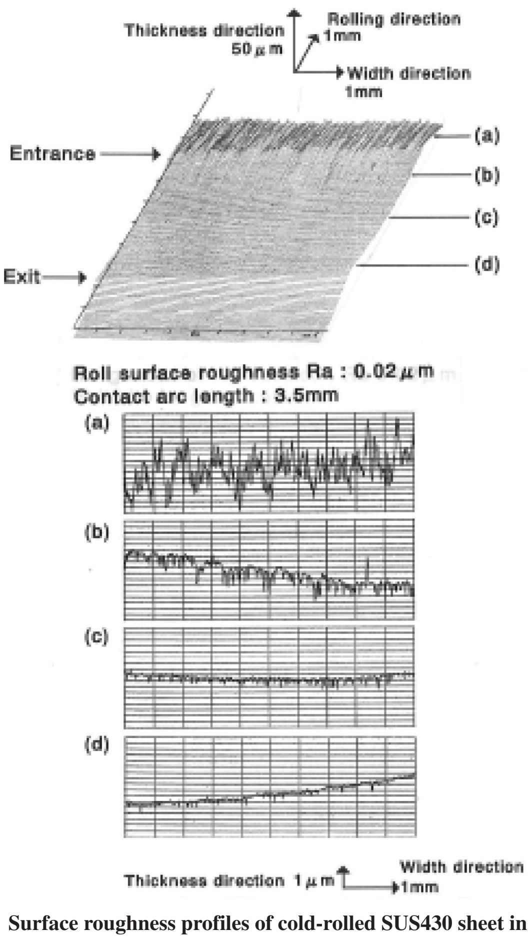

Fig. 1 Surface roughness profiles of cold-rolled SUS430 sheet in roll bite

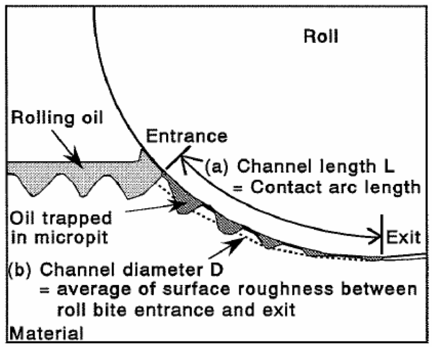

Fig. 2 Application of CJM model to cold rolling of stainless steel

$$ta = \frac{8\eta_0\gamma L^2}{\{R.M.S.(0) + R.M.S.(L)\}^2} \quad (1)$$

$$td = \frac{4L}{(4-r)\,Vr} \quad (2)$$

L : contact arc length
Vr : rolling speed
r : reduction

$$R.M.S.(0) = \sqrt{\{\sigma_R(0)\}^2 + \{\sigma_S(0)\}^2}$$

$$R.M.S.(L) = \sqrt{\{\sigma_R(L)\}^2 + \{\sigma_S(L)\}^2}$$

σ_R : roll surface roughness
σ_S : rolled steel surface roughness

When *ta* (the time by which the rolling oil transudes) is longer than *td* (the time by which the rolling oil moves in the roll bite), it is assumed that the rolling oil transudes only for td. In this case, the F-value is defined as *td/ta*. When *ta* is shorter than *td*, it is assumed that the rolling oil transudes sufficiently. In this case, the F-value is defined as 1.

$$F = \frac{td}{ta} \quad \text{when } ta \geq td \quad (3)$$

$$F = 1 \quad \text{when } ta < td \quad (4)$$

The above definitions indicate that the F-value always falls within the range 0 to 1. The larger the F-value is, the more the transudation of rolling oil is promoted. The F-value is regarded as the pass characteristic value.

3. Relationship between Surface Smoothness and Pass Schedule using F-Value

Here, we discuss the relationship between the surface smoothness of a cold-rolled SUS304 sheet using low-viscosity neat oil and the pass schedule using the F-value.

3.1 Experimental method

The material used in the experiment was a 1.5-mm-thick SUS304 sheet which had been annealed and pickled. A microphotograph of the material surface is shown in **Fig. 3**. The surface shows intergranular corrosion grooves in the form of a net unique to the SUS304 sheet. This material was rolled by a Sendzimir 20-high cluster mill with a roll diameter of 60 mm. The rolling conditions are shown in

Table 1 Rolling conditions

Pass number			0	1	2	3	4		5	
Thickness (mm)			1.50	1.15	0.95	0.79	0.68		0.59	
Reduction (%)			-	23	17	17	14		13	
Neat oil	Rolling speed (m/min)		-	150	240	290	340	150	200	250
	Roll surface roughness Ra (μ m)	A	-	0.05	0.05	0.05	0.05		0.05	
		B						-	0.05	-
		B’	-	0.20	0.20	0.20	0.05	0.05	-	-
		B”						-	-	0.05
		C	-	0.20	0.20	0.20	0.20	-	0.05	-
Emulsion oil	Roll surface roughness Ra (μ m)		-	0.20	0.20	0.20	0.05		0.05	
	Rolling speed (m/min)	D	-	150	500	500	400		200	
		E	-	50						

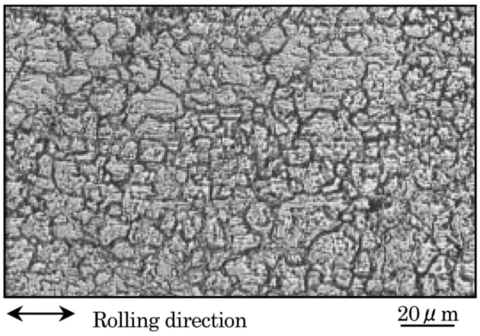

Fig. 3 Micrograph of surface of mother sheet

Table 2 Rolling oil properties

Oil type		Neat	Emulsion
Kinematic viscosity	40℃	10	8 *
ν (mm/s)	100℃	2	2 *
Pressure coefficient of viscosity γ (1/GPa) at 75℃		5	20 *
Density ρ (g/cm^3)		0.87	0.86 *
Emulsion diameter (μ m)		-	5
Oil concentration (%)		-	10

* Base oil properties

Table 1.

In the present experiment, the F-value was varied by changing the roll surface roughness, since it is influenced by the square of the roll surface roughness as shown by the above Equation (1). Namely, in Case A, the material was rolled using smooth rolls with a surface roughness of 0.05 μmRa on all passes. In Case B, rough rolls with a surface roughness of 0.20 μmRa were used in passes 1-3, and smooth rolls with a surface roughness of 0.05 μmRa were used in passes 4 and 5. In Case C, rough rolls with a surface roughness of 0.20 μmRa were used in passes 1-4, and smooth rolls with a surface roughness of 0.05 μmRa were used only in the final pass. In Cases B’ and B”, respectively, the rolling speed was varied. The rolls were ground with a rotary whetstone. As the rolling oil, the neat oil whose properties are shown in **Table 2** was used. After the rolling, the surface of each sample was studied under an optical microscope and the micro-pit area ratio of each sample was measured using an image analyzer.

3.2 Experimental results and discussions

As was clarified by a study conducted by Azushima et al.[13)], the amount of rolling oil that is led in between the roller and the material under the present experimental conditions is determined not by any hydrodynamic-based effect but by the effect of the oil mechanically trapped in micro-pits in the material surface.

3.2.1 Results of calculation of rolling oil transudation function F-value

Fig. 4 shows the F-values in the individual passes in pass schedules A, B and C using rolls of different surface roughness. The F-values were obtained first by calculating *ta* and *td* using Equations (1) and (2), and then by applying Equations (3) and (4) to them. The parameters necessary for the calculation of the F-value are shown in **Table 3**. As the value of η_0, the product of kinematic viscosity ν and density ρ of the rolling oil was used. The value of ν at a given temperature was obtained by using the Walther equation[14)], applying the values at 40℃ and 100℃. The roll bite temperature in each pass was calculated taking into account the temperature rise due to the rolling operation and friction and the temperature drop due to the

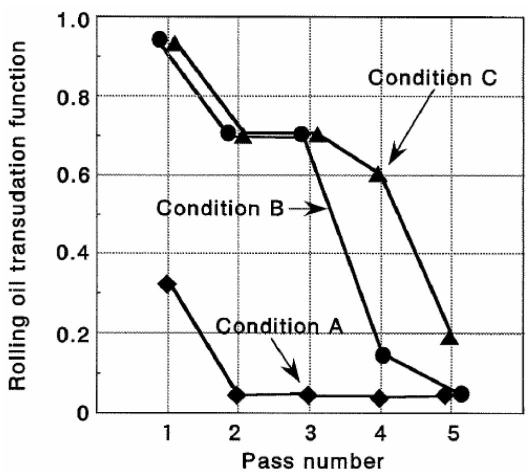

Fig. 4 Rolling oil transudation function in pass schedules under conditions A, B, and C

Table 3 Computational conditions to determine rolling oil transudation function

Pass number	1	2	3	4	5
Temperature of roll bite (℃)	111	122	127	118	96
Kinematic viscosity ν (cSt)	1.7	1.4	1.3	1.5	2.2
Viscosity η_0 (mPa · s)	1.5	1.2	1.1	1.3	1.9
Roll bite length L (mm)	3.2	2.4	2.2	1.8	1.6

cooling effect of the rolling oil[14-17]. The contact arc length was obtained from the roll radius R and reduction Δ h (i.e., the difference between sheet thickness before rolling and sheet thickness after rolling) by using the simple Equation (5).

$$L = \sqrt{(R \cdot \Delta h)} \tag{5}$$

In Case A, the F-value is relatively small—about 0.3 in the first pass and 0.1 or less in the subsequent passes. In Case C, by contrast, the F-value is relatively large—0.6 or more in the first four passes and about 0.2 in the final pass. In contrast, in Case B, the F-value is as large as 0.7 or more in the preceding passes, whereas it is 0.15 or less in the subsequent passes. Thus, Case B is in between Case A and Case C. By varying the roll surface roughness, we obtained three different patterns of pass schedules based on the F-value.

3.2.2 Relationship between pass schedule based on F-value and surface of rolled sheet

Fig. 5 shows the area ratio of micro-pits on the surface of a cold-rolled steel sheet in Cases A, B and C, respectively. The area ratio of micro-pits is about 4% in Case A and about 2% in Case C. In Case B, it is 0.9%, indicating that the surface of the cold-rolled sheet is the smoothest. In a comparison between photographs (b) and (c) in Fig. 5, in Case B, micro-pits decreased noticeably in the first pass, whereas in Case A, micro-pits did not decrease much. In contrast, in Case C, as shown by a comparison between photographs (e) and (f) in Fig. 5, the area ratio of micro-pits increased in the fifth pass because the number of oil pits increased.

From the standpoint of the rolling oil transudation model, in order to smooth the surface of SUS304 sheets in cold rolling, the use of rough rolls in the preceding passes and smooth rolls in the last two passes was effective. In the preceding passes, the rolling oil transuded from micro-pits formed by intergranular corrosion of the steel material and flowed out along the roll grooves, causing the micro-pits on the material surface to decrease (disappear). **Fig. 6** shows the relationship between the F-value and area ratio of micro-pits after rolling in the first pass. Here, assuming *td* = 0 for the steel sheet before rolling, the area ratio at F-value = 0 was adopted. Fig. 6 shows that as the F-value is increased in the first pass, the micro-pits on the steel sheet surface decrease.

In contrast, in order to ensure the desired surface brightness of a rolled steel sheet, it is necessary to use smooth rolls in the subsequent passes. Naturally, therefore, if the rolling speed is not changed, the F-value decreases in those passes. In Case C, the area ratio of micro-pits after rolling is nearly equivalent to that in the fourth pass in Case B. By using smooth rolls in two consecutive rolls as in Case B, it is possible to transude the rolling oil from micro-pits like oil pits and make those micro-pits decrease (disappear).

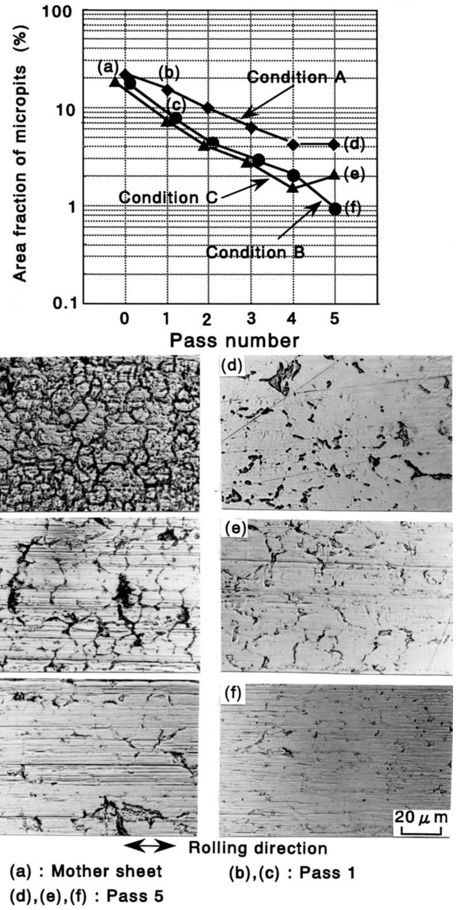

Fig. 5 Area fraction of micropits and micrographs of sheets rolled in pass schedules under conditions A, B, and C

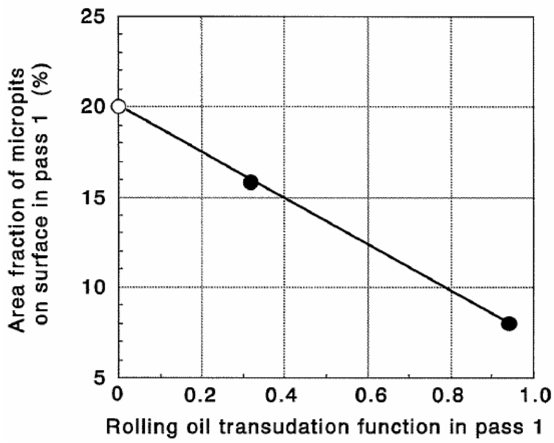

Fig. 6 Relationship between F value and area fraction of micropits on surface of sheet in pass 1

To verify the above point, using equivalent roll surface roughness to that in Case B, we conducted an additional rolling test in which the rolling speed in the fifth pass was changed to 150 m/min (Case B') and 250 m/min (Case B"). **Fig. 7** shows the relationship between the area ratio of micro-pits on the rolled sheet after the fifth pass and the F-value in the fifth pass. Here, assuming that *td* = 0 for the sheet surface before rolling, the area ratio at F-value = 0 was

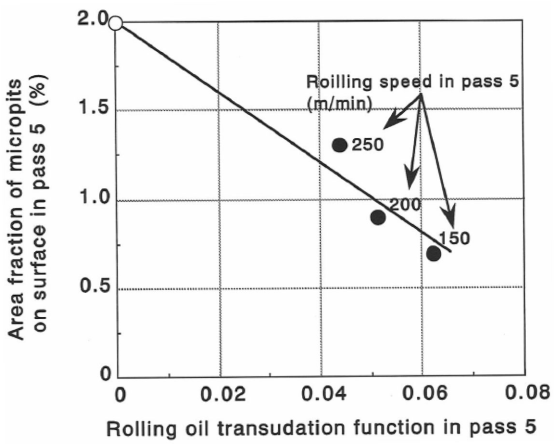

Fig. 7 Relationship between F value and area fraction of micropits on surface of sheet in pass 5 under conditions B, B', and B"

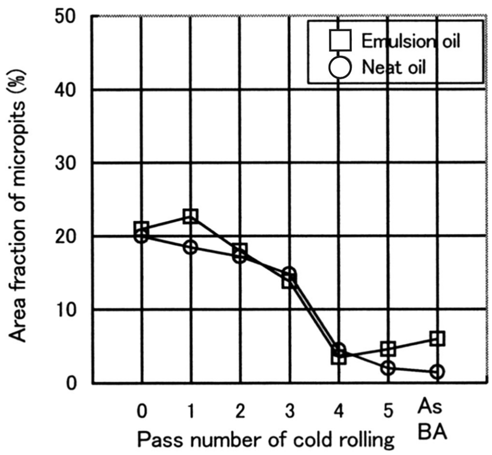

Fig. 8 Area fraction of micropits of sheets rolled in pass schedules under conditions B and D, and of sheets finished as BA

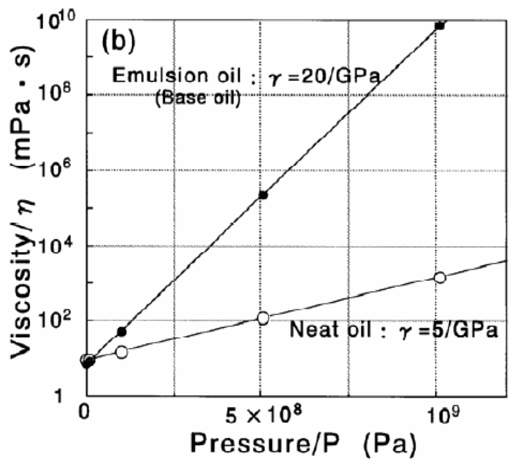

Fig. 9 Relationship between viscosity and pressure of emulsion oil and neat oil

adopted. The figure shows that with the increase in F-value in the fifth pass, micro-pits like oil pits on the sheet surface decrease. Therefore, even in the final pass, when the F-value is increased, transudation of the rolling oil from micro-pits occurs, making more of the micro-pits disappear.

4. Application of Emulsion Oil in Cold Rolling of Stainless Steel

The stainless steel material mentioned earlier was cold-rolled by Sendzimir 20-high cluster mill with a roll diameter of 80 mm using water-soluble emulsion oil as the rolling oil. The properties of the emulsion oil used are shown in Table 2.

Concerning the surface properties of cold-rolled sheets obtained in the individual passes in Case D, which has equivalent roll surface roughness to Case B, and those of bright-annealed (BA) sheets, the area ratios of micro-pits on their surfaces were measured. The measurement results are shown in **Fig. 8**.

Compared with the rolled sheet obtained using neat oil, the rolled sheet obtained using emulsion oil (the sheet obtained in the fifth pass) and the BA sheet have a large area ratio of micro-pits. This is because when the stainless steel material is rolled using emulsion oil in place of neat oil, the micro-pits caused by intergranular corrosion do not decrease significantly in any pass and almost all of them remain after the rolling.

We considered the reason for the above phenomenon as follows. As **Fig. 9** shows, the pressure dependence of emulsion oil viscosity is much greater than that of neat oil. Therefore, under the high pressure inside the roll bite, the movement of emulsion oil through the roll bite is much slower than that of neat oil. As a result, the emulsion oil that is mechanically trapped in the micro-pits formed before rolling cannot speedily transude from the roll bite, leaving most of the micro-pits on the rolled sheet.

Therefore, we discussed the type of rolling conditions that would permit the use of emulsion oil to obtain a cold-rolled sheet with a comparable surface smoothness to a cold-rolled sheet obtained using neat oil. With the emulsion oil used in the present experiment, the relationship h_1 (oil film thickness at entrance) < 2 hp holds true (hp: emulsion plate-out thickness). Therefore, assuming that the base oil is neat oil, the "rolling oil transudation model" can be applied[18].

Therefore, we conducted an additional rolling test in which the rolling speed in the first pass was slowed down to 50 m/min (Case E). **Fig. 10** shows the relationship between the F-value in the first pass (horizontal axis) and area ratio of micro-pits caused by intergranular corrosion in the first and fifth passes (vertical axis), obtained in Cases B, D and E, and the observation results for steel surfaces in the first and fifth passes in Cases D and E.

As Fig. 10 shows the area ratios of micro-pits in the first and fifth passes can be expressed by the F-value in the first pass, regardless of the type of rolling oil used. In Case E, in which the rolling speed in the first pass was slowed down and the F-value approached that obtained with neat oil, the micro-pits caused by intergranular corrosion decreased to one-half in the first pass and to about 2% in the fifth pass. Thus, we confirmed that even when emulsion oil was used in place of neat oil, it would be possible to obtain surface properties of a cold-rolled sheet comparable to those of a cold-rolled sheet obtained using neat oil.

5. Conclusions

(1) The surface properties of a half-rolled stainless steel sheet in cold rolling were examined. As a result, the phenomenon whereby the rolling oil trapped mechanically in micro-pits on the surface of the rolled sheet transuded along a linear channel was observed.
(2) As a pass characteristic value calculated from rolling conditions, etc., we proposed the F-value—a rolling oil transudation func-

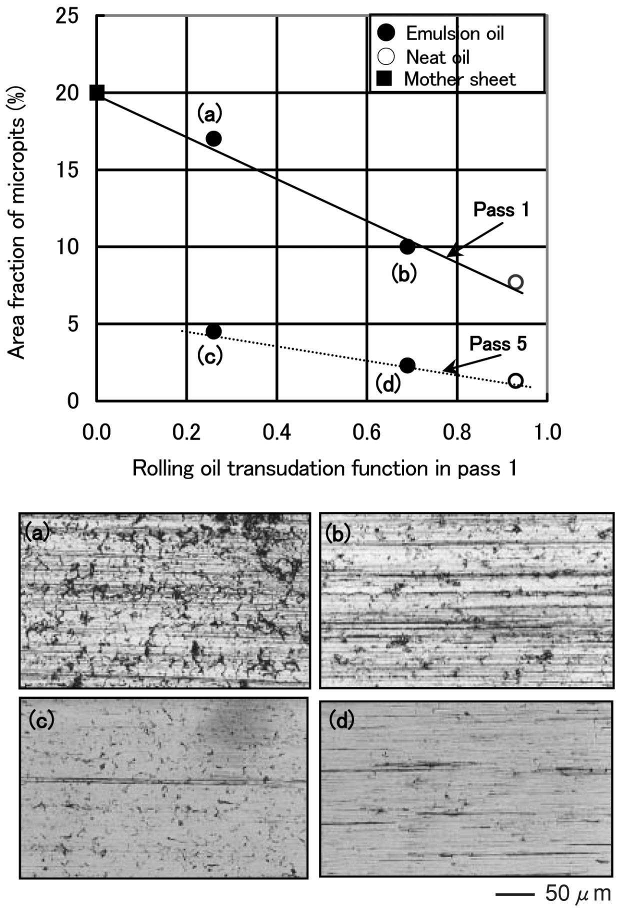

Fig. 10 Relationship between rolling oil transudation function in pass 1 and area fraction of micropits on surface of sheet in pass 1 and 5, and micrographs of sheets rolled under conditions D and E
(a) Pass 1 of condition D, (b) Pass 1 of condition E
(c) Pass 5 of condition D, (d) Pass 5 of condition E

tion. The F-value should permit expressing the behavior of rolling oil in the roll bite in each rolling pass.

(3) The emulsion oil used in the present experiment increases in viscosity under high pressure and can hardly move through the roll bite, which is under a high pressure. Therefore, when steel material is rolled under the same conditions as applied when neat oil is used, the surface brightness of the rolled sheet deteriorates. However, by increasing the F-value in the first pass, it is possible to obtain surface properties comparable to those of a rolled sheet obtained by using neat oil.

References

1) Azushima, A., Noro, K. et al.: Tetsu-to-Hagané. 77, 576 (1990)
2) Azushima, A.: Tetsu-to-Hagané. 80, 635 (1994)
3) Kenmochi, K. et al.: Tetsu-to-Hagané. 78, 1546 (1992)
4) Kenmochi, K. et al.: Tetsu-to-Hagané. 81, 809 (1995)
5) Fudanoki, F. et al.: CAMP-ISIJ. 7, 1375 (1994)
6) Inoue, S. et al.: CAMP-ISIJ. 8, 766 (1995)
7) Kataoka, S. et al.: Journal of the JSTP. 30, 709 (1989)
8) Kataoka, S. et al.: Journal of the JSTP. 30, 1058 (1989)
9) Kataoka, S. et al.: Collection of 1989 Plastic Forming Spring Lecture Papers. 1989, p.378
10) Kataoka, S. et al.: Collection of 2000 Plastic Forming Spring Lecture Papers. 1990, p.173
11) Kataoka, S. et al.: Journal of the JSTP. 33, 556 (1992)
12) Fudanoki, F. et al.: Journal of the JSTP. 39, 454 (1989)
13) Azushima, A.: Journal of the JSTP. 36, 737 (1995)
14) Japan Lubrication Society: Lubrication Handbook. Tokyo, Yokendo Co., Ltd., 1974, p.260
15) Kojima, Y. et al.: Journal of the JSTP. 30, 1004 (1989)
16) Tsuchida, M. et al.: Lubrication. 30, 116 (1985)
17) Inoue, S. et al.: CAMP-ISIJ. 7, 1376 (1994)
18) Fudanoki, F. et al.: Tetsu-to-Hagané. 83, 8 (1997)


Fumio FUDANOKI
Senior Manager, Automotive Stainless Steel Products Department, Nagoya Sales Office,
Nippon Steel & Sumikin Stainless Steel Corporation
2-13-18, Meieki-Minami, Nakamura-ku, Nagoya, Aichi


Shuichi INOUE
General Superintendent, Kanto Works, Manufacturing Technical Headquarters, SUS-TECH (former Manager of Sheet & Coil Quality, Production Planning & Quality Control Division, Hikari Works, Nippon Steel & Sumikin Stainless Steel Corporation)


Jun ARAKI
Manager, Cold Strip Technical Department,
Cold Strip Mill, Hikari Works, Production Division,
Nippon Steel & Sumikin Stainless Steel Corporation


Kazuhiro YANAI
Director and Executive Officer,
General Manager, Technical Control Division,
Nippon Steel & Sumikin Stainless Steel Corporation