KAWASAKI STEEL TECHNICAL REPORT
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Synopsis :
Evaluation methods of heat streak resistance and sheet surface cleaning property of cold rolling oil were established. The lubricity was evaluated by scoring limit load using the modified Timken tester and four-ball tester. Surface cleaning property was quantitatively evaluated by the quantity of carbon on the surface of the test piece after annealing. Through these methods, it was possible to develop high lubricity rolling oil with performance to increase 10 to 20% rolling speed and to decrease 15% oil consumption compared with those of the conventional rolling oil. The new surface clean rolling oil has a good surface cleaning property and lubricity that can be used in rolling of the steel sheet with 0.4mm thickness.

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1 Introduction

The cold rolling oil is required to have good lubricity and adequate emulsifying property. It must also promote corrosion-resistance of steel strip, cleanliness of annealed sheet surface, and easy treatment of waste water. All these requirements must be evaluated properly and, most desirably, lubricity and strip surface cleaning-property must be evaluated on an actual tandem cold rolling mill. But opportunities for the experiments are limited because of the scale of experiments and operational constraints.

For this reason, a number of methods were studied for evaluating the rolling oil on a laboratory scale. For the lubricity, methods using the Bowden tester[1], four-ball tester[2] and test mill[3,4] have been reported. For the annealed sheet surface cleaning property those using thermobalance and cup test are known.

(1) Rolling oil for cold rolling of steel strip that will be annealed without the electrolytic cleaning line (process) is called "mill clean" rolling oil and the degree of surface cleanliness in terms of pollution due to post-anneal residual oil and iron fines is called "the strip surface cleanliness".

(2) Under a high speed and high reduction rolling, both rolls and strip temperatures rise, occasionally causing oil film brakage and scoring, and leaving surface damages called "heat streaks".

Heat streak restricts the operational conditions such as rolling speed and reduction, thus decreasing productivity. The better the rolling oil's lubricity, the less likely it is that heat streak will occur. The heat streak resistance is regarded as an index to rolling oil's lubricity. Heat streak characteristically occurs on the back surface of strip where the lubrication is inferior to that on the upper surface. The authors have reported elsewhere on the mechanism of heat streak occurrence[5]. Recently, by using a testing machine, the authors successfully reproduced the same type of scoring as seen on the actual mill, and have confirmed that rolling oil properties as evaluated through the degree of scoring found at the testing machine corresponds to those encountered on the actual rolling mill. On the other hand, the mill-clean property of rolling oil was evaluated by measuring residual carbon on the annealed strip surface.

The present report relates the methods of evaluating the lubricity and the mill-clean property of rolling oil as examined in terms of heat streak resistance. It also introduces their applications to a high lubricity rolling oil and a new mill-clean rolling oil.

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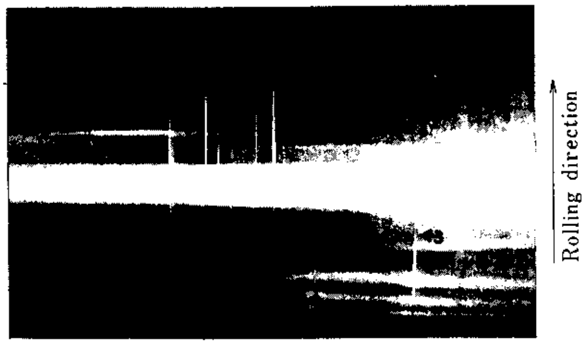
2 Evaluation of Heat Streak Resistance

2.1 Mechanism of Heat Streak Formation

2.1.1 Origin of heat streak

The occurrence of heat streak not only deteriorates the product quality but also increases the quantity ground of the roll (see **Photo 1**). The effects of various rolling conditions on the occurrence of heat streak are shown in **Figs. 1** and **2**. It is evident from these results that an increase in rolling reduction and speed,



(A) Work roll

(B) Strip

Photo 1 Heat streaks on work roll and strip surface

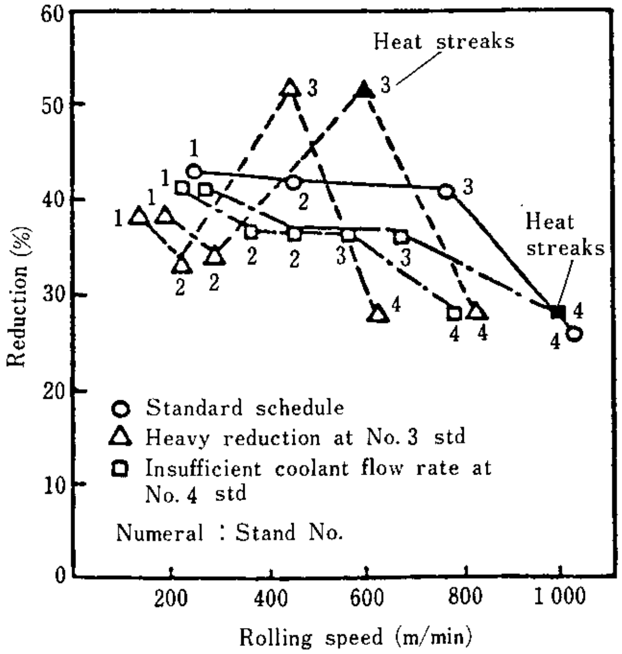


Fig. 1 Relation between cold rolling conditions and heat streaks (experimented in 4 stands cold tandem mill)

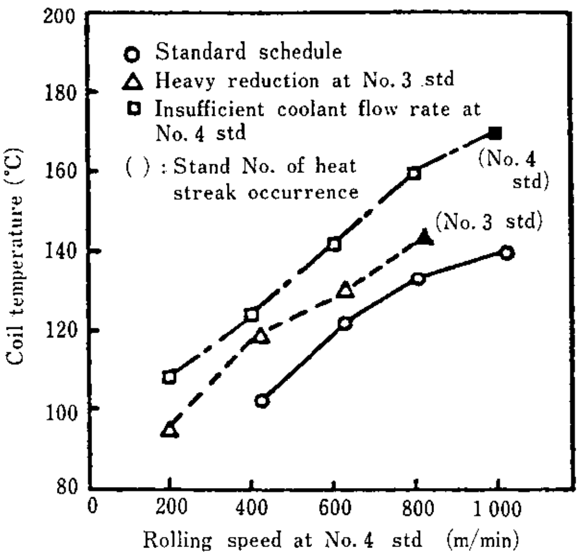
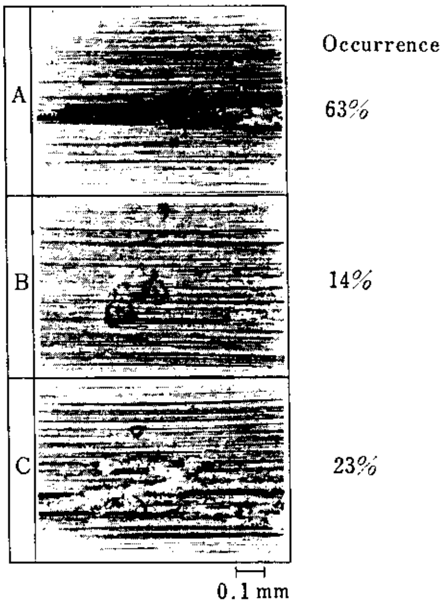
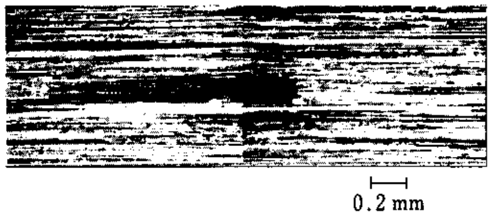


Fig. 2 Relation between coil temperature after rolling and rolling speed at No. 4 std (experimented in 4 stands cold tandem mill)



(A) Starting point of heat streak



(B) Scratch on work roll before rolling

Photo 2 (A) starting points of heat streaks on work roll and (B) surface scratch on work roll together with a decrease in coolant's flow rate, leads to a higher temperature, thus causing heat streak. On the assumption that heat streaks are triggered by some mechanism, the surfaces of rolls and rolled strip that were involved in the occurrence of heat streaks were observed in detail. Consequently, scratches were found on the roll surface in a manner considered to have developed during roll grinding from the origin of heat streaks. Classification of heat streaks, with the ratio of each class, is shown in **Photo** 2(A).

Photo 2(B) shows scratches on the surface of an unused roll, indicating that these scratch-like depressions are of the same type as A in **Photo** 2(A). Type A scratches are more frequent than those of types B and C, accounting for more than half of heat streak occurrences.

2.1.2 Analysis with elastohydrodynamic lubrication model

The lubricating condition of a roll having scratches on its surface was analyzed by adopting the theory of elastohydrodynamic lubrication using the data on heat streak occurred to the actual roll mill. As for the effects of micro-flaws on lubrication, Wymer et al.[6] performed an experiment under the conditions of elastohydrodynamic lubrication and ascertained that oil film breakage occurred around depressions. Moreover, Cheng et al.[7] performed numerical analysis of the lubrication under adiabatic conditions on the basis of the elastohydrodynamic lubrication theory and came to the conclusion that the pressure rose at the border of depression.

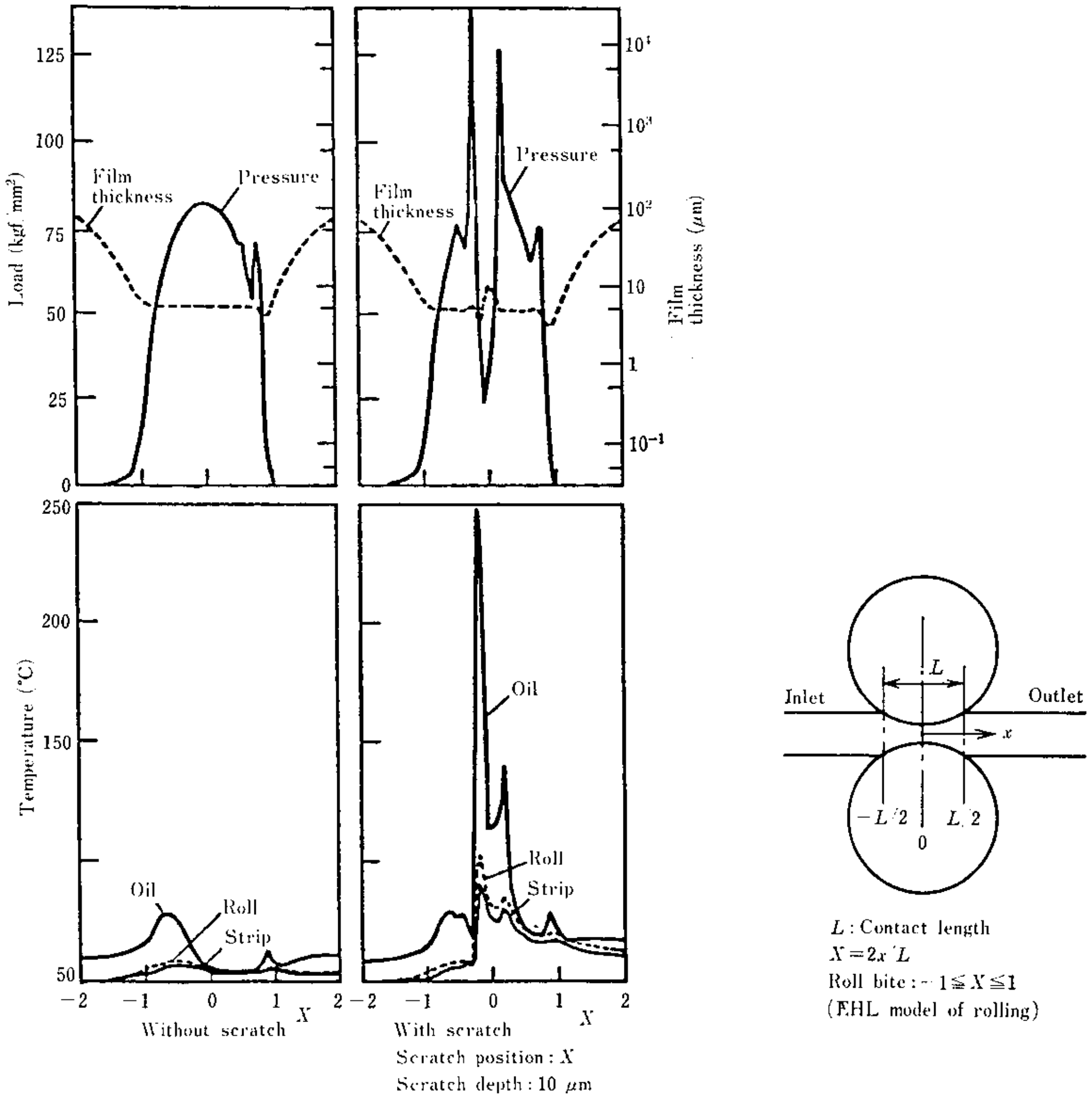


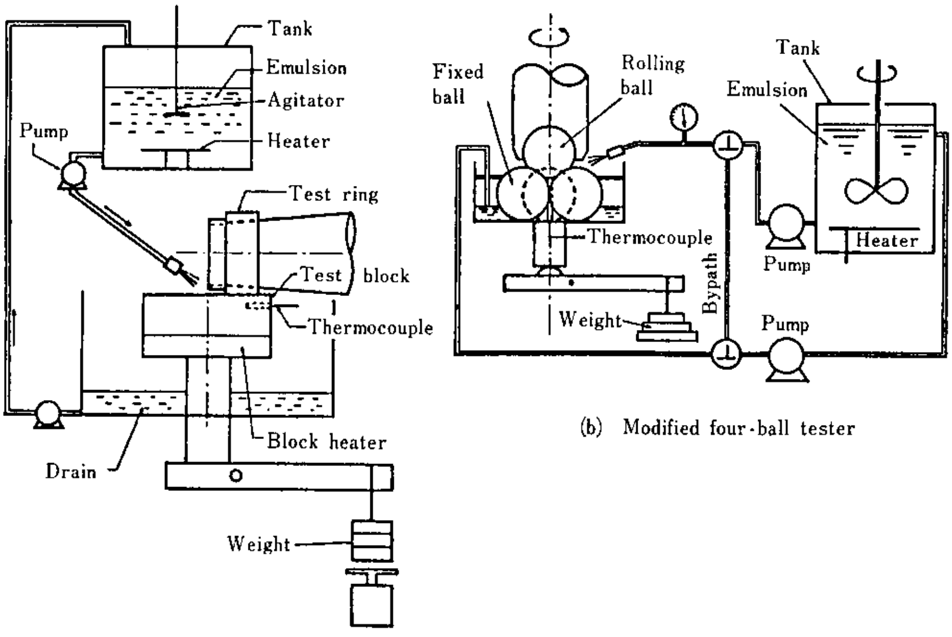
Fig. 3 Influence of the roll scratch on film thickness pressure and temperature

Based on the authors' own analysis the distributions of pressure, oil film thickness and temperature around a depression of 10 μm depth are shown in **Fig. 3**. The pressure distribution without scratch was nearly identical to Hertz's pressure distribution, with maximum pressure 82 kgf/mm^2, minimum oil film thickness 3.8 μm and maximum oil temperature approximately 79°C. On the contrary, when there were scratches, maximum pressure was 222 kgf/mm^2, minimum oil film thickness 3.4 μm, and maximum oil temperature 267°C, indicating that, compared with the case of no scratches, the scratches made the lubricating conditions more severe locally with pressure and temperature increased markedly and oil film made thinner.

2.2 Evaluation Using Modified Timken Tester and Modified Four-ball Tester

2.2.1 Testing equipments and experimental conditions

Schematic diagrams of the modified Timken tester and modified four-ball tester used for the evaluation of heat streak resistance of rolling oil are shown in **Fig. 4**. Both testers were modified so that emulsified test oil could be sprayed from a nozzle to the contact area of metals, recovered and recycled.



(a) Modified Timken tester

(b) Modified four-ball tester

Fig. 4 Schema of testers of lubricity

Table 1 Specification of modified Timken tester and four-ball tester, and experimental condition

	Modified Timken tester	Modified four-ball tester	Tandem mill
Average pressure (kgf/mm^2)	12 - 76 (Load : 20 - 800kgf)	52 - 346 (Load : 1 - 300kgf)	60 - 100
Relative velocity (m/min)	0.16 155 (1 - 1 000rpm)	0.035 - 34.5 (1 - 1 000rpm)	Inlet 100 - 300 Outlet 10 - 100
Test material temperature(°C)	Room temp. 300	Room temp. - 100	100 - 200
Supply of rolling oil	Emulsion recirculation	Emulsion recirculation	Emulsion recirculation
Experimental load (kg)	100 - 600 (100 kgf interval)	50 300 (25 kgf interval)	
Experimental rolling speed (rpm)	50, 200, 400, 600, 800, 1 000 (50 rpm interval at scoring vicinity)	50, 250, 500, 750, 1 000 (50 rpm interval at scoring vicinity)	

Moreover, the modified Timken tester was designed so as to permit temperature control of the test block, and the modified four-ball tester was provided with a by-pass circulation so as to ensure stable emulsification even while the experiment was halted. In the actual experiment, the test block and balls were replaced after each measuring session, irrespective of the existence of scoring, and an abrupt rise of frictional torque was regarded as an index for scoring.

Specifications and test conditions of two testers are shown in **Table 1**. While the modified four-ball tester provided greater load than the modified Timken tester, the relative velocity was greater in the latter. For this reason, it is considered that under the mixed lubrication condition, the modified Timken tester functions more in the hydrodynamic evaluation, with the modified four-ball tester more in the boundary lubrication evaluation.

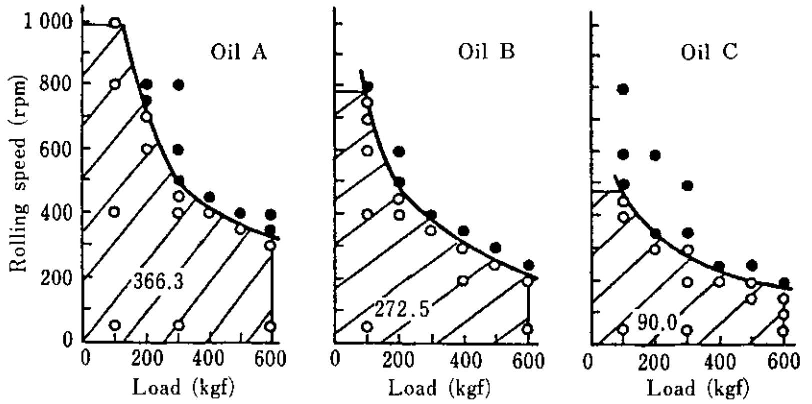
2.2.2 Testing with practical rolling oil

The evaluation was attempted by using three kinds of rolling oil of which lubricity had been ascertained through long-term application on the tandem mill, as shown in **Table 2**. Rolling oil A for thin gage rolling, which consisted of tallow as the base and ex-

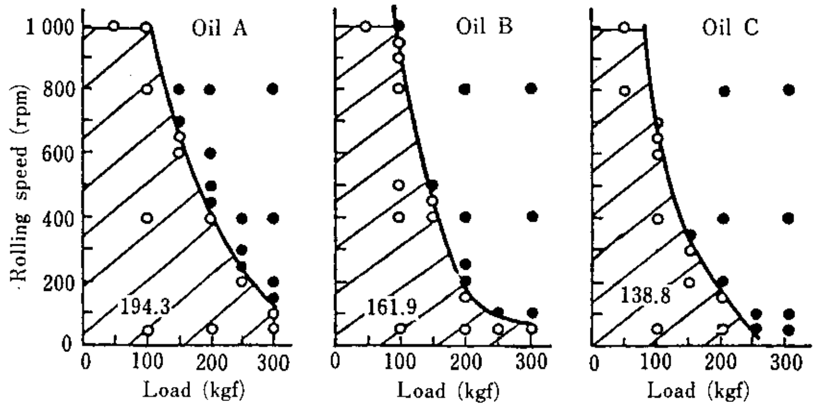
Table 2 Rolling oil used in Timken and four-ball test

	Base oil	Additive	Grade of Lubricity
A	Tallow (90%)	E.P. (2%)	Best (Used for thin gauge)
B	Tallow (60%)	Mineral oil(30%)	Good (Used for middle gauge)
C	Mineral(80%)	Ester (10%)	Bad (Used for thick gauge)

E.P. : Extreme pressure additive



(a) Modified Timken tester



(b) Modified four-ball tester

○ : Not scoring ● : Scoring

The shaded portion shows not scoring

Concentration of oil : 5 %

Temperature of oil : 50°C

Fig. 5 Scoring marginal curve of practically used rolling oil by testers treme pressure additive, had high lubricity for thin gage. Rolling oil C is mill clean rolling oil for heavy gage, consisting of mineral oil as the base. Its low lubricity was compensated by adding ester. Rolling oil B is of intermediate lubricity between A and C, composed of tallow, as the base, and a considerable amount of mineral oil.

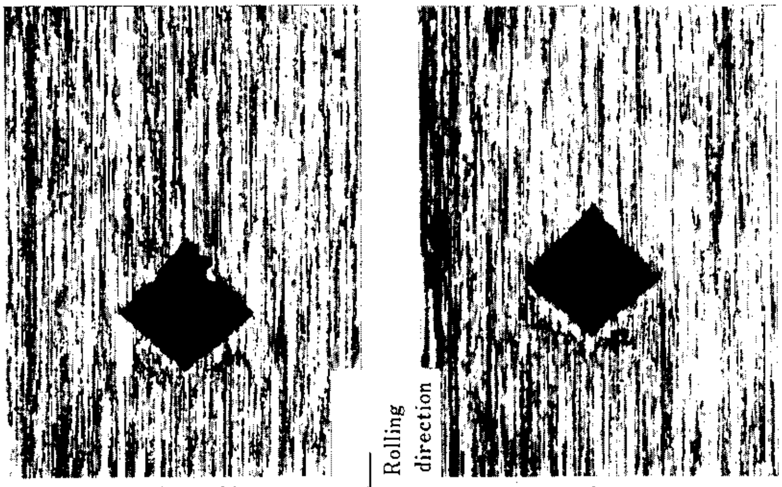
While the quality of rolling oil can be evaluated on the basis of friction coefficient, friction torque and wear scar diameter in both modified Timken tester and modified four-ball tester, the scoring marginal curve based on the velocity and load immediately before scoring most clearly indicates the lubricity difference between rolling oils, as shown in **Fig. 5**. That is, the rolling oil having the higher evaluation in the tandem mill has its scoring marginal curve shifted toward the sides of the higher load and the higher velocity.

It is said that the conditions of mixed lubrication occur in the roll bite of the tandem mill, and that the proportion of boundary and hydrodynamic lubrications varies depending upon the rolling conditions such as rolling load and velocity. Hence, the evaluation result was represented quantitatively by using the area under the scoring marginal curve (shaded in **Fig. 5**) with the ranges of rolling load and velocity set broader in the tester.

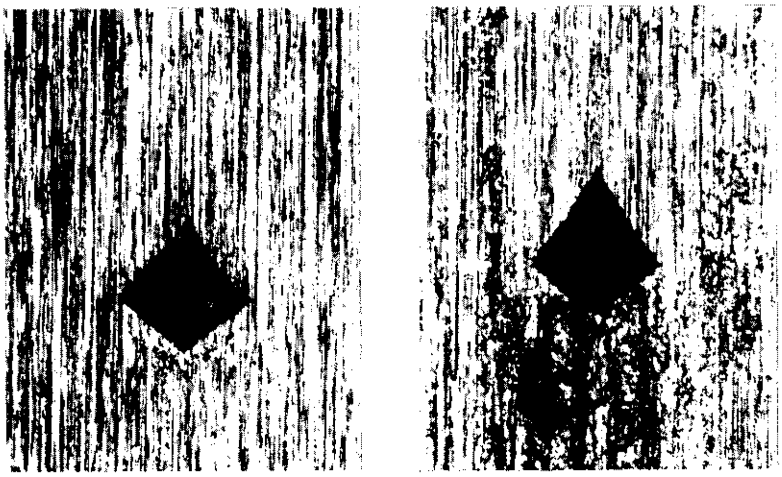
2.2.3 Reproduction of heat streak with modified Timken tester

As for the reproduction of heat streak in the laboratory, it has been reported that scoring like those produced with the tandem roll are formed on the Bowden tester$^{1)}$, an experimental high speed mill$^{8)}$, and a reversible testing mill$^{3)}$.

In the experiment with the modified Timken tester,



A. 200 kg 400 rpm B. 200 kg 500 rpm



C. 200 kg 550 rpm (Stop the first stage) D. 200 kg 550 rpm (Scoring)

Photo 3 Appearance of heat streak by modified Timken tester minute depressions like those found on the roll were created on the test ring, and mild steel sheets were used as test blocks. Under the conditions shown in **Photo** 3-A and B, traces of minute scoring or metallic contacts were recognized around scratches, suggesting severe lubricating conditions. Under condition C, the test block adhered to the test ring as seen in C2, causing complete scoring. The state immediately preceding is C1, in which the metallic contacts with trailing scratches are recognized.

2.2.4 Lubricating condition on testers

It is considered that the mixed lubrication similar to that in the tandem mill occurs in the modified Timken tester and the modified four-ball tester. The changes in the lubricating conditions such as rolling load and velocity are reflected in the frictional torque, which are classified into 4 patterns, (A)-(D), as shown in **Fig. 6**.

(A) Low load region: owing to a low rolling load, hydrodynamic lubrication prevails, giving nearly constant frictional torque.

(B) High load, low velocity region: because of a high rolling load, boundary lubrication occurs, to break oil film temporarily at the contact area and raise the frictional torque momentarily. However, since the velocity is low, less heat is produced, stopping short of overall scoring.

(C) High load, high velocity region: under severe lubricating conditions, scoring occurs instantly.

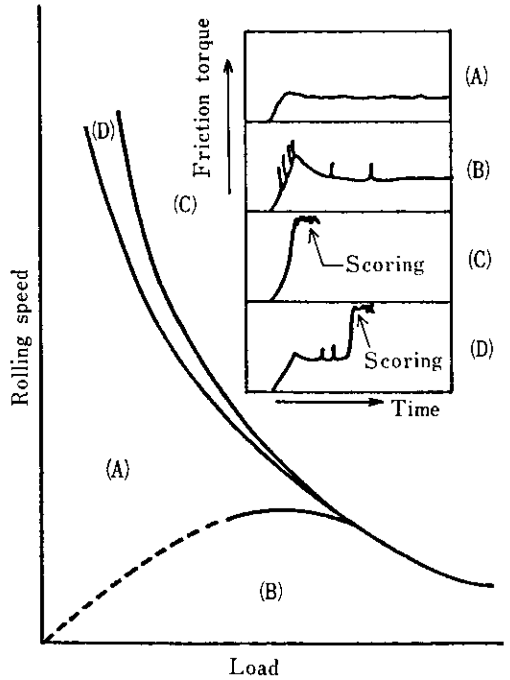


Fig. 6 Pattern of torque according to test conditions

(D) Vicinity of scoring foundary: while scoring rarely occurs in an earlier stage, heat is accumulated, as rolling progresses and causes scoring. In this region, scoring occurs as a probability, taking (A) or (B) pattern even under the same conditions. However, this region is so restricted that the scoring limit appears fairly distinctly.

3 Evaluation of Surface Cleaning Property

3.1 Staining Mechanism on Annealed Strip Surface

Using mill-clean oil for cold rolling provides considerable merit of reducing cost because it eliminates the subsequent cleaning process. To this end, however, it is necessary to maintain the surface cleanliness after annealing.

The principal causes of deterioration of the surface cleanliness are deposition on the strip surface of iron powder produced during rolling and amorphous carbon derived from rolling oil at the time of annealing (different from graphite carbon deposited from steel). The staining mechanism is illustrated in **Fig. 7**. That is, heat produced by deformation and friction in the course of rolling persists in the coil for a few hours at 100°C or higher. The main components of rolling oil such as tallow, ester, mineral oil and fatty acid are oxidized and polymerized to become less volatile, macromolecular substances. Similar reactions seem to occur in an earlier stage of annealing at lower temperatures (200°C or so). In either case, the reactions are accelerated by iron powder which is produced by rolling and works as a catalyst. The polymer substance produced in this way is carbonized by the heat at the time of annealing, as high as 700°C, to adhere to the strip surface. **Fig. 8** shows the result of a laboratory experiment which reveals that heating deteriorates the surface cleaning property. While in the absence of preheating at 130°C, even tallow of inferior surface cleaning property produces little staining, thus showing preheating causes marked staining. **Fig. 8** also shows the effect of antioxidant for suppressing stain. It is evident that the suppression of oxidation and polymerization at lower temperatures effectively contributes to the improvement of surface cleaning property.

3.2 Determination of Residual Carbon on Steel Strip Surface

If stain of steel strip surface with amorphous carbon derived from rolling oil exceeds 7 mg/m^2, the paintability and corrosion resistance are reduced[9]. For this reason, Ford Co., U.S.A., established the surface carbon level as an acceptance criterion. The Scotch tape test often adopted at site is one of the ways to

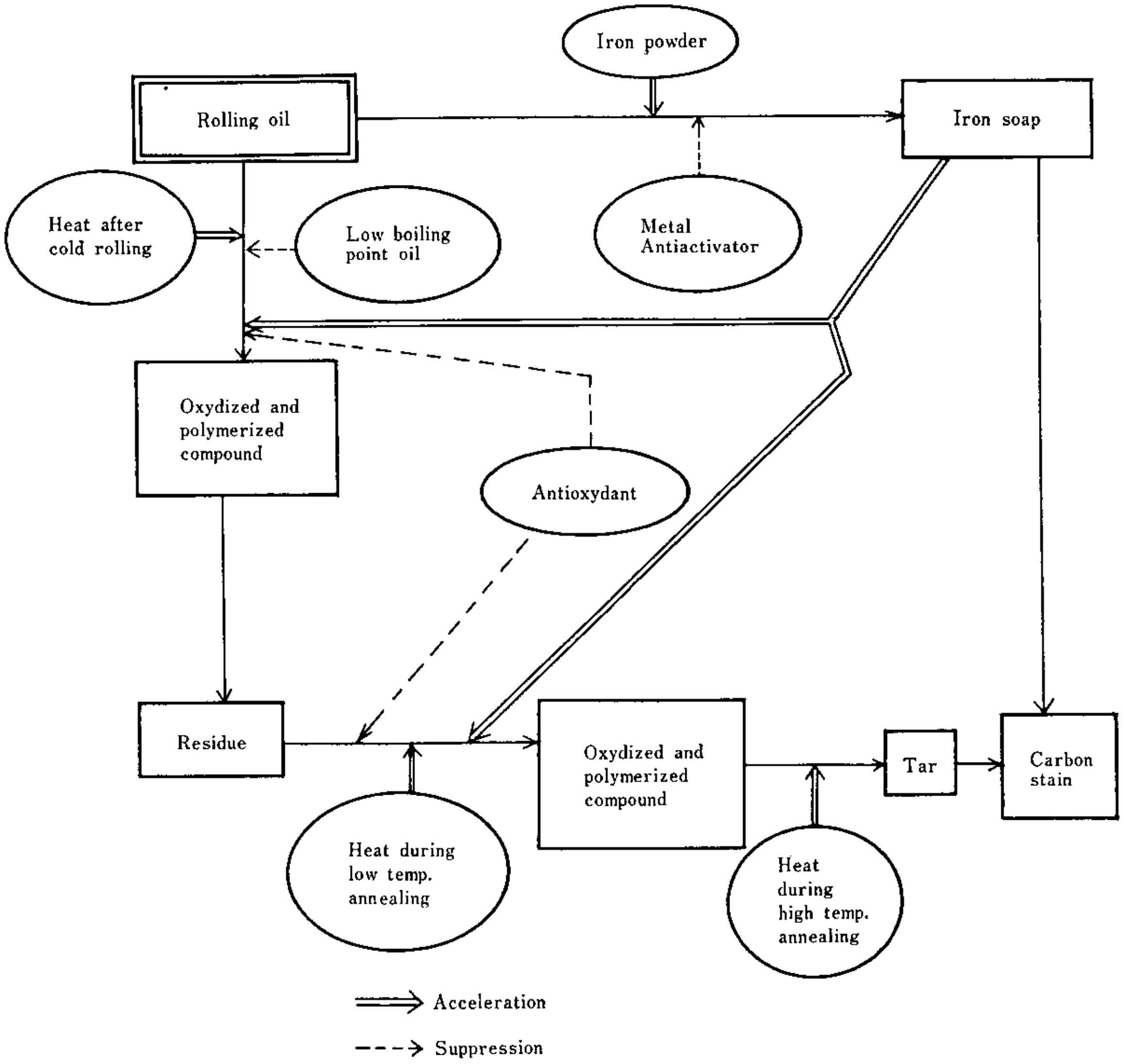


Fig. 7 Effect of factors on the change of rolling oil and carbon stain

find the quantity of carbon and iron powder on the surface of strip. In consideration of these facts, the authors adopted the surface carbon level as an index for the evaluation of surface cleanliness.

For testing, the test pieces (15 cm × 15 cm × 4 faces = 900 cm^2) were soaked in emulsified test oil and had superfluous fluid removed with teflon roll in consideration of squeezing in actual operation. Then, these test pieces were stacked and clamped at 50 kgf. In simulation of residual heat in the rolled coil, the test pieces were preheated for 4 hrs. at 130°C, and then annealed in the practical bell type annealing furnace in HN gas at 685°C for 4 hrs. The surface of annealed test piece was wiped with glass filter paper soaked in hydrochloric acid (1:1), and after having evaporated hydrochloric acid from filter paper in a drying oven (270°C, 1 hr), the carbon amount was determined with a micro-carbon analyzer (manufactured by Kawasaki Steel Instruments Co.). In order to compensate differences in oil wettability depending upon the roughness of test pieces and in the state of atmosphere gas around the test piece in the actual furnace, a control test piece coated with currently available mill-clean oil was prepared as reference and subjected to the same treatment simultaneously with other test pieces in each test. For the purpose of comparing data between different charges, the carbon content in the reference oil was set at 1.0 so as to represent the carbon levels in test oils in terms of ratio.

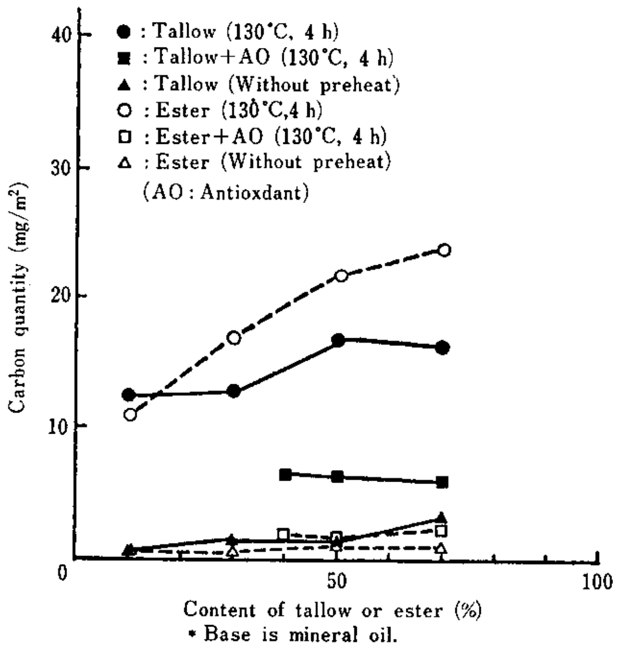


Fig. 8 Influence of preheat and additional antioxydant on carbon quantity on steel strip

4 Improvement of Rolling Oil through Application of Laboratory Evaluation Method

4.1 Improvement of Lubricity of Thin Gage Rolling Oil

4.1.1 Preparation and evaluation of trial manufactured rolling oil

On the basis of evaluation of lubricity with the modified Timken tester, it was attempted to improve the lubricity of tallow-based, thin gage rolling oil used in the 4-tandem mill.

Since the mill-clean rolling oil was used in the 4-tandem mill concurrently with the thin gage rolling oil, it is necessary to select base oil and additive which do not affect the surface cleanliness adversely when mixed with these oils, and the performance of selected lubricant was examined. Purified tallow was used as base oil, and the results of lubricity evaluation with various additives added are shown in **Fig. 9**.

In order to conduct the experiment in the emulsified state, emulsifier was added to each test oil so that the emulsion stability index (E.S.I.) would become 0.7 to 0.8.

As is evident from **Fig. 9**, adding mineral oil reduces the scoring limit at 300 kgf load, while the addition of extreme pressure additive and synthetic ester presents no difference from tallow. In case of polymerized fatty acid, the scoring limit rises in proportion to the amount added, improving the lubricity.

On the basis of these results, the compound system including purified tallow, polymerized fatty acid and synthetic ester was examined in consideration of lubricity and mixing with the mill-clean oil.

As seen in **Fig. 10** the viscosity-increasing effect of polymer and the effect of emulsifier to lubricity were little recognized because the scoring limit of every test oil was fairly superior to that of the conventional rolling oil, F. The effect of polymerized fatty acid was saturated at 6% or so concentration. The emulsification of D1 oil which presented excellent characteristics in the high speed operation is shown in **Fig. 11**. The particle size of D1 oil became smaller than that of the

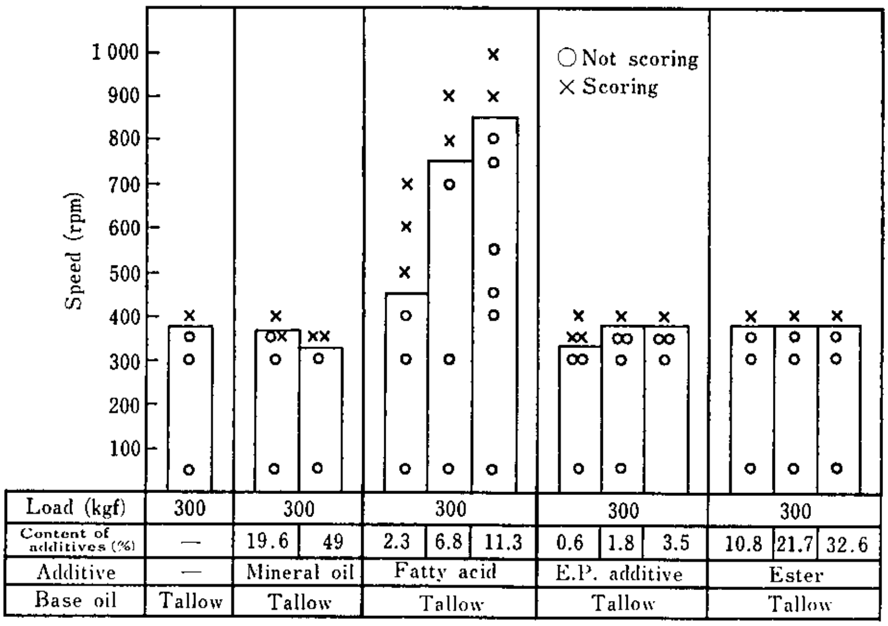
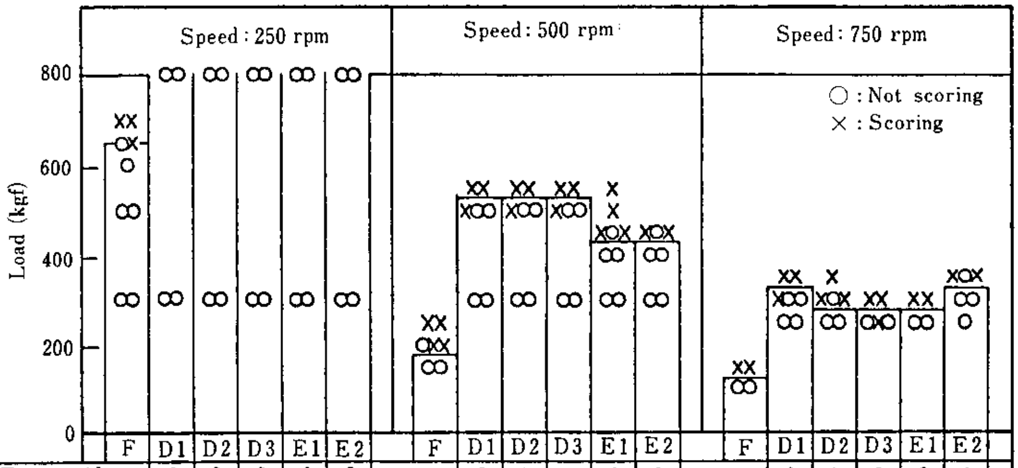


Fig. 9 Influence of various additives on lubricity (modified Timken tester)



Content (%)		F	D1	D2	D3	E1	E2	F	D1	D2	D3	E1	E2	F	D1	D2	D3	E1	E2
Fatty acid			6	8	8	6	6		6	8	8	6	6		6	8	8	6	6
Polymer			—	—	—	2	2		—	—	—	2	2		—	—	—	2	2
Emulsi -fier	(A)Ester		○	—	○	—	○		○	—	○	—	○		○	—	○	—	○
	(B)Ether		—	○	—	○	—		—	○	—	○	—		—	○	—	○	—

○: Added , —:Not added, F:Former oil

Fig. 10 Lublicity of experimental rolling oil (modified Timken tester)

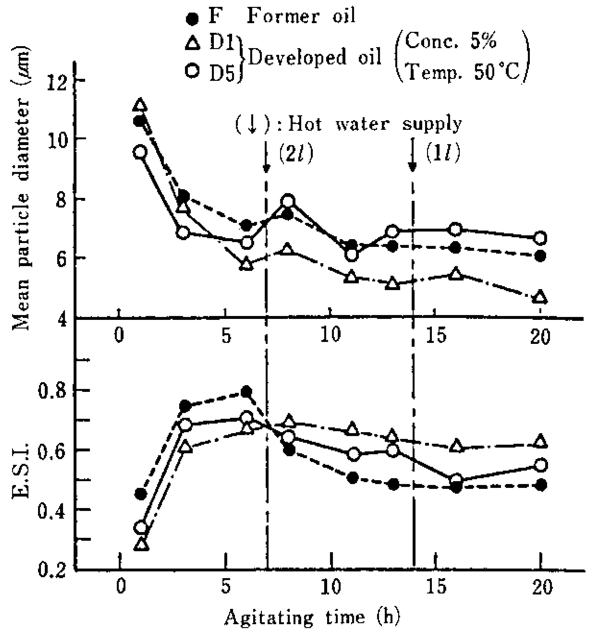


Fig. 11 Effect of agitating time on emulsion properties of former and developed oil (E.S.I.: Emulsion stability index)

conventional oil when stirred for a long time, increasing the E.S.I., resulting in a small amount of oil adhering to steel strip. Therefore, a lowering of lubricity was feared. For this reason, D5 oil with the addition of emulsifier reduced was prepared so as to keep the particle size and E.S.I. equal to those of the conventional oil.

4.1.2 Results of application to actual mill

In the actual application experiment of D5 oil using the 80-inch reversing mill, the lubricity was evaluated by measuring the rolling speed at the time of heat streak occurrence with the third pass set to heavy reduction. The results are shown in **Fig. 12**. With test oil D5, no heat streak occurred at 460 m/min, allowing the rolling at a speed higher than that with the conventional oil. In this case, the friction coefficient of the test oil was nearly equal to that of the conventional oil. On the basis of these results,

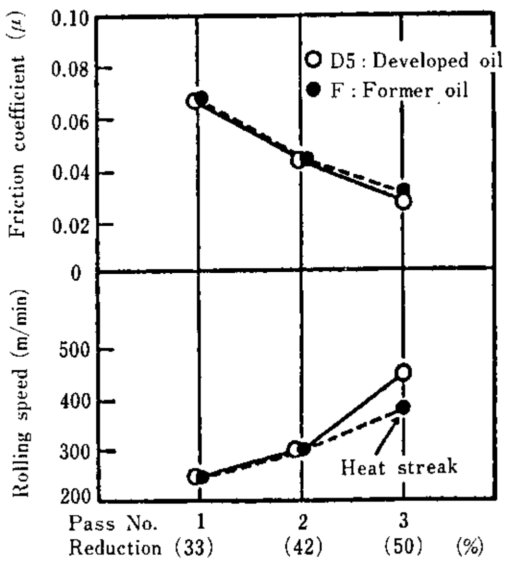


Fig. 12 Lubricity of former and developed oil by the use of 80-inch reversing mill

Table 3 Comparison of rolling speed and concentration of rolling oil between former and developed rolling oil at 4 stands cold tandem mill

Rolling oil \ Strip thickness	Rolling speed (m/min)			Concentration of rolling oil (%)
	0.300 -0.349	0.400 - 0.599	0.600 -0.799	
Former rolling oil (F)	1 022	1 008	923	4 - 5
Developed rolling oil (D5)	1 135	1 125	1 050	4 - 4.5

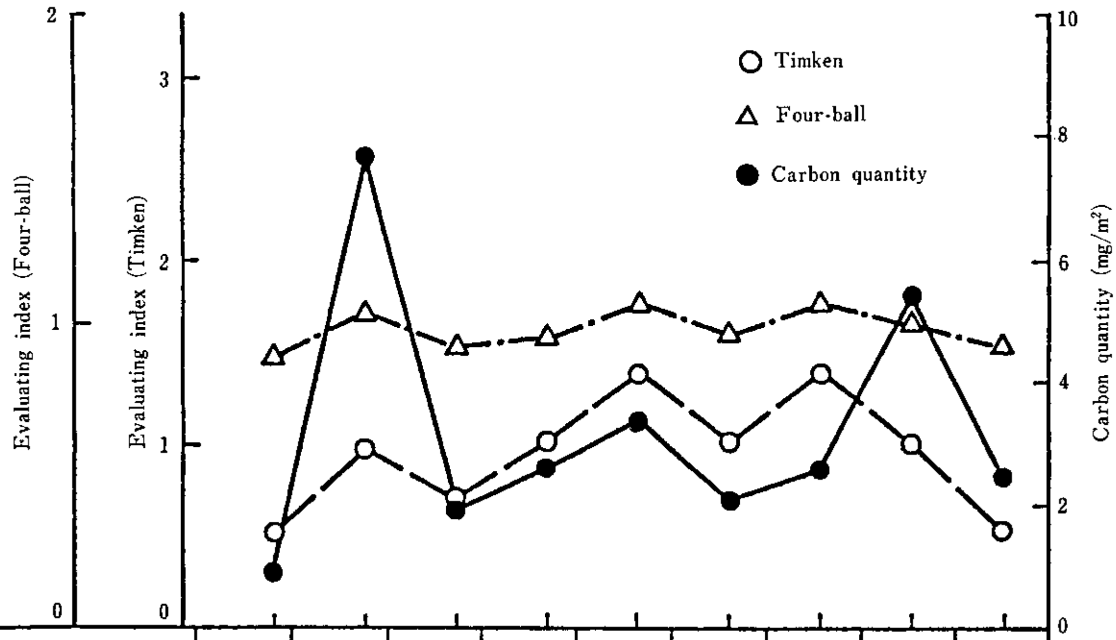
the new rolling oil has been applied to the 4-tandem mill at Chiba Works of Kawasaki Steel, since May 1980, without causing troubles. Consequently, as shown in **Table 3**, the rolling speed was increased by 10–12%, the occurrence of heat streaks was reduced, the frequency of roll changes was decreased by about 20%, the concentration of rolling oil was lowered by improving the lubricity and the energy consumption was reduced by 15%.

4.2 Development of New Mill-Clean Rolling Oil

4.2.1 Preparation and evaluation of test rolling oil

As previously mentioned in the section on the thin-gage rolling oil, the mill-clean rolling oil has been used on the 4-tandem mill at Chiba Works. Since improving the lubricity without deteriorating the surface cleaning property provided considerable merit by allowing finish-rolled strip to attain thinner gage than otherwise with the conventional mill-clean rolling oil, it was attempted to develop new mill-clean rolling oil.

The results of evaluating the characteristics, lubricity and surface cleaning property of trial-manufactured rolling oils are shown in **Fig. 13**. The target characteristics for lubricity were set to those of tallow-based, thin gage rolling oil (F-oil in Par. 4.1), and those for surface cleaning property were of currently available mineral oil-based mill-clean rolling oil S. The development steps are described below.



Symbol of oil		M1	M2	M3	M4	M5	M6	M7	F	S
Composition (%)	Mineral oil	83	—	23	—	—	—	—	Rolling oil based on tallow which is used in practice for thin gage	Rolling oil based on mineral oil which is used in practice for non-cleaning
	Tallow	—	90	—	—	20	—	20		
	Ester	—	—	60	87	69	87	69		
	Fatty acid	—	—	—	4	4	4	4		
	Antioxydant	A	A	A	A	A	A.B.C	A.B.C		

(Evaluating index : Not scoring area of rolling oil/Not scoring area of F oil)

Fig. 13 Test results of trially manufactured rolling oil at laboratory

The mineral oil-based M1 oil with various additives was used as the fundamental formula. When mineral oil was replaced with tallow (M2 oil), the lubricity was improved, though the surface carbon level rose. When the content of low boiling point, volatile ester was increased (M3 oil), the surface cleaning property was improved, while the lubricity was deteriorated. However, the lubricity of M3 oil was better than that of M1 oil. In order to improve the lubricity of M3 oil further, polymerized fatty acid was added to M4 oil, which attained the target lubricity of F oil. When tallow was added to M4 oil up to 20% (M5 oil), the lubricity was further improved. However, the surface carbon level increased in M4 and M5 oil, requiring further improvement of surface cleaning property. For this reason, as stated in Par. 3.1, the number and amount of antioxidants, which effectively suppressed oxydized and polymerization, were increased in M6 and M7 oils. In this way, the surface cleaning property similar to that of S oil was achieved.

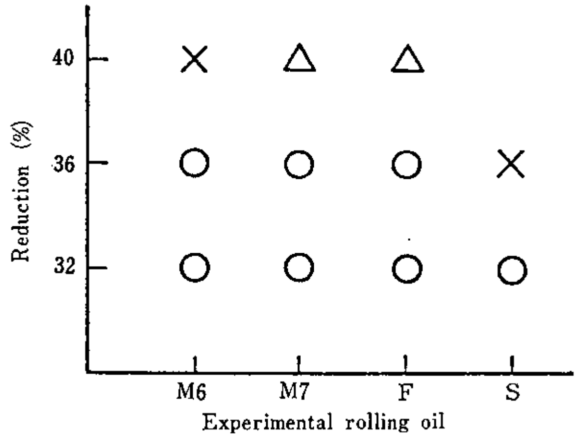
4.2.2 Results of application to actual mill

On the basis of laboratory evaluation, experiments were carried out with M6 and M7 oils, as well as F and S oils which were used as targets for lubricity and surface cleaning property, respectively, on the 80-inch reversing mill. In the experiment, the rolling speed was held constant and the reduction at the third pass was increased to 32, 36 and 40%. The lubricity was evaluated by the reduction ratio at which heat streaks occurred. As mentioned above, the heat streaks first appear on the under-side of strip where the lubricational conditions are inferior. Hence, if the heat streaks appear only on the under-side of the strip under the same reduction, the lubricating conditions may be regarded as better than in the case where they occur on both sides.

As shown in **Fig. 14**, the lubricity of M6 oil was slightly inferior to that of F oil, but the lubricity of M7 oil was nearly equal to the latter. As shown in **Fig. 15**, the temperature of rolled strip goes higher as the lubricity index as evaluated by heat streak occurrence becomes lower. This is not so definite in the case of the friction coefficient.

The surface cleanliness was evaluated not only by the surface carbon level but also by L value which was determined by peeling adherent on the strip surface with adhesive tape and by measuring the stain density of the tape with a color differencemeter. As seen in **Fig. 16**, M7 oil including tallow was inferior to M6 oil, but nearly equal to S oil, in terms of the surface carbon level and the L value.

As mentioned above, it was possible to bring the lubricity and strip surface cleaning property of trial manufactured mill-clean rolling oils as evaluated on the laboratory scale to a level required for the actual rolling mill.



Level of heat streak		
○	△	×
Heat streaks do not occur	Heat streaks occur on back side of strip	Heat streaks occur on both sides of strip

Fig. 14 Lubricity of experimental rolling oil by the use of 80-inch reversing mill (Level of heat streak)

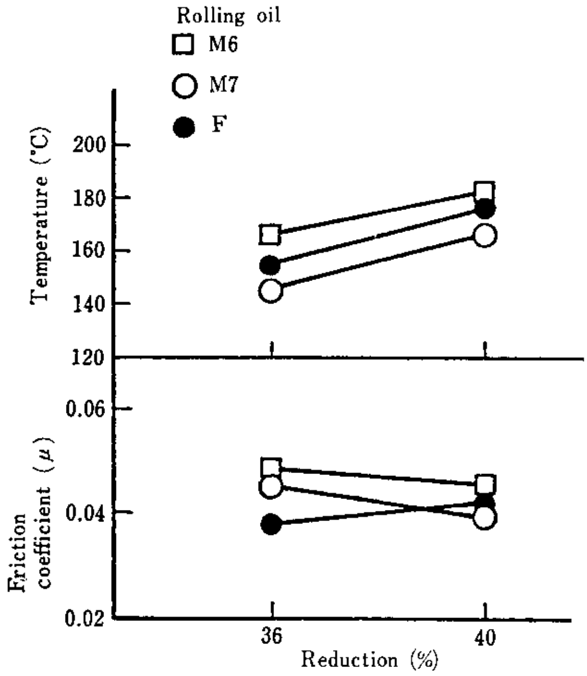


Fig. 15 Effect of reduction and rolling oil on temperature and friction coefficient by the use of 80-inch reversing mill

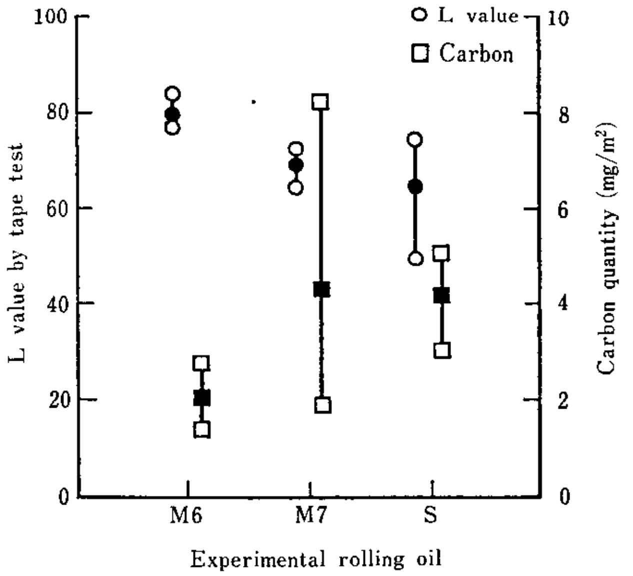


Fig. 16 Effect of rolling oil on surface cleanliness after annealing (80-inch reversing mill)

5 Conclusion

Methods for laboratory evaluation of lubricity in view of heat streak resistance and of the strip surface cleaning property in terms of strip surface carbon level in cold-rolling oil were established, and it was confirmed that the results of evaluation coincide with those obtained through application in the actual rolling mill. Moreover, the lubricity of thin gage rolling oil was improved, and new mill-clean rolling oils were developed through the application of these evaluating methods.

The problem in respect of lubricity involves not only heat streak resistance but also friction coefficient, and it is expected that the development of new cold strip mills will require severer lubricating conditions. On the other hand, the strip surface cleaning property involves not only the overall stain of strip surface, but also localized stains such as edge carbon.

In order to cope with these problems, integrated countermeasures must be taken, including the improvement of the oil feeding method and processes before and after rolling, in addition to the improvement of rolling oil.

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