

Akira Azushima

Tribology in Sheet Rolling Technology

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Preface

In Japan, the steel making industries have developed rapidly in the 1960s and 1970s. The production of steel has exceeded over 100 million tons, and the rolling speed in cold sheet rolling has exceeded over 2000 m/min. Then, the flow stress and the coefficient of friction in cold steel sheet rolling with higher rolling speed were unknown parameters, so that the parameters had intensely investigated in Japanese steel making industries. In 1970s, the joint researches on the flow stress and the coefficient of friction in cold sheet rolling with higher rolling speed were carried out in ISIJ. From these joint researches, the stress-strain curve involving the strain rate and the temperature for higher speed rolling was developed, and the experimental relationship between coefficient of friction and rolling speed over 2000 m/min was derived. In 1980s, the friction pick up in cold sheet rolling had intensely investigated in Japanese steel making industries. The evaluation testing of the friction pick up using tribo-simulators was carried out, so that it could be understood that an interface temperature among the tribological parameters was most important to evaluate the antiseizure property. Then, the microscopic analysis of the interface phenomena between roll and workpiece has been carried out from the viewpoint of the control of surface properties in ISIJ.

In hot sheet rolling, the rolling oil has been used around 1970 in Japan, and many researches on tribological behavior in hot sheet rolling were carried out in steel making industries. In these researches, the effects of rolling oil on rolling load reduction and roll wear reduction were examined and the lubrication mechanism in hot sheet rolling was investigated. In 1990s, researches on hot sheet rolling with higher reduction were carried out, and in the Japanese national project on PRO-TEUS from 2002 to 2006, the hot rolling technology with higher rolling reduction was developed in order to manufacture the ultra-fine-grain steel.

On the other hand, from 1985 to 1987, a joint research on estimation system of surface brightness in cold sheet rolling of stainless steel was carried out in ISIJ, and from 1989 to 2003, a joint research on mechanism of friction pick up in cold sheet rolling was carried out in ISIJ.

Under such an environment, the author began the study of flow stress of steels for high speed cold rolling in Master's course of Graduate School of the University of Tokyo, and in the Doctor's course, the experimental study of the tribological behavior in cold steel sheet rolling with higher rolling speed and the analytical study of the inlet oil film thickness between roll and workpiece have been continued. Then, the sliding-rolling-type tribo-simulator was newly developed in order to evaluate the tribological behavior in cold sheet rolling. In Yokohama National University, the author has studied on the tribology in cold sheet rolling and hot sheet rolling using the sliding-rolling-type tribo-simulator for 30 years. The author became leaders of the joint researches in ISIJ and the tribology division of the national project.

This book has been written based on research results published by the authors on the tribology in cold sheet rolling and hot sheet rolling. In this book, before the main chapters, the fundamental of tribology and the characteristics of tribology in metal forming have been written. The chapters of this book are as follows: Chapter 1 is Fundamental of Tribology, Chap. 2 is Characteristics of Tribology in Metal forming, Chap. 3 is Fundamental of Rolling, Chap. 4 is Tribology in Cold Sheet Rolling, and Chap. 5 is Tribology in Hot Sheet Rolling.

I would like to express my deep thanks to many colleagues in joint researches, many coworker in the University of Tokyo and Yokohama National University, and Dr. Y. Tanno, Dr. S. Inagaki, Mr. K. Uda, and Mr. D. Sugawara, my coworker in Yokohama National University, helped in creating figures and tables. Lastly, I would like to thank the editors of Springer and my wife.

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April 2015

Akira Azushima

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Chapter 1

Fundamentals of Tribology

1.1 Friction

1.1.1 Friction in History

It is well known that the friction at the interface between two sliding bodies under applied load exists from old days. In a painting of the transporting of an Egyptian colossus from a grotto at El Bersheh (1880 BC), in order to reduce the frictional force, a standing man pouring lubricant from a pot on the ground at the front of the sledge can be seen. Leonardo da Vinci (1452–1519) showed the concept of frictional force in his diary. He wrote that the friction was proportional to the normal load, and the area of the surfaces in contact had little effect on the friction under dry friction (solid friction). As for scientific works, Amontons [1] and Coulomb [2] conducted experiments and they proposed the friction laws under dry friction as follows:

1. The frictional force is proportional to the normal load.
2. The coefficient of friction is independent of the apparent contact area.

The equation derived by the first law of friction is expressed using Fig. 1.1, where P is the normal load and F is the frictional force (tangential force).

The first law is expressed as

$$F = \mu P \quad (1.1)$$

where μ is the coefficient of friction. This equation is generally referred to as the Amontons and Coulomb's law. Coulomb suggested that the frictional force is caused by the mechanical interlocking of asperities of two solids [2]. He suggested from his experimental results that surface roughness played an important role in frictional force compared with the adhesion of the contact area. However, later, the relationship between the coefficient of friction and surface roughness under dry condition

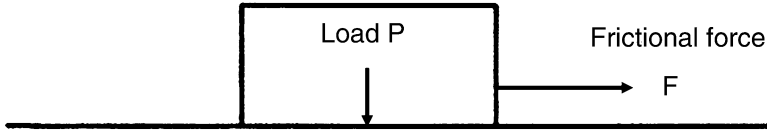


Fig. 1.1 Schematic representation of normal load P and frictional force F

was examined by Rabinowicz [3]. He reported that the coefficient of friction increased with decreasing surface roughness in the region of smaller surface roughness. It is shown that the phenomena of coefficient of friction did not obey the friction law proposed by Coulomb.

Hardy [4] suggested that the frictional force was due to the adhesion to a molecular-kinetic bond rupture process. Concerning with the adhesion, before Coulomb's paper, Desaguliers [5] proposed the hypothesis about the adhesion behavior between surfaces at the region of contact, based on the experimental results of his earlier work on the adhesion of lead. However, the second law of friction could not be explained by the adhesion model until the new contact model between surfaces with surface roughness (Holm's model) was proposed by Holm [6].

1.1.2 Contact Model Between Surfaces with Surface Roughness

Figure 1.2 shows the schematic representation of the contact model between surfaces with surface roughness. In a part of the contact region, tops of asperities of two surfaces are in contact, and others are far apart, where $A_{\square}$ is the apparent contact area and A_r is the real contact area. This real contact area was proposed by Holm from the experimental results obtained using an electrical resistance method. He gave the real contact area A_r as follows:

$$A_r = \frac{P}{p_m} \quad (1.2)$$

where P is the normal load and p_m is the plastic flow stress, that is, it is nearly equal to $3Y$. Y is the yield stress in uni-axis.

Moreover, Bowden and Tabor [7] used the contact model between surfaces with surface roughness in relative motion V as shown in Fig. 1.3 in order to explain the second model of friction, where V is the relative speed, p is the normal stress on the real contact area, and τ is the tangential stress (frictional stress).

In this case, the real contact area A_r is given by

$$A_r = \frac{P}{p} \quad (1.3)$$

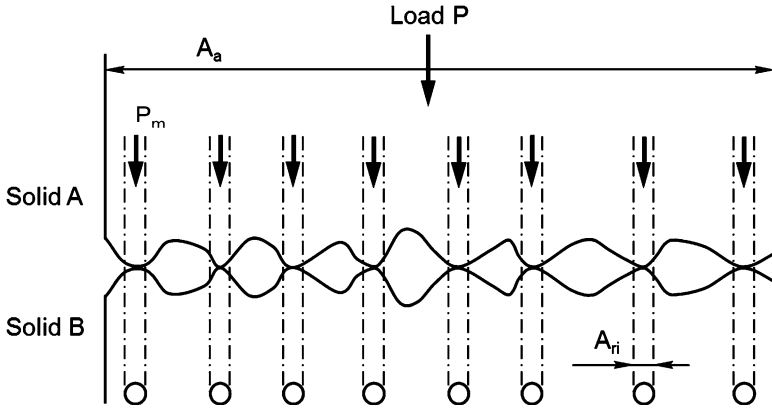


Fig. 1.2 Schematic representation of the contact model between surfaces with surface roughness

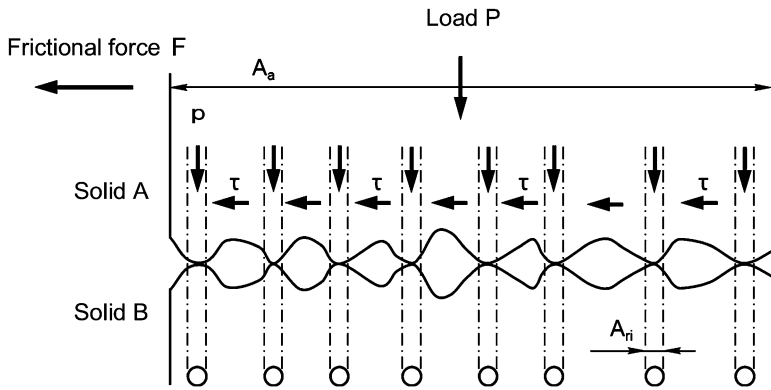


Fig. 1.3 Schematic representation of the contact model between surfaces with surface roughness in relative motion

As the frictional force F is given by

$$F = \tau A_r, \quad (1.4)$$

the coefficient of friction under dry friction is derived by Eqns. (1.3) and (1.4) as follows:

$$\mu = \frac{F}{P} = \frac{\tau A_r}{p A_r} = \frac{\tau}{p} \quad (1.5)$$

From Eqn. (1.5), it can be understood that the coefficient of friction is independent of the apparent contact area.

Rabinowicz [8] measured the coefficient of friction between two bodies with the mechanically clean surface in relative motion at a constant load for 20 kinds of

metals. In the measured values of the coefficient of friction, there are 80 % of the values from 0.4 to 0.6. It can be estimated that the coefficient of friction of the mechanical elements under dry friction will be 0.5 ± 0.1 .

On the other hand, concerning with the coefficient of friction between two bodies with physically clean surface, Bowden and Hughes [9] had a high coefficient of friction of 4.8 in the experiments between the coppers with physically clean surface under vacuum. Later, many researchers had the higher values between the coppers with physically clean surface.

1.1.3 Junction Growth of Real Contact Area

In the contact model between surfaces with relative motion of Fig. 1.3, the junction of the asperities deforms plastically as shown in Fig. 1.4, so that the normal stress p and the tangential stress τ must satisfy the yield criterion.

Tabor [10] derived the real contact area A_r . He gave the yield criterion as follows:

$$p^2 + \alpha^2 \tau^2 = p_m^2 \quad (1.6)$$

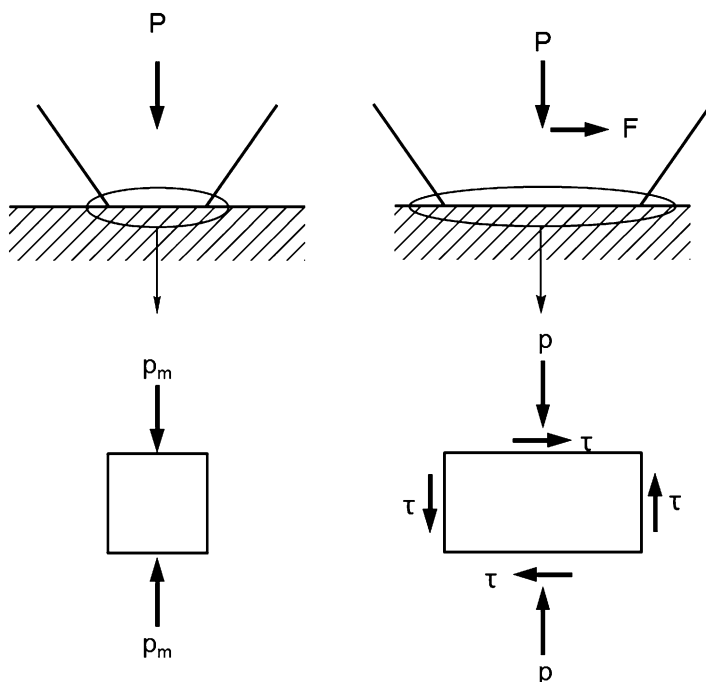


Fig. 1.4 Schematic representation of a junction

where α is a constant. When Eqns. (1.3) and (1.4) are substituted for Eqn. (1.6), the next equation is given by

$$\left(\frac{P}{A_r}\right)^2 + \left(\frac{F}{A_r}\right)^2 = p_m^2 \quad (1.7)$$

When $F = 0$ in Fig. 1.7, it is defined that the real contact area A_r is A_{r0} . Equation (1.2) is expressed as follows:

$$A_{r0} = \frac{P}{p_m} \quad (1.2a)$$

When Eqn. (1.2a) is substituted for Eqn. (1.7), the real contact area A_r is defined as follows:

$$A_r = A_{r0} \sqrt{1 + \alpha \left(\frac{F}{P}\right)^2} = A_{r0} \sqrt{1 + \alpha \mu^2} \quad (1.8)$$

The real contact area increases with increasing coefficient of friction between surfaces in relative motion. The tangential stress is defined as follows:

$$\tau = k\tau_m \quad (1.9)$$

where τ_m is the yield shear stress and $0 \leq \tau \leq \tau_m$. The coefficient of friction is expressed as follows:

$$\mu = \frac{F}{P} = \frac{\tau A_r}{p A_r} = \frac{\tau}{p} = \frac{1}{\sqrt{\alpha \left\{ (\tau_m/\tau)^2 - 1 \right\}}} = \frac{k}{\sqrt{\alpha(1 - k^2)}} \quad (1.10)$$

From Eqn. (1.10), when k equals to 0, the coefficient of friction becomes 0, and when k equals to 1, the coefficient of friction becomes ∞ .

Figure 1.5 shows the relationship between the coefficient of friction and k changing α value calculated by Muraki [11]. The values of the coefficient of friction become higher over 0.5 considering the junction growth of the contact area.

1.1.4 Effect of Surface Film

From Eqn. (1.10) and Fig. 1.5, it can be understood that the coefficient of friction under dry friction becomes higher. In order to reduce the coefficient of friction under dry friction, the soft layers on the solid are widely used as shown in Fig. 1.6.

Fig. 1.5 Relationship between the coefficient of friction and k changing α [11]

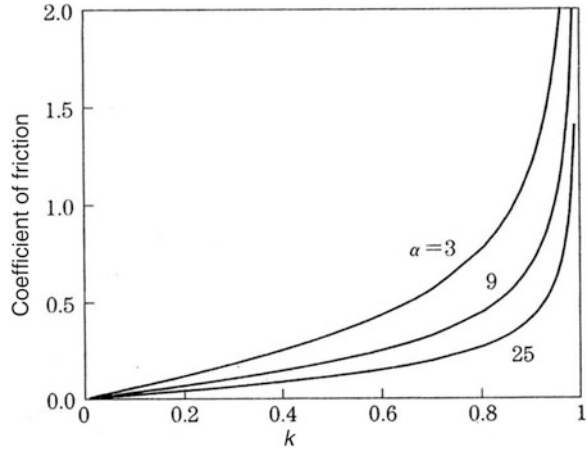
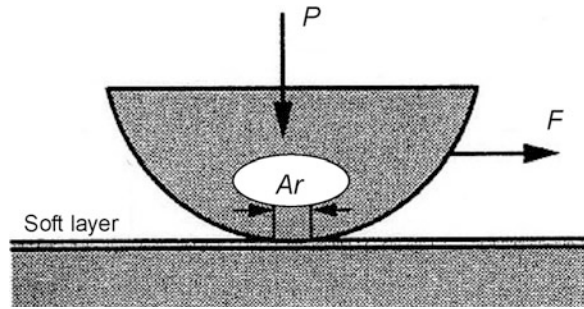


Fig. 1.6 Schematic representation of the contact model between surfaces with soft layer [11]



When the yield shear stress of surface layer τ_f is smaller than the yield shear stress of substrate metal τ_m , that is, k is small, Eqn. (1.10) is expressed as follows:

$$\mu \cong \frac{k}{\sqrt{\alpha}} = \frac{k\tau_m}{\sqrt{\alpha\tau_m^2}} = \frac{\tau_f}{p_m} \quad (1.11)$$

From Eqn. (1.11), it is understood that the yield shear stress of the surface layer is smaller and the yield flow stress of the substrate metal is larger in order to reduce the coefficient of friction under dry friction. For example, gold and silver metals are used widely as surface layer.

1.1.5 Plowing Term in Friction

The plowing term in friction must be considered, when the hard asperity is indented against the soft metal surface as shown in Fig. 1.7.

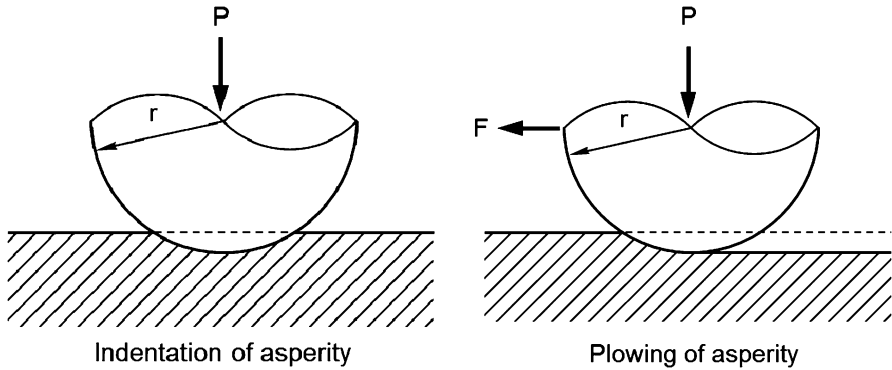


Fig. 1.7 Plowing term of friction for asperity sliding on soft metal

The frictional force F is expressed as follows:

$$F = F_a + F_p \quad (1.12)$$

where F_a is the frictional force of the adhesion term and F_p is the frictional force of the plowing term. F_a and F_p are defined, respectively, as follows:

$$F_a = \tau A_r, \quad F_p = A' p' \quad (1.13)$$

where A' is the grooving area and p' is the yield flow stress of the soft metal.

Generally, the frictional force of the plowing term in the mechanical elements can be neglected compared to that of the adhesion term.

1.2 Lubrication

1.2.1 Lubrication in History

“Lubricate” means to apply some oily or greasy substance to a machine, parts, etc., in order to diminish friction. Judging from the meaning, it is understood that lubricants have been used from old days. However, the lubricant behavior at the interface between two bodies has not been investigated until the end of the nineteenth century.

Tower [12] carried out experiments to determine the friction of the journal bearing. Then, he confirmed the existence of the thick film of lubricant between the bearing and axis and observed the pressure generated within the lubricant. Based on Tower’s results, Reynolds [13] applied the principles of fluid mechanics to the journal bearing and proposed the famous theory of hydrodynamic lubrication. The Reynolds equation is widely used at the present time.

On the other hand, Hardy [14] proposed the term boundary lubrication in the regime of thin film lubrication. Stribeck [15] carried out experiments on journal bearings and measured the coefficient of friction changing many tribological parameters. Later, his many experimental data were summarized as the famous Stribeck curve. The lubrication regime can be classified by the Stribeck curve.

1.2.2 Stribeck Curve

The Stribeck curve is shown in Fig. 1.8. In Fig. 1.8, the coefficients of friction are plotted as a function of the parameter $\eta V/P$, where η is the viscosity of lubricant, V is the velocity of lubricant, and P is the normal load.

In region I, the coefficient of friction is lower and increases with increasing parameter $\eta V/P$. In region III, the coefficient of friction is higher and maintains a constant value. In region II, the coefficient of friction decreases abruptly with increasing parameter. In region I, the thickness of the lubricant between two solids is larger than the surface roughness R , ($h \gg R$), and the lubrication regime is the hydrodynamic lubrication. In region II, the thickness is nearly equal to the surface roughness, ($h \approx R$), and the lubrication regime is the mixed lubrication. In region III, the thickness is nearly equal to 0, ($h \rightarrow 0$), and the lubrication regime is the boundary lubrication.

Recently, in order to classify the lubrication regime quantitatively, the λ value is introduced and it is given as follows:

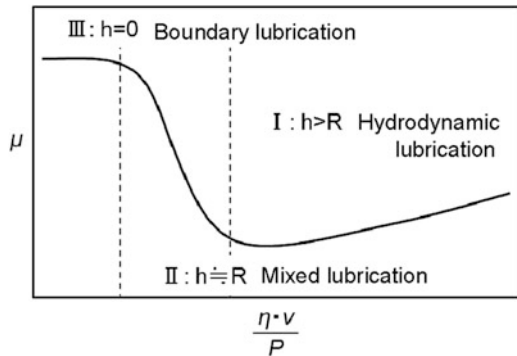
$$\lambda = \frac{\sigma}{h} \quad (1.14)$$

where σ is the combined surface roughness and is defined as

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} \quad (1.15)$$

where σ_1 is the surface roughness of solid 1 and σ_2 is the surface roughness of solid 2.

Fig. 1.8 Stribeck curve



The lubrication regime is classified by the λ value as follows:

- I : $\lambda > 4$ Hydrodynamic lubrication
 II : $4 > \lambda > 1$ Mixed lubrication
 III : $1 > \lambda$ Boundary lubrication

1.2.3 Hydrodynamic Lubrication

1.2.3.1 Reynolds Equation

Figure 1.9 shows the schematic representation of a three-dimensional lubricant flow channel. The upper surface moves at velocities of U_2 , V , and 0 in directions of x , y , and z . The lower surface moves at velocities of U_1 , 0, and 0 in directions of x , y , and z . In order to derive the Reynolds equation, the following assumptions are given:

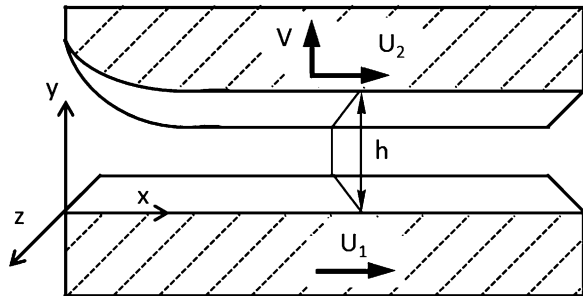
1. The fluid is Newtonian.
2. The fluid is laminar.
3. The fluid is incompressible.
4. The fluid inertia can be neglected.
5. The fluid weight can be neglected.
6. The fluid pressure is constant across the thickness of the fluid film.
7. The fluid adheres to the surfaces.

If the flow velocities in (x, y, z) directions at a point in the fluid are given by (u, v, w) , the Navier-Stokes equations become

$$\eta \frac{\partial^2 u}{\partial y^2} = \frac{\partial p}{\partial x} \quad (1.16)$$

$$\eta \frac{\partial^2 v}{\partial y^2} = \frac{\partial p}{\partial y} = 0 \quad (1.17)$$

Fig. 1.9 Schematic representation of a three-dimensional lubricant flow channel



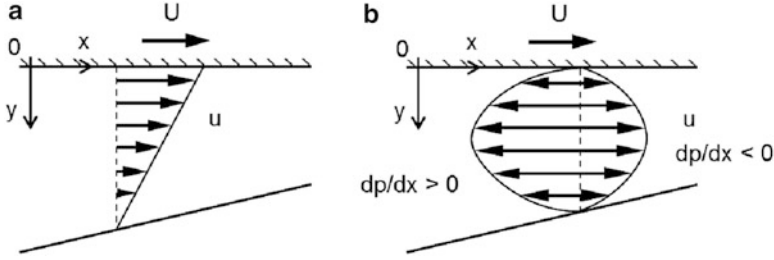


Fig. 1.10 Flow component of velocity. (a) Couette flow and (b) Poiseuille flow

$$\eta \frac{\partial^2 w}{\partial y^2} = \frac{\partial p}{\partial z} \quad (1.18)$$

where p is the pressure in the fluid. From the boundary conditions of $u = U_1$, $v = 0$, $w = 0$ at $y = 0$ and $u = U_2$, $v = V$, $w = 0$ at $y = h$, u , v , and w are given as follows:

$$u = \left\{ U_1 + (U_1 - U_2) \frac{h - y}{h} \right\} + \left\{ -\frac{y(h - y)}{2\eta} \frac{\partial p}{\partial x} \right\} \quad (1.19)$$

$$v = V \frac{y}{h} \quad (1.20)$$

$$w = \left\{ -\frac{y(h - y)}{2\eta} \frac{\partial p}{\partial z} \right\} \quad (1.21)$$

Equation (1.20) expresses the Couette flow and Eqn. (1.21) expresses the Poiseuille flow as shown in Fig. 1.10.

Equations (1.19), (1.20), and (1.21) are substituted into the continuity equation expressed as the next equation:

$$\int_0^h \frac{\partial u}{\partial x} dy + \int_0^h \frac{\partial v}{\partial y} dy + \int_0^h \frac{\partial w}{\partial z} dy = 0 \quad (1.22)$$

The Reynolds equation can be derived as follows:

$$\frac{\partial}{\partial x} \left(h^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left(h^3 \frac{\partial p}{\partial z} \right) = 6\eta(U_1 - U_2) \frac{\partial h}{\partial x} + 12\eta V \quad (1.23)$$

In Eqn. (1.23), the right-hand side contains the two terms for the pressure generation. The first term is the wedge term and the second term is the squeeze term as shown in Fig. 1.11a, b.

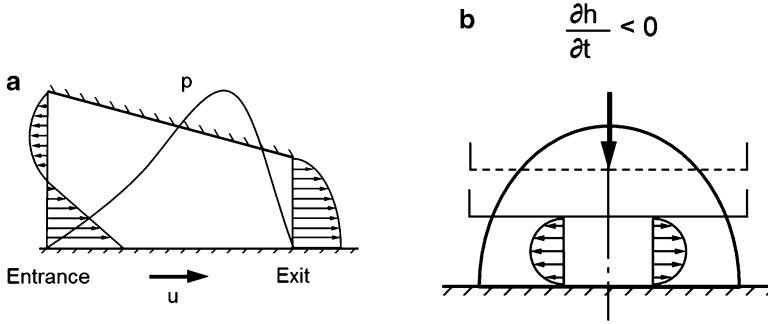


Fig. 1.11 Physical significance of right-hand side of Eqn. 1.23. (a) Wedge term (b) Squeeze term

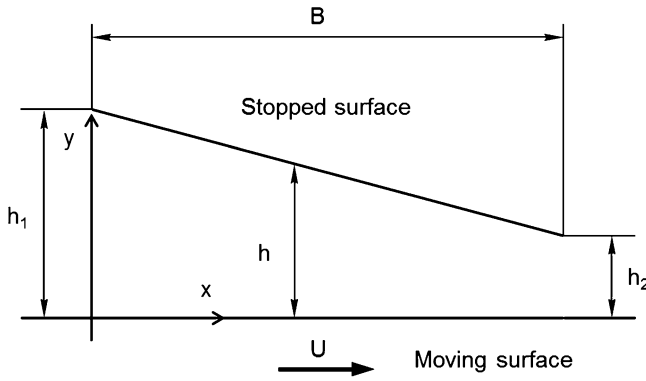


Fig. 1.12 Schematic representation of a plane bearing

1.2.3.2 Plane Bearing

In order to understand the pressure distribution of bearings, the plane bearing as shown in Fig. 1.12 may be considered. It is assumed that the plane bearing is infinitely long. In Fig. 1.12, h_1 is the inlet oil film thickness, h_2 is the exit oil film thickness, and B is the width.

The Reynolds equation in the infinitely long approximation at (x, y) coordinate axis is expressed as follows:

$$\frac{d}{dx} \left(h^3 \frac{dp}{dx} \right) = 6\eta U \frac{dh}{dx} \quad (1.24)$$

The oil film thickness h is given by

$$h = h_1 - \frac{x}{B}(h_1 - h_2) = h_2(m - mX + X) \quad (1.25)$$

where $m = \frac{h_1}{h_2}$ and $X = \frac{x}{B}$ ($0 \leq X \leq 1$).

Now, the Reynolds equation is integrated with respect to x across the channel. The result is as follows:

$$\frac{dp}{dx} = 6\eta U \left(\frac{1}{h^2} - \frac{h_m}{h^3} \right) \quad (1.26)$$

where $h = h_m$ when $\frac{dp}{dx} = 0$.

Next, substituting Eqn. (1.25) into Eqn. (1.26), the Reynolds equation (1.26) is integrated with respect to X across the channel at boundary conditions of $p = 0$ at $X = 0$ and $p = 0$ at $X = 1$. The result is as follows:

$$p = \frac{\eta UB}{h_2^2} \frac{6(m-1)(1-X)X}{(1+m)\{m+(1-m)X\}^2} \quad (1.27)$$

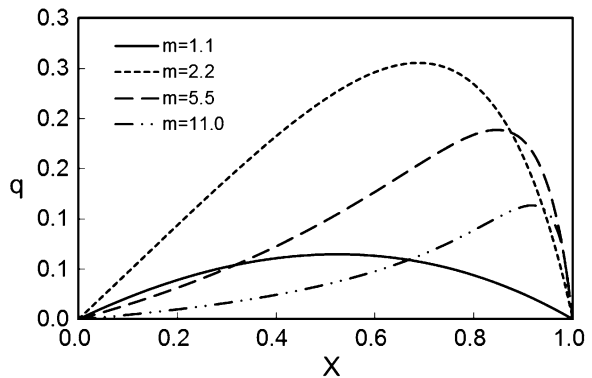
Since the pressure coefficient q is given by $q = \frac{6(m-1)(1-X)X}{(1+m)\{m+(1-m)X\}^2}$, the relationship between pressure coefficient q and nondimensional X changing the parameter m is shown in Fig. 1.13. From Fig. 1.13, the pressure becomes maximum when $m = 2.2$ and the position at the maximum of pressure moves in the exit side with increasing m value.

The load per unit width P_1 is given by the next equation:

$$\begin{aligned} P_1 &= B \int_0^1 p dX \\ &= \frac{\eta UB^2}{h_2^2} \frac{6}{(m-1)^2} \left\{ \ln m - \frac{2(m-1)}{m+1} \right\} \end{aligned} \quad (1.28)$$

It is found that the load increases with increasing viscosity and velocity.

Fig. 1.13 Relationship between the pressure coefficient and nondimensional X



Next, the frictional force per unit width F_0 in the moving surface is given by

$$\begin{aligned}
 F_0 &= B \int_0^1 [\tau]_{y=0} dX = B\eta \int_0^1 \left[\frac{\partial u}{\partial y} \right]_{y=0} dX \\
 &= -\frac{B\eta U}{h_2} \frac{1}{(m-1)} \left\{ 4 \ln m - \frac{6(m-1)}{m+1} \right\}
 \end{aligned} \quad (1.29)$$

The coefficient of friction in the moving surface can be given using Eqns. (1.27) and (1.29) as follows:

$$\mu = \frac{|F_0|}{P_1} = \frac{(m-1)h_2}{6B} = \frac{\left\{ 4 \ln m - \frac{6(m-1)}{m+1} \right\}}{\left\{ \ln m - \frac{2(m-1)}{m+1} \right\}} \quad (1.30)$$

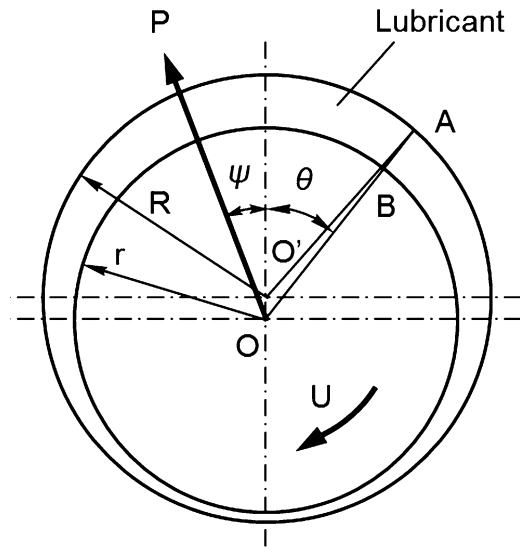
1.2.3.3 Journal Bearing

Figure 1.14 shows the schematic representation of a journal bearing with cross section. In Fig. 1.14, R is the radius of the bearing, r is the radius of the axis, $c = R - r$ is the radius gap, e (OO') is the eccentricity, and $\varepsilon = e/c$ is the eccentricity ratio.

The oil film thickness is determined from the geometries as follows:

$$h = c(1 + \varepsilon \cos \theta) \quad (1.31)$$

Fig. 1.14 Schematic representation of a journal bearing



The Reynolds equation in this case is expressed as follows:

$$\frac{1}{r^2} \frac{\partial}{\partial \theta} \left(h^3 \frac{\partial p}{\partial \theta} \right) + h^3 \frac{\partial^2 p}{\partial z^2} = \frac{6\eta U}{r} \frac{dp}{d\theta} \quad (1.32)$$

Now, since it is assumed that the journal bearing is infinitely long, the Reynolds equation becomes as follows:

$$\frac{1}{r^2} \frac{\partial}{\partial \theta} \left(h^3 \frac{\partial p}{\partial \theta} \right) = \frac{6\eta U}{r} \frac{dp}{d\theta} \quad (1.33)$$

When the boundary conditions are $p=0$ at $\theta=0$ and $p=0$ at $\theta=2\pi$, the Reynolds equation (1.33) is integrated twice with respect to X across the channel. The result is as follows:

$$p = \frac{6\eta UB}{c^2} \frac{\varepsilon(2 + \varepsilon \cos \theta) \sin \theta}{(2 + \varepsilon^2)(1 + \varepsilon \cos \theta)} \quad (1.34)$$

Since the pressure coefficient q is given by $q = \frac{\varepsilon(2 + \varepsilon \cos \theta) \sin \theta}{(2 + \varepsilon^2)(1 + \varepsilon \cos \theta)}$, the relationship between pressure coefficient q and θ changing the parameter ε is shown in Fig. 1.15.

1.2.3.4 Rolling Bearing

Figure 1.16 shows the schematic representation of a needle bearing with cross section. In Fig. 1.16, R_1 is the radius of the inner ring, R_2 is the radius of the outer ring, and r is the radius of the rolling element. Figure 1.17 shows the schematic representation of the lubricant flow channel of a needle bearing. In Figure 1.17, U_1^* is the rolling velocity of the rolling element, U_2^* is the velocity of the plane, h_0 is

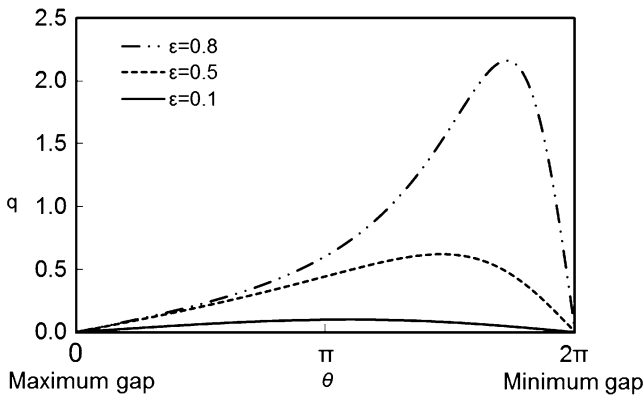


Fig. 1.15 Relationship between pressure coefficient q and θ

Fig. 1.16 Schematic representation of a needle bearing

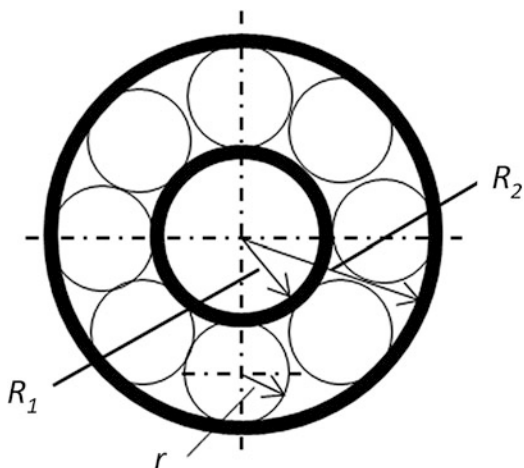
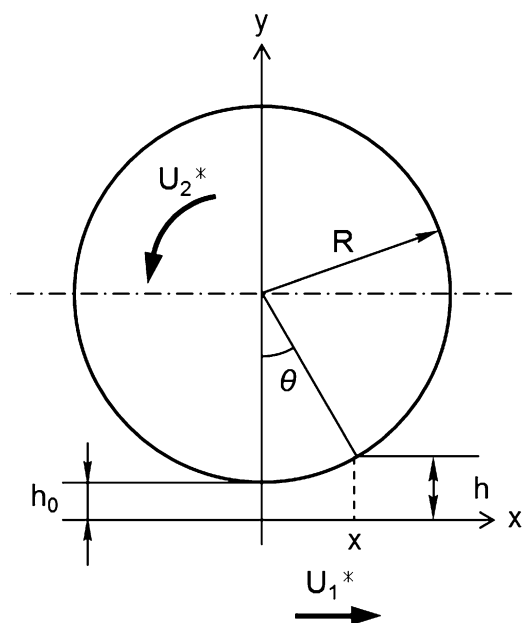


Fig. 1.17 Schematic representation of the lubricant flow channel of a needle bearing



the minimum oil film thickness, and R is the equivalent radius of the rolling element. In case of the contact between the inner ring and rolling element, $R = \frac{R_1 r}{R_1 + r}$, and in case of the contact between the outer ring and rolling element, $R = \frac{r R_2}{R_2 - r}$.

The oil film thickness is determined from the geometries as follows:

$$h = h_0 + \frac{x^2}{2R} \quad (1.35)$$

The Reynolds equation in this case is expressed as follows:

$$\frac{\partial}{\partial x} \left(h^3 \frac{\partial p}{\partial x} \right) = 6\eta(U_1 - U_2) \frac{dh}{dx} + 12\eta V \quad (1.36)$$

Now, the relationships between U_1 , U_2 , V and U_1^* , U_2^* are considered and are given by $U_1 = U_1^*$, $U_2 = U_2^*$, and $V = U_2^* \frac{dh}{dx}$.

From these relationships, the Reynolds equation is derived as follows:

$$\frac{\partial}{\partial x} \left(h^3 \frac{\partial p}{\partial x} \right) = 6\eta(U_1^* + U_2^*) \frac{dh}{dx} \quad (1.37)$$

Now, the Reynolds equation is integrated with respect to x across the channel. The result is as follows:

$$\frac{dp}{dx} = 12\eta U \left(\frac{1}{h^2} - \frac{h_m}{h^3} \right) \quad (1.38)$$

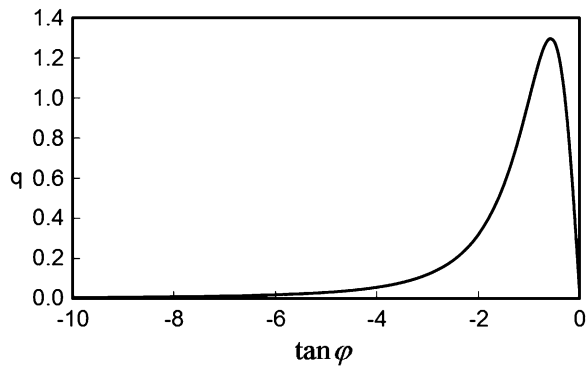
where $U = \frac{(U_1^* + U_2^*)}{2}$ and $h = h_m$ when $\frac{dp}{dx} = 0$.

When the boundary conditions are $p=0$ at $x=-\infty$ and $p=0$ at $x=0$, the Reynolds equation (1.37) is integrated twice with respect to x across the channel. The result is as follows:

$$p = \eta U \frac{\sqrt{2Rh_0}}{h_0^2} \left(\sin 2\varphi + \frac{1}{2} \sin 4\varphi \right) \quad (1.39)$$

where $\tan \varphi = \frac{x}{\sqrt{2Rh_0}}$. Since the pressure coefficient q is given by $q = \sin 2\varphi + \frac{1}{2} \sin 4\varphi$, the relationship between pressure coefficient q and $\tan \varphi$ is shown in Fig. 1.18.

Fig. 1.18 Relationship between pressure coefficient q and $\tan \varphi$



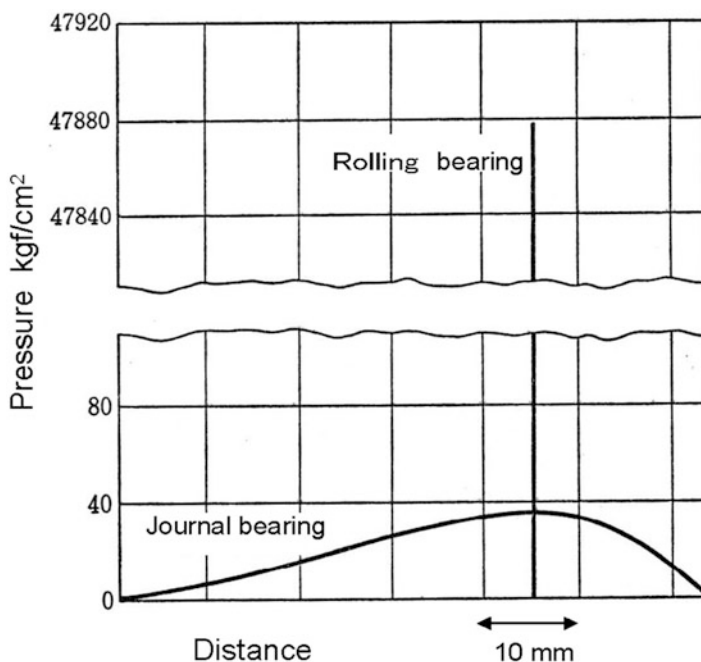


Fig. 1.19 Pressure distributions of a journal and rolling bearing

1.2.3.5 Pressure Distributions of Journal and Rolling Bearings

Kimura [16] compared the pressure distributions of a journal bearing and rolling bearing. In the journal bearing, the radius of the axis is 20 mm, the radius gap is 20 μm , and the load per unit length is 100 kgf/cm. The velocity is 2000 rpm and the viscosity of the lubricant is 5.1 cP. The pressure distributions are shown in Fig. 1.19.

From the calculated pressure distributions, the maximum value of pressure of the journal bearing is 35 kgf/cm², and on the other hand, the maximum value of pressure of the rolling bearing is near 5000 kgf/cm². The value of the journal bearing is reasonable, but the value of the rolling bearing is significantly high compared to the tensile strength of tool steels. Then, it is found that the oil film thickness between contact surfaces is significantly small. The development of the analysis of pressure distribution of the rolling bearing has been carried out by many researchers.

1.2.4 Elastohydrodynamic Lubrication

1.2.4.1 Effect of Viscosity of Lubricant

In order to obtain the right solution of pressure distribution of the rolling bearing, Gatcombe [17] considered the effect of pressure within a lubricant on viscosity η . He gave the viscosity equation of the lubricant as follows:

$$\eta = \eta_0 \exp(\alpha p) \quad (1.40)$$

where η_0 is the viscosity at atmospheric pressure and α is the pressure coefficient of viscosity.

Substituting Eqn. (1.40) into Eqn. (1.37), the Reynolds equation is given by

$$\exp(-\alpha p) \frac{dp}{dx} = 12\eta_0 U \left(\frac{1}{h^2} - \frac{h_m}{h^3} \right) \quad (1.41)$$

Now, it is assumed that $\frac{dq}{dx} = \exp(-\alpha p) \frac{dp}{dx}$. Since $q = 0$ at $p = 0$, the next equation can be given by

$$q = \frac{1 - e^{-\alpha p}}{\alpha} \quad (1.42)$$

where q is the reduced pressure. From Eqn. (1.42), the pressure is derived as follows:

$$p = \frac{1}{\alpha} (\alpha q + \alpha^2 q^2 + \alpha^3 q^3 + \dots) \quad (1.43)$$

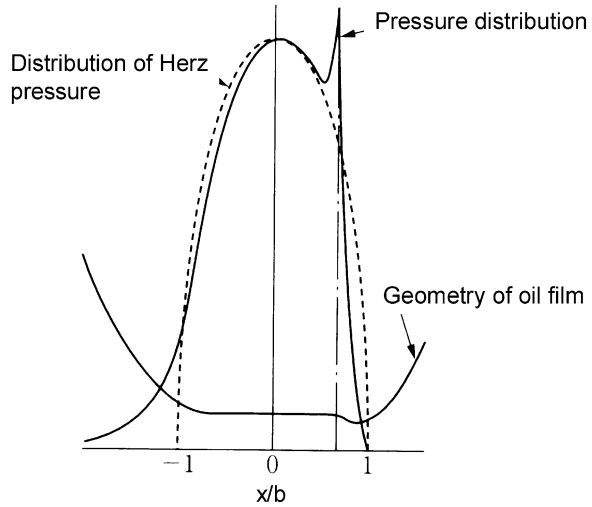
The pressure calculated from Eqn. (1.43) did not become smaller.

1.2.4.2 Elastic Deformation

Grubin [18] proposed that the elastic deformation of two bodies should be considered in order to reduce the pressure of the rolling bearing. Based on the elastic deformation calculated by the Hertz theory, he calculated analytically the pressure distribution and the oil film thickness using Eqns. (1.37) and (1.40). The pressure is similar to the Hertz pressure and the thicker oil film exists between two elastic deformed bodies.

Later, Dowson and Higginson [19] calculated numerically the pressure distribution and the oil film thickness. They carried out the coupled analysis of the Reynolds equation considering the elastic displacement δ . In the calculation, the Reynolds equation (1.37) and Eqn. (1.40) for the viscosity of lubricant were used.

Fig. 1.20 Pressure distribution in EHL



The oil film thickness is given by

$$h = h_0 + \frac{x^2}{2R} + \delta \quad (1.44)$$

where the elastic displacement δ is

$$\delta = -\frac{2}{\pi E'} \int_{s_2}^{s_1} p(s) \ln|x-s| ds + \text{const.} \quad (1.45)$$

Figure 1.20 shows the calculated pressure distribution in elastohydrodynamic lubrication (EHL). In Fig. 1.20, the oil film thickness becomes thinner in the exit region and the pressure spike at the exit is observed.

They proposed the equation of the minimum oil film thickness as follows:

$$\frac{h_{\min}}{R} = 1.6 \left(\frac{\eta_0 U}{E' R} \right)^{0.7} (\alpha E')^{0.6} \left(\frac{P}{E' R} \right)^{-0.13} \quad (1.46)$$

It is found that the oil film thickness is not affected strongly by the load in comparison with the velocity, the viscosity, and the pressure coefficient. Equation (1.46) is widely used as a minimum oil film thickness under EHL contact.

1.2.5 Boundary Lubrication

1.2.5.1 Boundary Lubrication Model

The lubrication regime of region III of the Stribeck curve shown in Fig. 1.8 is termed boundary lubrication. In region III, the λ value is smaller than 1 and the contact behaviors at the interface between solids are expressed as follows:

1. The surfaces between two solids are very close so that the contact between asperities takes place.
2. The effect of the bulk rheological properties of lubricants is little.
3. The coefficients of friction in the boundary lubrication do not depend on the speed, the viscosity, and the load.
4. The coefficients of friction depend on the surface properties of solids.

Hardy [4] introduced the term boundary lubrication in the regime of thin film lubrication. Before, Hardy [14] carried out experiments for measuring the coefficients of friction in the sliding contact between the ball and plane of glass, steel, and bismuth using alcohols with different molecular weights as lubricants. From the experimental results, he proposed the boundary lubrication model and reported that the coefficient of friction depends on the property of the thin boundary film absorbed on the metal surface.

In the Hardy's model, the metal surface is plane, but the actual metal surface has the roughness. Bowden and Tabor [7] proposed the developed boundary lubrication model considering the real contact area between asperities proposed by Holm. In this model, the load is supported in the real contact area A_r ; in a part of real contact area αA_r , the metal-to-metal contact occurs; and in another part of real contact area $(1 - \alpha) A_r$, the thin boundary film exists on the surface of metals.

Then, the frictional force is expressed as follows:

$$F = A_r \{ \alpha \tau_m + (1 - \alpha) \tau_l \} \quad (1.47)$$

where τ_m is the yield shear stress of the metal and τ_l is the shear stress of the boundary film. In order to reduce the coefficient of friction of the boundary lubrication, it is estimated that the α and τ_l values may become smaller.

1.2.5.2 Boundary Film

(a) Absorbed Film

In the absorbed film, there are two types of physically absorbed film and chemically absorbed film. The absorbed energy of physically absorbed film is a few kJ/mol, and on the other hand, the absorbed energy of chemically absorbed film is tens of kJ/mol. The chemically absorbed films are used as a boundary film of the metal surfaces of machine elements.

The typical oiliness agents that formed the chemically absorbed film are summarized in Table 1.1. The absorbed molecules of the chemically absorbed film consist of a long backbone of carbon atoms with an active polar end group. In Table 1.1, there are the polar end groups of $-\text{COOH}$ with fatty acids, $-\text{OH}$ with alcohols, and $-\text{NH}_2$ with amines. The used fatty acids are oleic acid and stearic acid, the used alcohols are lauryl alcohol and oleyl alcohol, and the used amine is cetylamine. The additives with these active polar end groups are added in the

Table 1.1 Typical oiliness agent

	Compound example	
Higher fatty acid	Oleic acid	$\text{CH}_3(\text{CH}_2)_7 - \underset{\text{H}}{\underset{\text{H}}{\text{C}}} = \underset{\text{H}}{\text{C}} - (\text{CH}_2)_7\text{COOH}$
	Stearic acid	$\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$
Higher alcohol	Lauryl alcohol	$\text{CH}_3(\text{CH}_2)_{11}\text{OH}$
	Oleyl alcohol	$\text{CH}_3(\text{CH}_2)_7 - \underset{\text{H}}{\underset{\text{H}}{\text{C}}} = \underset{\text{H}}{\text{C}} - (\text{CH}_2)_7\text{OH}$
Ester (glyceride)	Butyl stearate	$\text{CH}_3(\text{CH}_2)_{16}\text{COOC}_4\text{H}_9$
	Glyceryl monooleate	$\text{CH}_2\text{OCOC}_{17}\text{H}_{33}$ CHOH CH_2OH
Amine	1-Hexadecylamine	$\text{CH}_3(\text{CH}_2)_{14}\text{CH}_2\text{NH}_2$
Metallic soap	Ferric oleate	$(\text{C}_{17}\text{H}_{33}\text{COO})_2\text{Fe}$

base oils. The additives are called the oiliness agent. The properties required of the chemically absorbed film of oiliness agents are mentioned as follows:

1. The absorbed energy is larger.
2. The absorbed amount is larger.
3. The length of the polar group is long.
4. The characteristic of chain matching is superior.

(b) Chemically Reacted Film

In order to form the chemically reacted film on the contacting metal surfaces, either sulfur, phosphorus, or chlorine, called extreme pressure additive (EP additive), is added in the base oil. Over a certain temperature, sulfur, phosphorus, or chlorine results in the chemical reaction on the metal surface and the chemically reacted film forms. The typical EP additives are summarized in Table 1.2.

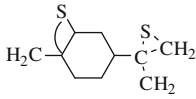
The sulfur EP additive results in the chemical reaction on the steel surface; thus the EP film of the FeS , FeS_2 , or FeSO_4 is formed. The phosphorus EP additive results in the chemical reaction on the steel surface; thus the EP film of the Fe_3P or FePO_4 is formed.

(c) Commercial Lubricant

As the commercial lubricants, the oiliness agent and the EP additive are added in the base oil of the mineral oil, the synthetic ester oil, and so on. The friction behavior of the commercial lubricants is shown in Fig. 1.21.

In Fig. 1.21, curve I is for a base oil. The coefficient of friction is relatively high and increases with increasing temperature. Curve II is for an oiliness agent in the base oil. The coefficient of friction is low up to a melting point of the metal soap θ_T ,

Table 1.2 Typical EP additives

Sulfur	Sulfur fat and oil	$\begin{array}{c} \text{CH}_3(\text{CH}_2)\text{-CH=CH}(\text{CH}_2)\text{COOR} \\ \\ \text{S}_n \\ \\ \text{CH}_3(\text{CH}_2)\text{-CH=CH}(\text{CH}_2)\text{COOR} \quad n \neq 2 \end{array}$
	Sulfur terpene	
	Polysulfide	$\text{R-S}_x\text{-R} \quad x \neq 4$
Phosphorus	Phosphate	$(\text{H}_3\text{C}-\text{C}_6\text{H}_4-\text{O})_3\text{P=O}$
	Phosphite	$(\text{C}_{12}\text{H}_{25}\text{O})_2\text{P-OH}$
	Amine salt of phosphate ester	$(\text{RO})_2\text{PO-O H}_2\text{-NR}'$
Chlorine	Chlorinated paraffin	$\begin{array}{c} \text{Cl} \quad \text{Cl} \\ \quad \\ \cdots \text{C} - \text{C} \cdots \\ \quad \end{array}$ $\text{Cl:40-70\%}$
Organic metal	Lead naphthenate	$\left(\begin{array}{c} \text{R} \quad \text{R} \\ \diagdown \quad \diagup \\ \text{C} \\ \diagup \quad \diagdown \\ \text{R} \quad \text{R} \end{array} \text{---} (\text{CH}_2)\text{CO-O} \right)_2 \text{Pb}$
	Zinc dialkylthiophosphate (zinc diarylthiophosphate)	$\begin{array}{c} \text{RO} \quad \text{S} \quad \text{S} \quad \text{OR} \\ \diagdown \quad \diagup \quad \diagdown \quad \diagup \\ \text{P} \quad \quad \text{P} \quad \text{H} \\ \diagup \quad \diagdown \quad \diagup \quad \diagdown \\ \text{RO} \quad \text{S-Zn-S} \quad \text{OR} \end{array}$

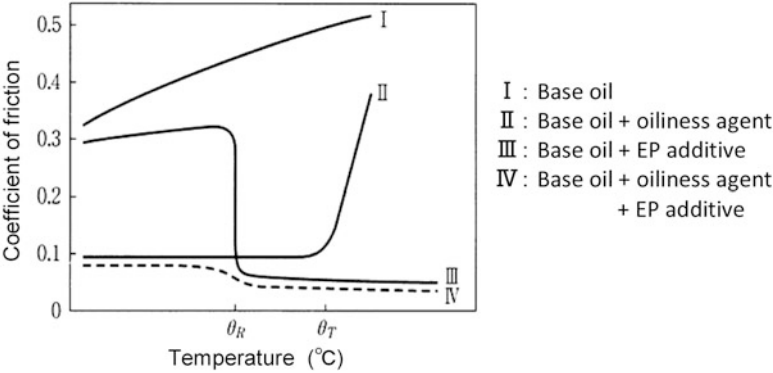


Fig. 1.21 Friction behavior of commercial lubricants

and above θ_T , it increases abruptly with increasing temperature. Curve III is for an EP additive in the base oil. The coefficient of friction is high up to a certain reaction temperature θ_R and, above θ_R , decreases abruptly for the formation of EP film. Curve IV is for a combination of an oiliness agent and EP additive in the base oil. The coefficient of friction is low from a low temperature to a high temperature. Good lubrication is provided when this lubricant is used.

1.2.6 Mixed Lubrication

The lubrication regime of region II of the Stribeck curve shown in Fig. 1.8 is termed mixed lubrication. In this region II, the λ value is larger than 1 and smaller than 4. In the mixed lubrication as shown in Fig. 1.22, the total normal load is supported by a part of the hydrodynamic action by the lubricant film and by another part of the asperity contacts. On the other hand, the total frictional force is supported by a part of the viscous friction force of the lubricant film and another part of the adhesion force on the real contact area. In Fig. 1.22, it is defined that the ratio of the boundary lubrication region is α and the contact area is A .

The normal load in the mixed lubrication P is expressed as follows:

$$P = p_r \alpha A + p_f (1 - \alpha) A \quad (1.48)$$

where p_r is the pressure acting on the real contact area and p_f is the pressure generated by the hydrodynamic action. On the other hand, the frictional force F is expressed as follows:

$$F = \tau_b \alpha A + \tau_f (1 - \alpha) A \quad (1.49)$$

where τ_b is the shear stress acting on the real contact area and τ_f is the viscous friction force of the lubricant film. τ_b and τ_f are derived by

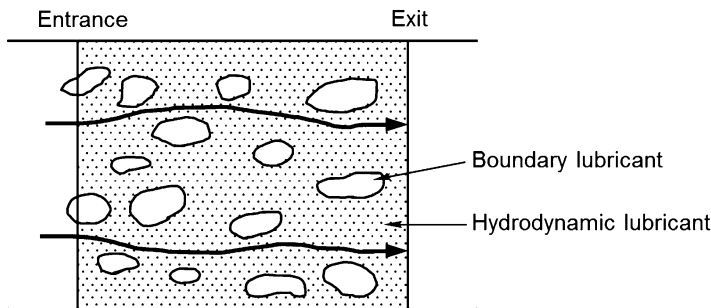


Fig. 1.22 Schematic representation of mixed lubrication

$$\tau_b = \mu_b p_r \quad (1.50)$$

$$\tau_f = \eta \frac{\partial u}{\partial y} \quad (1.51)$$

where μ_b is the boundary coefficient of friction.

The coefficient of friction in the mixed lubrication is expressed as follows:

$$\mu = \frac{F}{P} = \frac{\tau_b \alpha + \tau_f (1 - \alpha)}{p_r \alpha + p_f (1 - \alpha)} \quad (1.52)$$

Now, when it can be assumed that $\tau_b \gg \tau_f$, the coefficient of friction is given by

$$\mu = \frac{\mu_b}{1 + \frac{p_f}{p_r} \left(\frac{1 - \alpha}{\alpha} \right)} \quad (1.53)$$

1.3 Wear

Wear is defined as the removal of material from metal surfaces by mechanical action. The four main types of wear are classified in the following forms:

1. Adhesive wear
2. Abrasive wear
3. Corrosive wear
4. Fatigue wear

Adhesive wear occurs from the strong adhesive force acting on the real contact surfaces between asperities. Abrasive wear occurs when a rough hard asperity or the hard particle slides and plows on a soft surface by the formation of grooves. Corrosive wear occurs when the sliding between metals takes place in a corrosive environment. Fatigue wear occurs when the metal surfaces are repeatedly loading and unloading during sliding or rolling. In this book, adhesive wear and abrasive wear are explained.

The wear amount is evaluated by the following parameters:

1. Volume or weight (V or M)
2. Wear amount per unit distance (wear rate) (V/L or M/L)
3. Wear amount per unit load and unit distance (specific wear rate) (V/WL or M/WL)

Generally, specific wear rates are 10^{-5} – 10^{-7} in abrasive wear, 10^{-6} – 10^{-10} in adhesive wear under dry condition, and 10^{-8} – 10^{-13} in adhesive wear under lubricated condition.

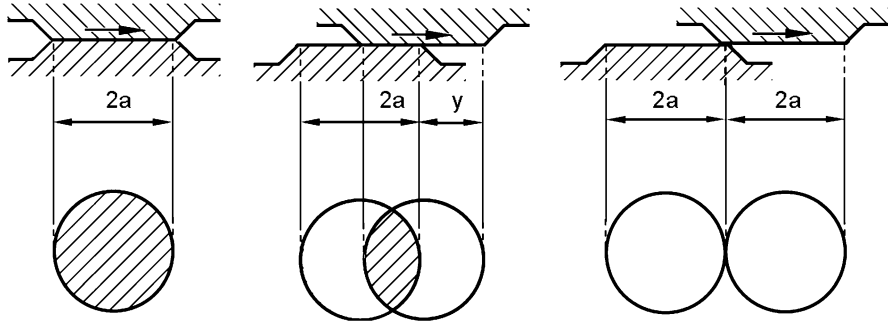


Fig. 1.23 Schematic representation of Archard's model

1.3.1 Adhesive Wear

Figure 1.23 shows the schematic representation of Archard's model of adhesive wear [20]. In Fig. 1.23, when the number of the contact point is n , the real contact area A_r is given by

$$A_r = n\pi a^2 \quad (1.54)$$

Now, when an asperity travels a distance l , the number of encounters of the asperity N_a is derived as follows:

$$N_a = \frac{Pl}{2\pi a^3 p_m} \quad (1.55)$$

If the ratio k of N_a becomes the wear particle and the volume of a particle is a half of volume of a sphere with radius a , the wear volume is derived by

$$V = \frac{kPl}{3p_m} \quad (1.56)$$

1.3.2 Abrasive Wear

Figure 1.24 shows the schematic representation of the abrasive wear model. In Fig. 1.24, θ is the half vertical angle and d is the depth of indentation. When the yield flow stress of the soft metal is p_m , the normal load P is given by

$$P = \pi(d \tan \theta)^2 p_m \quad (1.57)$$

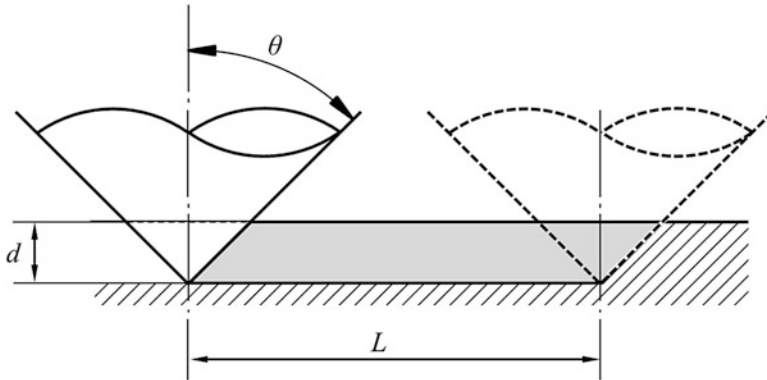


Fig. 1.24 Schematic representation of the abrasive wear model

When the asperity travels a distance l , the wear volume is given by

$$V = \frac{\cot \theta}{\pi} \frac{Pl}{p_m} \quad (1.58)$$

References

1. G. Amonton, Mem. Acad. Roy., (1699), 206–222.
2. C. A. Coulmb, Mem. Math. Phys., 10 (1785), 161–342.
3. E. Rabinowicz, Friction and Wear of Materials, Second Edition (John Wiley & Sons, Inc. 1995), 74.
4. W. B. Hardy, Collected scientific papers of Sir William Bate Hardy (Published under the auspices the Collid Committee of the Faraday Society, Cambridge W. B. Hardy, I. Doubleday, Proc. Roy. Soc. Lond., A100, (1922), 550–1;574. U.P 1936)
5. J. T. Desaguliers, Phil. Trans. R. Soc. Lond., 33 (1725),345.
6. H. Holm, H. Gergers Forlag, (1946), 2.
7. F. P. Bowden, D. Tabor, The Friction and Lubrication of Solids- Part I (Oxfords U.P., Oxford 1954).
8. E. Rabinowitz, ASLE Trans.,14 (1971), 198.
9. E. P. Bowden, T. P. Hugues, Proc. Roy. Soc. Lond., A212 (1939), 263.
10. D. Tabor, Proc. Roy. Soc. Lond., A251 (1959), 378–393.
11. M. Muraki, Tribology (Nikkankogyoshinbunsha, 2007), 43, 65.
12. B. Tower, Proc. Instn. Mech. Engrs. Jan. (1885), 58–70.
13. O. Reynolds, Phil. Trans. R. Soc., 177 (1886), 157–234.
14. W. B. Hardy, I. Doubleday, Proc. Roy. Soc. Lond., A100, (1922), 550–574.
15. R. Streibeck, Z. Ver. dt. Ing, 45 (1901) 73–125.
16. Y. Kimura, H. Okabe, Survey of Tribology (Yokendo 1982), 105.
17. E. K. Gatcombe, Trans. Amer. Soc. Mech. Engrs, 67 (1945), 177.
18. A. N. Grubin, I. E. Vinogradova, Investigation of the contact of machine component (Central Scientific Research Institute for Technology and Mechanical Engineering, Moscow 1949).
19. D. Dowson, G. R. Higgns, J. Mech. Engng. Sci. 1, No.1 (1959), 6–15.
20. J. A. Archard, J. Appl. Phys., 24, 8 (1953), 981–988.

Chapter 2

Tribology in Metalforming

2.1 Characteristics of Tribology in Metalforming

Figure 2.1 shows the schematic representation of the contact behavior between tool and workpiece in metalforming such as rolling, drawing, extrusion, forging, and so on.

Soda [1] who was a specialist in the field of tribology of mechanical elements reviewed about the tribology in metalforming as shown in Fig. 2.1 compared to the tribology of mechanical elements as follows:

1. The lubrication regime in metalforming is close to the boundary lubrication than the hydrodynamic lubrication.
2. In the contact region between tool and workpiece, the pressure is fairly higher than the yield stress of the workpiece, and the area of the contact region is significantly wide.
3. The interfacial temperature in metalforming is high.
4. The relative speed between tool and workpiece changes in the contact region and the direction changes in the contact region.
5. The lubricant is introduced and entrapped between tool and workpiece, and the workpiece surface is greatly influenced by the introduced and entrapped lubricants.
6. The virgin surface on the workpiece surface is generated in contact region by the plastic deformation.

Here, the items are explained in brief.

Fig. 2.1 Schematic representation of contact behavior between tool and workpiece

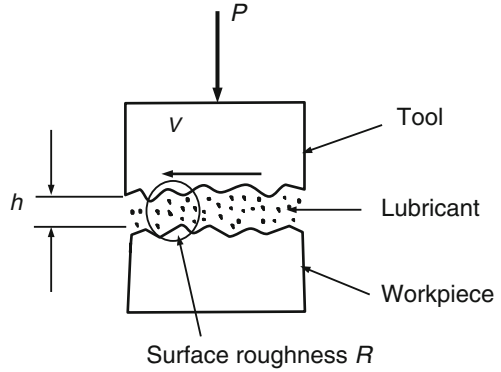
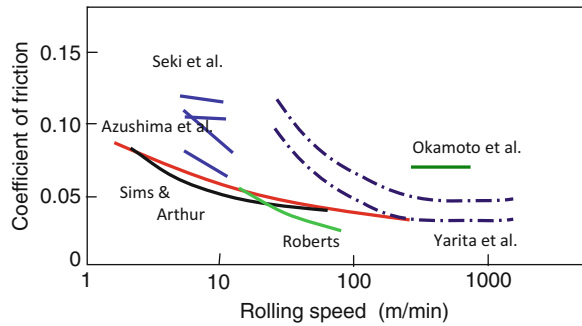


Fig. 2.2 Relationship between coefficient of friction and rolling speed [2]



2.1.1 Lubrication Regime

In order to consider the lubrication regime in metalforming, the coefficient of friction in metalforming must be examined. Figure 2.2 shows the relationship between coefficient of friction and rolling speed measured in cold sheet rolling by many researchers [2]. The coefficients of friction in Fig. 2.2 were calculated from the measured rolling load using the equation of rolling pressure and the friction equation of Eqn. (1.5). The values of the coefficient of friction in Fig. 2.2 are in the range of 0.02–0.13, and from the Stribeck curve in Fig. 1.15, it is estimated that the lubrication regime is corresponding to the mixed lubrication in cold rolling. Since the coefficients of friction of other metalforming processes such as extrusion, forging, and so on are higher, it is anticipated that the boundary lubrication is generally prevailed as the lubrication regime in metalforming.

Generally, the friction law expressed in Eqn. (1.5) has been widely used in metalforming processes. Then, the shear stress is given by

$$\tau = \mu p \leq k \quad (2.1)$$

Fig. 2.3 Schematic representation of mixed lubrication of hydrostatic lubrication and boundary lubrication

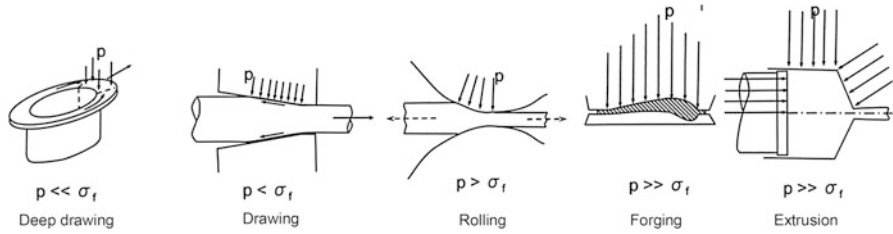
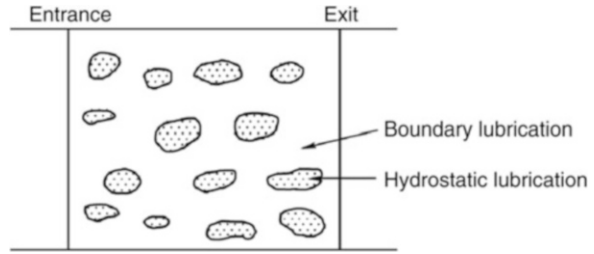


Fig. 2.4 Schematic representation of contact pressure in metalforming processes

where k is the yield shear stress. Equation (2.1) means that the shear stress in metalforming cannot be more than the yield shear stress k . From this reason, in metalforming process, the next friction law is also used:

$$\tau = mk \quad (2.2)$$

where m is the friction shear factor ($0 \leq m \leq 1$).

On the other hand, from the values of the coefficient of friction in cold sheet rolling shown in Fig. 2.2, the friction law of the mixed lubrication must be considered. When the hydrodynamic lubrication is prevailed in the mixed lubrication regime, Eqn. (1.53) is derived as the friction law. However, when the boundary lubrication is prevailed in the mixed lubrication as shown in Fig. 2.3, we must consider the hydrostatic lubrication and the new friction law must be proposed. Later, the friction law in the mixed lubrication is explained in detail.

2.1.2 Contact Pressure

Figure 2.4 shows the contact pressure acting on the interface between tool and workpiece in metalforming processes such as deep drawing, drawing, rolling, forging, and extrusion.

The ratios (p/σ_f) of the normal pressure p to the yield stress σ_f are summarized as follows;

1. In sheet forming and drawing, the ratio p/σ_f is from 0.1 to 1.0.
2. In rolling, it is from 1.0 to 3.0.
3. In forging and extrusion, it is from 2.0 to 5.0.

In the bulk-forming processes such as rolling, forging, and extrusion, the contact pressures are larger than the yield stress of metals.

2.1.3 Interfacial Temperature

The interfacial temperature of mechanical element rises by the friction energy. On the other hand, the interfacial temperature in metalforming process rises by the plastic deformation energy and the friction energy. The mean temperature rise T_{mW} by the plastic deformation in metalforming is given by

$$T_{mW} = \frac{\sigma_m \epsilon_m}{\rho} \quad (2.3)$$

where σ_m is the average stress, ϵ_m is the average strain, and ρ is the density. Figure 2.5 shows the temperature rises in the adiabatic deformation for the average strain of several metals.

From Fig. 2.5, it is found that the temperature rise of steel (S45C) becomes easily over 100 °C by the plastic deformation above a reduction of 50 %. The interfacial temperature rises considering the plastic deformation energy and the friction energy are shown in Fig. 2.6. From Fig. 2.6, it is found that the interfacial temperature rise becomes easily near 200 °C in high-speed cold rolling.

The interfacial temperature in metalforming process is summarized as follows:

1. In sheet forming, the interfacial temperature is from room temperature to about 150 °C.
2. In drawing and ironing, it is from room temperature to about 300 °C.
3. In rolling, it is from room temperature to about 200 °C.
4. In forging and extrusion, it is from room temperature to about 400 °C.

Later, the mean temperature rise by the friction energy in metalforming is explained in detail.

Fig. 2.5 Temperature rise by plastic deformation [3]

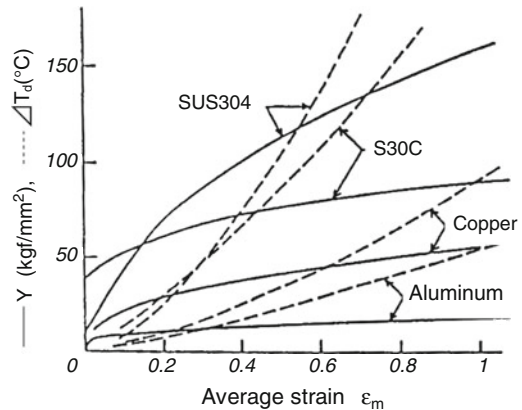


Fig. 2.6 Relationship between interfacial temperature rise and speed [3]

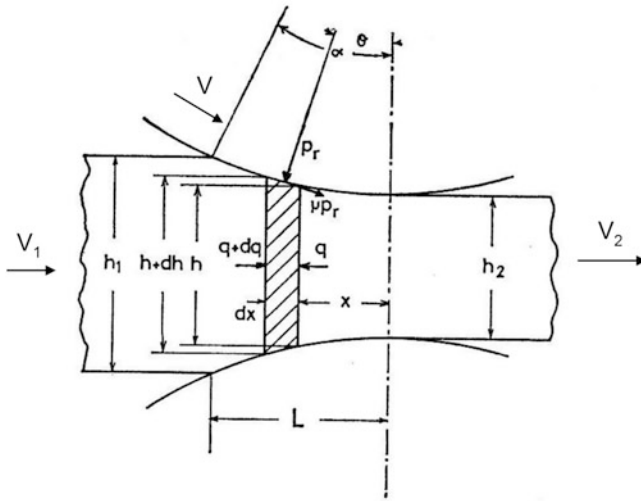
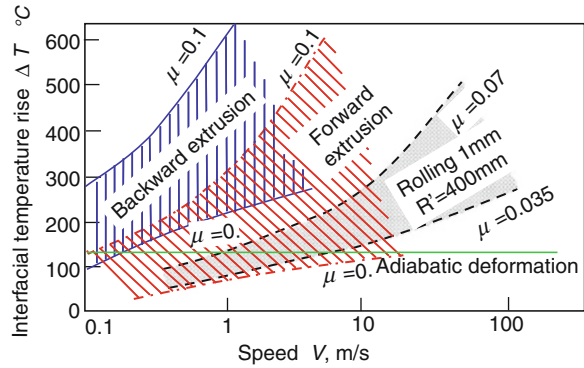


Fig. 2.7 Schematic representation of rolling process

2.1.4 Sliding Speed

Figure 2.7 shows the schematic representation of the rolling process. In Fig. 2.7, V is the roll speed, V_1 is the inlet speed of strip, and V_2 is the outlet speed of strip.

The relation among V , V_1 , and V_2 is expressed as follows:

$$V_1 \leq V \leq V_2 \quad (2.4)$$

The sliding speed in rolling process changes from inlet point to outlet point. At the neutral point, the roll and strip speeds are equal and the relative sliding speed becomes 0.

Fig. 2.8 Distribution of normal pressure in rolling [4]

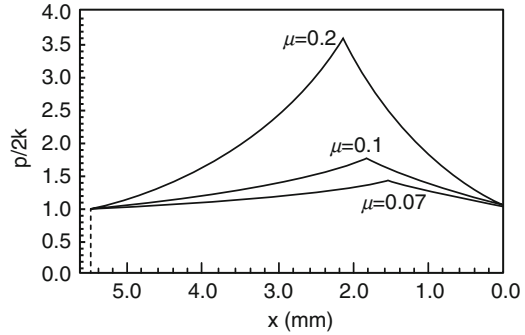
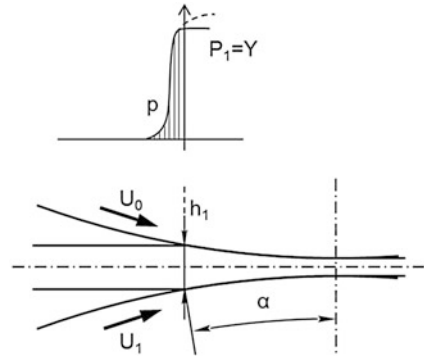


Fig. 2.9 Schematic representation of introducing model in rolling process



The direction of the frictional stress τ_f is reversed at the neutral point as shown in Fig. 2.7. In this case, the distributions of the normal pressure changing the coefficient of friction are shown in Fig. 2.8. From Fig. 2.8, it is found that the normal pressures at the neutral points are maximum.

2.1.5 Introducing and Entrapping Lubricant

The lubricant is introduced between tool and workpiece by the wedge effect and the squeeze effect of the Reynolds equation as shown in Fig. 1.11 in the steady-state metalforming processes such as drawing, rolling, and so on. In rolling process, the introducing model is shown in Fig. 2.9. On the other hand, the lubricant is entrapping between tool and workpiece by the squeeze effect of the Reynolds equation as shown in Fig. 1.11b in the unsteady-state metalforming such as forging and so on. In upsetting process, the entrapping model is shown in Fig. 2.10.

Next, the photographs of sheet surfaces of stainless steel with smooth surface rolled with the rolling speeds using machine oil are shown in Fig. 2.11.

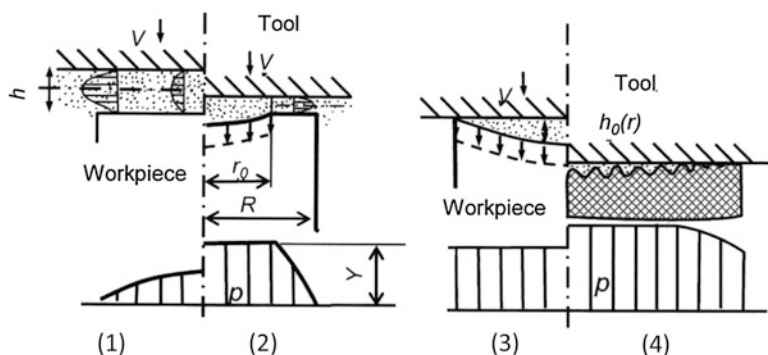


Fig. 2.10 Schematic representation of entrapping model in upsetting process [3]

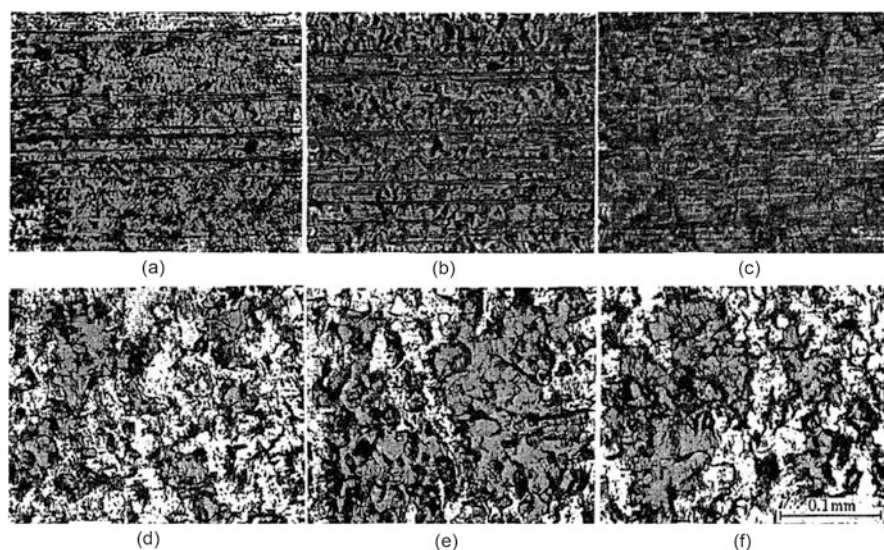


Fig. 2.11 Photographs of sheet surface rolled at six rolling speeds [5]. (a) $V = 5$ m/min. (b) $V = 17$ m/min. (c) $V = 48$ m/min. (d) $V = 78$ m/min. (e) $V = 300$ m/min. (f) $V = 1000$ m/min

From Fig. 2.11, it is found that the surface roughness increases with increasing rolling speed. Since the oil film thickness introduced between roll and sheet increases with increasing rolling speed, it can be understood that the sheet surface is greatly influenced by the oil film thickness introduced between roll and sheet.

Later, the oil film thickness introduced between tool and workpiece in the steady-state metalforming process is explained in detail.

2.1.6 Virgin Surface

The virgin surface area increases with increasing plastic deformation. The surface enlargement ratio by the plastic deformation in metalforming process is summarized as follows:

1. In sheet forming, the surface enlargement ratio is from 1 to about 1.5.
2. In drawing, it is from 1 to about 2.
3. In rolling, it is from 1 to 3.
4. In forging and extrusion, it is from 1 to 100.

In next chapter, the micro-contact behavior at the interface between tool and workpiece is explained in detail.

2.2 Micro-contact Between Tool and Workpiece

Generally, a schematic lubrication model at the interface between tool and workpiece in metalforming is shown in Fig. 2.12 [6]. In this model, it is explained that the lubrication between tool and workpiece consists of a boundary region in which the workpiece surface under the tool is dressed and a hydrostatic lubrication region in which the lubricant is filled in the small pockets on the workpiece surface.

2.2.1 Hydrostatic Pressure

In this hydrostatic-boundary lubrication regime, a part of the normal contact load is supported by the hydrostatic pressure q generated in the surface pockets of workpiece, and the remainder is supported by the normal pressure of the asperities, as shown in Fig. 2.13 [7].

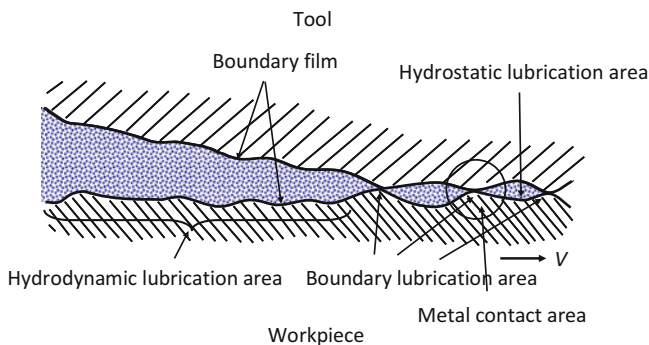


Fig. 2.12 Schematic lubrication model at interface between tool and workpiece in metalforming

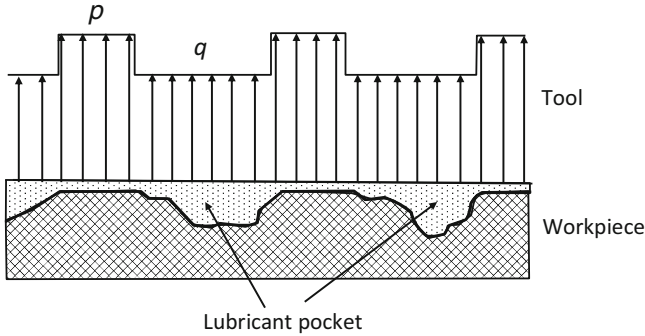
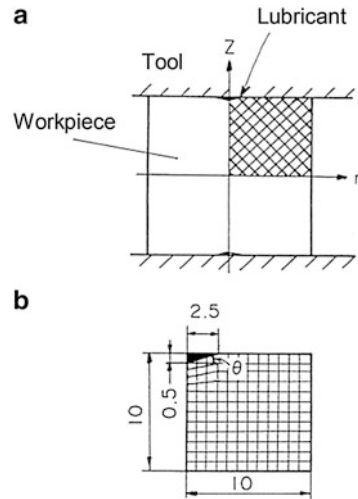


Fig. 2.13 Model of hydrostatic-boundary lubrication [7]

Fig. 2.14 Specimens of axisymmetrical upsetting of cylinder having central impression (a) and geometry and finite element discretization (b)



In compression process, it is estimated that the hydrostatic pressure q within oil pockets increases with increasing reduction in height. The hydrostatic pressure generated within the surface pocket of workpiece was calculated accompanied with reduction in height in upsetting of cylinders using the rigid-plastic element method by Azushima [8]. Figure 2.14 shows the schematic representation of the specimens of axisymmetrical upsetting of cylinder having a central impression (a) and geometry and finite element discretization (b).

In order to calculate the solution, the following functional Φ for the material is minimized:

$$\Phi = \int_v \left[\int \sigma d\epsilon \right] dV + \int_{sf} \tau_f \Delta V ds \quad (2.5)$$

where τ_f is the frictional shear stress and ΔV is the relative velocity between tool and workpiece. In order to calculate the hydrostatic pressure generated within the

surface pocket filled with lubricant, the compressibility of the lubricant is included. The hydrostatic pressure q is generated accompanied with the volume change of the surface pocket and is given by

$$q = \kappa \frac{\Delta V_1}{V_1} \quad (2.6)$$

where κ is the bulk modulus of the lubricant, V_1 is the volume of surface pocket, and ΔV_1 is the volume change of the surface pocket. The incremental hydrostatic pressure from $(n - 1)$ th step to n th step is given by

$$q^{(n)} - q^{(n-1)} = \kappa \frac{V^{(n)} - V^{(n-1)}}{V^{(n-1)}} \quad (2.7)$$

The coupled analysis is carried out numerically using Eqns. (2.5) and (2.6).

Figure 2.15 shows the distribution of the nondimensional normal pressure on the edge surface of cylinder having a central conical impression without lubricant (a) and filled with lubricant (b) at several reductions in height when the coefficient of friction is 0. In Fig. 2.15, Y is the yield stress, p is the normal stress, q is the hydrostatic pressure, and r is the reduction in height. In the case of the cylinder without lubricant (a), the volume of the conical impression decreases with increasing reduction in height. The marked volume shrinkage of the impression is observed. At a reduction in height of 19.5 %, the impression disappears.

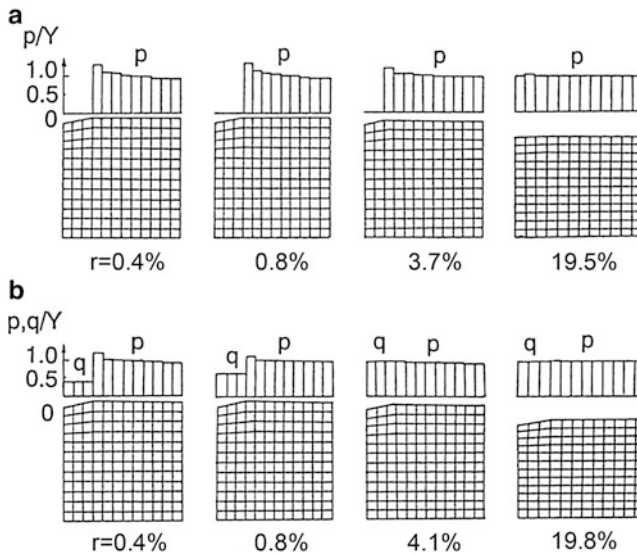


Fig. 2.15 Distribution of nondimensional pressure of surface cylinder having central conical impression without lubricant (a) and with lubricant (b)

Fig. 2.16 Change of hydrostatic pressure generated within lubricant with reduction in height when changing coefficient of friction

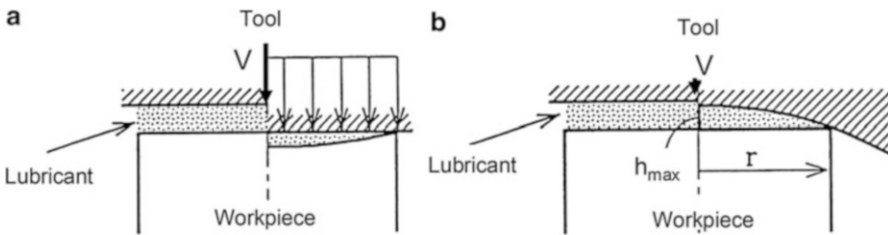
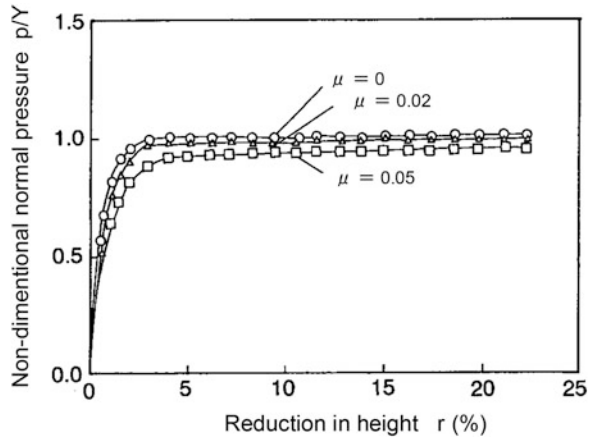


Fig. 2.17 Entrapping model of lubricant in upsetting process at high speed (a) and low speed (b)

On the other hand, in the case of the cylinder with lubricant (b), the hydrostatic pressure is generated within the lubricant trapped into the impression at a small reduction in height. At a reduction in height of 4.1 %, the value coincides with the normal pressure acting on the contact area.

Figure 2.16 shows the relationship between nondimensional hydrostatic pressure and reduction in height at several levels of coefficient of friction. The hydrostatic pressure increases rapidly up to a reduction in height of 4 % for each coefficient of friction. The value approaches to the normal pressure and it remains constant over 4 %.

2.2.2 Entrapped Lubricant in Upsetting

In upsetting of a cylindrical billet at high speed, liquid lubricant is entrapped between flat-smooth tool and workpiece surfaces by the squeeze effect of the Reynolds equation as shown in Fig. 2.17a. On the other hand, in upsetting of a cylindrical billet at low speed, liquid lubricant is entrapped by the elastic sinking of the tool surface as shown in Fig. 2.17b.

Fig. 2.18 Schematic representation of compression apparatus for in situ observation

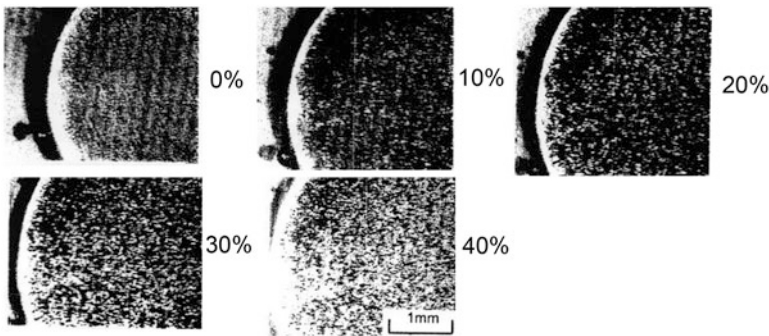
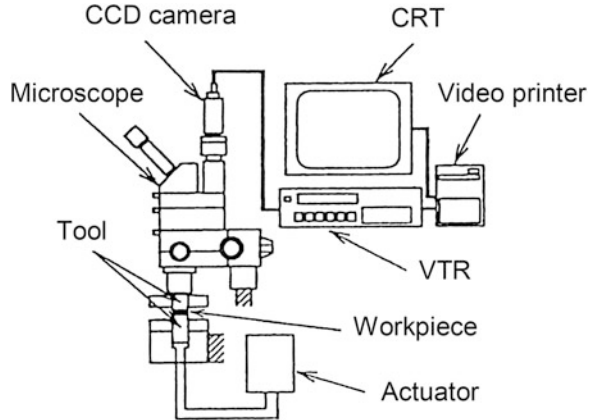


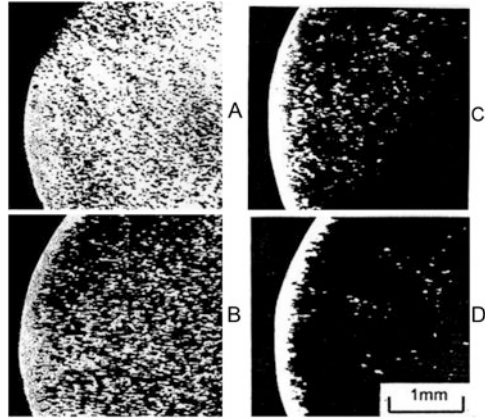
Fig. 2.19 Video photographs of interfaces at five different reductions in height for lubricant B

It is anticipated that the thick lubricant film is entrapped between tool and workpiece in upsetting process. Then, the compression proceeds, the workpiece surface starts to grow with surface roughening due to the bulk plastic deformation, and the asperity grown on the workpiece surface by surface roughening starts to contact to the tool surface. The lubrication regime is switched to the microscopically mixed boundary and hydrostatic lubrication.

Azushima et al. [9] carried out the visual in situ observation of tool-workpiece interface of the end surface of cylindrical billet during upsetting in order to examine the entrapped lubricant behavior and the ratio of the real contact area. The experiments are carried out using a newly developed compression apparatus which has a transparent tool made of quartz, a microscope with CCD camera and video system. The apparatus is shown in Fig. 2.18.

The workpiece material is A1100 aluminum. The experiments are carried out at a compression speed of 1 mm/min using four lubricants (A, B, C, and D) with viscosities of 80, 1460, 5850, and 23,800 cSt at 20 °C. The video photographs of the interfaces at five different reductions in height for the lubricant B are shown in Fig. 2.19.

Fig. 2.20 Interface appearances at same reduction of 30 % for four kinds of lubricants



At the beginning of upsetting ($r = 0\%$), since the lubricant is sealed at the edge of the cylinder billet, a thick film is entrapped between tool and workpiece inside the peripheral region of real contact. As upsetting proceeds, asperities on the surface start to grow. Since the prominent asperities are flattened by the flat-smooth tool, the isolated regions of real contact become observable. When the reduction in height proceeds, both the average area of the individual regions and the sum of the real contact regions become larger.

In Fig. 2.20, the interfacial appearances at a same reduction in height of 30 % for four lubricants (A, B, C, and D) are compared. From these appearances, it is observed that the real contact area decreases with increasing viscosity of lubricant. The average ratios of real contact area in the interior region using the image processor are 60 % for the lubricant A, 33 % for B, 15 % for C, and 5 % for D.

Next, the distributions of the ratio of real contact area at the four levels of reduction in height of lubricant B obtained from the binary images by image processor in Fig. 2.19 are illustrated in Fig. 2.21. The distributions of the ratio of lubricant D obtained are also illustrated in Fig. 2.22.

For the lubricant B, the value of the ratio of real contact area at each reduction in height is nearly uniform within a circle with a nondimensional radius of 0.8. It increases with increasing reduction in height, and the average values are 12 % at a reduction in height of 10 %, 20 % at 20 %, 33 % at 30 %, and 42 % at 40 %, respectively. For the lubricant D, the interior real contact zone is not observable at reductions in height of 10 and 20 %. In this case, since the thicker film is entrapped at the interface between tool and cylinder billet, the free surface roughening occurs on the edge surface of cylinder billet.

2.2.3 Roughening of Lubricated Surface by Thick Film

In order to examine the roughening behavior of the lubricated workpiece surface by thick lubricant film, a fluorescence observation technique which consists of an

Fig. 2.21 Distributions of ratio of real contact area of lubricant B

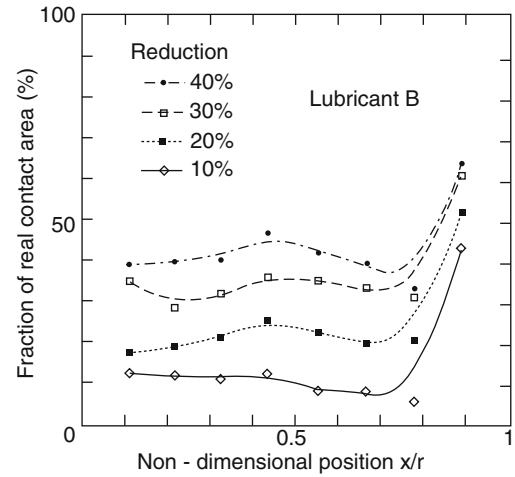
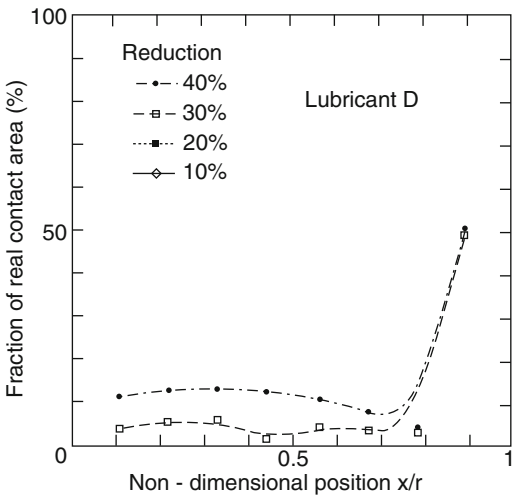


Fig. 2.22 Distributions of ratio of real contact area of lubricant D



optical microscope and a conventional fluorescent method shown in Fig. 2.23 is developed newly by Azushima [10]. The apparatus consists of a part of tool halves with flat surfaces, one made of high-speed steel and the other of transparent quartz, a fluorescent microscopy with an ultra high sensitivity CCD camera, a video system, an image processor, and a tensile machine. Next, the measurement part of the apparatus for oil film thickness measurement is shown in Fig. 2.24. The oil film thickness at the interface between tool and workpiece can be in situ measured during the plastic deformation using the fluorescence technique. The surface profile of the roughening surface lubricated by thick lubricant film can be measured from the distribution of the measured oil film thickness.

Fig. 2.23 Schematic representation of compression apparatus for direct observation

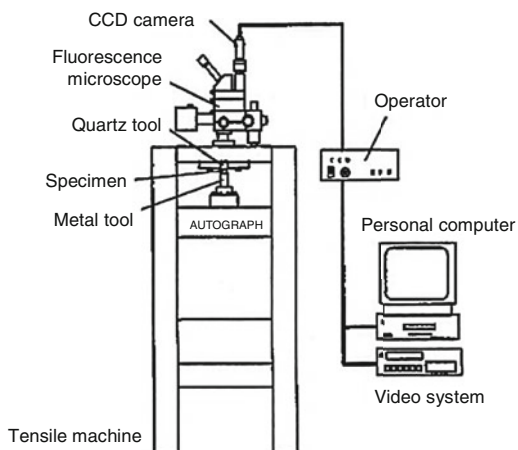
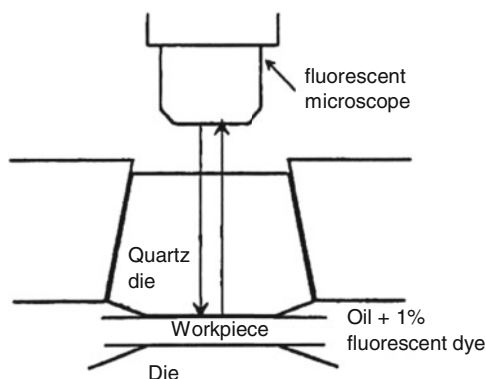


Fig. 2.24 Schematic representation of measurement part of fluorescent microscope



The workpiece material is A1050H aluminum. The experiments are carried out at a compression speed of 1 mm/min using a lubricant with viscosities of 20,000 cP at 20 °C. Thiophene compound is used as the fluorescent dye and the amount is fixed at a constant of 1 wt%. From the experiments for examination of the relationship between visible light intensity of fluorescent dye and oil film thickness, it is obtained that the visible light intensity increases linearly with increasing oil film thickness. The video photographs of the interface at reductions in height of 0, 20, and 40 % are shown in Fig. 2.25, and the distributions of the visible light intensity at reductions in height of 0, 20, and 40 % are shown in Fig. 2.26.

In Figs. 2.25 and 2.26, a thick film is entrapped between tool and workpiece inside the peripheral region of real contact at reductions in height of 0 and 20 %. In the central region on the edge surface of cylinder specimen, the free surface roughening occurs. When upsetting proceeds, the asperities on the surface grow and the prominent asperities are flattened by the flat tool.

Fig. 2.25 Photographs of edge surface of cylindrical specimen illuminated with UV light at reductions in height of 0, 20, and 40 %

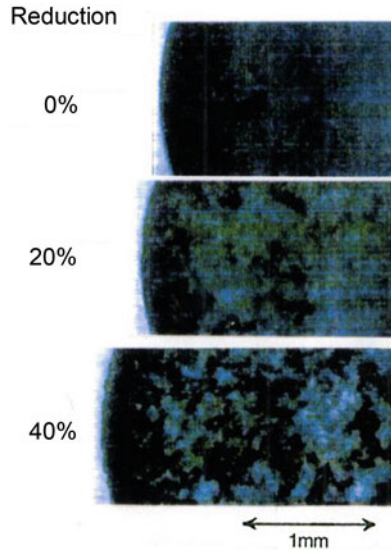
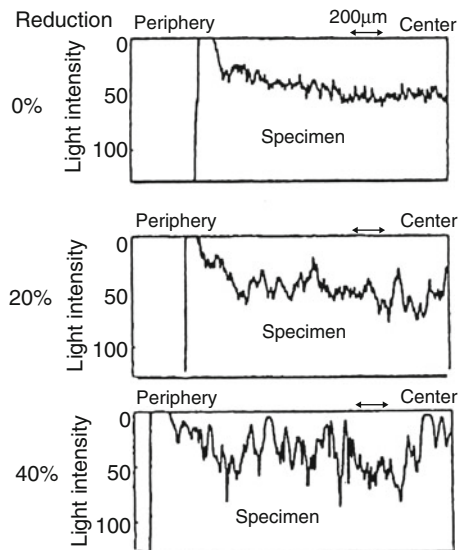


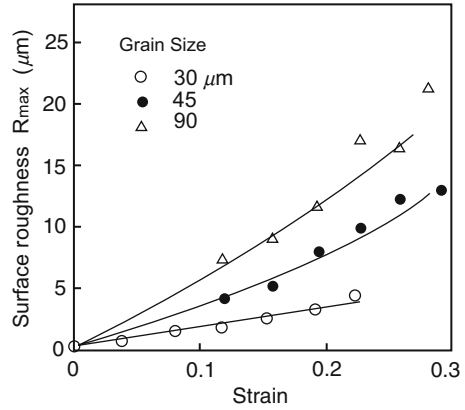
Fig. 2.26 Distribution of visible light at reductions in height of 0, 20, and 40 %



2.2.4 Free Surface Roughening

It is estimated that the free surface roughening of the lubricated workpiece surface under plastic deformation in metalforming is similar to that of the metal surface under plastic deformation without contacting a tool. Here, the free surface roughening of the metal surface under plastic deformation without contacting the tool is explained.

Fig. 2.27 Relationship between surface roughness and strain



It is well known that the surface roughness of the workpiece subjected to tensile deformation increases linearly with increasing plastic strain. The surface roughness R_0^{mate} depends on the grain size and is given as follows:

$$\begin{aligned}
 R_0^{mate} &= R_0 & (R_0^{mate} \leq R_0) \\
 R_0^{mate} &= R_0 + c(\varepsilon - \varepsilon_0)D & (R_0^{mate} \geq R_0)
 \end{aligned} \tag{2.8}$$

where R_0 is the initial surface roughness, D is the grain size, ε is the plastic strain, ε_0 is the initial plastic strain, and c is the constant. Azushima and Miyagawa [11] examined the effect of the grain size, the strain rate, the strain pass, the hydrostatic pressure, and the temperature on the surface roughness. Figure 2.27 shows the relationship between surface roughness and strain of aluminum specimens with grain sizes of 30, 45, and 90 μm .

Figure 2.28 shows the strain rate, the strain pass, the hydrostatic pressure, and the temperature dependences of the free surface roughening. In Fig. 2.28, it is found that the relationship between surface roughness and strain is independent of the strain rate, the strain pass, and the hydrostatic pressure except the temperature. From these results, the free surface roughening of the lubricated workpiece under plastic deformation may be independent of the deformation parameters in cold metalforming.

2.2.5 Asperity Deformation in Upsetting Test and Indentation Test

Knowledge of the interaction between surface asperities and lubricant in micro-contact conditions is of great importance for the understanding of tribological effects and the improvement of tribological technologies in cold metalforming. The behavior of the asperity deformation depends on the bulk deformation of

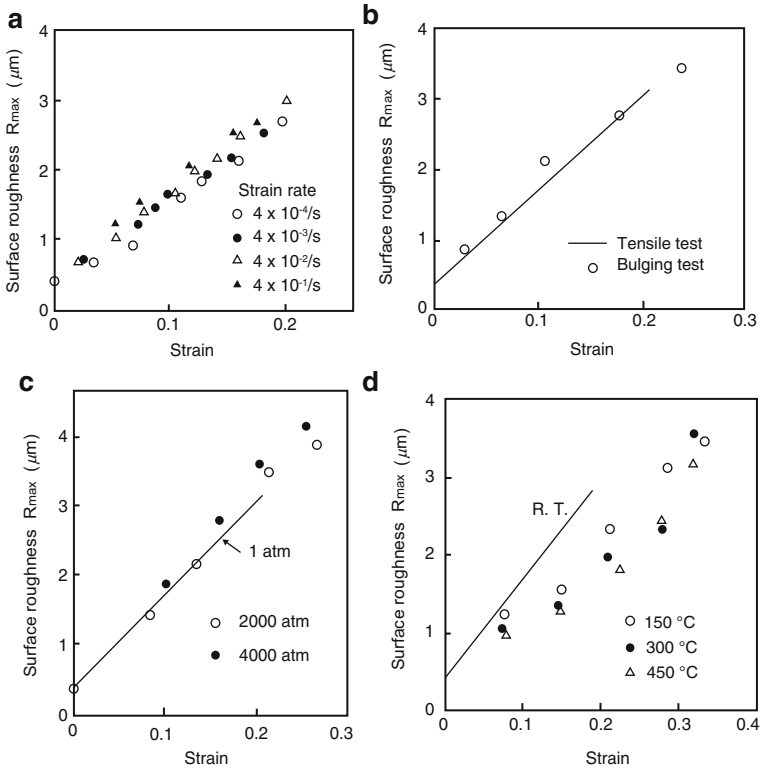


Fig. 2.28 Strain rate, strain pass, hydrostatic pressure, and temperature dependence of free surface roughening. (a) Strain rate dependence. (b) Strain pass dependence. (c) Hydrostatic pressure dependence. (d) Temperature dependence

workpiece and the existence of lubricant. Here, in order to examine the behavior of the asperity deformation, upsetting test as a metalforming with bulk deformation and indentation test as a metalforming without bulk deformation are carried out by Azushima et al. [12]. The experiments are carried out using the aluminum disks with a random rough surface without lubricant and with lubricant by means of the compression apparatus for direct observation. Figure 2.29 shows the schematic representation of the measurement part of apparatus for the direct observation of the interfaces of upsetting test (a) and indentation test (b).

The workpiece material used is A1100 aluminum. The specimen is sheet with a thickness of 1.0 mm and the surface roughness is R_a 5.22 μm . The experiments are carried out at a constant compression speed of 0.1 mm/min without lubricant and with lubricant. Mineral oils with viscosity of 391 cSt (A) and 2 cSt (B) at 40 °C are used.

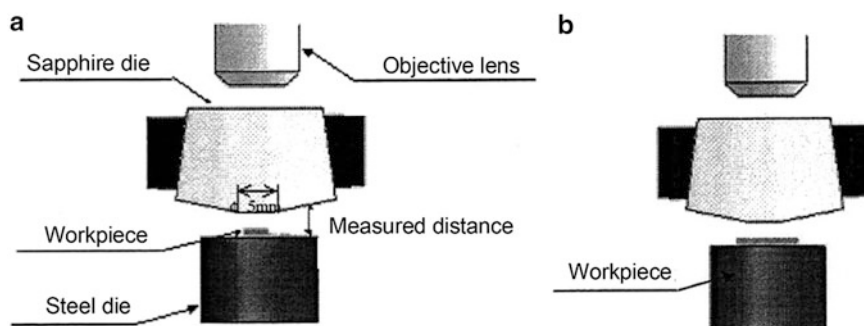


Fig. 2.29 Schematic representation of measuring part of apparatus of upsetting test (a) and indentation test (b)

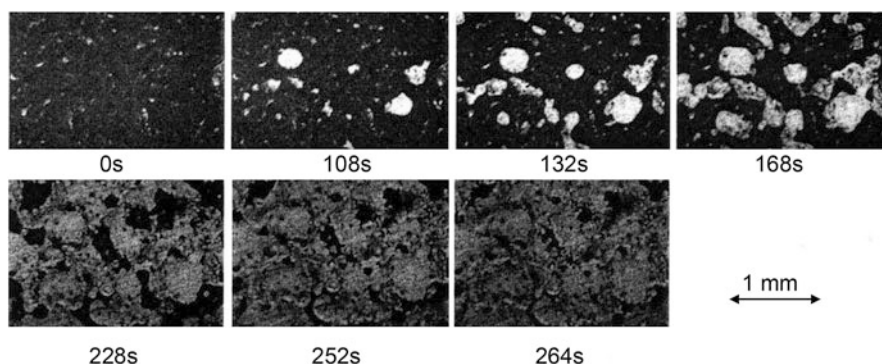


Fig. 2.30 Sequence appearances of interface between sapphire tool and workpiece in indentation test

2.2.5.1 Dry Condition

A sequence of images of the interface between sapphire tool and workpiece during indentation test without lubricant is shown in Fig. 2.30. The photographs are taken in the central region of the contact area. In Fig. 2.30, 0s indicates the time when the highest asperity starts to contact the tool surface. When the indentation proceeds, asperities are flattened by the flat sapphire tool. When the indentation time increases, the average area of the isolated real contact zones and the sum of the real contact area become larger. When the indentation time reaches 168 s, some of the distributed real contact zones start to interconnect. Figure 2.31 shows the relationship between real contact area and stress in the indentation and upsetting tests without lubricant.

In Fig. 2.31, the real contact area ratios in indentation and upsetting tests increase linearly with increasing stress up to a stress of 120 MPa. Over 120 MPa, the real contact area ratio in upsetting test increases rapidly, and on the other hand,

Fig. 2.31 Relationship between real contact area and stress in indentation and upsetting tests

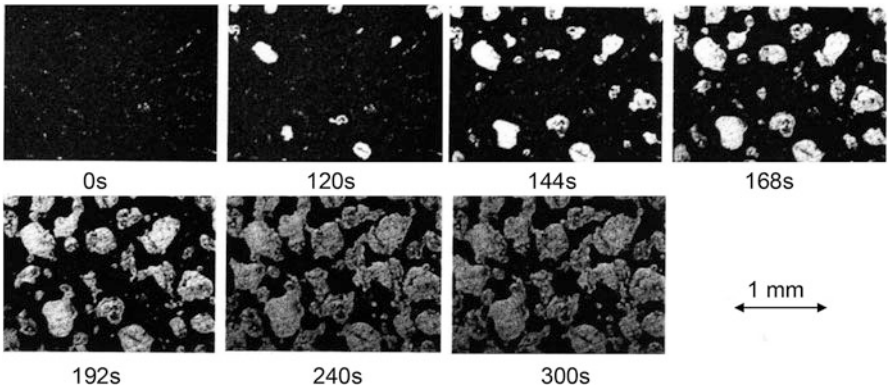
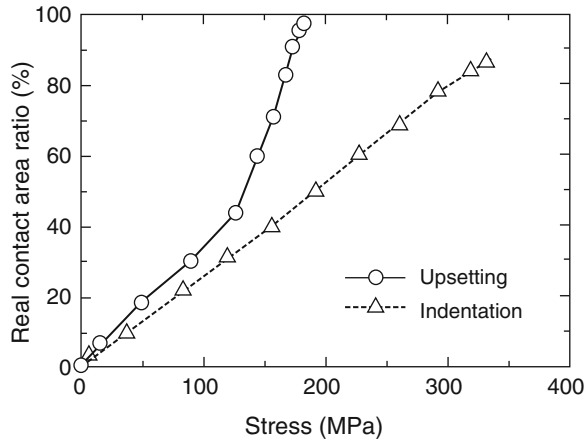


Fig. 2.32 Sequence appearances of interface between sapphire tool and workpiece in indentation test with lubricant A

the ratio in indentation test increases linearly with increasing stress. The difference of the real contact area ratio between indentation and upsetting tests is caused to the surrounding restraint of the bulk deformation. The bulk deformation in upsetting occurs at a stress of 120 MPa. On the other hand, the bulk deformation in indentation occurs at a stress of about 300 MPa. The value in indentation is about three times of that in upsetting.

2.2.5.2 Lubricated Condition

A sequence of appearances of the interface between sapphire tool and workpiece during indentation test with lubricant is shown in Fig. 2.32. The behavior of the asperity deformation in indentation test with lubricant is similar to that without lubricant up to about 200 s.

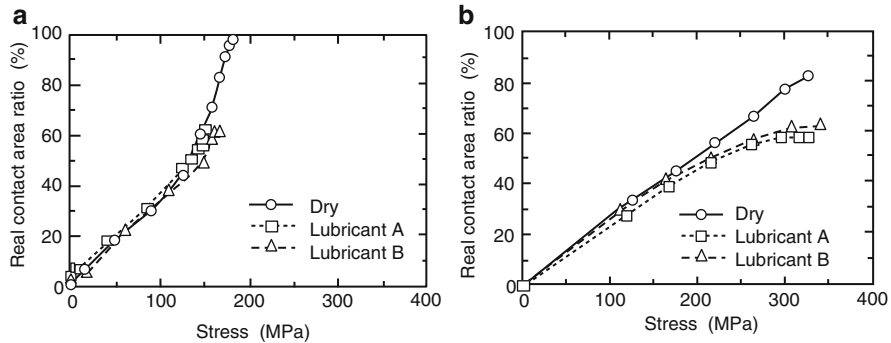


Fig. 2.33 Relationship between real contact area ratio and stress in upsetting (a) and indentation (b)

However, after about 200 s, some of the isolated real contact zones start to interconnect and the lubricants pool can be observed. Next, the relationships between real contact area and stress in upsetting and indentation with lubricant and without lubricant are shown in Fig. 2.33. In upsetting test with lubricant, the real contact area ratio increases linearly with increasing stress up to 120 MPa, and the values are in good agreement with that without lubricant. However, above 120 MPa, it increases abruptly and the value stops at 60 %. On the other hand, in indentation test with lubricant, the real contact area ratio increases with increasing stress, and above 150 MPa, the values are smaller than those without lubricant, and they reach a constant of 60 %.

From these experimental results, it can be understood that the asperity deformation depends on the bulk deformation in metalforming. The real contact area ratio increases linearly with increasing stress as derived by the Holm's theory, but it increases abruptly over the bulk-forming stress. Next, it can be also understood that after the lubricant is trapped within the pocket in metalforming with lubricant, the increases of the real contact area ratio decrease, and it becomes a constant value.

2.2.6 Micro-plastohydrodynamic Lubrication (Micro-PHL)

In the hydrostatic-boundary lubrication regime shown in Fig. 2.13, when the tool having a smooth surface moves in the tangential direction at a speed of V , it can be observed that the trapped lubricant within the surface pockets permeates into the real contact area as shown in Fig. 2.34 [13].

Azushima et al. [14] have tried to observe directly the permeation of the lubricant from the pocket to the real contact area using the newly developed apparatus for direct observation as shown in Fig. 2.35. The apparatus consists of a transparent die made of quartz, a microscope with a CCD video camera and a video system. The workpiece used is A1100 aluminum, 2 mm thick, 10 mm wide,

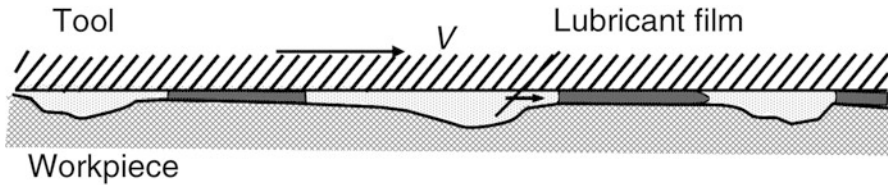


Fig. 2.34 Schematic representation of micro-plastohydrodynamic lubrication

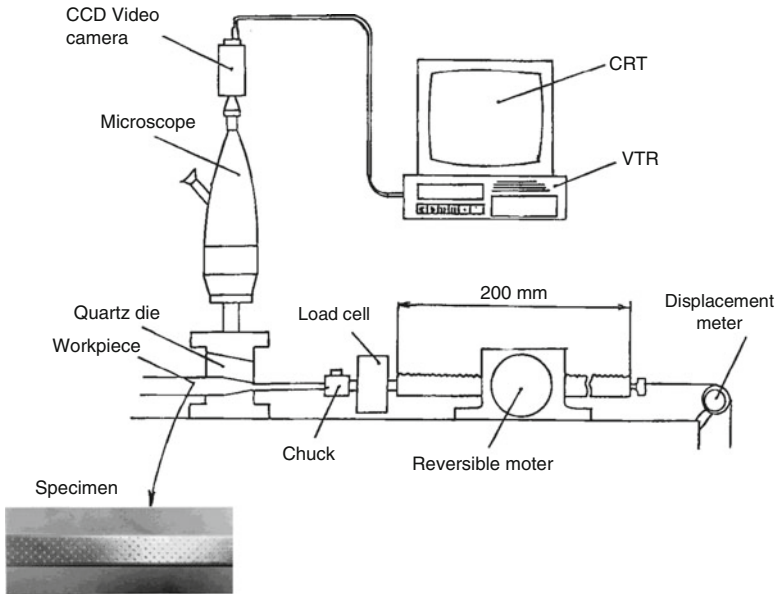


Fig. 2.35 Schematic representation of apparatus for direct observation

and 300 mm long. The specimen sheets are provided with uniformly distributed pyramidal indentation as shown in this figure. Drawing experiments are carried out at two speeds of 0.2 and 0.8 mm/s, changing the reduction in the range of 3–13 %. Three paraffinic oils with different viscosities are used.

The experimental results of the geometrical change of the pyramidal indentation are shown in Fig. 2.36. Figure 2.36a illustrates the sequence photographs of the working area taken during drawing at a drawing speed of 0.2 mm/s and at a reduction of 9.0 % with a lubricant having 100 cSt viscosity. When the lubricant is completely trapped in the surface pocket of the pyramidal indentation in the working area, the geometry observed does not change hardly during drawing. However, when the air in the pocket is introduced before the working area as shown in Fig. 2.36b, the geometry of indentation decreases largely with the deformation of workpiece. From these results, it will be seen that the hydrostatic pressure generated in the lubricant trapped completely in the pocket so that the indentation geometry in the working area does not change largely.

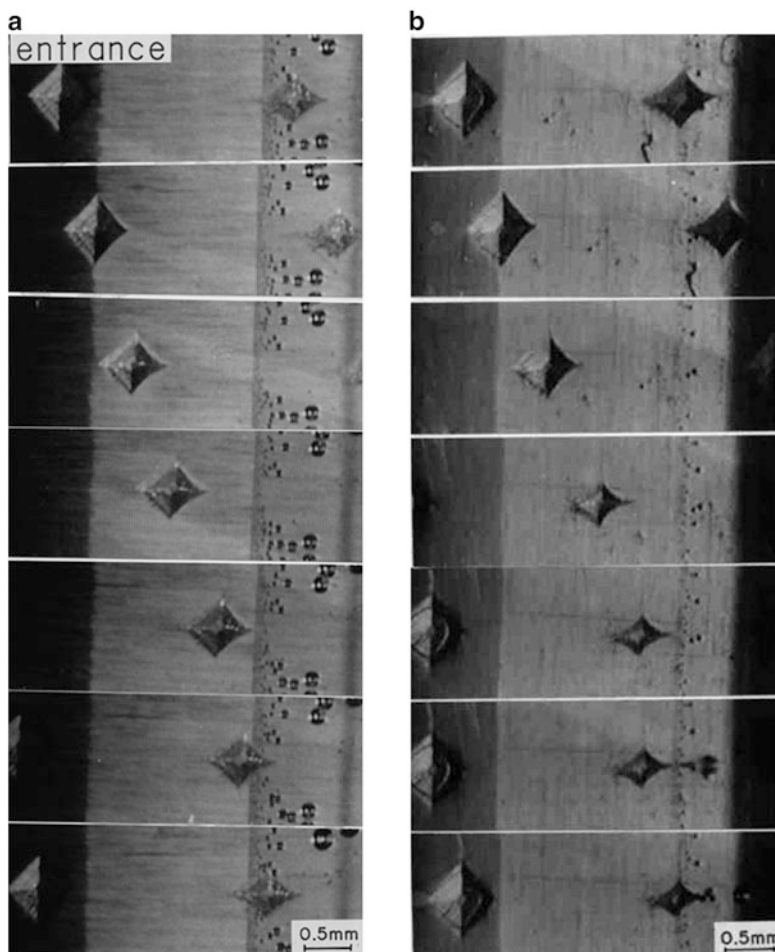


Fig. 2.36 Sequence photographs of surface of Alimimun sheet having pyramidal pockets with oil (a) and air (b) being drawn at a drawing speed 0.2 mm/s with oil having 100 cSt

Next, the experimental results of the behavior of the lubricant trapped in the pocket are shown in Fig. 2.37. From the detail observation of the figures, it can be understood that the lubricant trapped in the pocket is permeated to the real contact area. Figure 2.37a illustrates the sequence photographs of the working area taken during drawing with mixture lubricant added 4 % red paint to paraffinic oil having a viscosity 100 cSt at a speed of 0.8 mm/s and at a reduction of 9.7 %. It can be observed that the lubricant in the pocket permeates forward and backward at a same time into the real contact area. The permeation area on the real contact area extends with reduction. The amount of the forward-permeated lubricant from the pocket is larger than that of the backward-permeated lubricant.

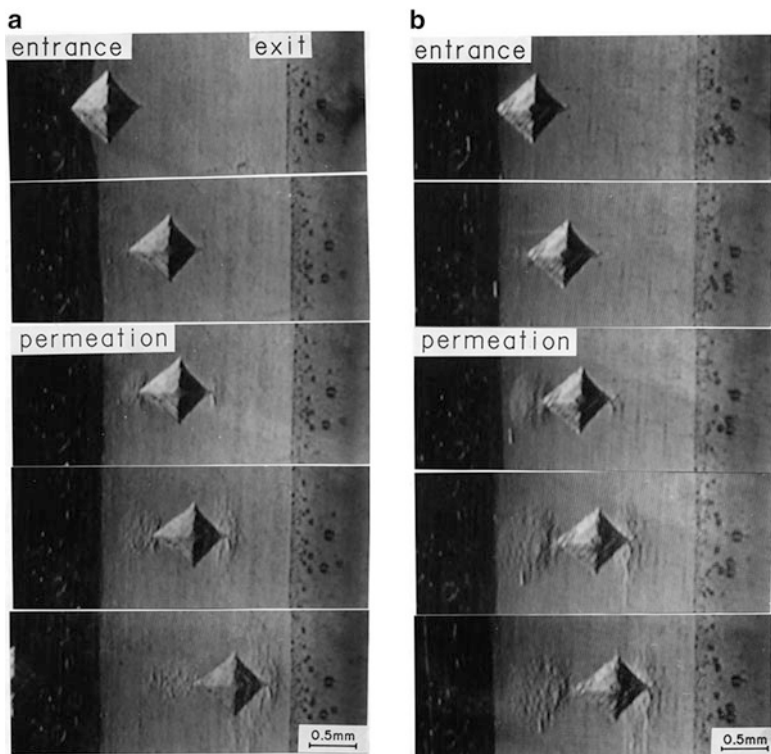


Fig. 2.37 Sequence photographs of permeation behavior of lubricant trapped in pyramidal pockets during sheet drawing at a drawing speed of 0.8 mm/s at a reduction of 9.7 % with oil having 100 cSt (a) and at a reduction of 9.2 % with oil having 1000 cSt

Figure 2.37b illustrates the sequence photographs of the working area taken during drawing with the mixture lubricant added 8 % red paint to paraffinic oil having a viscosity of 1000 cSt at a speed of 0.8 mm/s and at a reduction of 9.2 %. In this figure, the lubricant having higher viscosity seems to be squeezed much more backward into the real contact area. From these direct observations, it is seen that the permeation behavior of lubricant in the pocket depends considerably on the viscosity of lubricant.

Next, the behavior of lubricant permeation must be considered qualitatively. Figure 2.38 shows the schematic representation of two-dimensional model of the lubricant permeation. It is anticipated from the assessment of the lubricant pressure p_s in the surface pocket and the observation of the marked volume shrinkage of the pocket of pyramidal indentation shown in Fig. 2.37 that p_s reaches close to the pressure $p_r(x)$ on the real contact area when the workpiece undergoes bulk deformation. Moreover, it is well expected that p_d rises at the back margin on the pocket by the hydrodynamic effect depending on the product of viscosity of lubricant and drawing speed ηV .

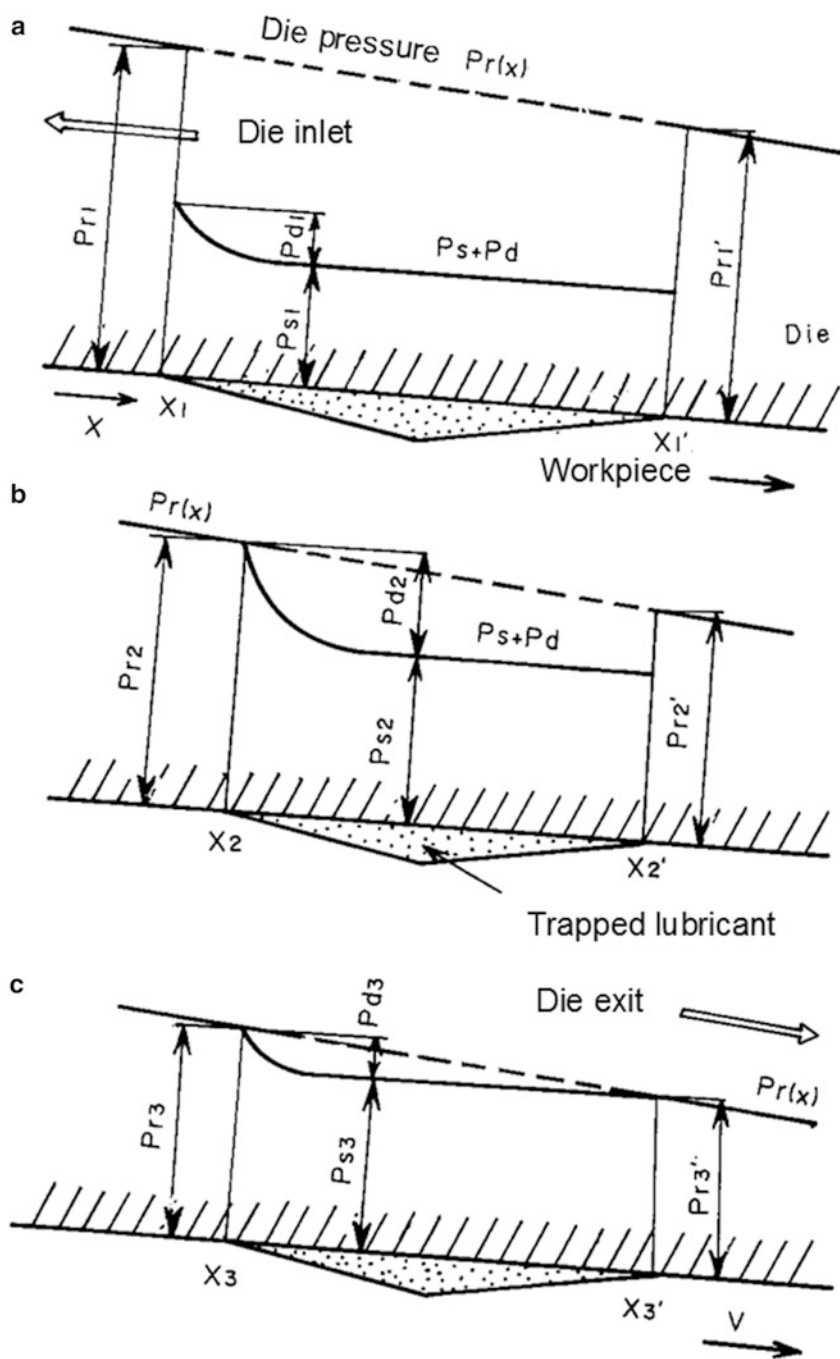


Fig. 2.38 Models to account for lubricant permeation from surface pocket into real contact surface area (a), backward permeation (b), and backward and forward permeations (c)

Fig. 2.39 Forward permeation and backward permeation

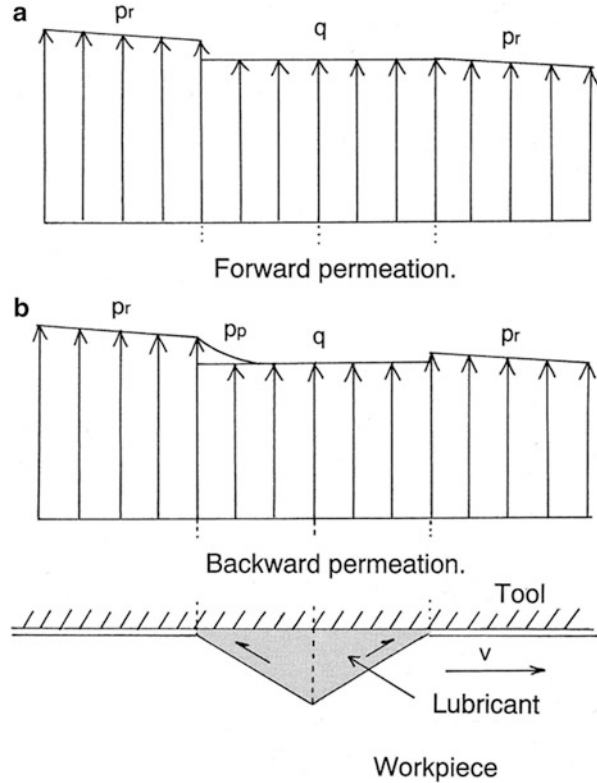


Figure 2.38a shows the general relation among $p_r(x)$, p_s , and p_d in the pocket. The hydrodynamic pressure p_d can be derived by the Reynolds equation. $p_r(x)$ generally decreases toward the tool exit in the drawing process, but p_s increases with the movement of the pocket from the tool entrance to the tool exit. It is well expected that $p_{s2} + p_{d2}$ is like to reach p_{r2} first (see Fig. 2.38b) when ηV is higher, thus resulting in backward permeation of the trapped lubricant. This model is in good agreement with the experimental results shown in Fig. 2.37b.

On the other hand, it is expected that p_{s3} is to reach p_{r3} at the front margin of the pocket and $p_{s3} + p_{d3}$ is to reach p_{r3} at the back margin as shown in Fig. 2.38c, thus resulting in forward permeation or backward permeation. Figure 2.39 shows the models of the forward permeation and the backward permeation.

2.2.7 Asperity Deformation in Sheet Metalforming

The direct observation of the micro-contact at the interface between tool with smooth surface and workpiece with random surface in metal sheet forming was carried out by Azushima [15]. Figure 2.40 shows the schematic representation of an

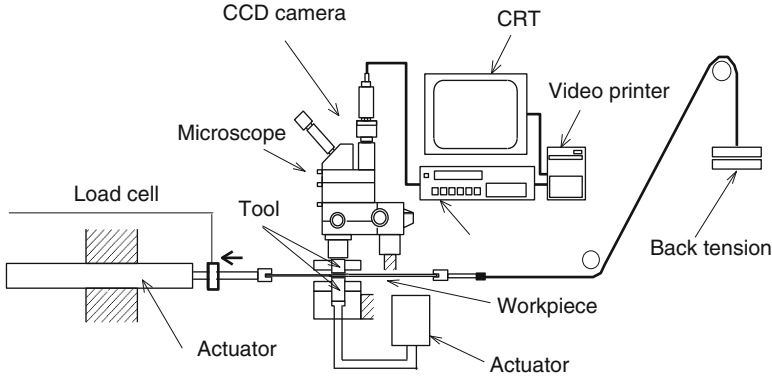
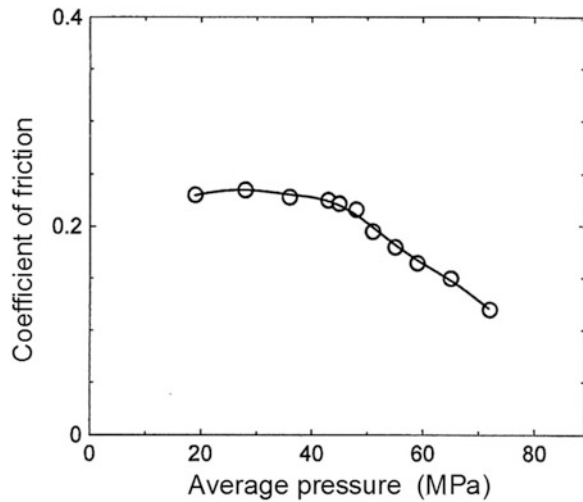


Fig. 2.40 Schematic representation of apparatus for in situ observation

Fig. 2.41 Relationship between coefficient of friction and average contact pressure



apparatus for in situ observation of the interface between tool and workpiece. The experimental apparatus consists of a pair of tool halves having flat surfaces: one is made of high-speed steel and the other is transparent quartz, a microscope with a CCD camera, and a video system. The model workpiece material is A1100 aluminum sheets with a random surface roughness of R_{max} 20 μm . The proof stress is 64 MPa. The experiments of the flat tool sheet drawing are carried out at a constant speed of 8.4 mm/min at six different average contact pressures within the range of 19–56 MPa. Paraffinic base oil having a viscosity of 1480 cSt with 5 % oleic acid is used as a lubricant.

Figure 2.41 illustrates the relationship between coefficient of friction and average contact pressure. The coefficient of friction remains constant at 0.23 up to an average contact pressure of 41 MPa and decreases from 0.23 to 0.12 over 41 MPa.

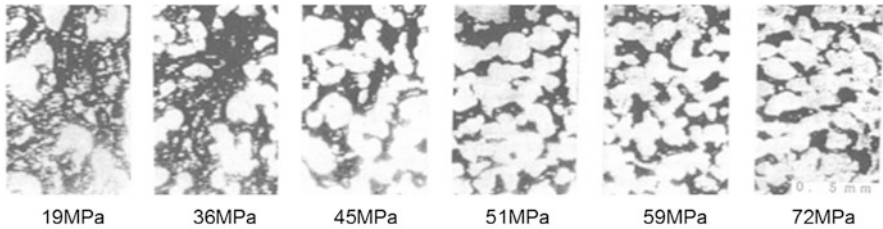


Fig. 2.42 Video images of aluminum workpiece for six different average contact pressure

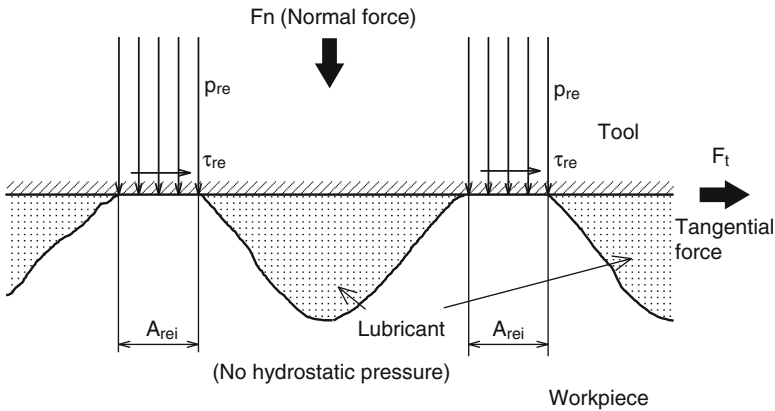


Fig. 2.43 Schematic representation of contact model between tool and workpiece in boundary lubrication

In Fig. 2.42, the interface appearances at six different average contact pressures from 19 to 72 MPa are compared. At low average contact pressures of 19 and 36 MPa, the real contact zones are isolated. The average area of the individual zones and the sum of the real contact area becomes larger when the pressure increases. The video photographs clearly show the free lateral flow of the lubricant under such lower contact pressures. When the normal contact pressure increases to 41 MPa, the real contact zones grow, and some of them start to connect so as to form closed lubricant pools in which no lateral flow is observable. Beyond 41 MPa, the number of isolated lubricant pockets increases gradually with increasing average contact pressure. When the average contact pressure increases to 59 MPa, the bright area of real contact suddenly becomes dull, suggesting that a kind of micro-roughening takes place. The contact area ratio at this stage is about 70 %.

In the lower pressures from 19 to 41 MPa, when it can be observed that the lubricant flows freely out through the interface gap, the coefficient of friction is constant. Accordingly, it is understood that the hydrostatic pressure within the lubricant is not generated and the lubrication mechanism can be accounted for the boundary lubrication regime as shown in Fig. 2.43.

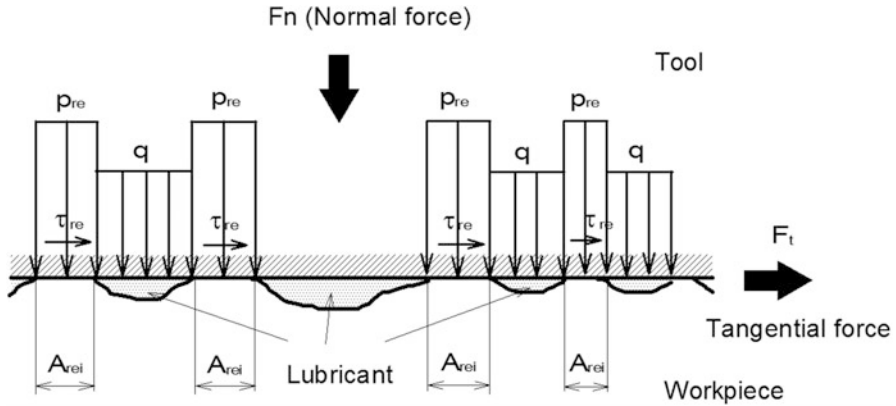


Fig. 2.44 Schematic representation of contact model between tool and workpiece in hydrostatic-boundary lubrication

Beyond the average contact pressure of 41 MPa, the coefficient of friction decreases with increasing average contact pressure p_m . In the pressure range from 41 to 51 MPa, it is confirmed from the CRT image of the interface that some of the real contact zones start to connect so as to form closed lubricant pools in which no lubricant flow is observable. Butler [16] first suggested that if the liquid lubricant is introduced at the interface, the lubricant is trapped within the pocket on the workpiece surface. Also, Kudo [17] and Wanheim and Bay [18] theoretically assessed the hydrostatic pressure q generated within the lubricant trapped in the surface pocket. The schematic representation of this hydrostatic-boundary lubrication is shown in Fig. 2.44.

Above an average contact pressure of 59 MPa, it is observed in the CRT image that the bright zone of real contact suddenly becomes dull, suggesting that a kind of micro-roughening takes place and that the lubricant trapped in the pocket permeates into the real contact area. In order to describe this phenomenon, Mizuno and Okamoto [19] proposed the concept of micro-plastohydrodynamic lubrication. Later, Azushima et al. [20] confirmed this hypothesis by observing the surface during sheet drawing through a transparent tool. The mechanism also supports the hypothesis that q approaches to p_{re} . The schematic representation of the lubrication mechanism is shown in Fig. 2.45.

Next, the micro-contact behavior at the interface between tool and workpieces with different surface topographies was observed in situ using the sheet drawing apparatus with flat dies for the direct observation, and the coefficients of friction were measured by Azushima et al. [21]. The specimens are A1100 aluminum sheets with five levels of surface topography. Figure 2.46 shows the surface microphotographs of specimens of A to E. The real contact area ratio and the surface roughness of specimens are summarized in Table 2.1. The drawing experiments are carried out at a constant speed of 0.14 mm/s in the range of 23–56 MPa using paraffinic oil having a viscosity of 1460 cSt with 5 % oleic acid.

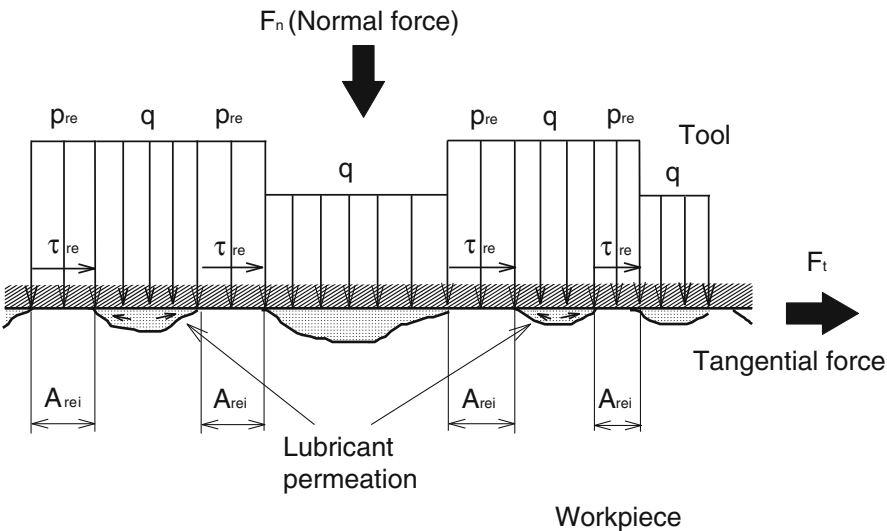


Fig. 2.45 Schematic representation of contact model between tool and workpiece in boundary-hydrostatic-micro-plastohydrodynamic lubrication

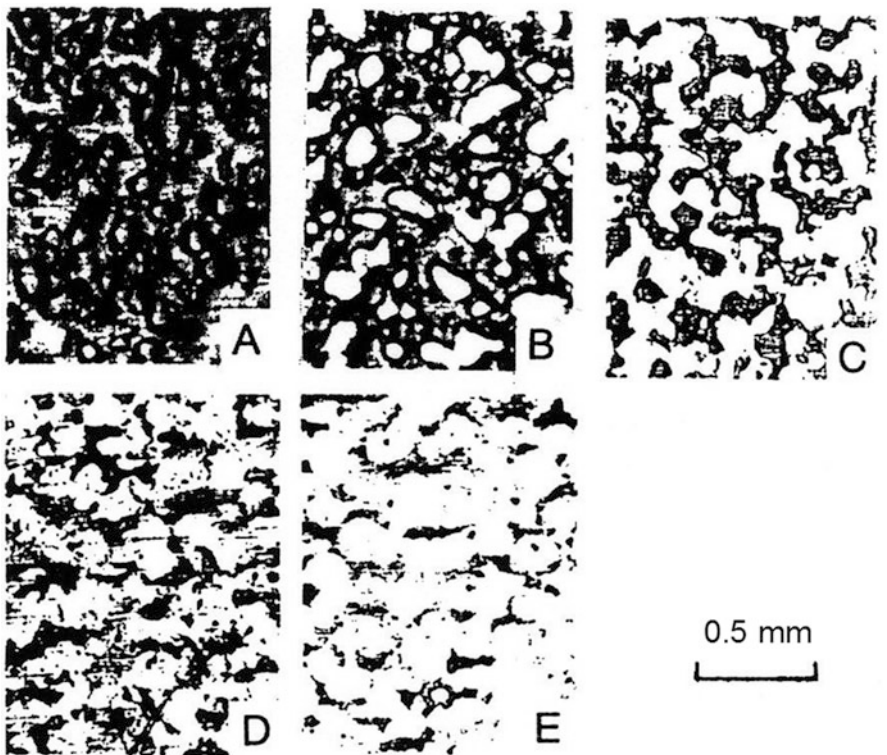


Fig. 2.46 Surface microphotographs of specimens of A to E

Table 2.1 Real contact area ratio and surface roughness of specimens

Specimen	Real contact area ratio	Surface roughness (Ra μm)
A	—	3.5
B	0.31	3.0
C	0.45	1.1
D	0.58	0.4
E	0.70	0.2

Fig. 2.47 Relationship between nominal coefficient of friction and average contact pressure

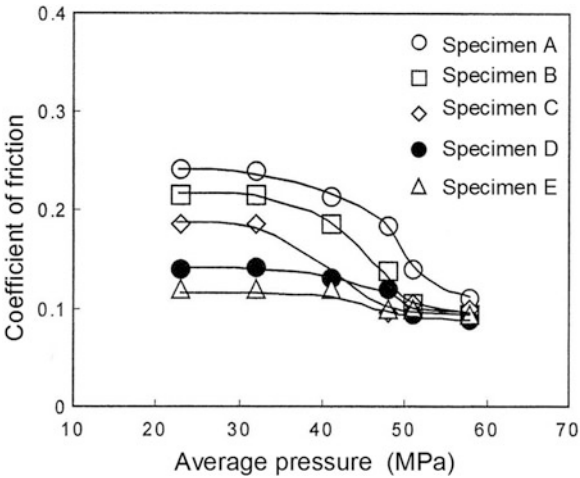


Figure 2.47 illustrates the relationship between coefficient of friction and average contact pressure. For the specimen A with random surface roughness, the coefficient of friction remains a constant of 0.23 in the lower average pressure up to 40 MPa and decreases from 0.23 to 0.1 over 40 MPa. The results are similar to those obtained in Fig. 2.41. For the specimen B with a real contact area ratio of 0.31, the coefficient of friction remains a constant of 0.23 up to 31 MPa and decreases to 0.1. For the specimen C with a ratio of 0.45, the coefficient of friction is 0.18 up to 31 MPa and it decreases to 0.1. For the specimens D and E with higher ratios of 0.56 and 0.70, the coefficients of friction are 0.13 and 0.12 up to 40 MPa. From these results, it is found that the higher the real contact area ratio becomes, the lower the coefficient of friction becomes in the lower average pressure.

In Fig. 2.48, the surface photographs of specimen D at six different average pressures are compared. In the lower average pressure, the pools trapping the lubricant can be observed. In this region, since the lubrication regime is the hydrostatic-boundary lubrication, the coefficient of friction becomes lower compared to that under the boundary lubrication. In higher average pressure, the permeation of the trapped lubricant into the real contact area cannot be observed, unlike the results obtained in Fig. 2.42. It is understood that in sheet drawing with flat dies, if the sheets with the real contact area ratio above 50 % are used, the coefficients of friction become lower.

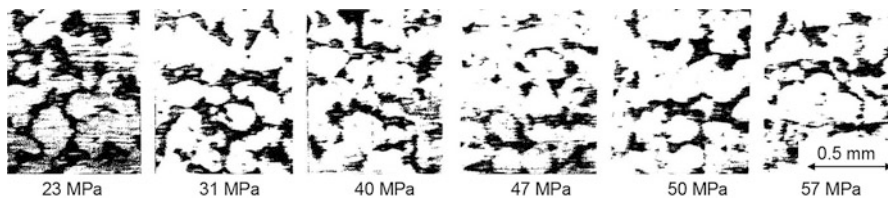
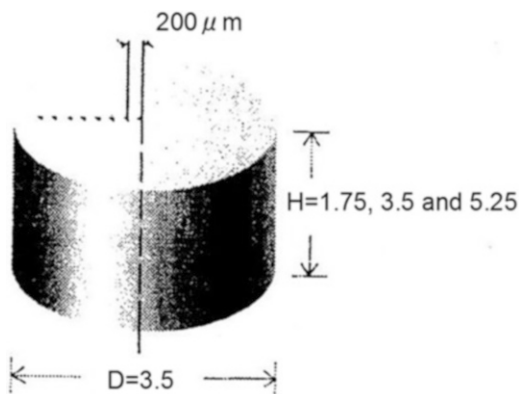


Fig. 2.48 Surface photographs of specimen D in six different average pressures

Fig. 2.49 Dimensions of cylindrical specimen



2.2.8 Oil Pocket Behavior on Edge Surface of Cylindrical Billet in Upsetting Process

Azushima and Tanaka [22] examined the behavior of the pockets filled with lubricant on the edge surface of the cylindrical billet in lubricated upsetting using direct fluorescent observation technique. The workpiece material is A1050 aluminum. The cylindrical specimens with a constant diameter of 3.5 mm and heights of 1.75, 3.5, and 5.25 mm are used. The top surface is provided with uniformly distributed pyramidal indentation by micro-Vickers hardness testing machine as shown in Fig. 2.49. The distance between pyramidal indentations is 200 μm , a side of the square of indentation is 120 μm , and the depth is 20 μm . The upsetting experiments are carried out at a constant compression speed of 0.3 mm/min up to a reduction in height of 50 %. Paraffinic mineral oil with 1 wt% thiophene compound is used as a lubricant.

In Fig. 2.50, the sequential photographs of the cylindrical specimen illuminated by UV light with a ratio of height to diameter H/D of 0.5 for six different reductions in height are compared. At the beginning of upsetting, lubricant is trapped within eight pyramidal indentations. Each size of pyramidal indentations decreases with increasing reduction in height. The size changes of pyramidal indentation in the

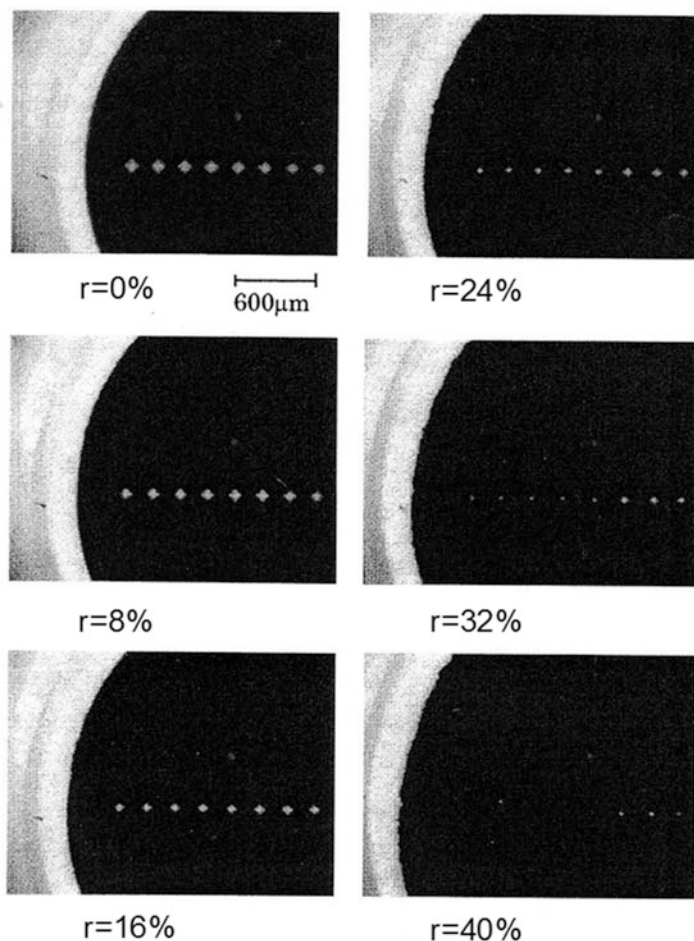


Fig. 2.50 Sequential photographs of cylindrical specimen with ratio H/D of 0.5 illuminated by UV light

peripheral region are larger than those in the central region, and at a reduction in height of 40 %, some pyramidal indentations in the peripheral region disappear.

From these observed results, it is understood that the lubricant trapped within the pyramidal indentation permeates into the contact area with reduction in height. The permeated lubricant volume in the peripheral region is larger than those in the central region. In Fig. 2.51, the sequential photographs of the cylindrical specimen with a ratio H/D of 1.5 illuminated by UV light are compared. In lower reduction in height, each size of the pyramidal indentation in the central region remains nearly constant and those in the peripheral region decrease slightly with increasing reduction in height. From Figs. 2.50 and 2.51, the large difference between the cylindrical specimens with the ratios of 0.5 and 1.5 can be observed. The behavior

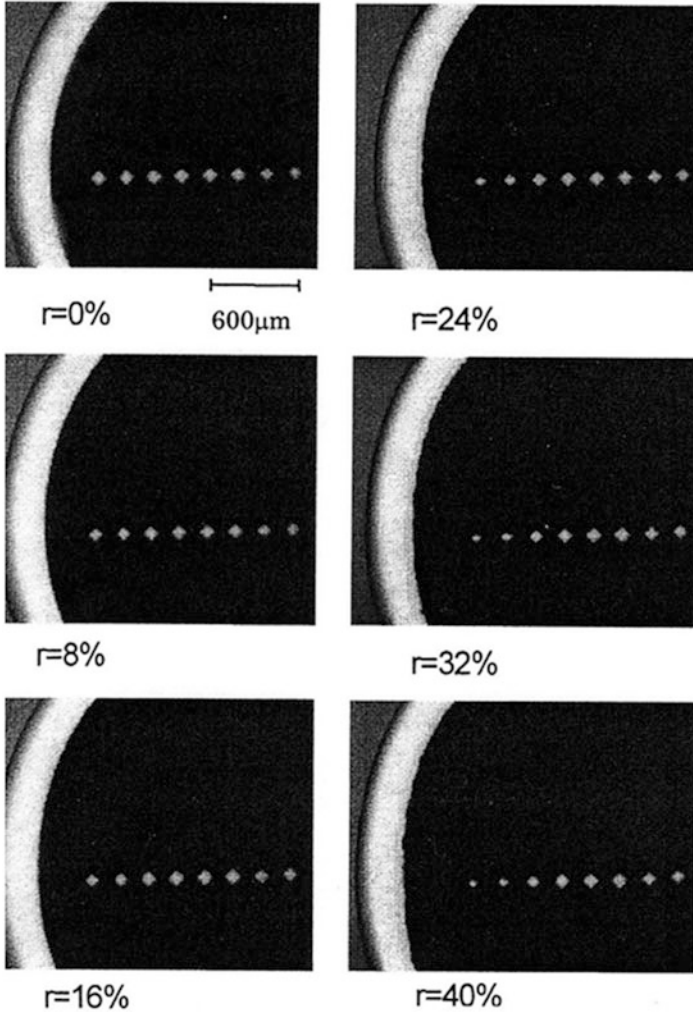


Fig. 2.51 Sequential photographs of cylindrical specimen with ratio H/D of 1.5 illuminated by UV light

of the pockets filled with lubricant on the edge surface of the cylindrical specimen depends on the specimen geometry and the pocket position.

Next, in Fig. 2.52 the in situ 3D geometries of the pyramidal indentation which is situated at the third position from the center on the end surface of the cylindrical specimen with a ratio H/D of 0.5 are compared. The large volume change of third pyramidal indentation with reduction in height can be visualized clearly. The volume of the pyramidal indentation can be measured using an image processor. Figure 2.53 shows the relationship between nondimensional volume and reduction in height of the specimen with a ratio H/D of 0.5 shown in Fig. 2.50.

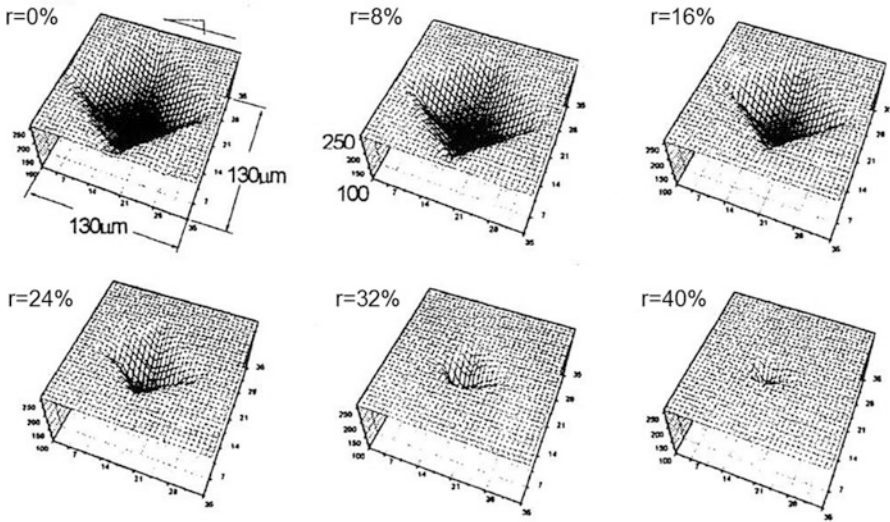


Fig. 2.52 In situ 3D geometries of pyramidal indentation

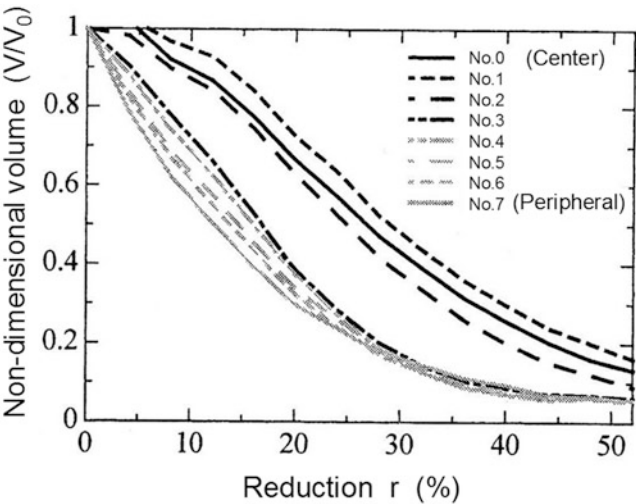


Fig. 2.53 Relationship between nondimensional volume and reduction in height of specimen with ratio H/D of 0.5

The nondimensional volume of each pyramid indentation decreases largely with increasing reduction in height. Figure 2.54 shows the volume change of each pyramidal indentation with reduction in height for specimen with a ratio of 1.5 shown in Fig. 2.51.

The volume of pyramidal indentation in the central region remains constant up to the medium reduction and decreases slightly in the higher reduction. On the other

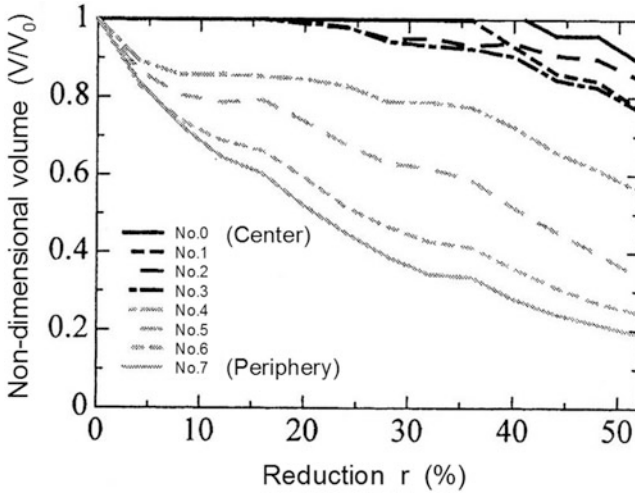


Fig. 2.54 Relationship between nondimensional volume and reduction in height of specimen with ratio of 1.5

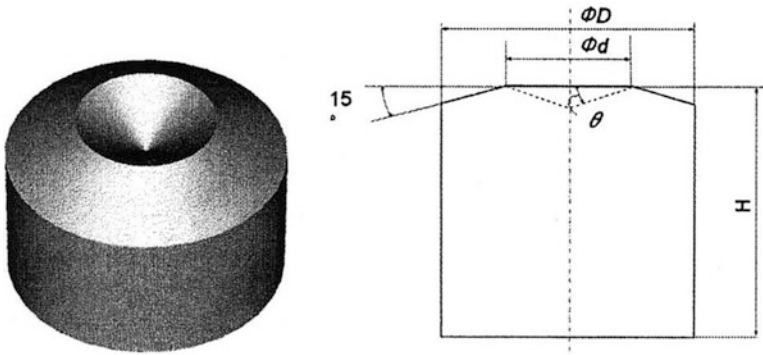


Fig. 2.55 Dimensions of specimen with central conical dent

hand, the volume of pyramidal indentation in the peripheral region decreases with increasing reduction in height. In a reduction in height of 50 %, the large difference between pocket volumes in the central and peripheral regions is observed. From these results, it can be understood that the permeation of the lubricant entrapped within the pyramidal indentation occurs and the permeated lubricant volume increases with increasing reduction in height. The permeation affects by the relationship between hydrostatic pressure generated within entrapped oil and normal pressure acting on the contact area.

Next, Azushima et al. [23] observed the permeation behavior of the lubricant entrapped within pocket into the real contact area on the end surface of cylinder specimen with a central conical dent. Figure 2.55 shows the dimensions of

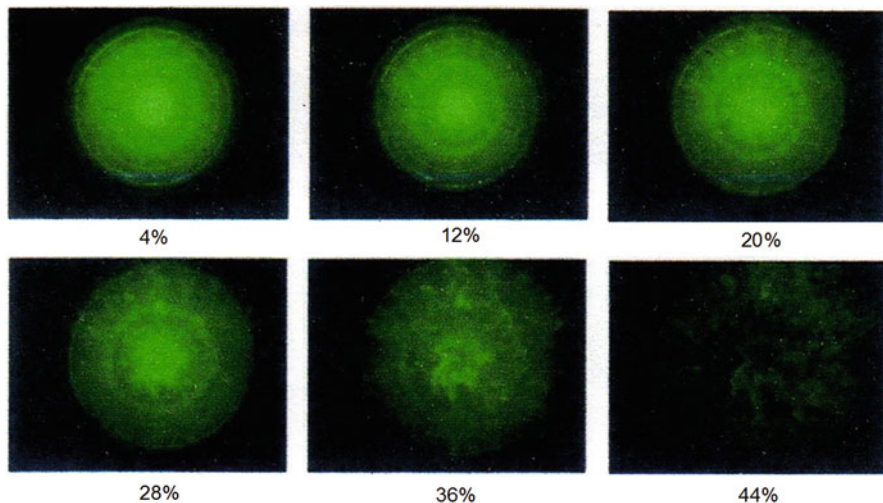


Fig. 2.56 Sequence appearance of interface between sapphire tool and end surface of cylinder with central conical dent

cylinder specimen. The specimen material is A1070H aluminum. The yield stress of specimen is 110 MPa. The diameter of specimen D is 2.5 mm, the height H is 2.5 mm, the diameter of recess d is 1.25 mm, and the cone flank angle θ is 15° . The upsetting experiments are carried out at a constant compression speed of 1.0 mm/min up to a reduction in height of 50 %. Paraffinic mineral oil with a viscosity of 142 cSt with 1 % thiophene compound is used as a lubricant.

Figure 2.56 shows the sequence photographs of the interface illuminated with UV light between sapphire tool and end surface of the cylinder at six different reductions in height of 4, 12, 20, 28, 36, and 44 %. At the beginning of upsetting, the contact shape of the central conical dent is round. As upsetting proceeds, the contact shape changes from the smooth circle to the serrated circle. The serration degree of the circle becomes remarkable with increasing reduction in height. At a reduction in height of 44 %, the outline of the central conical dent becomes blurred, so that the lubricant entrapped within the conical dent permeates into the peripheral contact area.

Figure 2.57 shows the profiles of the end surface using the fluorescent observation technique. At the beginning of upsetting, the profile exhibits the original shape. Up to a reduction in height of 28 %, the lubricant is entrapped within the conical dent, and the shape changes slightly due to the compressibility of lubricant. However, at 44 % the profile becomes flat and the lubricant permeates into the peripheral contact area.

Then, the volume of the lubricant entrapped within the central conical dent is calculated by integrating the visible light intensity. Figure 2.58 shows the relationship between volume changing fraction and reduction in height. The lubricant volume entrapped within the conical dent decreases gradually with increasing

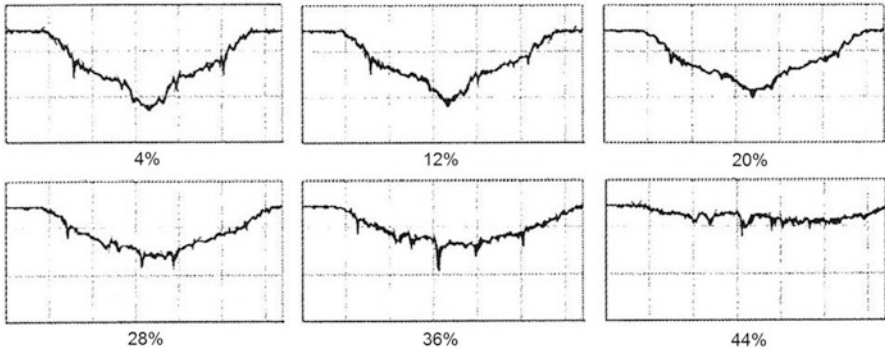
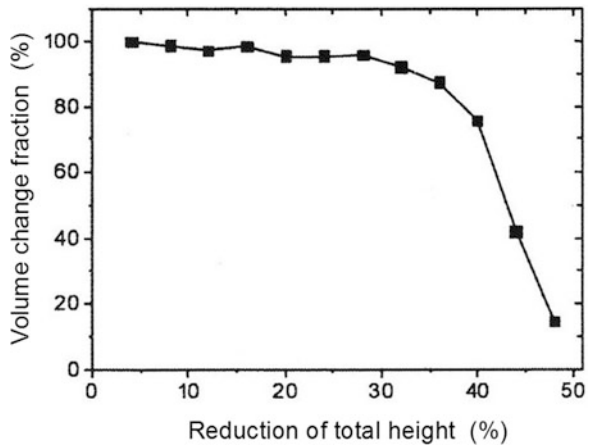


Fig. 2.57 Profiles of end surface of cylindrical specimen using fluorescent observation technique

Fig. 2.58 Relationship between volume, changing fraction, and reduction



reduction in height up to 36 %, and above 36 %, it decreases abruptly. The volume change is due to the compressibility of lubricant up to 36 %, and above 36 % the permeation of the entrapped lubricant into the contact area occurs.

Moreover, the hydrostatic pressure accompanied with the bulk deformation of the specimen is calculated using FEM-coupled analysis. Figure 2.59 shows the relationship among hydrostatic pressure, average die pressure, equivalent stress, contact area ratio, and reduction in height at the boundary between the conical dent and the real contact area. The hydrostatic pressure increases abruptly with increasing reduction in height up to 2 %. Then, it decreases gradually with increasing reduction in height up to 15 %, and above 15 %, it increases gradually. The average die pressure also increases abruptly with increasing reduction in height up to 1 %, and then it decreases up to 15 %, and above 15 %, it becomes stable. At a reduction in height of 37 %, the hydrostatic pressure exceeds the average die pressure. It is estimated that the entrapped lubricant permeates into the contact area when the hydrostatic pressure exceeds the average die pressure.

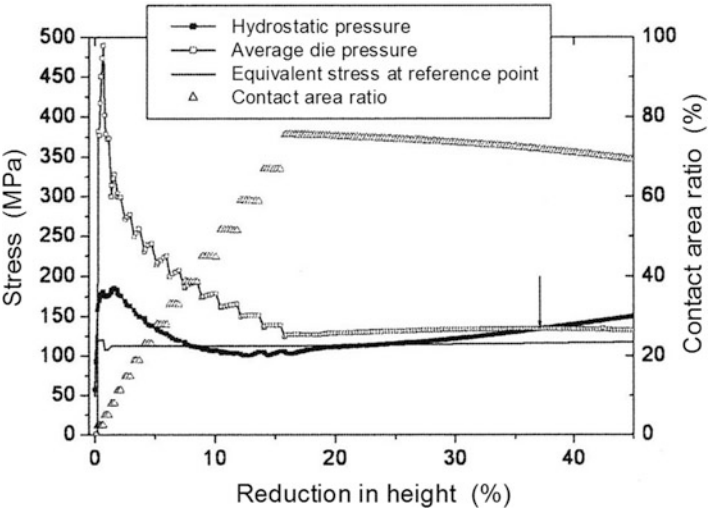


Fig. 2.59 Relationship among hydrostatic pressure, average die pressure, equivalent stress, contact area ratio, and reduction in height

2.3 Lubrication Mechanism and Frictional Stress

2.3.1 Lubrication Mechanism

As described in the Stribeck curve (see Fig. 1.15) in Sect. 1.2.2, the lubrication regimes in the machine elements are classified into the hydrodynamic lubrication, the mixed lubrication, and the boundary lubrication as follows:

I	$h \gg R$ ($\lambda > 4$)	Hydrodynamic lubrication
II	$h \approx R$ ($4 > \lambda > 1$)	Mixed lubrication (hydrodynamic lubrication + boundary lubrication)
III	$h \rightarrow 0$ ($1 > \lambda$)	Boundary lubrication

On the other hand, as described in the lubrication regimes in metalforming, the hydrostatic lubrication and the micro-plastohydrodynamic lubrication must be considered in addition to the three lubrication regimes which are the plasto-hydrodynamic lubrication, the mixed lubrication, and the boundary lubrication. Figure 2.60 shows the schematic representation of the lubrication regimes in metalforming.

The lubrication regimes in metalforming are classified as follows:

I	$h \gg R$ ($\lambda > 4$)	Plastohydrodynamic lubrication
II	$h \approx R$ ($4 > \lambda > 1$)	Mixed lubrication (plastohydrodynamic lubrication, micro-plastohydrodynamic lubrication, hydrostatic lubrication, and boundary lubrication)
III	$h \rightarrow 0$ ($1 > \lambda$)	Boundary lubrication

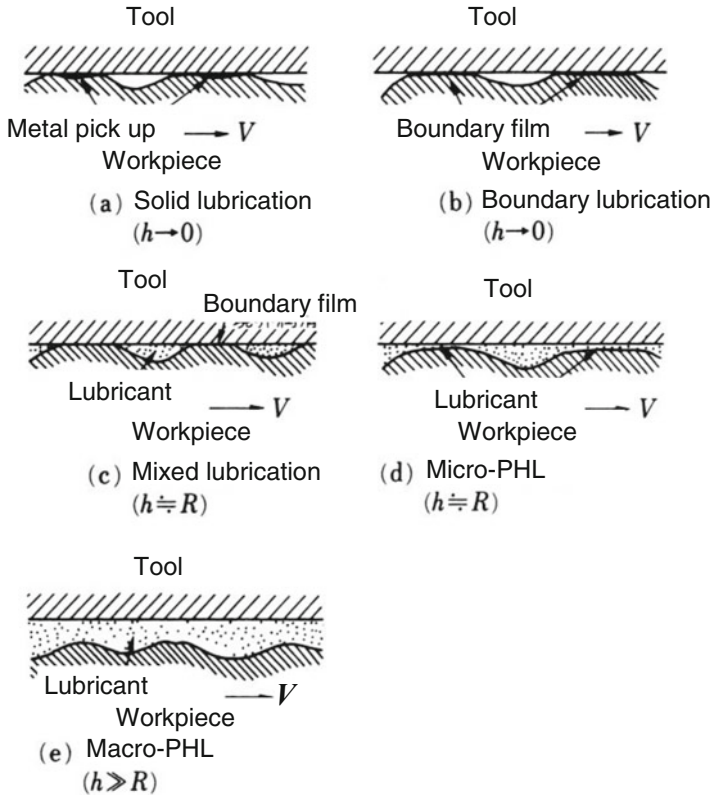


Fig. 2.60 Schematic representation of lubrication regimes in metalforming

2.3.2 Frictional Stress

2.3.2.1 Plastrohydrodynamic Lubrication

Figure 2.61 shows the schematic representation of the two-dimensional lubricant flow channel in metalforming with bulk deformation.

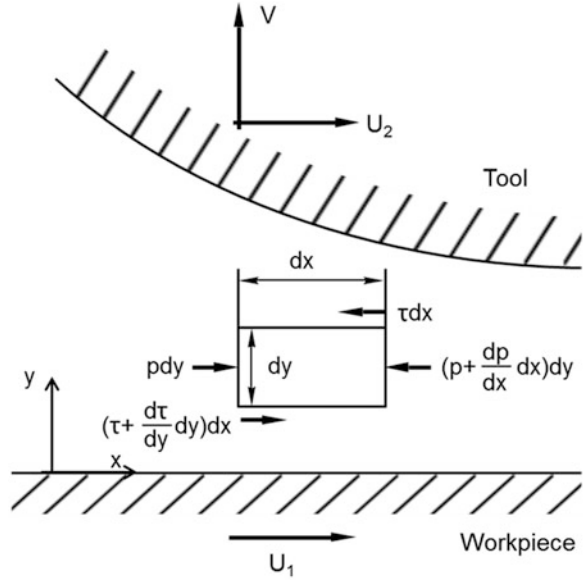
The frictional shear stress τ_{hf} in the plastrohydrodynamic lubrication is given by

$$\tau_{hf} = \eta \frac{\partial u}{\partial y} \quad (2.9)$$

From the boundary conditions of $u = U_1$ at $y = 0$ and $u = U_2$ at $y = h$, u is given by Eqn. (1.19). As the Poiseuille flow can be neglected in the working contact region between tool and workpiece, u is derived by

$$u = \left\{ U_1 + (U_1 - U_2) \frac{h - y}{h} \right\} \quad (2.10)$$

Fig. 2.61 Schematic representation of two-dimensional lubricant flow channel in metalforming



The frictional shear stress is derived by substituting Eqn. (2.10) into Eqn. (2.9) as follows:

$$\tau_{hf} = \eta \frac{U_1 - U_2}{h} \quad (2.11)$$

2.3.2.2 Boundary Lubrication

Figure 2.62 shows the schematic representation of the boundary lubrication in metalforming with bulk deformation.

In this boundary lubrication model in metalforming with bulk deformation, the average normal pressure acting on the working contact region between tool and workpiece is given instead of Bowden and Tabor's boundary lubrication model in machine element. Then, the normal load P and the tangential force T are given by

$$P = p_a A \quad T = \tau_b A \quad (2.12)$$

where A is the plastic contact area, p_a is the average normal pressure, and τ_b is the boundary shear stress.

The boundary shear stresses τ_b are given by two friction models of the friction law of Eqn. (2.1) and the frictional shear factor model, and they are as follows:

$$\tau_b = \mu_b p_a \leq k \quad (2.13)$$

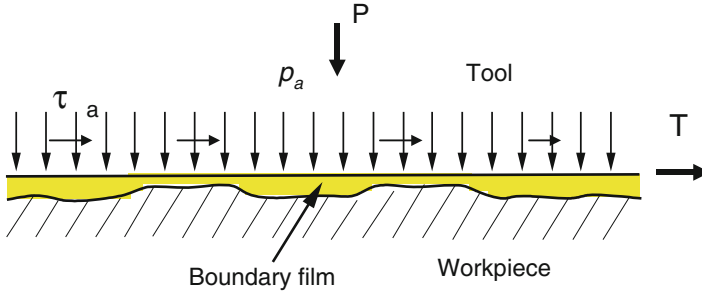


Fig. 2.62 Schematic representation of boundary lubrication in metalforming with bulk deformation

$$\tau_b = mk \quad (2.14)$$

where m is the frictional shear factor ($0 \leq m \leq 1$) and k is the yield shear stress of metal. In this book, the friction law of Eqn. (2.1) is used in the boundary lubrication in metalforming.

2.3.2.3 Micro-plastohydrodynamic Lubrication

The schematic representation of the micro-plastohydrodynamic lubrication in metalforming with bulk deformation is shown in Fig. 2.34. The frictional shear stress τ_{mf} in the micro-plastohydrodynamic in metalforming with bulk deformation is given by the next equation similar to Eqn. (2.9) in the hydrodynamic lubrication:

$$\tau_{mf} = \eta \frac{\partial u}{\partial y} \quad (2.15)$$

From the boundary conditions of $u = U_1$ at $y = 0$ and $u = U_2$ at $y = h$, the frictional shear stress is given by the next equation similar to the plastohydrodynamic lubrication:

$$\tau_{mf} = \eta \frac{U_1 - U_2}{h} \quad (2.16)$$

2.3.2.4 Mixed Lubrication

There are the plastohydrodynamic lubrication, the micro-plastohydrodynamic lubrication, the hydrostatic lubrication, and the boundary lubrication in the lubrication regimes in metalforming. In the mixed lubrication, a combination of various regimes of lubrication can be considered. In this chapter, the typical combinations are discussed.

(a) Combination of hydrodynamic lubrication and boundary lubrication

This mixed lubrication is explained in Sect. 1.2.6. The normal load in the mixed lubrication P is given by

$$P = p_r \alpha A + p_f (1 - \alpha) A \quad (1.48)$$

On the other hand, the frictional force F is given by

$$F = \tau_b \alpha A + \tau_f (1 - \alpha) A \quad (1.49)$$

From Eqn. (1.49), the frictional shear stress in the mixed lubrication can be derived by

$$\tau_{mixh} = \alpha \tau_b + (1 - \alpha) \tau_f \quad (2.17)$$

The coefficient of friction in the mixed lubrication is given by

$$\mu = \frac{F}{P} = \frac{\tau_b \alpha + \tau_f (1 - \alpha)}{p_r \alpha + p_f (1 - \alpha)} \quad (1.52)$$

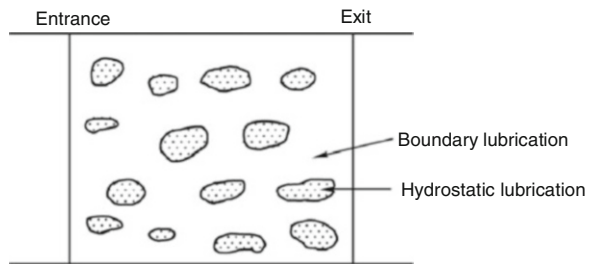
Now, since it can be assumed that $\tau_b \gg \tau_f$ and $p_r = p_f = p_a$ in metalforming with bulk deformation, the coefficient of friction and the frictional stress are given by

$$\mu_{mixh} = \alpha \mu_b, \quad \tau_{mixh} = \alpha \tau_b \quad (2.18)$$

(b) Combination of hydrostatic lubrication and boundary lubrication

Figure 2.63 shows the schematic representation of the mixed lubrication of the hydrostatic lubrication and the boundary lubrication. In this mixed lubrication, the total normal load is supported by a part of the hydrostatic pressure within the lubricant pocket and by another part of the real contact area. On the other hand, the total frictional force is supported by a part of the adhesion force on the real contact area. In Fig. 2.63, it is defined that the ratio of the boundary lubrication region is α and the contact area is A .

Fig. 2.63 Schematic representation of mixed lubrication of hydrostatic lubrication and boundary lubrication



The normal load in the mixed lubrication P is given by

$$P = p_r \alpha A + q(1 - \alpha)A \quad (2.19)$$

where q is the hydrostatic pressure generating within the lubricant pocket. On the other hand, since the frictional shear stress acting on the working contact region between tool and lubricant trapped within the pocket is 0, the frictional force F is given by

$$F = \tau_b \alpha A = \mu_b p_r \alpha A \quad (2.20)$$

From Eqn. (2.13), the frictional shear stress in the mixed lubrication can be derived by

$$\tau_{mixs} = \alpha \tau_b \quad (2.21)$$

The coefficient of friction in the mixed lubrication is given by

$$\mu_{mixs} = \frac{\mu_b}{1 + \frac{q}{p_r} \left(\frac{1 - \alpha}{\alpha} \right)} \quad (2.22)$$

Now, when it can be assumed that $p_r = q = p_a$ in metalforming with bulk deformation, the coefficient of friction and the frictional stress are given by

$$\mu_{mixs} = \alpha \mu_b, \quad \tau_{mixs} = \alpha \tau_b \quad (2.23)$$

(c) Combination of hydrodynamic lubrication, hydrostatic lubrication, and boundary lubrication

Figure 2.64 shows the schematic representation of the mixed lubrication of the hydrodynamic lubrication, the hydrostatic lubrication, and the boundary lubrication.

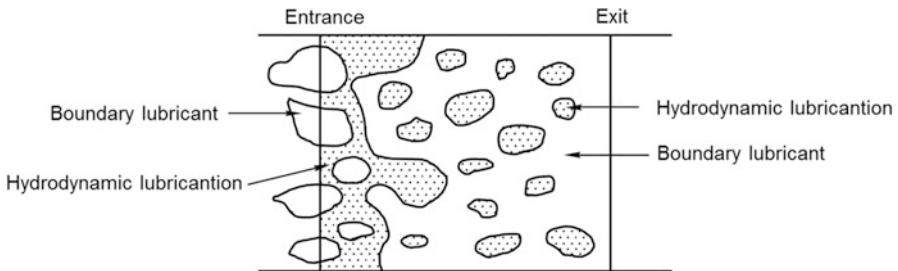


Fig. 2.64 Schematic representation of mixed lubrication of hydrodynamic lubrication, hydrostatic lubrication, and boundary lubrication

In Fig. 2.64, α is the ratio of the boundary lubrication region, β is the ratio of the hydrodynamic lubrication, and γ is the ratio of the hydrostatic lubrication. The ratios change from entrance to exit and the following relationship satisfies:

$$\alpha + \beta + \gamma = 1 \quad (2.24)$$

The normal load in the mixed lubrication P is given by

$$P = p_r \alpha A + p_f \beta A + q \gamma A \quad (2.25)$$

On the other hand, the frictional force F is given by

$$F = \tau_b \alpha A + \tau_f \beta A \quad (2.26)$$

From Eqn. (2.26), the frictional shear stress in the mixed lubrication can be derived by

$$\tau_{mixhs} = \alpha \tau_b + \beta \tau_f \quad (2.27)$$

The coefficient of friction in the mixed lubrication is expressed as follows:

$$\mu_{mixhs} = \frac{F}{P} = \frac{\tau_b \alpha + \tau_f \beta}{p_r \alpha + p_f \beta + q \gamma} \quad (2.28)$$

Now, when it can be assumed that $\tau_b \gg \tau_f$ and $p_r = p_f = q = p_a$ in metalforming with bulk deformation, the coefficient of friction and the frictional stress are given by

$$\mu_{mixhs} = \alpha \mu_b, \quad \tau_{mixhs} = \alpha \tau_b \quad (2.29)$$

2.4 Lubrication Mechanism and Surface Appearance of Workpiece

2.4.1 *Plastohydrodynamic Lubrication*

When the thicker lubricant film exists at the interface between tool and workpiece and the asperities on the workpiece surface do not contact on the tool surface in the plastohydrodynamic lubrication, it is known that the free surface roughening of workpiece occurs. The free surface roughening is explained in Sect. 2.2.4. At the beginning of plastic deformation, the thick film is introduced or entrapped between tool and workpiece. When the plastic deformation proceeds, the free surface roughening on the workpiece surface occurs. When the free surface roughening

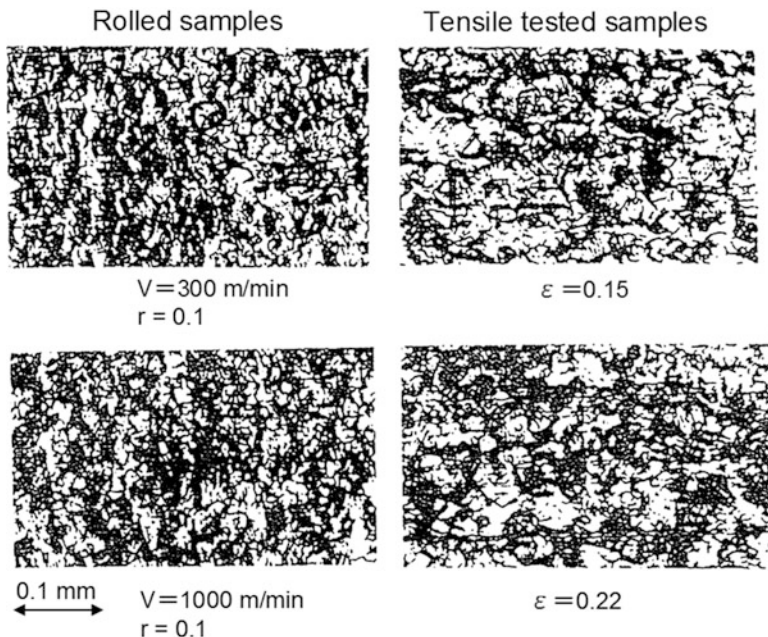


Fig. 2.65 Comparison of surface photographs of rolled samples with tensile-tested samples

becomes larger, asperities on the workpiece surface start to contact. It is shown that the surface roughness R_0^{mate} depends on the grain size and strain and is given by

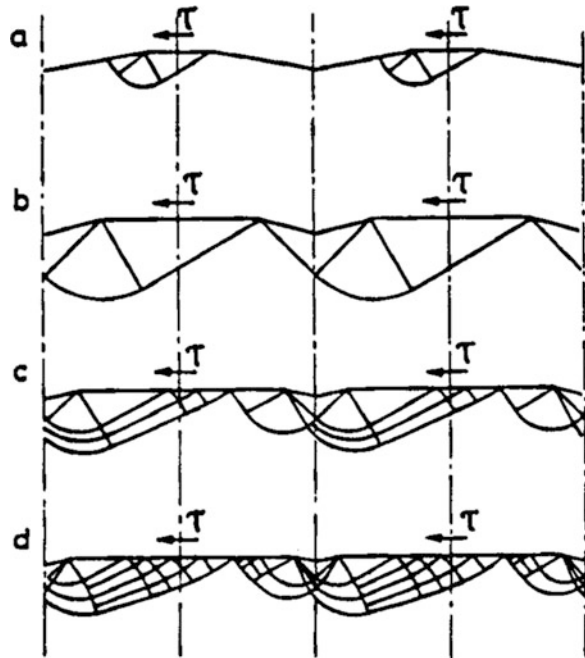
$$\begin{aligned} R_0^{mate} &= R_0 & (R_0^{mate} \leq R_0) \\ R_0^{mate} &= R_0 + c(\varepsilon - \varepsilon_0)D & (R_0^{mate} \geq R_0) \end{aligned} \quad (2.8)$$

Figure 2.65 shows the comparison of the surface photographs of samples rolled under the plastrohydrodynamic lubrication with the surface photographs of samples subjected to tensile deformation. The surface appearances of rolled sample and tensile test sample are significantly similar.

2.4.2 Boundary Lubrication

In order to manufacture the products with smooth surface, the boundary lubrication is used widely in metalforming. First, the flattening of asperities on the workpiece surface by the flat tool is explained. In Sect. 1.1.2, the plastic flattening of asperities of workpiece surface by flat tool surface in the absence of the macroscopic sliding under dry friction is explained in the tribology of machine elements. A concept of the real contact area which corresponds to the flattened area of asperities is

Fig. 2.66 Slip line field of regular arrays of wedge-shaped ridges deforming [24]



proposed by Holm. Tabor reported that when the tangential force in the presence of the macroscopic sliding acts, the real contact area increases with increasing coefficient of friction.

In the metalforming process, the slip-line solution for regular arrays of wedge-shaped ridges deforming under a high pressure and with an interfacial shear stress in combination with the asperities is reported by Bay and Wanheim [24]. Figure 2.66 shows the slip-line field and Fig. 2.67 shows the relationship between real contact area ratio and nondimensional pressure. The theoretical results show that the value of the frictional shear factor m markedly influences the asperity deformation. When the m value becomes higher, the real contact area ratio increases rapidly with the growing nondimensional pressure.

Ike and Makinouchi [25] used an elastic-plastic finite element method to analyze the plane-strain upsetting of a specimen having a regular array of wedges as shown in Fig. 2.68. Figure 2.69 shows the relationship between real contact area ratio and nondimensional pressure [26]. In this figure, the results as shown in Fig. 2.67 are added. The results indicate that the real contact area becomes nearly unity already at a workpiece reduction in height of 9 % due to the plastic deformation of the bulk. In these analyses, the friction at the real contact area is ignored. In this lubrication mechanism, the sheet with a mirror surface is produced by skin pass rolling. However, in the rolling process, the productivity with higher rolling speed cannot be obtained due to the occurrence of friction pick up.

Fig. 2.67 Relationship between real contact area ratio and nondimensional pressure [24]

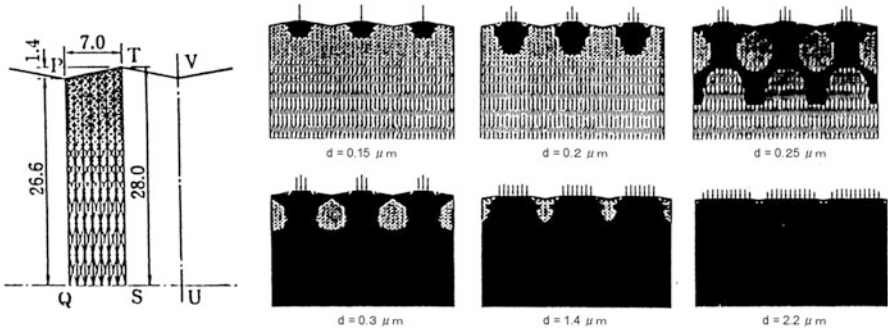
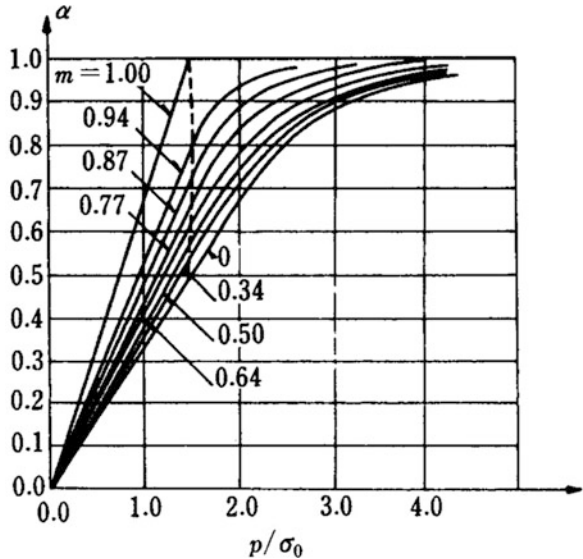


Fig. 2.68 Elastic-plastic finite element analysis of regular array of wedges [25]

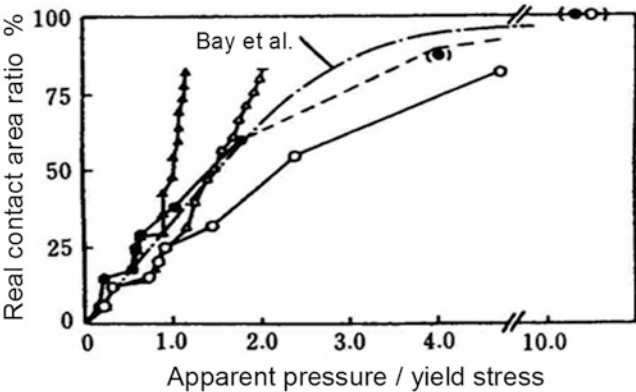


Fig. 2.69 Relationship between real contact area ratio and nondimensional pressure [26]

2.4.3 *Micro-plastohydrodynamic Lubrication*

In this micro-plastohydrodynamic lubrication regime, the tubes with a mirror surface of aluminum alloys are produced by ironing process for the production of photosensitive drums for copying machines. An example of industrial success obtained by the use of the micro-plastohydrodynamic lubrication is shown in Fig. 2.70 [27].

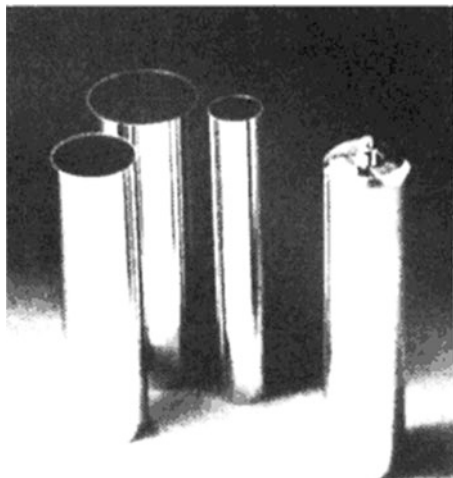
2.4.4 *Mixed Lubrication*

Generally, the mixed lubrication regime consists of the hydrodynamic lubrication and the boundary lubrication as shown in Fig. 1.33 or the hydrostatic lubrication and the boundary lubrication as shown in Fig. 2.63. In the mixed lubrication of the hydrodynamic lubrication and the boundary lubrication, if the combined surface roughness σ of tool and workpiece and the average oil film thickness h_m are estimated, the real contact area ratio α is given by

$$\alpha = 2 \int_{h_m}^{\infty} \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{z}{2\sigma^2}\right) dz \quad (2.30)$$

On the other hand, in the mixed lubrication of the hydrostatic lubrication and the boundary lubrication, it is understood that the volume change of the pocket filled with the lubricant during metalforming is remarkably small before the permeation of lubricant trapped within the pocket occurs. In this mixed lubrication, the sheet with a mirror surface of stainless steel is produced by multi-pass cold rolling. In this rolling, the surface texture of the rolled sheet is controlled using rolls with regular surface profiles, and in the final pass, the sheet with a mirror surface of stainless steel is rolled.

Fig. 2.70 Cold extruded and ironed photosensitive drums of aluminum alloy [27]



2.5 Oil Film Thickness at Interface Between Tool and Workpiece

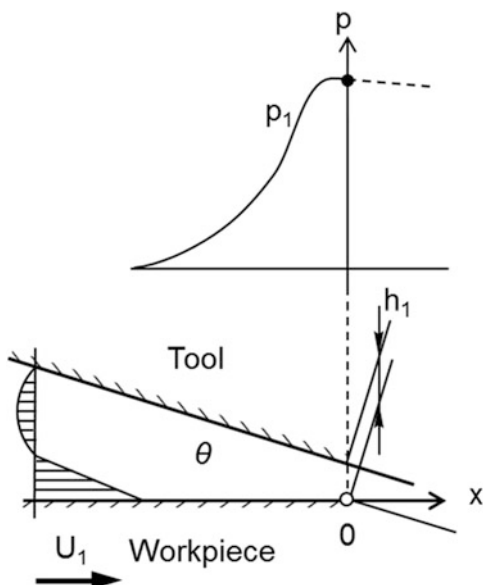
In order to decide the lubrication mechanism at the interface between tool and workpiece in metalforming and estimate the surface appearance of workpiece after plastic deformation, it is significantly important that the oil film thickness at the interface between tool and workpiece is calculated quantitatively. The lubricant is introduced between tool and workpiece by the wedge effect and the squeeze effect of the Reynolds equation in the steady-state metalforming. On the other hand, the lubricant is entrapped by the squeeze effect of the Reynolds equation in unsteady-state metalforming process.

2.5.1 Oil Film Thickness in Steady-State Metalforming Process

Figure 2.71 shows the introducing model in drawing process of steady-state metalforming. In Fig. 2.71, U_1 is the inlet speed of workpiece, h_1 is the inlet oil film thickness, and θ is the semi-angle of die gap. In the inlet zone, the following assumptions are given:

1. The tool and workpiece are rigid.
2. The surfaces of tool and workpiece are smooth.
3. The oil film thickness is the inlet oil film thickness h_1 when the pressure becomes the yield stress Y .

Fig. 2.71 Schematic representation of introducing model in drawing process



The Reynolds equation which is applied to the inlet zone is given by

$$\frac{dp}{dx} = 6\eta U_1 \left(\frac{h - h_1}{h^3} \right) \quad (2.31)$$

The oil film thickness h is given by

$$h = (\tan \theta)x \quad (2.32)$$

From Eqns. (2.31) and (2.32), Reynolds equation is derived by

$$\frac{dp}{dh} = \frac{6\eta U_1}{\tan \theta} \left(\frac{h - h_1}{h^3} \right) \quad (2.33)$$

The Reynolds equation is integrated with respect to h across the inlet channel at the boundary conditions of $p = 0$ at $h = \infty$ and $p = Y$ at $h = h_1$. In this calculation, the inlet oil film thickness can be calculated by the formulations of the viscosity of lubricant η as follows.

2.5.1.1 Constant Viscosity

The viscosity of lubricant is given by

$$\eta = \eta_0 \quad (2.34)$$

where η_0 is the viscosity of lubricant at an atmospheric pressure and a room temperature. Equation (2.33) is integrated at the boundary conditions of $p = 0$ at $h = \infty$ and $p = Y$ at $h = h_1$, and the inlet oil film thickness is given by

$$h_1 = \frac{3\eta_0 U_1}{(\tan \alpha)Y} \quad (2.35)$$

2.5.1.2 Viscosity Depending on Pressure

The viscosity of lubricant is given by

$$\eta = \eta_0 \exp(\alpha p) \quad (2.36)$$

where α is the pressure coefficient of viscosity. Equation (2.33) is integrated at the boundary conditions of $p = 0$ at $h = \infty$ and $p = Y$ at $h = h_1$, and the inlet oil film thickness is given by

$$h_1 = \frac{3\eta_0 U_1}{(1 - e^{-\alpha Y}) \tan \theta} \quad (2.37)$$

2.5.1.3 Viscosity Depending on Pressure and Temperature

The viscosity of lubricant is given by

$$\eta = \eta_0 \exp\{\alpha p - \beta(T - T_0)\} \quad (2.38)$$

where β is the temperature coefficient of viscosity and T_0 is the ambient temperature. The temperature of lubricant across the inlet channel is given by next energy equation when the fluid of lubricant is steady flow:

$$\rho C \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) - K \frac{\partial^2 T}{\partial y^2} = \eta \left(\frac{\partial u}{\partial y} \right)^2 - u \frac{T}{\rho} \frac{\partial p}{\partial T} \frac{\partial p}{\partial x} \quad (2.39)$$

When it can be assumed that the heat transferred by the lubricant is neglected and the heat generated by the compression is neglected in Eqn. (2.39), it is given by

$$K \frac{\partial^2 T}{\partial y^2} + \eta \left(\frac{\partial u}{\partial y} \right)^2 = 0 \quad (2.40)$$

Then, since u is given by Eqn. (1.19), the next equation can be derived by

$$\frac{\partial u}{\partial y} = -\frac{U}{h} + \frac{2y - h}{2\eta} \frac{\partial p}{\partial x} \quad (2.41)$$

Equation (2.40) is integrated at the boundary conditions of $T = T_0$ at $y = 0$ and $T = T_0$ at $y = h$ and the average temperature can be given.

Equations (2.33) and (2.40) are numerically integrated at the boundary conditions of $p = p^*$ at $h = 100h_1$ and $p = Y$ at $h = h_1$. In this calculation, it is assumed that the pressure is not affected by the temperature when $h \geq 100h_1$ so that p^* is given by the next equation:

$$p^* = \frac{1}{\alpha} \ln \left(\frac{1 - 0.06\eta_0 U \alpha}{h_1 \tan \theta} \right) \quad (2.42)$$

Azushima and Kitamura [28] calculated the inlet oil film thickness in sheet drawing considering the thermal effect. Figure 2.72 shows the flow chart for calculation of the inlet oil film thickness. In the calculation of the inlet oil film thickness, first the input data are given and second the value of h_1 is assumed. Third, the initial data when the pressure is p^* at $h = 100h_1$. Fourth, the pressures at given points are calculated using Reynolds equation of Eqn. (2.33) by the Runge-Kutta method. Fifth, the pressure at the outlet point is calculated and compared with the yield stress Y . If they are not in agreement, the representative calculations are carried out, changing the value of h_1 . Finally, the inlet film thickness is determined when they are in good agreement.

Fig. 2.72 Flow chart for calculation of inlet oil film thickness

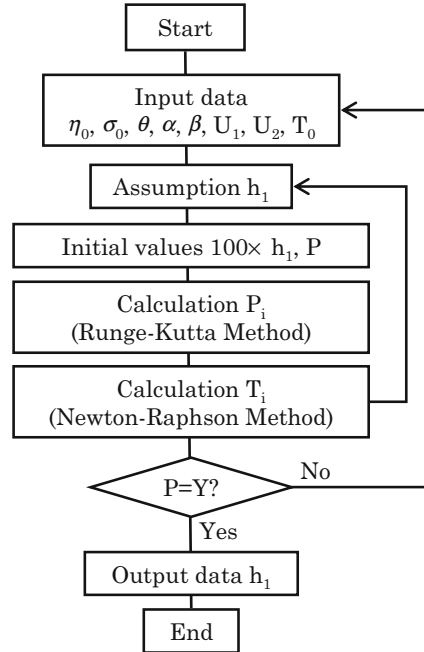


Figure 2.73 shows the relationship between inlet oil film thickness and drawing speed when the yield stress (a), the semi-angle of die (b), the pressure coefficient (c), and the temperature coefficient (d) change. From Fig. 2.73, it is understood that the inlet oil film thickness strongly depends on the thermal effect. The inlet oil film thickness without the thermal effect increases linearly with increasing drawing speed from Eqn. (2.35). However, the inlet oil film thicknesses considering the thermal effect increase linearly with increasing drawing speed until given drawing speeds, then they increase gradually, and above the given drawing speeds, they decrease with increasing drawing speed. In Fig. 2.73b, c, the drawing speeds at the maximum inlet oil film thickness are independent of the semi-angle of die and the pressure coefficient, but in Fig. 2.73a, d, they depend on the yield stress and the temperature coefficient. In Fig. 2.73a, the inlet oil film thicknesses decrease with increasing yield stress, but above 300 MPa, they are independent of the yield stress. In Fig. 2.73b, c, the inlet oil film thicknesses decrease with increasing semi-angle of die and pressure coefficient. In Fig. 2.73d, the inlet oil film thicknesses are independent of the temperature coefficient up to certain drawing speeds, but above the drawing speeds, they decrease with increasing temperature coefficient.

Next, Fig. 2.74 shows the relationship between inlet oil film thickness and drawing speed, changing the viscosity of lubricant. The inlet oil film thicknesses considering thermal effect also increase linearly with increasing drawing speed up to the given drawing speeds, then they increase gradually, and above the given drawing speeds, they decrease with increasing drawing speed. The inlet oil film thicknesses increase with increasing viscosity of the lubricant.

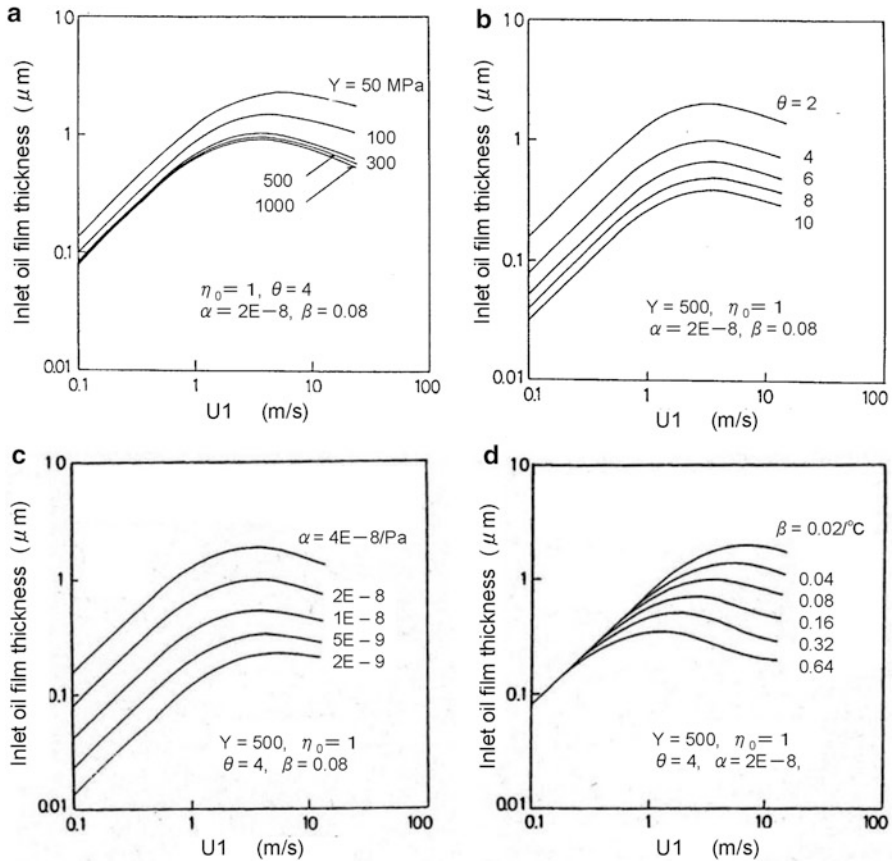
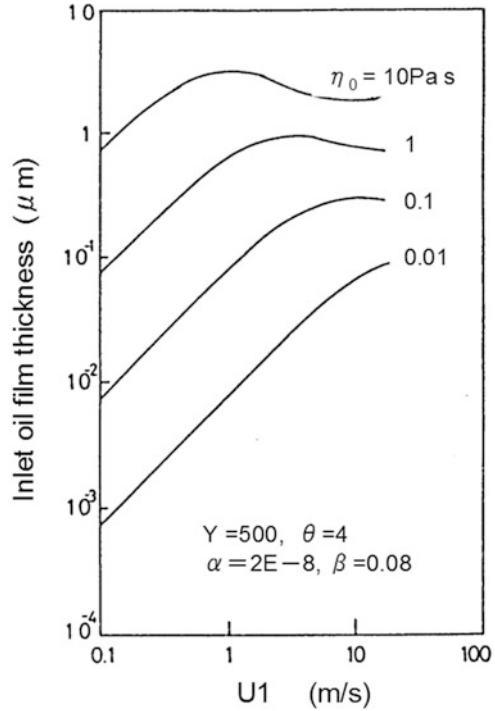


Fig. 2.73 Relationship between inlet oil film thickness and drawing speed. (a) Yield stress. (b) Semi-angle of die. (c) Pressure coefficient. (d) Temperature coefficient

2.5.2 Oil Film Thickness in Unsteady-State Metalforming Process

In Fig. 2.17, the entrapped models of lubricant in upsetting of cylindrical specimen are shown. In upsetting of cylindrical specimen at a high compression speed, the lubricant is entrapped by the squeeze effect of the Reynolds equation as shown in Figs. 2.10 and 2.17a. For predicting the amount of liquid lubricant entrapped between flat-smooth tool and workpiece surfaces, a plastohydrodynamic problem of lubricant entrapping was solved by Oyane and Osakada [29]. Next, in upsetting at a low compression speed, an elasto-hydrodynamic model of lubricant entrapping considering the elastic sinking of the tool surface was proposed by Osakada [30] as shown in Fig. 2.17b.

Fig. 2.74 Relationship between inlet oil film thickness and drawing speed, changing viscosity of lubricant



2.5.2.1 Upsetting at High Compression Speed

The Reynolds equation which is applied to the upsetting at a high compression speed is expressed as follows:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(\frac{r h^3}{\eta} \frac{\partial p}{\partial r} \right) = 12 \frac{dh}{dt} \quad (2.43)$$

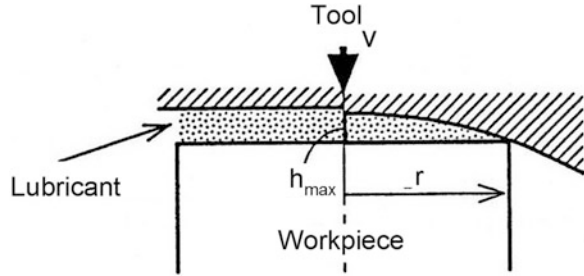
The thickest oil film thickness h_{max} is in the center of the cylindrical specimen and is derived by the next equation when the viscosity of lubricant is constant:

$$h_{max} = \sqrt[3]{\frac{3\eta_0 V r^2}{Y}} \quad (2.44)$$

where V is the compression speed and r is the radius of cylindrical specimen. Next, h_{max} is derived by the next equation when the viscosity of lubricant depends on the pressure [29]:

$$h_{max} = \left[\frac{3\eta_0 \alpha V r^2}{1 - \exp(-\alpha Y)} \right]^{\frac{1}{3}} \quad (2.45)$$

Fig. 2.75 Model for lubricant entrapping in slow speed compression



2.5.2.2 Upsetting at Low Compression Speed

As shown in Fig. 2.75, a cylindrical specimen with flat ends is compressed by two flat tools with liquid films, and the tool surface deforms elastically and becomes slightly concave due to the lubricant pressure. Entrapping of lubricant between tool and workpiece occurs. Then, the thickest oil film thickness h_{max} is in the center of the cylindrical specimen and is derived by the next equation when the viscosity of lubricant is constant [30]:

$$h_{max} = 10.6 \left(\frac{\eta V}{E} \right)^{\frac{1}{3}} r^{\frac{2}{3}} \quad (2.46)$$

In the upsetting of cylindrical specimen at low compression speed, Azushima [10] examined quantitatively the thickest oil film thickness h_{max} . The oil film thickness at the interface between tool and workpiece is in situ measured in upsetting process of a cylindrical specimen using the fluorescent observation technique explained in Sect. 2.2.3. The workpiece material is A1050H aluminum. The experiments are carried out at compression speeds of 0.01, 0.1, and 1.0 mm/min using a lubricant with viscosities of 20,000 cP at 20 °C. Thiophene compound is used as the fluorescent dye and the amount is fixed at a constant of 1 wt%. The video interface photographs at compression speeds of 0.01, 0.1, and 1.0 mm/min in a reduction in height of 0 % are shown in Fig. 2.76. In Fig. 2.76, the bright zone inside the peripheral region is observed, and the brightness and the area increase with increasing compression speed.

Figure 2.77 shows the distributions of the visible light intensity. In Fig. 2.77, it can be understood that a thick film is entrapped between tool and workpiece inside the peripheral region of real contact at a reduction in height of 0 % for each compression speed. The oil film thickness increases with increasing compression speed. Figure 2.78 shows the relationships between thickest central thickness and compression speed obtained from the experimental results of Fig. 2.77 and calculated from Eqn. (2.46). From Fig. 2.78, it is found that the central thicknesses increase with increasing compression speed and they are in good agreement.

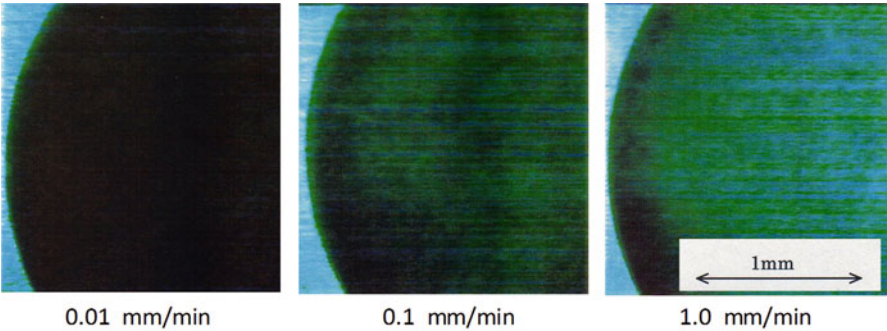


Fig. 2.76 Photographs of edge surface of cylindrical specimen illuminated with UV light at compression speeds of 0.01, 0.1, and 1.0 mm/min

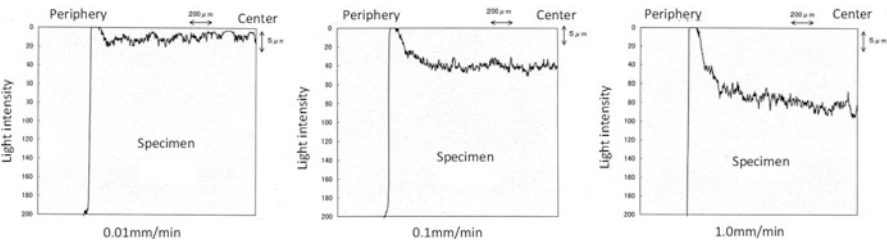
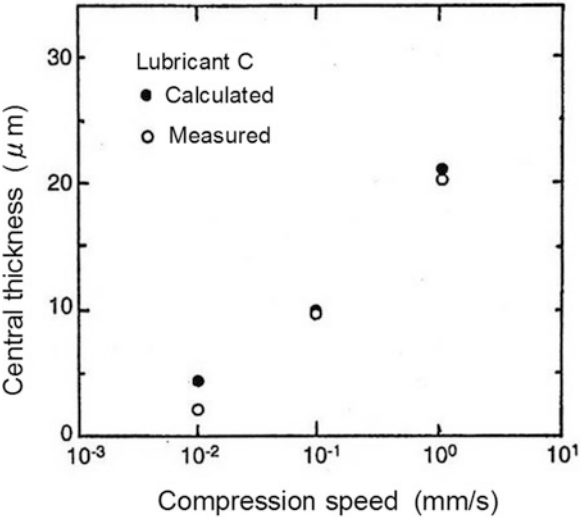


Fig. 2.77 Distributions of visible light at compression speeds of 0.01, 0.1, and 1.0 mm/min

Fig. 2.78 Comparison between central thicknesses obtained by experiments and calculated



2.6 Interfacial Temperature Between Tool and Workpiece

The interfacial temperature in metalforming rises by the friction energy acting on the real contact area in the boundary lubrication and the shear energy across the lubricant channel in the hydrodynamic lubrication.

2.6.1 Interfacial Temperature Rise by Friction Energy

The interfacial temperature rise by the friction energy acting on the real contact area between sliding bodies was derived by Archard [31]. Azushima [32] calculated the interfacial temperature using Archard's model. Figure 2.79 shows the schematic representation of the assumed junction model.

In Fig. 2.79, A is the round real contact area, B is the fixed solid, C is the moving solid, V is the sliding speed, and a is the radius of the real contact area. It is assumed that the heat Q is generated at the real contact area A and is conducted into the two solids. Assuming that the heat conducted into the B solid is Q_B and the heat conducted into the C solid is Q_C , the next equation is given by

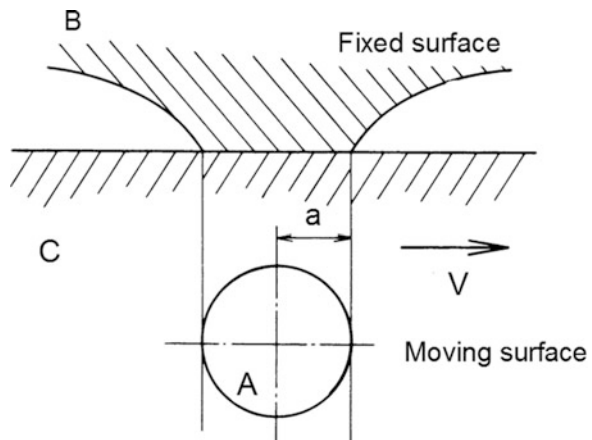
$$Q = Q_B + Q_C \quad (2.47)$$

Then, it is defined that the thermal conductivity, the specific heat, the density, and the thermal diffusivity of the solid B and C are K_B and K_C , c_B and c_C , ρ_B and ρ_C , and κ_B and κ_C .

When in the fixed solid B the heat flow is steady, the mean temperature rise on the sliding surface of solid B is given by

$$T_{Bm} = \frac{Q_B}{4aK_B} \quad (2.48)$$

Fig. 2.79 Schematic representation of assumed sliding junction model



When the heat flow of the moving solid C at a low sliding speed is steady, the mean temperature rise on the sliding surface of solid C is given by

$$T_{Cm} = \frac{Q_C}{4aK_C} \quad (2.49)$$

The mean temperature rise T_m on the contact area between solid B and solid C is given by

$$T_m = T_{Bm} = T_{Cm} \quad (2.50)$$

From Eqns. (2.48)–(2.50), the mean temperature rise is derived by

$$T_m = \frac{Q}{4aK_B + K_C} \quad (2.51)$$

where $Q = \mu PV$

On the other hand, since the heat flow of the moving solid C at a high sliding speed is unsteady, the mean temperature rise on the sliding surface of solid C is given by

$$T_{Cm} = \frac{Q_C}{3.25K_C a} \left(\frac{\kappa_C}{Va} \right) \quad (2.52)$$

From Eqns. (2.48), (2.52), and (2.50), the mean temperature rise is derived by

$$T_m = \frac{Q}{a} \frac{1}{4K_B + 3.25K_C \left(\frac{Va}{\kappa_C} \right)^{\frac{1}{2}}} \quad (2.53)$$

When the sliding speed is higher ($Va/2\kappa \geq 100$), it can be assumed that all the heat is conducted into the solid C, so that the mean temperature rise may be given by

$$T_m = T_{Cm} = \frac{Q}{3.25K_C a} \left(\frac{\kappa_C}{Va} \right)^{\frac{1}{2}} \quad (2.54)$$

The calculated results are shown in Figs. 2.80, 2.81, and 2.82. Figure 2.80 shows the comparison among the mean temperature rises calculated from Eqns. (2.51), (2.53), and (2.54). Figure 2.81 shows the mean temperature rise, changing the coefficient of friction using Eqn. (2.53). Figure 2.82 shows the mean temperature rise, changing the radius of round real contact area using Eqn. (2.53).

In Fig. 2.80, the mean temperature rise in the steady heat flow of Eqn. (2.51) increases abruptly with increasing sliding speed. Consequently, it is understood that Eqn. (2.51) cannot be used in higher rolling speed, that is, $Va/2\kappa \leq 4$. On the other

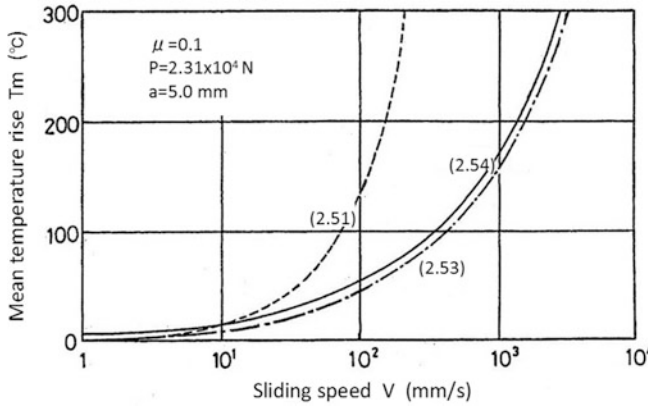


Fig. 2.80 Relationship between mean temperature rise and sliding speed calculated from Eqns. (2.51), (2.53), and (2.54)

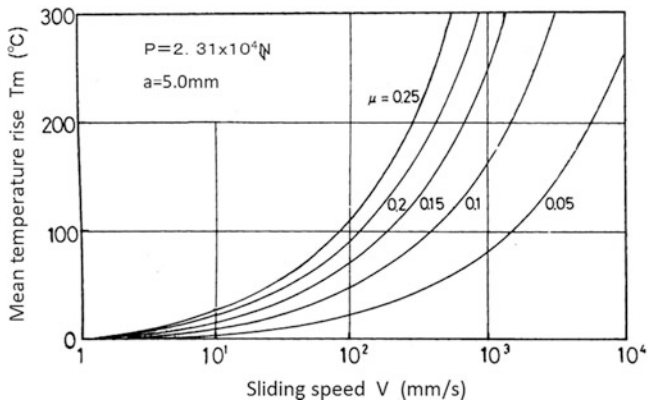


Fig. 2.81 Relationship between mean temperature rise and sliding speed, changing coefficient of friction

hand, when $Va/2\kappa \geq 100$, Eqn. (2.54) can be used instead of Eqn. (2.53) for the calculation of the mean temperature rise. In Fig. 2.81, the mean temperature rise strongly depends on the coefficient of friction and decreases significantly with decreasing coefficient of friction. In Fig. 2.82, the mean temperature rise also decreases with decreasing radius of the round contact area.

Next, the mean temperature rise at the interface between tool and workpiece in metalforming is explained. Figure 2.83 shows the schematic representation of contact region of sheet drawing.

In Fig. 2.83, h_1 is the entrance thickness of workpiece, h_2 is the exit thickness of workpiece, V_1 is the entrance speed of workpiece, V_2 is the exit speed of workpiece, $\ell_d (=2\ell)$ is the contact length, and w is the width of workpiece. The mean

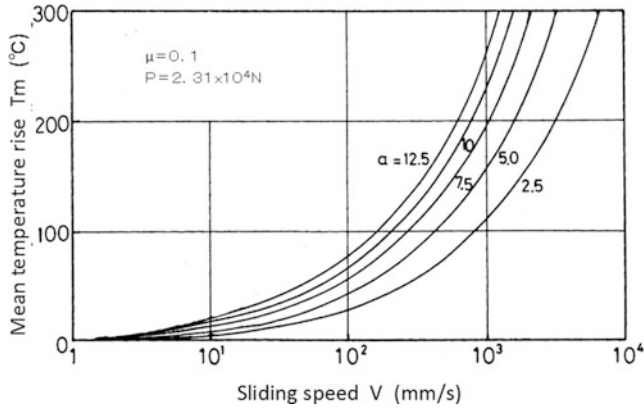
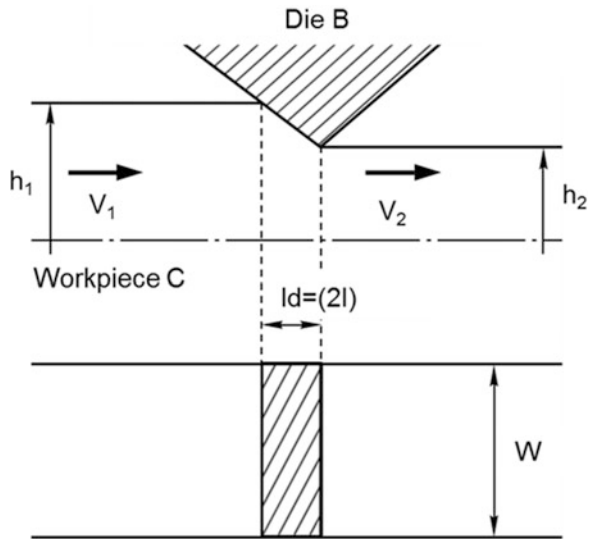


Fig. 2.82 Relationship between mean temperature rise and sliding speed, changing radius

Fig. 2.83 Schematic representation of contact region of sheet drawing



temperature rise in the sheet drawing at a low drawing speed is given by the next equation:

$$T_m = \frac{4l\mu p_m V}{4.24} \frac{1}{K_B + K_C} \quad (2.55)$$

where p_m is the mean normal pressure and $V = (V_1 + V_2)/2$. The mean temperature rise in the sheet drawing at a high drawing speed is given by

$$T_m = 4l\mu p_m V \frac{1}{4.24K_B + 3.76K_C \left(\frac{Vl}{K_C} \right)^{\frac{1}{2}}} \quad (2.56)$$

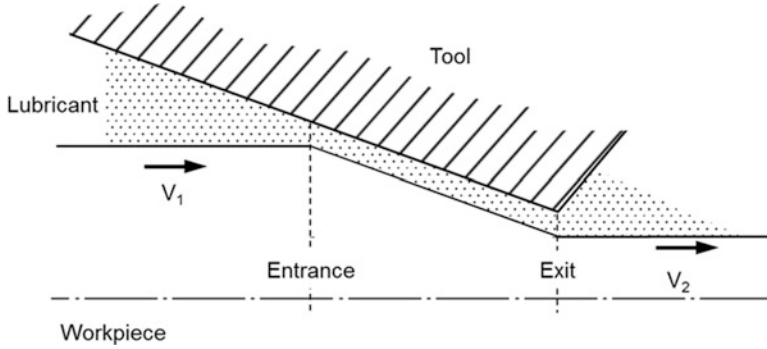


Fig. 2.84 Schematic representation of contact region under hydrodynamic lubrication in sheet drawing

2.6.2 Interfacial Temperature Rise by Shear Energy in Hydrodynamic Lubrication

Figure 2.84 shows the schematic representation of the contact region under the hydrodynamic lubrication in sheet drawing. The temperature rise of lubricant across the channel between tool and workpiece is given by the next energy equation of Eqn. (2.40) shown in Sect. 2.5.1:

$$K \frac{\partial^2 T}{\partial y^2} + \eta \left(\frac{\partial u}{\partial y} \right)^2 = 0 \quad (2.40)$$

Since the pressure generation by the Poiseuille flow can be neglected in the contact region between tool and workpiece, the next equation can be obtained:

$$\frac{\partial u}{\partial y} = -\frac{V}{h} \quad (2.57)$$

From Eqns. (2.40) and (2.57), the mean temperature rise is given by

$$T_m = \frac{\eta V^2}{12K} \quad (2.58)$$

2.6.3 Comparison of Results Calculated with Results Measured by Experiments in Sheet Drawing

Figure 2.85 shows the experimental results of interfacial temperature and coefficient of friction in drawing tests measured by Tsubouchi et al. [33]. On the other hand, the mean temperature rise in sheet drawing was calculated from Eqns. (2.51), (2.53), (2.58), and (2.59) using the values of coefficient of friction shown in

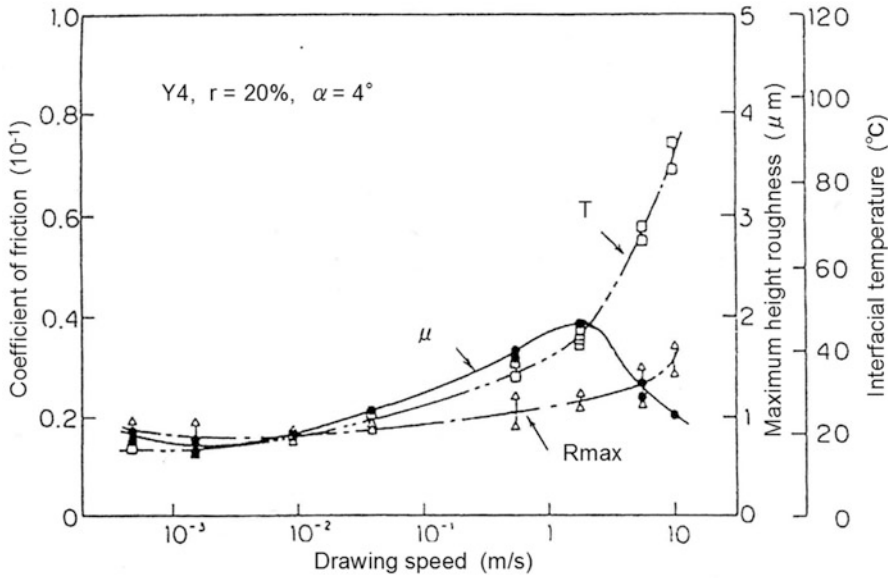


Fig. 2.85 Drawing speed dependence of interfacial temperature and coefficient of friction in drawing tests of aluminum sheet having etched surface [33]

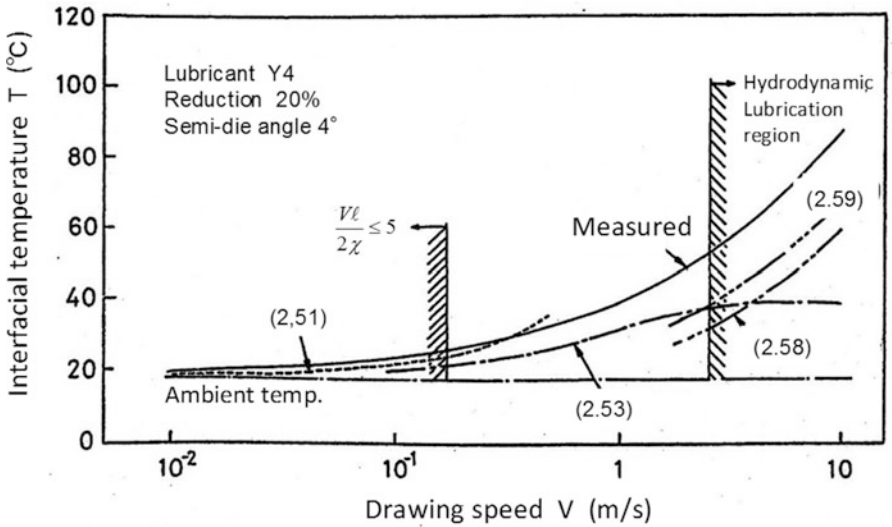


Fig. 2.86 Comparison between interfacial temperature calculated from Eqns. (2.51), (2.53), (2.58), and (2.59) and temperature measured

Fig. 2.86 and a mean contact pressure of 170 MPa by Azushima [32]. The calculated mean temperature rises are shown in Fig. 2.86.

In Fig. 2.86, it is observed that the calculated mean temperatures are smaller than that measured. In this calculation, the temperature rise by the plastic deformation is

neglected and the thermocouple for measurement of interfacial temperature is installed near the exit of tool. Therefore, the mean temperature rise by the plastic deformation is considered in Eqn. (2.58), and the next equation is given by

$$T_m = \frac{\eta V^2}{12K} + \frac{\sigma_m \epsilon_m}{2\rho c} \quad (2.59)$$

If the thermocouple position is considered, it can be estimated that the mean temperature rise calculated is in good agreement with that measured.

2.7 Seizure

2.7.1 Seizure in Machine Element

In the machine elements, the lubrication limit occurs due to the rapid increase of the interfacial temperature by the increase of the coefficient of friction, the decrease of the oil film thickness at the contact area, and so on. In such conditions, the breakdown of the oil film occurs and the relative motion between two solids stops. Such phenomena are called a seizure, a scoring, a scuffing, and so on.

Salomon [34] reported the experimental results of seizure generated in the four ball tester using lubricants without EP additives. Figure 2.87 shows the schematic diagram concerning seizure. In the lower sliding speed, the lubrication regime changes from I to II and moreover from II to III. On the other hand, in the higher sliding speed, the lubrication regime changes from I to III. It is reported that the interfacial temperature remains constant in the change from II to III of the lubrication regime at the lower sliding speed. In the boundary lubrication, the oil film thickness at the contact area decreases and the breakdown of the oil film occurs.

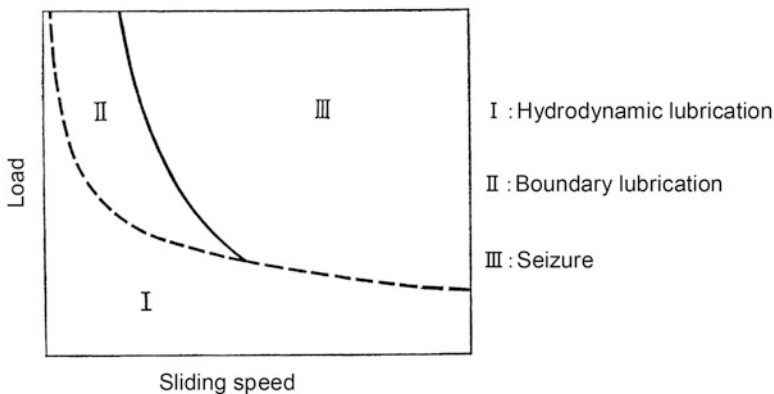


Fig. 2.87 Schematic diagram concerning seizure

From these experimental data concerning the seizure in the machine element, the generation cause of seizure is roughly classified by the following two conditions:

- 1. Critical temperature condition
The seizure occurs over a critical interfacial temperature. The critical temperature depends on materials and lubricants.
- 2. Critical oil film thickness condition
The seizure occurs at a critical value of the ratio of oil film thickness to surface roughness, that is, $\lambda = h/o$.

2.7.2 Seizure in Metalforming

In this chapter, the seizure in cold ironing process of stainless steel is explained. Azushima et al. [35] investigated the seizure in cold ironing using the ironing-type simulation testing machine. Figure 2.88 shows the schematic representation of the ironing-type simulation testing machine (a) and the main part (b). The ironing experiments are carried out using the stainless steel sheet with a thickness of 2 mm, the SKD11 die, and six kinds of commercial ironing oils at normal loads of 50, 70, 90, and 110 kN and at a sliding speed of 10 cm/s. Table 2.2 summarizes the compositions of used oils.

Figure 2.89 shows the relationship between coefficient of friction and sliding distance of the five oils of A, B, C, D, and E at a normal load of 70 kN. At the normal load of 70 kN, the seizure occurs for the C oil. Figure 2.90 shows the

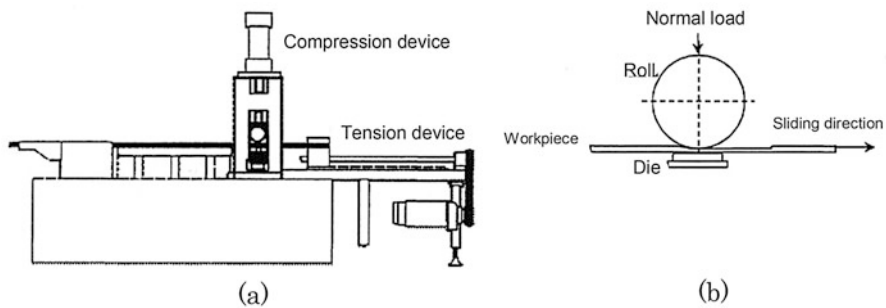


Fig. 2.88 Schematic representations of ironing-type simulation testing machine (a) and main part (b)

Table 2.2 Compositions of used oils

Lubricant	A	B	C	D	E
Mass %					
Zn	5.1	2.7	2.8	6.1	–
S	21.2	15.7	11.6	10.1	0.4
P	4.7	2.4	2.5	5.5	0.03
Ca	1.7	1.8	1.0	0.9	–
Cl	–	–	–	–	29.4

Fig. 2.89 Relationship between coefficient of friction and sliding distance of five oils of A, B, C, D, and E at normal load of 70 kN

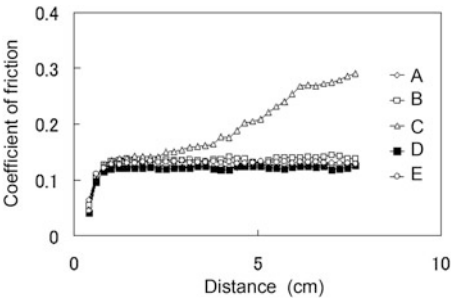
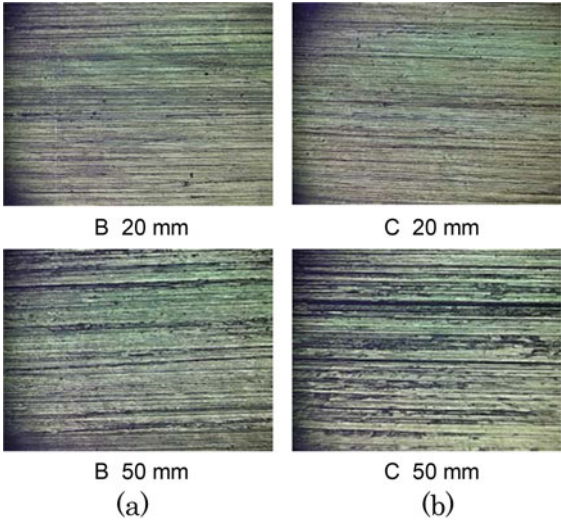


Fig. 2.90 Photographs of sheet surface after ironing for oils of B (a) and C (b)

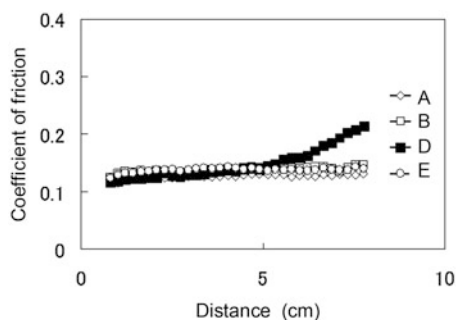


photographs of the sheet surface at sliding distances of 20 and 50 mm after ironing for the oils of B (a) and C (b).

From the photograph of the sheet surface at a sliding distance of 50 mm in Fig. 2.90b for the C oil, the Scratch marks can be observed. From these results, it is found that the generation cause of the seizure in cold ironing of stainless steel is due to the critical oil film thickness condition. This seizure is called the cold welding type.

Next, Fig. 2.91 shows the relationship between coefficient of friction and sliding distance of the five oils of A, B, D, and E at a normal load of 90 kN. At a normal load of 90 kN, the seizure occurs for the D oil.

Fig. 2.91 Relationship between coefficient of friction and sliding distance of the four oils of A, B, D, and E at 90 kN



2.8 Tribo-simulation in Metalforming

2.8.1 Relationship Between Tribological Conditions and Tribological Results

The tribological behavior is influenced by many factors such as the material factors, the process factors, the tribological factors and so on. Therefore, when solving a tribological problem, many experiments must be carried out in order to examine the effect of many tribological conditions on the tribological results. Figure 2.92 shows the relationship between tribological conditions and tribological results in tribological process.

For example, the coefficient of friction of the tribological results is influenced by many tribological conditions. If the micro-contact state between tribological conditions and tribological results in Fig. 2.93 is quantitatively understood, the quantitative relationship between coefficient of friction and tribological conditions can be obtained. However, since the information of the micro-contact state is almost unknown, the quantitative relationship cannot be obtained. Consequently, among the many tribological conditions, it is important to select tribological conditions which strongly influence on the coefficient of friction. Then, the qualitative relationship between a tribological condition and a tribological result must be derived. The symbolic representations of the tribological conditions and the tribological results are shown in Fig. 2.93.

The symbolic representation of tribological results and some tribological conditions is expressed as a qualitative relationship as follows:

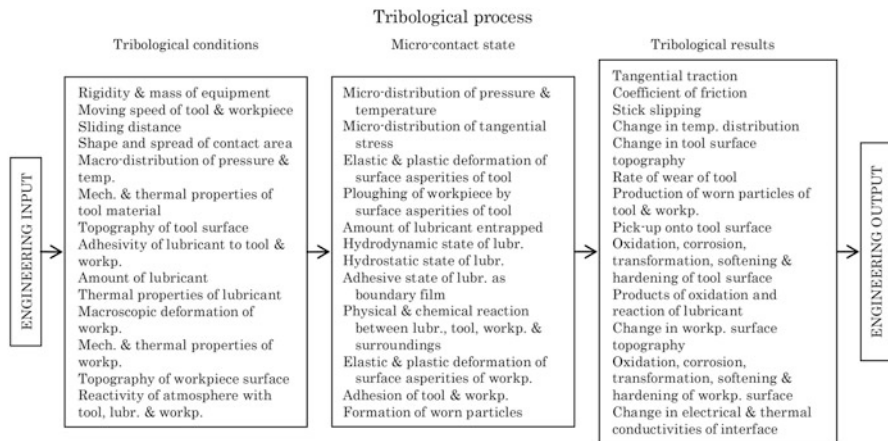


Fig. 2.92 Relationship between tribological conditions and tribological results in tribological process

Tribological conditions (Input)			Tribological results (Output)		
Velocity	Fast	V	Coefficient of friction	Large	M
	Slow	v		Small	μ
Sliding distance	Long	L	Temperature rising	High	Θ
	Short	l		Low	θ
Quantity of lubricant	Much	Q	Surface roughness of materials	Rough	Σ
	Little	q		Smooth	σ
Viscosity of lubricant	High	H	Tool surface (Pick up)	Much	T
	Low	η		Little	t
Oiliness of lubricant	High	O			
	Low	o			
	Rough	S			
Surface roughness of tools and materials					
	Smooth	s			
Pressure (Deformation resistance)	High	Y			
	Low	y			

Fig. 2.93 Symbolic representations of tribological conditions and tribological results

$$(\mu) \rightarrow \begin{bmatrix} V \\ l \\ Q \\ H \\ O \\ s \\ y \end{bmatrix} \quad (T) \rightarrow \begin{bmatrix} V \\ L \\ q \\ h \\ o \\ s \\ Y \end{bmatrix} \quad (R) \rightarrow \begin{bmatrix} V \\ l \\ Q \\ H \\ o \\ S \\ y \end{bmatrix} \quad (S) \rightarrow \begin{bmatrix} V \\ L \\ q \\ h \\ o \\ S \\ Y \end{bmatrix}$$

In order to derive these relationships, the data of the tribological results must be measured, changing the tribological conditions using tribo-simulator.

2.8.2 Tribo-simulator

The tribo-simulator for measuring the data of tribological results is broadly classified into two types as follows:

1. Fundamental tribo-simulator
2. Tribo-simulator for metalforming

In the fundamental tribo-simulator, there are many types as follows:

1. Four-ball machine
2. Pendulum oiliness tester
3. Timken machine
4. Falex machine
5. Almen machine
6. SAE machine
7. Others

In these fundamental tribo-simulators, the contact members are hard metals, and the contact mode is the Hertz contact between elastic bodies. The pressure is high, but the contact area is small compared to the contact interface between tool and workpiece in metalforming. The coefficient of friction and the load-carrying capacity in the machine elements are mainly measured using the fundamental tribo-simulator. However, for the tribo-simulation in metalforming, it is significantly important that one of the contact members is workpiece which deforms plastically and another is the hard metal as a tool.

As an example, in the tribo-simulator for metalforming, the tribo-simulators for sheet metalforming are shown in Fig. 2.94. The plane-strain drawing tests of the draw-type between flat tool (b), the drawing type (e), and the flat sliding type (h) in Fig. 2.94 are widely used for measuring the coefficient of friction of sheet metalforming of car bodies in automobile industries. In the draw-bending tests of the strip tension-bending type (c), the drawing bead type (d), and the plastic belt type (g), the sheet is bent during drawing. In the drawing bead type (d), the pickup and galling are easily observed. The deep drawing type (a) and the U-bending-ironing type (f) involve sliding-combined bending.

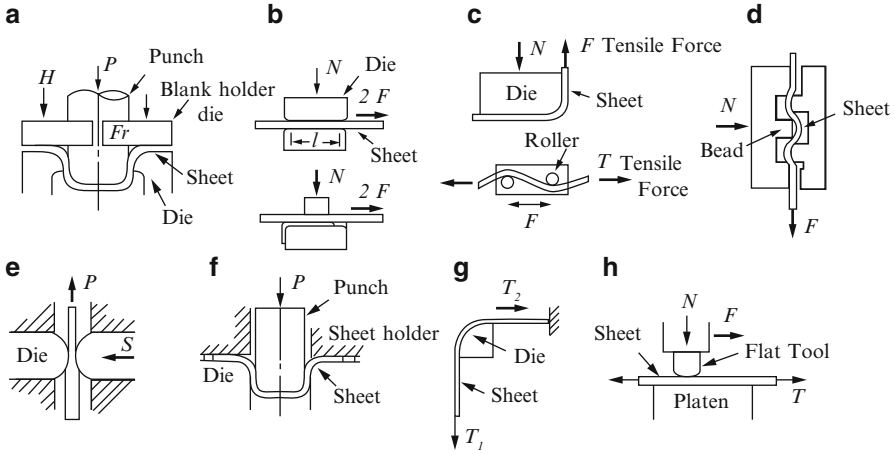


Fig. 2.94 Tribo-simulators in sheet metalforming [36]. (a) Deep drawing type. (b) Draw type between flat tool. (c) Strip tension-bending type. (d) Drawing bead type. (e) Drawing type. (f) U-bending-ironing type. (g) Plastic belt type. (h) Flat sliding type

The tribo-simulators of rolling, forging, extrusion, and so on can be similarly expressed. In the future, the new tribo-simulator for metalforming will be developed.

2.8.3 Tribo-simulation Tests for New Tribo-simulator in Metalforming

At the present time, when the micro-contact behaviors in the tribological process are unknown, the quantitative relationship between tribological conditions and tribological results in tribological process is not obtained. Therefore, it is required that the quantitative relationship between them is constructed by the simulation tests using the tribo-simulator. In order to carry out the simulation tests economically, the important conditions by understanding the micro-contact state in the tribological process must be determined among many tribological conditions.

From that standpoint, it is desired that the tribological conditions of the tribo-simulator are similar to those of actual metalforming processes in order to develop the tribo-simulator in metalforming. Moreover, in the tribo-simulator in metalforming, the next conditions must be satisfied as follows:

1. The element materials of the tool, the lubricant, and the workpiece of the tribo-simulator and the actual process are matched.
2. The geometry, the introducing or entrapping condition of the lubricant, and the contact conditions of the tribo-simulator are similar to those of the actual process.

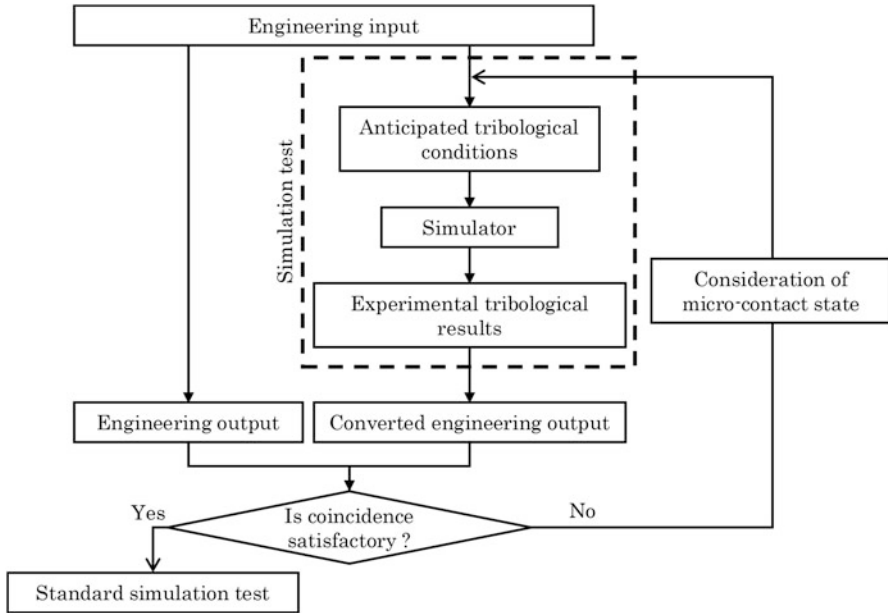


Fig. 2.95 Tribo-simulation test method

3. In order to match the micro-contact behavior of the tribo-simulator to that of the actual process, the tribological conditions can be controlled.
4. The coefficient of friction of the tribological result is calculated from the normal load and the tangential force measured individually.
5. The pick up, the interfacial temperature rise, the wear amount, and so on of the tribological results can be measured simply.

The tribo-simulation test method shown in Fig. 2.95 was proposed by Azushima [37]. The data of a tribological result are measured, changing the tribological conditions using the tribo-simulator. The data are compared to the data of the actual process, and the tribological conditions must be adjusted, considering the micro-contact behavior at the interface between tool and workpiece. Consequently, the criterion conditions for the simulation test can be obtained.

When the simulation tests are carried out, it can be advisable to investigate in the following order:

1. Recognition of the tribological problem
2. Observation of the tribological results
3. Collection of the data
4. Determination of the important tribological conditions
5. Understanding of the micro-contact behavior
6. Simulation test
7. Determination of the criterion conditions and the application to the actual process

References

1. M. Soda, Journal of the JSME, 62–489 (1969), 1498–1503. (in Japanese)
2. A. Azushima, Tetsu-to-Hagane, 64–2 (1978), 317–330. (in Japanese)
3. T. Mizuno, Textbook of 38th lectureship in JSTP, (1984), 1–12. (in Japanese)
4. T. Ishikawa, J. Jpn. Soc. Technol. Plast. 43–489 (2001), 1061–1066. (in Japanese)
5. A. Azushima, J. Kihara, I. Gokyu, J. Jpn. Soc. Technol. Plast. 18–1196 (1977), 337–343. (in Japanese)
6. T. Kasuga, K. Yamaguti, K. Kato, Transaction of the JSME, 33 (1967), 1294–1301. (in Japanese)
7. A. Azushima, Tetsu-to-Hagane, 78–112(1992), 317–330. (in Japanese)
8. A. Azushima, Journal of Tribology, ASME, 122 (2000), 822–827.
9. A. Azushima, S. Yoneyama, T. Yamaguchi, H. Kudo, Annal of the CIRP, 45–1 (1996), 205–210.
10. A. Azushima, Wear, 260 (2006), 243–248.
11. A. Azushima, M. Miyagawa, J. Jpn. Soc. Technol. Plast. 27–310 (1986), 1261–1267. (in Japanese)
12. A. Azushima, S. Kuba, S. Tani, D. D. Olsson, Wear, 260 (2006), 258–264.
13. H. Kudo, A. Azushima, J. Jpn. Soc. Technol. Plast., 27–300 (1986), 72–80. (in Japanese)
14. A. Azushima, M. Tsubouchi, H. Kudo, N. Furuta, K. Minemura, J. Jpn. Soc. Technol. Plast., 30–347 (1989), 1631–1638. (in Japanese)
15. A. Azushima, Annal of the CIRP, 44–1 (1995), 209–212.
16. L. H. Butler, Metallurgia, 58 (1960), 167–174.
17. H. Kudo, Int. J. Mech. Sci., 7 (1965), 383–388.
18. T. Wanheim, N. Bay, Annal of the CIRP, 27–1 (1978), 189–194.
19. T. Mizuno, M. Okamoto, J. Lubr. Technol., ASME, 104 (1982), 53–59.
20. A. Azushima, M. Tsubouchi, H. Kudo, Proc. 3rd Int. Conf. Technol. Plasticity, 1 (1990), 551–556. (in Japanese)
21. A. Azushima, J. Miyamoto, H. Kudo, Annal of the CIRP, 47–1 (1998), 479–482.
22. A. Azushima, T. Tanaka, Annal of the CIRP, 47–1 (2000), 165–168
23. A. Azushima, A. Yanagida, S. Tani, Journal of Tribology, ASME, 133 (2011), 011501-1-6.
24. N. Bay, T. Wanheim, Proc. 3rd ICTP, 4 (1990), 1677–1691.
25. H. Ike, A. Makinouchi, J. Jpn. Soc. Technol. Plast., 32–366 (1991), 848–855. (in Japanese).
26. A. Azushima, Tribologist, 43–11 (1998), 959–963. (in Japanese)
27. H. Kudo, A. Azushima, Proc. 2nd ICTP (1987), 373–384.
28. A. Azushima, K. Kitamura, Proc. Spring Conf. on Technol. Plasticity, (1986), 151–154. (in Japanese)
29. M. Oyane, K. Osakada, Bull. JSME, 12 (1969), 149–155. (in Japanese)
30. K. Osakada, Int. J. Mech. Sci., 19 (1977), 413–421.
31. J. F. Archard, Wear, 2 (1958/1959), 438.
32. A. Azushima, J. Jpn. Soc. Technol. Plast., 29–328 (1988), 492–497. (in Japanese)
33. M. Tsubouchi, H. Kudo, K. Okamura, K. Suzuki, J. Jpn. Soc. Technol. Plast., 27–311 (1986), 1369. (in Japanese)
34. G. Salomon, Wear, 36–1 (1970), 1.
35. A. Azushima, K. Nakazawa, Y. Hasegawa, Proc. 63rd Japanese Joint Conf. Technol. Plasticity, (2012), 133–134. (in Japanese)
36. Edited by JSTP, Process-tribology, (Corona Publishing Co. Ltd. Tokyo 1993), 76. (in Japanese)
37. A. Azushima, J. Jpn. Soc. Technol. Plast., 39–455 (1998), 1198–2001. (in Japanese)

Chapter 3

Fundamentals of Rolling

3.1 Mechanics of Rolling

Rolling is a metal-forming process where sheets of metal are passed between rolls to give them a certain thickness. Figure 3.1 shows the schematic representation of the rolling principle. In Fig. 3.1, V is the rolling speed, V_1 is the entrance speed of the workpiece, V_2 is the exit speed of the workpiece, R is the roll radius, h_1 is the entrance thickness of the workpiece, and h_2 is the exit thickness of the workpiece. The reduction and the strain in rolling are expressed as follows:

$$r = \frac{h_1 - h_2}{h_1} \quad (3.1)$$

$$\varepsilon = \ln \left(\frac{h_1}{h_2} \right) \quad (3.2)$$

The contact length is expressed as follows:

$$\ell_d = \sqrt{R(h_1 - h_2)} \quad (3.3)$$

Next, the details on workpiece speeds during rolling are shown in Fig. 3.2. In Fig. 3.2, x_n is the neutral point, V_n is the workpiece speed at the neutral point, h_n is the workpiece thickness at the neutral point, θ_n is the neutral angle, and R is the radius of the roll. The next relationship among V , V_1 , and V_2 is given by

$$V_1 \geq V \geq V_2 \quad (3.4)$$

Then, the forward slip is defined as $(V_2 - V)/V$.

Now, the point x_n where the workpiece speed is equal to the roll speed is called the neutral point. The velocity and the thickness of the workpiece at the neutral

Fig. 3.1 Schematic representation of the rolling principle

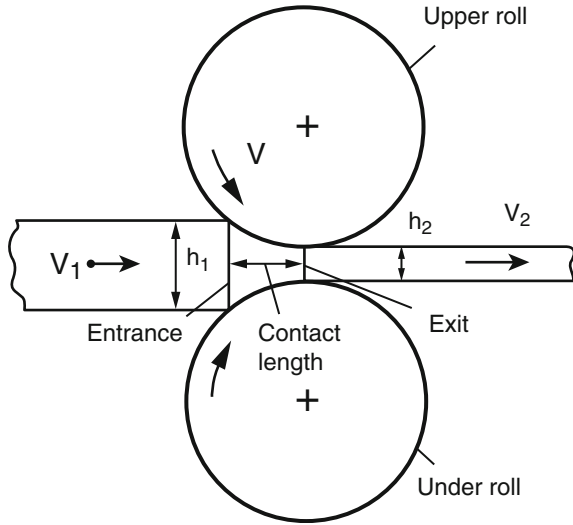
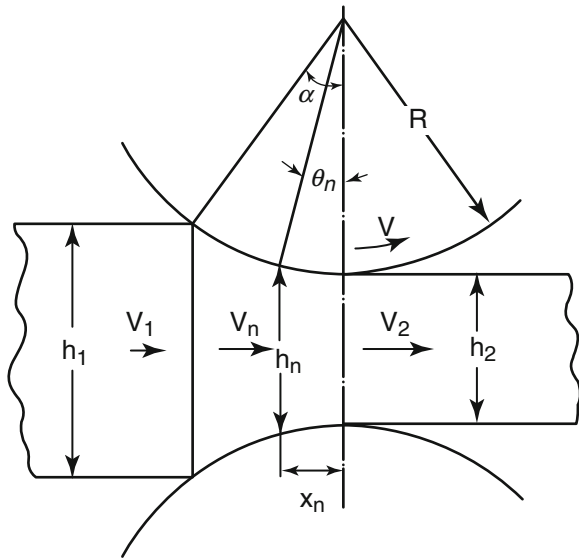


Fig. 3.2 Representation of workpiece speed during rolling



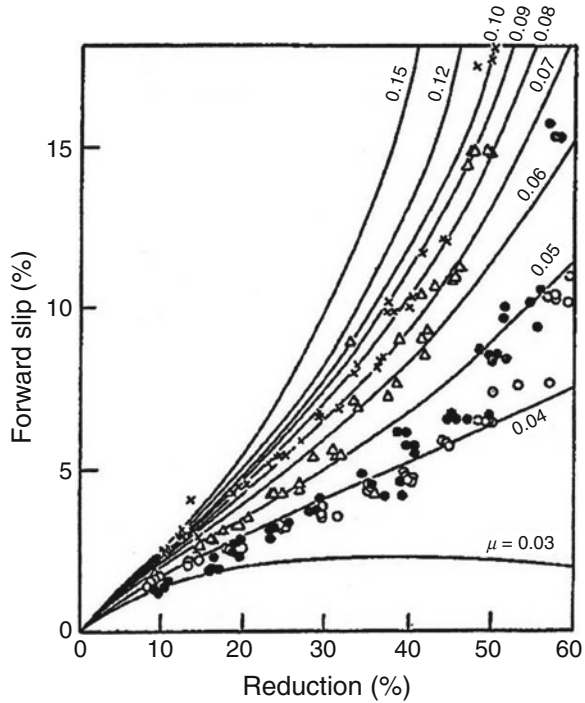
point are V_n and h_n . When the products of velocity and thickness are constant along the contact length, the next equation is given by

$$V_1 h_1 = V_n h_n = V_2 h_2 \quad (3.5)$$

Substituting $V_n = V \cos \theta_n$ into Eqn. (3.5), the next equation is given by

$$V \cos \theta_n h_n = V_2 h_2 \quad (3.6)$$

Fig. 3.3 Relationship between forward slip and reduction changing the coefficient of friction [1]



Consequently, the forward slip is derived by

$$\frac{V_2 - V}{V} = (1 - \cos \theta_n) \left(\frac{D \cos \theta_n}{h_2} - 1 \right) \quad (3.7)$$

The forward slip can be calculated from Eqn. (3.7) using the assumed coefficient of friction. Figure 3.3 shows the calculated forward slip changing the coefficient of friction by Saeki et al. [1]. The coefficient of friction can be roughly estimated by the value of forward slip. The relationship is widely used in the steelmaking factory. From Fig. 3.3, when the coefficient of friction becomes lower, it can be understood that the forward slip becomes minus and the workpiece cannot be rolled for slipping.

If the surfaces of the workpiece and roll are very smooth and the lubrication is very well, the rolls refuse to bite. Figure 3.4 shows the frictional conditions at a biting of rolling. This condition for biting is given by

$$\mu p_r \cos \alpha \geq p_r \sin \alpha \quad (3.8)$$

where α is the contact angle. From Eqn. (3.8), the next equation is given by

$$\mu \geq \tan \alpha \quad (3.9)$$

Fig. 3.4 Frictional conditions at biting of rolling

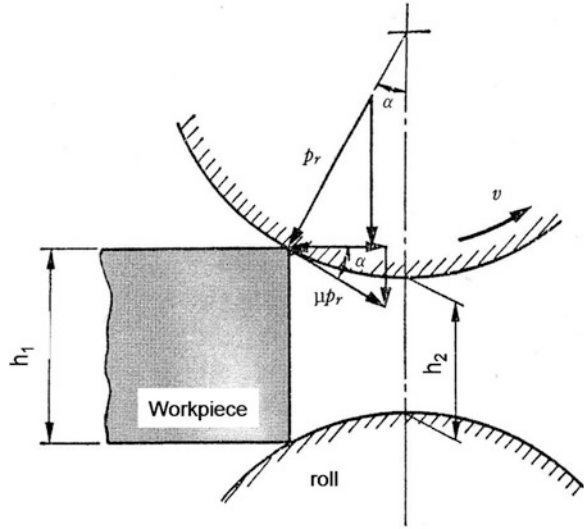
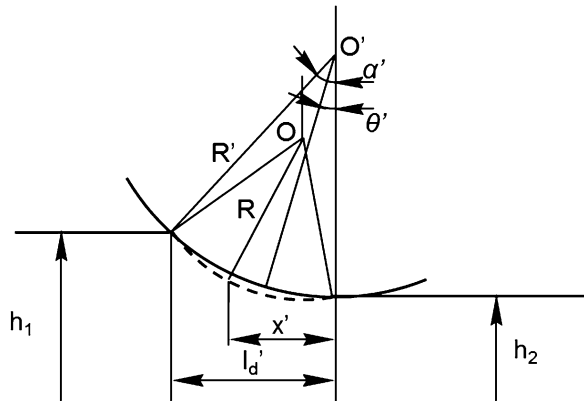


Fig. 3.5 Schematic representation of roll flattening



The maximum contact angle for biting is derived by

$$\alpha_{\max} = \tan^{-1} \mu \cong \mu_f \quad (3.10)$$

where μ_f is the friction angle. From Eqn. (3.10), the maximum draft is given by

$$(h_1 - h_2)_{\max} = 2R(1 - \cos \mu_f) \quad (3.11)$$

Next, when the roll is the elastic body, roll flattening occurs. Figure 3.5 shows the schematic representation of roll flattening.

By roll flattening, the roll radius changes from R to R' . The equation of R' is derived by Hitchcock as follows:

$$R' = R \left\{ 1 + \frac{cP}{b_1(h_1 - h_2)} \right\} \quad (3.12)$$

where b_1 is the entrance width of the workpiece and $c = 16 \left(\frac{1-\nu^2}{\pi E} \right)$. Eqn. (3.12) is called Hitchcock's equation.

3.2 Rolling Theory

In order to calculate the roll pressure distribution along the arc of contact, the rolling theory is developed.

3.2.1 Two-Dimensional Homogenous Deformation Theory for Rolling

In order to calculate the roll pressure distribution along the arc of contact, the slab method is used. Figure 3.6 shows the stresses acting on the element (slab) of sheet

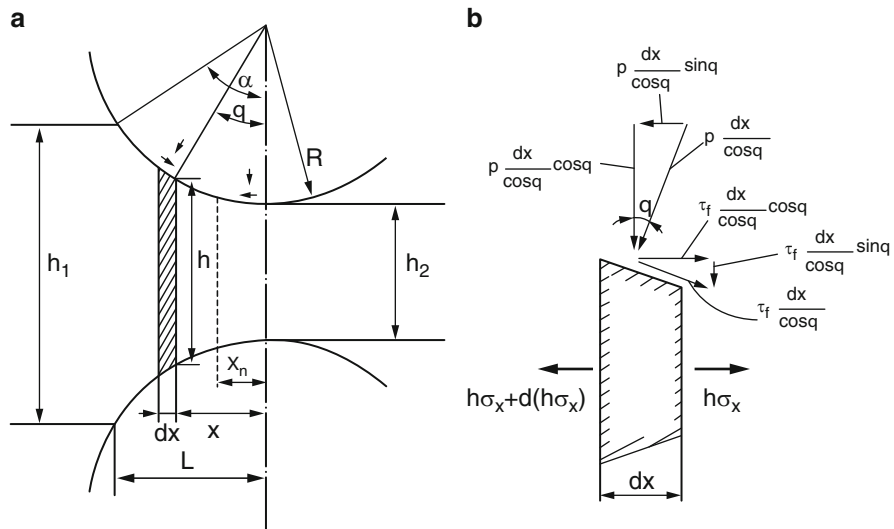


Fig. 3.6 Stresses acting on element (slab) of strip between rolls [2]

between rolls. The assumptions used in calculation of the roll pressure distribution in sheet rolling are as follows:

1. Plane-strain condition
2. Homogenous deformation
3. Constant frictional stress τ_f along the arc of contact
4. Constant circular arc of contact
5. Neutral point within the arc of contact
6. Negligible elastic deformation

As shown in Fig. 3.6, when the slab is situated between the entrance point and neutral point, the equilibrium of the horizontal force [3] is derived by

$$d(h\sigma_x) + 2p \frac{dx}{\cos \theta} \sin \theta - 2\tau_f \frac{dx}{\cos \theta} \cos \theta = 0 \quad (3.13)$$

From Eqn. (3.13), Karman's equation can be obtained as follows:

$$\frac{d(h\sigma_x)}{dx} + 2(p \tan \theta \mp \tau_f) = 0 \quad (3.14)$$

In this chapter, Nadai's method for calculation of the roll pressure distribution by Eqn. (3.14) is explained [4]. The frictional stress is expressed by

$$\tau_f = \mu p \quad (3.15)$$

Tresca's yield criterion of the workpiece when the coefficient of friction is small is expressed by

$$\sigma_x + p = 2k \quad (3.16)$$

where k is the yield shear stress of the workpiece. Now, the thickness of the workpiece can be given by

$$h = h_1 + \frac{x^2}{R} \quad (3.17)$$

Substituting Eqns. (3.15), (3.16), and (3.17) into Eqn. (3.14), Karman's equation is expressed as follows:

$$\left(h_2 + \frac{x^2}{R} \right) \frac{dp}{dx} \pm 2\mu - 4k \frac{x}{R} = 0 \quad (3.18)$$

In order to solve Eqn. (3.18), the following nondimensional equations are defined as follows:

$$z = \frac{x}{\sqrt{Rh_2}} \quad f = \frac{p}{2k} \quad a = 2\mu \sqrt{\frac{R}{h_2}} \quad (3.19)$$

Then, Eqn. (3.18) becomes as follows:

$$(1 + z^2) \frac{df}{dz} = \pm af = 2z \quad (3.20)$$

Moreover, substituting $z = \tan v$ into Eqn. (3.20), the next equation is given by

$$\frac{df}{dv} \pm af = 2 \tan v \quad (3.21)$$

Eqn. (3.21) can be integrated, when the front and the back tensions are 0, and the solutions are given as follows:

At the entrance side,

$$p = 2k \left[\left\{ 1 + \frac{2(1 - av_1)}{a^2} \right\} e^{a(v_1 - v)} - \frac{2(1 - av)}{a^2} \right]. \quad (3.22)$$

At the exit side,

$$p = 2k \left\{ \left(1 + \frac{2}{a^2} \right) e^{av} - \frac{2(1 + av)}{a^2} \right\}. \quad (3.23)$$

The calculated results of Eqns. (3.22) and (3.23) changing the coefficient of friction are shown in Fig. 2.8.

Next, Bland and Ford's method for calculation of the roll pressure distribution by Karman's equation of Eqn. (3.14) is explained [5]. The method is widely used in order to calculate the roll pressure in cold sheet rolling of steelmaking companies in Japan. Substituting Eqn. (3.15) into Eqn. (3.14) and using the equations of $\tan \theta \approx \theta$ and $x = R\theta$, the next equation is given by

$$\frac{d}{d\theta} \left(\frac{p}{k} \right) = \frac{p}{k} \frac{2R}{h} (\theta \pm \mu) \quad (3.24)$$

Equation (3.24) can be integrated, when the front and the back tensions are 0, and the solutions are given as follows:

At the entrance side,

$$p = \frac{kh}{h_1} e^{\mu H}. \quad (3.25)$$

At the exit side,

$$p = \frac{kh}{h_2} e^{\mu(H_1 - H)}. \quad (3.26)$$

where $H = \frac{2}{\sqrt{h_1/R}} \tan^{-1} \left(\frac{\theta}{\sqrt{h_1/R}} \right)$, $H_1 = \frac{2}{\sqrt{h_1/R}} \tan^{-1} \left(\frac{\alpha}{\sqrt{h_1/R}} \right)$, and α is the contact angle.

3.2.2 Two-Dimensional Inhomogenous Deformation Theory for Rolling

When the frictional stress acting along the arc contact between rolls is higher, Karman's equation cannot be used. Orowan proposed the inhomogenous deformation theory for rolling [6]. Figure 3.7 shows the stress acting on the element of sheet between rolls in the inhomogenous deformation model.

In this rolling theory, the inhomogenous deformation by the frictional stress acting along the arc of contact is considered. As shown in Fig. 3.7a, the position of the element within the deformation region is specified by θ and β . In the element shown in Fig. 3.7b, the equilibrium of the horizontal force is derived by

$$\frac{dQ}{d\theta} = 2R(p \sin \theta - \tau_f \cos \theta) \quad (3.27)$$

Q can be calculated by integrating Eqn. (3.27) as follows:

$$Q = \frac{h}{2 \sin \theta} \int_{-\theta}^{\theta} (q \cos \beta - \tau_f \sin \beta) d\beta \quad (3.28)$$

The frictional stress is expressed by the frictional shear factor law as follows:

$$\tau_f = \pm mk \quad (3.29)$$

where m is the interface frictional shear factor ($0 \leq m \leq 1$).

Tresca's yield criterion of the workpiece is given by

$$q = p - 2\sqrt{k^2 - \tau^2} \quad (3.30)$$

If it is assumed that the normal pressure p is constant along the arc of contact and $\tau = (\beta/\theta)\tau_f$, $q(=Q/h)$ becomes as follows:

$$q = \frac{Q}{h} = \frac{1}{\sin \theta} \left\{ p \int_0^{\theta} \cos \beta d\beta - 2k \int_0^{\theta} \sqrt{1 - m^2 \left(\frac{\beta}{\theta} \right)^2} \cos \beta d\beta \mp \frac{mk}{\theta} \int_0^{\theta} \beta \sin \beta d\beta \right\} \quad (3.31)$$

If Eqn. (3.31) can be integrated numerically, the calculated results of q can be obtained.

In order to calculate the roll pressure distribution with high accuracy, two parameters of the flow stress and the coefficient of friction in the rolling theory must be specified with high accuracy.

3.3 Flow Stress for Rolling Theory

3.3.1 Flow Stress in Cold Sheet Rolling

In order to obtain the flow stress in cold sheet rolling, the tensile test method and the combined method of the tensile test and the rolling test are used. In the tensile test, the load P and the elongation $\Delta\ell$ in the tensile specimen are measured. Figure 3.8 shows the relationship between load and elongation in the tensile test.

From the measured load and elongation, the nominal stress s and the nominal strain e are given by

$$s = \frac{P}{A_0} \quad (3.32)$$

$$e = \frac{\ell - \ell_0}{\ell_0} \quad (3.33)$$

where A_0 is the initial cross-sectional area and ℓ_0 is the initial gauge length.

Next, the true stress σ and the true strain ε are given by

$$\sigma = \frac{P}{A} \quad (3.34)$$

$$\varepsilon = \ln \frac{\ell}{\ell_0} = \ln(1 + e) \quad (3.35)$$

where A is the current cross-sectional area and ℓ is the current gauge length. Figure 3.9 shows the relationships between nominal stress and nominal strain and true stress and nominal strain. The stress increases linearly with increasing nominal

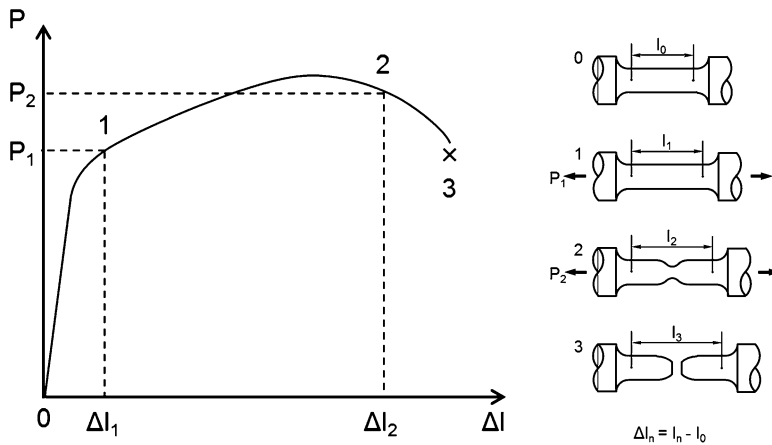


Fig. 3.8 Relationship between load and elongation in tensile test

Fig. 3.9 Relationships between nominal stress and nominal strain and true stress and nominal strain

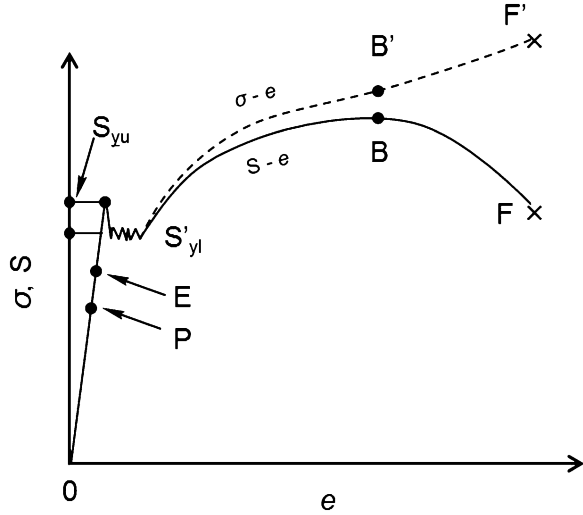
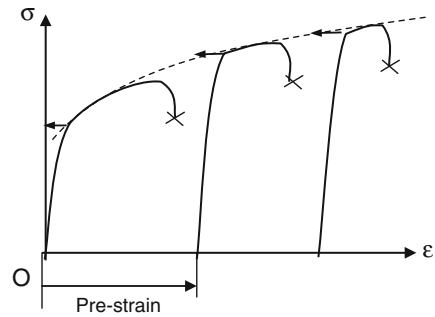


Fig. 3.10 Schematic representation of stress-strain curve measured by rolling and tensile test



strain by the point P and the nominal stress at the point E is called the elastic limit. S_{yu} is the yield stress (Y) and the maximum nominal stress at the point B is the ultimate tensile strength (UTS).

In metal-forming processes with larger plastic strain, the tensile test of sheets pre-strained by rolling is used to construct the relationship between stress and strain. Figure 3.10 shows the schematic representation of stress-strain curve measured by rolling and tensile test.

In order to obtain a constitutive equation of the workpiece, the relationship between true stress and true strain and the relationship between plastic strain and true strain are constructed as shown in Fig. 3.11.

The stress and strain curve for metal forming is derived on the base of the relationship between true stress and plastic strain shown in Fig. 3.11b. The relationship is given by

$$\sigma = Y + Fe^n \quad (\text{Ludwik's equation}) \quad (3.36)$$

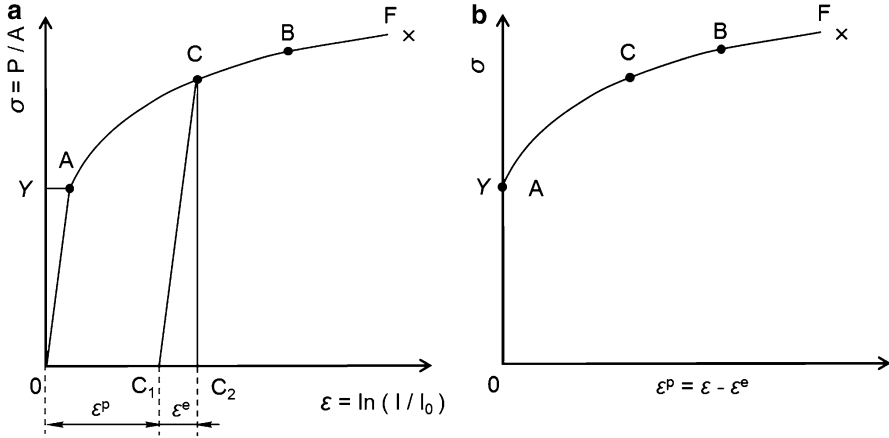


Fig. 3.11 Relationship between true stress and true strain (a) and relationship between plastic strain and true strain (b)

$$\sigma = c(a + \epsilon)^n \quad (\text{Swift's equation}) \quad (3.37)$$

When $Y = 0$, Ludwik's equation is given by

$$\sigma = F\epsilon^n \quad (3.38)$$

where F is the strength coefficient and n is the strain hardening exponent. The equation is widely used in metal forming.

Generally, the stress-strain relationship for metals is affected by the temperature and the strain rate. Equation (3.38) is satisfied in the low strain rate by $10^{-3}/s$ at a room temperature. However, in the cold sheet rolling, the strain rate is higher than $10^{-3}/s$ and the temperature is higher than room temperature due to the plastic deformation energy of the workpiece and the frictional energy at the interface between the tool and workpiece. Therefore, the stress must be expressed as the following equation involving the strain, the strain rate, and the temperature:

$$\sigma = f(\epsilon, \dot{\epsilon}, T) \quad (3.39)$$

The flow stress involving the strain, the strain rate, and the temperature for low-carbon steel and 17 %Cr stainless steel in cold sheet rolling was derived by Gokyu et al. [7] as follows:

$$\sigma = \sigma_0(\epsilon) + 9.8e^{6.5} \left\{ \frac{\dot{\epsilon}}{\dot{\epsilon}_0(\epsilon)} \right\}^{kT/0.14} \quad (\text{Low-carbon steel}) \quad (3.40)$$

$$\sigma = \sigma_0(\epsilon) + 9.8e^{4.4} \left\{ \frac{\dot{\epsilon}}{\dot{\epsilon}_0(\epsilon)} \right\}^{kT/0.32} \quad (17 \% \text{Cr stainless steel}) \quad (3.41)$$

where k is the Boltzmann constant.

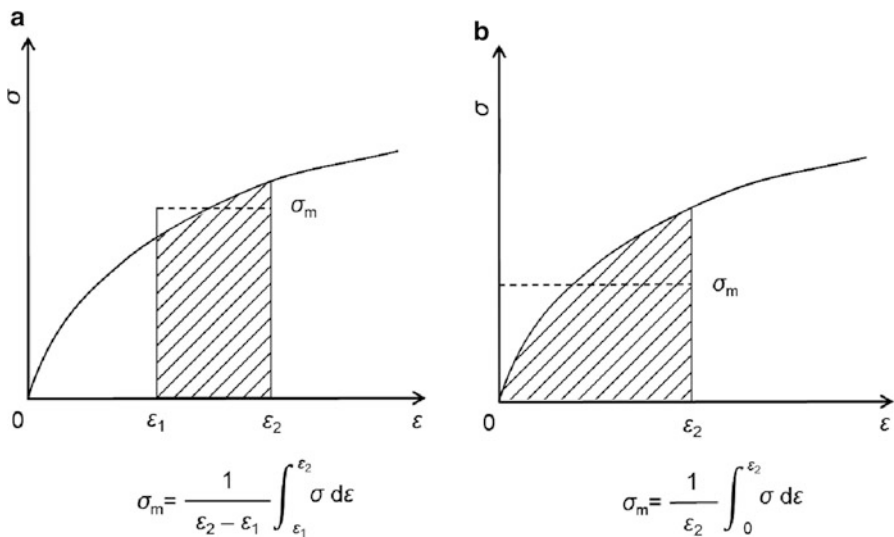


Fig. 3.12 Schematic representation of the mean flow stress

When the roll pressure in cold sheet rolling is calculated using the rolling theory, the mean flow stress is effective. Figure 3.12 shows the schematic representation of the mean flow stress.

The mean flow stress using Eqn. (3.40) of the low-carbon steel is calculated by Gokyu et al. [8]. Figure 3.13 shows the flow chart for calculation of mean flow stress using Eqn. (3.40) of the low-carbon steel. In the calculation of the mean flow stress, the temperature rise due to the plastic deformation is considered. The calculated results of low-carbon steel and 17 %Cr stainless steel are shown in Figs. 3.14 and 3.15.

In order to evaluate the calculated results of low-carbon steel and 17 %Cr stainless steel, the rolling experiments with the sticking condition are carried out using the same materials and the mean flow stress is calculated from the measured rolling force. Figure 3.16 shows the comparison of the mean flow stresses calculated with those measured. From Fig. 3.16, it is found that the mean flow stresses calculated are in good agreement with those measured. At the present time, Eqn. (3.40) is widely used for calculating the rolling force in cold sheet rolling of steelmaking companies in Japan.

3.3.2 Flow Stress in Hot Sheet Rolling

The flow stress in hot metal forming depends strongly on the strain rate and the temperature as compared to the flow stress in cold metal forming. Generally, the constitutive equation of the flow stress is given by

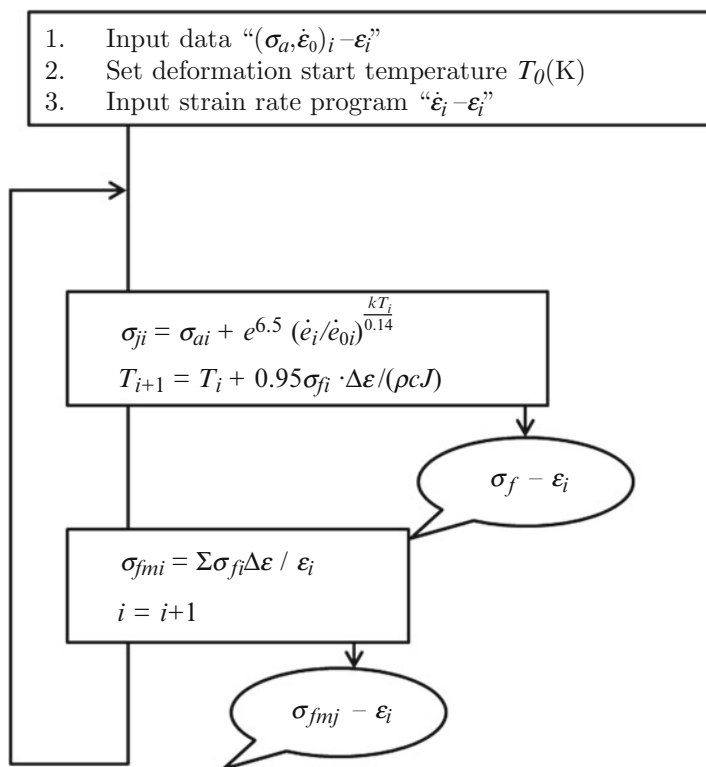


Fig. 3.13 Flow chart for calculation of mean flow stress of low-carbon steel

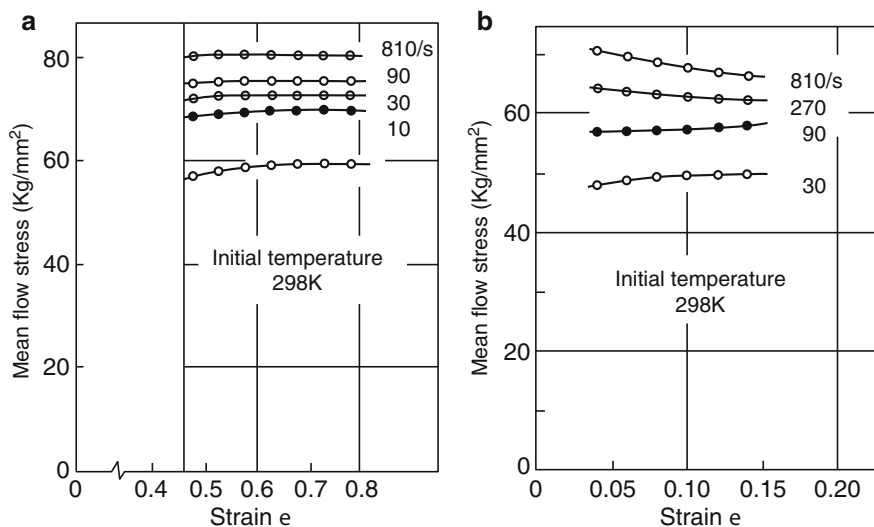


Fig. 3.14 Calculated mean flow stress of low-carbon steel: (a) low-carbon Al-killed steel and (b) low-carbon rimmed steel

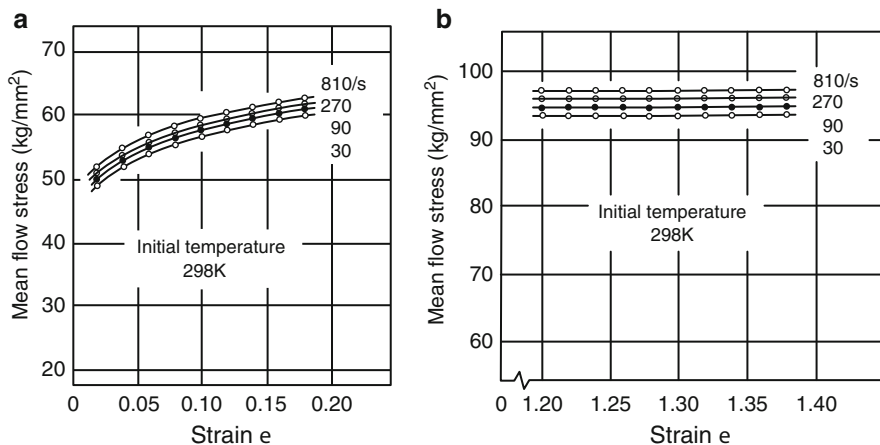
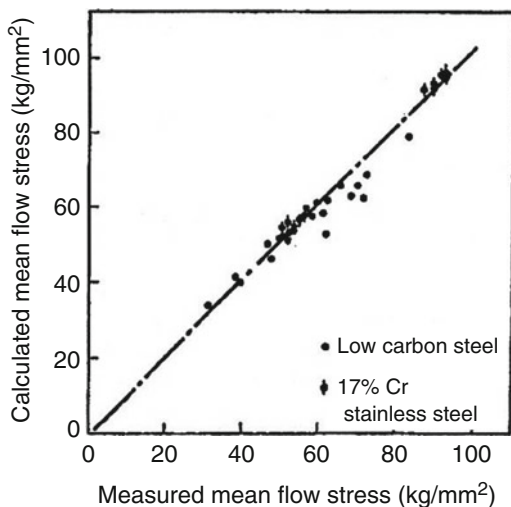


Fig. 3.15 Calculated mean flow stress of 17 %Cr stainless steel: (a) annealed 17 %Cr stainless steel and (b) hardened 17 %Cr stainless steel

Fig. 3.16 Comparison of mean flow stresses calculated with those measured [7]



$$\sigma = K \epsilon^n \dot{\epsilon}^m \exp\left(\frac{Q}{RT}\right) \quad (3.42)$$

where K is the material constant, Q is the activation energy, and R is the gas constant. The flow stress for calculating the rolling force in hot sheet rolling of the low-carbon steel is expressed as the following experimental equations:

1. Misaka's equation [9]

Shock compression tests are carried out changing the following parameters:

Carbon contents: $C = 0\text{--}1.2\%$

Strain: $\varepsilon = 0.1\text{--}0.5$

Strain rate: $\dot{\varepsilon} = 30\text{--}200/\text{s}$

Temperature: $T = 750\text{--}1200\text{ }^\circ\text{C}$

The data of mean flow stress are measured and the mean flow stress is given by

$$\sigma_m = K \varepsilon^{0.21} \dot{\varepsilon}^{0.13} \exp\left(\frac{A}{T}\right) \quad (3.43)$$

$$A = 2851 + 2968C - 1120C^2$$

$$K = \exp(0.126 - 1.75C + 0.594C^2)$$

2. Shida's equation [10]

Compression tests are carried out using the cam plastometer for measuring the flow stress changing the strain, the strain rate, and the temperature. The flow stress is given by

$$\sigma = F \left\{ 1.3 \left(\frac{\varepsilon}{0.2} \right)^n - 0.3 \left(\frac{\varepsilon}{0.2} \right) \right\} \left(\frac{\dot{\varepsilon}}{10} \right) \quad (3.44)$$

$$F = 0.28 \exp\left(\frac{5.0}{T} - \frac{0.01}{C + 0.05}\right) \quad (T \geq T_d)$$

$$F = 0.28g \exp\left(\frac{5.0}{T_d} - \frac{0.01}{C + 0.05}\right) \quad (T \leq T_d)$$

$$T = \frac{T_0}{1000}$$

$$g = 30.0(C + 0.90) \left(T - 0.95 \frac{C+0.49}{C+0.42} \right)^2 + \frac{C + 0.06}{C + 0.09}$$

$$T_d = 0.95 \frac{C + 0.41}{C + 0.32}$$

$$n = 0.41 - 0.07C$$

$$m = (-0.019C + 0.126)T + (0.075C - 0.050) \quad (T \geq T_d)$$

$$m = (0.081C - 0.154)T + (-0.019C + 0.207) + \frac{0.027}{C + 0.320} \quad (T \leq T_d)$$

3.4 Coefficient of Friction for Rolling Theory

In order to calculate the rolling force using the rolling theory in cold sheet rolling, the coefficient of friction must be determined with high accuracy similar to the flow stress. Since it is difficult to determine independently the coefficient of friction under the present circumstances, the method that the coefficient of friction is calculated from the rolling theory using the measured rolling force is used.

In the research committee on coefficient of friction in cold sheet rolling of low-carbon steel in ISIJ, the calculation method of the coefficient of friction was discussed and the joint research was carried out. Then, for calculating the coefficient of friction, Bland and Ford's equation for the rolling theory, Hitchcock's equation for roll flattening, and Eqn. (3.40) for the flow stress of the low-carbon steel were used. The experiments were carried out using the same low-carbon steel sheet and rolling oil. Figure 3.17 shows the relationship between the coefficient of friction and rolling speed obtained in the joint research. The purpose of this joint research was to understand the coefficient of friction over a rolling speed of 1500 m/min at the first time in the world.

From this joint research, the following subjects are found:

1. The coefficient of friction decreases with increasing rolling speed up to a rolling speed of 1000 m/min, and above 1000 m/min, it becomes slightly decreased.
2. The coefficient of friction depends on the roll diameter and it increases with decreasing roll diameter.
3. In order to determine the coefficient of friction for the rolling theory, the calculation method mentioned above is effective.

From these results, in order to understand the behavior of the coefficient of friction, the tribological behavior at the interface between the roll and workpiece must be investigated.

Fig. 3.17 Relationship between the coefficient of friction and rolling speed obtained in joint research [11]

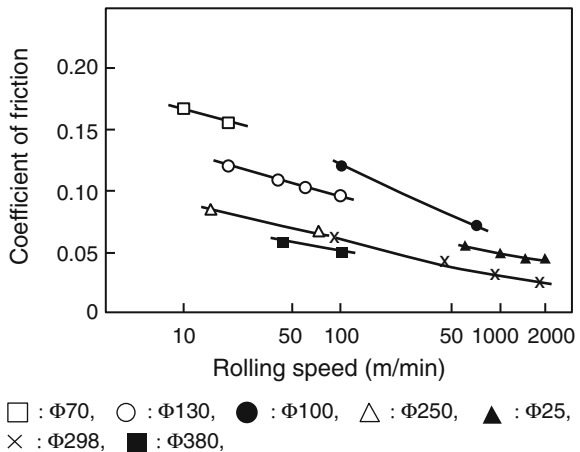


Fig. 3.18 Calculated results of mean flow stress-strain curve of low-carbon rimmed steel

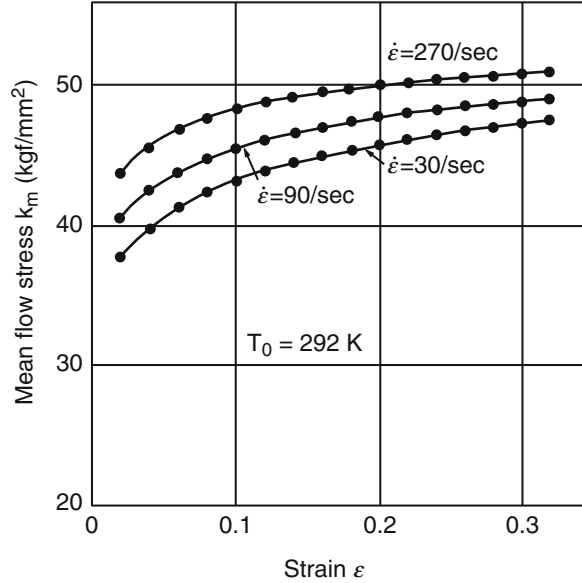
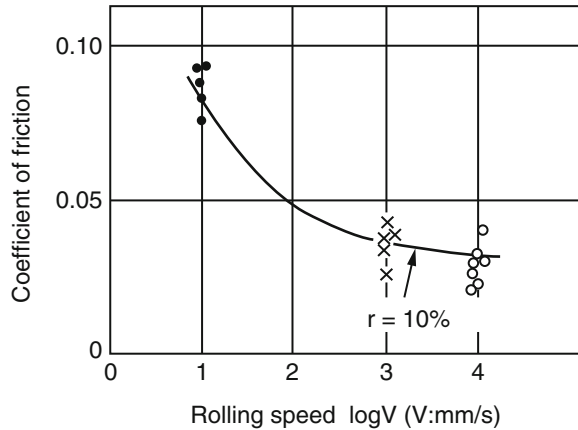


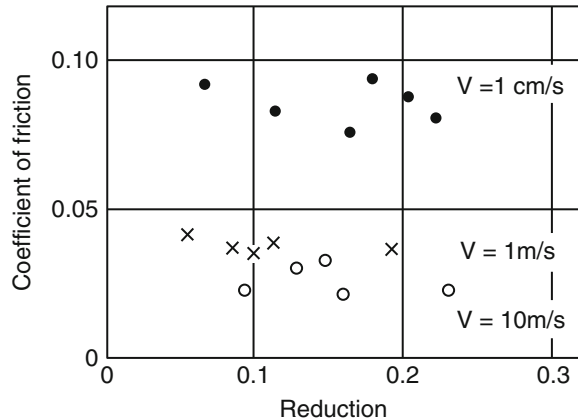
Fig. 3.19 Relationship between the coefficient of friction and rolling speed



The experiments for measuring the coefficient of friction using the same method were carried out by Gokyu et al. [12]. The low-carbon rimmed steel sheets as a workpiece and the machine oil as a lubricant are used. Figure 3.18 shows the calculated results of flow stress-strain curve of the low-carbon rimmed steel by Eqn. (3.40).

The coefficients of friction are calculated using Bland and Ford's equation and Hitchcock's equation and the calculated mean flow stress by Eqn. (3.40). Next, as for the experiment results, Fig. 3.19 shows the relationship between the coefficient of friction and rolling speed, and Fig. 3.20 shows the relationship between the coefficient of friction and reduction. From Figs. 3.19 and 3.20, it is found that the

Fig. 3.20 Relationship between the coefficient of friction and reduction



coefficient of friction decreases with increasing rolling speed and it is independent on the reduction. These data of the coefficient of friction are effective for calculating the rolling force by the rolling theory. However, they are insufficient for understanding the tribological behavior at the interface between the roll and workpiece.

The problems of this calculation method of the coefficient of friction are as follows:

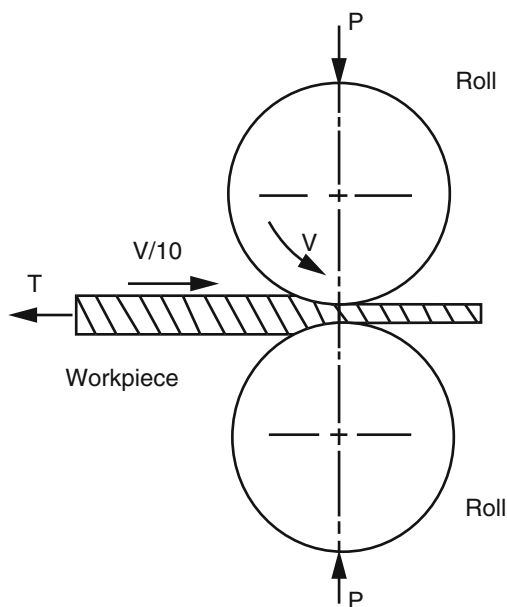
1. The tangential force cannot be measured directly.
2. The coefficient of friction is calculated from the rolling theory using the measured rolling force.
3. It is assumed that the frictional stress is given by Eqn. (3.15).

In order to solve the problems mentioned above and understand the tribological behavior at the interface between the roll and workpiece, the normal load and the tangential force must be measured independently.

3.5 Simulation Test for Coefficient of Friction

In order to understand the tribological behavior at the interface between the roll and workpiece in cold sheet rolling, the tribo-simulation test for the coefficient of friction as mentioned in Sect. 2.8 must be carried out. A new tribo-simulator in cold sheet rolling for the tribo-simulation of the tribological results such as the coefficient of friction and so on was developed by Azushima [13]. In the development of the new tribo-simulator, it is most important that the normal load and the tangential force are measured individually. Moreover, from the point of view that the geometry of the tribo-simulator must be similar to that of the actual process, it is considered that the workpiece sheet is passed between rolls. Therefore, the neutral point must be got out of the working contact region at the interface between the roll

Fig. 3.21 Conceptual representation of tribo-simulator for cold sheet rolling



and workpiece. Two processes where the neutral point is located in the outside of the entrance point and in the outside of the exit point are considered. Since in the former method the workpiece length becomes longer, the latter method is selected in the new tribo-simulator.

Figure 3.21 shows the conceptual representation of the tribo-simulator for cold sheet rolling. When the upper roll speed is V and the entrance speed of the workpiece is one tenth $V/10$, the neutral point is located in the outside of the entrance point. Moreover, the geometry of the tribo-simulator coincides with the geometry of the rolling. The characteristic of this tribo-simulator is that the workpiece is plastically deformed continuously during sliding and rolling.

Figure 3.22 shows the side view of the new sliding-rolling-type tribo-simulator and the specification of the sliding-rolling-type tribo-simulator is summarized in Table 3.1. The roll speed in sub-stand becomes one tenth $V/10$ of the roll speed in main stand V by the reducing gear. The workpiece sheet is rolled by the sub-stand and moves at a constant speed of $V/10$. The sliding-rolling experiments are carried out in the main stand changing the roll speed, the reduction, and the rolling oil. In the main stand, the roll speed of the upper roll is V and the under roll is rotated at a same speed of the workpiece.

The rolling force P , the torque of the upper roll T , and the back tension T_b are measured during sliding and rolling. The coefficient of friction as a ratio of the tangential force to the normal load is calculated by the rolling force and the torque of the upper roll or the back tension as follows:

$$\mu = \frac{T_b}{P} + \alpha \quad (3.45)$$

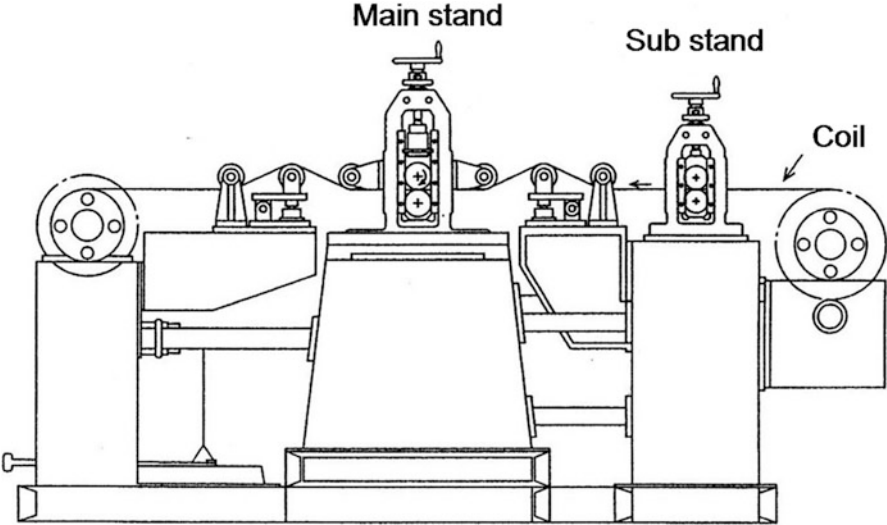


Fig. 3.22 Side view of the new sliding-rolling-type tribo-simulator

Table 3.1 Specification of sliding-rolling-type tribo-simulator

Main stand	DC motor	Power	22 kW
		Revolution	0–1750 rpm
	Magnetic clutch	8H type	
	Deceleration of roll	1:1, 1:1/2, 1:1/3	
	Main rolling mill	Roll geometry	76 mm $\varnothing \times 60$ mm
		Roll material	SUJ-2, $H_s \geq 90$
		Roll speed	0–420 m/min
		Rolling force	15cf Max.
	AC motor	Power	0.75 kW
		Revolution number	3–35 rpm
Sub-stand	Deceleration	Timing pulley	1:1, 1:1/3
		Reducing gear	1:1/10
	Sub-rolling mill	Roll geometry	70 mm $\varnothing \times 60$ mm
		Roll material	SUJ-2, $H_s \geq 90$
		Roll speed	0–42 m/min
		Rolling force	5cf Max.
	Un-coiler	Torque control geometry	200 mm $\varnothing \times 60$ mm

$$\mu = \frac{G}{PR} \tag{3.46}$$

where T_b is the back tension, G is the torque of the upper roll, α is the contact angle, and R is the radius of the upper roll.

Fig. 3.23 Relationship between the coefficient of friction and roll speed obtained by new sliding-rolling-type tribo-simulator

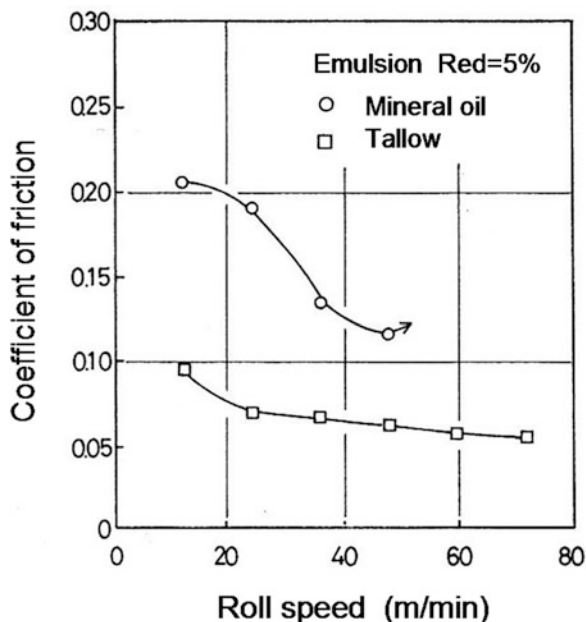


Figure 3.23 shows the relationship between the coefficient of friction and roll speed measured by the new sliding-rolling-type tribo-simulator. The sliding-rolling experiments of the tribo-simulator are carried out changing the roll speed at a constant reduction of 5 % with 3 % emulsion oils of machine base oil and tallow oil. The coefficient of friction is calculated using Eqn. (3.45). The coefficients of friction of the tallow oil are lower than those of the machine oil and decrease with increasing roll speed. On the other hand, the coefficients of friction of the machine base oil are higher and the friction pickup occurs at a roll speed of 48 m/min.

By using this sliding-rolling-type tribo-simulator, many data of the coefficient of friction are obtained and it is expected that the tribological behavior at the interface between the roll and workpiece in cold sheet rolling can be understood.

References

1. K. Saeki, Y. Hashimoto, J. Jpn. Soc. Technol. Plast. 6-55 (1965), 439-450. (in Japanese)
2. Y. Tozawa, Textbook of 86th Lectureship in JSTP, (2002), 27-49. (in Japanese)
3. T. von Karman, Z. Angew. Math. Mech., 7 (1925), 139.
4. A. Nadai, J. Appl. Mech., 6 (1939), 54.
5. D. R. Bland, H. Ford, Proc. Inst. Mech. Engr., 159 (1948), 144.
6. E. Orowan, Proc. Inst. Mech. Engr., 150 (1943), 140.
7. I. Gokyu, J. Kihara, A. Azushima, J. Jpn. Soc. Technol. Plast. 14-144 (1973), 12-17. (in Japanese)

8. I. Gokyu, J. Kihara. A. Azushima, J. Jpn. Soc. Technol. Plast. 14-152 (1973), 718-721. (in Japanese)
9. Y. Misaka, T. Yoshimoto, I. Gokyu, J. Kihara. A. Azushima, J. Jpn. Soc. Technol. Plast. 8-79 (1967), 414-422. (in Japanese)
10. S. Shida, I. Gokyu, J. Kihara. A. Azushima, J. Jpn. Soc. Technol. Plast. 10-103 (1969), 610-617 (in Japanese)
11. A. Azushima, Tetsu-to-Hagane, 64-2 (1978), 317-330. (in Japanese)
12. I. Gokyu, J. Kihara. A. Azushima, J. Jpn. Soc. Technol. Plast. 15-160 (1974), 400-406. (in Japanese)
13. A. Azushima, Tetsu-to-Hagane, 74-4 (1988), 696-702. (in Japanese)

Chapter 4

Tribology in Cold Sheet Rolling

4.1 Coefficient of Friction

4.1.1 *Coefficient of Friction in History*

In early reports about the coefficient of friction in cold sheet rolling, the coefficients of friction were calculated from the rolling theory applied in the friction law of Eqn. (2.1) along the arc of contact at the interface between roll and workpiece using the measured rolling force. In United States in the 1950s, Stone [1] calculated the coefficient of friction from the rolling theory and reported the relationship between coefficient of friction and rolling speed as shown in Fig. 4.1.

In Fig. 4.1, it is shown that the coefficient of friction decreases with increasing rolling speed in the lower rolling speed up to a rolling speed of 300 m/min, and it becomes constant in the higher rolling speed up to a rolling speed of 1300 m/min. Moreover, in Japan in the 1970s, the dependence of the rolling speed on the coefficient of friction over a rolling speed of 2000 m/min was examined in the research committee of ISIJ, and the relationship between coefficient of friction and rolling speed shown in Fig. 4.2 was obtained.

In Fig. 4.2, the coefficient of friction decreases slightly with increasing rolling speed in the higher rolling speed. In any case, in order to understand the dependence of the rolling speed on the coefficient of friction, the lubrication mechanism at the contact interface must be discussed, and the friction model must be constructed for calculating the rolling force.

Next, the relationship between coefficient of friction and rolling speed for several base oils with different viscosities was examined as shown in Fig. 4.3 [3]. From Fig. 4.3, it is found that the difference among the coefficients of friction of four base oils in the lower rolling speed is due to the difference of the boundary coefficient of friction and the degree of the rolling speed dependence of the coefficient of friction is due to the oil film thickness introducing at the contact interface between roll and workpiece depending on the viscosity of base oil. It is

Fig. 4.1 Relationship between coefficient of friction and rolling speed [2]

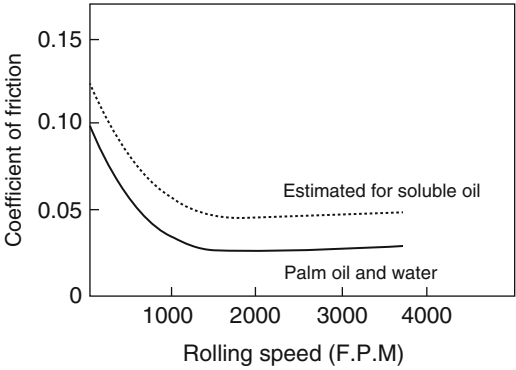


Fig. 4.2 Relationship between coefficient of friction and rolling speed obtained joint research in ISIJ [2]

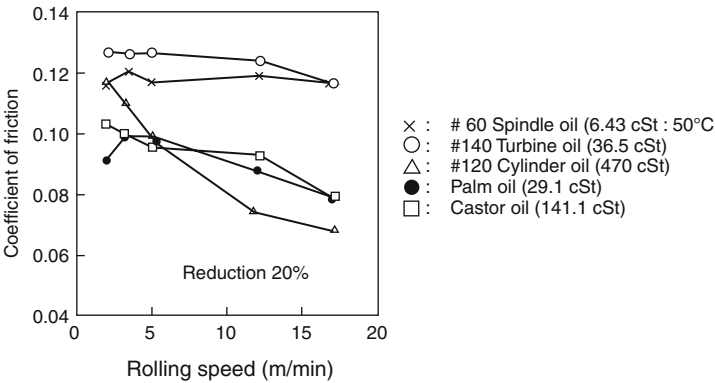
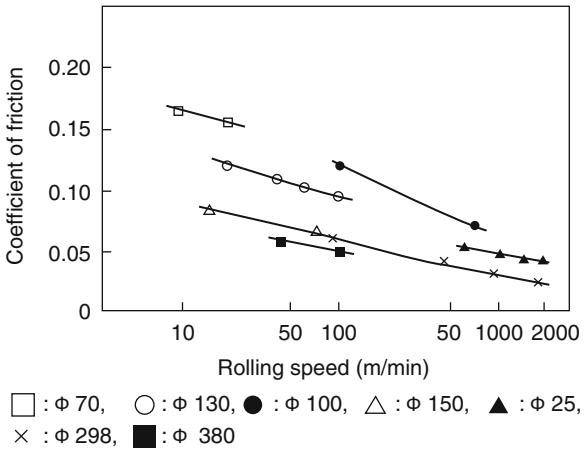


Fig. 4.3 Relationship between coefficient of friction and rolling speed for several base oils [3]

estimated that the lubrication regime in the lower rolling speed is the mixed lubrication in which the boundary lubrication is dominant and on the other hand the lubrication regime in the higher rolling speed is the mixed lubrication in which the hydrodynamic lubrication is dominant.

4.1.2 *Dependence of Coefficient of Friction from Rolling Theory*

Azushima et al. [4] investigated the dependence of the tribological conditions on the coefficient of friction to understand the tribological behavior at the interface between roll and workpiece in cold sheet rolling. The coefficients of friction are calculated from the Bland and Ford' equation and the Hitchcock's equation using the measured rolling force and the calculated mean flow stress. The low carbon steel sheets and the lubricants shown in Table 4.1 are used. The rolling experiments are carried out at two rolling speeds of 80 and 800 m/min in the range of the reduction from 5 to 40 %. The neat oil and the emulsion oil with a concentrate of 10 % for each lubricant are used. The rolling experiments with the neat oil and the emulsion oil are carried out at a room temperature and at 65 °C.

4.1.2.1 Coefficient of Friction in Neat Oils

Figure 4.4 shows the relationship between coefficient of friction and rolling speed of Nos. 1 and 2 naphthenic base oils with different viscosities of 29.5 and 50.0 cSt at 38 °C. In a rolling speed of 50 m/min, the coefficient of friction of No. 1 oil with a

Table 4.1 Properties of lubricants used

No.	Lubricant	Kinematic viscosity η_0 [cSt]		Viscosity index
		38 °C	99 °C	
1	Naphthenic base oil a	29.5	4.2	1
2		80.0	7.1	20
3	Paraffinic base oil b	29.7	4.6	65
4		55.4	7.1	93
5	Synthetic ester base oil c	29.4	7.1	233
6		15.0	3.6	139
7	Glycerin base oil d	31.0	3.7	–
8		31.5	3.8	–
9		31.8	3.8	–
10	Paraffinic base oil b + 5 % oleic acid e	50.5	6.9	103
11	Paraffinic base oil b + 5 % oleic acid e	4.0	1.5	115
12		4.3	1.6	118

Fig. 4.4 Relationship between coefficient of friction and rolling speed of Nos. 1 and 2 naphthenic base oils

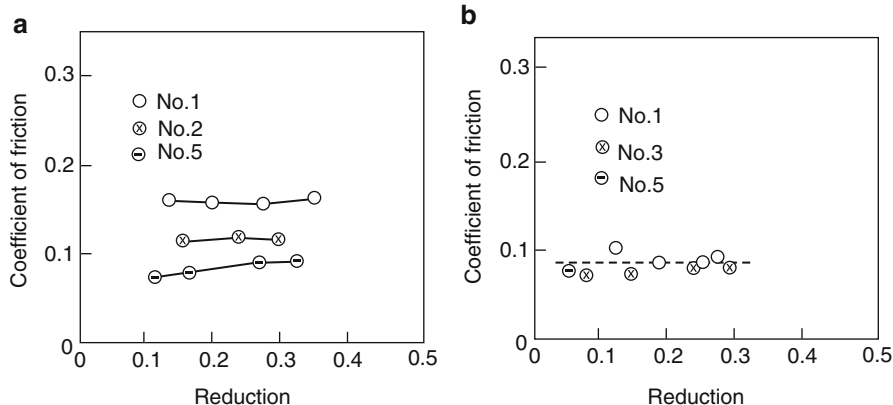
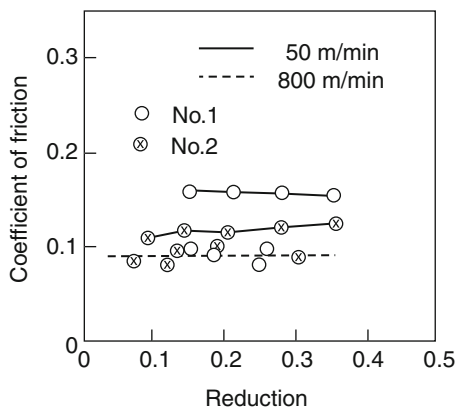


Fig. 4.5 Relationship between coefficient of friction and rolling speed of No. 1 naphthenic base oil, No. 3 paraffinic base oil, and No. 5 synthetic ester base oil. (a) 50 m/min. (b) 800 m/min

low viscosity is higher than that of No. 2 with a high viscosity. In a rolling speed of 800 m/min, the coefficients of friction of Nos. 1 and 2 oils are almost equal.

Generally, the lubrication regime in 50 m/min is the mixed lubrication in which the boundary lubrication is dominant, and the lubrication regime in 800 m/min is the mixed lubrication in which the hydrodynamic lubrication is dominant. In the mixed lubrication in which the boundary lubrication is dominant, it is estimated that the effect of the viscosity of lubricant on the coefficient of friction is large. On the other hand, in the mixed lubrication in which the hydrodynamic lubrication is dominant, the coefficient of friction is independent on the viscosity. The coefficients of friction are independent of the reduction.

Then, Fig. 4.5 shows the relationship between coefficient of friction and rolling speed of No. 1 naphthenic base oil, No. 3 paraffinic base oil, and No. 5 synthetic ester base oil with same viscosity at rolling speeds of 50 m/min (a) and 800 m/min (b). In a rolling speed of 50 m/min, the coefficients of friction depend on the composition

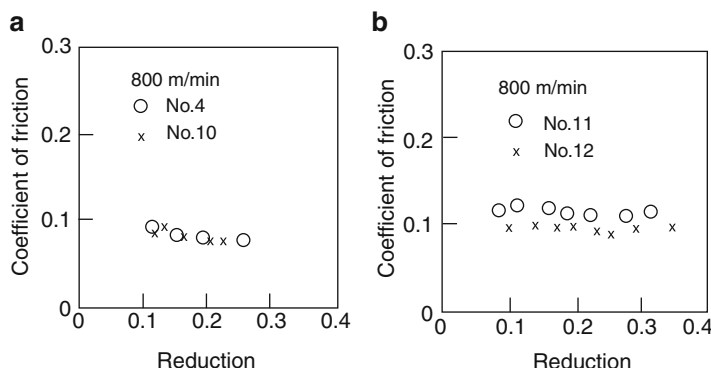


Fig. 4.6 Relationship between coefficient of friction and rolling speed of Nos. 4 and 11 paraffinic base oils, and Nos. 10 and 12 paraffinic base oils with additive of 5 % oleic acid. (a) Paraffinic base oil with high viscosity. (b) Paraffinic base oil with low viscosity

of lubricants, and the coefficients of friction become lower in the order of No. 1 oil, No. 3 oil, and No. 5 oil. On the other hand, in a rolling speed of 800 m/min, the coefficients of friction are almost similar to those in Fig. 4.4. It is estimated that when the boundary lubrication is dominant in 50 m/min, the coefficients of friction depend on the boundary film of base oils. When the hydrodynamic lubrication is dominant, the coefficient of friction is independent of the composition of lubricant.

Then, Fig. 4.6 shows the relationship between coefficient of friction and rolling speed of Nos. 4 and 11 paraffinic base oils, and Nos. 10 and 12 paraffinic base oils with an additive of 5 % Oleic acid at a rolling speed of 800 m/min. No. 4 is a high viscosity base oil and No. 11 is a low viscosity base oil. In Fig. 4.6a, the coefficients of friction of base oil with a high viscosity at 800 m/min are not affected on the boundary film formed by oleic acid. On the other hand, in Fig. 4.6b, the coefficients of friction of base oil with lower viscosity depend on the boundary film formed by oleic acid even at a high speed of 800 m/min.

From these results, it is understood that the coefficients of friction in cold sheet rolling with neat oils depend significantly on the lubrication regime determined by the ratio λ of the oil film thickness to the combined surface roughness.

4.1.2.2 Coefficient of Friction in Emulsion Oil

Figure 4.7 shows the relationship between coefficient of friction and rolling speed of Nos. 1 and 2 naphthenic emulsion oils with different viscosities. The coefficients of friction in the emulsion oils are higher than those in the neat oils, and they increase with increasing reduction in a rolling speed of 800 m/min. In 800 m/min, it is considered that the lubrication regime changes from the mixed lubrication in which the hydrodynamic lubrication is dominant to the mixed lubrication in which the boundary lubrication is dominant with increasing reduction. In a rolling speed

Fig. 4.7 Relationship between coefficient of friction and rolling speed of Nos. 1 and 2 naphthenic emulsion oils with different viscosities

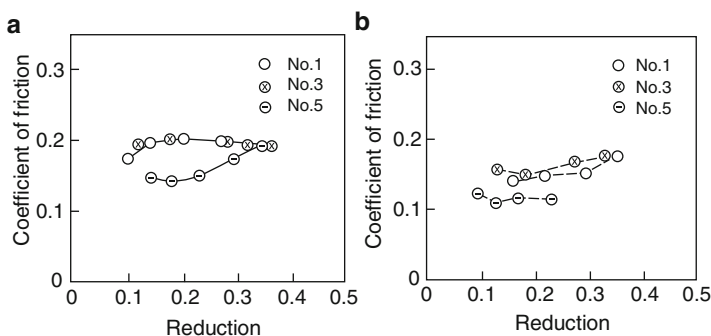
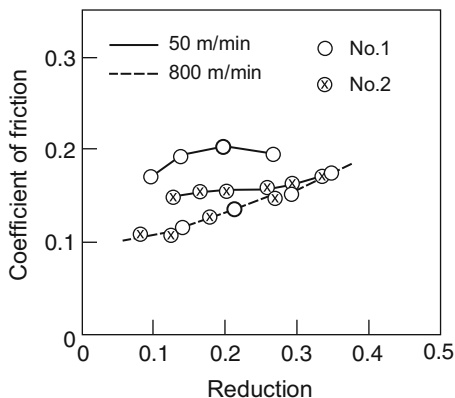


Fig. 4.8 Relationship between coefficient of friction and rolling speed of No. 1 naphthenic emulsion oil, No. 3 paraffinic emulsion oil, and No. 5 synthetic emulsion oil. (a) 50 m/min. (b) 800 m/min

of 50 m/min, the coefficients of friction of No. 1 oil with a low viscosity are higher than that of No. 2 with a high viscosity similar to those in the neat oils. The lubrication regime in 50 m/min is the mixed lubrication in which the boundary lubrication is dominant.

Next, Fig. 4.8 shows the relationship between coefficient of friction and rolling speed of No. 1 naphthenic emulsion oil, No. 3 paraffinic emulsion oil, and No. 5 synthetic ester emulsion oil at a rolling speed of 50 m/min (a) and a rolling speed of 800 m/min (b). In a rolling speed of 50 m/min, the coefficients of friction depend on the composition of lubricants, and the coefficients of friction of Nos. 1 and 3 oils are equal. On the other hand, the coefficients of friction of No. 5 are lower in lower reduction, but they increase with increasing reduction in higher reduction. In a rolling speed of 800 m/min, the coefficients of friction depend on the composition of lubricant in Fig. 4.8b. It is estimated that the boundary lubrication is dominant in 800 m/min in case of the emulsion oils.

Then, Fig. 4.9 shows the relationship between coefficient of friction and rolling speed of Nos. 4 and 11 paraffinic emulsion oils and Nos. 10 and 12 paraffinic

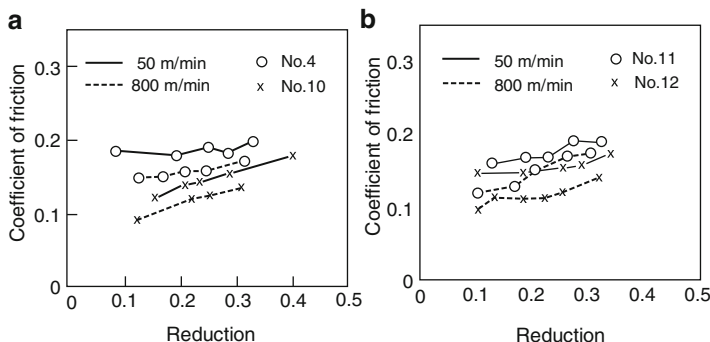


Fig. 4.9 Relationship between coefficient of friction and rolling speed of Nos. 4 and 11 paraffinic emulsion oils, and Nos. 10 and 12 paraffinic emulsion oils. (a) Paraffinic emulsion oil with high viscosity. (b) Paraffinic emulsion oil with low viscosity

emulsion oils with an additive of 5 % oleic acid at a rolling speed of 800 m/min. The coefficients of friction of emulsion oils with a low viscosity and a high viscosity at 800 m/min depend on the boundary film formed by oleic acid. The coefficients of friction of all the oils at rolling speeds of 50 and 800 m/min increase with increasing reduction. It is estimated that the lubrication regime changes from the mixed lubrication in which the hydrodynamic lubrication is dominant to the mixed lubrication in which the boundary lubrication is dominant.

The coefficients of friction are calculated from the rolling theory using the measured rolling force, and from these coefficients of friction, the tribological behavior at the contact interface in cold sheet rolling is considered. However, it is difficult to understand quantitatively the tribological behavior from the coefficients of friction. Therefore, it is expected that the new tribo-simulator will be developed and the normal load and the tangential force can be measured individually in order to determine the coefficient of friction.

4.1.3 Coefficient of Friction Measured by Sliding-Rolling-Type Tribo-Simulator Developed

The rolling force P and the back tension T_b are measured individually by the newly developed sliding-rolling-type tribo-simulator mentioned in Sect. 3.5. The coefficient of friction is calculated by Eqn. (3.45).

4.1.3.1 Evaluation of Coefficient of Friction Measured

In order to evaluate the coefficient of friction measured by the sliding-rolling-type tribo-simulator, the coefficients of friction measured using the three lubricants with different viscosities and three commercial rolling oils were measured by

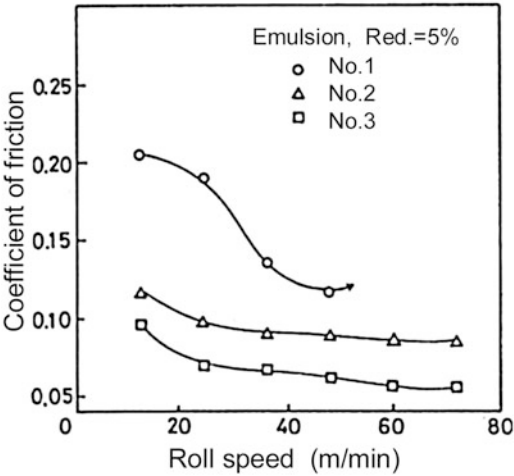
Table 4.2 Composition and viscosity of three lubricants

No.	Base oil	Additive	Composition ratio (wt%) (base oil/additive/emulsifier)	Viscosity (50 °C:cSt)
1	Mineral oil	–	95:0:5	7.1
2	Synthetic ester	–	95:0:5	6.8
3	Tallow	–	95:0:5	30.5

Table 4.3 Composition and properties of three commercial rolling oils

No.	Composition (%)						Properties	
	Mineral oil	Ester	Oiliness agent	EP agent	Emulsifier	Another additive	Viscosity (50 °C:cSt)	Saponification value (mg KOH/g)
A	62	23	1.5	0.5	3.0	10.0	9.7	49
B	44	48	1.5	–	1.5	5.0	11.7	90
C	32	45	10.0	2.0	6.0	5.0	41.5	112

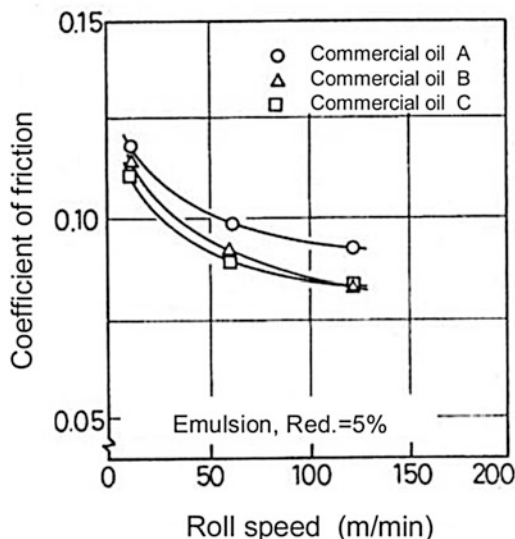
Fig. 4.10 Relationship between coefficient of friction and roll speed with 3 % emulsion oils of Nos. 1–3



Azushima et al. [5]. The composition and viscosity of three lubricants are summarized in Table 4.2, and the composition and properties of commercial rolling oils are summarized in Table 4.3.

The sliding-rolling experiments are carried out at roll speeds of 12, 24, 36, 48, 60, and 72 m/min in a constant reduction of 5 % using the low carbon steel. In the experiments with the lubricants of Nos. 1–3, the 3 % emulsion oils at 55 °C are used, and in the experiments with the commercial oils of A, B, and C, the 3 % emulsion oils at 55 °C are also used. Figure 4.10 shows the

Fig. 4.11 Relationship between coefficient of friction and roll speed with 3 % emulsion of A, B, and C commercial rolling oils



relationship between coefficient of friction and roll speed with 3 % emulsion oils of Nos. 1–3. The coefficients of friction measured by the sliding-rolling-type tribo-simulator decrease with increasing roll speed, and they become lower in the order of Nos. 1–3 oils. In the No. 1 oil, the friction pickup occurs at a roll speed of 60 m/min. It is understood that the effect of the composition of lubricant can be evaluated from the coefficient of friction measured by this tribo-simulator.

Next, Fig. 4.11 shows the relationship between coefficient of friction and roll speed with 3 % emulsions of A, B, and C commercial rolling oils. The coefficients of friction of A, B, and C commercial oils decrease with increasing roll speed, and they become lower in the order of A, B, and C oils. In the commercial oils with different saponification values, it is understood that the effect of the saponification value of rolling oil can be also evaluated from the coefficient of friction measured by this tribo-simulator. Consequently, it is found that this sliding-rolling-type tribo-simulator is effective to measure the coefficient of friction with high accuracy.

4.1.3.2 Evaluation of Additive in Mineral Base Oil by Coefficient of Friction

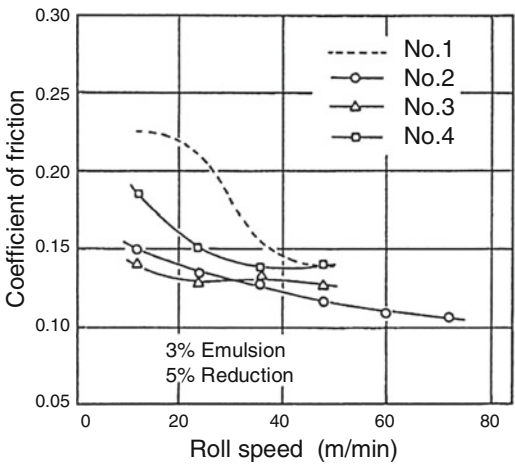
As shown in Fig. 4.10, the coefficients of friction of the mineral base oil are higher than those of the synthetic ester oil and the tallow oil, and the friction pickup occurs at a roll speed of 60 m/min. It is found that only the mineral base oil cannot be used as rolling oil. Therefore, some additives must be added in the mineral base oil. The effect of the additives on the coefficient of friction was examined using

Table 4.4 Composition and viscosity of lubricants used

No.	Composition		Property
	Additive	Ratio ^a	Viscosity (50 °C:cSt)
1	–	95:0:5	7.1
2	Oleic acid	85:10:5	7.8
3	Oleyl alcohol	85:10:5	7.3
4	Oleyl amine	85:10:5	6.6
5	Lauric acid	85:10:5	7.3
6	Myristic acid	85:10:5	7.6
7	Palmitic acid	85:10:5	7.9
8	Stearic acid	85:10:5	8.2
9	Polymerized acid	85:10:5	13.1
10	Zinc-di-thio-phosphate	85:10:5	7.3
11	Di-alkyl-phosphite	85:10:5	7.2
12	Alkyl-acid-phosphate	85:10:5	7.5
13	Tri-alkyl-phosphite	85:10:5	7.2

^aBase oil, additive, emulsifier (wt%)

Fig. 4.12 Effect of functional group of oiliness agents on coefficient of friction



13 lubricants of the mineral base oils using the sliding-rolling-type tribo-simulator by Azushima et al. [6]. The composition and viscosity of the lubricants are summarized in Table 4.4

The sliding-rolling experiments are carried out at roll speeds of 12, 24, 36, 48, 60, and 72 m/min in a constant reduction of 5 % using the low carbon steel. In the experiments, the 3 % emulsion oils at 50 °C are used. The coefficient of friction is calculated by Eqn. (3.44). Figure 4.12 shows the relationship between coefficient of friction and roll speed with 3 % emulsion oils of Nos. 1–4. In Fig. 4.12, the effect of the oiliness agent with different polar groups in the same alkyl group on the

Fig. 4.13 Relationship between coefficient of friction and roll speed with 3 % emulsion oils of Nos. 1, 5–8

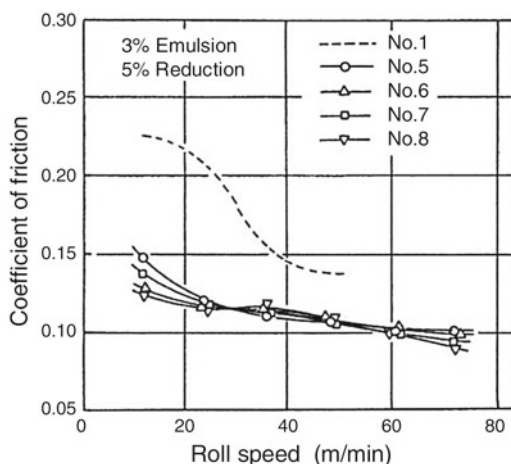
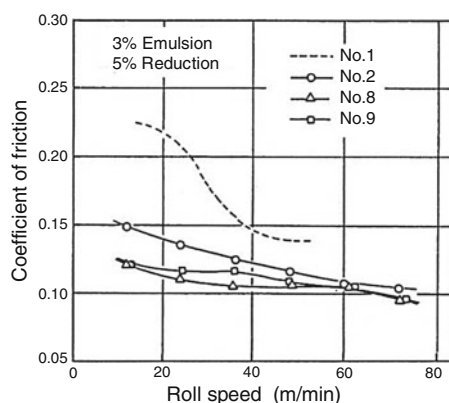


Fig. 4.14 Relationship between coefficient of friction and roll speed with 3 % emulsion oils of Nos. 1, 2, 8, and 9

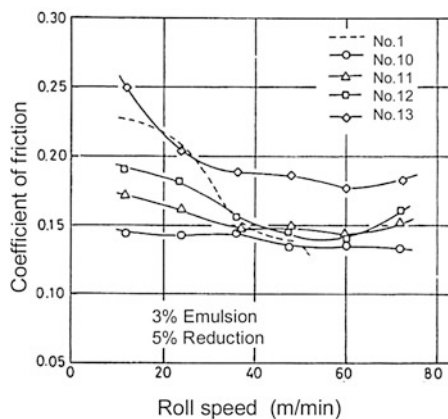


coefficient of friction is examined. The oiliness agents of the hydroxyl and carboxyl groups are effective to decrease the coefficient of friction.

Next, Fig. 4.13 shows the relationship between coefficient of friction and roll speed with 3 % emulsion oils of Nos. 1, 5–8. In Fig. 4.13, the effect of the carbon number of fatty acid on the coefficient of friction is examined. The coefficients of friction of all the oils of Nos. 5–8 are extremely lower than those of the mineral base oil of No. 1. The addition of the fatty acid is significantly effective to decrease the coefficient of friction.

Figure 4.14 shows the relationship between coefficient of friction and roll speed with 3 % emulsion oils of Nos. 1, 2, 8, and 9. In Fig. 4.14, the effect of the saturated and unsaturated fatty acids on the coefficient of friction is examined. The coefficients of friction of No. 9 oil added the Dimerized carboxylic acid are substantially the same as the coefficients of friction of No. 8 oil. The coefficients of friction of No. 9 oil added the dimerized carboxylic acid are the same as the low coefficient friction of No. 8 oil.

Fig. 4.15 Relationship between coefficient of friction and roll speed with 3 % emulsion oils of Nos. 1, 10–13



Next, the effect of the EP agents on the coefficient of friction is examined. Figure 4.15 shows the relationship between coefficient of friction and roll speed with 3 % emulsion oils of Nos. 1, 10–13. The coefficients of friction of Nos. 10–13 oils and the EP agents above a roll speed of 36 m/min are similar to those of No. 1 oil. The coefficients of friction of No. 13 are higher than those of No. 1 oil. The addition of the EP agent in the mineral base oil is not effective to decrease the coefficient of friction.

4.1.3.3 Evaluation of Tallow Base Oil by Coefficient of Friction

In the previous chapter, the effect of the additives in the mineral base oil on the coefficient of friction is evaluated. The coefficients of friction of the mineral base oil with additives are higher than those of the synthetic ester base oil and the tallow base oil. The lubricants consisted of the mineral base oil cannot be used in cold sheet rolling under severe rolling conditions. In this chapter, the behavior of coefficient of friction of the tallow base oil with high lubricity was examined by measuring the coefficient of friction using the tribo-simulator by Azushima et al. [6, 7].

First, the coefficients of friction are measured, changing the emulsion concentration of tallow base oil with 5 % emulsifier at a temperature of 55 °C using the sliding-rolling-type tribo-simulator. The coefficient of friction is calculated from Eqn. (3.45). The sliding-rolling experiments are carried out in roll speeds of 12, 60, 120, and 180 m/min at a constant reduction of 5 % using the low carbon steel.

Figure 4.16 shows the distribution of emulsion particle size with emulsion concentrations of 1, 2, 3, 4, and 5 %. The mean emulsion particle sizes are 6.8, 6.7, 6.5, 6.7, and 6.8 μm at emulsion concentrations of 1, 2, 3, 4, and 5 %. The mean emulsion particle sizes are almost the same in each emulsion concentration. The distribution of particle size at 1 % emulsion is broad compared to those of other concentrations.

Figure 4.17 shows the relationship between coefficient of friction and emulsion concentration at roll speeds of 12, 60, 120, and 180 m/min. The coefficient of

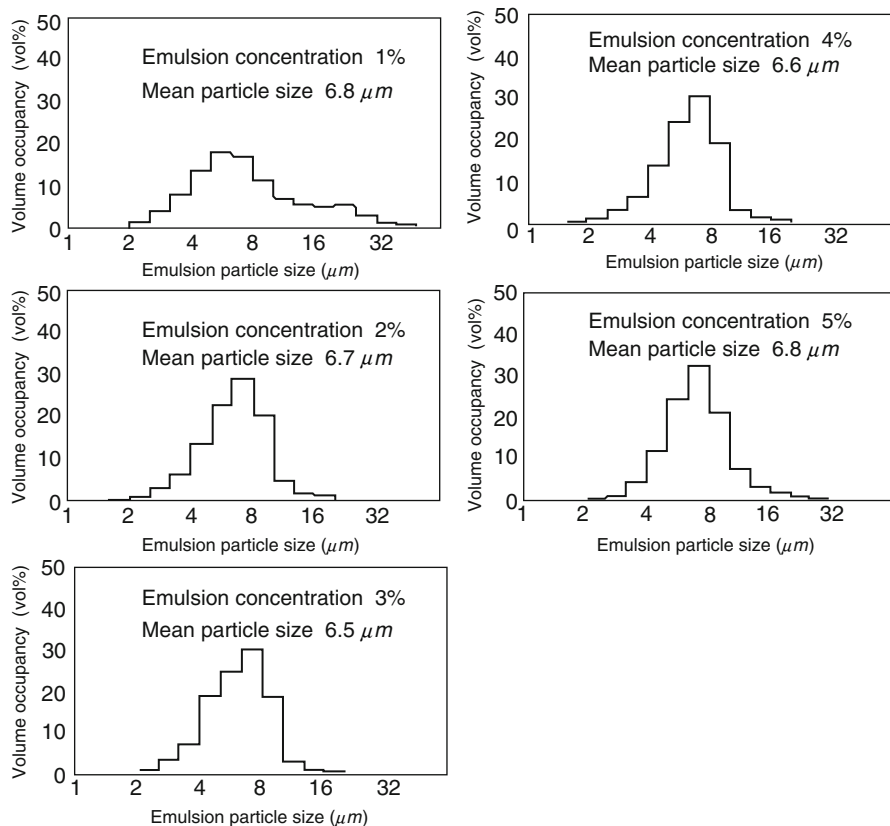


Fig. 4.16 Distribution of emulsion particle size with emulsion concentrations of 1, 2, 3, 4, and 5 %

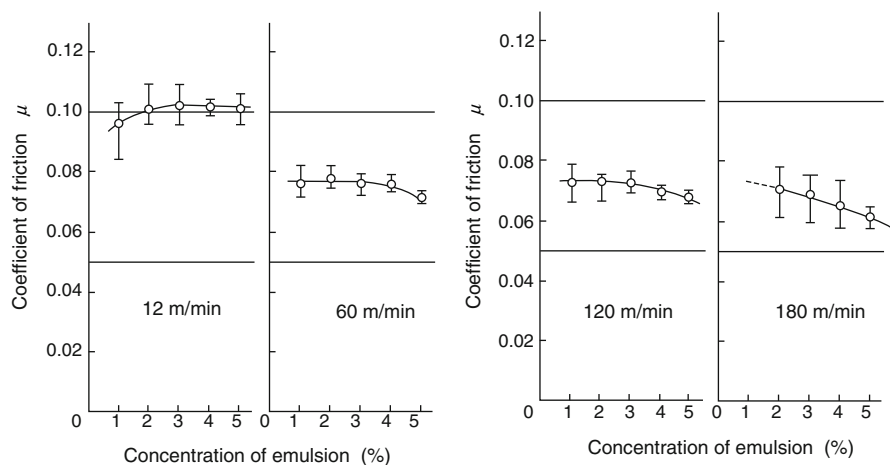


Fig. 4.17 Relationship between coefficient of friction and emulsion concentration at roll speeds of 12, 60, 120, and 180 m/min

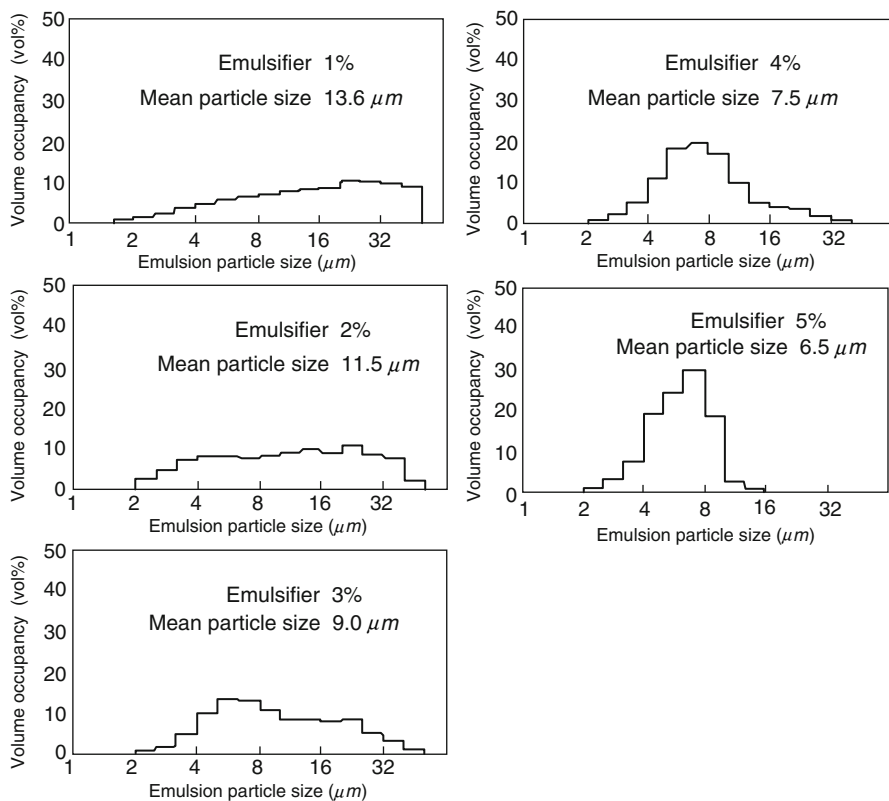


Fig. 4.18 Distribution of emulsion particle size with emulsifier concentrations of 1, 2, 3, 4, and 5 %

friction for each concentration decreases with increasing roll speed. At 12 m/min, the coefficient of friction is constant above 3 % emulsion, at 60 m/min it decreases with increasing emulsion concentration above 4 %, at 120 m/min it decreases above 3 %, and at 180 m/min it decreases above 2 %. It is found that the emulsion concentration may be increased in the higher rolling speed in order to decrease the coefficient of friction.

Second, the coefficients of friction are measured, changing the emulsifier concentration in tallow base oil with 3 % emulsion concentration at a temperature of 55 °C using the sliding-rolling-type tribo-simulator. The sliding-rolling experiments are carried out at roll speeds of 12, 60, 120, and 180 m/min at a constant reduction of 5 % using the low carbon steel. Figure 4.18 shows the distribution of emulsion particle size with emulsifier concentrations of 1, 2, 3, 4, and 5 %. The mean emulsion particle sizes for each concentration are 13.6, 11.5, 9.0, 7.5, and 6.5 μm at emulsion concentrations of 1, 2, 3, 4, and 5 %. The mean emulsion particle sizes decrease with increasing emulsifier concentration. The distribution of particle size becomes sharp with increasing emulsifier concentration.

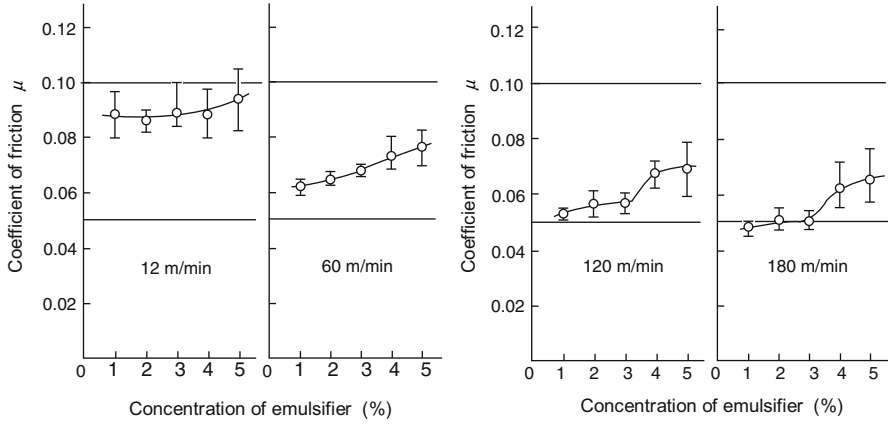


Fig. 4.19 Relationship between coefficient of friction and emulsifier concentration at roll speeds of 12, 60, 120, and 180 m/min

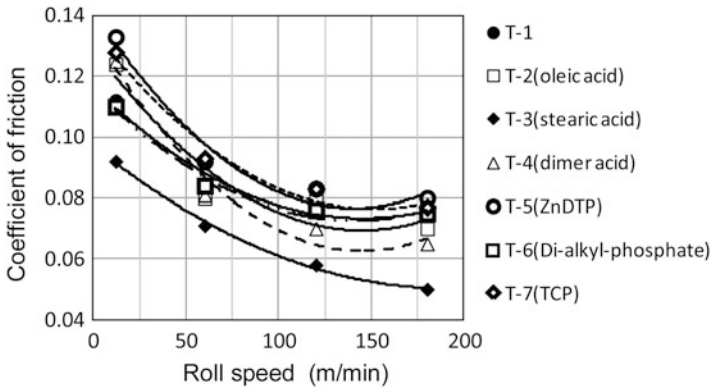


Fig. 4.20 Relationship between coefficient of friction and roll speed for seven lubricants

Figure 4.19 shows the relationship between coefficient of friction and emulsifier concentration at roll speeds of 12, 60, 120, and 180 m/min. The coefficient of friction in each concentration decreases with increasing roll speed. At 12 m/min, the coefficient of friction increases with increasing emulsifier concentration above 3 %. Above a roll speed of 60 m/min, it increases with increasing emulsifier concentration. It is found that the emulsifier concentration may be controlled under 3 % in order to decrease the coefficient of friction.

Third, the effect of the additives in the tallow base oil on the coefficient of friction is examined using seven lubricants. The used additives are oleic acid, stearic acid, dimmer acid, ZnDTP, di-alkyl-phosphate, and TCP. Figure 4.20 shows the relationship between coefficient of friction and roll speed for seven lubricants of T-1 to T-7. The coefficients of friction for the oiliness agents of

oleic acid, stearic acid, and dimmer acid become lower compared to that of the tallow base oil (T-1), and the coefficient of friction of the lubricant and stearic acid (T-3) is the lowest. On the other hand, the coefficients of friction for the EP agents of ZnDTP, di-alkyl-phosphate, and TCP are the same or higher compared to that of the tallow base oil.

4.1.3.4 Evaluation of Mixed Rolling Oil of Mineral Base Oil and Tallow Base Oil by Coefficient of Friction

From the results of coefficient of friction in Fig. 4.11, the effect of the saponification value of mixed rolling oil on the coefficient of friction must be examined quantitatively in order to develop the excellent mixed rolling oil. In this chapter, the coefficients of friction were measured for the mixed rolling oils with different saponification value using the sliding-rolling-type tribo-simulator by Azushima et al. [6]. The composition and the properties of the mixed rolling oil of mineral base oil and tallow base oil are summarized in Table 4.5. The nine rolling oils of Nos. 14–22 are the mixed oil of mineral base oil and tallow base oil, and the saponification values are in the range of 0–183 mg KOH/g. The coefficients of friction of the mixed oils with different saponification values in 3 % emulsion concentration are measured at a temperature of 55 °C using the sliding-rolling-type tribo-simulator. The sliding-rolling experiments are carried out at roll speeds of 12, 60, 120, and 180 m/min at a constant reduction of 5 % using the low carbon steel.

Figure 4.21 shows the relationship between coefficient of friction and saponification value in roll speeds of 12, 60, 120, and 180 m/min. The coefficient of friction for each saponification value decreases with increasing roll speed. In a roll speed of 12 m/min, the coefficient of friction decreases at a saponification

Table 4.5 Composition and property of mixed rolling oils

No.	Composition (wt%)			Property	
	Mineral oil	Tallow	Emulsifier	Saponification value (mg KOH/g)	Viscosity (50 °C:cSt)
14	95	–	5	0	28.4
15	72.5	22.5	5	44	28.6
16	50	45	5	88	29.0
17	35	60	5	114	29.4
18	20	75	5	142	29.7
19	15	80	5	153	29.8
20	10	85	5	164	30.2
21	5	90	5	170	30.5
22	–	95	5	183	30.8

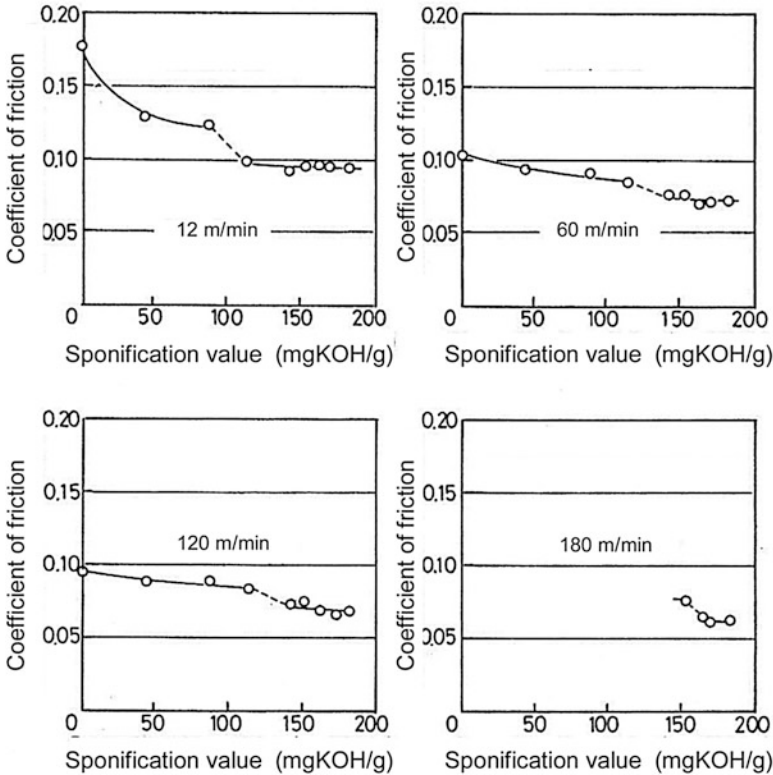


Fig. 4.21 Relationship between coefficient of friction and emulsifier concentration at roll speeds of 12, 60, 120, and 180 m/min

value of 90 mg KOH/g, in 60 m/min it decreases at 120 mg KOH/g, in 120 m/min it decreases at 120 mg KOH/g, and in 180 m/min it decreases at 160 mg KOH/g. It is found that the saponification value may be controlled at high value in the higher rolling speed in order to decrease the coefficient of friction.

4.2 Lubrication Mechanism and Rolling Pressure

As shown in Sect. 2.3, the lubrication regime in metalforming is classified as follows:

I	$h \gg R$ ($\lambda > 4$)	Plastohydrodynamic lubrication
II	$h \approx R$ ($4 > \lambda > 1$)	Mixed lubrication (plastohydrodynamic lubrication, micro-plastohydrodynamic lubrication, hydrostatic lubrication, and boundary lubrication)
III	$h \rightarrow 0$ ($1 > \lambda$)	Boundary lubrication

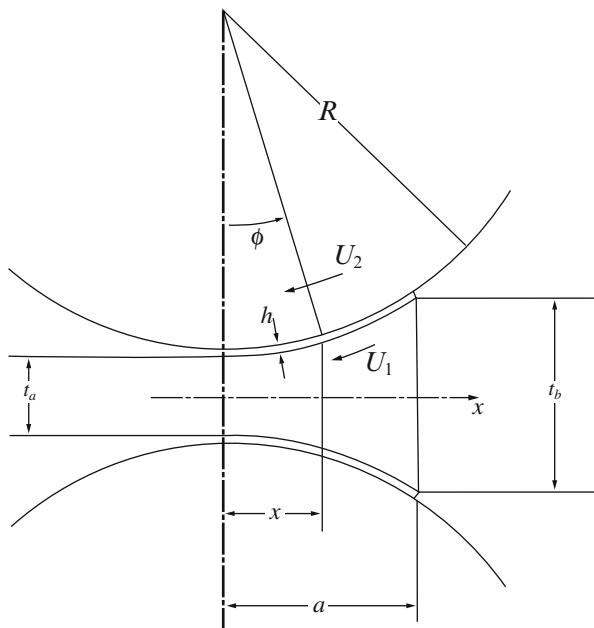
In this chapter, the calculation methods of the rolling pressure using the frictional stress are defined in the lubrication mechanism consisted of the elastohydrodynamic lubrication, micro-elastohydrodynamic lubrication, mixed lubrication, and boundary lubrication in Sect. 2.3.2, and the Karman's equation is given by

$$\frac{d(h\sigma_x)}{dx} + 2(p \tan \theta \mp \tau) = 0 \quad (3.14)$$

4.2.1 Macro-elastohydrodynamic Lubrication

Cheng [8] proposed the macro-elastohydrodynamic lubrication model, and he calculated the distribution of rolling pressure in the condition that the full hydrodynamic film was introduced throughout the interface contact between roll and workpiece in cold sheet rolling. Figure 4.22 shows the geometry of a cold rolling process. In Fig. 4.22, h is the oil film thickness, t_b is the entrance thickness of workpiece, t_a is the exit thickness of workpiece, U_1 is the workpiece speed, U_2 is the roll speed, and a is the contact length. The frictional shear stress is expressed assuming the Couette flow as follows:

Fig. 4.22 Geometry of a cold rolling process



$$\tau_f = \eta \left(\frac{U_2 - U_1}{h} \right) \quad (4.1)$$

Then, the viscosity of lubricant depends on the pressure and the temperature, and it is given by

$$\eta = \eta_0 \exp \left\{ \alpha p - \beta \left(\frac{1}{T_0} - \frac{1}{T_m} \right) + \gamma \frac{p}{T_m} \right\} \quad (4.2)$$

where η_0 and T_0 are the viscosity and temperature at the entrance; α , β , and λ are the lubricant parameters; and T_m is the mean temperature in the lubricant film.

The workpiece speed U_1 is governed by the continuity of the plastic flow and it is given by

$$U_1 = U_b \frac{t_b}{t} \quad (4.3)$$

Then, the film thickness distribution at the working contact interface between roll and workpiece can be given by

$$h = h_0 \left(\frac{U_1 + U_b}{U_2 + U_1} \right) \quad (4.4)$$

where h_0 is the film thickness at the entrance and it is calculated from the elastohydrodynamic lubrication of rolling and sliding cylinders.

The equation governing the temperature of the lubricant is the energy equation of Eqn. (2.40). Substituting Eqn. (4.1) into Eqn. (3.14), the rolling pressure can be calculated considering the thermal effect.

4.2.2 Boundary Lubrication

The boundary shear stress is given by the friction law of Eqn. (2.1). Substituting Eqn. (2.1) into Karman's equation of Eqn. (3.14), the rolling pressure can be calculated. The details are explained in Sect. 3.2.1. The pressure distributions at the entrance side and at the exit side can be given by Eqns. (3.22) and (3.23).

4.2.3 Micro-plastohydrodynamic Lubrication

The frictional shear stress in the micro-plastohydrodynamic lubrication is given by Eqn. (2.16) similar to Eqn. (4.1) in the macro-plastohydrodynamic lubrication. Substituting Eqn. (2.16) into Karman's equation of Eqn. (3.14), the

rolling pressure can be calculated. Then, since it is estimated that the oil film thickness in the micro- plastohydrodynamic lubrication is one order smaller than that in the macro-plastohydrodynamic lubrication, the frictional shear stress in the micro-plastohydrodynamic lubrication becomes larger than that in the macro-plastohydrodynamic lubrication.

4.2.4 Mixed Lubrication

4.2.4.1 Combination of Hydrodynamic Lubrication and Boundary Lubrication

The frictional shear stress in the mixed lubrication of hydrodynamic lubrication and boundary lubrication is given by Eqn. (2.17) as follows:

$$\tau_{mixh} = \alpha\tau_b + (1 - \alpha)\tau_f \quad (2.17)$$

Substituting Eqn. (2.17) into Karman's equation of Eqn. (3.14), the rolling pressure can be calculated. Before calculating, the ratio of the boundary lubrication region α must be determined. In order to determine the α value, the following assumptions are given as follows:

1. The distribution of the height of roughness of the workpiece surface is the normal distribution.
2. The contact of the roll with a random roughness and the workpiece with random roughness is equivalent to the contact of the roll with smooth surface and the workpiece with the combined surface roughness of roll surface roughness and workpiece surface roughness. The combined surface roughness σ is given by the next equation:

$$\sigma = \sqrt{\sigma_{roll}^2 + \sigma_{workpiece}^2} \quad (4.5)$$

where σ_{roll} is the root mean square height of roll and $\sigma_{workpiece}$ is the root mean square height of workpiece.

3. The normal distribution of height of the combined surface roughness is given by

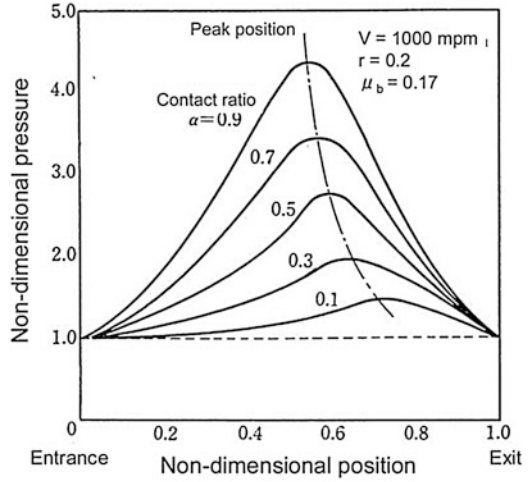
$$\varphi(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-z^2/2\sigma^2) \quad (4.6)$$

4. The asperities on the workpiece surface deform plastically.

The ratio of the boundary lubrication region α is roughly derived as follows:

$$\alpha = 2 \int_h^\infty \varphi(z) dz \quad (4.7)$$

Fig. 4.23 Pressure distribution in mixed lubrication of hydrodynamic lubrication and boundary lubrication in cold sheet rolling [9]



Nakajima et al. [9] calculated the pressure distribution in the mixed lubrication of hydrodynamic lubrication and boundary lubrication using the frictional shear stress of Eqn. (2.17) as shown in Fig. 4.23.

However, since the frictional shear stress of Eqn. (2.17) is complicated, it can be assumed that $\tau_b \gg \tau_f$ and $p_r = p_f = p_a$ in metalforming with bulk deformation. Then, the frictional shear stress is given by

$$\tau_{mixh} = \alpha \tau_b \quad (2.18)$$

Substituting Eqn. (2.18) into Karman's equation of Eqn. (3.14), the rolling pressure in the mixed lubrication of hydrodynamic lubrication and boundary lubrication can be calculated.

4.2.4.2 Combination of Hydrostatic Lubrication and Boundary Lubrication

The frictional shear stress in the mixed lubrication of hydrostatic lubrication and boundary lubrication is given by

$$\tau_{mixs} = \alpha \tau_b \quad (2.21)$$

Substituting Eqn. (2.21) into the Karman's equation of Eqn. (3.14), the rolling pressure in the mixed lubrication of hydrostatic lubrication and boundary lubrication can be calculated. Before calculating, the ratio of the boundary lubrication region α must be determined, and it can be calculated from Eqn. (4.7). From the experimental results shown in Fig. 2.40b, if the combined surface roughness is random, it can be understood that the α value becomes finally a constant of about 0.6.

4.2.4.3 Combination of Hydrodynamic Lubrication, Hydrostatic Lubrication, and Boundary Lubrication

The frictional shear stress in the mixed lubrication of hydrodynamic lubrication, hydrostatic lubrication, and boundary lubrication is given by

$$\tau_{mixhs} = \alpha\tau_b + \beta\tau_f \quad (2.27)$$

Since it can be assumed that $\tau_b \gg \tau_f$ and $p_r = p_f = q = p_a$ in metalforming with bulk deformation, the frictional shear stress is given by

$$\tau_{mixhs} = \alpha\tau_b \quad (2.29)$$

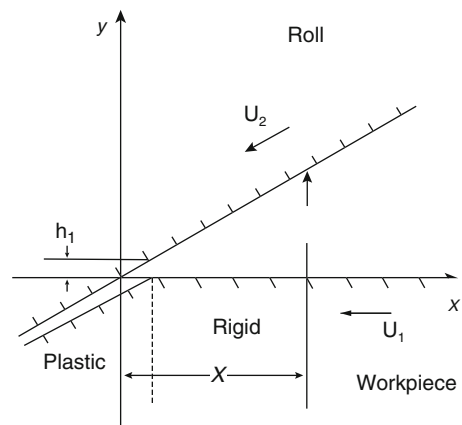
Substituting Eqn. (2.29) into Karman's equation of Eqn. (3.14), the rolling pressure in the mixed lubrication of hydrodynamic lubrication, hydrostatic lubrication, and boundary lubrication can be calculated.

4.3 Inlet Oil Film Thickness in Cold Sheet Rolling with Neat Oil

4.3.1 Calculation of Inlet Oil Film Thickness

In order to understand quantitatively the lubrication mechanism, it is significantly important that the inlet oil film thickness h_1 in cold sheet rolling is calculated with high accuracy. Figure 4.24 shows the geometry of the inlet zone between roll and workpiece in the cold sheet rolling.

Fig. 4.24 Geometry of inlet zone between roll and workpiece



For calculating the inlet oil film thickness, the following assumptions are given:

1. The materials of roll and workpiece in the inlet zone are rigid.
2. The surfaces of roll and workpiece in the inlet zone are smooth.
3. The workpiece deforms plastically when the pressure within the lubricant reaches at the yield stress Y .

Reynolds equation is derived by

$$\frac{dp}{dx} = -6\eta(U_1 + U_2)\left(\frac{h - h_1}{h^3}\right) \quad (4.8)$$

where U_1 is the entrance speed of workpiece, U_2 is the roll speed, and h_1 is the inlet oil film thickness. Next, in order to calculate the inlet oil film thickness considering the thermal effect, the following assumptions are given:

1. The heat transferred by the lubricant is neglected.
2. The heat generation by the compression is neglected.
3. The temperatures of the roll and workpiece surfaces are equal to the ambient temperature T_0 .
4. The viscosity of lubricant depends on the pressure and the temperature.

The energy equation is given by

$$K \frac{\partial^2 T}{\partial y^2} + \eta \left(\frac{\partial u}{\partial y} \right)^2 = 0 \quad (2.40)$$

The viscosity of lubricant is given by

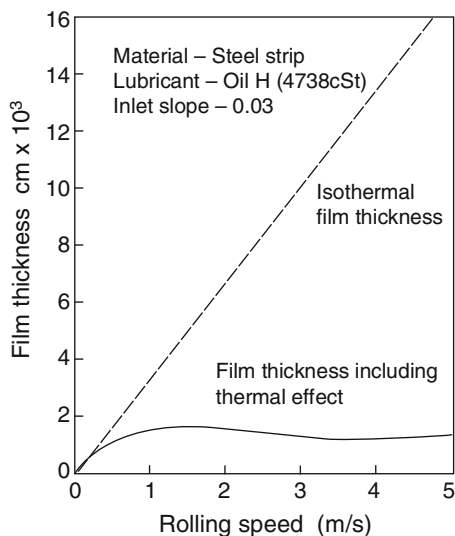
$$\eta = \eta_0 \exp\{\alpha p - \beta(T - T_0)\} \quad (4.9)$$

Dow et al. [10] integrated numerically Eqns. (4.8) and (2.40) and calculated the inlet oil film thickness in cold sheet rolling considering the thermal effect. Figure 4.25 shows the calculated relationship between inlet oil film thickness and rolling speed.

In Fig. 4.25, the large difference between the inlet oil film thicknesses with the thermal effect and without the thermal effect can be observed. The inlet oil film thickness with the thermal effect is lower than that without the thermal effect from the relatively low rolling speed. The inlet oil film thickness without the thermal effect increases linearly with increasing rolling speed. On the other hand, the inlet oil film thickness with the thermal effect becomes nearly constant above a rolling speed of 1 m/s.

This large difference is due to the reason why the viscosity of H oil (4738 cSt) is much larger than the viscosity of commercial oils. It is desired that the inlet oil film thickness of the commercial oils with the normal viscosity is calculated by means of the calculation method mentioned above. Azushima et al. [11] calculated the inlet

Fig. 4.25 Comparison between inlet oil film thicknesses with thermal effect and without thermal effect [10]



oil film thickness considering the thermal effect in cold sheet rolling. In the calculation, Eqns. (4.8) and (2.40) are numerically integrated at the boundary conditions of $p = p^*$ at $h = 100 h_1$ and $p = Y$ at $h = h_1$. In this calculation, it is assumed that the pressure is not affected by the temperature when $h \geq 100h_1$, so that p^* is given by Eqn. (2.42).

Figure 4.26 shows the relationship between inlet oil film thickness and roll speed at two relative speeds of 0.1 (a) and 0.4 (b) using lubricants with different viscosities of 0.01, 0.1, 1, and 10 Pa s. From Fig. 4.26, it is found that the inlet oil film thickness considering the thermal effect depends strongly on the relative speed. At a relative speed of 0.1, the inlet oil film thickness is almost independent of the thermal effect. On the other hand, at a relative speed of 0.4, the inlet oil film thickness depends strongly on the thermal effect. In the viscosity of rolling oils used in actual mill, it does not increase linearly with increasing roll speed above a roll speed of about 500 m/min.

Next, Fig. 4.27 shows the relationship between inlet oil film thickness and roll speed at a relative speed of 0.4, changing the temperature coefficient of lubricant viscosity from 0.02 to 0.32. From Fig. 4.27, it is found that the inlet oil film thickness considering the thermal effect depends strongly on the temperature coefficient of lubricant viscosity. In lower roll speed, the inlet oil film thickness is independent of the thermal effect, and it increases linearly with increasing roll speed. On the other hand, in higher roll speed, the inlet oil film thicknesses depend strongly on the thermal effect, and they do not increase linearly with roll speed and they decrease with increasing β value. Moreover, the value of roll speed that the thermal effect appears moves to the lower roll speed with increasing β value.

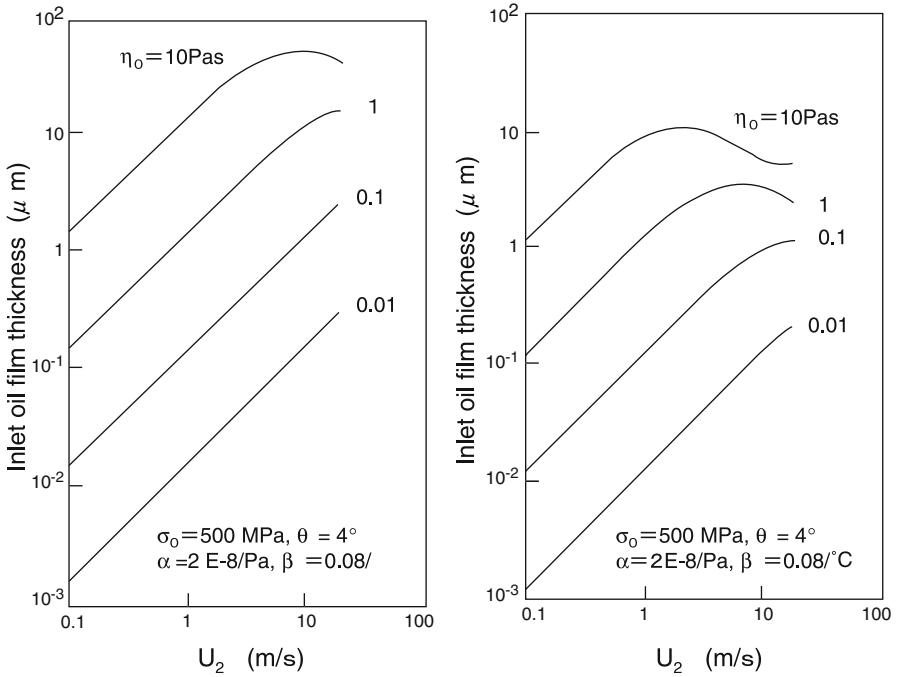
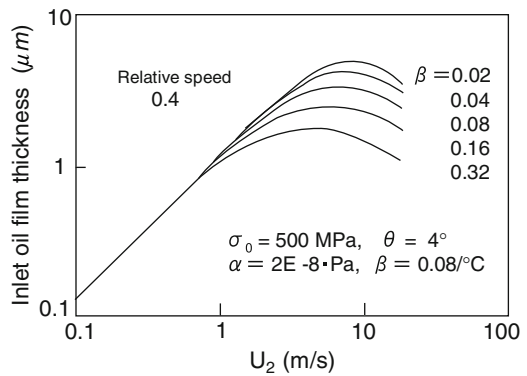


Fig. 4.26 Relationship between inlet oil film thickness and roll speed using lubricants with different viscosities of 0.01, 0.1, 1, and 10 Pa s. (a) Relative speed 0.1. (b) Relative speed 0.4

Fig. 4.27 Relationship between inlet oil film thickness and roll speed changing temperature coefficient of lubricant viscosity



4.3.2 Measurement of Inlet Oil Film Thickness

In order to examine the accuracy of the inlet oil film thicknesses calculated from the Reynolds equation considering the thermal effect, Azushima [12] measured the oil film thickness on the workpiece surface by means of the measurement method

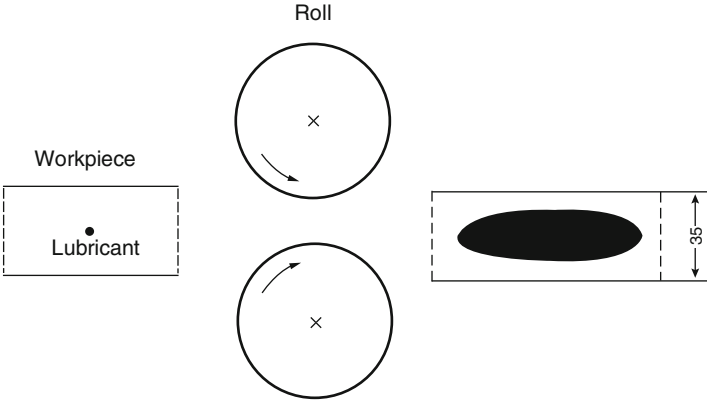


Fig. 4.28 Schematic representation of measurement method of oil film thickness

Table 4.6 Properties of used lubricants

No.	Lubricant	Kinematic viscosity η_0 [cSt]				Viscosity index
		12 °C	38 °C	50 °C	99 °C	
1	Machine oil	380	61	—	7	5
2	Paraffin base oil A	117	30	—	5	65
3	Paraffin base oil B	8	4	—	1.5	115

developed by Saeki et al. [13]. Figure 4.28 shows the schematic representation of the measurement method of the oil film thickness.

The measurement method of oil film thickness is as follows:

1. A small amount of oil measured the volume is dropped on the degreased surface of workpiece.
2. The workpiece is rolled changing the rolling speed, the reduction, the viscosity of lubricant, and so on.
3. The dropped oil spreads as shown in Fig. 4.28 and after rolling the area of expanded oil is measured.
4. The ratio of the volume to the area is the mean oil film thickness h_m .

The inlet oil film thickness h_1 is given by

$$h_1 = \frac{1}{1 - \frac{2}{3r}} h_m \tag{4.10}$$

The experiments for measuring the inlet oil film thickness changing the rolling speed, the reduction, and the viscosity of lubricants are carried out. The properties of lubricants used are summarized in Table 4.6. The rolling experiments are carried out at five rolling speeds of 4, 20, 70, 460, and 850 m/min in the reduction of 5–30 % using the 17 % Cr stainless steel. In the experiments at a temperature of 12 °C, the machine oil of No. 1 with a viscosity of 380 cSt is used.

Fig. 4.29 Relationship between mean oil film thickness and reduction at five rolling speeds of 4, 20, 70, 460, and 850 m/min

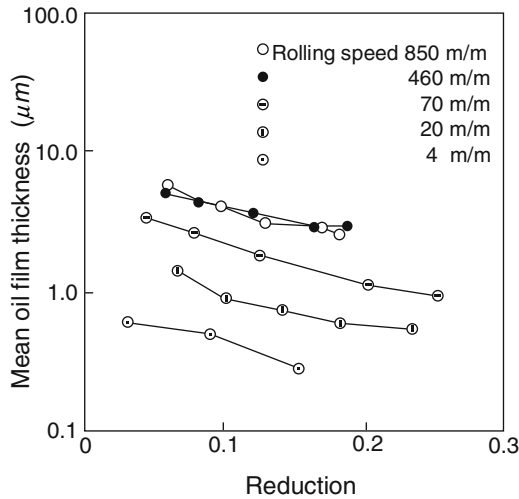


Fig. 4.30 Relationship between mean oil film thickness and reduction using three oils with different viscosities

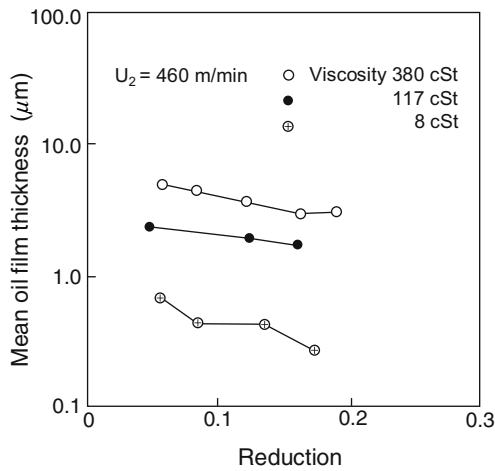
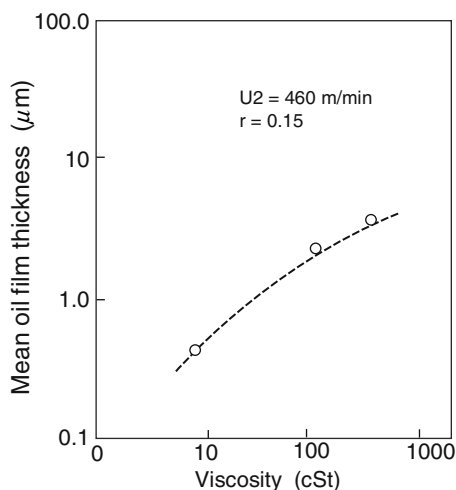


Figure 4.29 shows the relationship between mean oil film thickness and reduction at five rolling speeds of 4, 20, 70, 460, and 850 m/min using the machine oil of No. 1 at 12 °C. The mean oil film thickness decreases with increasing reduction for each rolling speed. It increases with increasing rolling speed up to 460 m/min, but above 460 m/min, it becomes almost constant. The rolling speed dependence of the mean oil film thickness is similar to the dependence obtained from the calculated results.

Next, Fig. 4.30 shows the relationship between mean oil film thickness and reduction at a constant rolling speed of 460 m/min and a constant reduction of 15 % using the three oils of Nos. 1–3 with different viscosities of 380, 117, and 8 cSt at

Fig. 4.31 Relationship between measured mean oil film thickness and viscosity



12 °C. The mean oil film thickness decreases with increasing reduction for each viscosity of lubricant. It increases with increasing viscosity of lubricant.

Next, Fig. 4.31 shows the relationship between measured mean oil film thickness and viscosity at a constant rolling speed of 460 m/min and a constant reduction of 15 %. In comparison with the calculated results shown in Fig. 4.26, it is found that the mean oil film thickness of No. 1 oil with a viscosity of 380 cSt is slightly affected on the thermal effect and those of Nos. 2 and 3 with lower viscosity are independent of the thermal effect. The rolling speed dependence on the mean oil film thickness at a rolling speed of 460 m/min obtained from the experiments is similar to the dependence obtained from the calculated results.

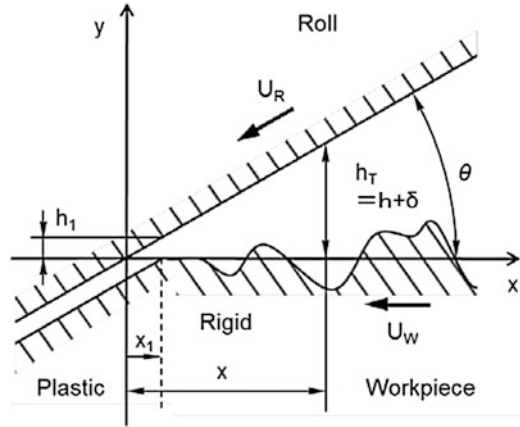
4.3.3 Inlet Oil Film Thickness for Workpiece with Random Surface Roughness

In the calculation method of the inlet oil film thickness, it is assumed that the surfaces of roll and workpiece are smooth. However, when there is a roughness on the workpiece surface, the surface roughness affects the introducing oil film thickness. In this chapter, the calculation method of the inlet oil film thickness from the Reynolds equation considering the surface roughness on the workpiece is explained. Azushima [14] calculated the inlet oil film thickness considering the surface roughness. Figure 4.32 shows the geometry of the inlet zone between roll and workpiece with rough surface in the cold sheet rolling.

For calculating the inlet oil film thickness, the following assumptions are given:

1. The materials of roll and workpiece in the inlet zone are rigid.
2. The surfaces of roll and workpiece in the inlet zone are rough.

Fig. 4.32 Geometry of inlet zone between roll and workpiece with rough surface in cold sheet rolling



3. The height of roughness of the workpiece surface is the normal distribution.
4. The contact of the roll with a random roughness and the workpiece with random roughness is equivalent to the contact of the roll with smooth surface and the workpiece with the combined surface roughness of roll surface roughness and workpiece surface roughness. The combined surface roughness σ is given by

$$\sigma = \sqrt{\sigma_R^2 + \sigma_W^2} \quad (4.11)$$

where σ_R is the root mean square height of roll and σ_W is the root mean square height of workpiece.

5. The roll surface is smooth and the workpiece surface has a root mean square height of σ .
6. The normal distribution of height of the combined surface roughness is given by

$$\varphi(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-z^2/2\sigma^2) \quad (4.12)$$

7. The workpiece deforms plastically when the pressure within the lubricant reaches the yield stress Y .
8. The pressure within the lubricant is not affected by the temperature when $h \geq 100h_1$, so that $p = 0$.

The Reynolds equation considering the surface roughnesses of roll and workpiece is derived by Patir and Cheng [15], and when the difference between the two surface speeds is small, the equation is derived by

$$\frac{\partial}{\partial x} \left(\phi_x \frac{h^3}{12\mu} \frac{\partial p}{\partial x} \right) = - \frac{(U_R + U_W)}{2} \frac{\partial h_T}{\partial x} \quad (4.13)$$

where ϕ_x is the pressure flow factor in x direction, U_R is the roll speed, U_W is the entrance speed of workpiece, and h_T is the average film thickness. When the surface roughness is random, ϕ_x is given by

$$\phi_x = 1 - 0.9e^{-0.56\frac{h}{\sigma}} \quad (4.14)$$

where $h/\sigma \leq 0.5$

Integrating Eqn. (4.13), the following equation is given by

$$\frac{dp}{dx} = -\frac{1}{\phi_x} \frac{6\eta(U_R + U_W)}{2} \left[\frac{h}{2} \left\{ 1 + \operatorname{erf} \left(\frac{h}{\sqrt{2}\sigma} \right) \right\} + \frac{\sigma}{\sqrt{2\pi}} \exp \left(-\frac{h^2}{2\sigma^2} \right) - h_{T1} \right] \quad (4.15)$$

where $h_{T1} = \frac{h_1}{2} \left\{ 1 + \operatorname{erf} \left(\frac{h_1}{\sqrt{2}\sigma} \right) \right\} + \frac{\sigma}{\sqrt{2\pi}} \exp \left(-\frac{h_1^2}{2\sigma^2} \right)$

The energy equation and the viscosity equation are given by

$$K \frac{\partial^2 T}{\partial y^2} + \eta \left(\frac{\partial u}{\partial y^2} \right)^2 = 0 \quad (2.40)$$

$$\eta = \eta_0 \exp \{ \alpha p - \beta(T - T_0) \} \quad (4.9)$$

Equations (4.15) and (2.40) are numerically integrated at the boundary conditions of $p=0$ at $h=100 h_1$ and $p=Y$ at $h=h_1$ and the inlet oil film thickness is calculated.

Figure 4.33 shows the relationship between inlet oil film thickness and rolling speed with and without consideration of surface roughness. In Fig. 4.33, in a combined surface roughness of $0.1 \mu\text{m}$, the difference between inlet oil film thicknesses with and without consideration of the surface roughness effect is

Fig. 4.33 Comparison between inlet oil film thicknesses with and without consideration of surface roughness

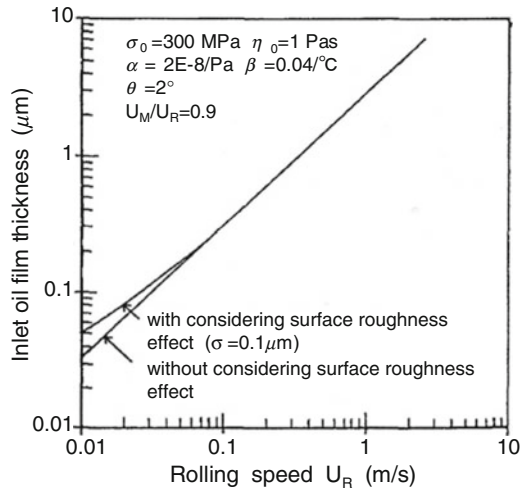
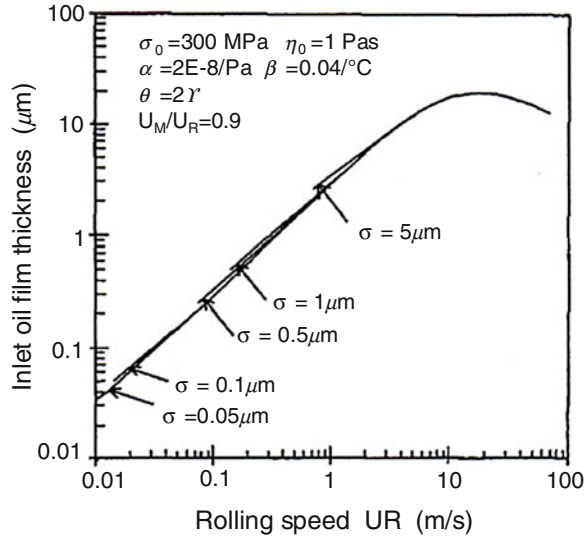


Fig. 4.34 Relationship between inlet oil film thicknesses and rolling speed for five combined surface roughnesses of 0.05, 0.1, 0.5, 1, and 5 μm



observed when the inlet oil film thickness is smaller than three times value of combined surface roughness 0.1 μm . The value is in good agreement with the λ value between hydrodynamic lubrication and mixed lubrication. At $h/\sigma = 0.5$, the inlet oil film thickness with consideration of the surface roughness effect becomes one and half times value without the surface roughness effect.

Next, Fig. 4.34 shows the relationship between inlet oil film thicknesses and rolling speed for five combined surface roughnesses of 0.05, 0.1, 0.5, 1, and 5 μm . The difference between inlet oil film thicknesses with and without consideration of the surface roughness effect is observed when the inlet oil film thickness is smaller than three times the value of each combined surface roughness. The effect of the surface roughness on the inlet oil film thickness at $h/\sigma = 0.5$ is the same in each combined surface roughness.

Next, in order to examine the accuracy of the inlet oil film thicknesses calculated by the Reynolds equation considering the surface roughness effect, Azushima [14] measured the oil film thickness on the workpiece surface by means of the measurement method developed by Saeki et al. [13]. The experiments for measuring the inlet oil film thickness are carried out at a constant reduction of 5 % using paraffinic oils with two viscosities of 0.084 and 0.3 Ps s at 20 °C, changing the rolling speed. The rolling experiments are carried out at 13 levels of rolling speeds using the low carbon steels with surface roughnesses of Ra 0.06 and 1.3 μm and the roll with smooth surface at a room temperature.

Figure 4.35 shows the relationship between inlet oil film thickness and rolling speed for the lubricant with a viscosity of 0.086 Ps s using the low carbon steel with a surface roughness of Ra 0.06 μm . In Fig. 4.35, the dependence of the surface roughness on the measured inlet oil film thickness appeared compared to the calculated results. In the higher rolling speed region, the measured inlet oil film

Fig. 4.35 Relationship between inlet oil film thickness and rolling speed using low carbon steel with surface roughness of Ra 0.06 μm

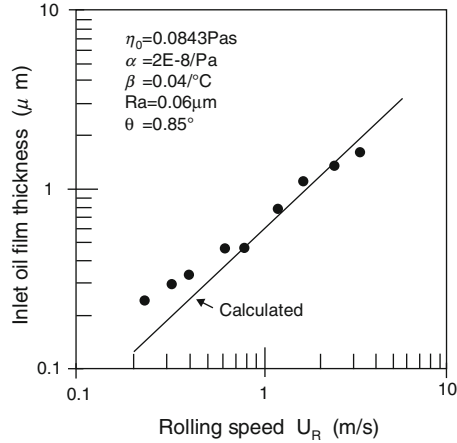
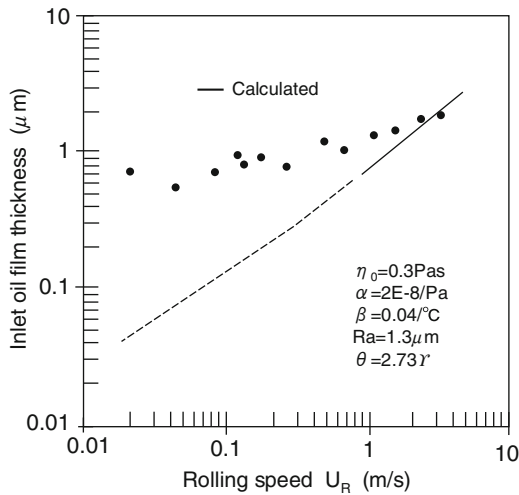


Fig. 4.36 Relationship between inlet oil film thickness and rolling speed using low carbon steel with surface roughness of Ra 1.3 μm



thicknesses are in good agreement with those calculated. From these results, it can be understood that the effect of the surface roughness on the inlet oil film thickness must be considered in the mixed lubrication.

Then, Fig. 4.36 shows the relationship between inlet oil film thickness and rolling speed for the lubricant with a viscosity of 0.3 Pa s using the low carbon steel with a surface roughness of Ra 1.3 μm . In the region of $h/\sigma \geq 0.5$, the relationship in Fig. 4.36 is similar to that in Fig. 4.35, but in the region of $h/\sigma \leq 0.5$, the inlet oil film thickness measured becomes almost constant. When the rolling speed is smaller than a specific value, it is estimated that the amount of lubricant entrapped within the concave portion at the entrance point becomes constant.

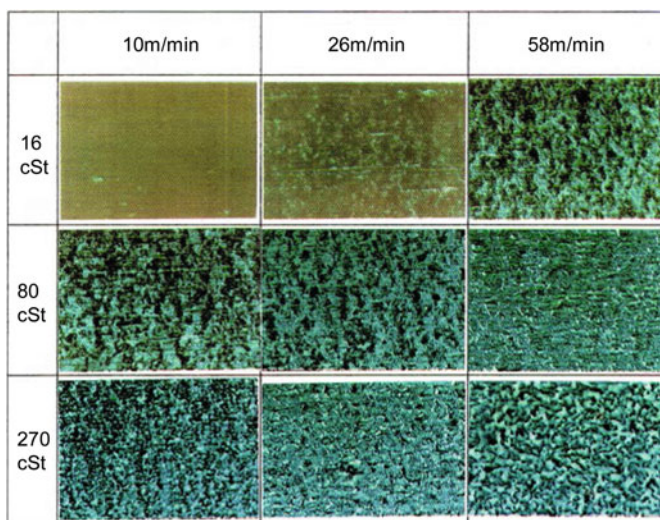


Fig. 4.37 Photographs of rolled workpiece surface illuminated with UV light for 17 % Cr stainless steel with mirror surface

Therefore, in order to confirm the lubricant behavior at the interface between roll with smooth surface and workpiece with rough surface as shown in Figs. 4.35 and 4.36, the oil film on the workpiece surface after rolling was observed by the fluorescence observation technique by Azushima et al. [16]. The rolling experiments for measuring the oil film on the workpiece surface are carried out at a constant reduction of 20 % using three paraffinic oils and 2 % Thiophene compound with viscosities of 16, 80, and 270 cSt at 20 °C. The rolling experiments are carried out at five rolling speeds of 10, 18, 26, 48, and 58 m/min using the 17 % Cr stainless steels with a mirror surface roughness of R_a 0.04 μm and a random surface roughness, and the SKH roll with mirror surface of R_a 0.025 μm at a room temperature.

Figure 4.37 shows the photographs of rolled workpiece surface illuminated with UV light for 17 % Cr stainless steel with mirror surface. In the bright region in photographs, the thicker oil film adheres on the workpiece surface, and in the black region, the oil film becomes thinner. The bright region increases with increasing rolling speed and viscosity of lubricant. It is anticipated that the inlet oil film thickness increases linearly with increasing rolling speed and viscosity in case of the roll and workpiece with mirror surface.

Then, Fig. 4.38 shows the relationship between oil film thickness and surface brightness for 17 % Cr stainless steel with mirror surface. In the mixed lubrication regime, the oil film thickness increases linearly with decreasing surface brightness. From the photograph of workpiece surface rolled at a rolling speed of 58 m/min using a lubricant with a viscosity of 270 cSt in Fig. 4.37, the lubrication regime is the hydrodynamic lubrication. On the other hand, from the photographs at a rolling speed of 10 m/min and with a viscosity of 16 cSt, the boundary lubrication is dominant.

Fig. 4.38 Relationship between oil film thickness and surface brightness

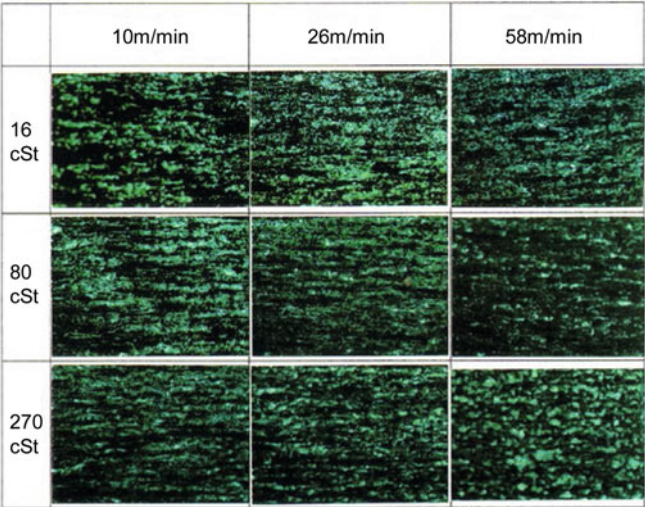
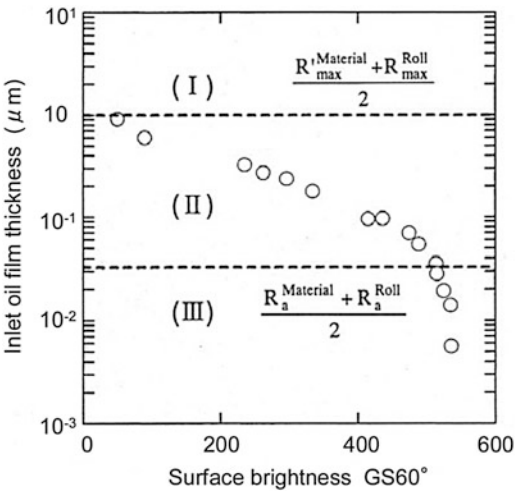


Fig. 4.39 Photographs of workpiece surface after rolling using workpiece with random rough surface

On the other hand, the photographs of workpiece surface after rolling using the workpiece with a random rough surface are shown in Fig. 4.39. In the photographs in Fig. 4.39, all the photographs are observed in the same appearance. The lubrication mechanism is the mixed lubrication of hydrostatic lubrication and boundary lubrication. The inlet oil film thicknesses in these conditions are the same as those in the condition of $h/\sigma \leq 0.5$ in Fig. 4.36.

4.4 Surface Appearance of Workpiece in Cold Sheet Rolling with Neat Oil

The relationship between lubrication mechanism in metalforming and surface appearance after metalforming processes is systematically discussed in Sect. 2.4. In this chapter, the surface appearance of workpiece after cold sheet rolling is extensively examined by cold rolling experiments. Then, the effect of the tribological conditions on the surface appearance is examined, and the important tribological condition parameter is determined. Moreover, the control method for the surface appearance in cold sheet rolling is discussed.

4.4.1 Surface Appearance by Rolling Experiments

Azushima et al. [17] carried out rolling experiments to examine the effect of the tribological condition on the surface appearance of workpiece after rolling. In these experiments, the 17 % Cr stainless steel sheet with a mirror surface roughness of $R_{\max}$ 0.25 μm and surface roughnesses of $R_{\max}$ 1.0 and 3.0 μm , the SUJ-2 rolls with surface roughnesses of $R_{\max}$ 1.0 and 2.0 μm , and the two lubricants of paraffinic base oil and machine oil with different viscosities of 4.0 and 61 cSt at 38 °C are used. The properties of lubricants used are summarized in Table 4.7. The rolling experiments are carried out at rolling speeds in the range of 0.6–1200 m/min and at reductions in the range of 5–50 %.

4.4.1.1 Effect of Rolling Speed and Reduction on Surface Appearance

The surface roughness and the brightness of workpiece surface rolled at three rolling speeds of 0.6, 60, and 800 m/min using the machine oil with a viscosity of 484 cSt at 10 °C changing the reduction are shown in Figs. 4.40 and 4.41.

In Fig. 4.40, at a rolling speed of 800 m/min, the surface roughness increases linearly with increasing reduction. This relationship is similar to that obtained in the tensile test. From these results, the lubrication mechanism is the hydrodynamic lubrication. At a reduction of 0.23, the slipping occurs. At a rolling speed of 60 m/min, up to a reduction of 0.2, the surface roughness increases linearly with increasing reduction similar to the relationship at 800 m/min, and the lubrication

Table 4.7 Properties of lubricant used

Lubricant	Viscosity η [cSt]			Viscosity index
	10 °C	38 °C	99 °C	
(a) Machine oil	484	61	7	5
(b) Paraffin base oil	–	4	1.5	115

Fig. 4.40 Surface roughness of workpiece surface rolled at three rolling speeds of 0.6, 60, and 800 m/min

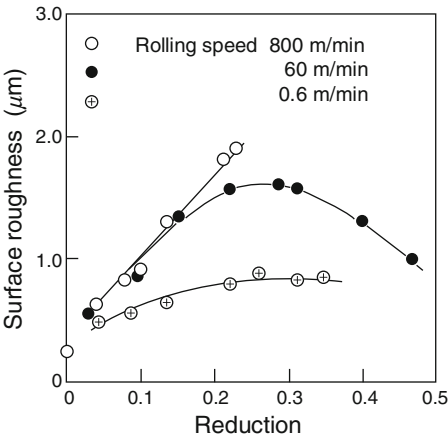
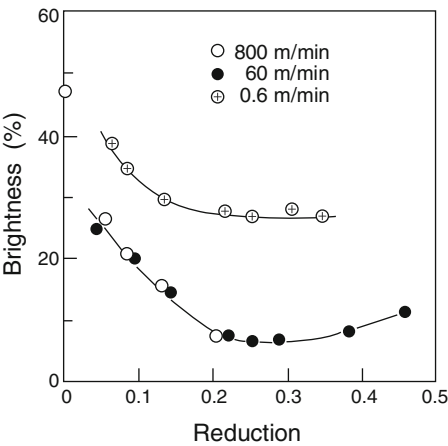


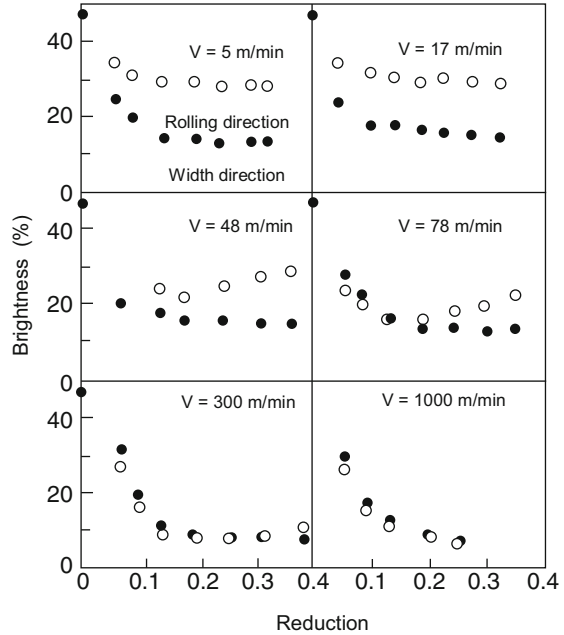
Fig. 4.41 Brightness of workpiece surface rolled at three rolling speeds of 0.6, 60, and 800 m/min



mechanism is the hydrodynamic lubrication. Above a reduction of 0.2, the roll surface starts to contact the asperities in the workpiece surface. The surface roughness decreases with increasing reduction, and the lubrication mechanism becomes the mixed lubrication of hydrodynamic lubrication and boundary lubrication. At a rolling speed of 0.6 m/min, above a reduction of 0.15, the surface roughness is hardly changed and the lubrication mechanism is almost the boundary lubrication. In the brightness in Fig. 4.41, the same behaviors are obtained. At 800 m/min, the relationship between brightness and reduction is similar to that in the tensile test. At 60 m/min, the brightness decreases with increasing reduction up to 0.2 and above 0.25 it increases with reduction. At 0.6 m/min, the brightness is constant above 0.15.

In order to understand the effect of the rolling speed in detail, the contact behavior of roll surface to workpiece surface is examined. When the roll surface

Fig. 4.42 Relationship between brightness values in the rolling direction and in the width direction, and reduction



is in contact with the workpiece surface in rolling, the roll mark in the rolling direction on the workpiece surface is observed. In such a contact condition, the brightness in the rolling direction is higher than that in the width direction. The rolling experiments are carried out at six rolling speeds of 5, 17, 48, 78, 300, and 1000 m/min using the machine oil at a temperature of 23 °C.

Figure 4.42 shows the relationships between brightness values in the rolling direction and in the width direction, and reduction. At the rolling speeds of 5 and 17 m/min, there is large difference between brightness values in the rolling direction and in the width direction, and above a reduction of 0.1, the value for each direction is constant. In these rolling speeds, it is considered that the roll surface is fairly in contact with the workpiece surface so that it is determined that the lubrication mechanism is the boundary lubrication. At the rolling speeds of 300 and 1000 m/min, the brightness in the rolling direction is equal to that in the width direction, so that it is determined that the lubrication mechanism is the hydrodynamic lubrication. At the rolling speeds of 48 and 78 m/min, the difference between the brightness value in the rolling direction and in the width direction is small in the lower reduction, but in the higher reduction, the difference becomes large. The lubrication mechanism is the mixed lubrication, and the ratio of the hydrodynamic lubrication area and the boundary region changes with the reduction.

The photographs of the surface appearance of workpiece rolled at a reduction of 0.1 and at six rolling speeds are shown in Fig. 4.43. From the photographs in Fig. 4.43, the explanation mentioned above can be understood well.

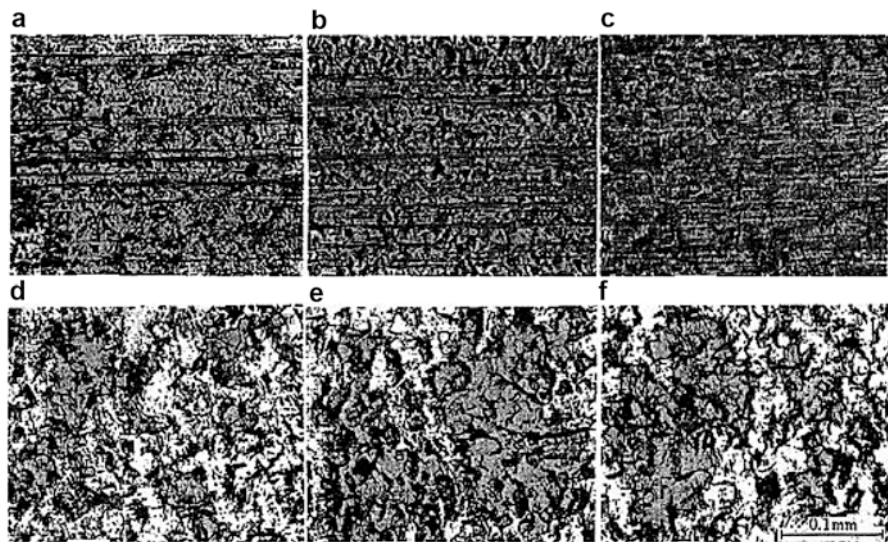


Fig. 4.43 Photographs of workpiece surface rolled at six rolling speeds. (a) $V = 5$ m/min. (b) $V = 17$ m/min. (c) $V = 48$ m/min. (d) $V = 78$ m/min. (e) $V = 300$ m/min. (f) $V = 1000$ m/min

4.4.1.2 Effect of Viscosity of Lubricant on Surface Appearance

The rolling experiments are carried out using three lubricants with viscosities of 8, 150, and 484 cSt changing the reduction. The surface appearance of surface roughness and brightness of workpiece surface rolled at a rolling speed of 800 m/min using three lubricants with viscosities of 8, 150, and 484 cSt are shown in Fig. 4.44a, b. For the lubricant with the higher viscosities of 150 and 484 cSt, the surface roughnesses increase linearly with increasing reduction, so that the hydrodynamic lubrication is dominant. On the other hand, in a lower viscosity of 8 cSt, the brightness in the rolling direction is higher than that in the width direction, so that the boundary lubrication is dominant.

Figure 4.45 shows the photographs of the surface appearance using lubricants with viscosities of 8 and 484 cSt. In Fig. 4.45, it is considered that when the viscosity is very low, even the higher rolling speed, the boundary lubrication is dominant. From these experimental results, it can be understood that the surface appearance depends strongly on the introduced oil film thickness.

4.4.1.3 Effect of Surface Roughnesses of Roll and Workpiece

First, in order to examine the effect of the surface roughness of workpiece on the surface appearance of workpiece after rolling, the rolling experiments are carried out using the workpieces with surface roughnesses of $R_{\max}$ 0.25, 1.0, and 2.0 μm , a roll with surface roughness of $R_{\max}$ 1.0 μm , and a machine oil at 23 °C at rolling

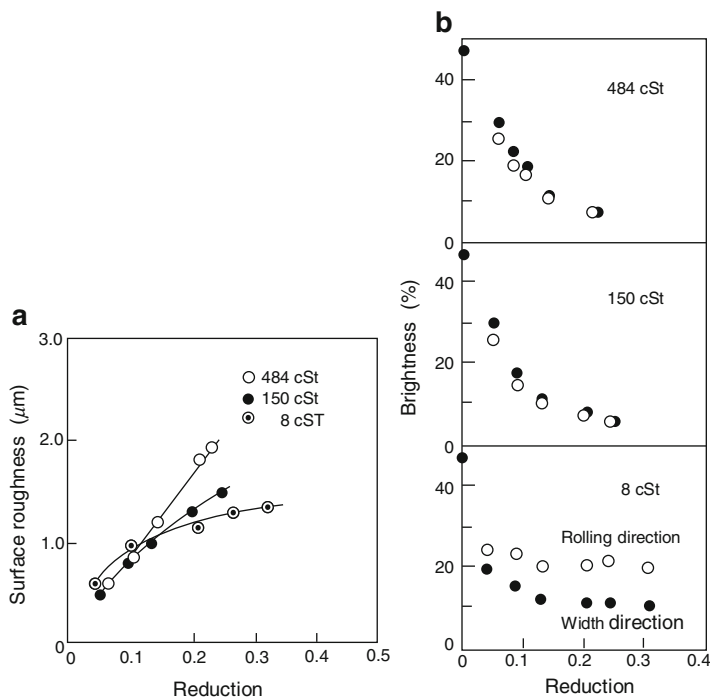
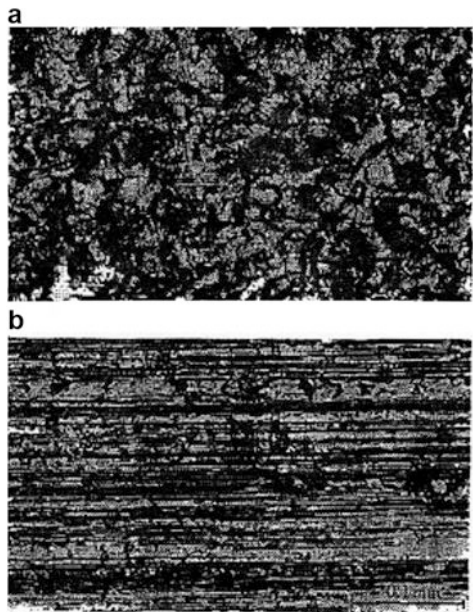


Fig. 4.44 Surface appearance of surface roughness (a) and brightness (b) of workpiece rolled using three lubricants with viscosities of 8, 150, and 484 cSt

Fig. 4.45 Photographs of surface appearance using lubricants with viscosities of 8 and 484 cSt



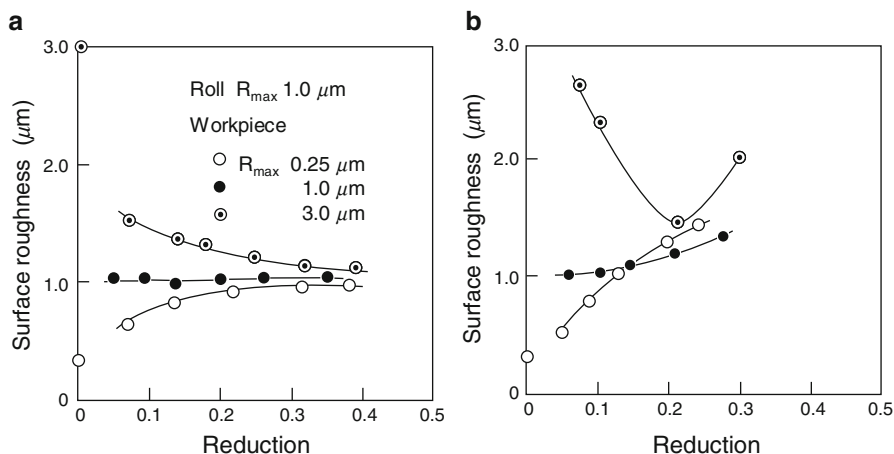


Fig. 4.46 Relationship between surface roughness and reduction changing surface roughness of roll. (a) $V = 0.6 \text{ m/min}$. (b) $V = 1000 \text{ m/min}$

speeds of 0.6 and 1000 m/min changing the reduction. Figure 4.46 shows the relationship between surface roughness and reduction changing the surface roughness of sheet. At a rolling speed of 0.6 m/min, up to a reduction of 0.25, the surface roughness of workpiece affects by the surface roughness before rolling. Above 0.25, it is independent of the surface roughness before rolling and is constant. At a rolling speed of 1000 m/min, up to a reduction of 0.25, the surface roughness of workpiece affects by the surface roughness before experiments similar to the results at 0.6 m/min. Above 0.25, it increases with increasing reduction for each workpiece.

Next, Fig. 4.47 shows the relationship between surface roughness and reduction changing the surface roughness of roll. At a rolling speed of 0.6 m/min, the surface roughness depends on the surface roughness of workpiece before rolling up to a reduction of 0.25 as shown in Fig. 4.46a. At a rolling speed of 1000 m/min, the surface roughnesses of workpiece increase with increasing reduction, and it is estimated that the lubrication regimes for rolls with surface roughnesses of $R_{\max} 1.0$ and $2.0 \mu\text{m}$ are the hydrodynamic lubrication.

4.4.2 Surface Brightness of Low Carbon Steel

Azushima et al. [18] carried out rolling experiments to examine the relationship between surface brightness of workpiece and oil film thickness. In these experiments, the as-received low carbon steel with a smooth surface of $R_a 0.07 \mu\text{m}$ and the surface roughened low carbon steel sheets with surface roughnesses of $R_a 0.1, 0.18, 0.29$, and $0.54 \mu\text{m}$ by tensile tests; the SUJ-2 rolls with surface roughnesses of $R_a 0.01, 0.02, 0.07$, and $0.11 \mu\text{m}$; and the five paraffinic oils with different

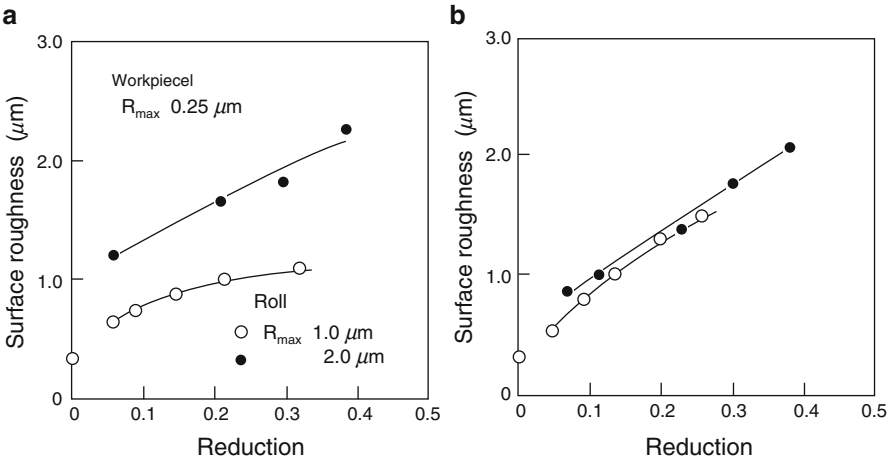


Fig. 4.47 Relationship between surface roughness after rolling and reduction changing surface roughness of roll. (a) $V = 0.6 \text{ m/min}$. (b) $V = 1000 \text{ m/min}$

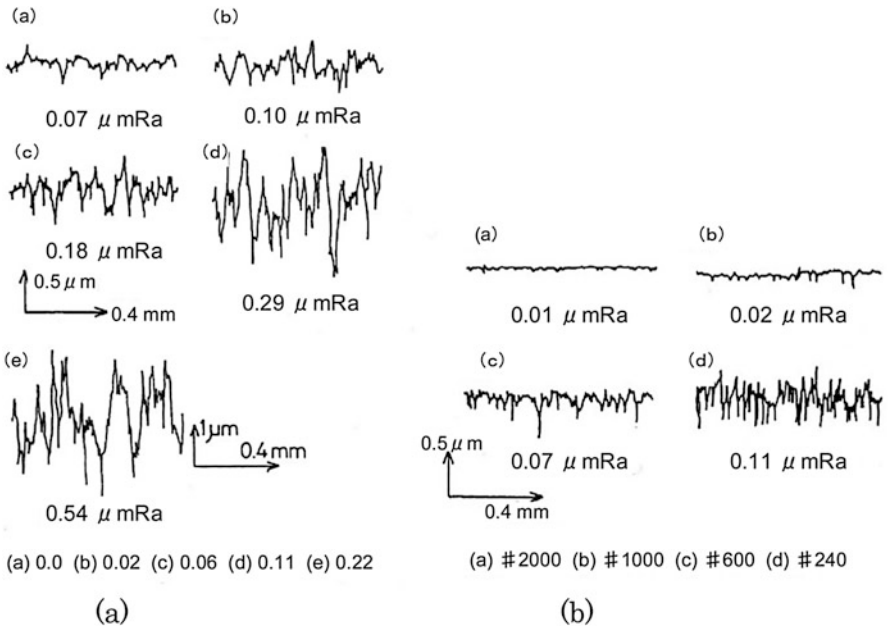


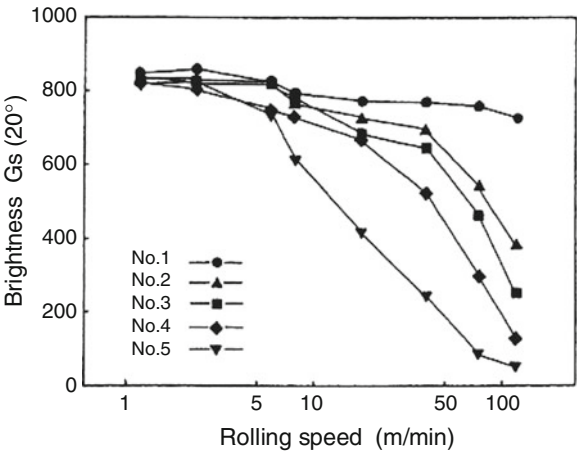
Fig. 4.48 Surface profiles of low carbon steel sheets (a) and rolls (b)

viscosities are used. The roll surfaces are grinded in the rolling direction using emery papers. The surface profiles of low carbon steels (a) and rolls (b) are shown in Fig. 4.48. The viscosities of lubricants are summarized in Table 4.8. The rolling

Table 4.8 Viscosity of lubricant used

No.	Viscosity at 20 °C (cSt)
1	2.8
2	17.0
3	23.5
4	37.3
5	97.4

Fig. 4.49 Relationship between surface brightness and rolling speed at reduction of 20 % using roll with surface roughnesses of 0.01 μmRa and sheet with 0.07 μmRa



experiments are carried out at rolling speeds in the range of 2.4–121 m/min and at reductions of 10 and 20 % at a room temperature of 20 °C.

4.4.2.1 Surface Brightness for Roll and Sheet with Smooth Surface

Figure 4.49 shows the relationship between surface brightness and rolling speed at a reduction of 20 % using lubricants of Nos. 1–5 when the surface roughnesses of roll and sheet are 0.01 and 0.07 μmRa . The surface brightness for each lubricant is almost same and constant up to a rolling speed of 6.0 m/min. Above 6 m/min, they decrease with increasing rolling speed, and the degree of decrease becomes larger with increasing viscosity of lubricant.

Figure 4.50 shows the surface photographs of sheet rolled at rolling speeds of 1.2, 6.0, 40, and 121 m/min at a reduction of 20 % using lubricants of Nos. 1, 3, and 5. For the No. 1 lubricant with a viscosity of 2.8 cSt, the roll marks in the rolling direction can be observed in the photographs in higher rolling speed similar to those in lower rolling speed, and the surface brightness is almost independent of the rolling speed. The lubrication regime is the boundary lubrication. For the No. 5 lubricant with 97.4 cSt, from the photograph at a rolling speed of 121 m/min, the free roughening of the sheet surface can be observed, so that it is found that the lubrication regime is the hydrodynamic lubrication. From the photographs of

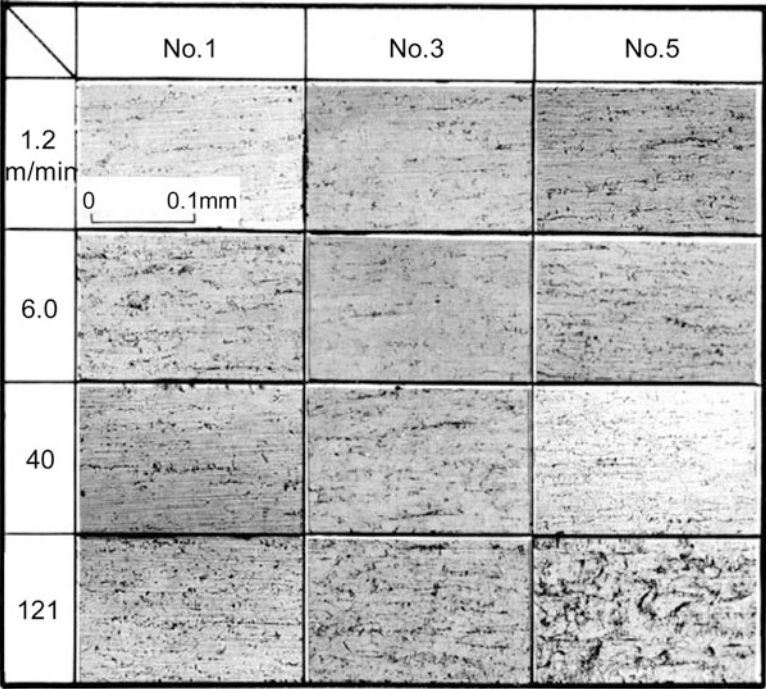


Fig. 4.50 Surface photographs of sheet rolled at rolling speeds of 1.2, 6.0, 40, and 121 m/min at reduction of 20 % using lubricants of Nos. 1, 3, and 5

the lubricants on Nos. 2–4, the change of the ratio of the hydrodynamic lubrication region to the boundary lubrication region in the mixed lubrication can be understood.

4.4.2.2 Effect of Roll Surface on Surface Brightness

The rolling experiments are carried out at a reduction of 20 % using the rolls with surface roughnesses of 0.01, 0.02, 0.07, and 0.11 μmRa under the conditions of the sheet with a constant surface roughness of 0.07 μmRa and the lubricants of Nos. 1 and 3 changing the rolling speed. Figure 4.51 shows the relationship between surface brightness and rolling speed at a reduction of 20 % for a sheet of a surface roughness of 0.07 μmRa using the lubricants of No. 1 (a) and No. 3 (b). In Fig. 4.51a, in case of the sheet with a smooth surface and the lubricant with the lowest lubricant No. 1, the surface brightness for each roll with different surface roughness is independent of the rolling speed and is almost constant. The surface brightness decreases with increasing surface roughness of roll. In Fig. 4.51b, in case of the sheet with a smooth surface and the lubricant with the medium viscosity No. 3, when the surface roughness of roll is higher, the contact of the roll surface to

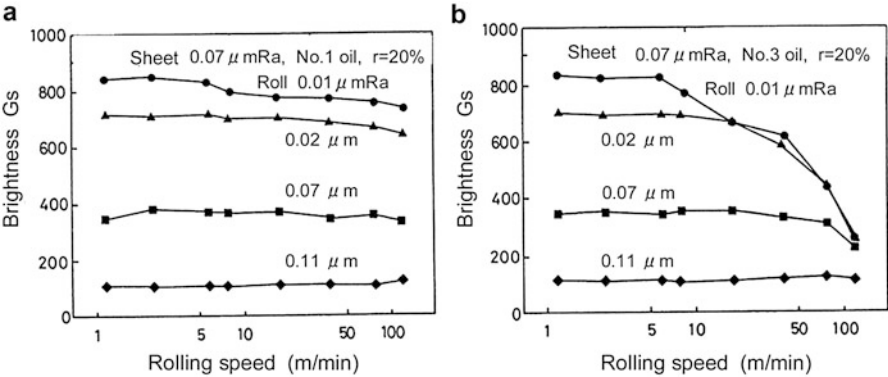


Fig. 4.51 Relationship between surface brightness and rolling speed of lubricants of No. 1 (a) and No. 3 (b)

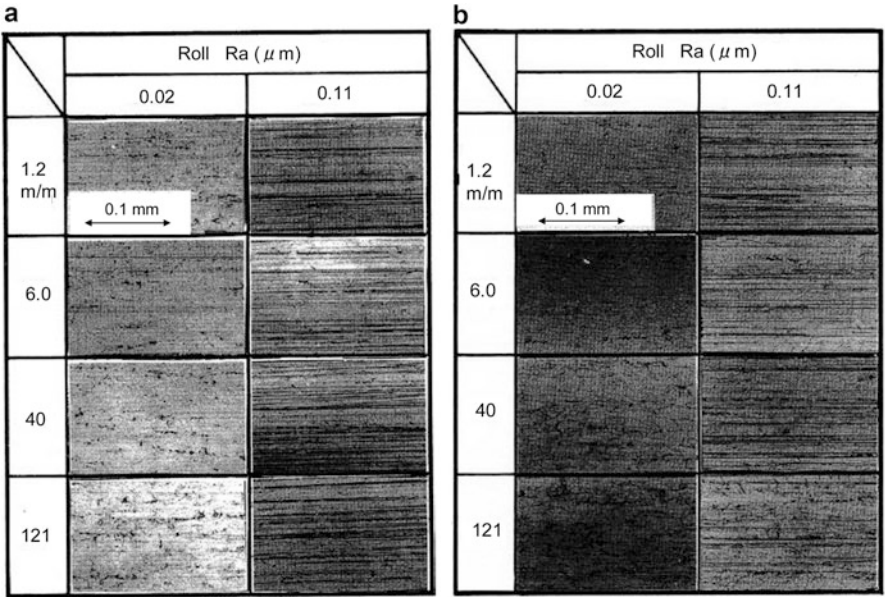


Fig. 4.52 Surface photographs of sheet rolled for rolls with surface roughnesses of 0.02 and 0.11 μmRa and sheet with constant surface roughness of 0.07 μmRa using lubricants of No. 1 (a) and No. 3 (b)

the sheet surface becomes strong and the surface brightness is independent of the rolling speed.

Next, Fig. 4.52 shows the surface photographs of sheet rolled at rolling speeds of 1.2, 6.0, 40, and 121 m/min for the rolls with surface roughnesses of 0.02 and 0.11 μmRa and the sheet with a constant surface roughness of 0.07 μmRa using the

lubricants of No. 1 (a) and No. 3 (b). In Fig. 4.52a, b, for the roll with a surface roughness of $0.11 \mu\text{mRa}$, the roll marks in the rolling direction on the sheet surfaces in all the conditions can be observed so that it is found that the contact of the roll surface to the sheet surface becomes strong.

4.4.2.3 Effect of Surface Roughness of Sheet on Surface Brightness

The rolling experiments are carried out at a reduction of 20 % using the sheets of the low carbon steel with surface roughnesses of 0.07, 0.10, 0.18, 0.29, and $0.59 \mu\text{mRa}$ under the conditions of the roll with a constant surface roughness of $0.01 \mu\text{mRa}$ and the lubricants of Nos. 1 and 3 changing the rolling speed. Figure 4.53 shows the relationship between surface brightness and rolling speed at a reduction of 20 % for the roll with a surface roughness of $0.01 \mu\text{mRa}$ using the sheets with surface roughnesses of 0.07, 0.10, 0.18, 0.29, and $0.59 \mu\text{mRa}$ and the lubricants of No. 1 (a) and No. 3 (b).

In Fig. 4.53a, in the case of the roll with a smooth surface and the lubricant with the lowest viscosity of No. 1, the surface brightness for each sheet with different surface roughness decreases slightly with increasing rolling speed. In Fig. 4.53b, in the case of the roll with a smooth surface and the lubricant with the medium viscosity of No. 3, when the surface roughnesses of sheet are 0.07, 0.10, and $0.18 \mu\text{mRa}$, the surface brightness depends strongly on the rolling speed and the surface roughnesses are almost same. On the other hand, for the sheets with surface roughnesses of 0.29 and $0.54 \mu\text{mRa}$, the roll surface with a smooth surface contacts to the sheet surface, so that the oil pockets on the sheet surfaces will be formed.

Next, Fig. 4.54 shows the surface photographs of sheet rolled at rolling speeds of 1.2, 6.0, 40, and 121 m/min using the sheets with surface roughnesses of 0.18 and $0.54 \mu\text{mRa}$, the roll with a constant surface roughness of $0.01 \mu\text{mRa}$, and the

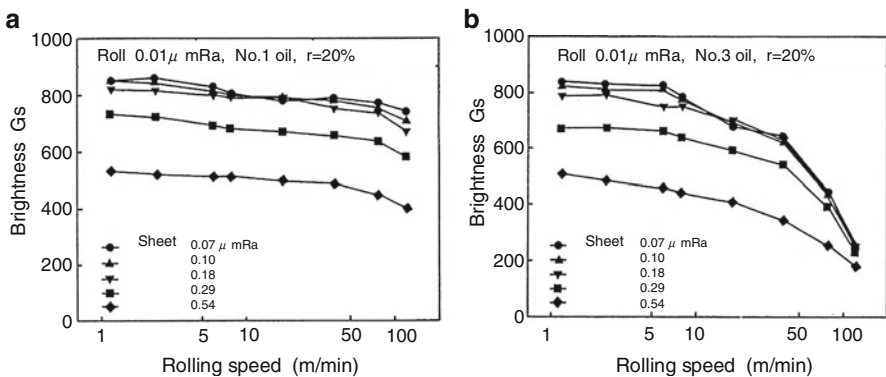


Fig. 4.53 Relationship between surface brightness and rolling speed at reduction of 20 % using sheets with surface roughnesses of 0.07, 0.10, 0.18, 0.29, and $0.59 \mu\text{mRa}$ and lubricants of No. 1 (a) and No. 3 (b)

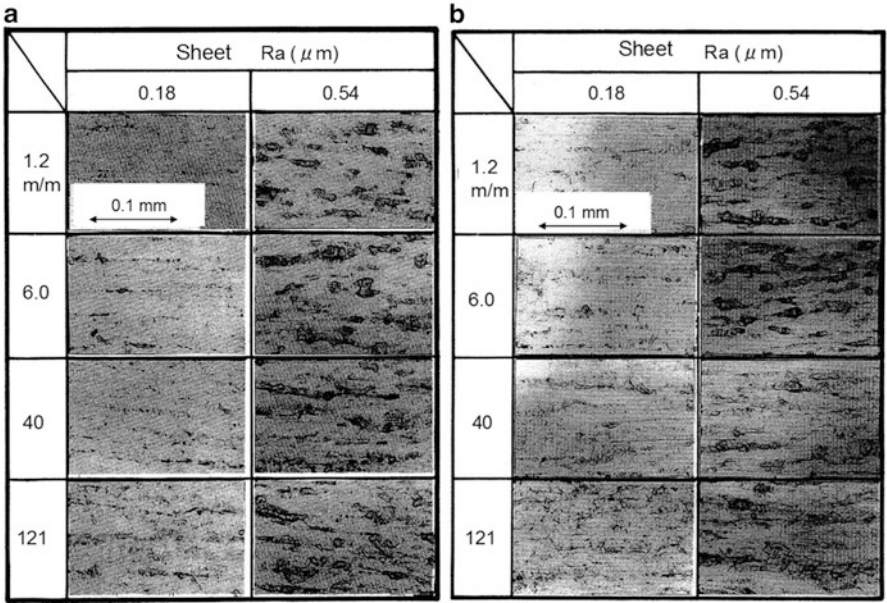


Fig. 4.54 Surface photographs of sheet rolled using sheets of surface roughnesses of 0.18 and 0.54 μmRa , roll of constant surface roughness of 0.01 μmRa , and lubricants of No. 1 (a) and No. 3 (b)

lubricants of No. 1 (a) and No. 3 (b). In Fig. 4.54a, b, for the sheet with a surface roughness of 0.54 μmRa , the oil pockets on the workpiece surfaces in all the conditions can be observed so that it is found that the lubrication mechanism becomes the mixed lubrication of the hydrostatic lubrication and the boundary lubrication.

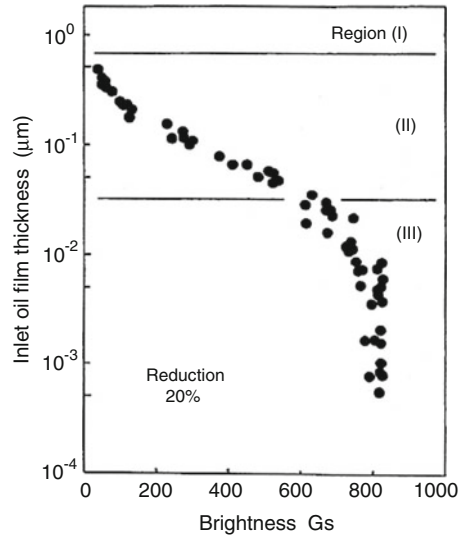
4.4.2.4 Relationship Between Surface Brightness and Inlet Oil Film Thickness

It is known that the surface brightness G_s depends on many tribological conditions as follows:

$$G_s = G_s(V_r, V_1, h_1, r, R, Y, \eta_0, \alpha, \beta, R_a^{\text{roll}}, R_a^{\text{workpiece}} \text{ etc}) \quad (4.16)$$

In Fig. 4.40 in Sect. 4.3.3, it is shown that the surface brightness depends on the oil film thickness. In this chapter, the inlet oil film thicknesses in experimental conditions in Fig. 4.49 are calculated numerically using the calculation method. Figure 4.55 shows the relationship between inlet oil film thickness and surface brightness for the roll and sheet with smooth surface. From Fig. 4.55, it is found that when the roll and sheet surfaces are smooth, the surface brightness can be expressed as a function h_1 as follows:

Fig. 4.55 Relationship between inlet oil film thickness and surface brightness for roll and sheet with smooth surface



$$G_S = G_S(h_1) \quad (4.17)$$

Particularly, in the mixed lubrication regime in the region II, it can be expressed that the relationship between surface brightness and inlet oil film thickness is linear.

On the other hand, when the roll and sheet surfaces are rough, the surface brightness depends on the inlet oil film thickness, the roll surface roughness, and the sheet surface roughness. Consequently, it is expressed instead in Eqn. (4.16) as follows:

$$G_S = G_S(h_1, R_a^{roll}, R_a^{workpiece}) \quad (4.18)$$

4.4.3 Estimation System for Surface Brightness of Rolled Sheet

In order to produce the strip with high surface qualities in stainless steel cold rolling, the rolls with smaller diameters and the lubricants with lower viscosities have been used in mill operation. Recently the rolling mills in actual process were operated at higher rolling speed. Therefore, it is desired that the surface brightness of rolled sheet is estimated and controlled with high accuracy in actual mill operation. The surface brightness can be expressed by three factors of the inlet oil film thickness and the surface roughnesses of roll and sheet before rolling as expressed in Eqn. (4.18).

In this chapter, the outline of a new system for estimating the surface brightness of the strip after each pass in actual mill for stainless steel cold rolling by using this Eqn. (4.18) is explained. Then, the case study of Eqn. (4.18) is discussed.

4.4.3.1 Outline of New Estimation System

Since the surface brightness of the rolled sheet can be estimated from Eqn. (4.18), it is desired that the experimental equation of Eqn. (4.18) is derived from rolling experiments. In order to derive the experimental equation, the enormous rolling experiments must be carried out. In the current situation, another estimation system must be considered. Azushima [19] proposed the new estimation system of rolled sheets based on Eqn. (4.18). The flow chart of the estimation system is shown in Fig. 4.56.

Experiments for the estimation must be carried out as follows:

1. Preparation of as-hot rolled sheet
2. Input of the rolling conditions at each pass
3. Calculation of the inlet oil film thickness at each pass
4. Determination of the rolling conditions in each pass in the laboratory mill

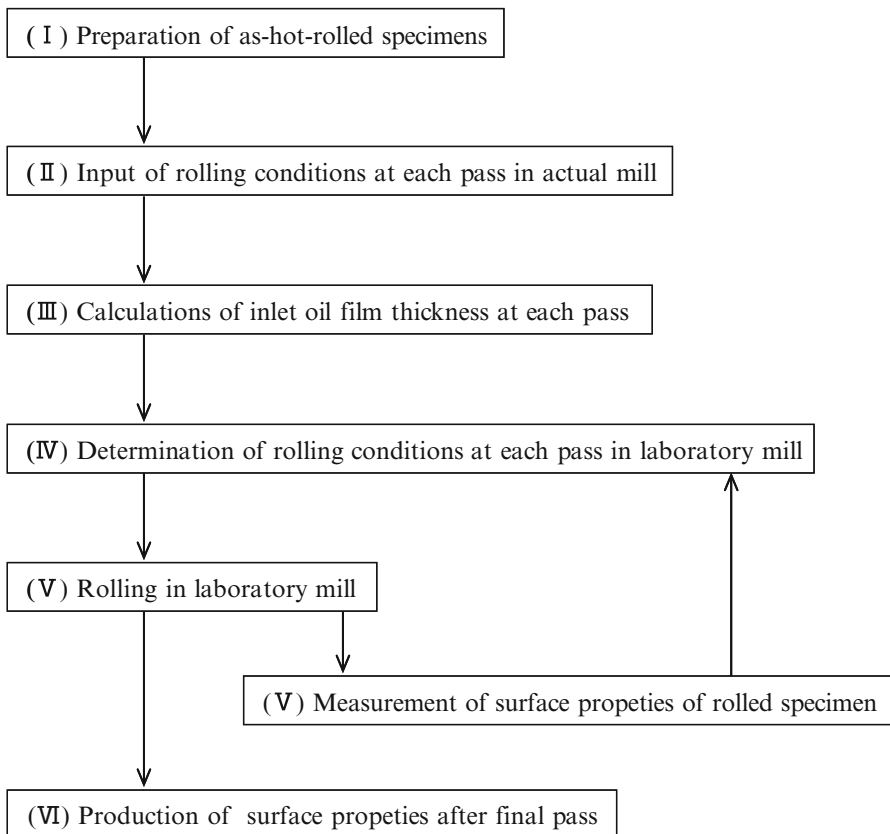


Fig. 4.56 Flow chart of estimation system for rolled sheet

5. Simulation rolling in laboratory mill and measurement of the surface brightness of rolled sheet
6. Output of the surface brightness after the final pass

4.4.3.2 Evaluation of Estimation System in Joint Research

In order to evaluate the new system for estimating the surface brightness of rolled sheet before rolling, seven stainless steel-making companies in Japan participated in the joint research of ISIJ [20]. In this chapter, the two examples in the experimental results are introduced. The rolling conditions of actual mills in A and B companies are summarized in Table 4.9. In A company, the rolling is carried out seven passes at the reduction of sheet thickness from 4.0 to 1.0 mm. The rolling speeds are 210 m/min at one pass, 240 m/min from 2 to 4 passes, 270 m/min from six pass, and 160 m/min at seven pass. In B company, the rolling is carried out at nine passes in the reduction of sheet thickness from 4.0 to 0.60 mm. The rolling speeds are 170 m/min at one pass, 250 m/min from 2 to 7 passes, 200 m/min at eight pass, and 150 m/min at nine passes.

4.4.3.3 Simulation Method

The rolling simulation tests are carried out using a laboratory mill. The roll diameter is 76 mm and the roll speed ranges from 0.2 to 450 m/min. The roll material used are SKD 11 and SKH (JIS). The dimensions of workpiece sheet are a width of 20 mm and a length of 250 mm, and the thicknesses of each pass are shown in Table 4.9. The workpiece sheets are cut off from the strip after five passes in A company and the as-hot-rolled strip in B company.

Next, the lubricant used in the simulation rolling test is a paraffinic oil with a high viscosity of 340 cSt (20 °C). The rolling speed of the laboratory mill are determined as the inlet oil film thickness in the simulation rolling is equal to that calculated in actual mill rolling for each pass. The roll surface is ground as the surface roughness R_a is consistent with the value of the surface roughness of roll in the actual mill. The other simulation conditions are the same as the actual mill rolling conditions. The simulation rolling is carried out at a room temperature (20 °C).

In A company, the workpiece sheets cut off from the rolled strip after five passes in actual mill are used. Then, the surface brightness of the sheets rolled at six and seven passes is estimated by the new estimation system. In B company, the workpiece sheets cut off from the as-hot-rolled strip are used. The surface brightness of the sheets rolled from 1 to 9 passes is also estimated. The rolling conditions of simulation tests using the laboratory mill for A and B companies are summarized in Table 4.10.

Table 4.9 Rolling conditions of actual mills in A and B companies

(a) A company											
Pass			1	2	3	4	5	6	7		
Rolling condition	Thickness (mm)	4	3.35	2.84	2.3	1.8	1.42	1.15	0.98		
	Reduction (%)		16.3	15.2	19.1	21.7	21.1	19	14.8		
	Front tension (kgf/mm ²)		11	13	17	21	25	27	27		
	Back tension (kgf/mm ²)		7	8	10	12	16	18	20		
	Rolling speed (m/min)		160	250	250	250	300	300	160		
	Oil temp. (°C)		50	50	50	50	50	50	50	50	
(b) B company											
Pass			1	2	3	4	5	6	7	8	9
Rolling condition	Thickness (mm)	4	3.5	2.85	2.27	1.78	1.4	1.1	0.87	0.7	0.6
	Reduction (%)		12.5	18.6	20.4	21.6	21.3	21.4	20.9	20.7	14.5
	Front tension (kgf/mm ²)		10	12	14	18	19	23	27	31	31
	Back tension (kgf/min ²)		—	6	7	9	14	16	18	24	27
	Rolling speed (m/min)		170	250	250	250	250	250	210	200	150
	Oil temp. (°C)		40	40	40	40	40	40	40	40	40

4.4.3.4 Simulation Results

Figure 4.57 shows the comparison of the surface brightnesses obtained by the simulation rolling tests with those by the actual mill in A company. Figure 4.58 shows the comparison of the surface brightnesses obtained by the simulation rolling tests with those by the actual mill in B company.

In Figs. 4.57 and 4.58, the estimation values of surface brightness are in good agreement with those in actual mill. From these evaluation results, it is confirmed that the surface brightness of rolled sheet after each pass can be estimated with high accuracy by the new estimation system. By the estimation system for the surface brightness of strip rolled in actual mill, it is understood that the new pass schedule for manufacturing the strip of stainless steel with mirror surface can be developed. Moreover, when the new cold mill line for stainless steel is built, the new pass schedule will be estimated by the new estimation system.

4.4.3.5 Improvement of Surface Brightness

Azushima [19] reported the improvement of the surface brightness of rolled strip in the final pass and the process schedule of the roll surface roughness in order to produce the rolled sheet with a bright surface.

Table 4.10 Rolling conditions of simulation tests using laboratory mill in A and B companies

(a) A company					6 pass			7 pass	
Roll material					SKH			SKH	
Diameter (mm)					76.0			76.0	
Surface roughness of roll Ra (μm)					0.029			0.029	
Inlet angle (°)					4.74			3.48	
Reduction (%)					18.6			12.3	
Rolling speed (m/s)					0.142			0.084	
Viscosity of lubricant (Pa s)					0.27			0.27	
Intel of film thickness (μm)					0.0481			0.0394	
(b) B company									
	1 pass	2 pass	3 pass	4 pass	5 pass	6 pass	7 pass	8 pass	9 pass
Roll material	SKD								SKH
Diameter (mm)	76.0								
Surface roughness of roll Ra (μm)	0.317							0.166	0.030
Inlet angle (°)	6.58	7.51	7.10	6.52	5.74	5.10	4.46	3.84	2.94
Rolling speed (m/s)	0.085	0.127						0.098	0.075
Viscosity of lubricant (Pa s)	0.27								
Inlet of film thickness (μm)	0.0210	0.0270	0.0285	0.0309	0.0352	0.0397	0.0454	0.0409	0.0414

Fig. 4.57 Comparison of surface of brightness obtained by simulation rolling tests with those by actual mill in A company

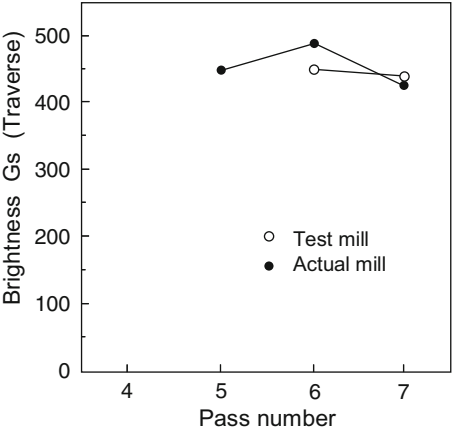


Fig. 4.58 Comparison of the surface brightnesses obtained by simulation rolling tests with those by actual mill in B company

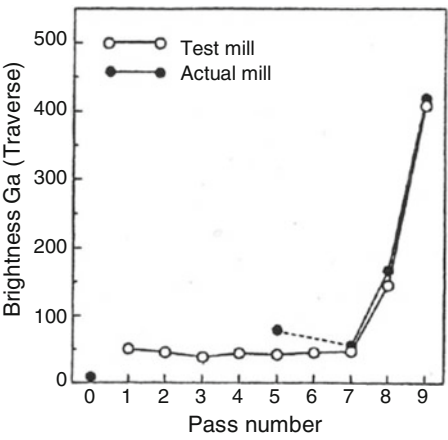
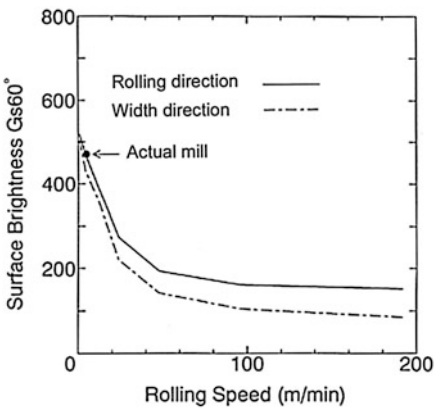


Fig. 4.59 Effect of rolling speed on surface brightness



(a) Final pass

The improvement of the surface brightness of rolled strip in the final pass in B company shown in Table 4.9b is discussed in this chapter. From Table 4.9b, the surface properties of the strip after eight passes are the surface brightness of 298 in the rolling direction and 166 in the width direction and the surface roughness of 0.115 μmRa , and the thickness is 0.7 mm.

The simulation rolling conditions of nine passes shown in Table 4.9b are the rolling speed of 0.075 m/s, the thickness reduction from 0.7 to 0.6 mm, the viscosity of lubricant of 0.27 Pa s, and the surface roughness of SKH roll of 0.03 μmRa . In order to improve the surface brightness, the rolling speed, the viscosity of lubricant, and the roll material are changed.

Figure 4.59 shows the relationship between surface brightness and rolling speed. It is understood that the surface brightness depends significantly on the rolling

Fig. 4.60 Effect of viscosity of lubricant on surface brightness

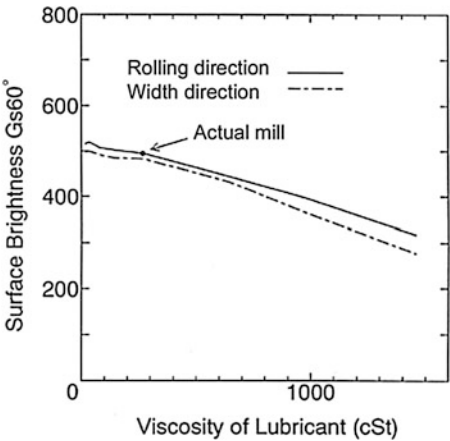
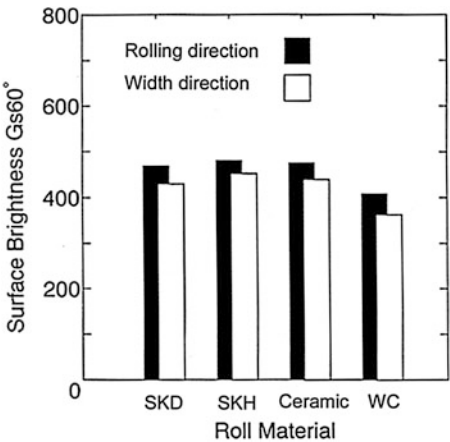


Fig. 4.61 Effect of roll material on surface brightness



speed in the range of rolling speed in actual mill, so that if the rolling speed increases, it is anticipated that the surface brightness decreases rapidly.

Then, Fig. 4.60 shows the relationship between surface brightness and viscosity of lubricant. It is understood that the surface brightness is nearly independent of the viscosity of lubricant in lower viscosity of lubricant, so that even if the viscosity of lubricant is reduced, it is not expected that the surface brightness increases.

Next, the rolling experiments are carried out using the roll materials of SKD 11 with a surface roughness of 0.024 μmRa , SKH with 0.01 μmRa , ceramic with 0.026 μmRa , and WC with 0.038 μmRa . Figure 4.61 shows the effect of the roll material on the surface brightness. From the experimental results, it is understood that the surface brightness is almost independent of the roll material in actual mill and depends significantly on the surface roughness of rolls.

(b) Process schedule of roll surface roughness

From these evaluation results mentioned above, it is confirmed that the surface roughness of roll affects significantly the surface brightness after rolling. Therefore, the rolling experiments are carried out changing the pass schedule of the surface roughness of rolls. The rolling conditions in actual mill are shown in Table 4.11a. In the actual mill, the as-hot strip with a thickness of 4.0 mm is rolled using the rolls with a diameter of 60 mm in Sendzimir mill and the paraffinic oil with a viscosity of 10 cSt (20 °C). Therefore, the estimation rolling conditions in the laboratory mill are shown in Table 4.11b. The rolling simulation tests are carried out using the laboratory mill shown in Sect. 4.4.3.3 and the paraffinic oil with a viscosity of 340 cSt (20 °C).

In the experiment [1], the surface roughness for each pass is a constant surface roughness of 0.015 μmRa . In the experiment [2], the surface roughness of rolls changes as shown in Table 4.12. In the experiment [2] of the rolling simulation tests, the surface roughness of rolls of 1 and 2 passes is 0.40 μmRa , one of 3 and 4 passes is 0.14 μmRa , one of 5 and 6 passes is 0.045 μmRa , and one of 8 and 9 passes is 0.015 μmRa . Figure 4.62 shows the relationship between surface roughness and pass number in the experiments of [1] and [2]. The surface brightness after final pass in the experiment of [2] is higher than that in the experiment of [1]. It is understood that the excellent surface brightness of strip after final pass can be manufactured by designing the pass schedule of the roll surface roughness.

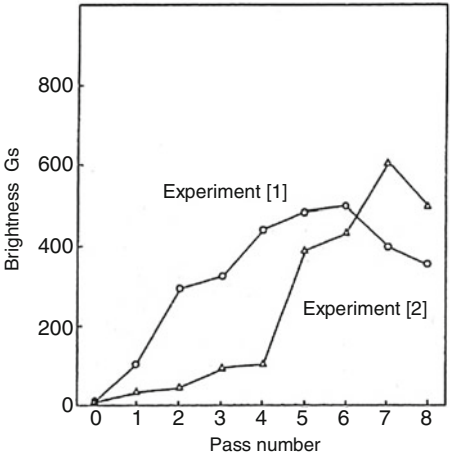
Table 4.11 Rolling conditions in actual mill and simulation rolling conditions in laboratory mill

(a) Actual mill		
Pass	Strip thickness (mm)	Rolling speed (m/min)
1	3.5	100
2	2.9	100
3	2.4	100
4	1.9	200
5	1.5	200
6	1.2	200
7	1.0	200
8	0.8	200
(b) Laboratory mill		
Pass	Reduction (%)	Rolling speed (rpm)
1	13	17
2	13	17
3	13	17
4	17	33
5	18	33
6	18	33
7	17	33
8	17	33

Table 4.12 Change of surface roughness of rolls in simulation rolling tests

Pass	Reduction (%)	Rolling speed (rpm)	Roll surface	
			Sandpaper #	Surface roughness Ra (μm)
1	13	17	120	0.40
2	13	17	120	0.40
3	13	17	240	0.14
4	17	33	240	0.14
5	18	33	400	0.045
6	18	33	400	0.045
7	17	33	1500	0.015
8	17	33	1500	0.015

Fig. 4.62 Comparison between surface brightnesses in experiments [1, 2]



4.5 Inlet Oil Film Thickness in Emulsion Oil

In cold steel sheet rolling, O/W emulsions are used as the rolling oil. The emulsion is explained in the Webster’s dictionary that “any colloidal suspension of a liquid in another liquid.” In the O/W emulsion used in cold steel sheet rolling, the oil is emulsified in the water to make emulsions with high stability as shown in Fig. 4.63.

4.5.1 Emulsion Lubrication in History

Baba et al. [21] examined the surface appearance of workpiece after rolling in cold sheet rolling with O/W emulsion using five stands tandem mill. The experiments were carried out using the low carbon steel strip and the O/W emulsion of palm oil with a concentration of 25 % at 90 °C changing the rolling speed from 152 to 1433 m/min.

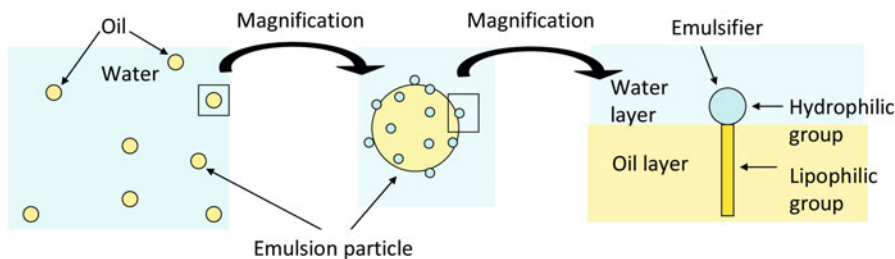


Fig. 4.63 Schematic representation of O/W emulsion

Fig. 4.64 Relationship between surface qualities and rolling speed in five stands tandem mill [21]

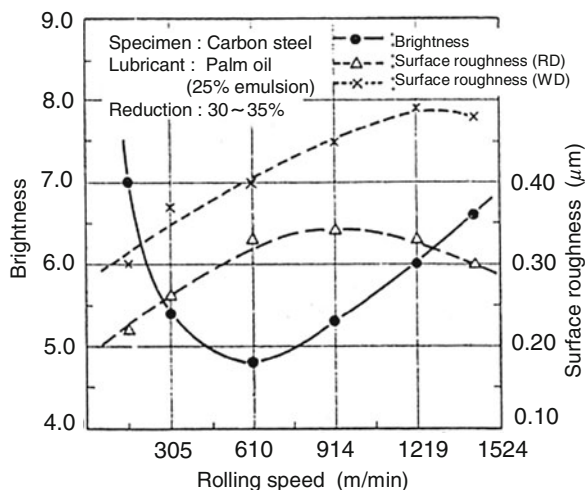


Figure 4.64 shows the relationship between surface qualities and rolling speed in five stands tandem mill. Next, Fig. 4.65 shows the surface photographs of the strip rolled changing the rolling speed. The surface roughness increases with increasing rolling speed up to 610 m/min, and above 610 m/min, it decreases with increasing rolling speed. On the other hand, the surface brightness decreases with increasing rolling speed up to 610 m/min, and above 610 m/min, it increases with increasing rolling speed. In this paper, the introducing oil film thickness is not discussed. However, from these experimental results, it is estimated that the introducing oil film thickness increases with increasing rolling speed up to 610 m/min, and on the other hand, above 610 m/min, it decreases with increasing rolling speed.

Later, Azushima et al. [22] compared the surface brightness of the sheet rolled in O/W emulsion oil with that of the sheet rolled in neat oil. The experiments were carried out using the low carbon steel with a surface roughness of $0.07 \mu\text{m}$ and the paraffinic oils with five viscosities and the O/W emulsion oils with a concentration of 3 % at a constant reduction of 20 % changing the rolling speed from 1.2 to 121 m/min. The properties of paraffinic oils used are summarized in Table 4.13.

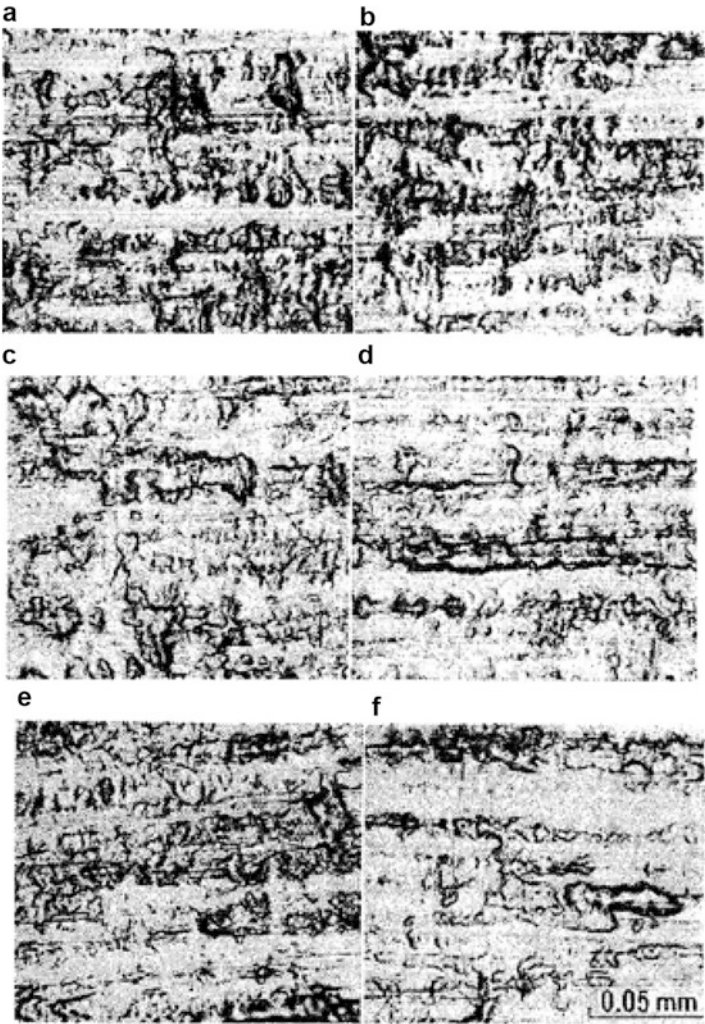


Fig. 4.65 Surface photographs of strip rolled changing rolling speed [21]. (a) 152 m/min. (b) 305 m/min. (c) 610 m/min. (d) 914 m/min. (e) 1219 m/min. (f) 1433 m/min

Table 4.13 Properties of paraffinic oils used

Rolling oil	Viscosity η [cSt] (20 °C)	Emulsifier (%)	Emulsion concentration (%)	Particle size (mm)
No. 1	2.8	5	3	3.8
No. 2	17.0			6.1
No. 3	23.5			8.7
No. 4	37.3			12
No. 5	97.4			19

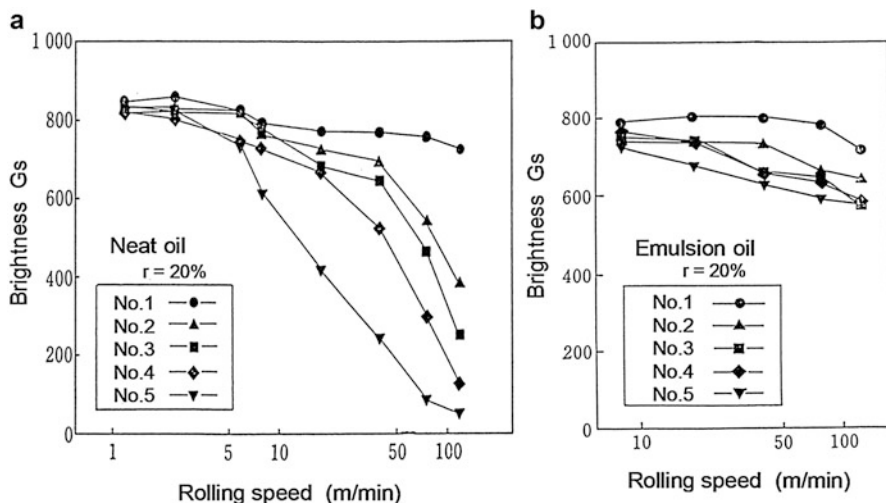


Fig. 4.66 Relationship between surface brightness and rolling speed in neat oils (a) and emulsion oils (b)

Figure 4.66 shows the relationship between surface brightness and rolling speed in neat oils (a) and the emulsion oils (b). The significant difference between surface brightnesses in the neat oil and the emulsion oil is observed. The differences become larger when the rolling speed and the viscosity become higher. In order to understand quantitatively the difference of surface brightness, the inlet oil film thickness is calculated from the calculation method mentioned in Sect. 2.5. On the other hand, the inlet oil film thickness is measured using the estimation method proposed by Azushima et al., [23] mentioned later in detail.

Figure 4.67 shows the relationship between inlet oil film thickness and rolling speed in the emulsion oils (a) and the neat oils (b). The difference between the inlet oil film thicknesses in emulsion oil and in neat oil can be understood quantitatively from Fig. 4.67a, b. The difference becomes larger in the conditions of higher rolling speed and higher viscosity of lubricant.

Consequently, the new introducing model between roll and workpiece in cold sheet rolling with O/W emulsion oils needs instead the introducing model in the neat oil as mentioned in Sect. 2.3. Nakajima et al. [23] proposed the plating out model in inlet zone between roll and workpiece for the emulsion lubrication as shown in Fig. 4.68.

In the plating out model, the emulsion layer and the plating out layer on the workpiece surface in the inlet zone are adhered, and the oil of the plating out layer is preferentially introduced in the contact zone between roll and workpiece. However, this model remains in the qualitative description. The quantitative introducing model has been proposed after the direct observation of the emulsion behavior in EHL contact.

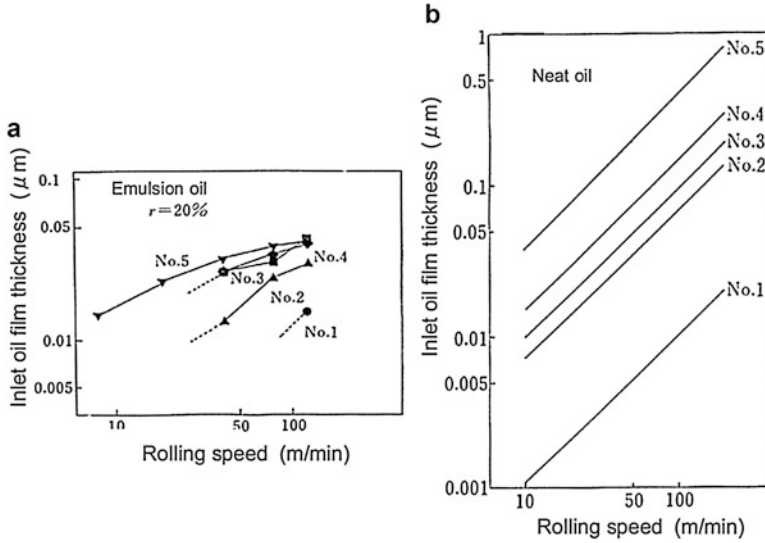


Fig. 4.67 Relationship between inlet oil film thickness and rolling speed in emulsion oils (a) and neat oils (b)

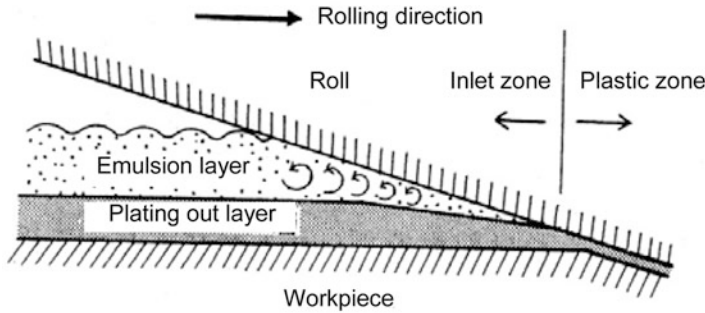
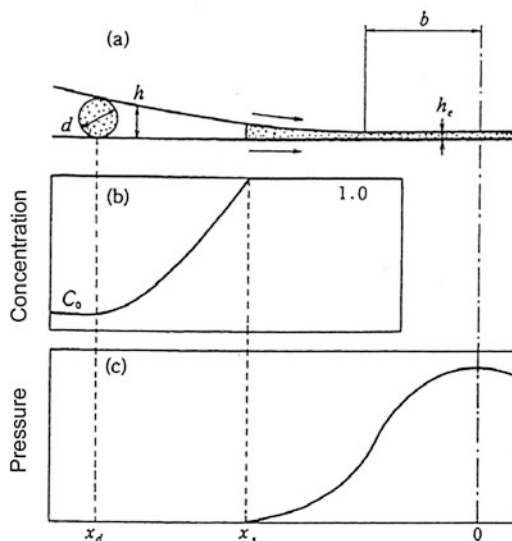


Fig. 4.68 Schematic representation of plating out model in inlet zone between roll and workpiece for emulsion lubrication [23]

4.5.2 Emulsion Behavior in EHL Contact

Hamaguchi et al. [24] measured the elastohydrodynamic lubrication (EHL) film thickness of O/W and W/O emulsions of paraffinic oil in a rolling point contact using an optical interference method. They reported that for W/O emulsions, EHL film was observed, but for O/W emulsion, negligible EHL film formation was observed. Kimura et al. [25] conducted the experiments for measuring the EHL film thickness in a four-roller machine using O/W emulsion of tallow oil. They found that even at the oil concentrations as low as several percent, thick

Fig. 4.69 Hypothetical model of inlet region [25]



elastohydrodynamic films were formed. From these experimental results, they proposed a theory to give a tentative explanation as shown in Fig. 4.69.

Figure 4.69a shows the inlet region of an elastohydrodynamic conjunction. Figure 4.69b shows the concentration change of O/W emulsion. When an oil particle is introduced, it adheres at the certain clearance between surfaces of roll and workpiece at x_d where the clearance h is equal to the particle diameter d . The concentration increases according to the next equation:

$$c = c_0 \frac{d}{h} \quad (4.19)$$

where c_0 is the initial oil concentration of the emulsion. Figure 4.69c shows the pressure distribution. It is assumed that the pressure generates at the point x_s that the emulsion concentration becomes 100 %.

On the other hand, Nakahara et al. [26] proposed the phase inversion of O/W to W/O emulsions from the direct observation results as shown in Fig. 4.70. From these results, it is confirmed that the oil film in EHL contact region for the O/W emulsion exists.

Moreover, Zhu et al. [27] carried out the experiments for measuring the oil film thickness using the EHL machines in point contact and line contact. The experimental results are shown in Fig. 4.71. From these experimental results, it is found that at low speed, the oil film thickness in O/W emulsion oil is equal to that in neat oil; above a first critical speed depending on the emulsion, it increases gradually with increasing rolling speed and then it decreases. Above a second critical speed, it increases again.

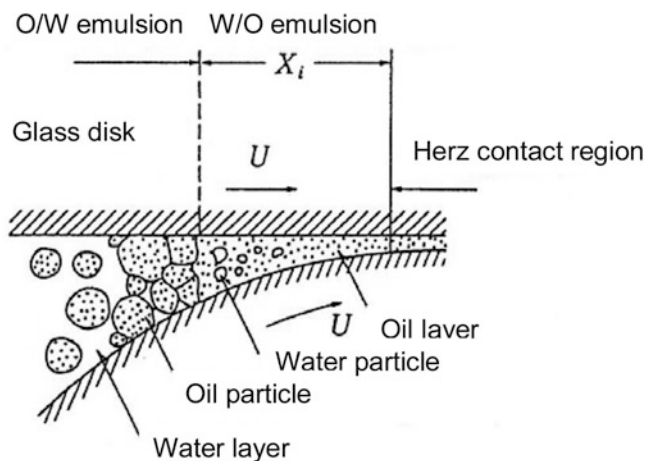


Fig. 4.70 Schematic representation of phase inversion region in inlet zone of EHL contact [26]

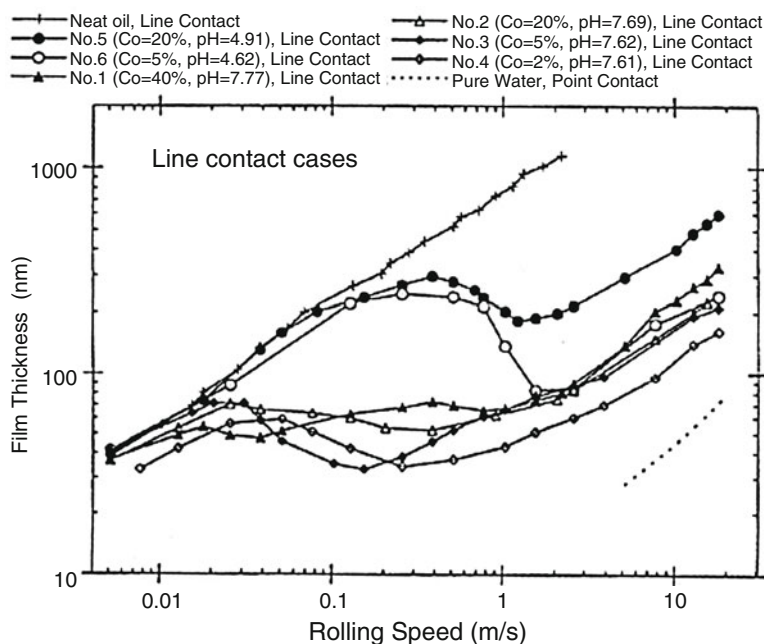


Fig. 4.71 Results of film thickness for line contact cases [27]

Then, Wilson et al. [28] proposed the dynamic concentration model shown in Fig. 4.72. They thought that a continuum model cannot apply in the inlet zone of EHL contact, so that they proposed the dynamic concentration model that the concentration increase starts when the gap between two contact solids is equal to

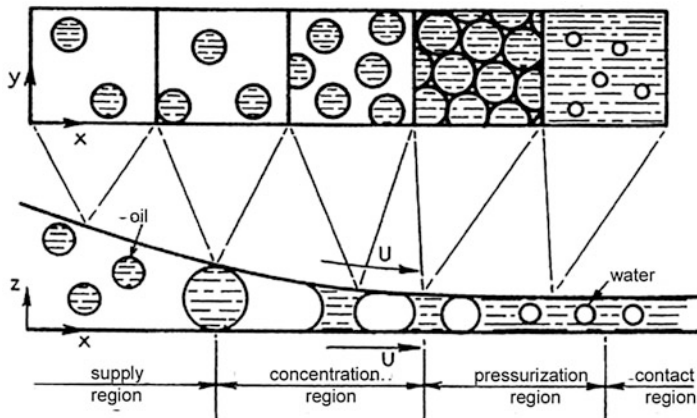


Fig. 4.72 Schematic representation of dynamic concentration model of emulsion lubrication in EHL inlet zone [28]

the diameter of the oil droplet and the droplet is adhered on the solid surfaces. The emulsion concentration increases and then the pressure within the oil generates and increases. This model is similar to the hypothetical model proposed by Kimura et al. shown in Fig. 4.69.

4.5.3 Inlet Oil Film Thickness in Cold Sheet Rolling with Emulsion Oil

The analysis of the inlet oil film thickness in cold sheet rolling with O/W emulsion was carried out by Schmid et al. [29], Azushima et al. [30, 31], and Cassarini et al. [32]. In this chapter, the analysis by Azushima et al. is explained in detail.

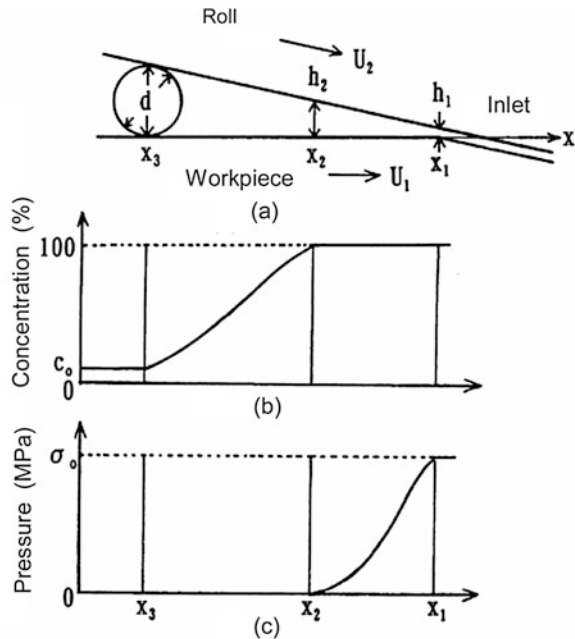
4.5.3.1 Analysis of Inlet Oil Film Thickness by Dynamic Concentration Model

First, Azushima et al. [30] analyzed the inlet oil film thickness using the dynamic concentration model. Figure 4.73 shows the schematic representation of the inlet zone in cold sheet rolling with O/W emulsion in the dynamic concentration model. In Fig. 4.73, d is the diameter of oil particle and c_0 is the initial emulsion concentration.

The assumptions employed in the calculation are as follows:

1. The roll and workpiece are rigid and the surfaces are smooth.
2. The oil droplet in the O/W emulsion adheres to the surfaces of roll and workpiece at x_3 where the diameter d is equal to the gap distance between the surfaces of roll and workpiece.

Fig. 4.73 Schematic representation of inlet zone in cold sheet rolling with O/W emulsion (a), concentration change (b), and pressure change (c) by dynamic concentration model



3. The emulsion concentration c increases from an initial concentration c_0 at x_3 to 100 % at x_2 . The emulsion concentration depends on the trapping ratio λ .
4. The pressure increases from 0 at x_2 to Y at x_1 . Y is the yield stress of the workpiece.
5. The Reynolds equation is applied for a steady and an incompressible flow.
6. The heat transferred by the lubricant is neglected.
7. The heat generation by the compression is neglected.
8. The temperature of the roll and the workpiece surfaces are equal to the ambient temperature T_0 .
9. The viscosity of lubricant depends on the pressure and the temperature. The temperature is the mean temperature across the oil film.
10. The surfaces of roll and workpiece are clean up to x_3 .

The Reynolds equation, the energy equation, and the viscosity equation are given by

$$\frac{dp}{dx} = -6\eta(U_1 + U_2) \left(\frac{h - h_1}{h^3} \right) \quad (4.8)$$

$$K \frac{\partial^2 T}{\partial y^2} + \eta \left(\frac{\partial u}{\partial y} \right)^2 = 0 \quad (2.40)$$

$$\eta = \eta_0 \exp\{\alpha p - \beta(T - T_0)\} \quad (4.9)$$

Equations (4.8) and (2.40) are numerically integrated at the boundary conditions of $p=0$ at $x=x_2$ and $p=Y$ at $x=x_1$.

Next, since u in Eqn. (2.40) is expressed by Eqn. (1.19), Eqn. (2.40) is integrated at the boundary conditions of $T=T_0$ at $y=0$ and $T=T_0$ at $y=h$, and the mean temperature can be given. Last, the oil film h_2 is derived by

$$h_2 = \frac{c}{100100} \frac{\gamma}{d} d \quad (4.20)$$

where γ is the trapping ratio.

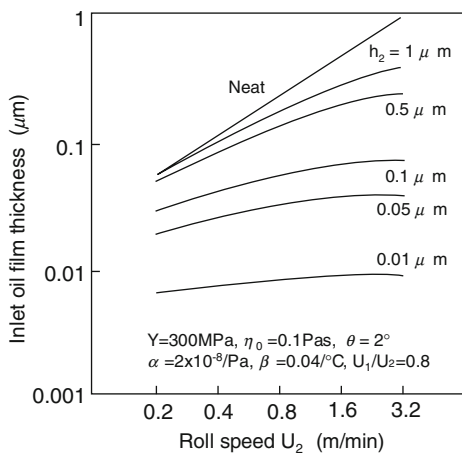
4.5.3.2 Calculated Results of Inlet Oil Film Thickness

In this chapter, the calculated results by Azushima et al. [30] are shown. Figure 4.74 shows the relationship between inlet oil film thickness and roll speed changing the oil film thickness of h_2 in cold sheet rolling with O/W emulsion at a viscosity of 0.1 Pa s, a yield stress of 300 MPa, and a slip ratio of 0.2. The inlet oil film thicknesses in O/W emulsion oil are smaller than those in neat oil for all conditions and the differences between them decrease with increasing h_2 .

Next, the effect of the viscosity of lubricant on the inlet oil film thickness in O/W emulsion is shown in Fig. 4.75. The calculation is carried out at a constant h_2 of 0.1 μm for the viscosities of 0.05 and 0.01 Pa s. From Figs. 4.74 and 4.75, it is found that if the value of h_2 is the same, the inlet oil film thicknesses in O/W emulsions for oil with viscosities under 0.05 Pa s are significantly smaller than those in neat oil.

Then, the effect of the diameter of oil particle on the inlet oil film thickness in the cold sheet rolling at a emulsion concentration 3 % and a trapping ratio of 30 % for

Fig. 4.74 Relationship between inlet oil film thickness and roll speed changing oil film thickness of h_2



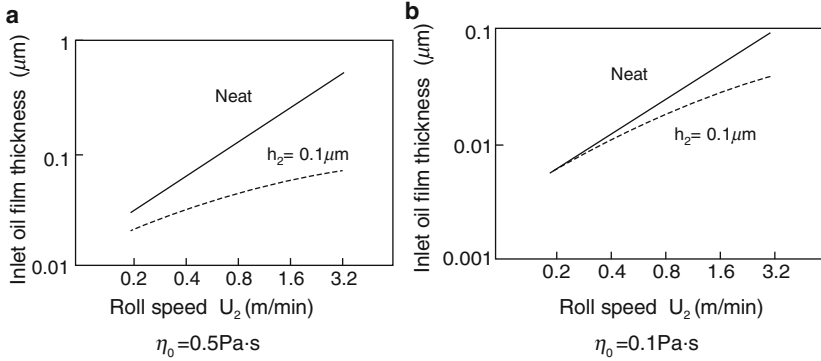
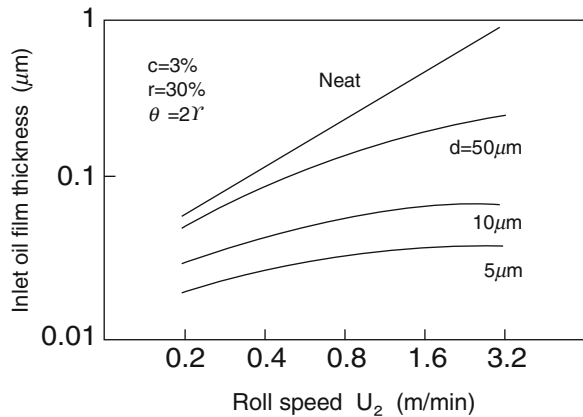


Fig. 4.75 Relationship between inlet oil film thickness and roll speed constant h_2 of $0.1 \mu\text{m}$ for viscosities of 0.05 and $0.01 \text{ Pa}\cdot\text{s}$

Fig. 4.76 Relationship between inlet oil film thickness and roll speed for diameters of 5 , 10 , and $50 \mu\text{m}$



the diameters of 5 , 10 , and $50 \mu\text{m}$ is shown in Fig. 4.76. If the emulsion concentration and the trapping ratio are constant, the inlet oil film thickness in O/W emulsion with the oil particles having larger diameter becomes larger.

4.5.3.3 Comparison Between Inlet Oil Film Thicknesses Calculated and Measured

In order to check the inlet oil film thickness calculated in O/W emulsion, the experiments in the cold sheet rolling under the starved lubrication condition were carried out by Azushima et al. [30]. In these rolling experiments, the specimens plating out the thinner oil film on the sheet surface are rolled. Figure 4.77 shows the schematic representation of the inlet zone under the starvation condition.

Fig. 4.77 Schematic representation of the inlet zone under starvation condition

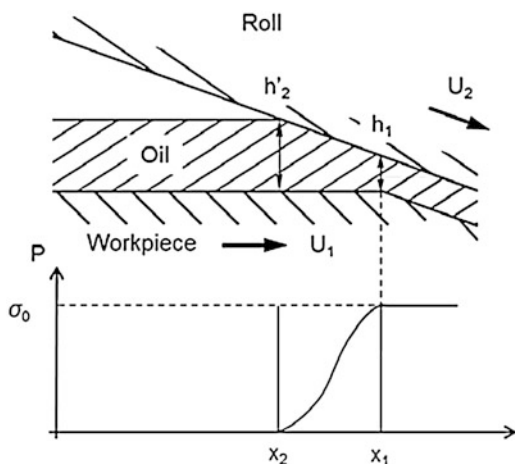
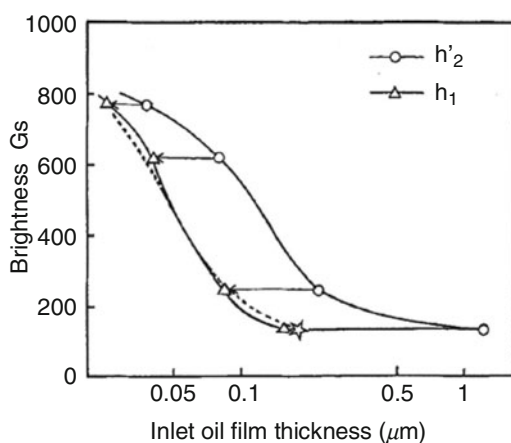


Fig. 4.78 Relationship between surface brightness and oil film thickness changing plating out film thickness



The sheet that the thinner oil film h'_2 is plated out on the surface is rolled, and then the surface brightness of rolled sheet is measured. At the same time, the inlet oil film thickness is calculated using the calculation method of the inlet oil film thickness in O/W emulsion. On the other hand, the same sheet is rolled in the neat lubrication and the surface brightness of rolled sheet is measured. The experiments are carried out using the low carbon steel with a surface roughness of $0.06 \mu\text{m}$, the SUJ-2 roll with a surface roughness of $0.01 \mu\text{m}$, and the paraffinic oil with a viscosity of $37.3 \text{ mm}^2/\text{s}$ at 20°C , at a constant rolling speed of 2 m/s and a constant reduction of 20% changing the plating out film thickness. Figure 4.78 shows the relationship between surface brightness and inlet oil film thickness changing the plating out film thickness.

In Fig. 4.78, Δ denotes the calculated inlet oil film thickness h_1 , $\circ$ denotes the plating out oil film thickness, and $\star$ denotes the calculated inlet oil film thickness

and the measured surface brightness in neat lubrication. The relationship (Δ) between surface roughness and inlet oil film thickness in the rolling under starved lubrication condition is in good agreement with that (dashed line) in the rolling with neat lubrication. From these experimental results, this calculation method might be used for estimating the inlet oil film thickness in rolling with O/W emulsion.

However, in the cold sheet rolling with O/W emulsion of actual mill, the oil film formed on the workpiece surface by plating out model is important, similar to the oil film formed in the inlet zone between roll and workpiece by the dynamic concentration model. Therefore, Azushima et al. [31] proposed the new calculation method for the inlet oil film thickness in the rolling with O/W emulsion.

4.5.4 Discussion of Inlet Oil Film Thickness in O/W Emulsion

In cold sheet rolling, the inlet oil film thickness depends on the dynamic concentration effect and the plating out effect. In this chapter, the effects of the dynamic concentration and the plating out on the inlet oil film thickness were examined by experiments carried out by Azushima et al. [18, 31]. As mentioned in Sect. 4.4.2.4, in rolling with neat oil using the roll and the sheet with a smooth surface, the relationship between the surface brightness of the rolled sheet and the inlet oil film thickness calculated from the Reynolds equation and the energy equation is given by

$$Gs = Gs(h_1) \quad (4.17)$$

In the mixed lubrication of the region II, the surface brightness can be expressed by

$$Gs = a \ln h_1 + b \quad (4.21)$$

where a and b are the experimental constants. It is confirmed that in cold sheet rolling with neat oils, the inlet oil film thickness can be estimated from the measured surface brightness of cold rolled sheet using Eqn. (4.21) [18].

On the other hand, in cold sheet rolling with O/W emulsion, the inlet zone is subdivided into three regions of the supply region, the concentration region and the pressurized region. In the pressurized region, it will be estimated that W/O emulsion has viscous properties similar to the neat oil. Consequently, it can be approximated that the neat oil is also introduced into the work zone between roll and sheet in cold sheet rolling with O/W emulsion. Therefore, in cold sheet rolling with O/W emulsion, the inlet oil film thickness can be estimated from the measured surface brightness of the rolled sheet using Eqn. (4.21).

Azushima et al. [31] carried out the rolling experiments using the SUJ-2 roll with a surface roughness of 0.02 μm , the A1050H aluminum sheet, and the mineral oil with a viscosity of 0.235 Pa s at a constant rolling speed of 30 m/min and at a

Fig. 4.79 Relationship between surface brightness and inlet oil film thickness in neat oil

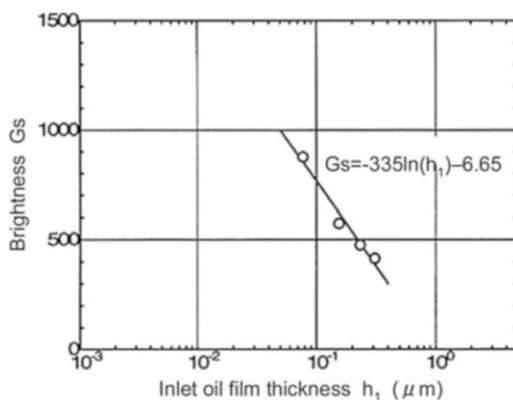
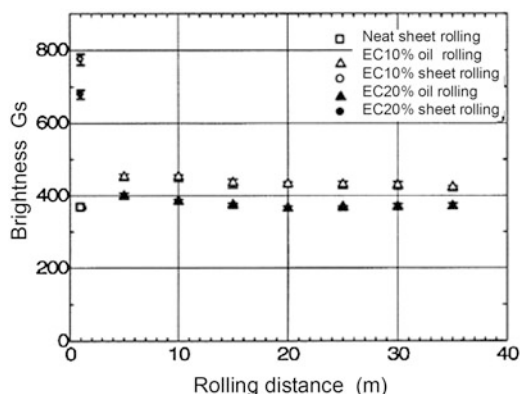


Fig. 4.80 Relationship between surface brightness and rolling distance in coil rolling for emulsions



constant reduction of 13 %. The emulsion concentrations are 10 and 20 % and the average particle diameters are 10 and 12 μm . First, the cold sheet rolling experiment with neat oil is carried out in order to obtain Eqn. (4.21). Figure 4.79 shows the relationship between surface brightness and inlet oil film thickness in rolling with neat oil. From the experimental data, Eqn. (4.21) is given by

$$Gs = -335 \ln(h_1) - 6.65 \quad (4.22)$$

Figure 4.80 shows the relationship between surface brightness and rolling distance in the coil rolling for emulsions with two concentrations of 10 and 20 %. In Fig. 4.80, the surface brightness values measured in the sheet rolling with two emulsions and the surface brightness in neat oil are also plotted. The surface brightness values of the rolled coil with O/W emulsions with concentrations of 10 and 20 % are higher than that of the rolled sheet with neat oil, but they are lower than those of the rolled sheets.

Fig. 4.81 Relationship between inlet oil film thickness and emulsion concentration in coil rolling and sheet rolling for O/W emulsions with concentrations of 10 and 20 %

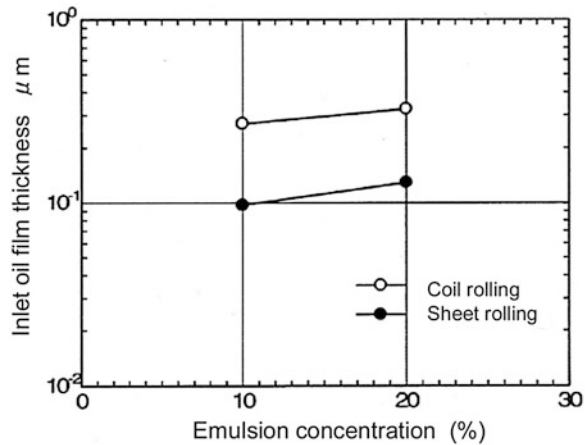


Figure 4.81 shows the relationship between inlet oil film thickness and emulsion concentration in the coil rolling and the sheet rolling for O/W emulsions with concentrations of 10 and 20 %. The inlet oil film thicknesses are estimated from Eqn. (4.22) using the data of surface brightness. The inlet oil film thickness in the coil rolling for each concentration is higher than that in the sheet rolling. In the coil rolling and the sheet rolling, the inlet oil film thicknesses in the emulsion with a concentration of 20 % are higher than those in the 10 % emulsion.

4.5.5 New Model for Calculation of Inlet Oil Film Thickness in O/W Emulsion

From the discussion in Sect. 4.5.4, it is recognized that the inlet oil film thickness in the cold sheet rolling with O/W emulsion depends on both of the dynamic concentration effect and the plating out effect. The new model in inlet zone of sheet rolling with O/W emulsion must be developed considering both effects. A new model for calculation of the inlet oil film thickness in cold sheet rolling with O/W emulsion was developed by Azushima et al. [31]. Figure 4.82 shows the schematic representation of new model in inlet zone of sheet rolling with O/W emulsion. The new model combines the dynamic concentration model and the plating out model.

Then, Fig. 4.83 shows the schematic representation of inlet zone (a), concentration distribution (b), and pressure distribution (c). In the new model shown in Fig. 4.82, with a gap distance of $(h_2'' + d)$ at a point x_3 , the oil droplet adheres to the surfaces of roll and workpiece, and the emulsion concentration increases to 100 % at a point x_2 as shown in Fig. 4.83b. The oil film thickness is $h_2 = h_2' + h_2''$ at x_2 and at the point the pressure within the oil is generated. Then, the pressure increases with decreasing oil film thickness. At the inlet oil film thickness h_1 , the pressure becomes the yield stress of the workpiece as shown in Fig. 4.83c.

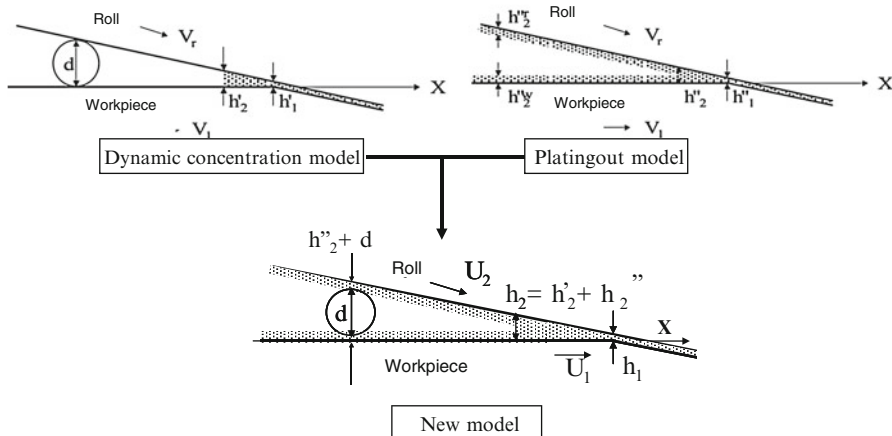
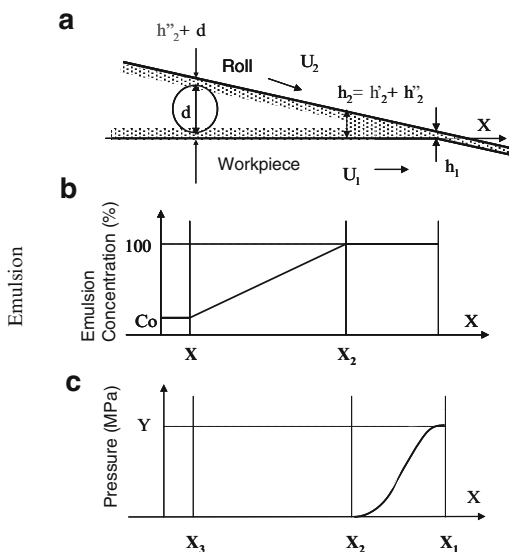


Fig. 4.82 Schematic representation of new model in inlet zone of sheet rolling

Fig. 4.83 Schematic representation of inlet zone (a), concentration distribution (b), and pressure distribution (c)



The assumptions employed in the calculation are as follows:

1. The roll and workpiece are rigid and the surfaces are smooth.
2. The oil film thickness plating out on the surfaces of roll and workpiece is as follows:

$$h_2'' = h_2''^r + h_2''^w \quad (4.23)$$

where $h_2''^r$ is the oil film thickness plating out on the roll surface and $h_2''^w$ is the oil film thickness on the workpiece surface.

3. The oil droplet in O/W emulsion adheres to the surfaces of roll and workpiece with plating out oil film at x_3 where the diameter d is equal to the gap distance between the surfaces of roll and workpiece with plating out oil film.
4. The emulsion concentration c increases from an initial concentration c_0 at x_3 to 100 % at x_2 . The emulsion concentration depends on the trapping ratio λ and is expressed as follows:

$$h'_2 = \frac{c}{100} \frac{\gamma}{100} d \quad (4.24)$$

5. The pressure increases from 0 at x_2 to Y at x_1 . Y is the yield stress of the workpiece.
6. The Reynolds equation is applied for a steady and an incompressible flow.
7. The viscosity of lubricant is constant across the film and is a function of the pressure.

The Reynolds equation and the viscosity equation are given by

$$\frac{dp}{dx} = -6\eta(U_1 + U_2) \left(\frac{h - h_1}{h^3} \right) \quad (4.8)$$

$$\eta = \eta_0 \exp(\alpha p) \quad (4.25)$$

Equation (4.8) is numerically integrated at the boundary conditions of $p=0$ at $x = x_2$ and $p=Y$ at $x = x_1$.

Figure 4.84 shows the relationship between inlet oil film thickness and roll speed for emulsions of the base oil with a viscosity of 0.1 Pa s at four levels of h_2 of 0.01, 0.1, 1, and 10 μm . In the low-speed region of Fig. 4.84, the inlet oil film thickness in O/W emulsion is generally equal to that calculated in neat oil. In this region, the inlet oil film thickness increases linearly with increasing roll speed. Above the critical roll

Fig. 4.84 Relationship between inlet oil film thickness and roll speed for emulsion of base oil with viscosity of 0.1 Pa s

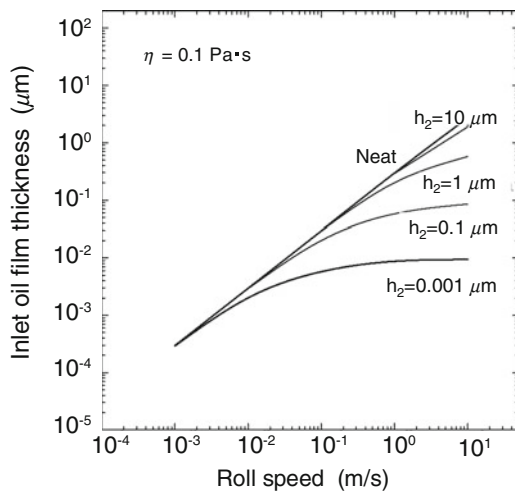
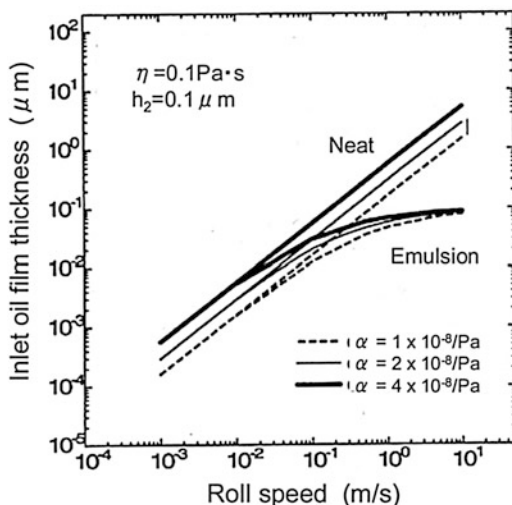


Fig. 4.85 Relationship between inlet oil film thickness and roll speed at three levels of pressure coefficient of viscosity



speeds, the inlet oil film thickness for each emulsion increases gradually due to the oil starvation. The critical roll speed corresponds to the first critical speed observed by Zhu et al. [27]. The rate of increase of the inlet oil film thickness in O/W emulsion decreases gradually with increasing roll speed, and it becomes smaller than that in neat oil. It is dependent on the lubricant viscosity and the oil film thickness h_2 . The critical roll speed increases with increasing lubricant viscosity and h_2 .

Figure 4.85 shows the relationship between inlet oil film thickness and roll speed for emulsions of base oil with a viscosity of 0.1 Pa s at three levels of pressure coefficient of viscosity at a constant h_2 of 0.1 μm . In the lower roll speeds, the inlet oil film thickness increases with increasing pressure coefficient, but in the higher roll speed, the inlet oil film thickness becomes the same value. The critical roll speed is independent of the pressure coefficient of viscosity.

4.6 Surface Appearance of Workpiece in Cold Sheet Rolling with Emulsion Oil

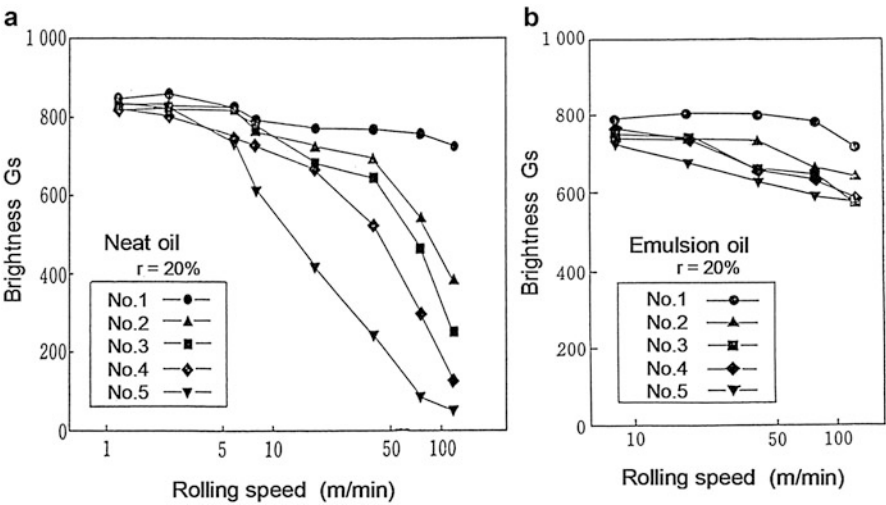
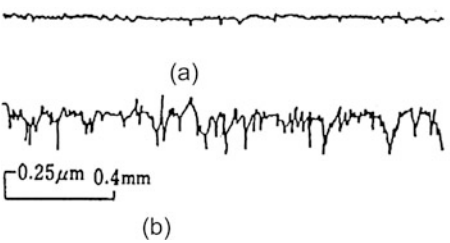
In the surface appearance of workpiece after rolling with O/W emulsion, as mentioned in Sect. 4.5, Baba et al. [21] showed the surface appearance of rolled sheet in the actual cold tandem mill with O/W emulsion, and some researchers also showed the surface appearance of rolled sheet in the laboratory mill with O/W emulsion. From these data, in the lower rolling speed, the surface appearance in O/W emulsion oil is similar to that in neat oil. On the other hand, in the higher rolling speed, the difference between surface appearance between them becomes larger with increasing rolling speed. In this chapter, the surface appearance in O/W emulsion oil and neat oil are compared, and the effect of the tribological conditions on the surface appearance in emulsion oil is examined.

4.6.1 Comparison of Surface Appearance in O/W Emulsion Oil with That in Neat Oil

Azushima et al. [22] compared the surface appearance of the sheet rolled in O/W emulsion oil with that of the sheet rolled in neat oil. The experiments are carried out using the low carbon steel with a surface roughness of 0.07 μm , the SUJ-2 roll with a surface roughness of 0.01 μm and a diameter of 78 mm, and the paraffinic oils with five viscosities at a constant reduction of 20 % changing the rolling speed from 1.2 to 121 m/min. The surface profiles of roll and workpiece are shown in Fig. 4.86. The properties of paraffinic oils used were already summarized in Table 4.13.

The relationship between surface brightness and rolling speed in the neat oils (a) and the emulsion oils (b) was already shown in Fig. 4.66. This figure is again shown for reference.

Fig. 4.86 Surface profiles of roll (a) and workpiece (b)



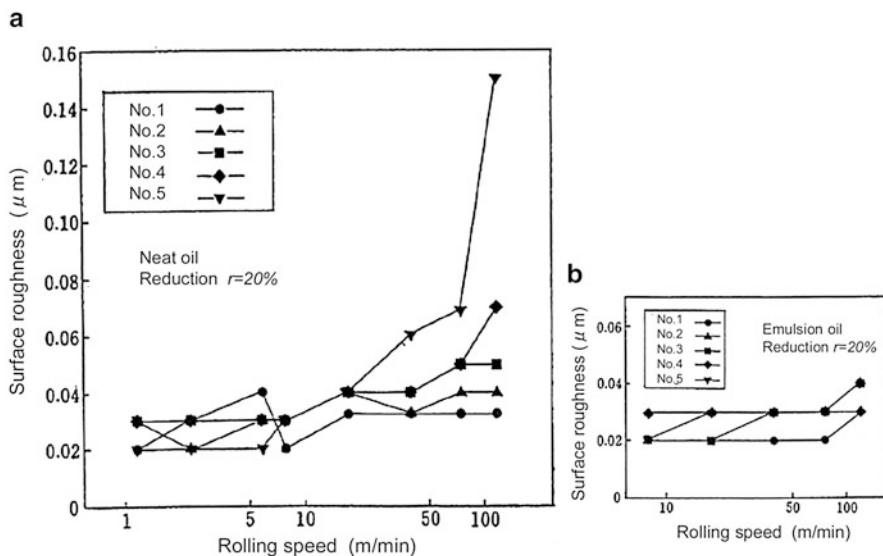


Fig. 4.87 Relationship between surface roughness and rolling speed in neat oils (a) and emulsion oils (b)

Next, Fig. 4.87 shows the relationship between surface roughness and rolling speed in the neat oils (a) and the emulsion oils (b). In Fig. 4.87, the surface roughness in neat oil increases with increasing rolling speed and viscosity of lubricant for each lubricant. On the other hand, the surface roughness in emulsion oil hardly increases with increasing rolling speed for each lubricant, and the difference of the surface roughnesses between them becomes larger with increasing rolling speed.

Figure 4.88 shows the surface photographs of the rolled sheet in neat oil (a) and emulsion oil (b). In Fig. 4.88, from the surface photographs for the neat oil of No. 5, the oil pits on the sheet surface can be observed and the number increases with increasing rolling speed. At a rolling speed of 121 m/min, it is observed that the free surface roughening occurs on the sheet surface. Next, from the surface photographs for the neat oil of No. 1, the roll marks can be observed and the large change of the surface appearance cannot be observed. On the other hand, from the surface photographs for the emulsion oil of No. 5, the large change of the surface appearance cannot be observed and the number of the oil pit increases slightly with increasing rolling speed. Next, from the surface photographs of the emulsion oil of No. 1, the surface appearances at all the rolling speeds are similar to those of the neat oil.

Then, in order to understand the difference between them, the comparison of the difference between surface brightnesses in neat oil and in emulsion oil among Nos. 1, 3, and 5 are shown in Fig. 4.89. In Fig. 4.89, the difference between surface brightness in neat oil and in emulsion oil can be understood clearly.

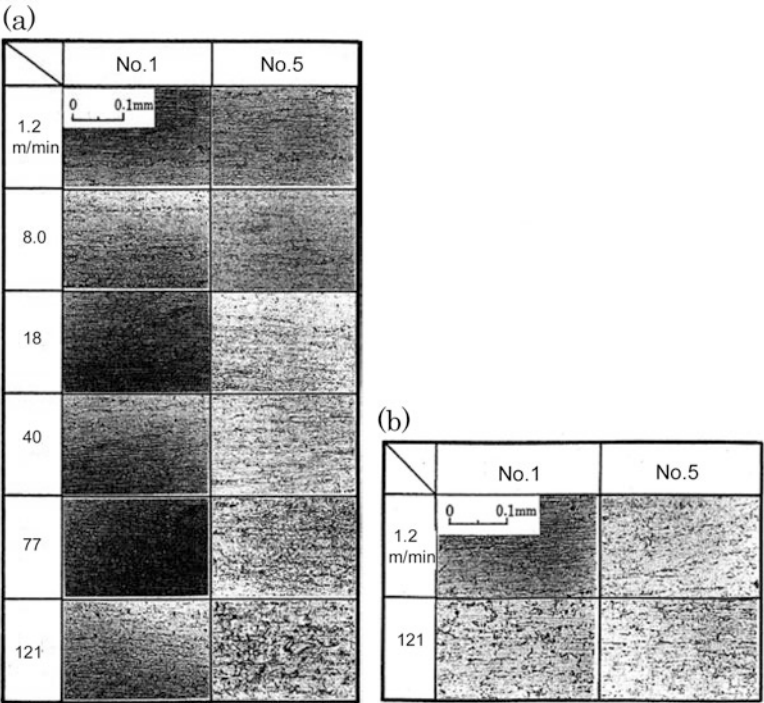


Fig. 4.88 Surface photographs of rolled sheet in neat oil (a) and emulsion oil (b)

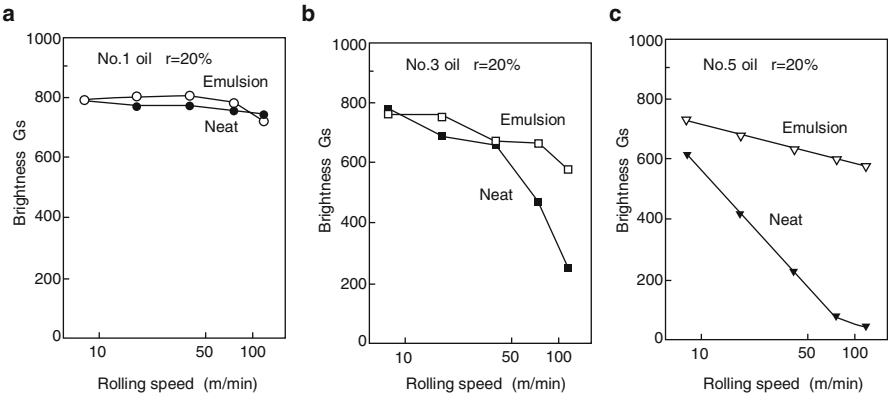


Fig. 4.89 Comparison between surface brightnesses in neat oil and in emulsion oil. (a) No. 1 oil. (b) No. 3 oil. (c) No. 5 oil

4.6.2 Effect of Tribological Conditions on Surface Appearance with Emulsion Oil

4.6.2.1 Effect of Emulsion Property on Surface Brightness

Azushima et al. [33] examined the effect of the emulsion property on the surface brightness. The experiments are carried out using the low carbon steel with a surface roughness of 0.07 μm , the SUJ-2 roll with a surface roughness of 0.01 μm and a diameter of 78 mm, and the paraffinic oils at a constant reduction of 20 % changing the rolling speed from 1.2 to 121 m/min. The properties of paraffinic oils of Nos. 1–5 used were already summarized in Table 4.13. The properties of paraffinic oils of Nos. 6–9 added are summarized in Table 4.14.

Figure 4.90 shows the relationships between surface brightness and rolling speed in the emulsion with concentrations of 3, 10, and 20 % and in the emulsion with emulsifier amounts of 1, 3, and 5 %. In Fig. 4.90a, the surface brightness decreases slightly with increasing concentration. In the lower rolling speed, the

Table 4.14 Properties of paraffinic oils used

Rolling oil	Viscosity η [cSt] (20 °C)	Emulsifier (%)	Emulsion concentration (%)	Particle size (μm)
No. 6	37.3	5	10	11
No. 7			20	11
No. 8		3		15
No. 9		1	3	21

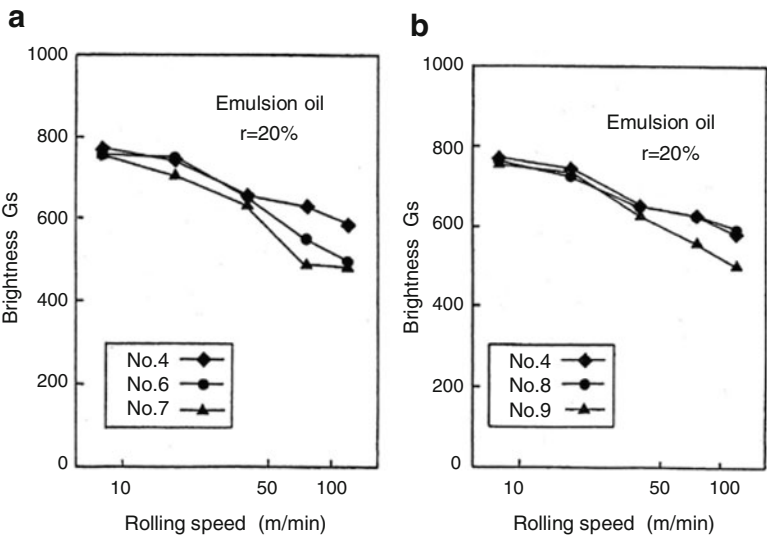


Fig. 4.90 Effect of concentration (a) and emulsifier amount (b) on surface brightness

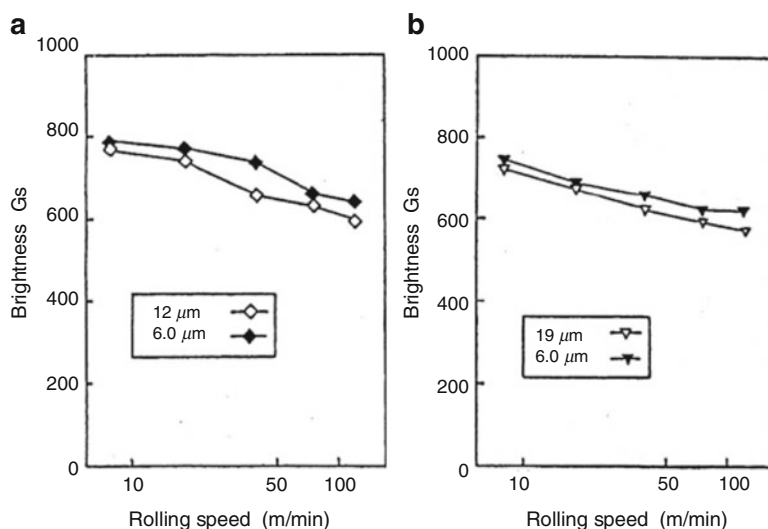


Fig. 4.91 Effect of diameter of emulsion oil particle on surface brightness. (a) No. 4 oil. (b) No. 5 oil

decrease degree is small, but in the higher rolling speed, the decrease degree becomes large. In Fig. 4.90b, in the lower rolling speed, the surface brightness is independent of the emulsifier amount, but in the higher rolling speed, the surface brightness of No. 9 oil with a concentration 1 % is lower than those of other oils.

Next, Fig. 4.91 shows the relationship between surface brightness and rolling speed changing the diameter of emulsion oil particle using No. 4 oil with 6.0 and 12 μm (a) and No. 5 oil with 6.0 and 19 μm (b). The surface brightnesses of two emulsion oils decrease with increasing diameter of the emulsion oil particle.

4.6.2.2 Effect of Oil Property on Surface Appearance

The effect of the viscosity of lubricant on the surface brightness was already shown in Fig. 4.66b. The surface brightness at each rolling speed decreases with increasing viscosity of lubricant. The difference becomes larger with rolling speed, but the difference is very small compared to the neat lubrication. Azushima et al. [33] examined the effect of the emulsion property on the surface brightness. The experiments are carried out using the low carbon steel with a surface roughness of 0.07 μm , the SUJ-2 roll with a surface roughness of 0.01 μm and a diameter of 78 mm, and the paraffinic oils at a constant reduction of 20 % changing the rolling speed from 1.2 to 121 m/min. The properties of paraffinic oils of Nos. 1–9 used were already summarized in Tables 4.13 and 4.14. The properties of paraffinic oils of Nos. 10–13 added are summarized in Table 4.15.

Table 4.15 Properties of paraffinic oils of Nos. 10–13

No.	Composition %		Viscosity η [cSt] (20 °C)	Emulsifier (%)	Emulsion concentration (%)	Saponification value (mg KOH/g)	Particle size (μm)
	Mineral oil	Ester					
5	95	0	97.4	5	3	0	3.8
10	71	24	89.2			66	6.1
11	47.5	47.5	87.6			118	8.7
12	24	71	88.5			171	12
13	0	95	89.7			225	19

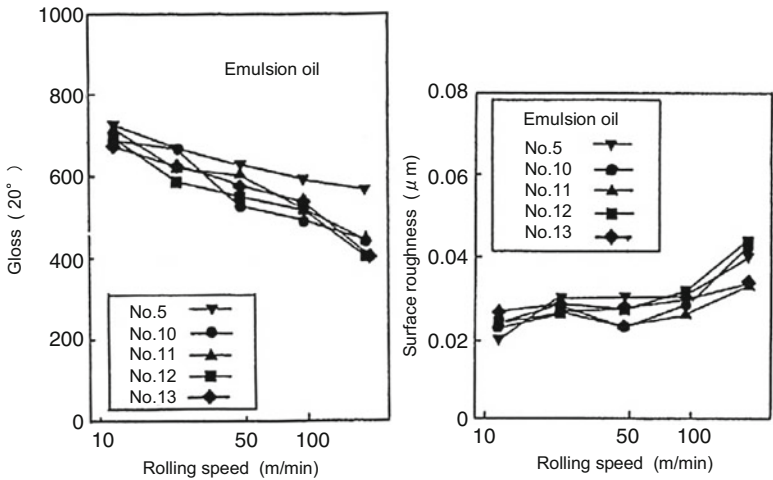
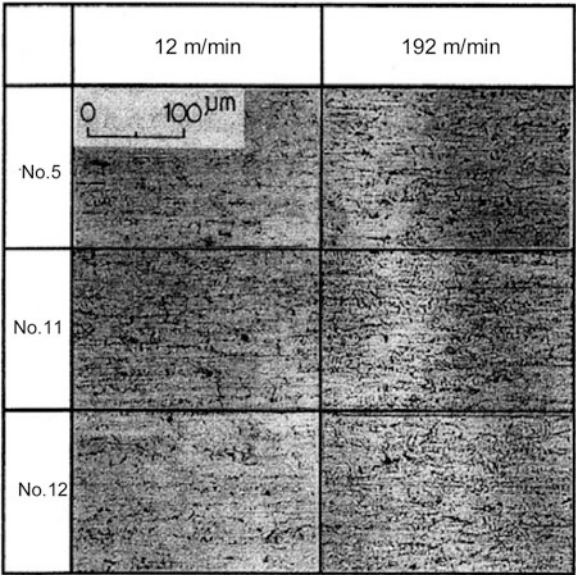


Fig. 4.92 Relationships between surface brightness and rolling speed (a) and between surface roughness (b) and rolling speed in emulsion oil changing saponification value

Figure 4.92 shows the relationship between surface brightness and rolling speed and the relationship between surface roughness and rolling speed in the emulsion oil changing the saponification value. In Fig. 4.92a, the surface brightness for each rolling speed decreases slightly with increasing saponification value. It is estimated that the oil film layer plating out by the absorption of oil with higher saponification in O/W emulsion becomes thicker, so that the inlet oil film thickness becomes thicker with increasing saponification value. Then, Fig. 4.93 shows the surface photographs of the rolled sheets. The difference of the surface photographs among Nos. 5, 11, and 12 oils in the low rolling speed cannot almost be observed, but in the high rolling speed, the oil pits on the sheet surface can be observed, and the number of oil pits increases with increasing saponification value.

Fig. 4.93 Surface photographs of the rolled sheets

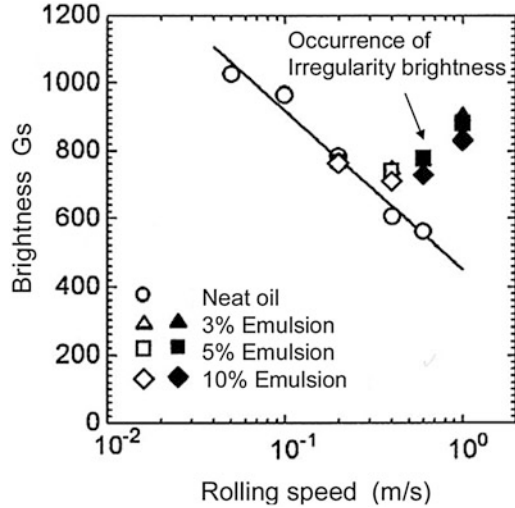


4.6.3 Surface Brightness Irregularity in Cold Sheet Rolling of Stainless Steel with O/W Emulsion

In cold sheet rolling of stainless steel, the manufacture of stainless sheets with higher brightness is desired. In order to manufacture stainless steel sheets with higher brightness, cold rolling under lower rolling speed and lower reduction using neat oils with lower viscosity and rolls with smaller diameter has been carried out. Productivity in manufacturing stainless steel sheet with higher brightness is improved using emulsion oil. However, in cold rolling of stainless steel with emulsion oil, the surface brightness irregularity on the sheet surface after rolling occurs when the rolling speed becomes higher. If the surface brightness irregularity occurs in manufacturing stainless steel with higher brightness, the rolled sheets come to the products with surface defect. Therefore, the cause of the surface brightness irregularity needs to be examined and the control system must be developed for productivity in manufacturing. Azushima et al. [34] carried out the rolling experiments of the stainless steel with O/W emulsion at various rolling speeds. In this chapter, the experimental results are shown and the cause of the surface brightness irregularity is discussed.

Rolling experiments are carried out at constant reduction of 25 % and four rolling speeds of 0.2, 0.4, 0.6, and 1.0 m/s using emulsion concentrations of 3, 5, and 10 % as the base oil of the ester compound with a viscosity of 100 cSt at 20 °C. Figure 4.94 shows the relationship between surface brightness and rolling speed in sheet rolling of stainless steel with O/W emulsion. In Fig. 4.94, the solid line shows the experimental results with neat oil.

Fig. 4.94 Relationship between surface brightness and rolling speed in sheet rolling of stainless steel with O/W emulsion



At a rolling speed of 0.2 m/s, the surface brightness after rolling with O/W emulsion is similar to that with neat oil. At a rolling speed of 0.4 m/s, the surface brightness is slightly larger than that with neat oil, and the oil starvation in emulsion rolling occurs in the inlet zone. At a rolling speed of 0.6 m/s, the surface brightness is quite larger than that with neat oil and the surface brightness irregularity on the rolled sheet surface occurs. At a rolling speed of 1.0 m/s, the surface brightness is markedly larger and the difference between them becomes bigger. The surface brightness irregularity is also observed.

At the same time, the inlet oil film thickness is estimated from the values of the surface brightness in neat oil, and consequently, the oil film thickness h_2 in O/W emulsion is calculated. On the other hand, when the starvation in cold sheet rolling with O/W emulsion occurs, the following equation is assumed from the calculated oil film thicknesses for the neat oil and the O/W emulsion:

$$h_{2c} = 10h_{1n} \quad (4.26)$$

where h_{2c} is the critical oil film thickness of h_2 when the starvation occurs and h_{1n} is the inlet oil film thickness for the neat oil when the starvation occurs.

The degree of starvation S is defined by

$$S = h_2/h_{2c} \quad (4.27)$$

It can be expected that when S exceeds a limit value, the surface brightness irregularity in cold sheet rolling of stainless steel with O/W emulsion occurs.

In order to evaluate the surface brightness irregularity, the rolling speed is accelerated from a constant initial rolling speed at a constant reduction of 15 % using 10 % emulsion of ester oil with a viscosity of 100 cSt. Figure 4.95 shows the

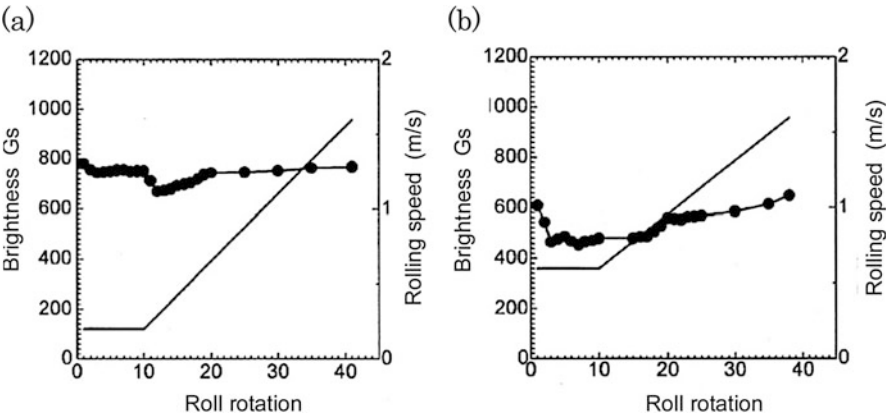


Fig. 4.95 Relationship between surface brightness and roll rotation at constant initial rolling speeds of 0.2 m/s (a) and 0.4 m/s (b)

Table 4.16 Calculated oil film thicknesses h_{2c} , h_{1n} , and h_2 for each rolling speed

Rolling speed (m/s)	h_{2c} (μm)	h_{1n} (μm)	h_2 (μm)	S (h_2/h_{2c})
0.2	0.57	0.028	0.092	0.16
0.4	1.14	0.055	0.176	0.15
0.6	1.14	0.056	0.183	0.16

relationship between surface brightness and roll rotation when the rolling speed is a constant of 0.2 m/s (a) up to ten rotations, and above ten rotations, it accelerates linearly up to 1.6 m/s and a constant of 0.4 m/s (b).

In a constant rolling speed of 0.2 m/s shown in Fig. 4.95a, the surface brightness remains constant up to ten rotations. After ten rotations, it decreases with increasing roll rotation, but above 13, it increases with increasing roll rotation. At 13 rotations, the surface brightness irregularity on the coil surface is observed. In Fig. 4.95b, the surface brightness remains constant up to ten rotations, and after ten rotations, it decreases with increasing roll rotation, but above 21 rotations, it increases with increasing roll rotation. At 21 rotations, the surface brightness irregularity on the coil surface is observed.

From the experimental result shown in Fig. 4.95, the degree of oil starvation in coil rolling is estimated. The calculated oil film thicknesses h_{2c} , h_{1n} , and h_2 for each rolling speed are summarized in Table 4.16. From the values of the calculated oil film thickness, the degrees of oil starvation S in three rolling speeds are nearly 0.16. It is estimated that the surface brightness irregularity occurs when S becomes 0.16. It is expected that the occurrence of surface brightness irregularity can be controlled using the value of the starvation degree.

4.7 Interfacial Temperature in Cold Sheet Rolling

In Sect. 2.6, the interfacial temperature between tool and workpiece in metalforming is explained generally. In this chapter, the interfacial temperature between roll and sheet in cold sheet rolling is explained.

4.7.1 Calculation of Interfacial Temperature in Cold Sheet Rolling

The mean temperature rise at the interface between roll and sheet in cold sheet rolling was explained by Azushima [35]. Figure 4.96 shows the schematic representation of the contact region of sheet rolling.

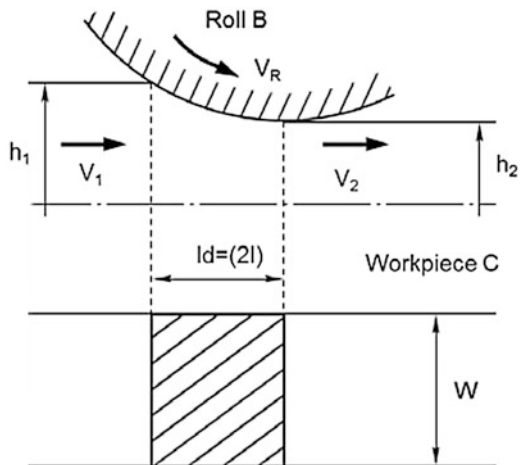
The mean temperature rise in the sheet rolling at higher rolling speeds is given by

$$T_m = \frac{1.06\ell\mu p_m \Delta V}{(V_R \ell)^{1/2}} \frac{1}{\frac{K_B}{\kappa_B^{1/2}} + \frac{K_C}{\kappa_C^{1/2}}} \quad (4.28)$$

where $\Delta V = \frac{(h_1 - h_2)(h_1 + 5h_2)}{16h_1h_2} V_R$.

Then, considering the heat generated by the plastic deformation, Eqn. (4.28) becomes the following equation:

Fig. 4.96 Schematic representation of contact region of sheet rolling



$$T_m = \frac{1.06\ell\mu p_m\Delta V + K_C\left(\frac{V_R\ell}{\kappa_C}\right)^{1/2}T_{mW}}{\left(\frac{1}{V_R\ell}\right)^{1/2}\left(\frac{K_B}{\kappa_B^{1/2}} + \frac{K_C}{\kappa_C^{1/2}}\right)}$$

(4.29)

where T_{mW} is the heat generated by the plastic deformation and is given by Eqn. (2.3)

4.7.2 Temperature Measurement of Roll Surface by Thermocouple

Azushima et al. [36] measured the surface temperature of roll during rolling. In order to measure the surface temperature of roll, the new sliding-rolling type tribo-simulator shown in Fig. 3.22 is used. Figure 4.97 shows the measurement system of roll surface temperature (a) and the detail of the measuring section (b). Three thermocouples are embedded in the holes which are situated at the distances of 1.5, 3.0, and 4.5 mm from the surface in the roll as shown in Fig. 4.97b. The tip of thermocouple arrives to the roll center in a distance of 17.5 mm from the side edge. The temperatures are measured by a recorder connected through a slip ring from the thermocouples.

The sliding-rolling experiments are carried out using the low carbon steel and three lubricants at rolling speeds of 12, 36, 60, 90, and 120 m/min, at rolling distances of 30 and 80 m and at reductions of 5–16 %. The compositions of lubricants used are shown in Table 4.17.

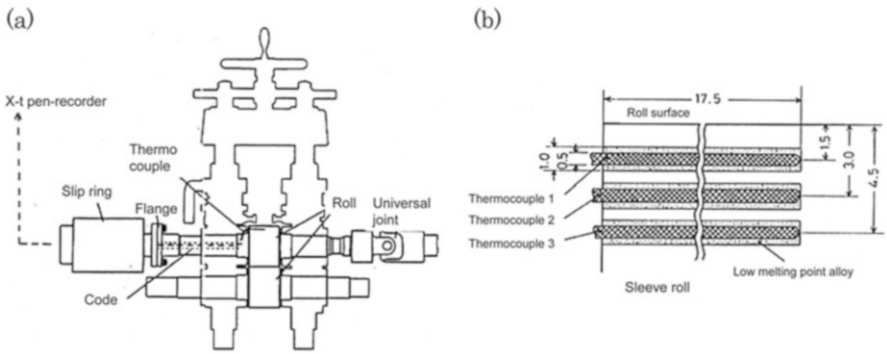


Fig. 4.97 Measurement system of roll surface temperature (a) and detail of measuring section (b)

Table 4.17 Composition of lubricant used

	Lub. A	Lub. B	Lub. C
Synthetic ester A	95	–	20
Synthetic ester B	–	95	–
Mineral oil	–	–	75
Emulsifying agent	5	5	5

Fig. 4.98 Measured temperatures of three thermocouples of 1, 2, and 3

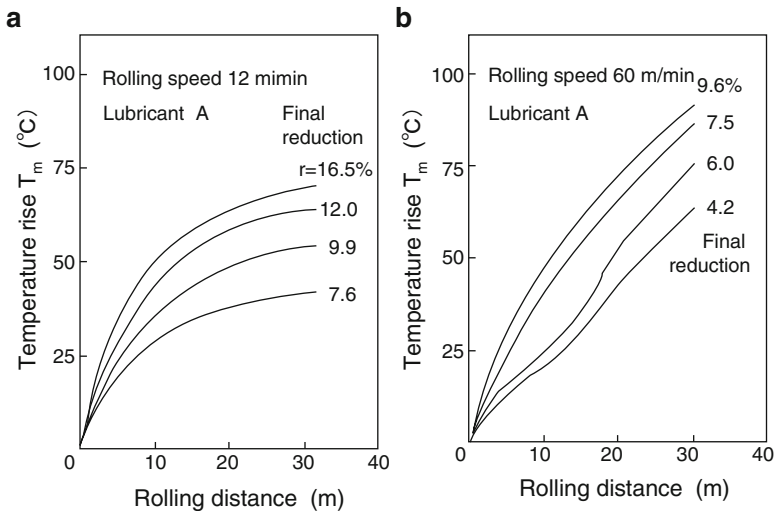
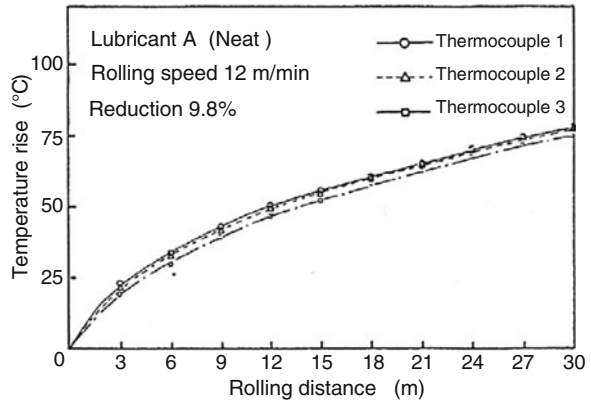


Fig. 4.99 Relationship between temperature rise and rolling distance at rolling speeds of 12 m/min (a) and 60 m/min (b)

Figure 4.98 shows the measured temperatures of three thermocouples of 1, 2, and 3 in the rolling with the neat oil of lubricant A at a reduction of 9.8 % and a rolling speed of 12 m/min. In Fig. 4.98, the measured temperatures are lower in the order of thermocouples 1, 2, and 3 and the difference is small. Therefore, the measured result of the thermocouple 1 is used as a value of temperature rise.

Next, the effect of the rolling speed on the temperature rise is examined. Figure 4.99 shows the relationship between temperature rise and rolling distance at rolling speeds of 12 m/min (a) and 60 m/min (b) changing the reduction. In Fig. 4.99, both temperature rises increase with increasing reduction. In a rolling speed of 12 m/min, the temperature rise is saturated at a rolling distance of 30 m, but in a rolling speed of 60 m/min, the temperature is not saturated.

Fig. 4.100 Relationship between temperature rise and rolling distance changing rolling speed at final reduction of 7.5 %

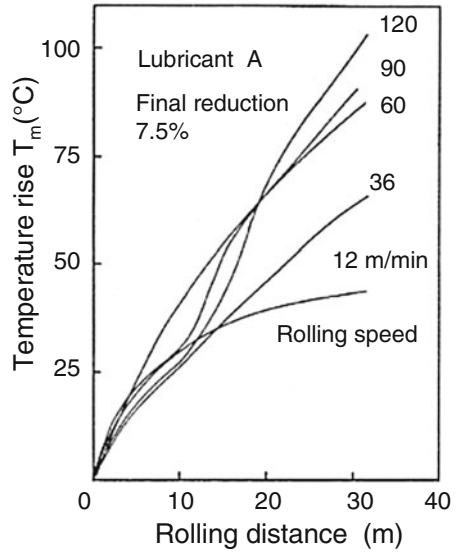
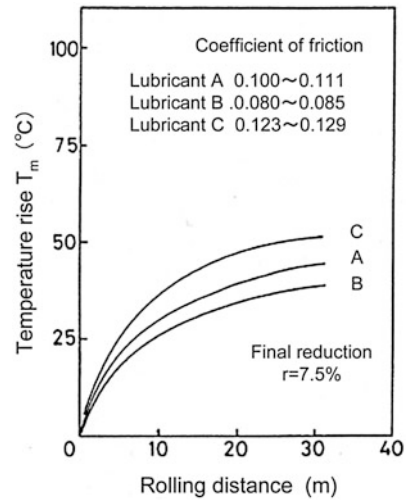


Fig. 4.101 Relationship between temperature rise and rolling distance using three lubricants of A, B, and C



Then, Fig. 4.100 shows the relationship between temperature rise and rolling distance changing the rolling speed at a final reduction of 7.5 %. The temperature rise over a rolling distance of 10 m increases with increasing rolling speed. Up to a rolling distance of 10 m, the temperature rises are almost independent of the rolling speed.

Then, Fig. 4.101 shows the relationship between temperature rise and rolling distance using three lubricants of A, B, and C at a rolling speed of 12 m/min and a

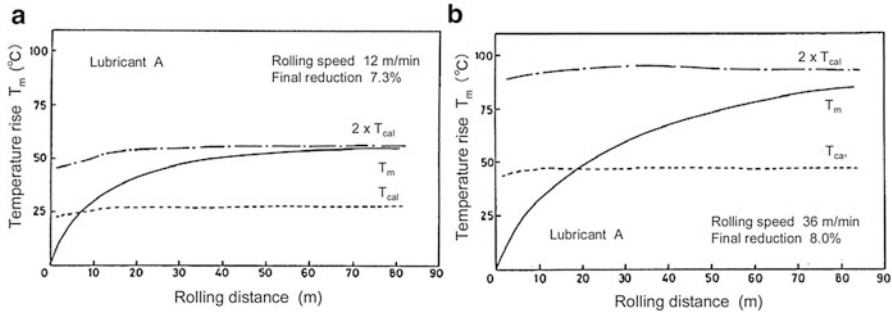


Fig. 4.102 Relationships between temperature rise and rolling distance measured and calculated at rolling speed of 12 m/min (a) and 36 m/min (b)

final reduction of 7.5 %. The temperature rise depends on the lubricant, and it decreases with decreasing coefficient of friction. Namely, the temperature rise decreases in the order of lubricants C, A, and B.

Next, the measured temperature rises are compared to the calculated temperature rises by Eqn. (4.29). Figure 4.102 shows the relationships between measured and calculated temperature rises and rolling distance in the rolling experiments at a rolling speed of 12 m/min and a final reduction of 7.3 % (a) and at a rolling speed of 36 m/min and a final reduction of 8.0 % (b). In a rolling speed of 12 m/min of Fig. 4.102a, the measured temperature rise increases with increasing rolling distance up to a rolling distance of 30 m/min. Above 30 m/min, it increases gradually and becomes constant. The constant value of temperature rise is equal to twice of the calculated temperature rise. On the other hand, at a rolling speed of 36 m/min of Fig. 4.102b, the measured temperature rise increases with increasing rolling distance up to a rolling distance of 60 m. Above 60 m, it increases gradually and will become constant. The constant value of temperature rise will be also equal to twice of the calculated temperature rise.

4.7.3 Temperature Measurement of Interface Between Roll and Sheet by Thermoelectric Method

Figure 4.103 shows the measurement system of interfacial temperature (a) and the detail of the measuring section of upper roll (b) in the new sliding-rolling-type tribo-simulator shown in Fig. 3.22. Jimbo et al. [37] measured the interfacial temperature between roll and sheet by thermoelectric method. In order to measure the interfacial temperature, the thermocouple circuit of the two points of the upper roll and the sheet of the tribo-simulator is constituted as shown in Fig. 4.103a. The ring roll is insulated from the sleeve shaft of the upper roll as shown in Fig. 4.103b, and the interfacial temperature is measured by a recorder connected through a slip ring from the insulated ring roll.

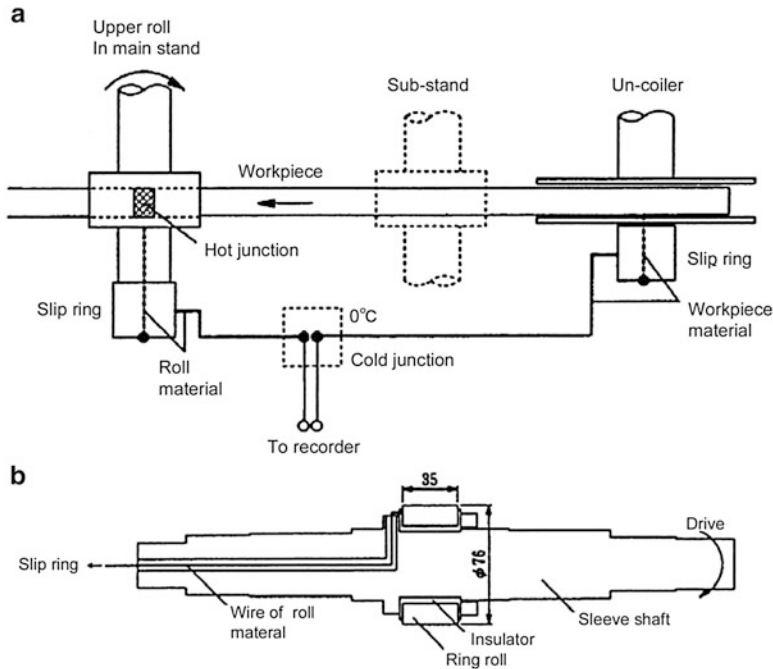


Fig. 4.103 Schematic representation of measurement system of interfacial temperature (a) and detail of measuring section of upper roll (b)

The sliding-rolling experiments are carried out using the low carbon steel and the paraffinic oil with a viscosity of $80 \text{ mm}^2/\text{s}$ at upper roll speeds of 24, 48, 72, 107, and 143 m/min. The neat oil of paraffinic oil is used in sliding-rolling. Figure 4.104 shows examples of the relationships between voltage, load, torque, and rolling time.

From Fig. 4.104, it can be checked that the stable data are obtained. Figure 4.105 shows the relationships between interfacial temperature and rolling time (a) and coefficient of friction and rolling time (b) changing the roll speed at a reduction of 3 %. At a roll speed of 24 m/min, the interfacial temperature is a constant of 60°C during sliding-rolling, but in the higher roll speeds, they increase gradually with increasing roll speed. At a roll speed of 143 m/min, the interfacial temperature rises from 90 to 105°C , and at the same time, the coefficient of friction decreases with increasing roll speed. It is found that the interfacial temperature depends on the roll speed and the coefficient of friction.

Then, Fig. 4.106 shows the relationships between interfacial temperature and rolling time (a) and coefficient of friction and rolling time (b) changing the reduction at a roll speed of 24 m/min. At a roll speed of 24 m/min, the interfacial temperature is independent of the rolling time and the reduction. The interfacial temperature for each reduction is constant during sliding-rolling, and the constant value increases with increasing reduction. The coefficient of friction for each reduction is also constant, and the value increases slightly with increasing reduction.

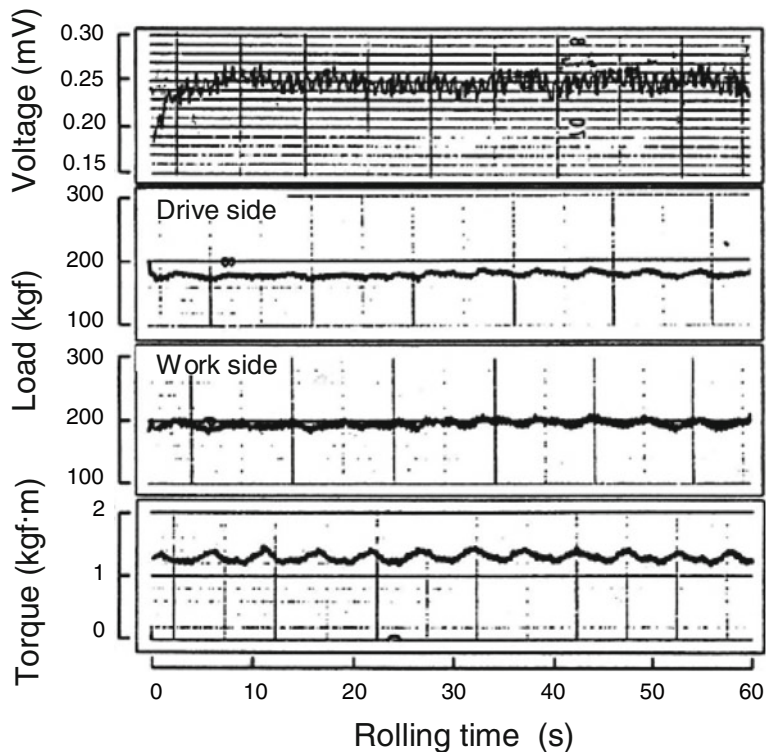


Fig. 4.104 Example of measured data of voltage, load, and torque in rolling at reduction of 3.1 % and roll speed of 24 m/min

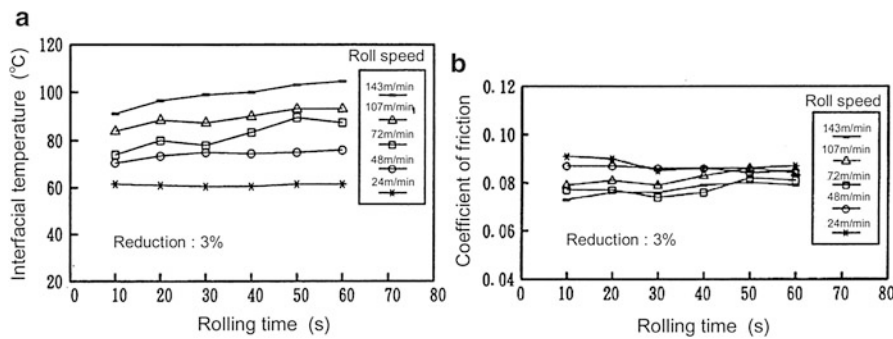


Fig. 4.105 Relationships between interfacial temperature and rolling time (a) and coefficient of friction (b) and rolling time changing

Next, Fig. 4.107 shows the same relationship in a roll speed of 143 m/min. At a roll speed of 143 m/min, the interfacial temperature for each reduction increases gradually with increasing rolling time, and it increases with increasing reduction.

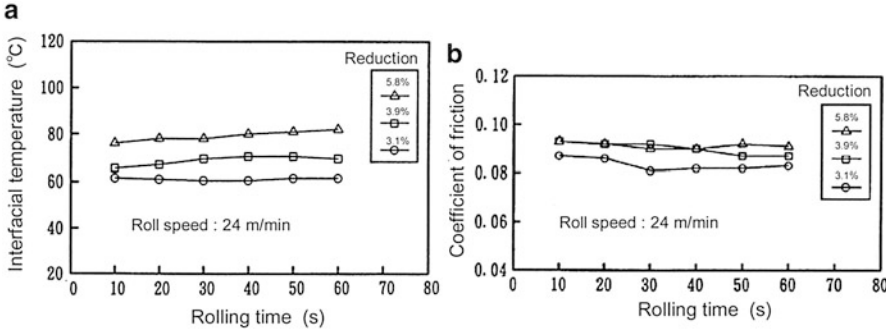


Fig. 4.106 Relationships between interfacial temperature and rolling time (a) and coefficient of friction and rolling time (b) changing reduction at roll speed of 24 m/min

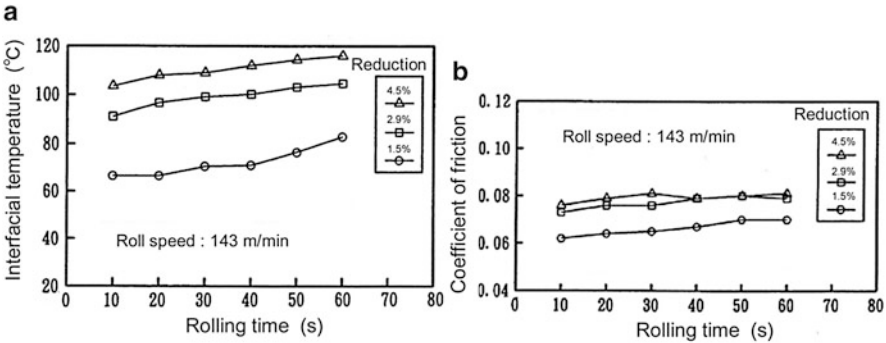


Fig. 4.107 Relationships between interfacial temperature and rolling time (a) and coefficient of friction and rolling time (b) changing the reduction at roll speed of 143 m/min

The coefficient of friction for each reduction increases slightly with increasing rolling time and it increases with increasing reduction.

Next, the interfacial temperature when the friction pickup occurs is examined. Figure 4.108 shows the interfacial temperature when the friction pickup occurs at roll speeds of 24 m/min (a) and 143 m/min (b). The black mark indicates the occurrence of friction pickup. At a roll speed of 24 m/min, the friction pickup occurs at a rolling time of 60 s in a reduction of 7.6 % and at a rolling time of 40 s in a reduction of 8.8 %. Both of these interfacial temperatures are about 90 °C. At a roll speed of 143 m/min, the friction pickup occurs at a rolling time of 60 s in a reduction of 5.3 % and at a rolling time in a reduction of 5.9 %. Both of these interfacial temperatures are about 130 °C.

Then, Fig. 4.109 shows the relationship between interfacial temperature and rolling speed at the occurrence of the friction pickup. From Fig. 4.109, up to 72 m/min, the interfacial temperature at the occurrence of the friction pickup increases with increasing roll speed. Above 72 m/min, the interfacial temperature increases

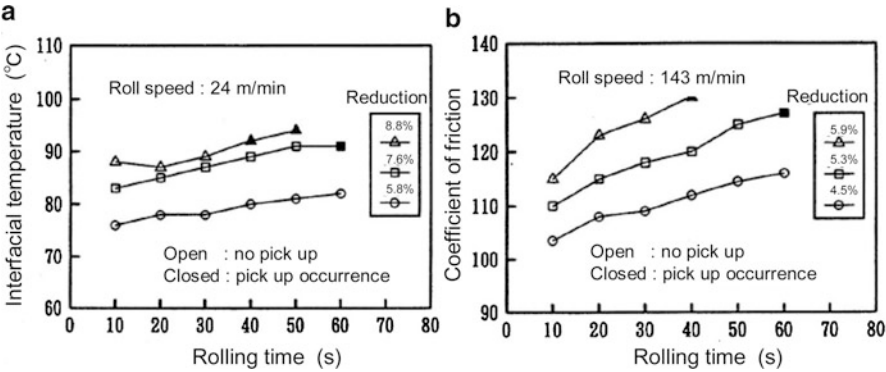
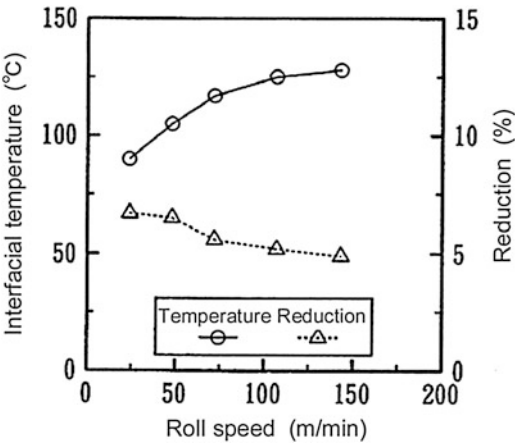


Fig. 4.108 Interfacial temperature when the friction pickup occurs at roll speeds of 24 m/min (a) and 143 m/min (b)

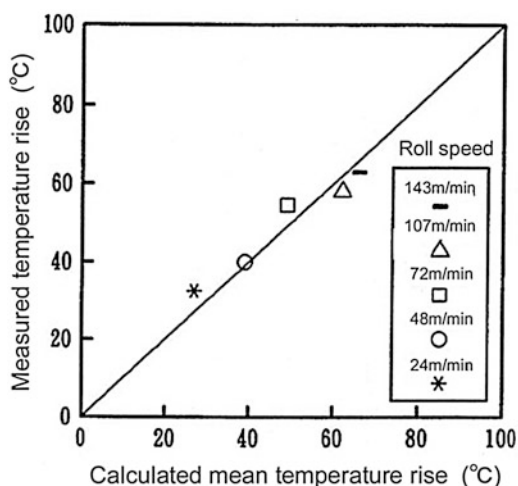
Fig. 4.109 Limitation line of occurrence of friction pickup



gradually, and over 107 m/min, it becomes constant. When the interfacial temperature above 100 m/min is constant, it is estimated that the cause is due to the heat type. On the other hand, it is estimated that the cause in the lower roll speed is due to the cold welding.

The interfacial temperature rise consists of the temperature rise by the friction energy and the temperature rise by the plastic deformation energy. The temperature rise by the friction energy is obtained using Eqn. (4.28). Figure 4.110 shows the relationship between measured temperature rise corrected and the calculated mean temperature rise by Eqn. (4.28). The measured temperature is corrected by the strip temperature before rolling and the temperature rise by the plastic deformation energy by Eqn. (4.29). From Fig. 4.110, it can be understood that the measured temperatures corrected are in good agreement with the calculated temperature rises. From these results, it is confirmed that the mean temperature rise calculated from

Fig. 4.110 Comparison of measured temperature rise and calculated temperature rise



Eqn. (4.29) in cold sheet rolling can evaluate the interfacial temperature with high accuracy, and Eqn. (4.28) is significantly effective in order to estimate the temperature rise by the friction energy.

4.8 Friction Pickup (Heat Streak)

4.8.1 Friction Pickup in History

If the friction pickup occurs in the actual cold sheet rolling mill, a part of steel sheet surface adheres on the roll surface as shown in Fig. 4.111a, and then the steel sheet with the surface fault is manufactured as shown in Fig. 4.111b. In the 1980s in Japan, the many researches concerning the friction pickup in cold sheet rolling were carried out in Japanese steel-making companies.

Mase et al. [38] evaluated the antiseizure property of four rolling oils shown in Table 4.18. As shown in Table 4.18, they reported that the order of the antiseizure property of four rolling oils obtained by the four ball-type testing machine is different from that obtained in actual mill. Therefore, in order to evaluate the antiseizure property of the rolling oils instead of the four ball-type testing machine, they used the Bowden-Leven testing machine. Figure 4.112 shows the relationship between coefficient of friction and sliding number of the four rolling oils and other oils. They showed that the antiseizure property of the rolling oils could be evaluated by the sliding number when the coefficient of friction became 0.15 using Bowden and Leven sliding testing machine.

However, in these results, it can be understood that the good correlation between the actual mill and the fundamental testing machine can be obtained among the

Fig. 4.111 Photographs of roll surface (a) and sheet surface (b) when friction pickup occurs in actual mill

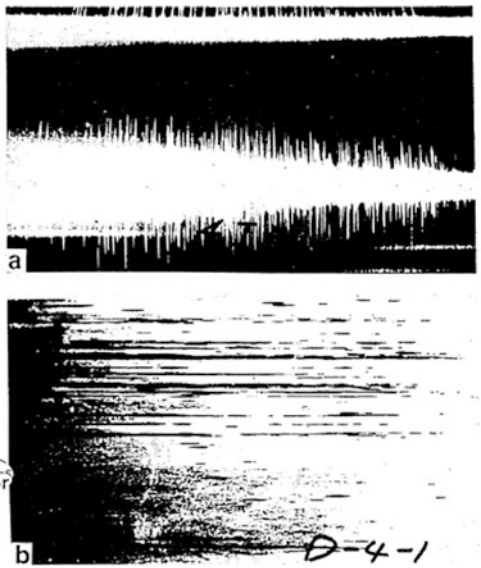


Table 4.18 Composition and properties of rolling oils evaluated [38]

Rolling oil	Oil film strength (kg/cm ²)	Anti-heat scratch ranking in actual equipment
Mineral oil A	4.0	3
Mineral oil B	8.0	4
Mixed oil A	6.0	2
Tallow oil A	7.5	1

Fig. 4.112 Relationship between coefficient of friction and sliding number of four rolling oils [38]

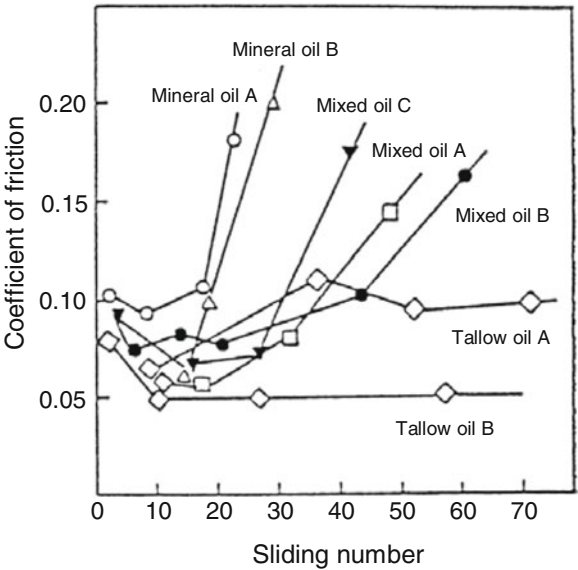
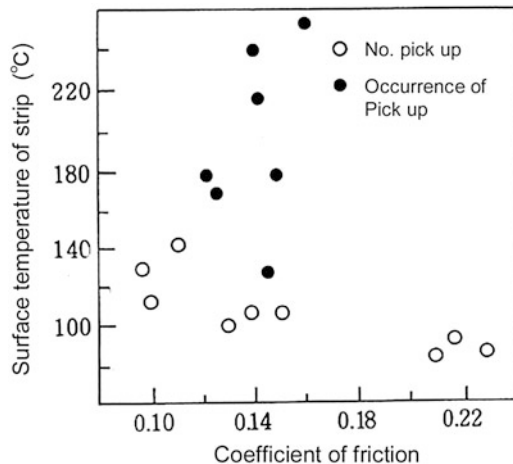


Fig. 4.113 Relationship between surface temperatures of strip and coefficient of friction [39]



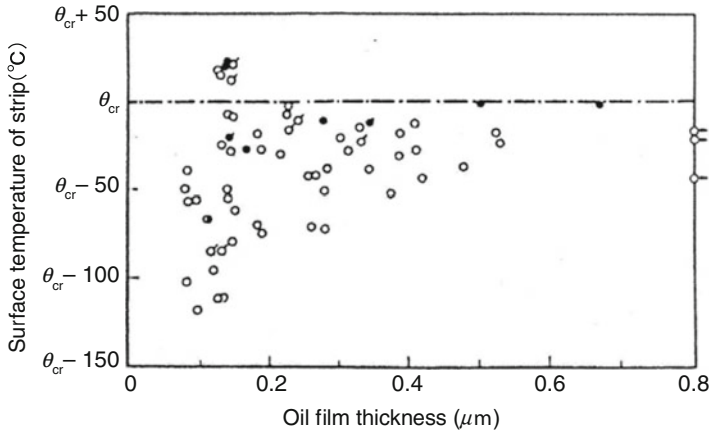


Fig. 4.114 Relationship between surface temperature of sheet and oil film thickness in actual cold sheet rolling mill [40]

4.8.2.1 Evaluation of Antiseizure Property of Tallow Oil

The antiseizure property of the tallow oil was evaluated by Azushima et al. [41]. The sliding-rolling experiments are carried out using the low carbon steel coil with a surface roughness of $0.5 \mu\text{m } R_{\text{max}}$, the SUJ-2 roll with a constant surface roughness, and the 3 % emulsion of the tallow oil at roll speeds of 12, 24, 36, 48, 60, 72, 96, 120, and 144 m/min. The experiments for evaluation of the friction pickup are carried out changing the reduction at a constant rolling speed by the occurrence of friction pickup.

Figure 4.115 shows the limit curve of friction pickup in cold sheet rolling changing the rolling speed and the reduction. The friction pickup occurs with increasing roll speed and reduction. Namely, the friction pickup occurs with increasing interfacial temperature and with decreasing oil film thickness. It is estimated that the seizure in cold rolling also occurs at the critical interfacial temperature condition or at the critical oil film thickness condition.

Figure 4.116 shows the photographs of roll surface after rolling when the friction pickup occurs in regions of C-I and C-II. Next, Fig. 4.117 shows the photographs of workpiece surface during rolling when the friction pickup occurs in the regions of C-I (a) and C-II (b). From Figs. 4.116 and 4.117, it is found that the generation cause of the friction pickup in C-I is due to the critical oil film thickness condition and the cause in C-II is due to the critical interfacial temperature condition.

Next, the measured results of the roll surface temperature after rolling by the thermocouple are shown in Fig. 4.118. The surface temperatures of the roll are measured by the thermocouple which is pressed against the upper roll surface at the exit side. The black marks indicate the occurrence of the friction pickup. The surface temperature for each roll speed increases with increasing reduction. The degree of the temperature rise becomes larger with increasing roll speed. In the

Fig. 4.115 Limit curve of friction pickup in cold rolling

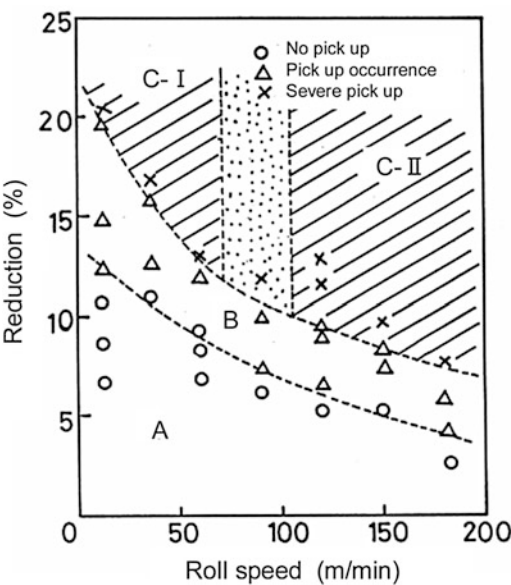


Fig. 4.116 Photographs of roll surface after rolling when friction pickup occurs. (a) C-I. (b) C-II

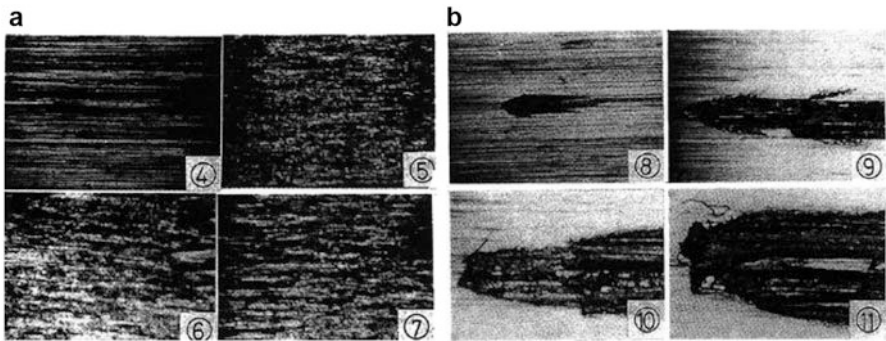
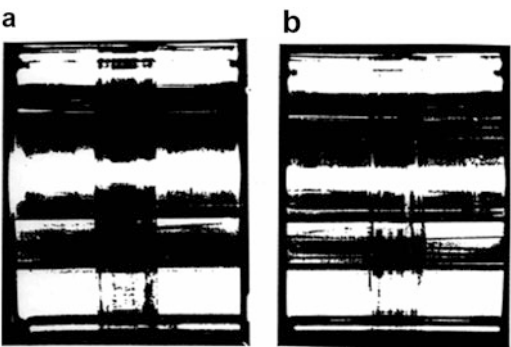


Fig. 4.117 Photographs of workpiece surface during rolling when friction pickup occurs. (a) C-I. (b) C-II

Fig. 4.118 Relationship between roll surface temperature after rolling by thermocouple and reduction changing roll speed

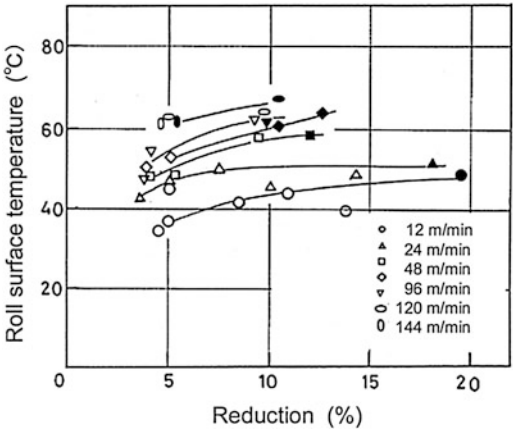
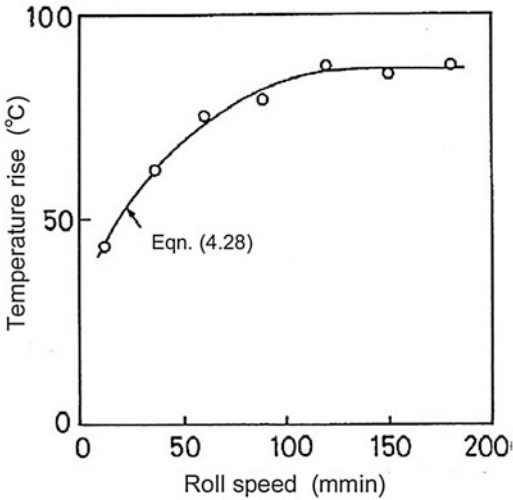


Fig. 4.119 Calculated results of interfacial temperature when seizure occurs



region C-I of Fig. 4.115, the surface temperature at the occurrence of friction pickup increases with increasing roll speed, but in the region C-II, it becomes constant.

Then, the results of the temperature rise calculated by Eqn. (4.28) when the friction pickup occurs are shown in Fig. 4.119. From the results in Figs. 4.118 and 4.119, in the higher roll speed (C-II), the interfacial temperature rise remains constant so that it is found that friction pickup occurs at a critical interface temperature. The friction pickup is called the heat type. On the other hand, in the lower roll speed (C-I), the interfacial temperature rise depends on the roll speed and decreases with decreasing roll speed. The friction pickup is called the cold welding type. It is suspected that the roll surface temperatures measured in Fig. 4.118 are quite lower than the interfacial temperature as shown in Fig. 4.119.

It must be considered that the temperature rises for the friction energy calculated by Eqn. (4.28) must be quite correct considering the temperature rise for the plastic deformation energy of the sheet expressed by Eqn. (4.29).

4.8.2.2 Evaluation of Antiseizure Property of Commercial Oils

The antiseizure property of the commercial oils is evaluated using the sliding-rolling-type tribo-simulator by Azushima et al. [42]. The sliding-rolling experiments are carried out using the low carbon steel coil with a surface roughness of $0.5\text{ }\mu\text{m } R_{\text{max}}$, the SUJ-2 roll with a constant surface roughness, and the commercial oils at roll speeds of 12, 36, 60, 96, 120, and 144 m/min changing the reduction. Table 4.19 summarizes the composition and property of commercial oils. The commercial oils are the mixed oils of mineral oil and ester oil with different viscosities and saponification values.

Figure 4.120 shows the relationship between coefficient of friction and roll speed (a) and the relationship between limitation reduction at occurrence of friction pickup and roll speed (b). From Fig. 4.120, the coefficients of friction of the

Table 4.19 Composition and property of commercial oils

No.	Composition (%)						Properties	
	Mineral oil	Ester	Oiliness agent	EP agent	Emulsifier	Another additive	Viscosity (50 °C: cSt)	Saponification value (mg KOH/g)
A	62	23	1.5	0.5	3.0	10.0	9.7	49
B	44	48	1.5	—	1.5	5.0	11.7	90
C	32	45	10.0	2.0	6.0	5.0	41.5	112

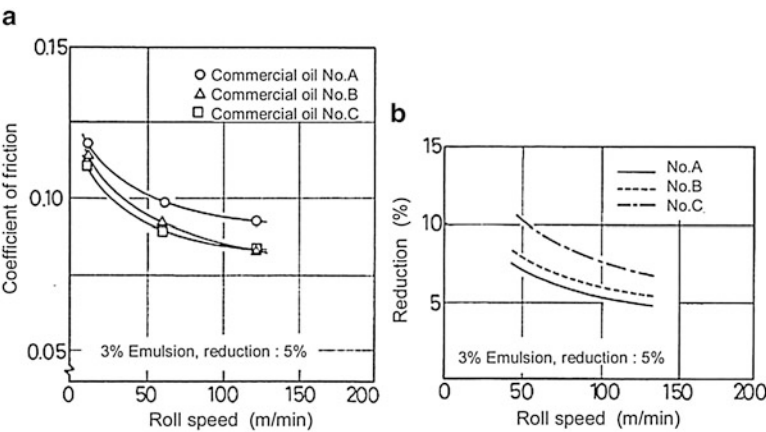


Fig. 4.120 Relationship between coefficient of friction and roll speed (a) and relationship between limitation reduction and roll speed (b)

commercial oils decrease in the order of A, B, and C oils, and the limitation reductions become larger in the order of A, B, and C oils. Consequently, it is recognized that the temperature rises also become higher in the order of A, B, and C. The order is equal to that in the actual rolling mill.

4.8.3 Development of Commercial Oil with High Antiseizure Property

In order to increase the productivity in cold sheet rolling mill, the rolling oils with the high antiseizure property must be developed. Azushima et al. [43] developed the evaluation system for using the newly developed rolling oil in actual cold sheet rolling mill and developed the new commercial oil with high antiseizure property. The flow chart of evaluation system for calculating the maximum rolling speed for the new developed oil is shown in Fig. 4.121.

Table 4.20 summarizes the composition (a) and the properties (b) of the conventional oil A and the developed oil B. In comparison with the conventional oil, the developed oil has a high antiseizure property and a high cleanliness. Table 4.21 summarizes the cleanliness after annealing.

From Table 4.21, it is found that the cleanliness of the developed oil after annealing is equal to that of the conventional oil with high cleanliness. Figure 4.122 shows the relationships between coefficient of friction and roll speed of A and B oils (a) and the relationships between limitation reduction at occurrence of friction pickup and roll speed of A and B oils (b). The coefficient of friction of the

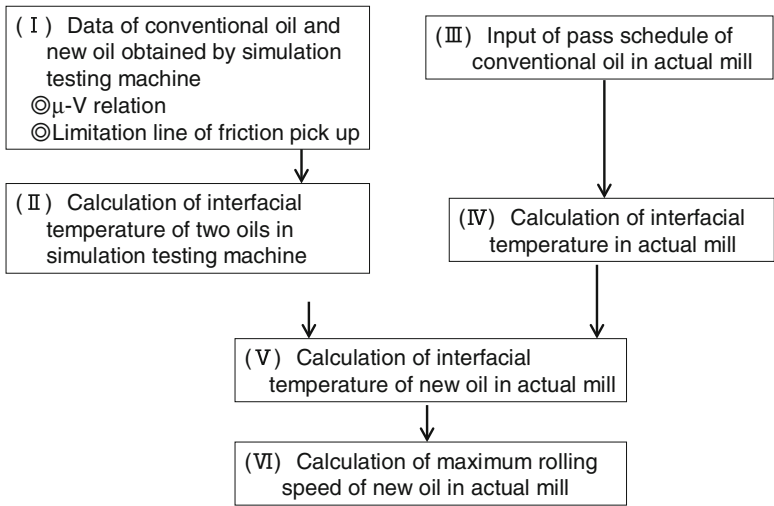


Fig. 4.121 Flow chart of evaluation system for calculating maximum rolling speed for new developed oil

Table 4.20 Compositions (a) and properties (b) of conventional oil A and developed oil B

(a) Compositions		
Compositions (%)	Conventional oil A	Developed oil B
Tallow	30	–
Wax oxide	–	10
Monoester	10	–
Tri-ester A	–	40
Tri-ester B	–	10
Mineral oil	55	35
MC improver	3.5	2.0
Oiliness agent	3.0	–
EP agent	1.0	1.0
VI improver	2.0	–
Emulsifier	1.5	1.5
(b) Properties		
Properties	Conventional oil A	Developed oil B
Viscosity (cSt at 40 °C)	18	24
Acid value (mg KOH/g)	12	5
Saponification value (mg KOH/g)	86	112

Table 4.21 Cleanliness after annealing of conventional oil A and developed oil B

Test methods	Conventional oil A		Developed oil B	
	Oil rolling	Water rolling	Oil rolling	Water rolling
Cleanliness after annealing at 600 °C	43.0	38.5	44.7	43.2
Cleanliness after annealing at 680 °C	51.0	44.3	50.3	49.6

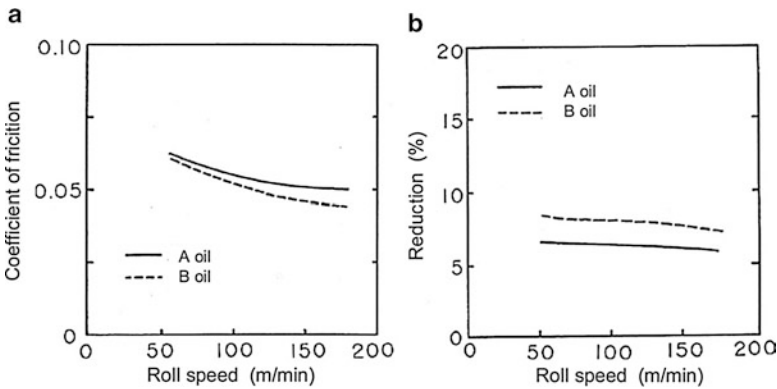


Fig. 4.122 Relationships between coefficient of friction and roll speed (a) and between limitation reduction and roll speed (b) of A and B oils

developed oil is smaller than that of the conventional oil by 0.003 in the higher roll speed of the actual rolling mill. The limitation reduction at the occurrence of friction pickup of the developed oil is larger than that of the conventional oil by 2 %. The results of (I) in the evaluating system are obtained.

The temperature rises of A and B oils at the interface between contact surfaces are calculated from these experimental data using Eqn. (4.28). Figure 4.123 shows the relationships between temperature rise and rolling speed of the conventional oil A and the developed oil B.

Up to a rolling speed of 120 m/min, the temperature rise increases gradually with increasing rolling speed, and above 120 m/min, it almost remains constant. The difference of the temperature rise between A and B oils in the region of these rolling speeds is 3 °C as shown in Fig. 4.123. The result the evaluating system (II) is obtained. Next, the pass schedule in actual rolling mill of the evaluating system (III) is summarized in Table 4.22. In the pass schedule in Table 4.22, the friction pickup occurs at No. 4 stand. In the evaluating system (IV), the temperature rise is calculated, and the value of 93.5 °C is obtained. If the developed oil is used in the actual rolling mill, the temperature rise will be 96.5 °C (V). The rolling speed at the No. 4 stand is back-calculated using the temperature rise of 96.5 °C and the rolling speed at the occurrence of friction pickup increases from 900 to 1100 m/min.

Fig. 4.123 Relationships between temperature rise and rolling speed of conventional oil A and developed oil B

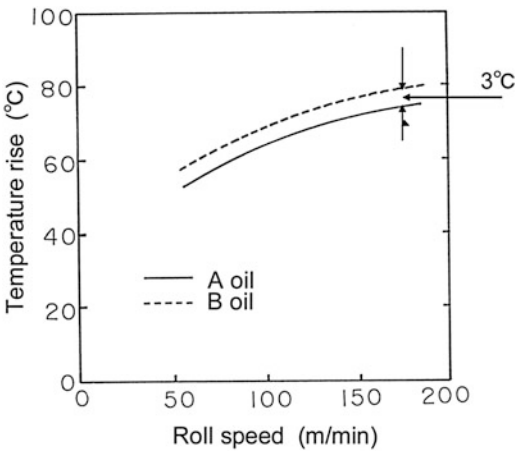
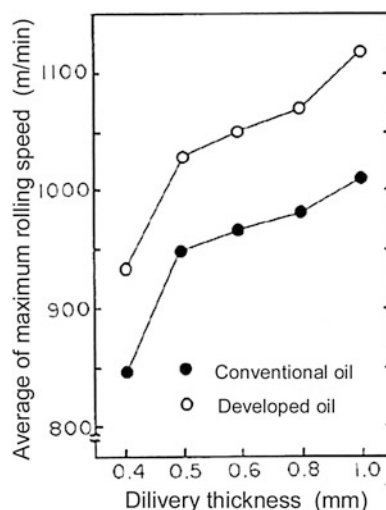


Table 4.22 Pass schedule for the high strength steel in actual rolling mill

STD	Roll diameter (mm ϕ)	Exit thickness (mm)	Reduction (%)	Mean pressure (kgf/mm ²)	Rolling speed (m/min)
No. 1	600	2.4	20	80	350
No. 2	600	1.8	25	90	500
No. 3	650	1.25	30	100	700
No. 4	650	0.9	30	110	900
No. 5	650	0.8	10	115	1000

Fig. 4.124 Comparison between maximum rolling speed of conventional oil A and developed oil B at various delivery thickness in actual mill



It is expected that the maximum rolling speed of final stand increases from 1000 to 1190 m/min (VI).

Later, the developed oil is used in the actual rolling mill instead of the conventional oil. The performance in the actual rolling mill with the developed oil is shown in Fig. 4.124. When the developed oil is used, the stable operation is carried out in the rolling speed with increase of 10 %.

4.8.4 *Estimation of Antiseizure Property in Cold Sheet Tandem Mill of Stainless Steel*

In order to manufacture the strip with high productivity in cold rolling of stainless steel, tandem mills have been used. Under such a circumstance, the tribological problems such as the friction pickup and so on occur. The evaluating system developed was used in order to evaluate the antiseizure property in cold sheet tandem mill of stainless steel by Azushima et al. [44].

4.8.4.1 *Evaluation of Antiseizure Property by Sliding-Rolling-Type Tribo-Simulator*

The sliding-rolling experiments are carried out using the SUS430 stainless steel sheet with a smooth surface, the SUJ-2 roll with a surface roughness of $0.05 \mu\text{mRa}$, and 10 % emulsion of the two commercial oils at roll speeds of 24, 48, and 96 m/min changing the reduction. The sliding-rolling experiments are carried out changing the reduction at a constant rolling speed until the friction pickup occurs. In the

Table 4.23 Properties of commercial oils used

Lubricant	Viscosity (cSt:40 °C)	Acid value (mg KOH/g)	Saponification value (mg KOH/g)
A	21.0	0.7	19
B	19.0	12.0	281

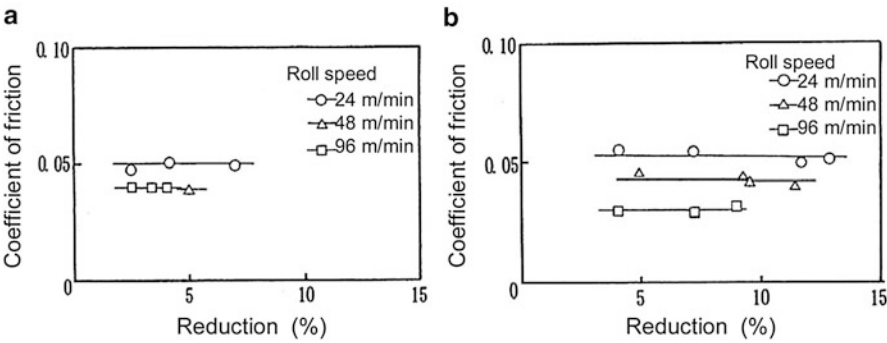
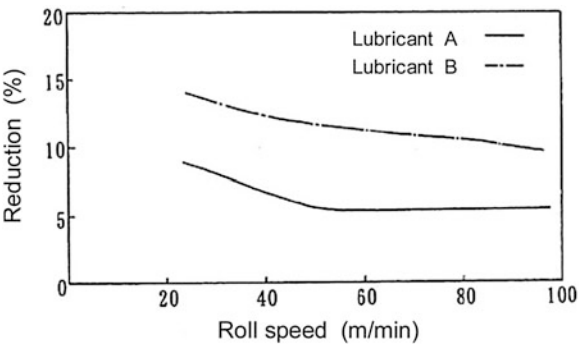


Fig. 4.125 Relationship between coefficient of friction and reduction for commercial oil A (a) and commercial oil B (b)

Fig. 4.126 Relationships between limitation reduction and roll speed for commercial oil A and commercial oil B

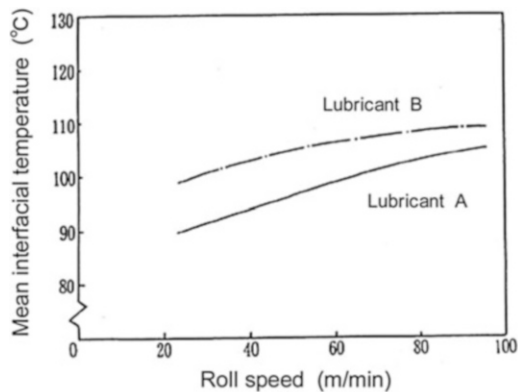


low carbon steel, the slip ratio of the sheet speed to the roll is 1/10, but since in the stainless steel sheet the friction pickup easily occurs compared to the low carbon steel sheet, the ratio is increased to 4/10. Table 4.23 summarizes the properties of commercial oils used.

Figure 4.125 shows the relationship between coefficient of friction and reduction for the commercial oil A (a) and the commercial oil B (b). The coefficients of friction in the roll speeds of 24, 48, and 96 m/min for commercial oils are independent of the reduction, and they are constant. They decrease with increasing roll speed.

Next, Fig. 4.126 shows the relationships between limitation reduction and roll speed for the commercial oil A and the commercial oil B. The limitation reductions

Fig. 4.127 Relationship between mean interfacial temperature and roll speed for commercial oils A and B



for two commercial oils decrease with increasing roll speed up to a roll speed of 50 m/min, and above 50 m/min, they become almost constant. The limitation reduction for the commercial oil B is larger than that for the commercial oil A by 5 % in the higher roll speed above 50 m/min.

Then, the mean interfacial temperature during sliding-rolling is calculated from these experimental data. The mean interfacial temperature consists of the temperature rise by the friction energy, the temperature rise by the plastic deformation energy, and the sheet and roll temperatures in the inlet region, and it is derived by the next equation:

$$T_m = \frac{1}{4.24K_w + K_r \left(\frac{V_r \ell}{\kappa_r} \right)} \left\{ 4\ell\mu p_m \Delta V + 3.76K_r \left(\frac{V_r \ell}{\kappa_r} \right)^{1/2} T_r^0 + 4.24K_w (T_w^0 + T_p) \right\} \quad (4.30)$$

where T_r^0 is the roll temperature in the inlet region, T_w^0 is the workpiece temperature in the inlet region, and T_p is the temperature rise by the plastic deformation energy.

The mean interfacial temperatures T_m are calculated from Eqn. (4.30) using the experimental data. Figure 4.127 shows the relationships between calculated mean interfacial temperature and roll speed for the commercial oils A and B. The mean interfacial temperature of the commercial oil B is larger than that of the commercial oil A, and it is expected that the commercial oil B has better antiseizure property compared to the commercial oil A.

4.8.4.2 Evaluation of Antiseizure Property by Normal Rolling

Next, in order to check the mean interfacial temperature at the occurrence of friction pickup, the normal rolling tests are carried out. The reductions at the occurrence of friction pickup in the normal rolling of the commercial oils A and

Table 4.24 Reduction of friction pickup occurrence at rolling speed of 96 m/min

Lubricant	Reduction (%)	Evaluation of pickup
A	30	○
	32	○
	35	×
B	30	○
	35	○
	38	×
	43	×

Table 4.25 Pass schedule in tandem mill with five stands for stainless steel

Stand	1	2	3	4	5
Roll diameter (mm)	500	500	500	500	500
Thickness of strip (mm)		2.5	1.8	1.4	1.0
Reduction (%)	28	22	29	20	13
Rolling speed (m/min)	39	50	70	88	100
	78	100	140	175	200

B are shown in Table 4.24. From Table 4.24, in the normal rolling at a rolling speed of 96 m/min, the reduction at the occurrence of friction pickup for the commercial oil A is 34 % and that for the commercial oil B is 37 %.

On the other hand, the reductions at the occurrence of friction pickup for the commercial oils A and B are calculated from the evaluating system. The mean interfacial temperature in the normal rolling is derived by the next equation:

$$T_m = 1.06 \frac{\ell \mu p_m \Delta V}{(V_r \ell)^{1/2} \left[\frac{K_r}{\kappa_r^{1/2}} + \frac{K_w}{\kappa_w^{1/2}} \right]} + \frac{\left[\frac{K_r}{\kappa_r^{1/2}} \right] T_r^0 + \left[\frac{K_w}{\kappa_w^{1/2}} \right] (T_w^0 + T_p)}{\frac{K_r}{\kappa_r^{1/2}} + \frac{K_w}{\kappa_w^{1/2}}} \quad (4.31)$$

The reduction can be back-calculated from Eqn. (4.31) using the experimental data. The reduction value for the commercial oil A is 35 % and that for the commercial oil B is 38 %. The calculated reductions of the commercial oils A and B are in good agreement with those obtained in the normal rolling shown in Table 4.24.

From these results, it is expected that the evaluating system of the antiseizure property can be used effectively in cold sheet rolling of stainless steel. Then, the mean interfacial temperature in the pass schedule of the tandem mill for stainless steel using the commercial oils A and B was estimated by Azushima et al. [44].

4.8.4.3 Estimation of Mean Interfacial Temperature in Tandem Mill

Table 4.25 shows the pass schedule in five stands tandem mill for stainless steel. In the pass schedule, the stainless steel with a thickness of 2.5 mm is rolled to a thickness of 0.7 mm by five passes in the tandem mill having rolls with a diameter

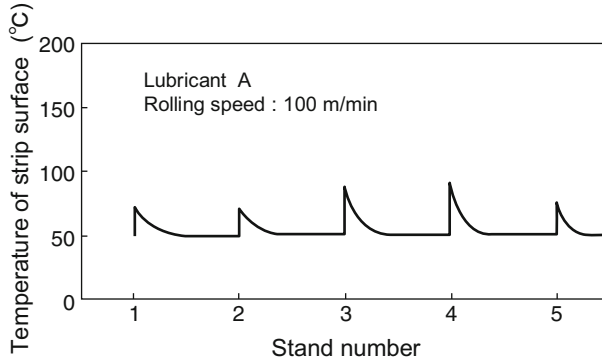


Fig. 4.128 Temperature change of strip surface in tandem mill at rolling speed of 100 m/min in fifth stand using commercial oil A

of 500 mm using the commercial oils of A and B. The mean interfacial temperature for each stand is calculated in the case of pass schedules of the final speeds of 100 and 200 m/min as shown in Table 4.25.

In this calculation, the mean interfacial temperature is calculated from Eqn. (4.32), and the surface temperature of strip T_s between stands is calculated from the Newton's cooling equation expressed as follows:

$$T_s = T_c^0 + (T_m - T_c^0) \exp\left(-\frac{2HL}{V\rho ch}\right) \quad (4.32)$$

where T_c^0 is the coolant temperature, H is the heat transfer rate, and L is the distance between stands.

Figure 4.128 shows the temperature change of strip surface in tandem mill at a rolling speed of 100 m/min in fifth stand using the commercial oil A. In this calculation, the coolant temperature is 50 °C. In this pass schedule of tandem mill of stainless steel using the commercial oil A, the mean interfacial temperature at the fourth stand is 92 °C. Since it is already understood that the friction pickup of the commercial oil A occurs at a mean interfacial temperature of 90 °C, it can be estimated that the friction pickup in actual mill occurs at the fourth stand.

On the other hand, Fig. 4.129 shows the temperature change of strip surface in tandem mill at a rolling speed of 200 m/min in fifth using the commercial oil B. In this pass schedule of tandem mill of stainless steel using the commercial oil B, the mean interfacial temperature at the fourth stand is 97 °C. Since it is already understood that the friction pickup of the commercial oil B occurs at a mean interfacial temperature of 100 °C, it can be estimated that the friction pickup does not occur at the fourth stand.

From these results, if it is desired to manufacture the stainless steel sheet in tandem mill with high productivity, the rolling oil with an excellent antiseizure property must be developed.

Fig. 4.129 Temperature change of strip surface in tandem mill at rolling speed of 200 m/min in fifth stand using commercial oil B

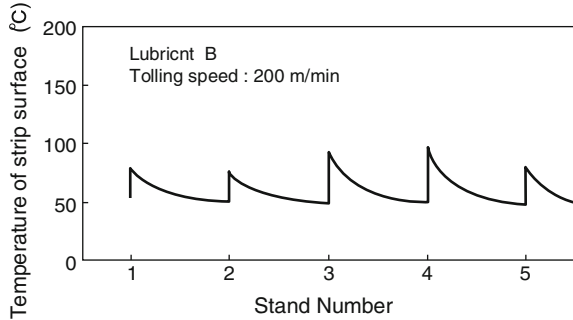


Table 4.26 Rolling oil types and additives used in cold sheet rolling of metals

Work piece	Steel	Stainless steel	Copper	Aluminum
Oil type	Emulsion	Neat emulsion	Neat emulsion	Neat
Additives	Oiliness additive (alcohol, fatty acid, ester), EP additive (phosphorus, sulfur, chlorine), emulsifier (anionic, cation, nonionic) etc.			

4.9 Cold Rolling Oil

In cold sheet rolling, there are neat oil and emulsion oil types as shown in Table 4.26. In cold sheet rolling of the carbon steel, the emulsion oil is used, and in the stainless steel, the neat oil and the emulsion oil are used. In this chapter, the cold rolling oils of the carbon steel is explained.

4.9.1 Cold Rolling Oil in History

In the 1940s, a palm oil was used as base oil in cold sheet rolling of carbon steel, and then, a tallow oil began to be used instead of the palm oil in Japan. In the late 1950s, the rolling oils of the mineral base oil were developed, and then the emulsifier changed from anion to nonion. In the circuit system of the emulsion, there were an emulsion recirculation system and a direct application system, and recently the emulsion recirculation system has increased.

At the present time, as the rolling base oils in the emulsion, mineral base oils, mixed base oils, and fats and oils are used as shown in Table 4.27. In the recirculation system of emulsion, the mineral base oils are used for the sheet gage steel, the fats base oils with saponification values of 180 to 200 are used for the thin plate steel, and the mixed base oils of mineral oil and fats oil with saponification values of 50 to 150 are used for both steels. On the other hand, in the direct application system, the fats and palm oil and tallow oil are used for the thin steel plate. The rolling oils with higher saponification values are excellent in antiseizure

Table 4.27 Classification of emulsion in cold sheet rolling

Supply system	Base oil	Characteristics
Circuit supply system	Mineral oil	Low- and middle-viscosity oil: saponification value approx. 30 additive agent: fat, fat acid, emulsifying agent, antioxidant, corrosion inhibitor
	Mineral oil • fat and oil mix	Middle-viscosity oil fat • synthetic ester: saponification value approx. 110–160
		Additive agent: oiliness agent, mill clean agent
	Fat and oil	Fat and oil (beef tallow, palm oil, whale oil etc.):
		Saponification value approx. 190–200
		Synthetic ester, phosphorus system EP agent
Direct supply system	Fat	Beef tallow, palm oil: saponification value approx. 190–200
		Tandem mill front stand 10–20 %
		Tandem mill rear stand 15–20 %

Table 4.28 Properties required in cold rolling oils for sheet gage steel and thin plate steel

		Common steel	
		Thin sheet	Sheet gage
Traditional demand	Lubricating property	Great	Good
	Mill clean property	Poor	Okay
	Anti-rust property	Good	Good
	Anti-oil stain property	Great	Good
	Emulsion stability	Good	Good
	Effluent treatment property	Good	Good
Recent demand	Mill cleaning property	Good	Great
	Sheet cleaning property	Great	Great
	Sludge decomposition property	Good	Good
	Oil decomposition property	Good	Good
	Surface homogeneity	Great	Good
	Maintenance free	Good	Good

property, and the rolling oils with lower saponification values are excellent in the cleanliness property. Recently, the synthetic ester base oils and the cationic dispersant-type emulsion oils are used. The properties required in cold rolling oils for the sheet gage steel and the thin plate steel are summarized in Table 4.28.

4.9.1.1 Emulsion Particle

In the 1980s, a cationic dispersant (DP)-type emulsion with a constant particle size was developed. Figure 4.130 shows the photographs of the oil particle in the

Fig. 4.130 Photographs of oil particle in emulsion with cationic DP emulsifier (a) and emulsion with nonionic emulsifier (b) [45]

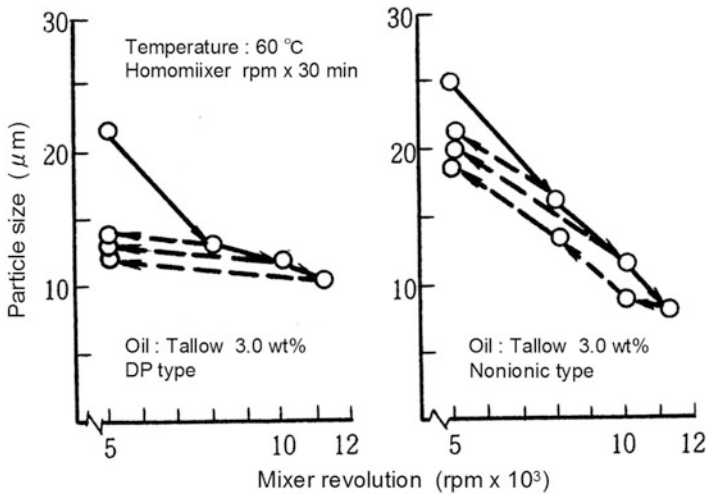
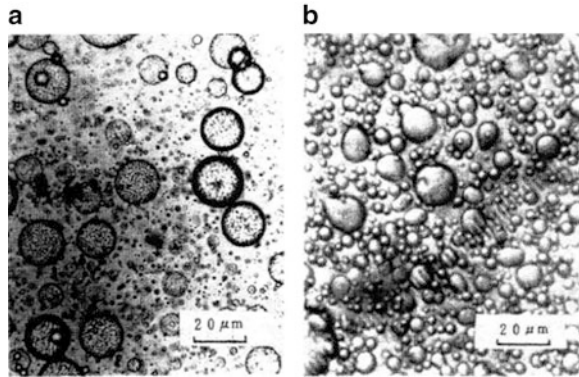


Fig. 4.131 Relationship between particle size and mixer revolution in emulsions with cationic DP emulsifier and conventional nonionic emulsifier [46]

emulsion with DP emulsifier (a) and the emulsion with nonionic emulsifier (b) [45]. From the photographs of Fig. 4.130, it is understood that the particle size in the emulsion with cationic DP emulsifier is uniform compared to that in the emulsion with conventional nonionic emulsifier.

Next, the effect of the mixer revolution number on the emulsion particle size in the emulsions with cationic DP emulsifier and conventional nonionic emulsifier is shown in Fig. 4.131 [46]. The particle size of the two emulsions at the first cycle is approximately the same. However, after two cycles, the particle size of the emulsion with cationic DP emulsifier is independent of the mixer revolution number, but that in the emulsion with conventional nonionic emulsifier depends on the mixer revolution number, and it decreases with increasing mixer revolution.

4.9.1.2 Plating Out

As mentioned in Sect. 4.5.1, the plating out of the oil layer on the sheet surface is significantly important in cold sheet rolling with emulsion. The plating out amount has been measured by the plating out testing machine as shown in Fig. 4.132 [47]. In the plating out tests machine, the test piece was dropped from a high place, and the spray time was controlled by the dropped speed.

Figure 4.133 shows the relationship between plating out amount and emulsion concentration for three emulsion oils. The plating out amount increases with increasing emulsion concentration for each emulsion.

Next, the effect of the temperature of sheet surface on the plating out amount (a) [48] and the effect of the particle size in emulsion on the plating out amount (b) [49] is shown in Fig. 4.134. In Fig. 4.134a, the nozzle pressure was 5 kg/cm^3 and the spray time was 20 msec. The plating out amount increases with increasing temperature of sheet surface up to a temperature of 125°C , and above 125°C , it decreases with increasing temperature of sheet surface for each nozzle. The plating out amount of the cone nozzle was larger than that of the flat nozzle. In Fig. 4.134b, the plating out amount increases with increasing particle size.

Fig. 4.132 Schematic representation of plating out testing machine [47]

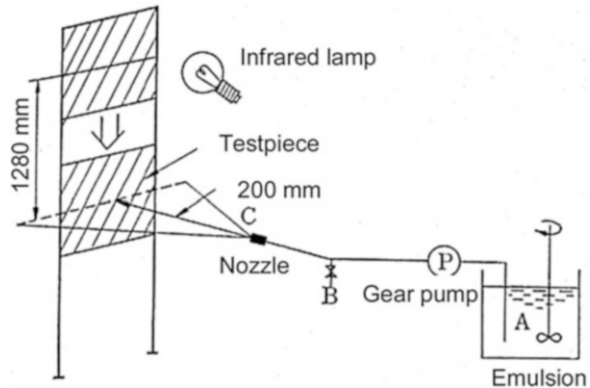
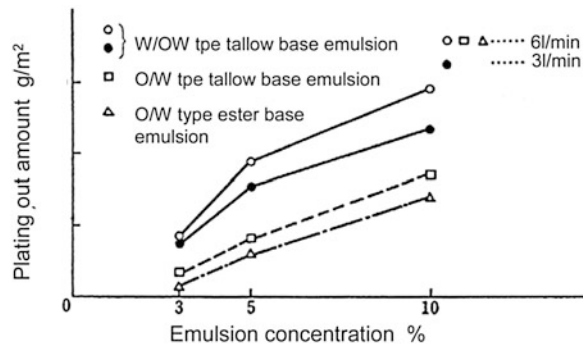


Fig. 4.133 Relationship between plating out amount and emulsion concentration [47]



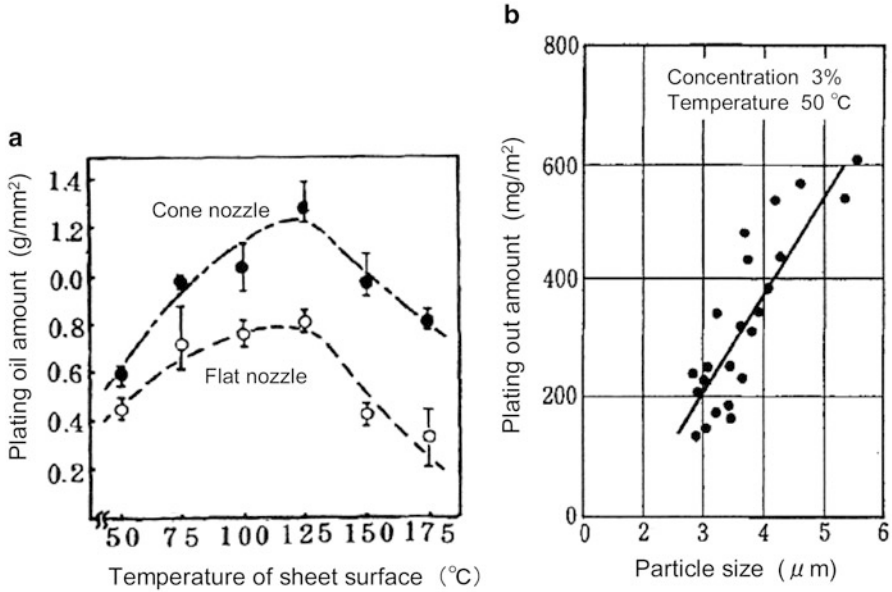


Fig. 4.134 Relationships between plating out amount and temperature of sheet surface (a) [48] and between plating out amount and particle size (b) [49]

4.9.2 Development of New Rolling Oil with High Lubricity

The prevention of friction pickup which occurs under the conditions in high rolling reduction, and high rolling speed is required to improve the productivity in cold sheet rolling. In order to prevent the friction pickup in high-speed cold rolling, a new rolling oil of emulsion type is developed. The antiseizure property of the new oil was evaluated using the sliding-rolling-type tribo-simulator by Azushima et al. [50].

4.9.2.1 Experiment

The sliding-rolling experiments are carried out using the low carbon steel with a thickness of 0.4 mm and a surface roughness of 0.02 μm and the SUJ-2 roll with a surface roughness of 0.05 μm at a roll speed of 143 m/min. The base oil of the new emulsion oil is a synthetic ester oil with a viscosity of 100 cSt at 40 °C, the additives used are active sulfur and calcium sulfonate, and the emulsifiers A and B used are nonionic ethers with HLB values of 7.9 and 5.7. The emulsion concentrations are 3, 5, and 10 %. The sliding-rolling experiments are carried out changing the reduction at a constant roll speed until the friction pickup occurs. The coefficient of friction is calculated by Eqn. (3.46) as follows:

$$\mu = \frac{G}{PR} \quad (3.46)$$

4.9.2.2 Results

First, the effect of the emulsion concentration of the synthetic ester base oil on the antiseizure property is examined. Figure 4.135 shows the experimental results of the coefficient of friction (a) and the limitation reduction (b). The coefficient of friction for each concentration is independent of the reduction, and it decreases in the order of the concentrations of 3, 5, and 10 %. The limitation reduction increases with increasing emulsion concentration. From these results, the mean temperature rises by the friction energy are calculated and the results are shown in Fig. 4.136. It is found that the mean temperature rise is independent of the emulsion concentration.

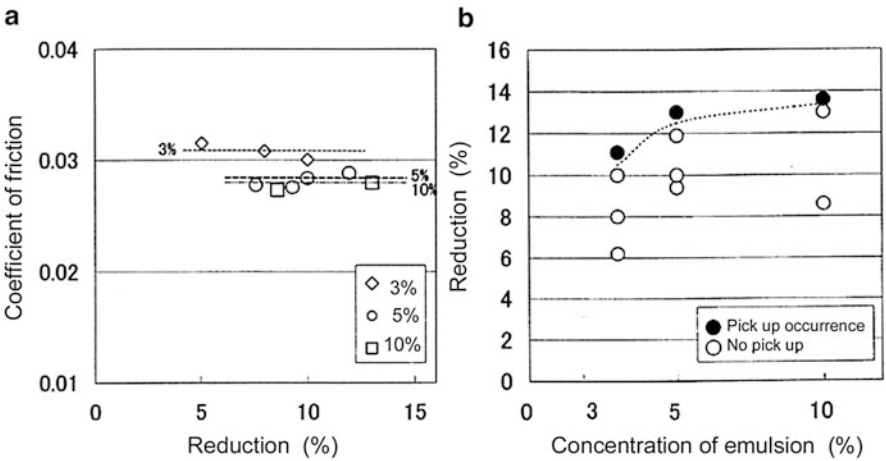
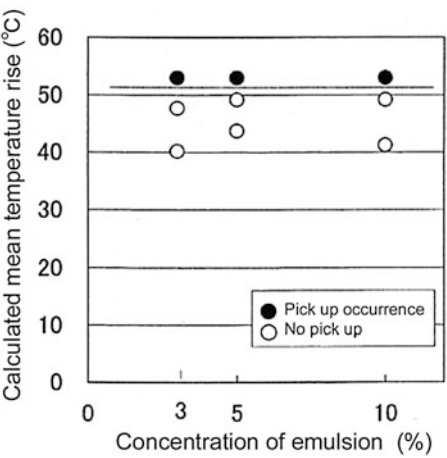


Fig. 4.135 Relationship between coefficient of friction and reduction (a) and relationship between limitation reduction at occurrence of friction pickup and emulsion concentration (b)

Fig. 4.136 Relationship between calculated mean temperature rise and emulsion concentration



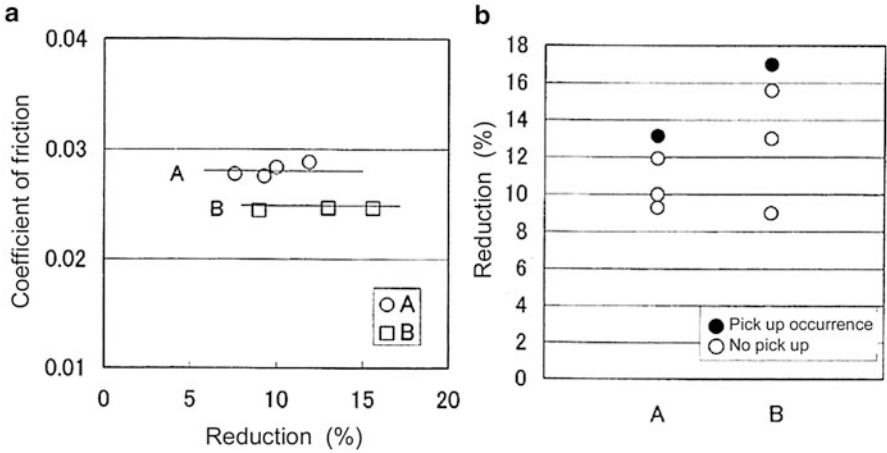
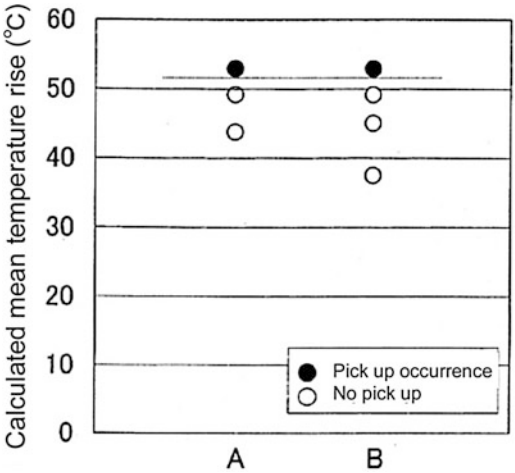


Fig. 4.137 Relationship between coefficient of friction and reduction of emulsions with emulsifier of A and B (a) and limitation reduction at occurrence of friction pickup (b)

Fig. 4.138 Mean temperature rises of emulsions with different emulsifiers



Next, the effect of the emulsifiers A and B in emulsion on the antiseizure property is examined. Figure 4.137 shows the experimental results of the coefficient of friction (a) and the limitation reduction (b). The coefficients of friction for emulsions with emulsifiers of A and B are independent of the reduction. The coefficient of friction of the emulsifier B is lower than that of the emulsifier A. The limitation reduction of the emulsifier B is higher than that of the emulsifier B. It is recognized that the coefficient of friction is lower and the limitation reduction is higher for the emulsion with emulsifier B. It is due to the reason that the oil particle size in the emulsion is larger.

From these results, the mean temperature rises by the friction energy are calculated, and the results are shown in Fig. 4.138. It is found that the mean temperature rise is independent of the emulsifier.

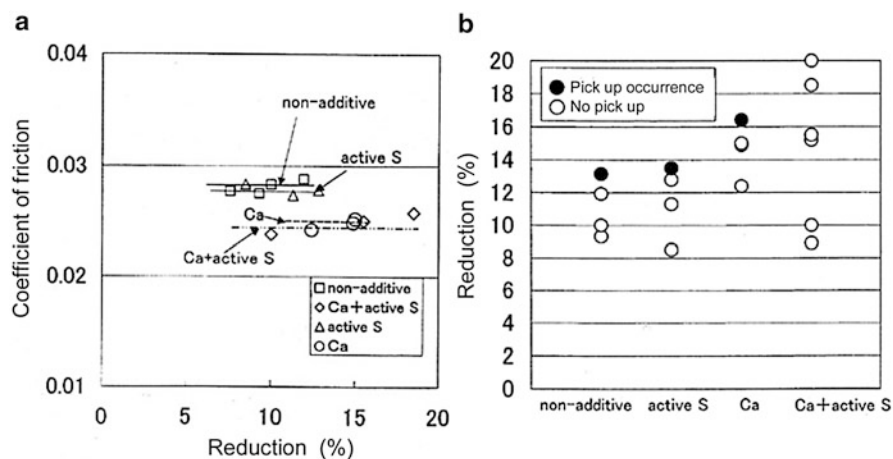


Fig. 4.139 Relationship between coefficient of friction and reduction of emulsions with additives (a) and limitation reduction (b)

First, the effect of the additives in emulsion on the antiseizure property is examined. Figure 4.139 shows the experimental results of the coefficient of friction (a) and the limitation reduction (b). The coefficient of friction for each emulsion with additives is independent of the reduction. The coefficients of friction of the emulsions with calcium sulfonate and active sulfur plus calcium sulfonate are lower than that of the emulsion without additives. The coefficient of friction of the emulsion with active sulfur is approximately equal to that of the emulsion without additives. The limitation reduction of the emulsion with active sulfur is approximately equal to that of the emulsion without additives. The limitation reduction of the emulsion with calcium sulfonate is larger than that of the emulsion without additives. From these experimental results, it is understood that the addition of the active sulfur is not effective in the improvement of antiseizure property, but the addition of the calcium sulfonate is effective. Moreover, for the emulsion with active sulfur plus calcium sulfonate, the friction pickup does not occur at a reduction of 20 %.

From these results, the mean temperature rises by the friction energy are calculated, and the results are shown in Fig. 4.140. The mean temperature rise of the emulsion with calcium sulfonate is higher than those of the emulsions without additive and with active sulfur by about 2 °C. On the other hand, the mean temperature rise of the emulsion with active sulfur plus calcium sulfonate is over 70 °C, and the temperature is 20 °C higher than that of the emulsion without additive. If the emulsion of the synthetic ester base oil with additives of active sulfur plus calcium sulfonate is used in cold sheet rolling, it is estimated that the rolling in actual tandem mill can be performed in rolling speeds of more than 3000 m/min.

Fig. 4.140 Mean temperature rise of emulsion with additives

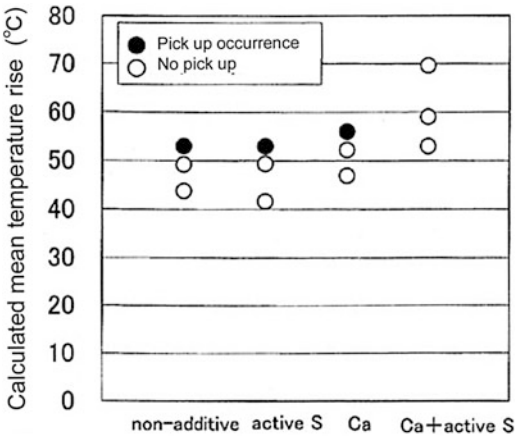
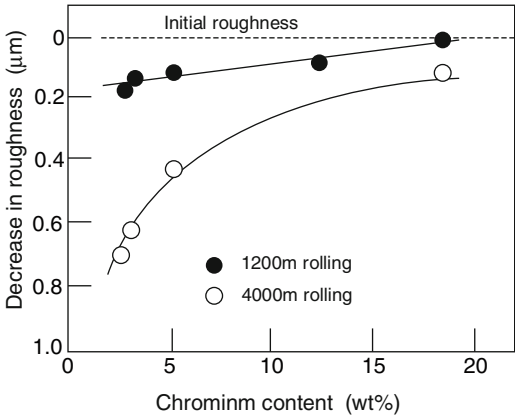


Fig. 4.141 Relationship between decrease in roughness and chromium content [51]



4.10 Cold Roll

4.10.1 Cold Roll in History

In Japan, before 1960s, 1.8 % Cr bearing steel was used as a material for the cold rolls in cold sheet rolling. However, in order to improve the roll efficiency, it was desired that the cold rolls with high wear resistance were developed. In order to decrease the roll wear, the rolls with higher Cr contents were developed. Figure 4.141 shows the relationship between decrease in roughness and chromium content in rolling distances of 1200 and 4000 m obtained in the laboratory mill [51]. The decrease in roughness decreases with increasing chromium content in both rolling distances of 1200 and 4000 m. It is recognized that the addition of higher Cr content is significantly effective for the wear resistance [52].

From these results, 10 % Cr forging steel roll was developed for the actual mill, and the results of roll wear (a) and rolling throughput per unit diameter (b) are shown in Fig. 4.142 [51]. The roll wear of 10 % Cr forging steel roll became one third of that of 3 % Cr forging steel roll, and the rolling throughput per unit diameter became three times of that of 3 % Cr roll. However, since the grindability of 10 % Cr forging steel roll was bad, the roll has not been used. At the present time, 5 % Cr forging steel rolls have been used widely in cold sheet rolling in Japanese steel-making companies.

In order to improve the wear resistance of 5 % Cr forging steel roll, a new roll with addition of 1 % Ti in the roll with the same compositions was developed. The change in surface roughness of the new roll is shown in Fig. 4.143 [53]. These data were measured in six stands tandem actual mill for thin gage plate. For the 5 % Cr forging steel roll, the surface roughness decreased with increasing rolling length due to the roll wear so that the coefficient of friction became lower and there was a

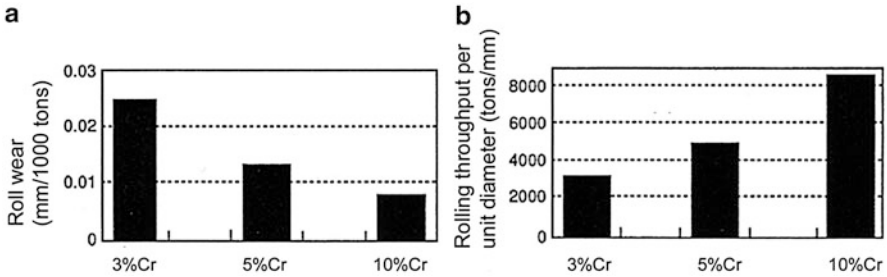


Fig. 4.142 Roll wear (a) and rolling throughput per unit diameter (b) in different Cr content [52]

Fig. 4.143 Relationship between change in surface roughness and rolling distance [53]

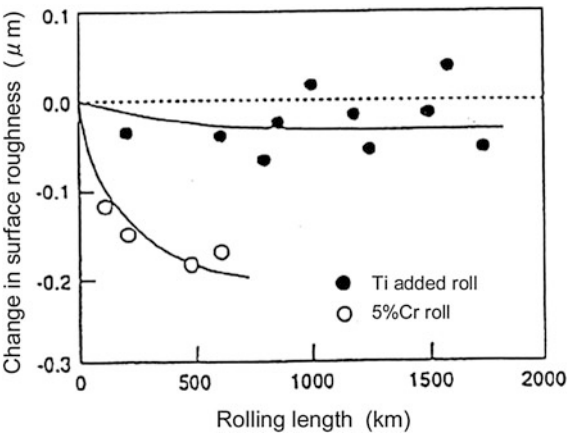
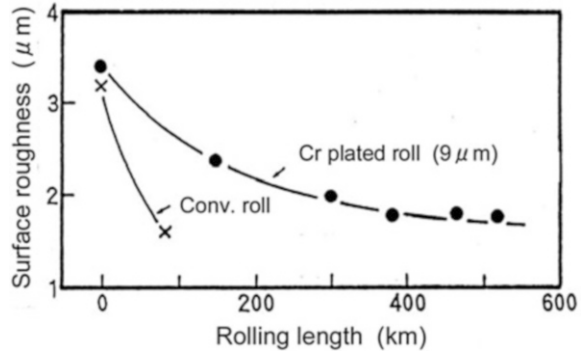


Fig. 4.144 Comparison of change of surface roughness between Cr-plated roll and conventional roll [54]



possibility that slipping occurred. On the other hand, for the 5 % Cr forging steel roll and 1 % Ti, since the roughness was reproduced due to the desorption of the hard TiCN precipitates, the change of the surface roughness became small.

In the temper rolling of the carbon steel, the Cr-plated roll was used and the relationship between change of roll surface roughness and rolling length is shown in Fig. 4.144 [54]. The decrease of the surface roughness of Cr-plated roll was smaller than that of the conventional roll, and the life became seven times than that of conventional roll. However, in the Cr-plated roll, since the peeling of the Cr layer plated on the roll surface is likely to occur, it is difficult to use the Cr-plated rolls in cold sheet tandem mill.

Recently, the ceramic rolls have been used in cold sheet rolling of stainless steel in order to manufacture the strip with a high brightness surface. The surface brightness of strip stainless steel rolled by the sialon ceramic roll was higher than that by the die steel roll, and the surface roughness was lower than that by the die steel roll [55].

4.10.2 Evaluation of Antiseizure Property of Commercial Rolls

Hitherto, attention has been focused on the development of the rolls with high wear resistance. Recently, much attention is paid to the lubricity of the work roll, and it is desired that the work rolls with high lubricity are developed. Azushima et al. [56] evaluated the antiseizure property of the commercial rolls in order to develop new rolls with high antiseizure property.

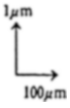
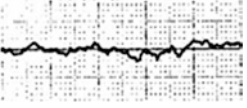
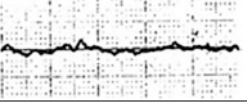
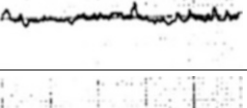
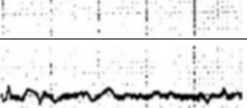
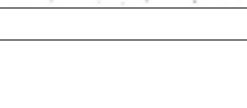
4.10.2.1 Experiment

The sliding-rolling experiments are carried out using the low carbon steel with a thickness of 0.4 mm and a surface roughness of $0.15\mu\text{m}$ and the rolling oil of 5 %

Table 4.29 Chemical composition of evaluated commercial rolls

Material	Chemical composition (wt%)								
	C	Si	Mn	P	S	Cr	Mo	V	W
SUJ2	1.01	0.23	0.45	0.020	0.006	1.45	—	—	—
SKD11	1.45	0.28	0.41	0.025	0.005	11.80	0.88	0.42	—
SKH51	0.85	0.35	0.35	0.025	0.005	4.10	4.90	1.90	5.95
5Cr	0.85	0.27	0.37	0.013	0.001	4.98	0.45	—	—
S-HSS	1.00	0.92	0.49	0.011	0.003	5.30	3.10	1.15	—

Table 4.30 Hardness and surface roughness of evaluated commercial rolls

Material	Hardness (HRC)	Surface roughness		Ra (μm)
SUJ-2	65.0			0.053
SUJ-2	65.0			0.053
SKD11	64.8			0.050
SKH51	64.7			0.046
5Cr	64.4			0.050
S-HSS	65.1			0.040

emulsion of tallow at roll speeds of 24, 72, and 143 m/min. The materials of evaluated commercial rolls are SUJ-2, SKD11, SKH51, 5 % Cr steel, and S-HSS. The chemical composition is summarized in Table 4.29, and the hardness and surface roughness are summarized in Table 4.30. The sliding-rolling experiments are carried out changing the reduction at a constant roll speed by the occurrence of friction pickup. The coefficient of friction is calculated from the rolling load and torque measured using Eqn. (3.46).

4.10.2.2 Results

Figure 4.145 shows the experimental results of the coefficient of friction (a) and the limitation reduction of the occurrence of friction pickup (b). The coefficient of friction for each commercial roll at a rolling speed of 143 m/min is almost independent of the reduction, and it decreases in the order of SUJ2 roll, 5 % Cr forging steel roll, SKD11 SKH51, and S-HSS. At a rolling speed of 143 m/min, the limitation reductions of SUJ2 roll and 5 % Cr forging steel roll are lower than those of SKD11, SKH51, and S-HSS by about 10 %.

From these results, the mean temperature rises by the friction energy are calculated, and the results are shown in Fig. 4.146. Since the friction pickup occurring in the actual cold tandem mill is the heat type, the limitation reductions at a roll speed of 143 m/min in Fig. 4.145 must be considered. The limitation reduction increases in the order of SUJ2 roll, 5 % Cr forging steel roll, S-HSS,

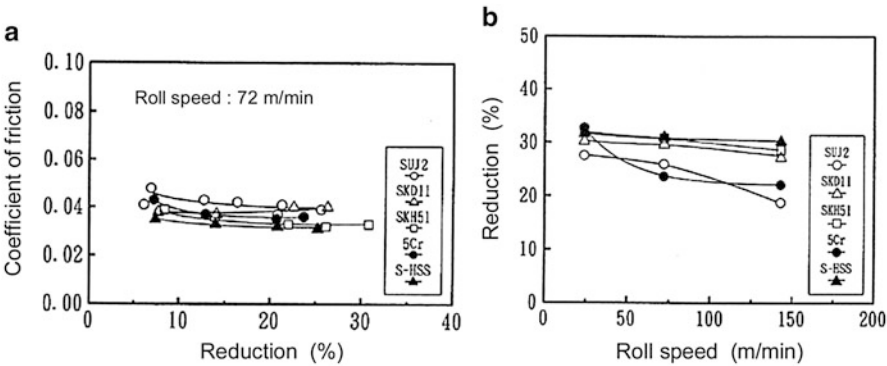


Fig. 4.145 Relationship between coefficient of friction and reduction (a) and relationship between limitation reduction at occurrence of friction pickup and roll speed (b)

Fig. 4.146 Relationship between mean temperature rise and roll speed

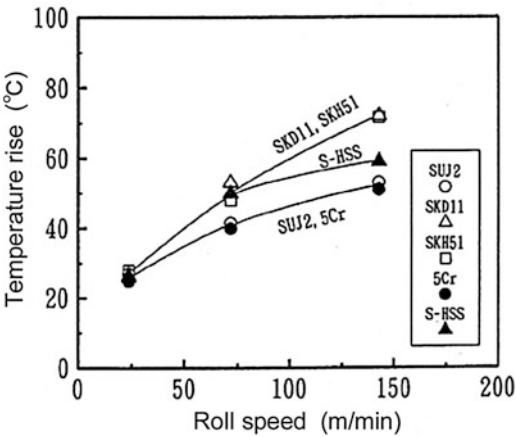


Table 4.31 Carbide type and content of evaluated rolls

Material	Carbide type	Carbide content (area %)
SUJ2	M ₃ C	<1
SKD11	M ₇ C ₃	10.7
SKH51	M ₆ C+MC	9.5
5Cr	M ₃ C	<1
S-HSS	M ₆ C+MC	4.4

Table 4.32 Pass schedule in actual tandem mill and mean temperature rise

STD	Roll diameter (mm)	Exit thickness (mm)	Reduction (%)	Mean pressure (MPa)	Rolling speed (m/min)	Heat streak	Mean temperature rise (°C)
No. 1	534	1.55	32.6	628	280	No occurrence	31.2
No. 2	515	0.97	37.6	438	483	No occurrence	30.0
No. 3	518	0.63	34.6	492	739	No occurrence	34.6
No. 4	568	0.37	41.8	593	1270	No occurrence	65.4
No. 5	566	0.27	26.6	864	1730	No occurrence	63.9

SKH51, and SKD11. It is estimated that the friction pickup of the commercial rolls depends on the carbide content on the roll surface. The carbide type and the carbide content of the evaluated commercial rolls are summarized in Table 4.31. The carbide contents of SUJ2 roll and 5 % Cr forging steel roll are less than 1 %, the S-HSS is 4 %, and the SFH51 and SKD11 are about 10 %. It is recognized that the antiseizure property is improved with increasing carbide content.

Then, using the mean temperature rise at a roll speed of 143 m/min shown in Fig. 4.146, the maximum rolling speeds in the actual cold tandem mill are estimated from the evaluating system shown in Fig. 4.121. Table 4.32 summarizes the pass schedule of low carbon steel in actual tandem mill and the mean temperature rise for each stand. In this simulation, it is understood that the critical rolling speeds in fourth stand at the occurrence of the friction pickup are 1320, 1680, and 1830 m/min for S-HSS roll, SKD51 roll, and SKD11 roll. It is expected that if the SKD11 roll and SKH51 roll are used, the maximum rolling speed increases more than 500 m/min compared to the conventional rolling speed.

4.10.3 Development of Roll with High Antiseizure Property

In Sect. 4.10.2, it is found that the antiseizure property of the cold roll depends strongly on the carbide content. The effect of the carbide property of the rolls made of high-chromium steels and high-speed steels on the antiseizure property was

examined by Azushima et al. [57]. The coefficients of friction for the reduction and the limitation reduction at the occurrence of the friction pickup are measured using the sliding-rolling-type tribo-simulator.

4.10.3.1 Experiment

The sliding-rolling experiments are carried out using the low carbon steel with a thickness of 0.4 mm and a surface roughness of 0.15 μm and the rolling oil of 5 % emulsion of tallow oil at a constant roll speed of 143 m/min. The materials of roll are seven kinds of high-chromium steel (DS-A–DS-G) having M_7C_3 carbide and four kinds of high-speed steels (HS-A–HS-D) having MC and M_6C carbides. The chemical composition, the carbide area, and the carbide mean spacing of evaluated rolls are summarized in Table 4.33.

The photographs of the microstructure of the rolls are shown in Fig. 4.147. In Fig. 4.147, the carbide area is given by the ratio of the area occupied by carbides to the area inspected (2 mm²), and the carbide mean spacing is given by the number of carbides existing on 100 lines each 1 mm in length. All the rolls are heat-treated to about HRC 65 and are ground in the rolling direction. The surface roughnesses are controlled at about 0.05 μmRa . The sliding-rolling experiments are carried out, changing the reduction at a constant roll speed until the friction pickup occurs. The coefficient of friction is calculated from the rolling load and torque measured using Eqn. (3.45).

4.10.3.2 Results

Figure 4.148 shows the relationship between coefficient of friction and reduction at a rolling speed of 143 m/min of the rolls of DS-A–G (a) and the rolls of HS-A–D (b). The coefficients of friction of both rolls of DS and HS depend slightly on the composition in the lower reduction, but above a reduction of 10 %, they become almost the same.

Then, Fig. 4.149 shows the relationship between limitation reduction at the occurrence of friction pickup and carbide content at a rolling speed of 143 m/min for the rolls of DS-A–G (a) and the rolls of HS-A–D (b). In the rolls of DS, the limitation reduction increases linearly with increasing carbide content up to a carbide content of 10 % for the roll of DS-D, and above 10 %, it becomes gradually saturated. The limitation reductions of DS-F and DS-G rolls are almost same. For the rolls of HS, the limitation reduction increases linearly with increasing carbide content. In the comparison between the limitation reductions of DS rolls and HS rolls, it is found that the limitation reduction of the HS rolls with MC and M_6C carbides is higher than that of the DS rolls with M_7C_3 carbide at the same carbide area by 1 %. The experimental results on the antiseizure property indicate that the carbides on the roll surface should be effective for preventing the friction pickup.

Table 4.33 Chemical composition, carbide area, and carbide mean spacing of rolls

Symbol	Chemical composition (wt%)							Carbide properties			
	C	Si	Mn	Cr	Mo	V	Co	W	Type	Area (%)	Spacing (μm)
DS-A	0.93	0.42	0.34	7.86	0.89	0.45	—	—	—	1	86
DS-B	1.03	0.45	0.34	8.92	0.88	0.45	—	—	—	3	73
DS-C	1.25	0.50	0.37	10.06	0.97	0.48	—	—	—	6	55
DS-D	1.51	0.45	0.35	12.46	0.88	0.46	—	—	M7C3	11	32
DS-E	1.86	0.52	0.38	14.90	0.95	0.48	—	—	—	16	23
DS-F	2.16	0.52	0.39	17.15	0.95	0.48	—	—	—	21	15
DS-G	2.43	0.52	0.40	19.73	0.98	0.48	—	—	—	26	14
HS-A	1.00	0.92	0.49	5.30	3.10	1.15	—	—	—	3	60
HS-B	1.10	0.30	0.30	3.75	9.50	1.15	8.00	1.50	MC	8	39
HS-C	0.84	0.27	0.32	3.96	0.66	2.00	—	18.30	+M6C	12	23
HS-D	1.57	0.31	0.42	4.56	0.56	4.97	5.10	13.32	—	13	20

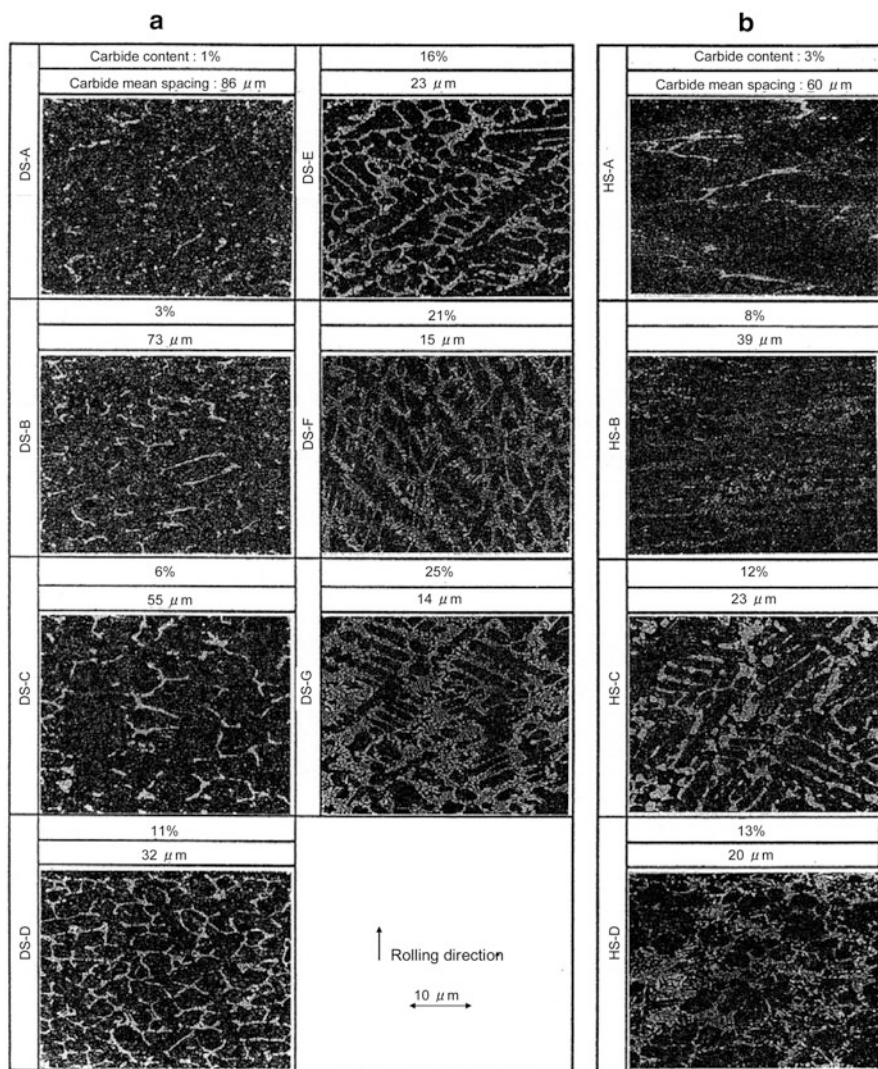


Fig. 4.147 Photographs of microstructure of evaluated rolls. (a) DS-A–G. (b) HS-A–D

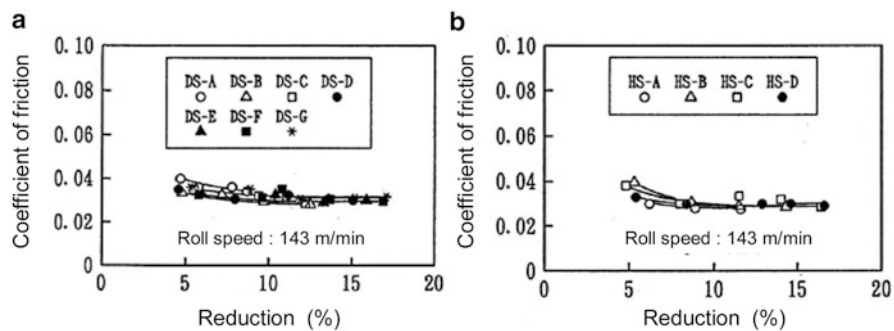


Fig. 4.148 Relationship between coefficient of friction and reduction at rolling speed of 143 m/min. (a) DS-A–G. (b) HS-A–D

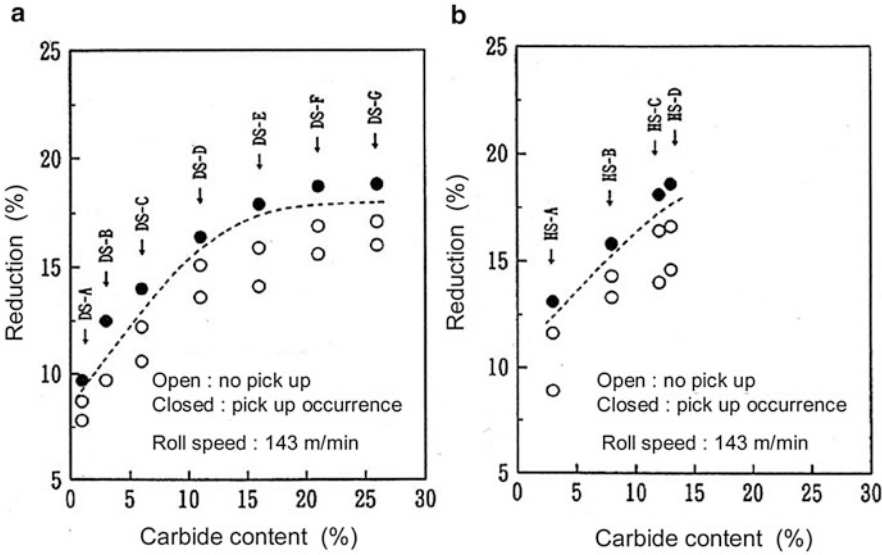


Fig. 4.149 Relationship between limitation reduction at occurrence of friction pickup and carbide content at rolling speed of 143 m/min. (a) DS-A-G. (b) HS-A-D

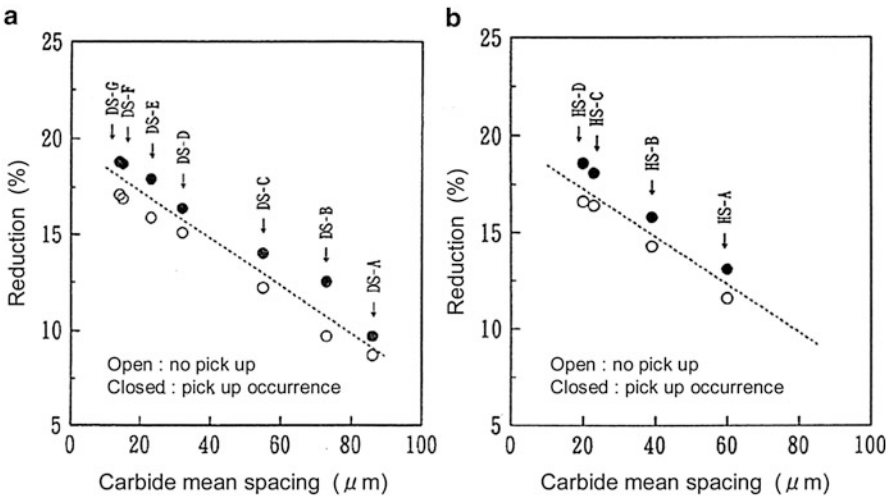


Fig. 4.150 Relationship between limitation reduction and carbide mean spacing. (a) DS-A-G. (b) HS-A-D

From the observation of the surface appearance after rolling, it is obvious that the friction pickup begins in the matrix structure and it ends at the carbides.

Figure 4.150 shows the relationships between limitation reduction and carbide mean spacing for the rolls of DS-A-G (a) and the rolls of HS-A-D (b). The

limitation reduction of the DS rolls increases linearly with increasing carbide mean spacing in Fig. 4.150a, and the limitation reduction of the HS rolls increases also with increasing carbide mean spacing in Fig. 4.150b. It is confirmed that the limitation reduction of friction pickup has a strong correlation with the carbide mean spacing of roll material.

4.10.4 Verification of Relationship Between Limitation Reduction and Carbide Mean Spacing

In order to verify the relationship between limitation reduction and carbon mean spacing, the antiseizure property of the cemented carbide rolls with different carbide contents was evaluated using the sliding-rolling-type tribo-simulator by Azushima et al. [58]. The sliding-rolling experiments are carried out using the low carbon steel with a thickness of 0.4 mm and a surface roughness of 0.15 μm and the rolling oil of 5 % emulsion of tallow at roll speeds of 24, 72, and 143 m/min. The materials of evaluated roll are three kinds of cemented carbide rolls of WC-4%Co, WC-10%Co, and WC-20%Co. The chemical composition (a) and the carbide area and carbide mean spacing (b) are summarized in Table 4.34. The carbide areas of WC-4%Co, WC-10%Co, and WC-20%Co are 87, 74, and 55 %, but these carbide mean spacing values are lower than 1 μm . All the rolls are controlled at a constant surface roughness of about 0.04 μm . The sliding-rolling experiment is carried out changing the reduction at a constant roll speed until the friction pickup occurs. The coefficient of friction is calculated from the rolling load and torque measured using Eqn. (3.45).

Figure 4.151 shows the relationship between limitation reduction at the occurrence of the friction pickup and carbide area of the cemented carbide rolls of WC-4%Co, WC-10%Co, and WC-20%Co at a roll speed of 143 m/min. The limitation reductions of friction pickup are independent of the carbide area, and they are constant at about 21 %.

Table 4.34 Chemical compositions (a) and carbide area and carbide mean spacing (b) of evaluated cemented carbide rolls

(a)			
Symbol	Chemical composition (wt%)		
	W	C	Co
WC-4Co	89.9	5.9	4.2
WC-10Co	84.8	5.5	9.7
WC-20Co	75.5	4.9	19.6
(b)			
Symbol	Carbide content (area%)	Carbide mean spacing (μm)	
WC-4Co	87	0.3	
WC-10Co	74	0.4	
WC-20Co	55	0.7	

Fig. 4.151 Relationship between limitation reduction and carbide area of cemented carbide rolls

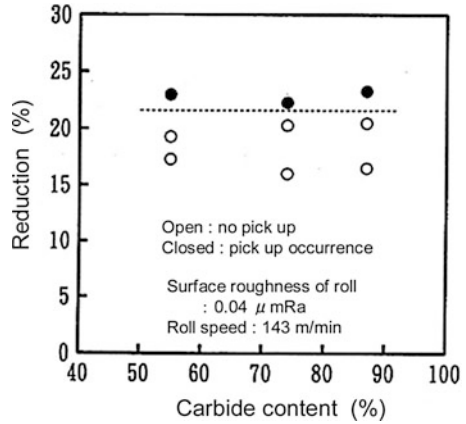
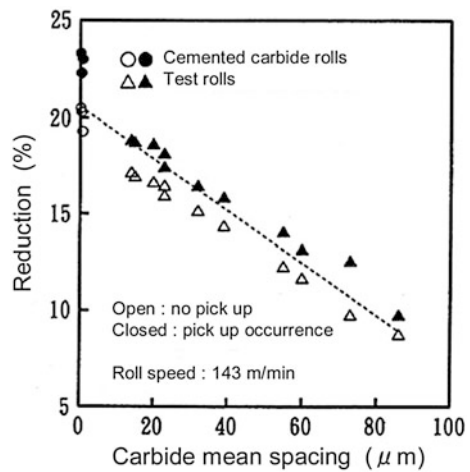


Fig. 4.152 Relationship between limitation reduction and carbide mean spacing of cemented carbide rolls

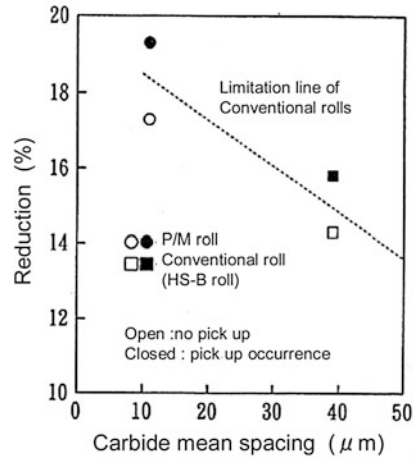


Then, Fig. 4.152 shows the relationship between limitation reduction and carbide mean spacing of the cemented carbide rolls of WC-4%Co, WC-10%Co, and WC-20%Co at a roll speed of 143 m/min. In Fig 4.152, the data of the cemented carbide rolls are added with the data in Fig. 4.151. It is understood that the limitation reduction of all the data increases linearly with decreasing carbide mean spacing.

Then, when the cemented carbide rolls are used in the actual cold tandem mill, the maximum rolling speeds are estimated from the evaluating system using the pass schedules and the mean temperature rise for each stand shown in Table 4.32. In this simulation, the critical rolling speeds in fourth stand at the occurrence of the friction pickup are 3120 m/min for the WC-10%Co roll. It is expected that if the cemented carbide rolls are used, the maximum rolling speed is over 3000 m/min.

Next, the antiseizure property of the powder metallurgy (P/M) roll with same composition instead of the casted HS-B roll is evaluated by the same evaluating method. The carbide content of the newly developed M/P roll is equal to 8 % of the

Fig. 4.153 Relationship between limitation reduction and carbide mean spacing of P/M roll and HS-B roll



HS-B roll. The carbide mean spacing is 11 μm and the value is one third of that of the HS-B roll. Figure 4.153 shows the relationships between limitation reduction and carbide mean spacing of the P/M roll and HS-B roll. The limitation reduction of friction pickup of the P/M roll is 18 %, the value is located on the limitation reduction line defined in Fig. 4.150b, and it is higher than that of the HS-B roll by 3 %. When the cemented carbide rolls are used in the actual cold tandem mill shown in Table 4.32, the critical rolling speed in fourth stand at the occurrence of the friction pickup are 2020 m/min for the P/M roll.

4.10.5 Application of New Developed Roll to Cold Tandem Mill

When the P/M rolls with high carbide content is used in cold tandem mills, many problems such as the size limitation and the high cost must be solved. Therefore, the high-chromium steel roll with M_7C_3 carbide is manufactured, the antiseizure property of the roll is evaluated using the sliding-rolling-type tribo-simulator, and the roll was applied the final stand of a cold tandem mill for tin plate (No. 3 TCM) at the Nagoya Works of Nippon Steel Corporation by Azushima et al. [59]. The properties of the carbide-controlled roll and the conventional roll of 5 % Cr steel roll are summarized in Table 4.35. The specifications of No. 3 TCM at the Nagoya Works are summarized in Table 4.36. The carbide area of the carbide-controlled roll is 6 % and the carbide mean spacing is 55 μm . The antiseizure property of the carbide-controlled roll is superior to that of the 5 % Cr steel roll.

Figure 4.154 shows an example of the test results that the rolling speed increases step-by-step for every two coils up to a maximum mill speed of 2300 m/min. For the conventional roll of 5 % Cr steel roll, the friction pickup occurs at a rolling speed of

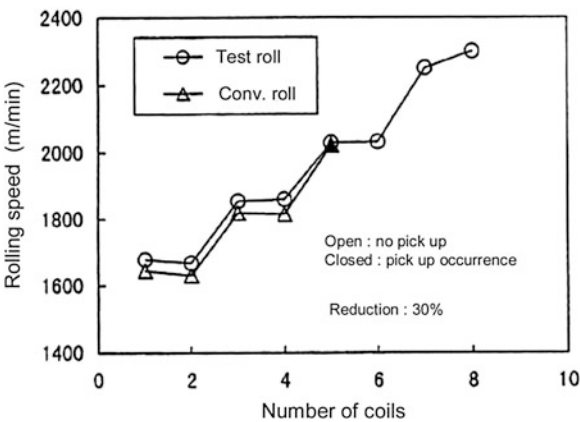
Table 4.35 Properties of carbide-controlled roll and conventional roll

	Carbide-controlled roll	Conventional roll
Material	High-Cr steel	5 % Cr steel
Carbide type	M7C3	M7C3+M3C
Carbide area	6 %	<1 %
Mean carbide spacing	55 μm	>200 μm

Table 4.36 Specifications of No.3 TCM at the Nagoya Works of Nippon Steel Corporation

Type	6 stands tandem mill (No. 6STD:6Hi)
Rolled material	Mild steel for tin plate
Delivery thickness	0.15–1.0 mm
Strip width	508–1070 mm
Maximum mill speed	2300 m/min
Work roll diameter	No. 6STD: 410–440 mm
Roll coolant	Direct application system

Fig. 4.154 Example of test results of occurrence of friction pickup in No. 3 TCM



2000 m/min. On the other hand, for the carbide-controlled roll, the friction pickup is not observed even at a maximum mill speed of 2300 m/min. Similar tests are conducted several times in order to obtain a good estimation of the limitation speed of both rolls. Then, both rolls are used under the condition close to respective limitation speed, and the data are collected. Figure 4.155 shows the relative ratio of the average speed in rolling of the controlled roll and the conventional roll. The average rolling speed of the carbide-controlled roll is faster than that of the conventional roll by 18 %. The value is close to that calculated from the evaluation system. A rolling speed of 2300 m/min is the maximum speed in this tandem mill.

Next, Fig. 4.156 shows the rate of roll change due to the friction pickup for both rolls (a) and the relative ratio of the rolled tonnage (b) when both rolls must be changed due to the friction pickup. The rate of roll change due to the friction pickup decreases to half of the conventional roll, and the rolled tonnage is about two times

Fig. 4.155 Comparison between relative ratio of rolling speed of test roll and conventional roll

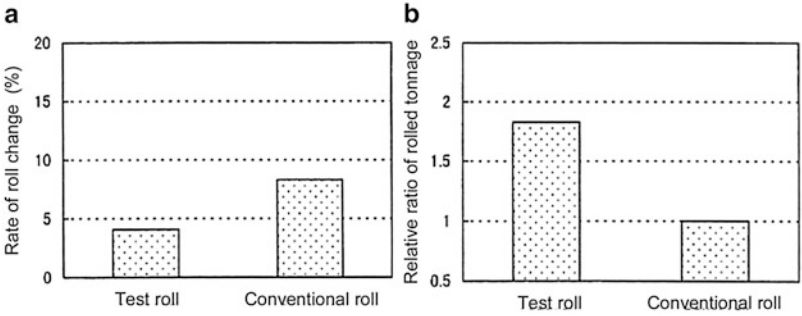
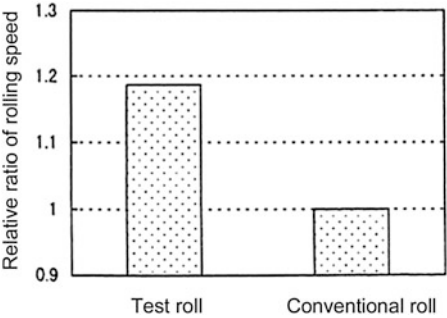
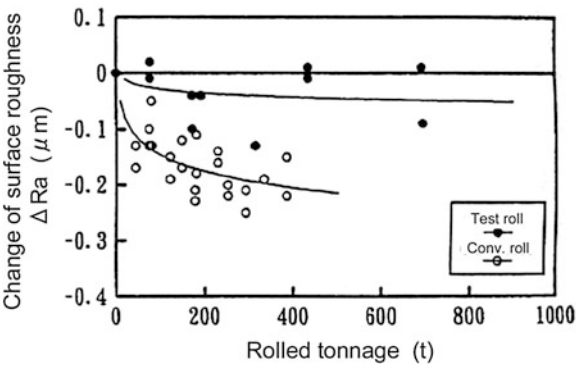


Fig. 4.156 Rate of roll change for both rolls (a) and relative ratio of rolled tonnage (b)

Fig. 4.157 Changes of surface roughness of both roll



as much as that of the conventional roll. These facts show that the carbide-controlled rolls can be used at higher reduction and higher speed.

The newly developed carbide-controlled roll also has a good wear resistance. Figure 4.157 shows the changes of surface roughness of both rolls. Moreover, examples of the roughness profile before and after rolling are shown in Fig. 4.158. The change of surface roughness of the carbide-controlled roll is very small compared to the conventional roll.

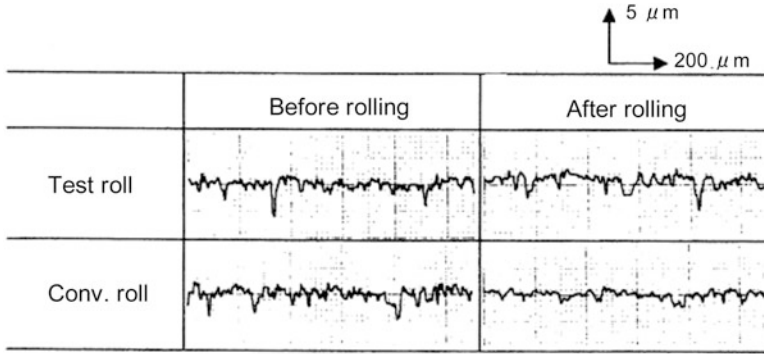


Fig. 4.158 Examples of roughness profile before and after rolling

Table 4.37 Properties of surface-treated rolls

Sample	Basic material	Coated film material	Coated film thickness (μm)	Surface roughness R_a (μm)	Basic material hardness
SUJ-2 roll	SUJ-2	—	—	0.13	Hs 90
Cr-plated roll	SUJ-2	Cr	5	0.12	Hs 90
TRD-treated roll	SKD-11	VC	8	0.054	HRC 57
PVD-treated roll	SKD-11	TiN	2–3	0.045	HRC 58

4.10.6 Evaluation of Surface-Treated Rolls

In Sect. 4.10.4, it is confirmed that the antiseizure property of roll is improved by the increase of carbide content. From these results, in order to improve the antiseizure property, it is expected that the surface-treated rolls by the ceramic materials are effective. The antiseizure property of the surface-treated rolls was evaluated using the sliding-rolling-type tribo-simulator by Azushima et al. [60].

The sliding-rolling experiments are carried out using the low carbon steel with a thickness of 0.4 mm and the 2 % emulsion of commercial rolling oil with a sponification of 86 at roll speeds of 48, 96, and 192 m/min. Table 4.37 summarizes the properties of the evaluated surface-treated rolls of Cr-plated roll, TRD-treated roll, and PVD-treated roll. The sliding-rolling experiments are carried out changing the reduction at a constant roll speed until the friction pickup occurs. The coefficient of friction is calculated from the rolling load and torque measured using Eqn. (3.46).

Figure 4.159 shows the relationship between coefficient of friction and reduction at a rolling speed of 96 m/min (a) and the relationship between limitation reduction and rolling speed (b) of the SUJ-2 roll and the surface-treated rolls. In Fig. 4.159a, the coefficients of friction of the surface-treated rolls increase slightly with increasing reduction, but the coefficient of friction of the SUJ-2 roll is almost independent

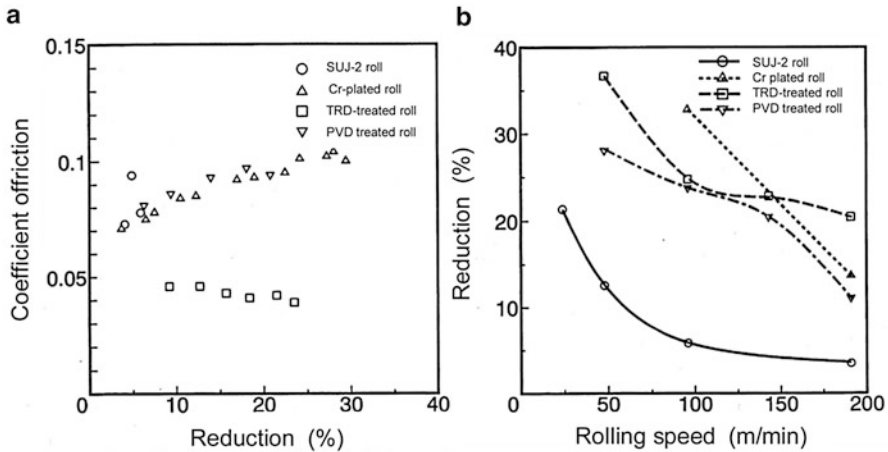


Fig. 4.159 Relationship between coefficient of friction and reduction at rolling speed of 96 m/min (a) and relationship between limitation reduction and rolling speed (b)

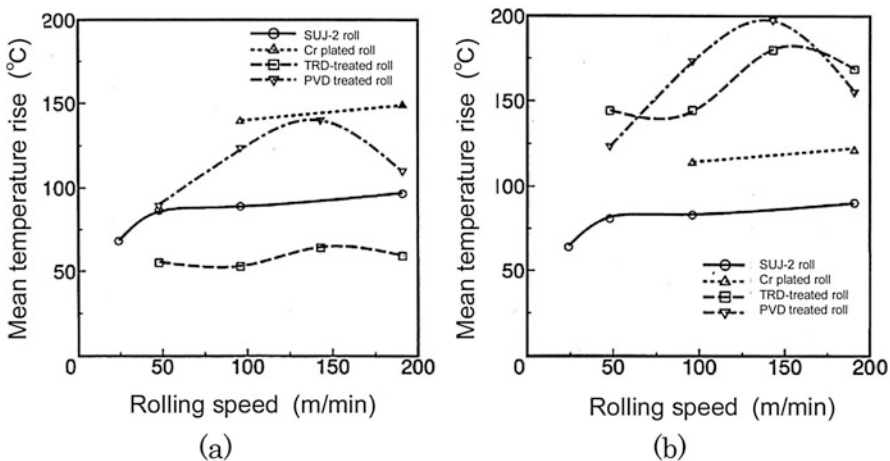


Fig. 4.160 Relationships between mean temperature rise and rolling speed when values of substrate of roll are used (a) and values of surface coating and plating materials are used (b)

of the reduction and the values are about half of those of the surface-treated rolls. In Fig. 4.159b, the limitation reductions of the surface-treated rolls are larger than that of SUJ-2 roll.

Next, from these experimental data, the mean temperature rise is calculated. Figure 4.160 shows the relationship between mean temperature rise and rolling speed when the values of the substrate of roll are used as the values of heat conductivity and thermal conductivity (a) and the values of surface coating and plating materials are used (b). In Fig. 4.160a, it is shown that the mean temperature

rise of the VC-coated roll (TRD-treated roll) is lower than those of other rolls. On the contrary, it is observed that the surface temperature of the TRD-treated roll is higher than that of SUJ-2 roll. In Fig. 4.160b, when the values of the surface coating and plating materials are used as the values of heat conductivity and thermal conductivity, the mean temperature rises of the surface-treated rolls are higher than that of SUJ-2 roll.

References

1. M. P. Stone, *Iron and Steel Engr.*, 30 (1953), 61-74.
2. A. Azushima, *Tetsu-to-Hagane*, 64-2(1978), 317-330. (in Japanese)
3. K. Saeki, Y. Hashimoto, *J. Jap. Soc. Technol. Plast.*, 7-63 (1966), 183-192. (in Japanese)
4. A. Azushima, H. Nagamori, J. Kihara, I. Gokyu, *J. Jap. Soc. Technol. Plast.*, 18-194 (1977), 189-196. (in Japanese)
5. A. Azushima, Y. Kita, T. Shima, M. Mitsuhashi, *Tetsu-to-Hagane*, 74 (1988), 1978-1985. (in Japanese)
6. A. Azushima, Y. Kita, T. Takaishi, *Tetsu-to-Hagane*, 74 (1988), 1986-1992. (in Japanese)
7. A. Azushima, Y. Kita, *Proc. 35th Joint Conf. Technol. Plast.* (1995), 29-32. (in Japanese)
8. H. S. Cheng, *Friction and Lubrication in Metal Processing*, (ASME, New York 1966).
9. K. Nakajima, Y. Shibata, Y. Kamibori, *Proc. Spring Conf. Technol. Plast.* (1978), 189-192. (in Japanese)
10. T. A. Dow, J. W. Kannel, S. S. Bupera, *Trans. ASME*, F98 (1976), 4-13.
11. A. Azushima, K. Kitamura, *Proc. Spring Conf. Technol. Plast.*, (1986), 151-154. (in Japanese)
12. A. Azushima, *Trans. JSME*, 44-377 (1978), 332-339. (in Japanese)
13. K. Saeki, Y. Hashimoto, *J. Jap. Soc. Technol. Plast.*, 8-72 (1967), 34-42. (in Japanese)
14. A. Azushima, *J. Jap. Soc. Technol. Plast.*, 36-414 (1995), 737-742. (in Japanese)
15. N. Patir, H. S. Cheng, *Trans. ASME*, F100 (1978), 13.
16. A. Azushima, M. Natsui, S. Inagaki, T. Sugai, *Tetsu-to-Hagane*, 86 (2000), 755-760. (in Japanese)
17. A. Azushima, J. Kihara, I. Gokyu, *J. Jap. Soc. Technol. Plast.*, 18-196 (1977), 337-343. (in Japanese)
18. A. Azushima, K. Noro, Y. Iyanagi, H. Degawa, *Tetsu-to-Hagane*, 76 (1990), 576-583. (in Japanese)
19. A. Azushima, *Tetsu-to-Hagane*, 80 (1994), 635-640. (in Japanese)
20. A. Azushima, *Proc. 7th Intern. Conf. Steel Rolling*, (1998), 473-478.
21. K. Baba, M. Iwasaki, *J. Jap. Soc. Technol. Plast.*, 13-139 (1972), 609-617. (in Japanese)
22. A. Azushima, K. Noro, Y. Iyanagi, *J. Jsp. Soc. Tribologists*, 34-12 (1988), 879-886. (in Japanese)
23. K. Nakajima, Y. Shibata, Y. Kamibori, *Proc. Spring Conf. Technol. Plast.* (1979), 379-382. (in Japanese)
24. H. Hamaguchi, H. A. Spikes, A. Cameron, *Wear*, 43 (1977), 17-24.
25. Y. Kimura, K. Okada, *Tribologist*, 34(1989), 200-207. (in Japanese)
26. T. Nakahara, S. Shiokawa, K. Kyogoku, *Tribologist*, 33(1990), 907-913. (in Japanese)
27. D. Zhu, G. S. Biresaw, J. Clark, T. J. Kasun, *Trans. ASME, J. Tribology*, 116 (1994), 310-320.
28. W. R. D. Wilson, Y. Sakaguchi, S. R. Schmid, *Tribology Trans.* 37 (1994), 543-551.
29. S. R. Schmid, W. R. D. Wilson, *Tribology Trans.* 38 (1995), 452-458.
30. A. Azushima, K. Noro, *J. Jap. Soc. Technol. Plast.*, 39-455 (1989), 1238-1241. (in Japanese)
31. A. Azushima, S. Inagaki, *Tribology Trans.* 52 (2009), 427-434.
32. S. Cassarini, M. Laugier, P. Montmitonnet, *Proc. ICTMP (Yokohama)*, (2007), 713-720.

33. A. Azushima, K. Noro, Y. Iyanagi, Proc. Spring Conf. Plast. Technol., (1987), 115-118. (in Japanese)
34. A. Azushima, S. Inagaki, Tribology Trans. 54 (2011), 685-690.
35. A. Azushima, J. Jap. Soc. Technol. Plast., 29-328 (1988), 493-497. (in Japanese)
36. A. Azushima, Y. Kita, K. Hashiyama, Proc. Spring Conf. Plast. Technol., (1986), 155-158. (in Japanese)
37. Y. Jimbo, T. Hirosige, A. Azushima, Tetsu-to-Hagane, 84 (1998), 423-428. (in Japanese)
38. T. Mase, H. Yamamoto, T. Nishima, J. Jap. Lub. Engr. 27 (1982), 552.
39. H. Tamura, H. Hosono, K. Toguchi, Y. Kobayashi, Proc. Spring Conf. Technol. Plast., (1979), 387-390.
40. Y. Kimura, K. Okada, J. Jap. Soc. Lub. Engr., 29 (1984), 809-816. (in Japanese)
41. A. Azushima, Tetsu-to-Hagane, 74 (1988), 696-702. (in Japanese)
42. A. Azushima, Y. Kita, T. Shima, M. Mitsunashi, Tetsu-to-Hagane, 74 (1988), 1978-1985. (in Japanese)
43. A. Azushima, Y. Kita, 76 (1990), 1270-1275. (in Japanese)
44. A. Azushima, Y. Morita, T. Inoue, Tetsu-to-Hagane, 76 (1990), 576-583. (in Japanese)
45. S. Iwado, Textbook of 148th Nishiyama Memorial Lecture, (1993), 37-60. (in Japanese)
46. H. Nagamori, J. Jap. Soc. Lub. Engr., 30 (1985), 109-115. (in Japanese)
47. M. Shirata, K. Sakai, J. Jap. Soc. Lub. Engr., 27 (1981), 594-599. (in Japanese)
48. T. Mase, T. Kono, H. Yamamoto, Proc. Spring Conf. Technol. Plast., (1978), 249-252. (in Japanese)
49. S. Semoto, T. Okamoto, J. Jap. Soc. Technol. Plast., 33-378 (1992), 790-796. (in Japanese)
50. A. Azushima, J. Sano, T. Yagi, Tetsu-to-Hagane, 90 (2004), 128-133. (in Japanese)
51. J. Kihara, S. Sukumoda, A. Manba, Tetsu-to-Hagane, 73 (1987), 528-535. (in Japanese)
52. T. Mori, M. Jitsukawa, K. Shiraishi, Proc. Spring Conf. ISIJ, (1991), 470-473. (in Japanese)
53. M. Kobayashi, T. Yamada, F. Kosumi, K. Ueda, K. Aoki, Proc. Spring Conf. ISIJ, (1991), 474-477. (in Japanese)
54. T. Izushi, J. Jap. Soc. Technol. Plast., 32-363 (1991), 458-463. (in Japanese)
55. M. Nakagawa, M. Sobue, M. Taguchi, Tetsu-to-Hagane, 76 (1990), 406-413. (in Japanese)
56. A. Azushima, Y. Jimbo, T. Kaneda, Tetsu-to-Hagane, 81 (1995), 64-69. (in Japanese)
57. A. Azushima, Y. Jimbo, Tetsu-to-Hagane, 81 (1995), 1150-1155. (in Japanese)
58. A. Azushima, Y. Jimbo, Tetsu-to-Hagane, 83 (1997), 359-364. (in Japanese)
59. Y. Jimbo, A. Azushima, IJMTM, 41 (2001), 347-369.
60. A. Azushima, Y. Morita, ISIJ International, 32 (1992), 1232-1237.

Chapter 5

Tribology in Hot Sheet Rolling

5.1 Tribology in Hot Sheet Rolling in History

In the late 1960s, rolling oils in hot sheet rolling were used in Europe and the United States. In Japan, the rolling oils have begun to be used in hot sheet rolling in the 1970s, and the use of the rolling oils has achieved significant results in the reductions of rolling load and roll wear.

5.1.1 *Actual Hot Tandem Mill*

Figure 5.1 shows the rolling power ratio of mechanical loss energy, friction energy in rolling and deformation energy in rolling in actual hot tandem mill [1]. From Fig. 5.1, it can be substantially understood that the friction energy in hot rolling accounts for a large ratio in the rolling power. In particular, the ratio of the friction energy is larger than 50 % in the third, fourth, fifth, and sixth stands. It is expected that the rolling power decreases by the use of rolling oils.

Next, Fig. 5.2 shows the comparison between the rolling powers without lubricant and with lubricant in hot sheet rolling [2]. The rolling power decreases by the use of lubricant in the actual hot tandem mill. Moreover, Fig. 5.3 shows the comparison between the rolling loads with lubricant and without lubricant [3]. The rolling load also decreases by the use of lubricant in the actual hot tandem mill. In Japan, the use of rolling oil in the actual hot sheet tandem mill began in parallel with the fundamental data obtained from experiments in the laboratory mill or the simulator.

Then, the rolling load (a) and the rolling power (b) measured at a certain stand in the actual tandem mill were shown in Fig. 5.4 [3]. In this hot sheet rolling, the lubricant was applied after biting and it was cut before finishing. In Fig. 5.4, it can

Fig. 5.1 Rolling power ratio of mechanical loss energy, friction energy in rolling and deformation energy in rolling [1]

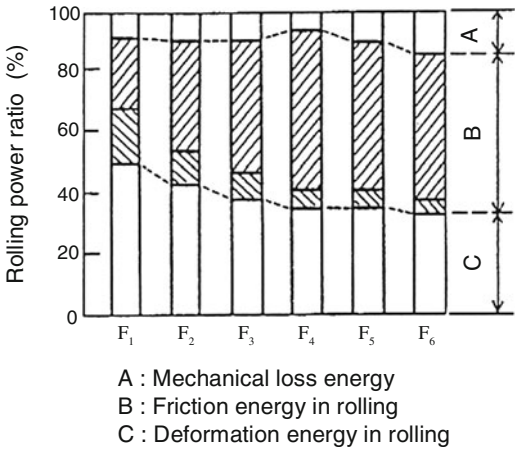
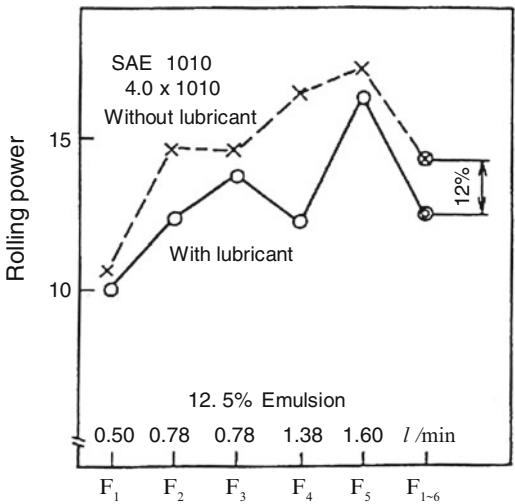


Fig. 5.2 Comparison between the rolling powers without lubricant and with lubricant in hot rolling [2]



be clearly recognized that the rolling load and the rolling power decreased by the application of the lubricant.

Next, the use of the lubricant is also effective for the roll wear. Figure 5.5 shows the comparison between the surface profiles of rolls after rolling with lubricant and without lubricant in the actual tandem mill [4]. From Fig. 5.5, it can be clearly recognized that the roll wear after rolling with lubricant becomes smaller compared to that after rolling without lubricant.

At the same time, the relationships between wear in diameter and rolling amount in the rolling with lubricant and without lubricant are shown in Fig. 5.6. The wear volume of roll after rolling with lubricant is one fourth of that after rolling without lubricant, so it is expected that the roll life becomes four times using rolling oil in actual hot tandem mill.

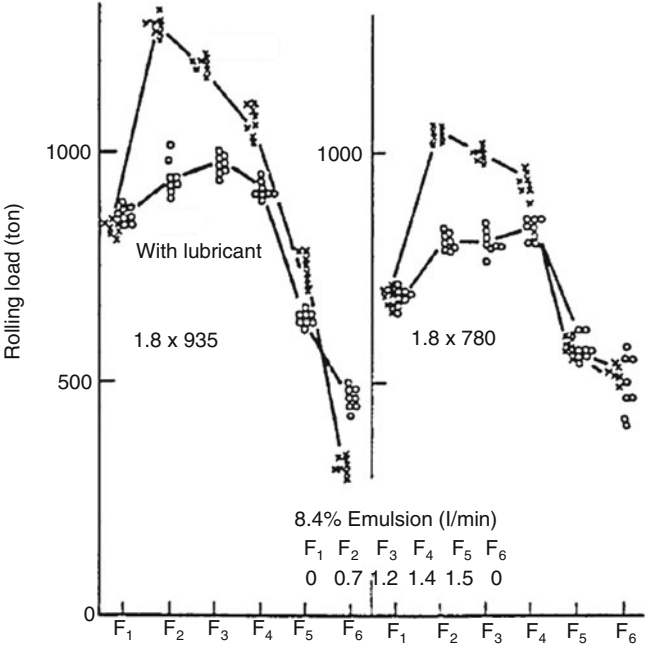


Fig. 5.3 Comparison between the rolling loads with lubricant and without lubricant [2]

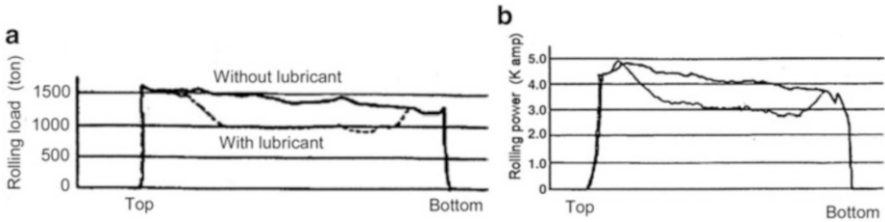


Fig. 5.4 Rolling load (a) and rolling power (b) measured in actual tandem mill [3]

5.1.2 Laboratory Mill

5.1.2.1 Effect of Lubricant on Rolling Load

Nishizawa et al. [5] examined the effect of the composition of base oils on the rolling load. Figure 5.7 shows the relationship between the reduction rate of rolling load and reduction in the rolling with different base oils. The rolling load with lubricant is lower from 10 to 20 % compared to that without lubricant. It depends on the reduction, and the reduction rate increases with increasing reduction. In this experiment, it is less dependent on the composition of base oils.

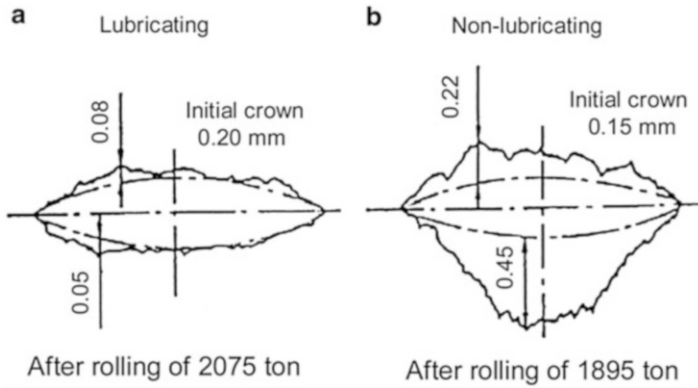


Fig. 5.5 Comparison between surface profiles of rolls after rolling with lubricant (a) and without lubricant (b) in actual tandem mill [4]

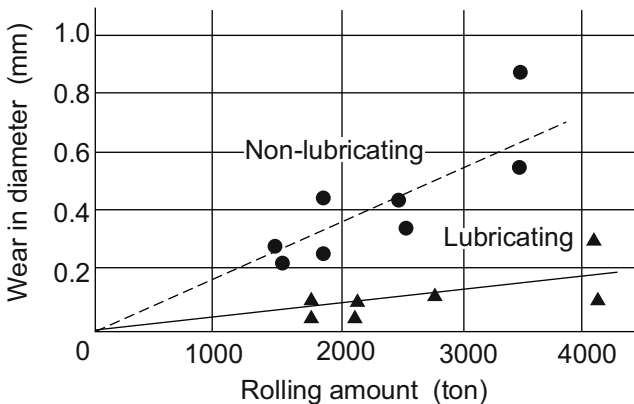


Fig. 5.6 Relationships between wear in diameter and rolling amount at rolling with lubricant and without lubricant [4]

Then, Kihara et al. [6] examined the effect of the compositions of base oil on the rolling pressure in detail using the laboratory mill. They used the rolling oils with different ratios of tallow oil to mineral oil. Figure 5.8 shows the relationship between the rolling pressure and reduction (a) and the relationship between the rolling pressure and concentration ratio of the tallow oil at a reduction of 0.46. The rolling pressure decreases with increasing concentration ratio of the tallow oil up to 20 %, and above 20 %, it becomes almost constant.

Ueda et al. [7] examined the effect of the additive on the rolling load. Figure 5.9 shows the effect of the fatty acids on the rolling load. They used stearic acid, oleic acid, and linoleic acid as fatty acids. The reduction rate of rolling load increases with increasing concentration of each fatty acid. The reduction rate of stearic acid added as lubricant is larger than those of other acids. It is estimated that stearic acid

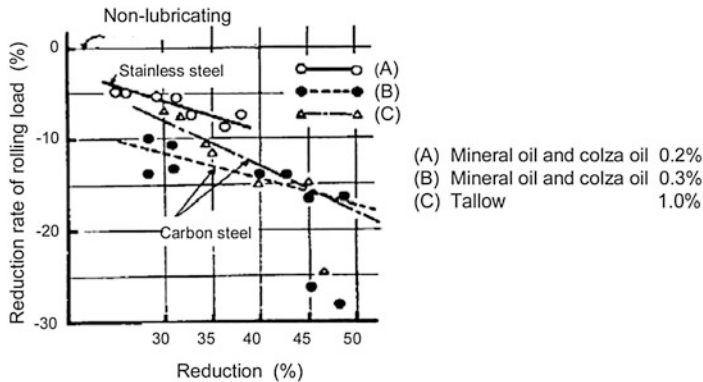


Fig. 5.7 Relationship between the reduction rate of rolling load and reduction [5]

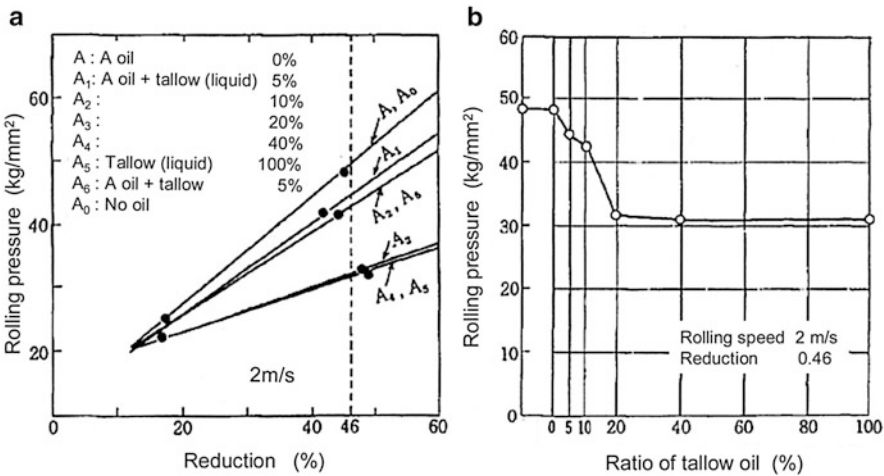


Fig. 5.8 Relationship between rolling pressure and reduction (a) and relationship between rolling pressure and concentration ratio of tallow oil (b) [6]

is effective in reducing the rate of rolling load compared to the unsaturated acids in hot rolling.

Next, Tasiro et al. [8] examined the rolling pressures in the rolling with water, emulsion, and neat oil. Figure 5.10 shows the relationship between the rolling pressure and reduction in the rollings with the water, the emulsion, and the neat oil. The rolling pressure of the water is the largest compared to those of the other rolling oils, and the difference increases with increasing reduction. The rolling pressure of the neat oil is smaller than those of the two emulsions, and the rolling pressure depends on the emulsion concentration. In this experiment, it was shown that the rolling pressure for the emulsion depended on the roll surface roughness, and in the case of the rolls with larger surface roughnesses, the rolling pressure for the emulsion with lower concentration was close to that for the water.

Fig. 5.9 Effect of fatty acids on rolling load [7]

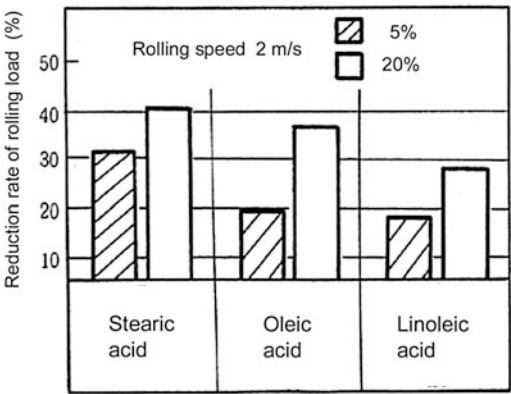
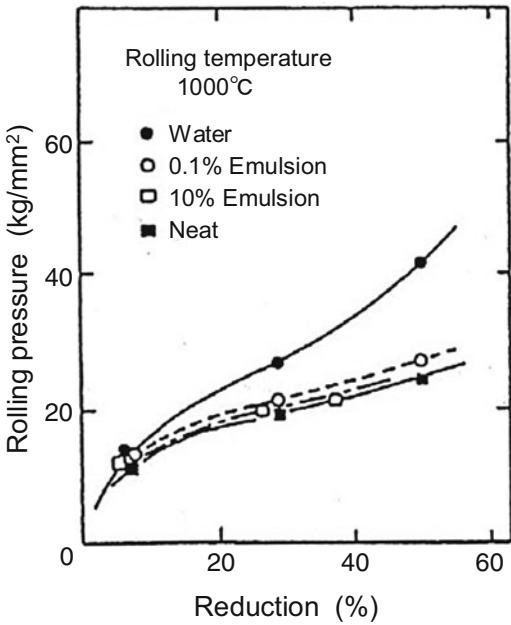


Fig. 5.10 Relationship between the reduction rate of rolling pressure and reduction [8]



5.1.2.2 Effect of Tribological Factor

Hira et al. [9] examined the effect of plating-out oil film thickness on the rolling surface pressure. Figure 5.11 shows the relationship between the rolling load and plating-out oil film thickness. The rolling load decreases abruptly with increasing oil film thickness plated out on the roll surface up to an oil film thickness of about 0.5 μm , and over 0.5 μm , it becomes almost constant.

In hot sheet rolling, when the lubricant is used in actual tandem mill, the coefficient of friction becomes lower, so the slipping at biting is likely to occur.

Fig. 5.11 Relationship between rolling load and oil film thickness [9]

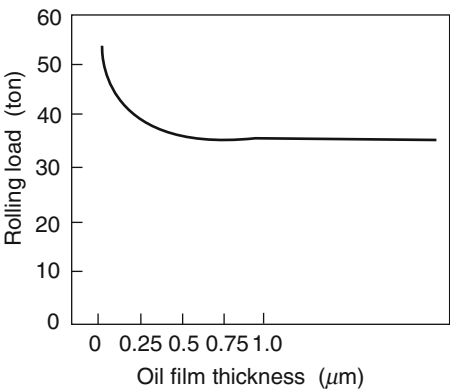


Fig. 5.12 Relationship among maximum biting angle, coefficient of friction, and rolling speed [1]

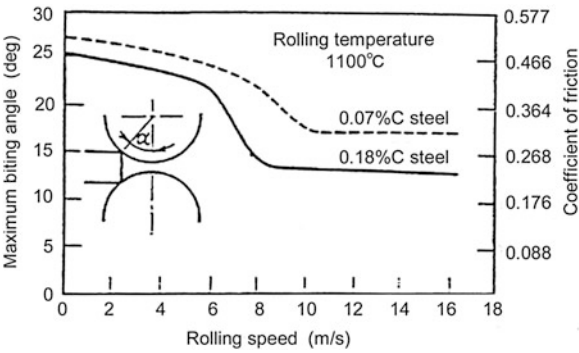


Figure 5.12 shows the relationship among maximum biting angle, coefficient of friction, and rolling speed.

5.2 Coefficient of Friction

5.2.1 Coefficient of Friction in History

The coefficients of friction in cold sheet rolling have been calculated from the measured rolling force using the equation of rolling pressure and the friction equation of Eqn. (2.1). However, the coefficient of friction for hot sheet rolling was calculated from the normal load and the tangential force measured using the tribo-simulator in contrast to the method in cold sheet rolling. Nishizawa et al. [5] measured the coefficient of friction using the sliding type tribo-simulator shown in Fig. 5.13.

In this experiment, the sliding experiments were carried out in 10 s and then the supply of lubricant was stopped using seven rolling oils. Figure 5.14 shows the relationship between coefficient of friction and rolling time. During the sliding,

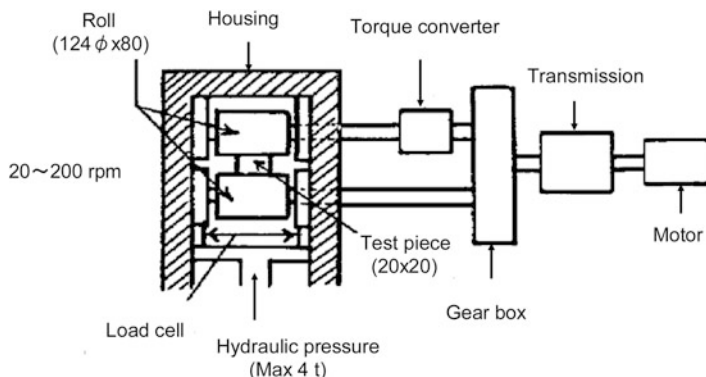


Fig. 5.13 Schematic representation of sliding type tribo-simulator [5]

the coefficient of friction is constant, and after stopping the rolling oil, the coefficient of friction increases abruptly. From the two properties of the coefficient of friction, the evaluation of the rolling oil for hot sheet rolling is carried out. The good rolling oil is evaluated when the constant coefficient of friction is low and then the increase in the rate of coefficient of friction is small. From these results, the tallow oil and the venta erythritol ester oil are evaluated as the good hot rolling oils.

Inoue et al. [10] measured the coefficient of friction of 11 grease base oils for the hot sheet rolling using the SRV testing machine. The compositions of rolling oils used are shown in Table 5.1. The SRV experiments were carried out at a load of 98 N, a frequency of 5 Hz, an amplitude of 2 mm, and temperatures of 500, 600, 700, and 800 °C. During the SRV tests, the rolling oil was supplied 0.5 cc every 5 s on the disk surface using a syringe.

Figure 5.15 shows the relationship between coefficient of friction and temperature. For the rolling oils of B, C, D, E, and K in Fig 5.15a, the coefficient of friction at a temperature of 800 °C increases abruptly compared to those under 700 °C. For the rolling oils of A, F, G, H, I, and J in Fig. 5.15b, the coefficient of friction at a temperature of 800 °C is similar to those under 700 °C. From these results, it is understood that the solid lubricants of Ply-1, graphite, and KPO 3 are effective for the lubricity in hot sheet rolling.

Next, Hibi et al. [11] measured the coefficients of friction of three rolls of Ni-Gr, Hi-Cr, and HSS using the hot Timken testing machine. Figure 5.16 shows the comparison among the coefficients of friction of three rolls using two oils of ester and ester with Ca compound. For the ester oil, the coefficient of friction increases in the order of Ni-Gr roll, Hi-Cr roll, and HSS roll. On the other hand, for the ester oil with Ca super fine particle compound, the coefficient of friction decreases in the order of Ni-Gr roll, Hi-Cr roll, and HSS roll.

Later, Inoue et al. [12] measured the coefficient of friction of ten grease base lubricants with solid lubricants for the hot sheet rolling using the hot rolling wear tester shown in Fig. 5.17 [13]. The compositions of lubricants used are shown in

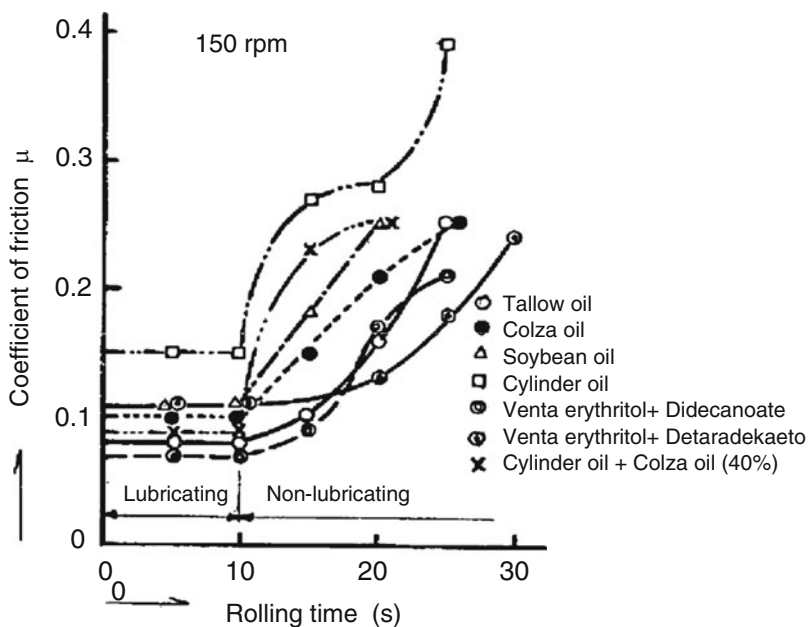


Fig. 5.14 Relationship between coefficient of friction and rolling time [5]

Table 5.1 Composition of rolling oils used [10]

Lub-A	Li-grease + poly-1 (5 wt%)
Lub-B	Li-grease + poly-2 (5 wt%)
Lub-C	Li-grease + poly-3 (5 wt%)
Lub-D	Li-grease + poly-4 (5 wt%)
Lub-E	Li-grease + poly-5 (5 wt%)
Lub-F	Li-grease + graphite (10 wt%)
Lub-G	Li-grease + KPO_3 (10 wt%)
Lub-H	Li-grease + graphite (10 wt%) + KPO_3 (10 wt%)
Lub-I	Li-grease + graphite (10 wt%) + poly-1 (5 wt%)
Lub-J	Li-grease + graphite (10 wt%) + KPO_3 (10 wt%) + poly-1 (5 wt%)
Lub-K	Li-grease

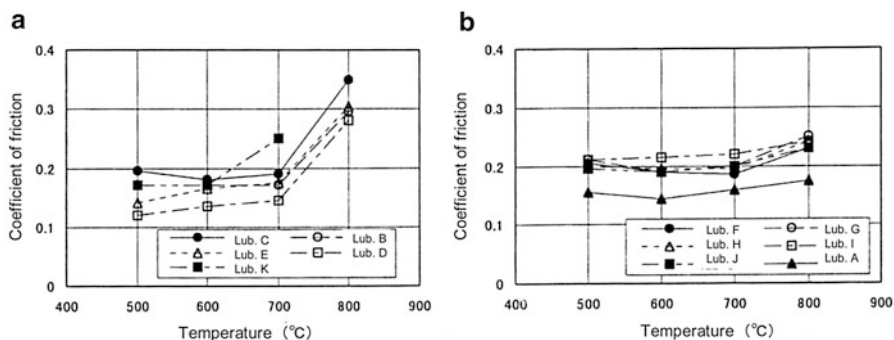


Fig. 5.15 Relationship between coefficient of friction and temperature [11]

Fig. 5.16 Comparison among coefficients of friction for three rolls [11]

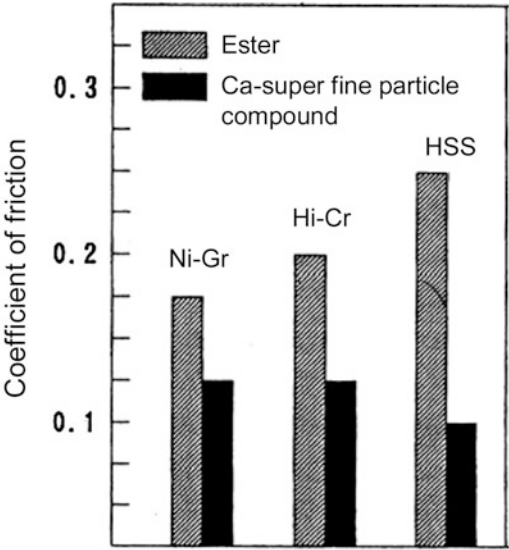


Fig. 5.17 Schematic representation of hot rolling wear tester [13]

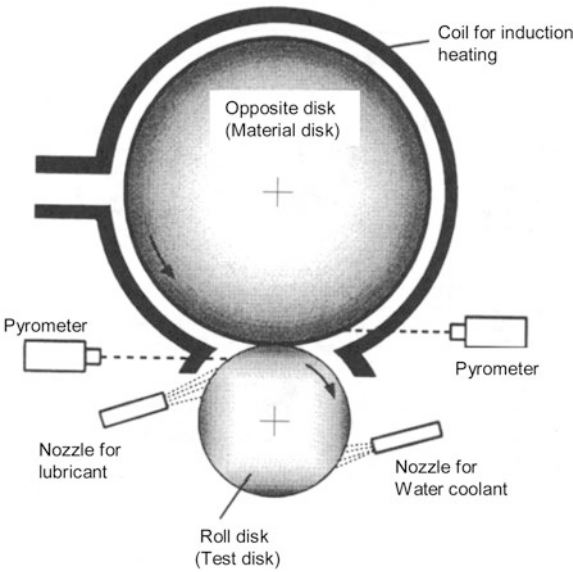


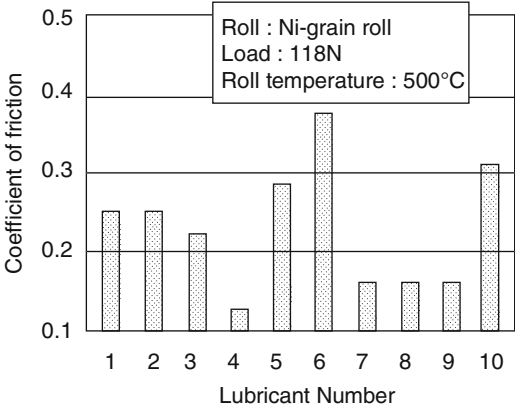
Table 5.2. The experiments were carried out at a load of 118 N, a velocity of test disk of 126 m/min, a slip ratio of 10 %, and a roll temperature of 500 °C.

Figure 5.18 shows the coefficient of friction of ten lubricants. The coefficients of friction of Nos. 4, 7, 8, and 9 lubricants are smaller than that of No. 1 lubricant of Li-grease.

Table 5.2 Compositions of lubricants used [12]

No.	Liquid lubricants	Solid lubricants (mass%)		
		Graphite	Mica	KPO ₃
1	Li-grease	0	0	0
2		10	0	0
3		0	10	0
4		0	0	10
5		10	0	10
6		0	10	10
7		5	5	10
8	Ester	0	10	0
9		0	10	10
10	Mineral oil	0	0	0

Fig. 5.18 Coefficient of friction of ten oils [12]



5.2.2 Coefficient of Friction Measured by SRV Testing Machine

From the research results of the coefficient of friction in hot sheet rolling in Sect. 5.2.1, the evaluation system of the oils for hot sheet rolling by means of the coefficient of friction measured by the new measuring method in the SRV testing machine was proposed by Azushima et al. [14]. Figure 5.19 shows the schematic representation of SRV testing machine (a) and new measuring method (b). The SRV tests are carried out at a test load of 400 N, a stroke of 1 mm, a frequency of 80 Hz, and a temperature of 500 °C. The new measuring method is explained as follows: first, the test is carried out under dry condition during 60 s, and then one drop of oil at an interval of 4.5 s is supplied on the disk surface using a micro-tube pump shown in Fig. 5.19b. Table 5.3 summarizes the compositions of rolling oils used.

Figure 5.20 shows the relationship between coefficient of friction and testing time at one dropped oil (a), two dropped oils (b), three dropped oils (c), and

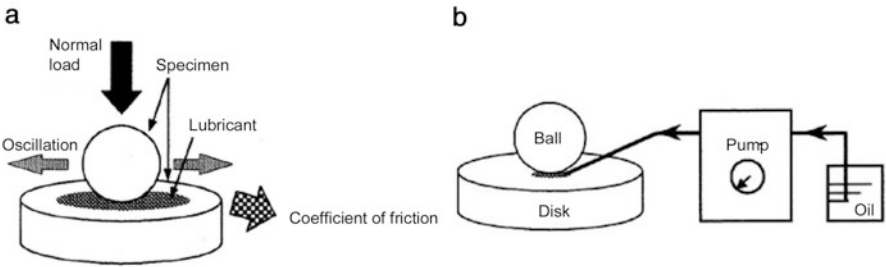


Fig. 5.19 Schematic representation of SRV testing machine (a) and new measuring method (b)

Table 5.3 Compositions of rolling oils used

Lubricant	Compositions
A	Colza oil
B	Mineral oil with high viscosity
C	Mineral oil with low viscosity
D	Synthetic ester
A1	Colza oil (95 %) + oleic acid (5 %)
A2	Colza oil (95 %) + fatty oil sulfide (5 %)
A3	Colza oil (90 %) + graphite (10 %)
A4	Colza oil (90 %) + MoS ₂ (10 %)
A5	Colza oil (90 %) + mica (10 %)
E	Base oil (≥95 %) + additive agent (≤5 %)
F	Base oil (60–70 %) + additive agent (30–40 %)

continuous dropped oils (d) using oil A. The coefficient of friction decreases rapidly from a high value under dry condition to a low value under lubricated condition after dropped oil. On the other hand, after stopping the dropped oil, the coefficient of friction increases rapidly from the low value to the high value.

From these experimental results, the relationship between coefficient of friction and testing time at three dropped oils is used in order to evaluate the lubricity of lubricants for hot rolling. Figure 5.21 shows the relationship between coefficient of friction and testing time for the lubricants of A, B, C, and D. In the new measuring method using the SRV testing machine, the significant difference among the coefficients of friction of lubricants with different compositions cannot be observed. However, it is expected that the change of the coefficient of friction after stopping the dropped oil is affected by the lubricity of lubricants.

Figure 5.22 shows the relationships between coefficient of friction and testing time for the colza oil A and the colza oils with different additives of A1 to A5. From Fig. 5.22, it is observed that the increase rate of coefficient of friction after stopping dropped oils depends on the additive in oil. The increase rate of the lubricant of A2 is smaller compared to those of the other lubricants, so it can be recognized that the additive of sulfide is most effective for the lubricity of lubricant in hot sheet rolling.

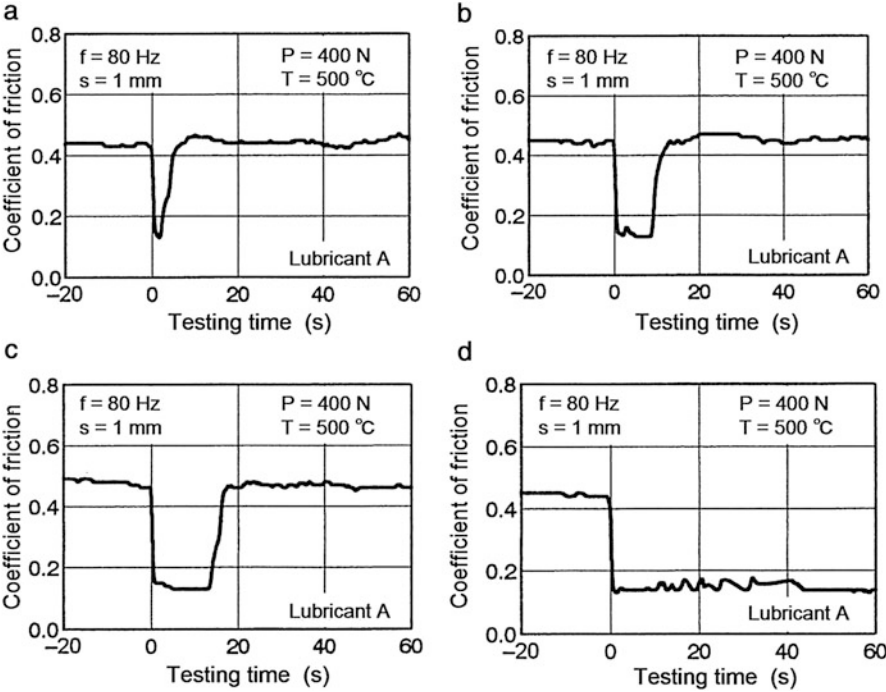
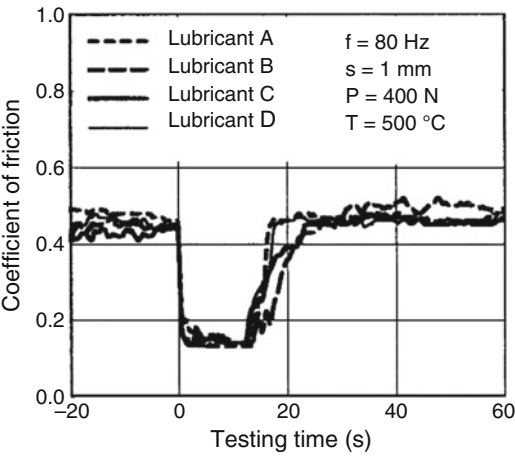


Fig. 5.20 Relationship between coefficient of friction and testing time at one dropped oil (a), two dropped oils (b), three dropped oils (c), and continuous dropped oils (d)

Fig. 5.21 Relationships between coefficient of friction and testing time for lubricants of A, B, C, and D



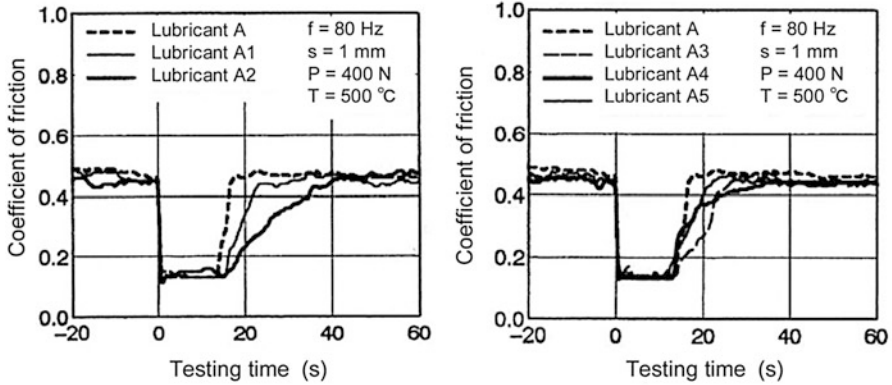


Fig. 5.22 Relationships between coefficient of friction and testing time for colza oil A and colza oils with additives of A1 to A5

5.2.3 Coefficient of Friction Measured by Hot Sliding-Rolling Type Tribo-Simulator Newly Developed

5.2.3.1 Hot Sliding-Rolling Type Tribo-Simulator

Azushima et al. [15, 16] developed a new tribo-simulator in hot sheet rolling for the tribo-simulation of the tribological results. The conceptual representation of the tribo-simulator for hot sheet rolling is shown in Fig. 3.21. In the hot sliding-rolling type tribo-simulator, when the roll speed is V , the entrance speed of workpiece is one twenty $V/20$. Figure 5.23 shows the side view of new hot tribo-simulator, and the specification of tribo-simulator is summarized in Table 5.4.

The roll speed in the sub-stand becomes one twenty $V/20$ of the roll speed V in the main stand by the reducing gear. The workpiece sheet is rolled by the sub-stand and moves at a constant speed of $V/20$. The sliding-rolling is carried out in the main stand changing the roll speed, the reduction, and the rolling oil. In the main stand, the roll speed of the upper roll is V and the under roll drives at the same speed of workpiece $V/20$. The maximum stroke of the tension device is 1 m and the forward tension can be changed up to 3.5 kN. In the infrared image furnace, 48 infrared image lamps are installed. The atmosphere in the furnace is controlled by Ar gas.

The rolling force P , the torque of upper roll G , and the back tension T_b are measured during sliding-rolling. The coefficient of friction is calculated by the rolling force and the torque of upper roll using Eqn. (3.46) as follows:

$$\mu = \frac{G}{PR} \quad (3.46)$$

Figure 5.24 shows the schematic representation of the measuring method of coefficient of friction. As shown in Fig. 5.24a, the sheet is first set on the table and a

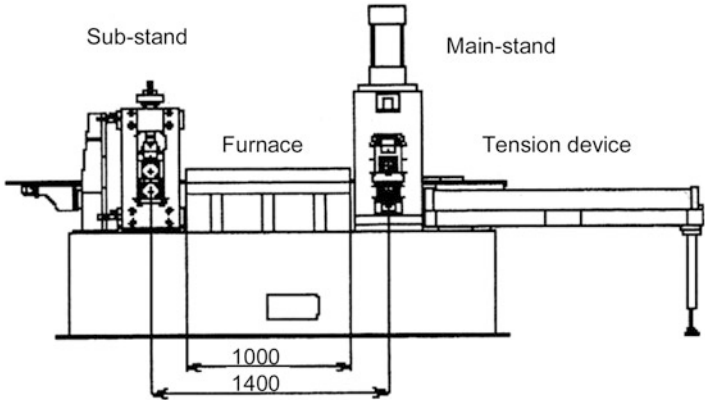


Fig. 5.23 Side view of new hot tribo-simulator

Table 5.4 Specification of tribo-simulator

Velocity of main roll	U	≤ 207 m/min
Ratio of velocity	R_v	6.3–24
Velocity of sub-roll	v	≤ 32 –8 m/min
Rolling load	P	200kN
Rolling torque	G	≤ 800 Nm
Furnace temperature	T_f	≤ 1100 °C
Forward tension	T_F	≤ 3.5 kN

load of about 26 kN is applied at the sub-stand. Then, the sheet end is clumped with the cluck part of the tension device, and a load of about 0.9 kN is applied. The sheet is heated at a given temperature during a constant time using the infrared image furnace. As shown in Fig. 5.24b, the sheet with a front tension secondly moves to the main stand by rolling in the sub-stand. Next, as shown in Fig. 5.24c, when the heated zone of the sheet comes to the main stand, the heated sheet is compressed at a given rolling load by the upper roll and the sheet is rolled at a constant speed.

In order to examine the property of infrared image furnace, the temperature of the sheet during heating and then during moving is measured. Figure 5.25 shows the relationship between the temperature of sheet and time (a) and the relationship between the temperature and moving distance (b). The furnace temperature becomes a constant temperature of 770 °C after 60 s. On the other hand, the sheet temperature increases abruptly up to 120 s; after 120 s, it increases gradually with increasing time; and above 360 s, it remains constant. From these results, after the sheet is held in the furnace for 360 s, the sheet moves at a speed of 1.5 m/min. From Fig. 5.25b, it is found that the sheet can be rolled at about 800 °C.

Figure 5.26 shows the relationship between coefficient of friction and rolling reduction (a) and the relationship between coefficient of friction and roll speed (b). It is found that the coefficients of friction are independent of the rolling reduction and the roll speed.

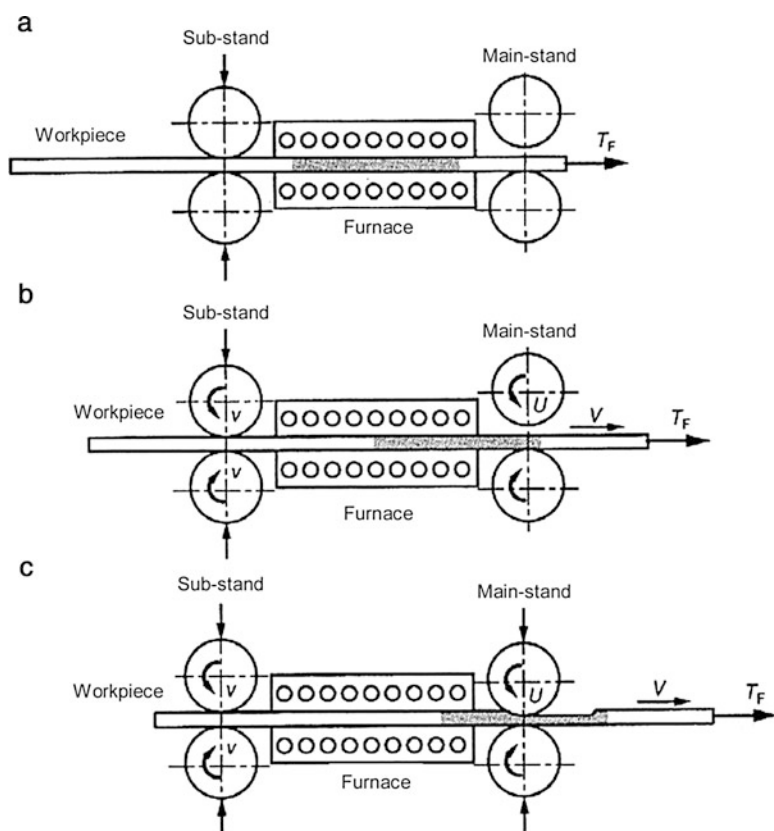


Fig. 5.24 Schematic representation of measuring method. (a) Heating of specimen, (b) moving specimen for loading in the main stand, (c) slip rolling in the main stand

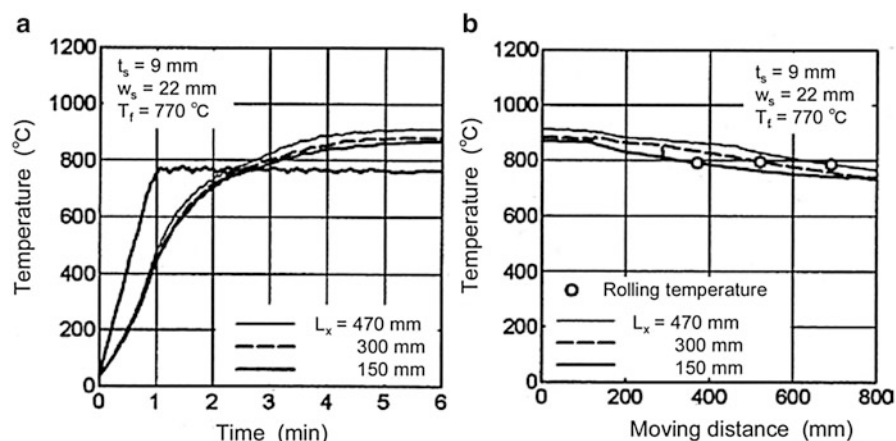


Fig. 5.25 Relationship between temperature of sheet and time (a) and relationship between temperature and moving distance (b)

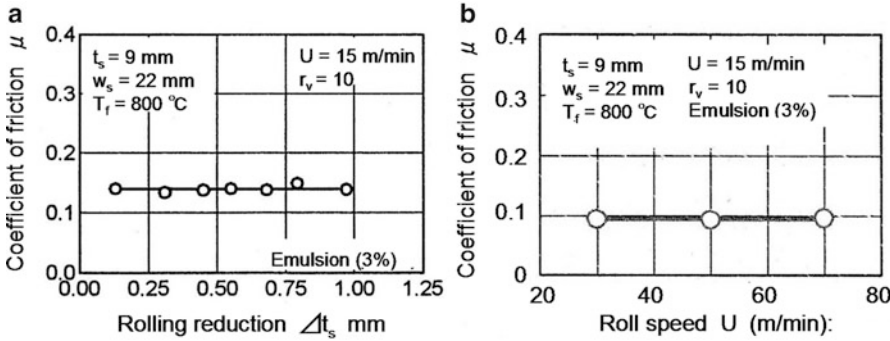


Fig. 5.26 Relationship between coefficient of friction and rolling reduction (a) and relationship between coefficient of friction and roll speed (b)

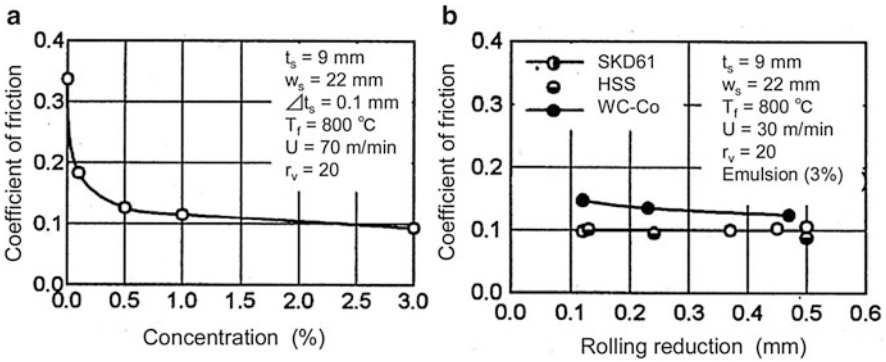


Fig. 5.27 Relationships between coefficient of friction and emulsion concentration (a) and between coefficient of friction and rolling reduction for roll materials of SKD61, HSS, and WC-Co (b)

Then, Fig. 5.27 shows the relationship between coefficient of friction and emulsion concentration (a) and the relationship between coefficient of friction and rolling reduction for roll materials of SKD61, HSS, and WC-Co (b). The coefficient of friction depends on the emulsion concentration. It decreases with increasing emulsion concentration up to 1.0 %, and above 1.0 %, it becomes constant. In Fig. 5.27b, the coefficient of friction also depends on the roll material. The coefficient of friction of WC-Co roll depends on the rolling reduction, and it is higher than those of SKD61 and HSS rolls.

5.2.3.2 Effect of Surface Roughness of Roll on Coefficient of Friction

The effect of the surface roughness of roll on the coefficient of friction was examined using the hot sliding-rolling type tribo-simulator by Azushima et al. [17]. The used

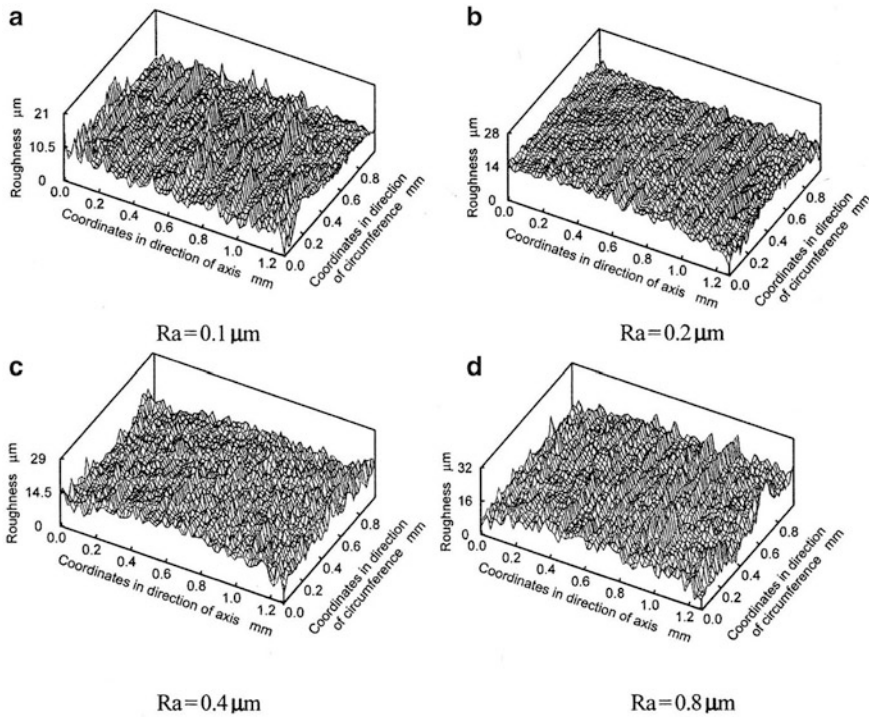


Fig. 5.28 Three-dimensional surface profiles of rolls with surface roughnesses of 0.1, 0.2, 0.4, and 0.8 μmRa

rolls are SKD61 with surface roughnesses of 0.1, 0.2, 0.4, and 0.8 μmRa , and the three-dimensional surface profiles are shown in Fig. 5.28. The sliding-rolling experiments are carried out using the SPHC sheet and the SKD61 roll at roll speeds of 30, 50, and 70 m/min, at rolling reductions of 0.1, 0.3, and 0.5 mm and at a temperature of 800 °C. The colza oils with emulsion concentrations of 0.1 and 3.0 % at 40 °C are used.

Figure 5.29 shows the relationships between coefficient of friction and surface roughness of roll in the rolling reductions of 0.1, 0.3, and 0.5 mm at an emulsion concentration of 3.0 % (a) and 0.1 % (b). For the emulsion concentration of 3.0 %, the coefficient of friction is independent of the rolling speed and the surface roughness is up to 0.2 μmRa . The coefficients of friction up to a surface roughness of 0.2 μmRa are constant and above 0.2 μmRa ; the coefficient of friction increases slightly with increasing surface roughness. For the emulsion concentration of 0.1 %, the coefficient of friction of the roll with a surface roughness of 0.2 μmRa is the smallest at higher rolling reduction, and above 0.2 μmRa , the coefficient of friction increases significantly with increasing surface roughness.

Figure 5.30 shows the relationships between coefficient of friction and surface roughness of roll at the rolling speeds of 30, 50, and 70 m/min for emulsion concentrations of 3.0 % (a) and 0.1 % (b). For the emulsion concentration of

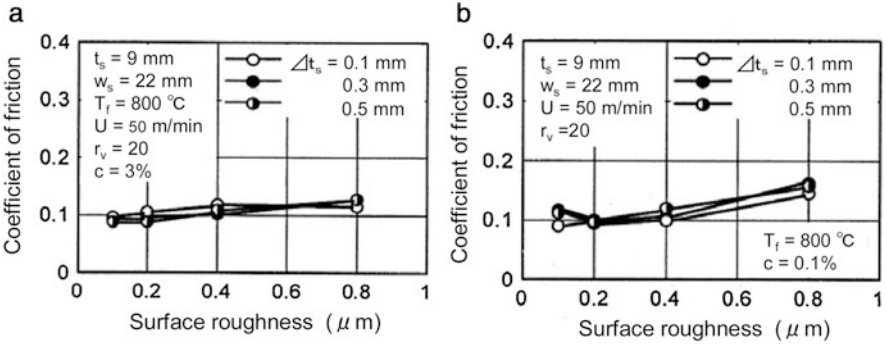


Fig. 5.29 Relationships between coefficient of friction and surface roughness of roll in rolling reductions of 0.1, 0.3, and 0.5 mm. (a) 3.0 %, (b) 0.1 %

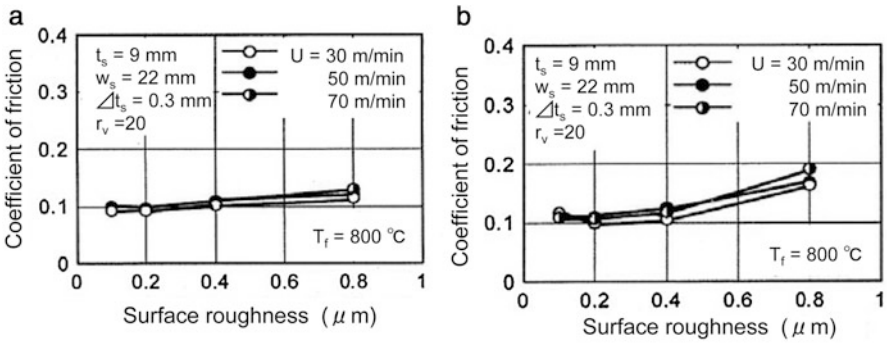


Fig. 5.30 Relationships between coefficient of friction and surface roughness of roll in rolling speeds of 30, 50, and 70 m/min. (a) 3.0 %, (b) 0.1 %

3.0 %, the coefficient of friction is independent of the rolling speed and the surface roughness is up to 0.2 μmRa . The coefficient of friction above 0.2 μmRa increases slightly with increasing surface roughness and rolling speed. For the emulsion concentration of 0.1 %, the coefficient of friction of the roll with a surface roughness of 0.2 μmRa is the smallest. Above 0.2 μmRa , the coefficient of friction increases significantly with increasing surface roughness, and it increases slightly with increasing rolling speed.

5.3 Lubrication Mechanism

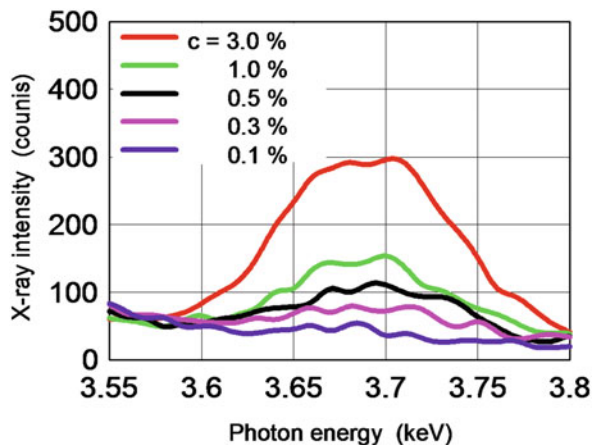
As shown in Sect. 4.2, the lubrication regime in cold sheet rolling can be classified into the plastohydrodynamic lubrication, micro-plastohydrodynamic lubrication, the mixed lubrication, and the boundary lubrication by the λ value. However, in

hot sheet rolling the lubrication behavior at the contact interface between roll and workpiece is not understood yet. In hot sheet rolling, the oil film thickness in the contact region between roll and workpiece and the lubricant behavior at the contact interface cannot be quantitatively understood. There was an interesting result of the relationship between the rolling load and oil film thickness plating out on the roll surface shown in Fig. 5.11. In Fig. 5.11, the rolling load decreases abruptly with increasing oil film thickness plating out on the roll surface up to an oil film thickness of about $0.5\text{ }\mu\text{m}$, and above $0.5\text{ }\mu\text{m}$, it becomes almost constant. Moreover, it is desired that the relationship between rolling load and oil film thickness at the contact interface should be measured.

The oil film thickness introduced at the interface between roll and workpiece in hot sheet rolling was measured by Azushima et al. [18]. In order to measure the oil film thickness introduced at the contact interface, the colza oil with a calcium sulfonate of 30 % is used as a lubricant and the emulsion concentrations of the lubricant are changed from 0.1 to 3.0 %. In order to measure the oil film thickness introduced, the amount of Ca on the sheet surface after rolling is measured using an energy-dispersive fluorescence analyzer. The sliding-rolling experiments are carried out at a roll speed of 50 m/min, a velocity ratio of 20, a rolling reduction of 0.3 mm, and a temperature of $800\text{ }^{\circ}\text{C}$ using the hot sliding-rolling type tribo-simulator. Then, the rolling load and the torque of upper roll are measured for calculating the coefficient of friction using Eqn. (3.45).

Figure 5.31 shows the distribution of the X-ray intensity for the emulsion concentrations of 0.1, 0.3, 0.5, 1.0, and 3.0 % of the colza oil with the calcium sulfonate of 30 %. The amount of Ca remaining on the sheet surface after rolling is analyzed and the peak of the X-ray intensity of Ca is situated at a photon-energy of 3.69 keV. Since the integral intensity of Ca is proportional to the oil film thickness introduced, the oil film thickness at the contact interface between roll and workpiece can be quantitatively measured. From Fig. 5.31, it can be

Fig. 5.31 Distribution of the X-ray intensity for emulsion concentrations of 0.1, 0.3, 0.5, 1.0, and 3.0 %



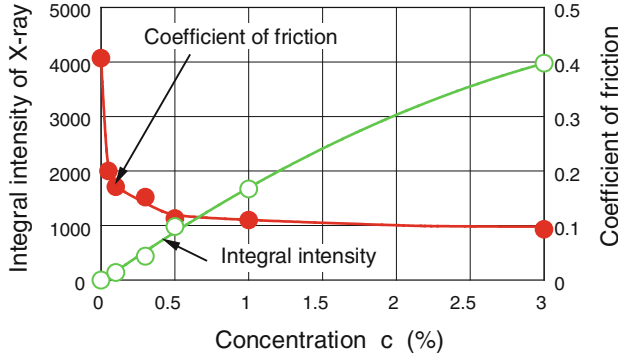


Fig. 5.32 Relationship between integral intensity of X-ray, coefficient of friction, and emulsion concentration

estimated that the oil film thickness introduced increases with increasing emulsion concentration.

Then, Fig. 5.32 shows the relationship between integral intensity of X-ray, coefficient of friction, and emulsion concentration. The integral intensity increases linearly with increasing emulsion concentration. Consequently, it is estimated that the oil film thickness introduced increases linearly with increasing emulsion concentration. On the other hand, the coefficient of friction becomes constant above an emulsion concentration of 1.0 % in spite of the increase of the oil film thickness introduced. Up to 1.0 %, the coefficient of friction decreases with increasing emulsion concentration or oil film thickness.

From these experimental results, it can be understood that the coefficient of friction becomes constant in the region where the oil film thickness introduced at the interface between roll and workpiece exceeds a certain value. On the other hand, in the region that the oil film thickness is lower than the certain value, the coefficient of friction increases with decreasing oil film thickness introduced. These results are similar to those shown in Fig. 5.11.

Figure 5.33 shows the schematic representation of the lubrication mechanism at the contact interface between roll and workpiece for the emulsion concentrations of $c > 1.0$ % (a) and $c < 1.0$ % (b) in hot sheet rolling. In the lubrication mechanism in Fig. 5.33a, the lubrication film covers the all contact interface under a mean contact pressure p_a . On the other hand, in the lubrication mechanism in Fig. 5.33b, the contact interface consists of the region covered with lubrication film and the region without the lubrication film. In the former model, the coefficient of friction becomes constant and is independent of the oil film thickness introduced at the contact interface. In the latter model, the coefficient of friction increases with the increasing ratio of the region without the lubrication film.

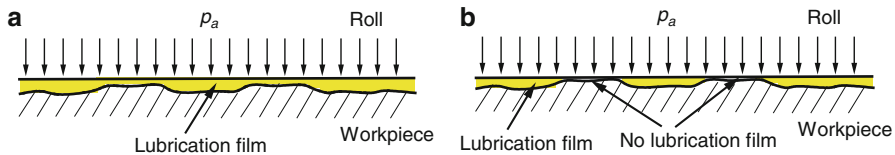


Fig. 5.33 Schematic representation of lubrication mechanism at contact interface between roll and workpiece. (a) $c > 1.0\%$, (b) $c < 1.0\%$

5.4 Friction Model

5.4.1 Emulsion Concentrations of $c > 1.0\%$

At emulsion concentrations of $c > 1.0\%$, the coefficient of friction is independent of the emulsion concentration or the oil film thickness as shown in Fig. 5.32 [18], and it is constant as follows:

$$\mu = \mu_b^h \quad (5.1)$$

where μ_b^h is the coefficient of friction indicating the properties of boundary lubrication in hot sheet rolling. From the experimental results obtained, this coefficient of friction is independent of the rolling reduction, the roll speed, the emulsion concentration, the viscosity of lubricant, the additive agent, and the roll with a surface roughness of less than $0.2\ \mu\text{m}$. On the other hand, it depends on the composition of base oil.

5.4.2 Emulsion Concentrations of $c < 1.0\%$

At emulsion concentrations of $c < 1.0\%$, the coefficient of friction decreases with increasing emulsion concentration [18]. In this region of emulsion concentration, the contact interface consists of the region covered with lubrication film and the region without the lubrication film. The coefficient of friction in the region covered with lubrication film is μ_b^h and the ratio of the region covered with lubrication film is α . The coefficient of friction in the region without the lubrication film is regarded as the coefficient of friction under water lubrication μ_w . The coefficient of friction in this region μ_{mix}^h is expressed by the next equation:

$$\mu_{mix}^h = \alpha\mu_b^h + (1 - \alpha)\mu_w \quad (5.2)$$

The effect of the composition of base oil and the additive agent on the coefficient of friction can be explained by the fact that the ratio of the region covered with lubrication film depends on the composition of base oil and the additive agent.

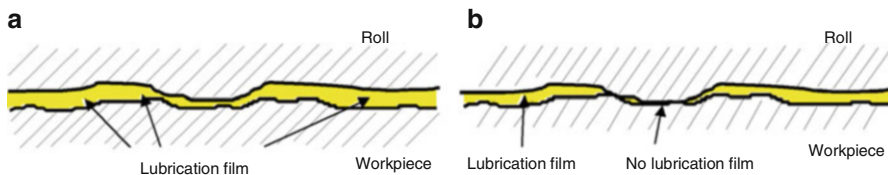


Fig. 5.34 Schematic representations of lubrication mechanism at contact interface between roll with surface roughness and workpiece with surface roughness. (a) $c > 1.0\%$, (b) $c < 1.0\%$

5.4.3 Effect of Surface Roughness of Roll on Coefficient of Friction

Next, the effect of the surface roughness of roll on the coefficient of friction was examined by Azushima et al. [17, 19]. Figure 5.34 shows the schematic representations of the lubrication mechanism at the contact interface between roll with surface roughness and workpiece with surface roughness.

At emulsion concentrations of $c > 1.0\%$, the coefficient of friction consists of the coefficient of friction indicating the properties of boundary lubrication in hot rolling and the coefficient of friction due to plowing by the asperity on roll surface, and it is expressed by

$$\mu = \mu_b^h + \mu_p \quad (5.3)$$

where μ_p is the coefficient of friction due to plowing by the asperity on roll surface. It can be understood that the coefficient of friction increases with increasing surface roughness of roll due to plowing by the asperity on roll surface above a roll surface roughness of $0.2 \mu\text{mRa}$ as shown in Figs. 5.29 and 5.30.

At emulsion concentrations of $c < 1.0\%$, the ratio of the region covered with the lubrication film depends on the surface roughness of roll, and then, the ratio changes from α to α' . The coefficient of friction is expressed by

$$\mu = \alpha' \mu_b^h + (1 - \alpha') \mu_w + \mu_p \quad (5.4)$$

The effect of the surface roughness of roll on the coefficient of friction in the region of the emulsion concentrations of $c < 1.0\%$ can be expressed using Eqn. (5.4).

5.4.4 Effect of Roll Speed on Coefficient of Friction

The effect of the roll speed on the coefficient of friction was examined using the hot sliding-rolling type tribo-simulator, and the friction model was proposed Azushima et al. [19]. The experiments are carried out using the SPHC sheet, the SKD61 roll

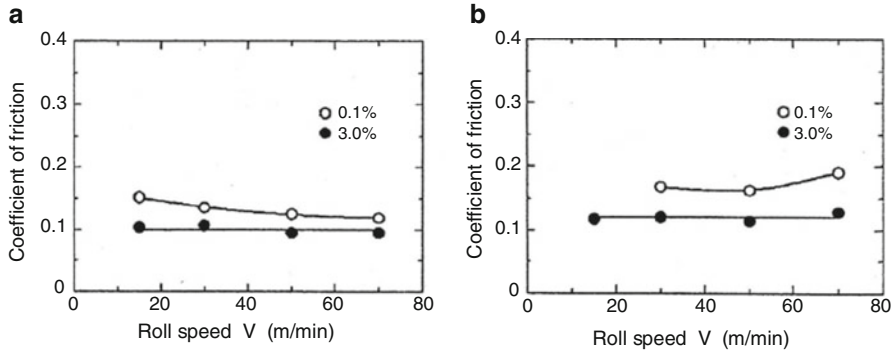


Fig. 5.35 Relationship between coefficient of friction and roll speed in emulsion concentration of 0.1 and 3.0 %. (a) 0.05 μmRa, (b) 0.8 μmRa

with surface roughnesses of 0.05 and 0.8 μmRa, and the colza oil with emulsion concentrations of 0.1 and 3.0 % at a velocity ratio of 20, a rolling reduction of 0.3 mm, a temperature of 800 °C, and roll speeds of 15, 30, 50, and 70 m/min. Figure 5.35 shows the relationship between coefficient of friction and roll speed in the emulsion concentration of 0.1 and 3.0 % for the rolls with surface roughness of 0.05 μmRa (a) and 0.8 μmRa (b).

At emulsion concentrations of 3.0 %, the coefficient of friction is independent of the roll speed and the surface roughness of roll. On the other hand, at an emulsion concentration of 0.1 %, the coefficient of friction depends on the roll speed and the surface roughness of roll. For the roll with a surface roughness of 0.05 μmRa, the coefficient of friction is expressed by Eqn. (5.2). It is estimated that the area ratio covered with the lubrication film increases with roll speed due to the reason that the oil film thickness introduced increases with increasing roll speed. Consequently, the coefficient of friction decreases with increasing roll speed.

For the roll with a surface roughness of 0.8 μmRa, it is observed that the friction pickup occurs at a roll speed of 70 m/min. Therefore, the friction pickup for the friction model must be additionally considered. If the friction pickup occurs in the region without the lubrication film, the ratio of the region is defined as β . The coefficient of friction is expressed by the next equation:

$$\mu = \alpha' \mu_b^h + (1 - \beta) \left(1 - \alpha' \right) \mu_w + \beta \left(1 - \alpha' \right) \mu_m + \mu_p \quad (5.5)$$

where μ_m is the coefficient of friction in the region in which the friction pickup occurs.

Then, the roll speed dependence on the oil film thickness introduced was examined by Azushima et al. [19]. In order to measure the oil film thickness introduced at the contact interface, the colza base oil with the calcium sulfonate of 30 % is used as a lubricant, and the emulsion concentration of the lubricant is 1.0 %. In order to measure the oil film thickness introduced, the amount of Ca on the

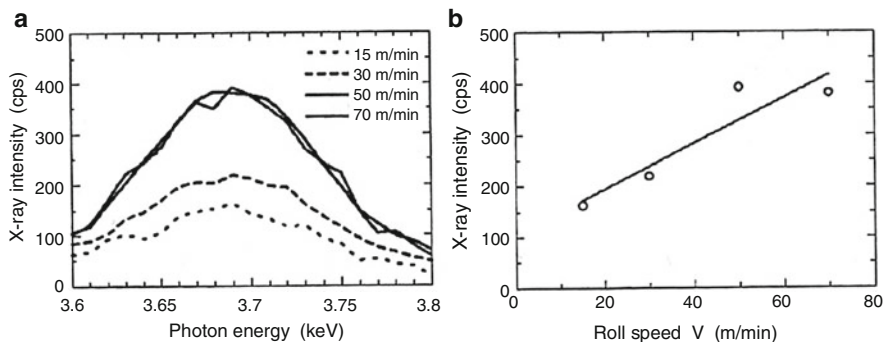


Fig. 5.36 Distribution of X-ray intensity changing roll speed (a) and relationship between X-ray intensity and roll speed (b)

sheet surface after rolling is measured using an energy-dispersive fluorescence analyzer. The experiments are carried out using the SKD61 roll with a surface roughness of $0.05 \mu\text{mRa}$ at roll speeds of 15, 30, 50, and 70 m/min, a velocity ratio of 20, a rolling reduction of 0.3 mm, and a temperature of 800°C using the hot sliding-rolling type tribo-simulator.

Figure 5.36 shows the distribution of the X-ray intensity changing the roll speed (a) and the relationship between X-ray intensity and roll speed (b). It can be understood that the oil film thickness introduced increases with increasing roll speed. From these results, at emulsion concentrations of $c < 1.0\%$, it is estimated that the coefficient of friction decreases with increasing roll speed due to the increase of the oil film thickness introduced.

5.4.5 Confirmation of Friction Law

In hot sheet rolling, the friction law of Eqn. (2.1) is widely used. In order to simplify the calculation of the rolling force and so on, the constant friction law (the shear factor friction law) of Eqn. (2.2) is rarely used. The research for the confirmation of the friction laws was carried out using the hot sliding-rolling type tribo-simulator by Azushima et al. [20].

Figure 5.37 shows the schematic representation of the main part of hot sliding-rolling type tribo-simulator. Sliding-rolling is carried out, changing the front tension T_f at constant rolling reductions of 0.3 and 0.5 mm, and the rolling load and the torque of upper roll are measured. The experiments are carried out using the SPHC sheet, the SKD61 roll, and the lubricant of the colza oil at an emulsion concentration of 3.0 %, changing the front tensions of 0.7, 2.0, and 3.0 kN at constant rolling reductions of 0.3 and 0.5 mm.

Figure 5.38 shows the relationship between rolling pressure and front tension (a) and the relationship between torque per unit width and front tension (b) at rolling

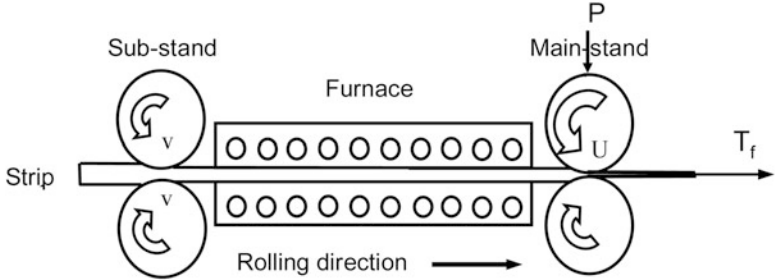


Fig. 5.37 Schematic representation of main part of hot sliding-rolling type tribo-simulator

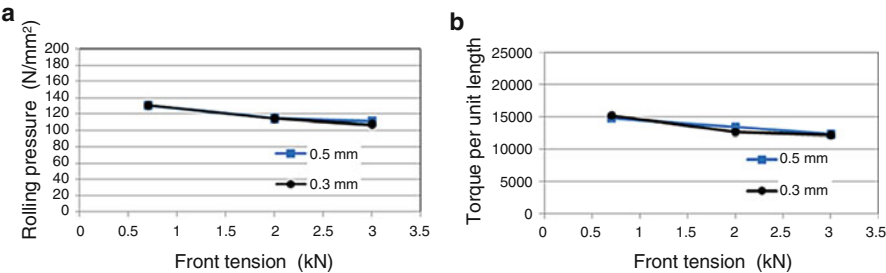
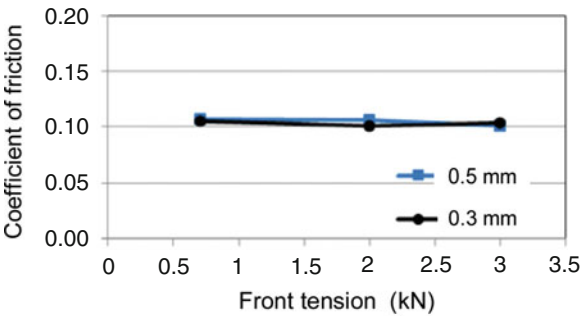


Fig. 5.38 Relationship between rolling pressure and front tension (a) and relationship between torque per unit width and front tension (b)

Fig. 5.39 Relationship between coefficient of friction and front tension



reductions of 0.3 and 0.5 mm. In Fig. 5.38a, the rolling pressures at rolling reductions of 0.3 and 0.5 mm in three front tensions are the same, and the rolling pressures decrease with increasing front tension. In Fig. 5.38b, the torques per unit width at rolling reductions of 0.3 and 0.5 mm are also the same, and they decrease with increasing front tension.

Figure 5.39 shows the relationship between coefficient of friction and front tension at the rolling reductions of 0.3 and 0.5 mm. The coefficient of friction is calculated using Eqn. (3.46). The coefficients of friction at rolling reductions of 0.3 and 0.5 mm in three front tensions are the same values of 0.1. The coefficient

of friction is independent of the front tension and the values are constant. From these results, it is confirmed that the friction law of Eqn. (2.1) is satisfied in the hot sheet rolling.

5.5 Friction Pickup

In hot sheet rolling of low carbon steels, the friction pickup for the carbon steels is rarely to occur due to the scale on the sheet surface. On the other hand, for the stainless steels, the friction pickup is likely to occur.

5.5.1 Friction Pickup in History

Sasaki et al. [21] examined the friction pickup behavior in hot sheet rolling with high reduction of carbon steels. The experiments were carried out using the 0.2 %C steel; the rolls of Ni-Gr, Hi-Cr, and Ni-Gr-Hi-Cr materials; and the rolling oil with graphite at rolling speeds from 8 to 27 m/min and a temperature of 950 °C changing the reduction using the 2-high laboratory mill with the rolls of a diameter of 300 mm.

Figure 5.40 shows the occurrence of friction pickup for the Ni-Gr, Hi-Cr, and Ni-Gr-Hi-Cr rolls changing the reduction and the rolling speed without lubricant (a) and with lubricant (b). In the rolling without lubricant, the reduction at the occurrence of friction pickup decreases with increasing rolling speed. The occurrence reduction is about 60 % at a rolling speed of 20 m/min. However, in the

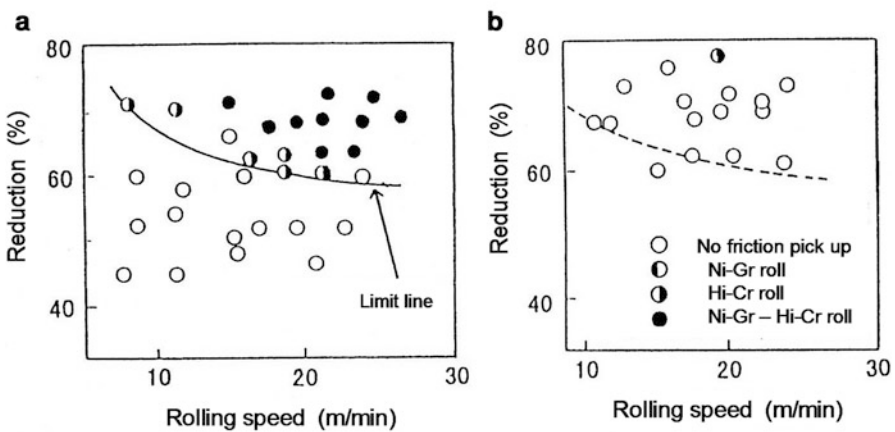
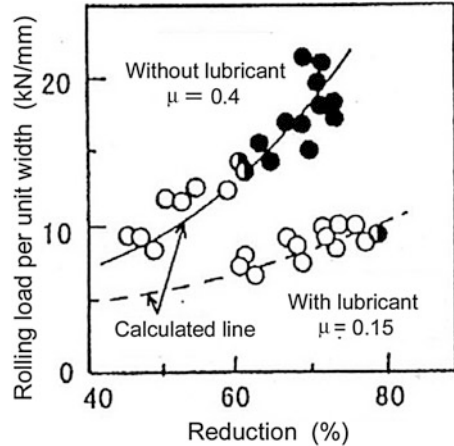


Fig. 5.40 Occurrence of friction pickup for Ni-Gr, Hi-Cr, and Ni-Gr-Hi-Cr rolls changing reduction and rolling speed [21]. (a) Without lubricant, (b) with lubricant

Fig. 5.41 Relationship between rolling load per unit width and reduction [21]



rolling with lubricant, the friction pickup does not occur under a reduction of 75 %. The friction pickup for the Hi-Cr roll only occurs at a reduction of near 80 %. From these results, it is found that the friction pickup for the carbon steels does not occur rarely in hot sheet rolling.

Figure 5.41 shows the relationship between rolling load per unit width and reduction. From Fig. 5.41, it is found that the friction pickup is independent of the rolling load. In hot sheet rolling, the friction pickup in the rolling without lubricant depends on the scale on the sheet surface, and the friction pickup with lubricant depends on the scale and the lubrication film.

Since the friction pickup for the stainless steels is likely to occur, there were many papers concerning the development of the new lubricant and the new roll material in order to prevent the friction pickup in hot sheet rolling of stainless steel. Inoue et al. [22] examined the characteristics of the lubricants of the particles mixed with organic and inorganic powders for the prevention of the friction pickup in hot rolling of stainless steel using the hot rolling wear tester shown in Fig. 5.17.

Table 5.5 summarizes the compositions of lubricants used. In Table 5.5, PPS is the polyphenylene sulfide and PE is the polyethylene. The experiments were carried out using the SUS430 stainless steel sheet and the Hi-Cr roll at a load of 784 N, at a slipping ratio of 10 to 240 %, at a rotating roll velocity of 50 rpm, at a revolution number of 50, and at the roll and workpiece temperatures of 500 and 850 °C. Figure 5.42 shows the antiseizure property of lubricants used. From Fig. 5.42, the slipping ratio of the Lub-G is higher compared to other lubricants, so that the antiseizure property is excellent. It is found that the addition of PPS is effective for the prevention of friction pickup.

Then, Gotoh et al. [23] examined the characteristics of the high-based organic metal salts for the prevention of the friction pickup in hot rolling of stainless steel using the friction tester at elevated temperature. Table 5.6 summarizes the compositions of lubricants used. The viscosity of lubricants of Nos. 1–11 was controlled at

Table 5.5 Compositions of lubricants used [22]

No.	Composition of lubricant/mass%				
	Grease	PPS	PE	Graphite	KPO ₃
Lub-A	95	5	—	—	—
Lub-B	95	—	5	—	—
Lub-C	90	—	—	10	—
Lub-D	90	—	—	—	10
Lub-E	80	—	—	10	10
Lub-F	85	5	—	10	—
Lub-G	75	5	—	10	10
Lub-H	75	—	5	10	10
Lub-I	100	—	—	—	—

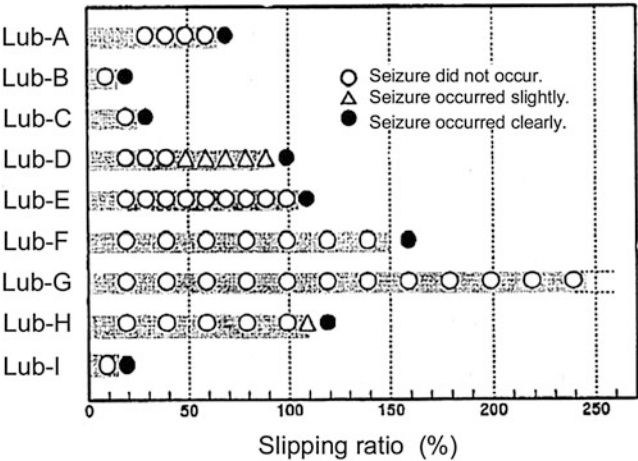


Fig. 5.42 Antiseizure property of lubricants used [22]

120 cSt at 40 °C. Nos. 12 and 13 oils were comparison oils. The experiments were carried out using the SUS430 stainless steel sheet and the HSS and Hi-Cr rolls at a load of 980 N, at a rotating roll velocity of 0.1 m/s, and at a block temperature of 1100 °C. The lubricants were applied at a thickness of 0.5 g/m² on the sliding surface. The sliding surface was controlled at a surface roughness of 0.2 μm. The property of the antiseizure was evaluated by means of the area ratio of friction pickup after 30 s.

Figure 5.43 shows the relationship between area ratio of seizure on roll surface and base number of organic metal salts (a) and the relationship between area ratio of seizure on roll surface and content of organic metal salts (b). From Fig. 5.43a, it is found that the Ca sulfonate is effective for the antiseizure property compared to Ba and Mg sulfonates, and moreover, the antiseizure property becomes better with increasing base number of organic metal salts. From Fig. 5.43b, the antiseizure

Table 5.6 Composition of lubricants used [23]

No.	Type	Base number	Content	Others
		(mgKOH/g)	(wt%)	
1	Ca sulfonate	22	40	Mineral oil
2	Ca sulfonate	100	40	
3	Ca sulfonate	250	40	
4	Ca sulfonate	400	40	
5	Ca sulfonate	250	20	
6	Ca sulfonate	250	60	
7	Ca sulfonate	400	20	
8	Ca sulfonate	400	60	
9	Ba sulfonate	70	40	
10	Mg sulfonate	400	40	
11	Ca phenate	250	40	
12	Commercially available hot rolling oil (synthetic esters base)			Li-grease
13	Graphite (particle diameter, 3 μ m)		10	

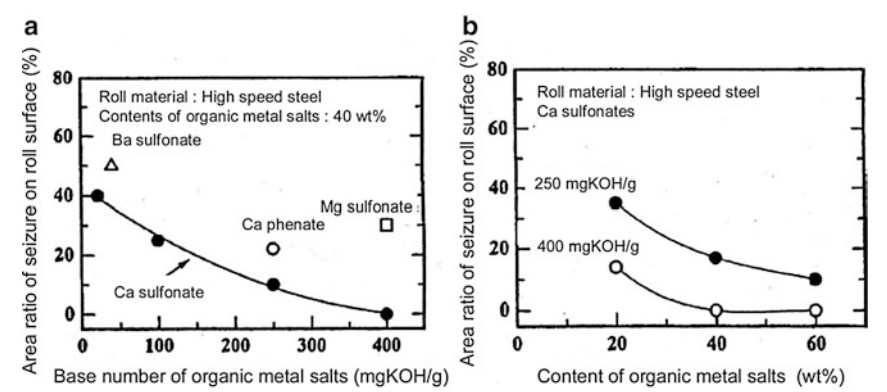


Fig. 5.43 Relationship between area ratio of seizure on roll surface (a) and relationship between area ratio of seizure on roll surface and content organic metal salts (b) [23]

property becomes better with increasing content of organic metal salts for each Ca sulfonate with 150 and 400 mgKOH/g.

Figure 5.44 shows the relationship between coefficient of friction and area ratio of seizure on roll surface of the newly developed oil of No. 4 and the commercial oils of Nos. 12 and 13 for the Hi-Cr and HSS rolls. The antiseizure property of the newly developed oil of No. 4 is better than those of the commercial oils of Nos. 12 and 13. The area ratio of seizure and the coefficient of friction for the HSS roll are smaller than those for the Hi-Cr roll.

Then, Ikeda [24] examined the seizure load of lubricants using the hot Timken testing machine. The lubricants used were the fine particle Ca sulfonate, the PC compound, the synthetic ester oil, the mineral oil, and the sulfide ester. The

Fig. 5.44 Relationship between coefficient of friction and area ratio of seizure on roll surface of newly developed oil of No. 4 and commercial oils of Nos. 12 and 13 [23]

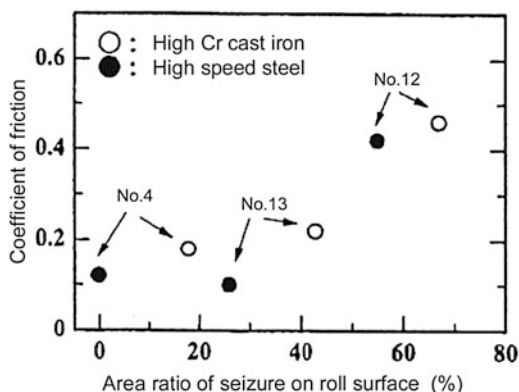
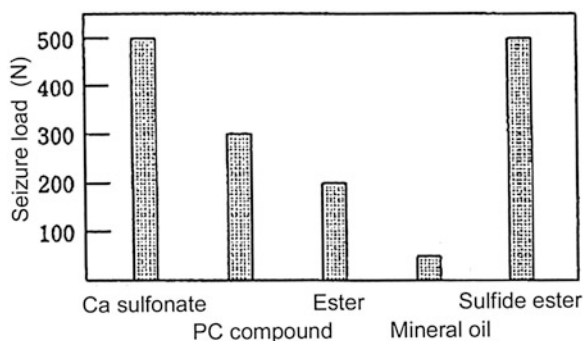


Fig. 5.45 Seizure load of lubricants examined using hot Timken testing machine [24]



experiments were carried out using the SUS304 sheet and the HSS roll at a rotating roll velocity of 150 rpm and at a temperature of 900 °C.

Figure 5.45 shows the seizure load of lubricants used using hot Timken testing machine. The seizure loads of the fine particle Ca sulfonate and the sulfide ester are larger than those of the PC compound, the synthetic ester oil, and the mineral oil, and they are effective for the antiseizure property of stainless steel in hot sheet rolling.

5.5.2 Friction Pickup of Carbon Steel with High Strength

The antiseizure property of the carbon steel with high strength was examined using the hot sliding-rolling type tribo-simulator by Toriumi et al. [25]. The sliding-rolling experiments are carried out using the SPHC sheet with a tensile strength of 590 MPa and the SKD61 rolls with surface roughness of 0.2, 0.8, and 1.6 μm at roll speeds of 30, 50, and 70 m/min and at a temperature of 800 °C in the rolling reductions of 0.5, 1.5, 1.8, and 2.1 mm. Figure 5.46 shows the photographs of the

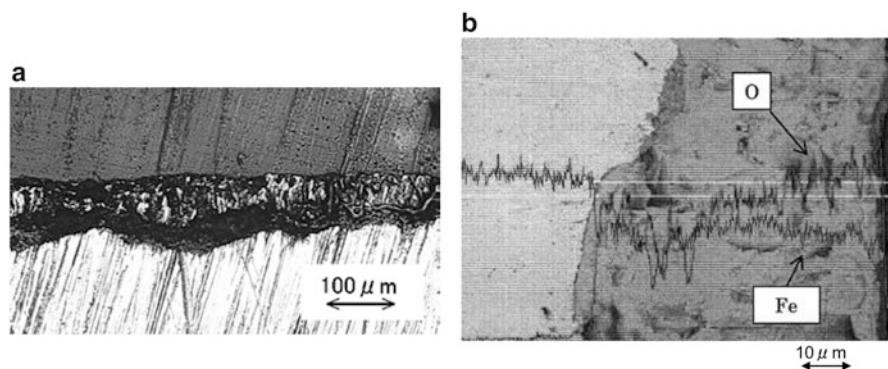


Fig. 5.46 Photographs of cross section of scale on sheet surface (a) and EDX analysis of cross section of scale (b)

cross section of scale on the sheet surface (a) and the EDX analysis of the cross section of scale (b). From Fig. 5.46a, the scale thickness on the sheet surface after heating is about 60 μm . Figure 5.46b shows the intensity distributions of iron and oxygen across the sheet section with a scale thickness of 60 μm obtained from EDX analysis. It can be observed that in the surface layer up to 20 μm , the oxygen intensity is larger than the iron intensity, so the chemical composition of the scale is Fe_3O_4 , and in the layer from 20 μm depth to the interface between scale and steel substrate, the iron intensity is almost equal to the oxygen intensity, so the chemical composition of the scale is FeO .

Figure 5.47 shows the occurrence of friction pickup of the SPHC with high strength changing the rolling reduction and the rolling speed for the SKD61 rolls with surface roughnesses of 0.2 μm (a), 0.8 μm (b), and 1.6 μm (c). From Fig. 5.47, it is found that the occurrence of the friction pickup is independent of the surface roughness of roll and depends on the rolling reduction and the roll speed. The critical rolling reduction decreases with increasing rolling reduction and roll speed.

Next, the dependence of the rolling reduction on the friction pickup is explained by the experimental results at a roll speed of 50 m/min of Fig. 5.47c. Figure 5.48 shows the photographs of the sheet surface rolled at rolling reductions of 0.5 mm (a), 1.5 mm (b), and 1.8 mm (c). In the scale surface on the sheet rolled at a rolling reduction of 0.5 mm, many cracks over the entire surface can be observed due to the Fe_3O_4 scale layer with a high hardness. On the other hand, the scale on the sheet surface rolled at a rolling reduction of 1.5 mm changes to a smooth and blackish scale without the crack. On the sheet surface rolled at a rolling reduction of 1.8 mm, the friction pickup can be observed. It can be recognized that the occurrence of the friction pickup in hot sheet rolling depends significantly on the scale composition.

Figure 5.49 shows the photograph of the cross section of scale on the sheet surface and the EDX analysis of the cross section of scale on the sheet surface after rolling at a rolling reduction of 1.5 mm shown in Fig. 5.48b. The iron intensity is

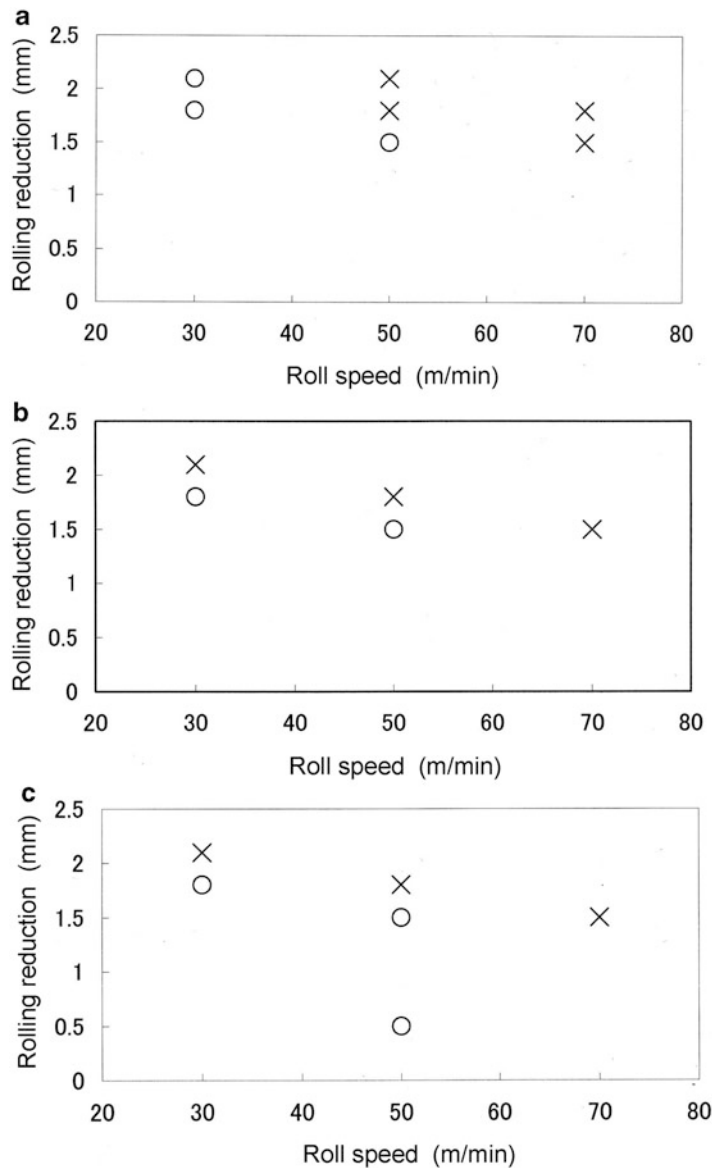


Fig. 5.47 Occurrence of friction pickup of SPHC with high strength changing rolling reduction and roll speed. (a) 0.2 μmRa , (b) 0.8 μmRa , (c) 1.6 μmRa

almost equal to the oxygen intensity, so it is estimated that the chemical composition of the scale is FeO .

Then, the coefficients of friction of the sheet rolled at rolling reductions of 0.5, 1.5, and 1.8 mm are measured. Figure 5.50 shows the relationship between

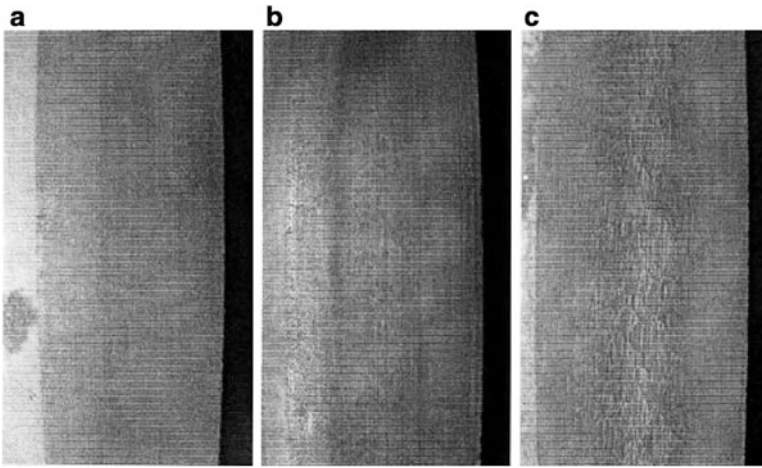


Fig. 5.48 Photographs of sheet surface rolled at rolling reductions of 0.5 mm (a), 1.5 mm (b), and 1.8 mm (c)

Fig. 5.49 Photograph of cross section of scale on sheet surface and EDX analysis of cross section of scale

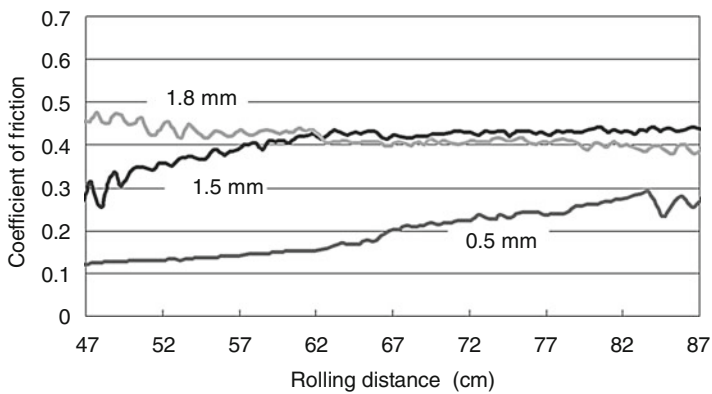
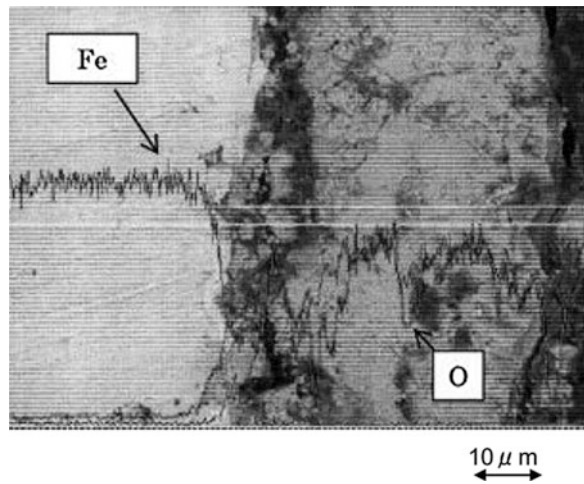


Fig. 5.50 Relationship between coefficient of friction and rolling distance

coefficient of friction and rolling distance. The coefficient of friction at a rolling reduction of 0.5 mm increases from 0.15 to 0.30, and the coefficient of friction at 1.5 mm increases from 0.3 to 0.43 during sliding-rolling. The coefficient of friction at 0.5 mm is lower than that at 1.5 mm, even though the friction pickup does not occur on both the sheet surfaces. It is considered that the difference is due to the phenomenon wherein the scale composition on the sheet surface changes from the Fe_3O_4 scale to the FeO scale.

5.6 Scale on Workpiece Surface

5.6.1 Characteristics of Scale

In Sects. 5.2 and 5.5, it is shown that the scale on the sheet surface in hot sheet rolling gives the significant effect on the tribological behavior. As shown in Sect. 5.5.2, there are the following three types of iron oxides at elevated temperatures:

- (I) Wustite (FeO)
- (II) Magnetite (Fe_3O_4)
- (III) Hematite (Fe_2O_3)

Figure 5.51 shows the photographs of the cross section of the scale on the sheet surface of the low carbon steel after heating at a temperature of above 1000°C . In Fig. 5.51, it can be observed that the scale of the outer surface of low carbon steel is the hematite (Fe_2O_3), the following scale is the magnetite (Fe_3O_4), and the scale in contact with the substrate is wustite (FeO). The ratio of the scales depends on the heating temperature. At temperatures above 700°C , the ratio of the scales becomes constant and the ratio of the scales of the wustite, the magnetite, and the hematite is 95 %, 4 %, and 1 %.

The relationship between tensile strength and temperature and the relationship between elongation and temperature of the scales of the wustite, the magnetite, and the hematite of low carbon steel were examined by Hidaka et al. [26]. They reported



Fig. 5.51 Photographs of cross section of scale on sheet surface of low carbon steel

that the tensile strength of the scales decreased with increasing temperature, and the tensile strength of the wustite is smaller than those of the magnetite and the hematite. On the other hand, the elongation increased with increasing temperature for the scales of wustite and magnetite, and there is little elongation for the hematite.

Next, Munther et al. [27] examined the effect of the scale thickness on the coefficient of friction. They found that the coefficient of friction decreased with increasing scale thickness for each temperature, and the coefficients of friction of the sheet with thick scale thickness decreased with increasing temperature, but the coefficient of friction with thinner scale thickness was independent of the temperature. Moreover, Yu et al. [28] examined the quantitative relationship between coefficient of friction and scale thickness in hot sheet rolling of the carbon steel.

The abovementioned results were limited when the ratio of the scale compositions of the wustite, the magnetite, and the hematite was 95 %, 4 %, and 1 %. Luong et al. [29] examined the effect of the different ratio of the scale composition on the friction using hot ring compression test. They reported that the coefficient of friction depended on the scale composition, and it decreased with decreasing ratio of the wustite of scale composition.

5.6.2 Effect of Scale Thickness on Coefficient of Friction

The effect of the scale thickness of low carbon steel (SPHC) on the coefficient of friction was examined using the hot sliding-rolling type tribo-simulator by Azushima et al. [30]. The sliding-rolling experiments are carried out using the SPHC sheet, the SKD61 roll with a surface roughness of 0.2 μm , and the colza oil with emulsion concentrations of 0.1 and 3.0 % at a velocity ratio of 20, a roll speed of 50 m/min, and a temperature of 800 $^{\circ}\text{C}$, changing the rolling reductions from 0.3 to 1.0 mm. Figure 5.52 shows the photographs of the cross section of the scale of SPHC sheet with different scale thicknesses after heating.

Figure 5.53 shows the relationship between coefficient of friction and scale thickness at rolling reductions of 0.3, 0.5, and 1.0 mm using colza oils with emulsion concentrations of 3.0 % (a) and 0.1 % (b). At an emulsion concentration of 3.0 %, the coefficients of friction are independent of the rolling reduction above a

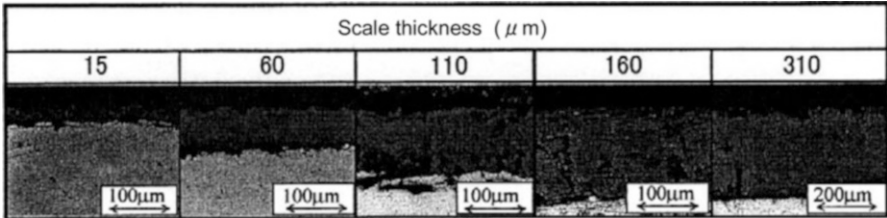


Fig. 5.52 Photographs of cross section of scale after heating

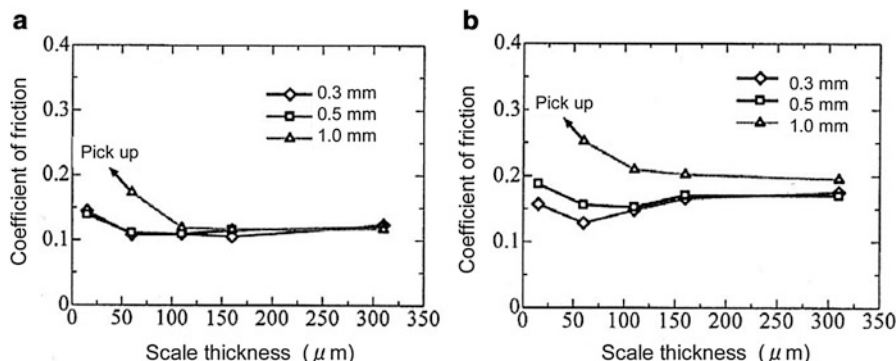


Fig. 5.53 Relationship between coefficient of friction and scale thickness at rolling reductions of 0.3, 0.5, and 1.0 mm using lubricants with emulsion concentrations of 3.0 % (a) and 0.1 % (b)

scale thickness of 110 μm , and they are also constant for the scale thickness. Below 110 μm , the coefficient of friction at a rolling reduction of 1.0 mm increases and the friction pickup occurs at a scale thickness of 15 μm . On the other hand, the coefficients of friction at rolling reductions of 0.3 and 0.5 mm are the same, and for the scale thickness of 15 μm , they become higher in all the rolling reductions.

At an emulsion concentration of 0.1 %, the coefficients of friction are higher than those at 3.0 %. The coefficient of friction at a rolling reduction of 1.0 mm for each scale thickness is higher than those at rolling reductions of 0.3 and 0.5 mm. It is constant above a scale thickness of 110 μm , and below 110 μm , it increases, and at 15 μm , the friction pickup occurs. On the other hand, the coefficients of friction at rolling reductions of 0.3 and 0.5 mm show the complicated change. The coefficient of friction at a rolling reduction of 0.5 mm decreases with increasing scale thickness up to 110 μm , then it increases with increasing scale thickness, and it becomes constant above 160 μm . The coefficient of friction at a rolling reduction of 0.3 mm decreases with increasing scale thickness up to 60 μm , then it increases with increasing scale thickness, and it becomes constant above 160 μm .

In order to discuss quantitatively the effect of the scale thickness on the coefficient of friction, Fig. 5.54 shows the photographs of the sheet surface after rolling with emulsion concentrations of 3.0 and 0.1 % at rolling reductions of 0.3 mm (a), 0.5 mm (b), and 1.0 mm (c). The white regions on the sheet surface can be observed from photographs of the sheets with scale thicknesses of 15 and 60 μm after rolling at rolling reductions of 0.3 and 0.5 mm using the lubricant with emulsion concentrations of 0.1 and 3.0 %. In the white regions, it is estimated that the scale is peeled off from the sheet surface. In these regions, it is considered that the coefficient of friction increases by the contact between roll surface and substrate surface of steel sheet.

The cracks of scale on the sheet surface from all the photographs of the sheets with scale thicknesses of above 110 μm can be observed. The degree of the cracks increases with increasing scale thickness, and the degree at an emulsion concentration of 0.1 % is larger than that at 3.0 %. It is estimated that at an emulsion

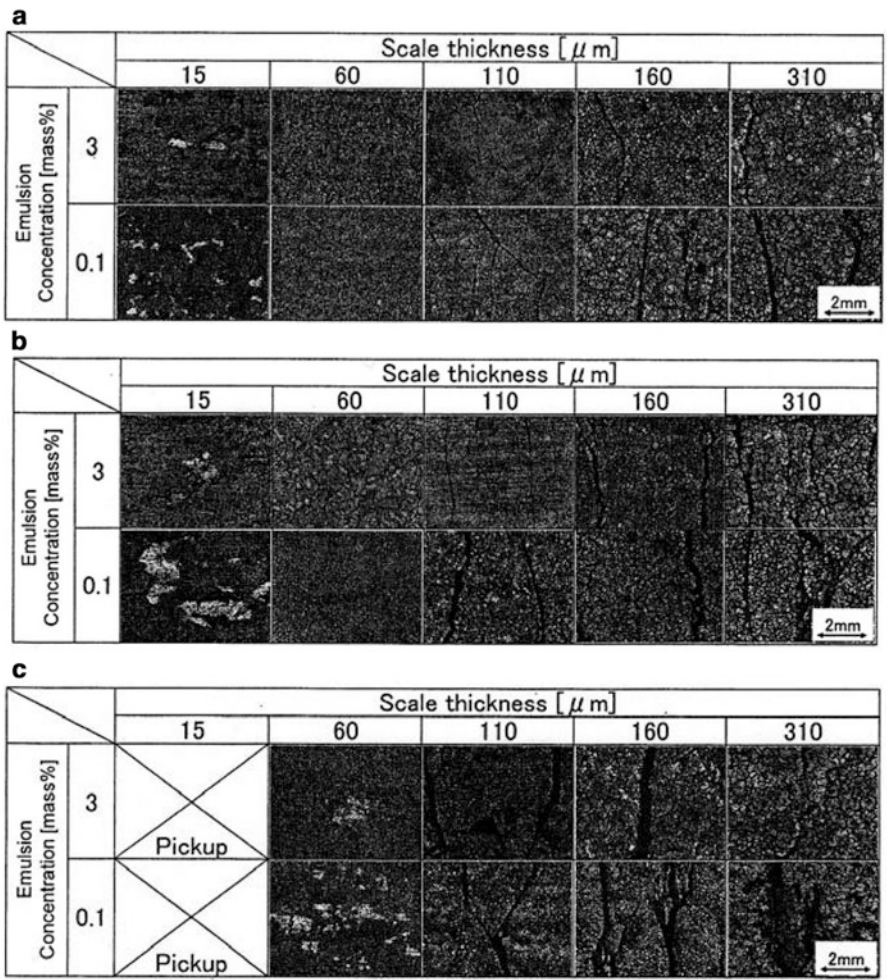


Fig. 5.54 Photographs of the sheet surface after rolling at rolling reductions of 0.3 mm (a), 0.5 mm (b), and 1.0 mm (c)

concentration of 3.0 %, all the areas of the surface with the cracks are covered with the lubrication film; at 0.1 %, the surface with cracks in the area under the water lubrication increases with increasing scale thickness. Consequently, the coefficient of friction at an emulsion concentration of 0.1 % increases with increasing scale thickness.

In order to examine the formation of white regions observed at thinner scale thicknesses, Fig. 5.55 shows the photographs of the roll surface after rolling using the sheet with a scale thickness of 15 μm (a) and 110 μm (b). In Fig. 5.55a, the black band layer can be observed on the roll surface after rolling at a scale thickness of

Fig. 5.55 Photographs of roll surface appearance after rolling. (a) Scale thickness of 15 μm , (b) scale thickness of 110 μm

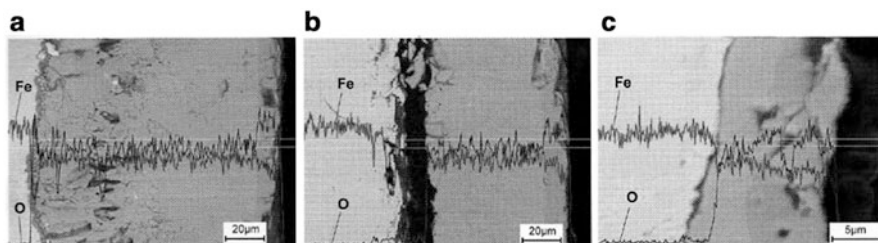
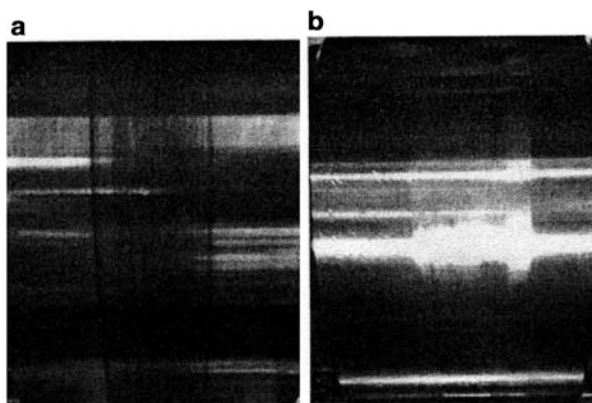


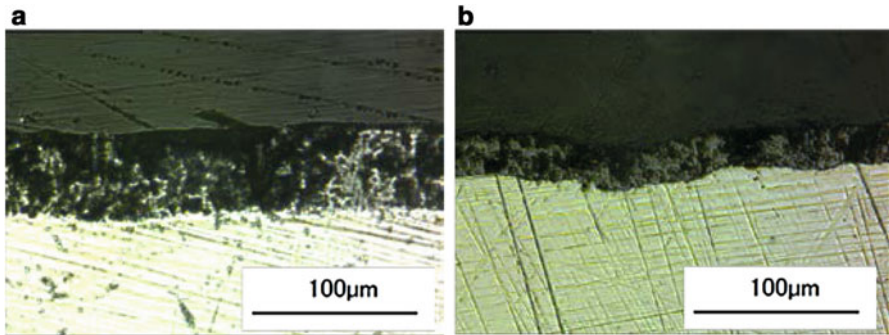
Fig. 5.56 Intensity distribution of iron and oxygen across section of sheet obtained from EPMA analysis (a) 110 μm , (b) 60 μm , (c) 15 μm

15 μm . On the other hand, the roll surface at 110 μm is clear. From the difference between two roll surfaces, it is considered that the scale compositions are different between the specimens with different scale thicknesses.

Next, Fig. 5.56 shows the intensity distribution of iron and oxygen across the sections of the sheets with scale thicknesses of 110 μm , (a), 60 μm (b), and 15 μm (c) obtained from EPMA analysis. It can be observed that in the surface layer up to a depth of about 10 μm in all the photographs, the oxygen intensity is larger than the iron intensity, so the chemical composition is Fe_3O_4 . In the layer from 10 μm depth of the scale surface to the interface between scale and steel substrate, the iron intensity is almost equal to the oxygen intensity, so the chemical composition is FeO . From these analyses, the ratio of the composition (Fe_3O_4) of the scale layer at a scale thickness of 15 μm is significantly different compared to those at 60 and 110 μm . The scale at 15 μm is easily peeled off from the steel substrate due to the hard scale of Fe_3O_4 , resulting in the formation of the white regions on the sheet surface and the black band layer on the roll surface after rolling.

Table 5.7 Chemical compositions of SPHC sheet and HTSS sheet

	C	Si	Mn	P	S
SPHC	0.110	0.210	0.560	0.025	0.033
HTSS	0.130	0.400	1.550	0.019	0.004

**Fig. 5.57** Photographs of cross section of scale of SPHC sheet (a) and HTSS sheet (b)

5.6.3 Effect of Chemical Composition of Sheet on Coefficient of Friction

The effect of the scale composition on the coefficient of friction was examined using the hot sliding-rolling type tribo-simulator by Satta [31]. The sliding-rolling experiments are carried out using the SPHC sheet and the high tensile strength steel (HTSS) sheet, the SKD61 roll with a surface roughness of 0.2 μm and the colza oil with emulsion concentration of 3.0 % at a velocity ratio of 20, a roll speed of 50 m/min, and a temperature of 800 °C, changing the rolling reduction from 0.3 to 1.0 mm. Table 5.7 summarizes the chemical compositions of the SPHC sheet and the HTSS sheet.

Figure 5.57 shows the photographs of the cross section of the scale of SPHC sheet (a) and HTSS sheet (b) after heating. From Fig. 5.57, the scale thickness of the SPHC sheet is 60 μm, and the scale thickness of the HTSS sheet is 30 μm. In order to examine the scale compositions of the SPHC sheet and the HTSS sheet, the EPMA and EDX analyses are carried out.

Figure 5.58 shows the intensity distribution of iron and oxygen across the sections of the SPHC sheet (a) and the HTSS sheet (b). In Fig. 5.58a, in the surface layer up to a depth of about 10 μm of the SPHC sheet, the oxygen intensity is larger than the iron intensity, so the chemical composition is Fe₃O₄. In the layer from 10 μm depth to the interface between scale and steel substrate, the iron intensity is almost equal to the oxygen intensity, so the chemical composition is FeO. On the other hand, in Fig. 5.58b the scale of the surface layer up to a depth of 20 μm of the HTSS sheet is Fe₃O₄ and in the layer from 20 μm to the interface is FeO. The reason that the Fe₃O₄ scale layer of the HTSS sheet is thicker is due to the existence of Si.

Next, Fig. 5.59 shows the relationship between coefficient of friction and rolling reduction for the SPHC sheet (a) and for the HTSS sheet (b). The coefficient of

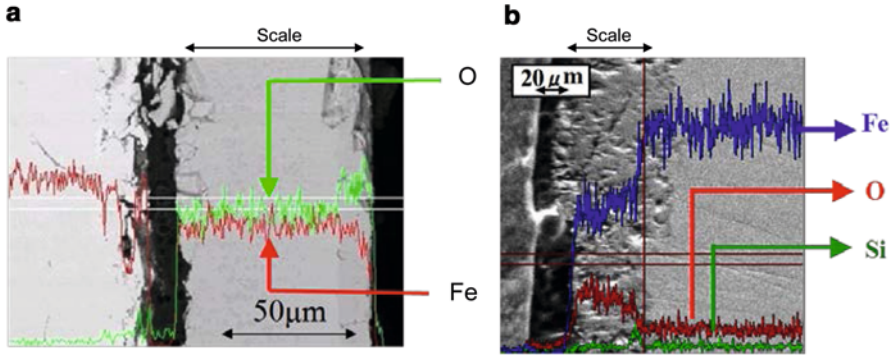


Fig. 5.58 Intensity distribution of iron and oxygen across section of sheets (a) SPHC, (b) HTSS

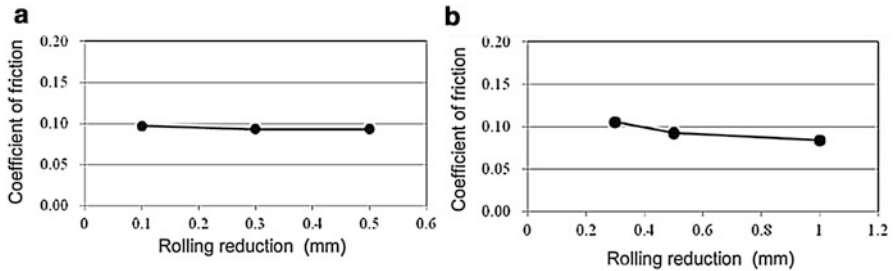


Fig. 5.59 Relationship between coefficient of friction and rolling reduction for SPHC sheet (a) and for HTSS sheet (b)

friction of the SPHC sheet is independent of the rolling reduction, and it is a constant of 0.1. On the other hand, the coefficient of friction of the HTSS sheet depends on the rolling reduction, and it decreases with increasing rolling reduction.

Then, the mechanism of the phenomenon where the coefficient of friction of the HTSS sheet decreases with increasing rolling reduction is examined. In the experiment results in Fig. 5.59, the scales on the roll surface after rolling using the SPHC sheet and the HTSS sheet at rolling reductions of 0.3 and 1.0 mm can be observed. Figure 5.60 shows the photographs of the roll surface after rolling using the HTSS sheet at rolling reductions of 0.3 mm (a) and 1.0 mm (b). It can be observed that the degree of the scale at a rolling reduction of 1.0 mm is higher compared to that at a rolling reduction of 0.3 mm. It may be estimated that the compositions of the scale on the roll surface after rolling using the SPHC sheet and the HTSS sheet at rolling reductions of 0.5 and 1.0 mm are Fe_3O_4 .

Next, the experiments at a rolling reduction of 0.3 mm are carried out using the rolls after rolling using the SPHC sheet and the HTSS sheet at rolling reductions of 0.5 and 1.0 mm under the same experimental conditions. Figure 5.61 shows the relationship between coefficient of friction and rolling reduction of the SPHC sheet (a) and the HTSS sheet (b). In Fig. 5.61, the coefficients of friction of the SPHC

Fig. 5.60 Photographs of the roll surface after rolling using the HTSS sheet (a) 0.3 mm, (b) 1.0 mm

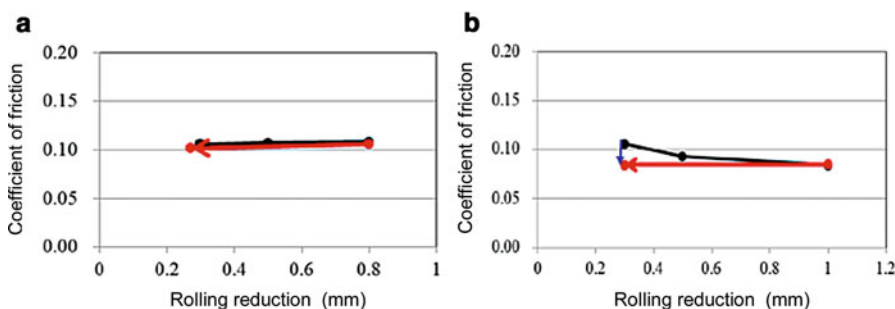
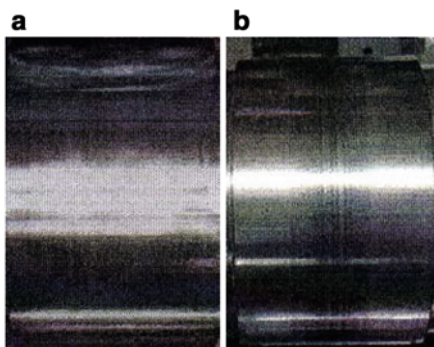


Fig. 5.61 Relationship between coefficient of friction and rolling reduction of SPHC sheet (a) and HTSS sheet (b)

sheet and the HTSS sheet in Fig. 5.59 are added. For the SPHC sheet, the coefficient of friction is equal to that in Fig. 5.59. On the other hand, for the HTSS sheet, the coefficient of friction is smaller than that in Fig. 5.59.

Moreover, the experiments are carried out using 3 % emulsion of the colza base oil with 40 % Ca sulfonate and the HTSS sheet at the same rolling conditions. The scale formation on the roll surface is prevented by the Ca sulfonate. Figure 5.62 shows the photographs of the roll surface after rolling using the HTSS sheet at rolling reductions of 0.3 mm (a), 0.5 mm (b), and 1.0 mm (c). From the photographs in Fig. 5.62, the scales on the roll surface after rolling at rolling reductions of 0.3 and 0.5 mm cannot be observed, and the thinner scale at a rolling reduction of 1.0 mm can be observed.

Figure 5.63 shows the relationship between coefficient of friction and rolling reduction using the HTSS sheet and 3 % emulsion of the colza oil with 40 % Ca sulfonate. The coefficient of friction using the colza oil with 40 % Ca sulfonate is almost independent of the rolling reduction.

From these results, it can be understood that the difference between coefficients of friction of the SPHC sheet and the HTSS sheet is due to the difference of the scale compositions of the SPHC sheet and the HTSS sheet. For the SPHC sheet, when the scale layer with a composition of Fe_3O_4 on the roll surface and the scale

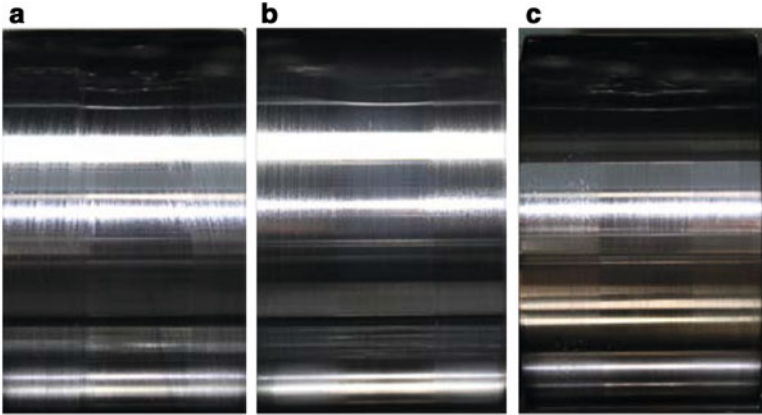


Fig. 5.62 Photographs of roll surface after rolling using HTSS sheet at rolling reductions of 0.3 mm (a), 0.5 mm, (b) and 1.0 mm (c)

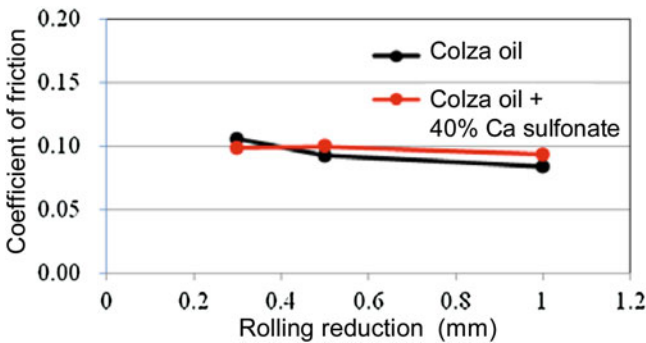


Fig. 5.63 Relationship between coefficient of friction and rolling reduction in rolling using HTSS sheet and 3 % emulsion of colza base oil with 40 % Ca sulfonate

layer with a composition of FeO on the sheet surface contact at the interface between roll and sheet, the coefficient of friction is independent of the rolling reduction. On the other hand, for the HTSS sheet, when the scale layer with a composition of Fe_3O_4 on the roll surface and the scale layer with a composition of Fe_3O_4 on the sheet surface contact at the interface, the coefficient of friction depends on the rolling reduction, and it becomes lower.

5.6.4 Effect of Si Content of Carbon Steel on Coefficient of Friction

The effect of the Si content of carbon steel on the coefficient of friction was examined using the hot sliding-rolling tribo-simulator by Azushima et al. [32]. The sliding-rolling experiments are carried out using the carbon steels

Table 5.8 Chemical compositions of low carbon steels

	C	Si	Mn	P	S	Al
Si 0.01 % steel	0.103	0.013	1.80	0.001	0.001	0.002
Si 0.2 % steel	0.105	0.206	1.82	0.001	0.001	0.003
Si 1.0 % steel	0.102	1.011	1.81	0.003	0.002	0.003

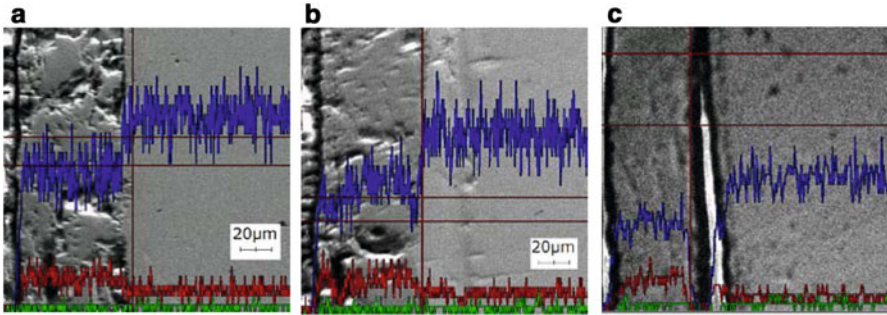


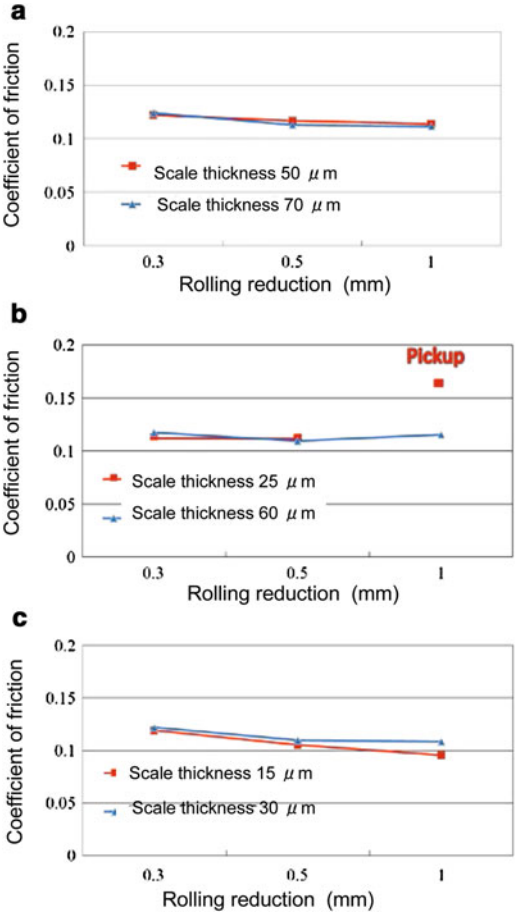
Fig. 5.64 Intensity distribution of iron and oxygen in across section of sheets. (a) Si 0.01 % steel, (b) Si 0.2 % steel, (c) Si 1.0 % steel

with different Si contents of 0.013, 0.206, and 1.011, the SKD61 roll with a surface roughness of 0.2 μm , and the colza oil with an emulsion concentration of 3.0 % at a velocity ratio of 20, at a roll speed of 50 m/min, at a temperature of 800 $^{\circ}\text{C}$, and at rolling reductions of 0.3, 0.5, 0.7, and 1.0 mm. Table 5.8 summarizes the chemical compositions of the carbon steels. After heating, the scale thicknesses of Si 0.01 % steel are 50 and 70 μm , the Si 0.2 % steel are 25 and 60 μm , and the Si 1.0 % steel are 15 and 30 μm .

Figure 5.64 shows the intensity distribution of iron and oxygen in the cross sections of the sheets of Si 0.01 % steel (a), Si 0.2 % steel (b), and Si 1.0 % steel (c). In Fig. 5.64a, b, in the surface layer up to a depth of about 10 μm of the Si 0.01 and Si 0.2 % steel sheets, since the oxygen intensity is larger than the iron intensity, the chemical composition is Fe_3O_4 . In the layer from 10 μm depth to the interface between scale and steel substrate, since the iron intensity is almost equal to the oxygen intensity, the chemical composition is FeO . On the other hand, in Fig. 5.64c in the surface layer up to the interface, since the oxygen intensity is larger than the iron intensity, the chemical composition is almost Fe_3O_4 .

Next, Fig. 5.65 shows the relationship between coefficient of friction and rolling reduction for the Si 0.01 % steel (a), the Si 0.2 % steel (b), and the Si 1.0 % steel (c). The coefficients of friction of the Si 0.01 and 0.2 % steel sheets are independent of the rolling reduction. On the other hand, the coefficient of friction of the Si 1.0 % steel sheets depends on the rolling reduction, and it decreases with increasing rolling reduction.

Fig. 5.65 Relationship between coefficient of friction and rolling reduction for Si 0.01 % steel (a), Si 0.2 % steel, (b) and Si 1.0 % steel (c)



5.7 Scale on Roll Surface

In hot sheet tandem mill rolling, the roll surface is covered with the black scale layer as shown in Fig. 5.66. The stable black scale layer on the work roll protects the roll surface and improves the wear resistance of the work roll. In the actual sheet tandem mill rolling, it is desired that the stable black scale layer is generated early, and it is maintained for a long time. However, when the black scale layer becomes thicker, it peels off partially from the roll surface, resulting in the roll banding as shown in Fig. 5.67. If the damaged rolls are used, the surface quality of the rolled product sheet becomes poor.



Fig. 5.66 Black scale layer on work roll in tandem mill

Fig. 5.67 Photograph of work roll surface caused by roll banding



5.7.1 Scale on Roll Surface in History

The black scale layer on the work roll surface affects significantly the tribological behavior at the interface between roll and sheet. However, there are few researches concerning the black scale layer, and at the present time, the formation conditions and mechanism of the black scale layer on the work roll cannot be clearly clarified.

In the 1970s, there were some researches concerning the black scale layer using the laboratory mill [33–35]. In these researches, by the reproduction of the black scale layer in the laboratory mill, the analysis of the black scale layer was carried out, and the proposal of the formation mechanism was made. From these researches, it was confirmed that the composition of the black scale layer was

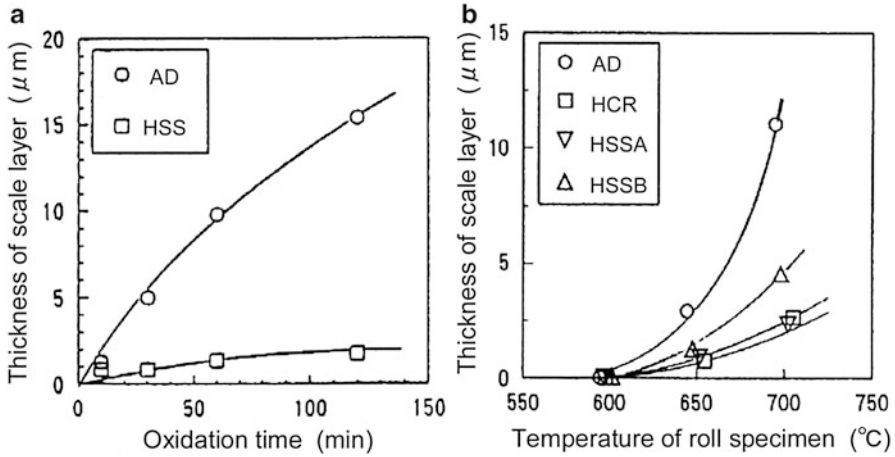


Fig. 5.68 Relationship between thickness of the scale layer and oxidation time (a) and relationship between the thickness of the scale layer and temperature of roll specimen (b) [36]

mainly Fe_3O_4 . The two formation mechanisms were proposed. First, the scale (FeO) adhered on the roll surface from the scale of the sheet surface during rolling was transformed into the scale (Fe_3O_4), and second, the scale (Fe_3O_4) on the roll surface was formed by the oxidation of the roll surface material.

In the 1990s, the researches using the tribo-simulators were carried out. Araya et al. [36] measured the composition and the thickness of the black scale layer on the roll surface using the hot wear tester shown in Fig. 5.17. The experiments were carried out at a load of 500 N, at a rotation velocity of specimen of 4 m/s, at a slip ratio of 4.4 %, and at a temperature of 600 $^{\circ}\text{C}$ up to a number of rotation of 10^4 cycles.

Figure 5.68 shows the relationship between the thickness of the scale layer and oxidation time for the AD roll and the HSS roll (a) and the relationship between the thickness of the scale layer and temperature of roll specimen for the AD roll, the HCR roll, and the HSS roll (b). The thicknesses of the black scale layer for the AD roll and the HSS roll increased with increasing oxidation time, and the layer thickness for the AD roll was larger than that for the HSS roll. In Fig. 5.68b, up to a temperature of roll specimen of 600 $^{\circ}\text{C}$, the black scale layer for all the rolls was not formed, and above 600 $^{\circ}\text{C}$, the layer thickness increased with increasing temperature of the roll specimen. The thickness of the scale layer for the AD roll was the largest.

Moreover, they [37] examined the effect of the thickness of black scale layer on the wear and the coefficient of friction for the AD roll, the HCR roll, and the HSS roll. Figure 5.69 shows the relationship between the amount of wear and thickness of the scale layer (a) and the relationship between coefficient of friction and thickness of the scale layer (b) for the AD roll, the HCR roll, and the HSS roll. The amount of wear for all the rolls decreased with increasing thickness of the scale layer, and the wear for the AD roll was larger than those for the HCR roll and the

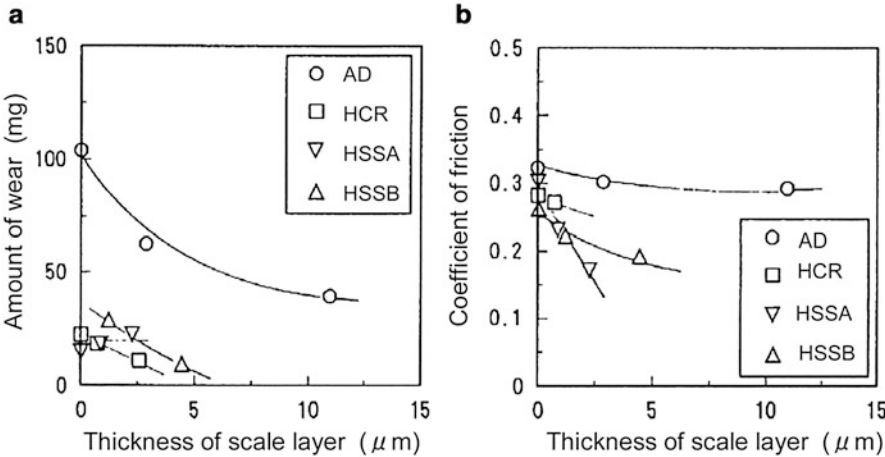


Fig. 5.69 Relationship between the amount of wear and thickness of the scale layer (a) and relationship between coefficient of friction and thickness of the scale layer (b) [37]

Table 5.9 Thickness of black scale layer [23]

Lubricant no.	High-speed steel		High-Cr cast iron (μm)
	1.5 %C (μm)	2.0 %C (μm)	
4	1.0	1.8	3.1
12	3.6	4.6	6.5

HSS roll. The coefficient of friction for all the rolls decreased with increasing thickness of the scale layer. The wear for the AD roll was larger than those for the HCR roll and the HSS roll.

Ohata et al. [38] examined fundamentally the formation mechanism of the black scale layer using the rolling simulator. They analyzed the compositions of the black scale layer formed on the roll surfaces of the AD roll and the HCR roll in actual tandem mill and confirmed that it was Fe₃O₄. The experiments were carried out using the AD roll and the HCR roll and the SPCC sheet using the rolling simulator. They reported that first, the FeO scale on the SPCC sheet surface adhered to the roll surface during rolling, and second, the FeO scale adhered to the roll surface transformed into the Fe₃O₄ scale.

Next, Gotoh et al. [23] examined the effect of the additive agent on the thickness of the black scale layer on the roll surface. The experiments were carried out using the HCR roll and the HSS roll, the SPCC sheet, and the lubricants of Nos. 4 and 12 shown in Table 5.6 at a reduction of 30 %, at a rolling speed of 150 m/min, and at a rolling temperature of 950 °C. Table 5.9 summarizes the thickness of the black scale layer for the HCR roll and the HSS rolls. The composition of lubricant No. 4 was the mineral base oil with 40 % Ca sulfonate, and No. 12 was the commercial synthetic base oil for hot sheet rolling. The thicknesses of black scale

layer of all the rolls using lubricant No. 4 were thinner than those for all the rolls using lubricant No. 12. It was understood that the thickness of the black scale layer became thinner by the additive of Ca sulfonate.

5.7.2 Formation Condition of Black Scale Layer

The formation condition of the black scale layer changing the tribological conditions was examined using the sliding-rolling type tribo-simulator by Azushima et al. [39–41].

5.7.2.1 The Effect of the Scale Thickness of the Sheet Surface on the Formation Condition

First, the effect of the thickness of the scale layer on the sheet surface on the formation condition of the black scale layer on the roll surface was examined by Azushima et al. [39]. The sliding-rolling experiments are carried out using the SPHC sheet with scale thicknesses of 20, 40, and 80 μm , the SKD61 roll with a surface roughness of 0.2 μm , and the colza oil with an emulsion concentration of 3 % at a velocity ratio of 20, at a roll speed of 50 m/min, and a temperature of 800 $^{\circ}\text{C}$ in the rolling reductions of 0.3, 0.5, and 1.0 mm. Figure 5.70 shows the photographs of the cross section of the scale of SPHC sheet with scale thicknesses of 20 μm (a), 40 μm (b), and 80 μm (c).

Figure 5.71 shows the relationship between rolling reduction and scale thickness of the SPHC sheet for the formation condition of the black scale layer. In Fig. 5.71, the photographs of the roll surface after sliding-rolling are also shown, and the black scale layers formed on the roll surface are classified into the four stages of nothing, thinner, normal, and thicker. It can be understood that the black scale layer on the work roll surface forms at a larger rolling reduction when the scale thickness on the sheet surface becomes thicker.

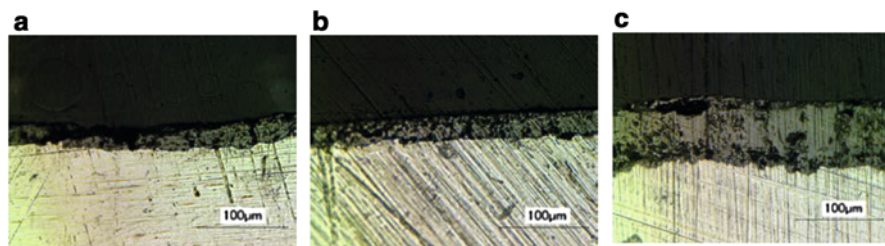


Fig. 5.70 Photographs of cross section of scale of SPHC sheet. (a) 20 μm , (b) 40 μm , (c) 80 μm

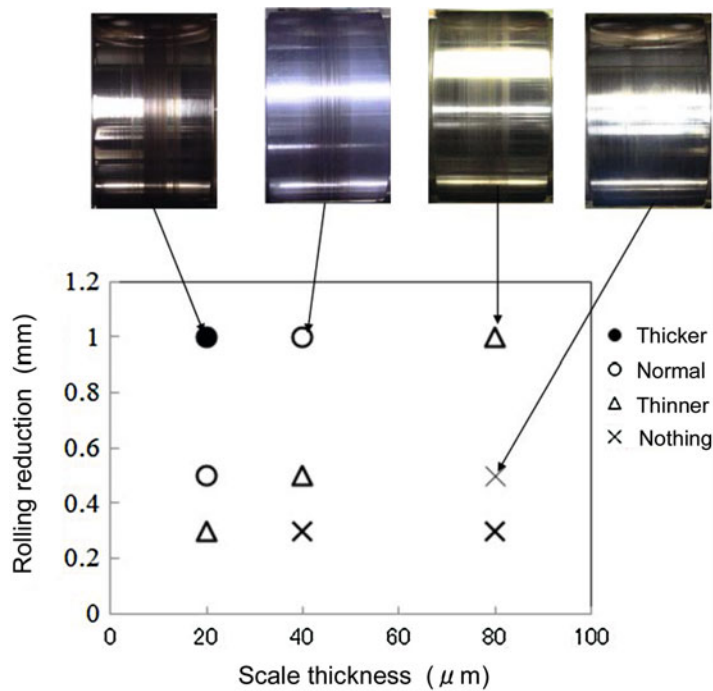


Fig. 5.71 Relationship between the rolling reduction and scale thickness of SPHC sheet

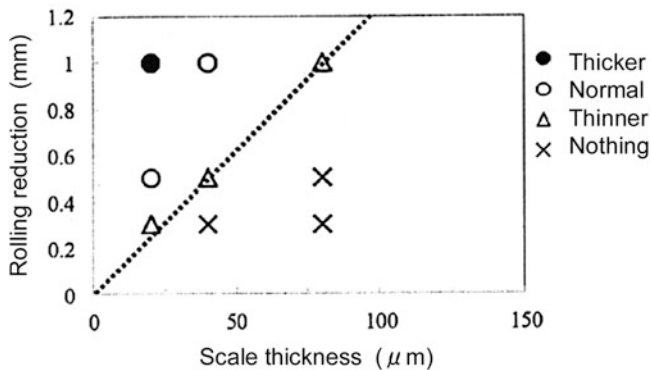


Fig. 5.72 Relationship between rolling reduction and scale thickness added limitation line of formation of black scale layer

Then, Fig. 5.72 shows the same relationship in which the limitation line of the formation of the black scale layer is added in Fig. 5.71. The limitation line of the formation condition can be expressed as the straight line between the rolling reduction and scale thickness.

5.7.2.2 The Effect of the Composition of Sheet on the Formation Condition

Second, the effect of the composition of sheet on the formation condition of the black scale layer on the roll surface was examined by Azushima et al. [40]. The experiments are carried out using the steel sheets with different compositions, the SKD61 roll with a surface roughness of $0.2\text{ }\mu\text{m}$, and the colza oil with an emulsion concentration of 3 % at a velocity ratio of 20, at a roll speed of 50 m/min, and a temperature of $800\text{ }^{\circ}\text{C}$, changing the rolling reductions of 0.3, 0.5, and 1.0 mm. Table 5.10 summarizes the compositions of steel sheets used.

Figure 5.73 shows the photographs of the cross section of the scale of the steel sheets of A, B, and C with different scale thicknesses. In Fig. 5.73, the scale

Table 5.10 Compositions (wt%) of steel sheets used

	C	Si	Mn	P	S
Steel A	0.150	0.010	0.740	0.200	0.002
Steel B	0.110	0.210	0.560	0.025	0.033
Steel C	0.130	0.400	1.550	0.019	0.004

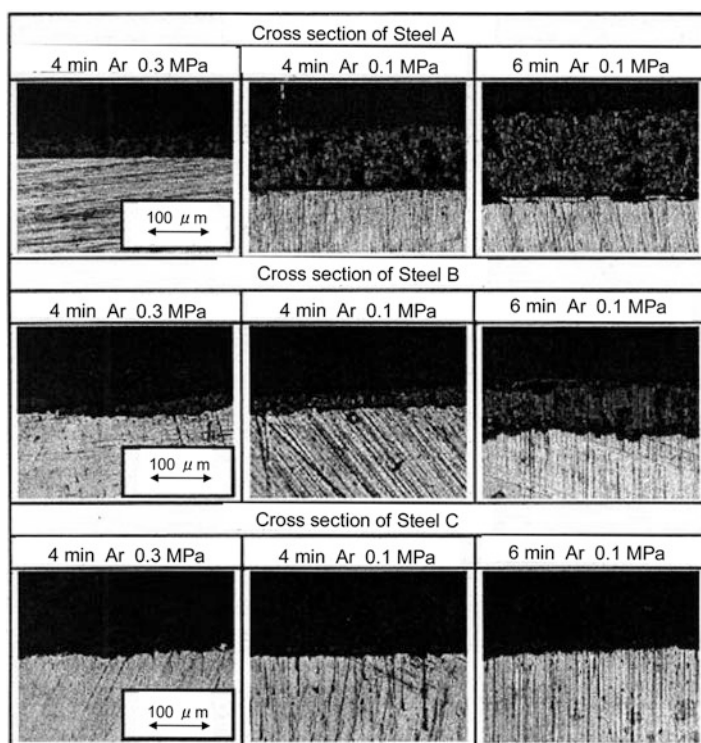


Fig. 5.73 Photographs of cross section of scale of steel sheets of A, B, and C

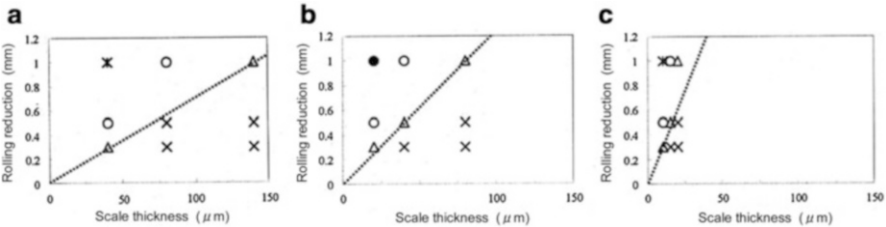


Fig. 5.74 Relationship between the rolling reduction and scale thickness of the formation line of scale layer. (a) Steel A, (b) steel B, (c) steel C

Table 5.11 Values of parameter α

<i>Steel A</i>			
Scale thickness of workpiece	40 μm	80 μm	140 μm
Value of α	0.0075	–	0.0073
<i>Steel B</i>			
Scale thickness of workpiece	20 μm	40 μm	80 μm
Value of α	0.0150	0.0125	0.0125
<i>Steel C</i>			
Scale thickness of workpiece	10 μm	15 μm	20 μm
Value of α	0.0300	0.0333	0.0500

thicknesses for the steel A are 40, 80, and 140 μm ; for the steel B are 20, 40, and 80 μm ; and for the steel C are 10, 15, and 20 μm .

Figure 5.74 shows the relationship between the rolling reduction and scale thickness of the steel A (a), the steel B (b), and the steel C (c). From Fig. 5.74, it can be understood that the black scale layer on the work roll surface for the steels A, B, and C forms when the scale thickness on the sheet surface becomes thicker and the rolling reduction becomes larger. The limitation line of the formation condition for the steels A, B, and C can be expressed as the straight line in the relationship between the rolling reduction and scale thickness. The slope of the straight line depends on the steel composition, and the slopes increase in the order of the steel A, the steel B, and the steel C.

In order to estimate quantitatively the formation condition of the black scale layer on the work roll, a parameter α of a ratio of the rolling reduction to the scale thickness of sheet is proposed as follows:

$$\alpha = r/t \tag{5.6}$$

where r is the rolling reduction and t is the scale thickness of sheet. Table 5.11 summarizes the values of parameter α of the steels A, B, and C as shown in Fig. 5.74.

The values of parameter α of the steels A, B, and C are independent of the scale thickness. It can be understood that the black scale layer on the work roll surface forms when the values of parameter achieve a certain value in the steels. From

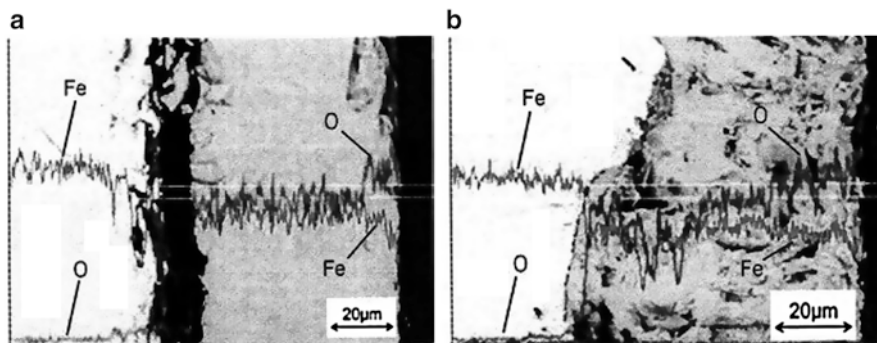


Fig. 5.75 Intensity distribution of iron and oxygen across section of sheet of steel B (a) and steel C (b)

Fig. 5.74, the α values of the formation lines of the steels A, B, and C are about 0.007, 0.013, and 0.04. The values increase in the order of steels A, B, and C. Consequently, it can be understood that the black scale layer forms easily in the order of steels A, B, and C. It is estimated that the difference of the formation of the black scale layers is due to the difference of the chemical composition of the scale layer of the sheet surface.

Figure 5.75 shows the intensity distribution of iron and oxygen across a section of sheet of steel B (a) and steel C (b). From Fig. 5.75, it can be understood that FeO layer in the black scale layer increases in the order of the steels A, B, and C. It is estimated that the reason of this phenomenon is due to the Si content of the steels. From the experimental results and the EPMA analyses, it can be estimated that the scale layer of the sheet surface adheres on the work roll surface when the ratio of FeO layer in the scale of sheet surface is larger, and the black scale layer on the work roll adheres to the work roll surface, and the black scale layer on the work roll surface forms strongly by the transformation of FeO to Fe_3O_4 .

5.7.2.3 The Effect of Emulsion Concentration on the Formation Condition

Third, the effect of the emulsion concentration on the formation condition of the black scale layer on the work roll surface was examined by Nakazawa [41]. The experiments are carried out using the SPHC sheet with a scale thickness of 40 μmRa and the SKD11 roll with a surface roughness of 0.2 μmRa at a velocity ratio of 20, at a rolling speed of 50 m/min and at a temperature of 800 C in rolling reductions of 0.3, 0.5 and 1.0 mm. The lubricants of the mineral base oil, the colza base oil and the synthetic base oil added the additives of 5 % Ca sulfonate, 5 % Sulfide and 5 % Phosphite are used with emulsion concentrations of 0.5 and 3.0 %. The photographs of the cross section of the scale of SPHC sheet with scale thicknesses of 20 μm (a), 40 μm (b), and 80 μm (c) are shown in Fig. 5.70.

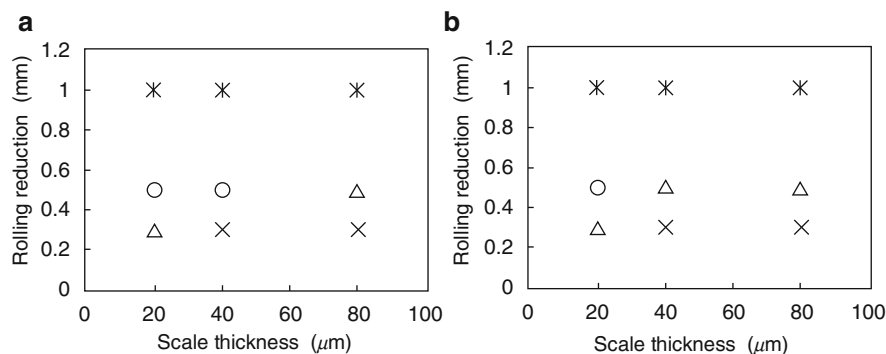


Fig. 5.76 Relationship between the rolling reduction and scale thickness using colza oil with emulsion concentrations of 0.5 % (a) and 1.0 % (b)

Figure 5.76 shows the relationship between rolling reduction and scale thickness of the SPHC sheet for the formation condition of the black scale layer using the colza oil with emulsion concentrations of 0.5 % (a) and 1.0 % (b). In Fig. 5.76, the friction pickup occurs at a rolling reduction of 1.0 mm, compared to the relationship for the colza oil with an emulsion concentration of 3.0 % shown in Fig. 5.71. It is understood that when the emulsion concentration is lower, the black scale layer occurs at lower rolling reduction.

5.7.2.4 The Effect of Base Oil and Additive on the Formation Condition

Fourth, the effects of the base oil and the additive of lubricant on the formation condition of the black scale layer on the roll surface were examined [41]. The experiments are carried out using the SPHC sheet with a scale thickness of 40 μm Ra and the SKD11 roll with a surface roughness of 0.2 μm Ra at a velocity ratio of 20, at a rolling speed of 50 m/min and at a temperature of 800 C in rolling reductions of 0.3, 0.5 and 1.0 mm. The lubricants of the mineral base oil, the colza base oil and the synthetic base oil added the additives of 5 % Ca sulfonate, 5 % Sulfide and 5 % Phosphite are used, with emulsion concentrations of 0.5 and 3.0 %. The photograph of the cross section of the scale of SPHC sheet with scale thickness of 40 μm is shown in Fig. 5.70b.

Figure 5.77 shows the relationship between the rolling reduction and additive for the mineral oil, the colza oil, and the synthetic ester oil with emulsion concentrations of 0.5 % (a) and 3.0 % (b) using the SPHC sheet with a scale thickness of 40 μm . Concerning with the effect of the base oils on the formation condition of the black scale layer, at an emulsion concentration of 0.5 %, the formation condition is independent of the base oils, and at a rolling reduction of 0.5 mm, the formation of the black scale layer starts. Moreover, at an emulsion concentration of 3 %, the formation condition is independent of the base oils, and at a rolling reduction of 0.5 mm, it also starts.

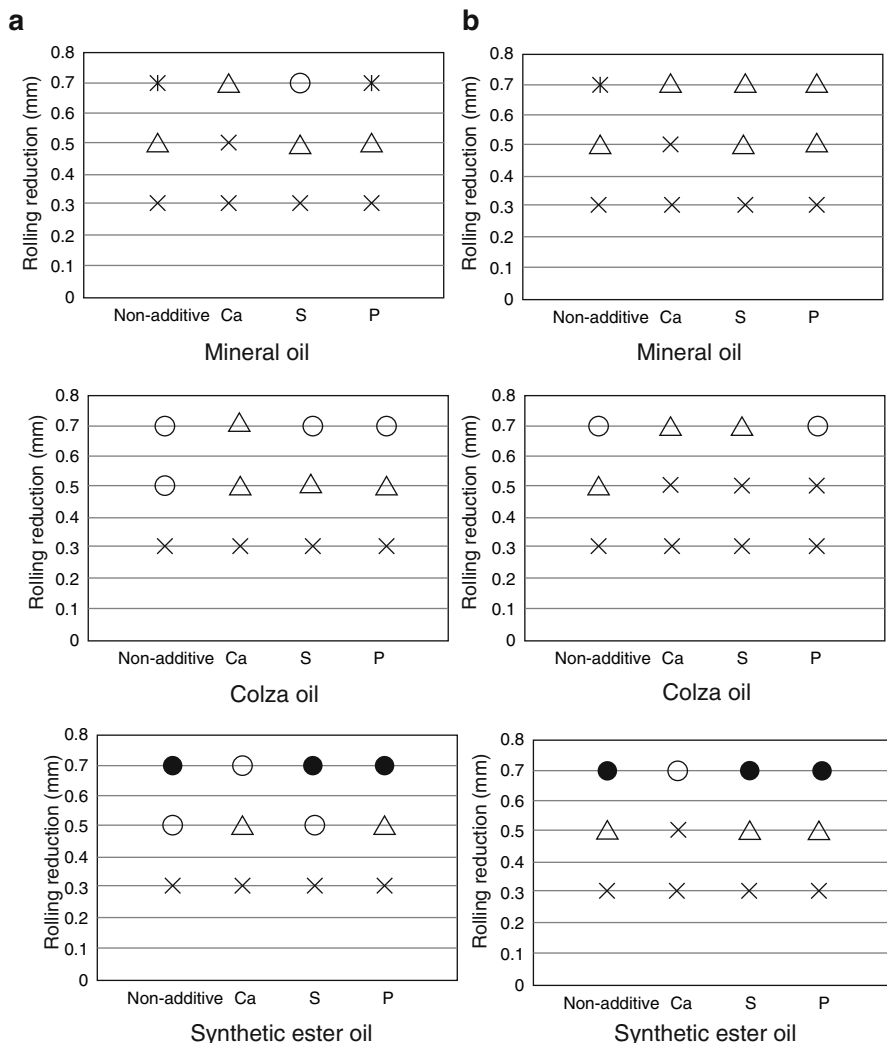


Fig. 5.77 Relationship between the rolling reduction and additive for mineral oil, colza oil, and synthetic ester oil with emulsion concentrations of 0.5 % (a) and 3.0 % (b)

Then, concerning with the effect of the additive on the formation condition of the black scale layer, at an emulsion concentration of 0.5 %, the formation condition depends on the additive and the rolling reduction. For the mineral oil, the rolling reduction of the formation of the black scale layer increases from 0.5 to 1.0 mm. On the other hand, for the colza oil and the synthetic ester oil, the rolling reductions of the formation are the same. Next, at an emulsion concentration of 3.0 %, the formation condition depends on the additive. For the mineral oil, the rolling reduction of the formation increases from 0.5 to 1.0 mm by the addition of the Ca

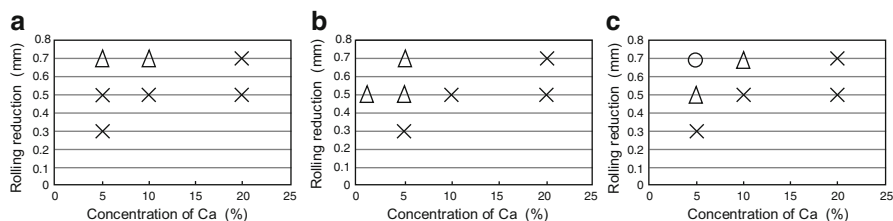


Fig. 5.78 Relationship between the rolling reduction and concentration of Ca sulfonate using mineral oil (a), colza oil (b), and synthetic ester oil (c) with emulsion concentration of 0.5 %

sulfonate. For the colza oil, it increases from 0.5 to 1.0 mm by the addition of the Ca sulfonate, the sulfide, and the phosphate. For the synthetic ester oil, it increases from 0.5 to 1.0 mm by the addition of the Ca sulfonate.

From these results, it is found that the addition of the Ca sulfonate is significantly effective for the formation of the black scale layer. Then, the experiments are carried out using the SPHC sheet with a scale thickness of 40 μm and the SKD61 roll with a surface roughness of 0.2 μmRa at a velocity ratio of 20, at a roll speed of 50 m/min and at a temperature of 800 C in rolling reductions of 0.3, 0.5 and 1.0 mm. The lubricants of the mineral base oil, the colza base oil and the synthetic ester base oil added the additives of 5 %, 10 % and 20% Ca sulfonates are used with an emulsion concentration of 0.5 %.

Figure 5.78 shows the relationship between the rolling reduction and concentration of Ca sulfonate using the mineral oil (a), the colza oil (b), and the synthetic ester oil (c) with an emulsion concentration of 0.5 % for the formation condition of the black scale layer. It is recognized that for all the base oils, the rolling reduction of the formation condition of the black scale layer increases with increasing concentration of Ca sulfonate.

5.8 Hot Rolling Lubricant

5.8.1 Hot Rolling Lubricant in History

In the late 1960s, rolling lubricants in hot sheet rolling were used in Europe and the United States, and in Japan, the hot rolling lubricants were used in the 1970s. In base oils of the hot rolling oil, the mineral oils, the fats oils, and the synthetic ester oils were used, and in the additive agents of the base oils, the oiliness agents for the decrease of the coefficient of friction and the EP agents for the prevention of pickup were used.

The supply system of the rolling oil is essentially different from that in cold sheet rolling. There is a water injection system, a steam atomizing system, and so on. For an example, Fig. 5.79 shows the schematic representation of the water injection

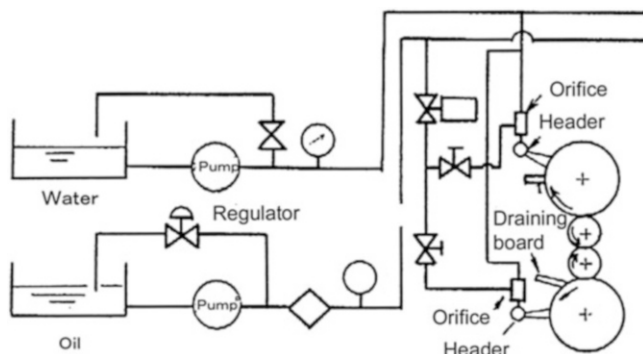
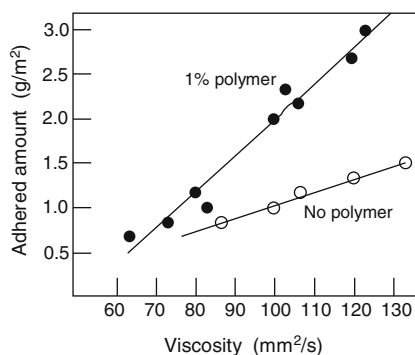


Fig. 5.79 Schematic representation of water injection system [1]

Fig. 5.80 Relationship between the adhered amount and viscosity of rolling oil [24]



system. The water injection system has been used the most widely in Japan. The oil and the water are mixed in the pipe, an emulsion is made, and the emulsion is supplied on the surface of backup rolls through the nozzles. In order to enhance the lubricating effect of rolling oil, it is significantly important that a thick oil film adheres to the work roll surface.

Figure 5.80 shows the relationship between the adhered amount and viscosity of rolling oil [24]. The adhered amount on the roll surface increases linearly with increasing viscosity. The adhered amount of the lubricant with 1 % polymer is larger than that without polymer.

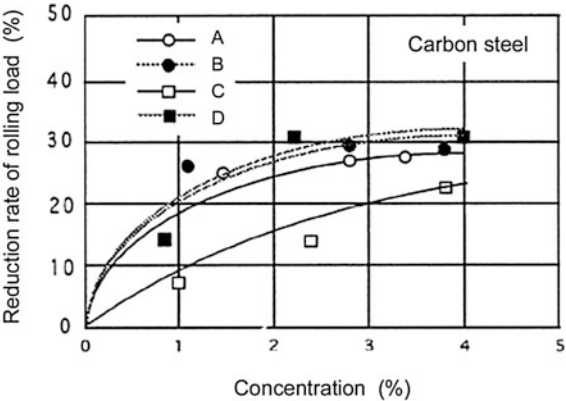
Imae et al. [42] examined the rolling load in the rolling experiments using the commercial hot rolling oils shown in Table 5.12 using the laboratory mill. The experiments were carried out using the carbon steel sheet and the HSS rolls at a reduction of 50 % and at a rolling speed of 100 m/min. Figure 5.81 shows the relationship between the reduction rate of rolling load and emulsion concentration for four commercial oils.

In Fig. 5.81, the reduction rates of the rolling load for the lubricants of A and B with higher saponification value are larger than that for the lubricant C with lower saponification value. However, for the lubricant D with lower value, the reduction rate is larger by the action of the additives of ester and Ca compound.

Table 5.12 Compositions and properties of commercial oils used [42]

Lubricant	Composition	Acid value	Saponification mgKOH/g	Viscosity mm ² /s, 40 °C
A	Mineral oil, synthetic ester 59 %, EP agent	7	126	71
B	Mineral oil, synthetic ester 59 %, EP agent	7	126	110
C	Mineral oil, ester 5 %, Ca compound	7	—	220
D	Mineral oil, ester 10 %, Ca compound	7	—	240

Fig. 5.81 Relationship between the reduction rate of rolling load and emulsion concentration [42]



5.8.2 Evaluation of Hot Rolling Oil by Hot Sliding-Rolling Type Tribo-Simulator

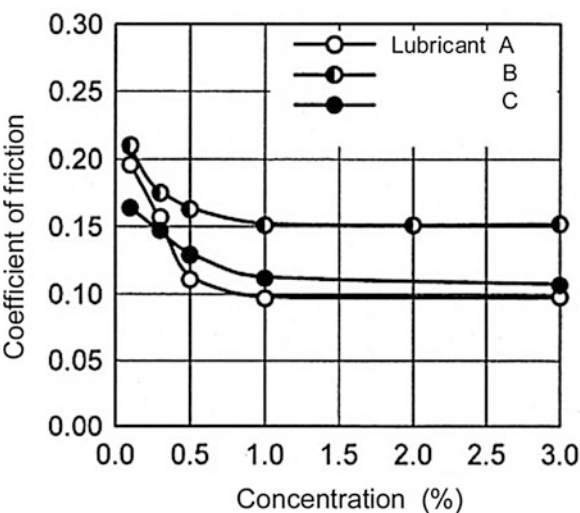
In this chapter, in order to evaluate the hot rolling oil, the effect of the lubricant factors of the composition, the viscosity of base oil, the additive agents, and the emulsion concentration on the coefficient of friction using the hot sliding-rolling type tribo-simulator was examined by Azushima et al. [43]. Table 5.13 summarizes the compositions of the lubricants used.

First, the effect of the composition of lubricants on the coefficient of friction is examined. The experiments are carried out using the lubricants of A, B, and C at a roll speed of 50 m/min. The sliding-rolling experiments are carried out using the SPHC sheet, the SKD61 roll at a temperature of 800 °C, at a rolling reduction of 0.3 mm, and at a velocity ratio 20. The lubricants are used in the emulsion at 40 °C, and the concentrations are 0.1, 0.3, 0.5, 1.0, 2.0, and 3.0 %. Figure 5.82 shows the relationship between coefficient of friction and emulsion concentration for the castor oil (a), the mineral oil (b), and the synthetic ester oil (c). Over an emulsion concentration of 1.0 %, the coefficients of friction for the lubricants of A, B, and C become constant and the coefficient of friction for the mineral oil (b) is higher than

Table 5.13 Compositions of lubricant used

Lubricant	Composition
A	Colza oil (35 mm ² /s at 40 °C)
B	Mineral oil with low viscosity (40 mm ² /s at 40 °C)
C	Synthetic ester oil with low viscosity (50 mm ² /s at 40 °C)
D	Mineral oil with high viscosity (170 mm ² /s at 40 °C)
E	Synthetic ester oil with high viscosity (200 mm ² /s at 40 °C)
A1	Colza oil A (95 %) + oleic acid (5 %)
A2	Colza oil A (95 %) + fatty oil sulfide (5 %)
A3	Colza oil A (98 %) + graphite (2 %)
A4	Colza oil A (98 %) + MoS ₂ (2 %)
A5	Colza oil A (98 %) + mica (2 %)
B1	Mineral oil B (95 %) + oleic acid (5 %)
B2	Mineral oil B (95 %) + fatty oil sulfide (5 %)
B3	Mineral oil B (98 %) + graphite (2 %)
B4	Mineral oil B (98 %) + MoS ₂ (2 %)
B5	Mineral oil B (98 %) + mica (2 %)
C1	Synthetic ester oil C (95 %) + oleic acid (5 %)
C2	Synthetic ester oil C (95 %) + fatty oil sulfide (5 %)
C3	Synthetic ester oil C (98 %) + graphite (2 %)
C4	Synthetic ester oil C (98 %) + MoS ₂ (2 %)
C5	Synthetic ester oil C (98 %) + mica (2 %)

Fig. 5.82 Relationship between coefficient of friction and emulsion concentration



those for the colza oil and the synthetic ester oil. The values of A, B, and C oils are 0.10, 0.15, and 0.11. On the other hand, up to 1.0 %, the coefficients of friction increase with decreasing emulsion concentration. The concentration dependence of the coefficients of friction is different depending on the composition of lubricant.

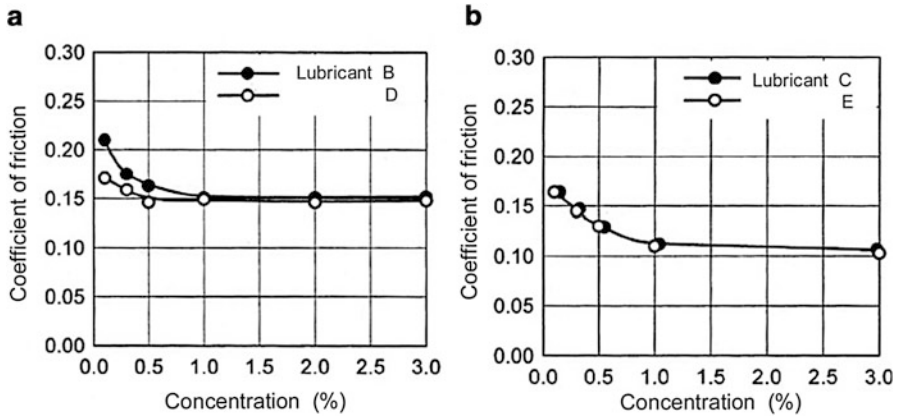


Fig. 5.83 Relationship between coefficient of friction and emulsion concentration for mineral oils (a) and synthetic ester oils (b)

Second, the effect of the viscosity of lubricant on the coefficient of friction is examined, changing the emulsion concentration. The experiments are carried out using the lubricants of B, D and C, E at a roll speed of 50 m/min, at a rolling reduction of 0.3 mm, and at a velocity ratio 20. The lubricants are used in the emulsion at 40 °C, and the concentrations are 0.1, 0.3, 0.5, 1.0, 2.0, and 3.0 %. Figure 5.83 shows the relationship between coefficient of friction and emulsion concentration for the mineral oils (a) and the synthetic ester oils (b). For the synthetic ester oils (C and E), the coefficient of friction is independent of the viscosity of lubricant. On the other hand, for the mineral oils (B and D), the coefficients of friction are the same above an emulsion concentration of 1.0 %, and up to 1.0 %, the coefficient of friction for the mineral oil B with lower viscosity is higher than that for the mineral oil C with higher viscosity.

Third, the effect of the additive agents on the coefficient of friction is examined. The experiments are carried out using the lubricants of A1 to A5, B1 to B5, and C1 to C5 at a roll speed of 50 m/min, at a rolling reduction of 0.3 mm, and at a velocity ratio 20. The lubricants are used in the emulsion at 40 °C, and the concentrations are 0.1 and 3.0 %. Figure 5.84 shows the coefficients of friction for the colza oils with additive agents of A1 to A5 at emulsion concentrations of 0.1 % (a) and 3.0 % (b). Figure 5.85 shows the coefficients of friction for the mineral oils with additive agents of B1 to B5 at emulsion concentrations of 0.1 % (a) and 3.0 % (b). Figure 5.86 shows the coefficients of friction for the synthetic ester oils with additive agents of C1 to C5 at emulsion concentrations of 0.1 % (a) and 3.0 % (b).

The coefficients of friction for three oils of the colza oil, the mineral oil, and the synthetic ester oil at an emulsion concentration of 3.0 % are nearly independent of the additive agents. The coefficient of friction for each oil at 0.1 % depends on the additive agents. For the colza oil, the additive agent of oleic acid is most effective; for the mineral oil, fatty oil sulfide is most effective; and for the synthetic ester oil, graphite is most effective.

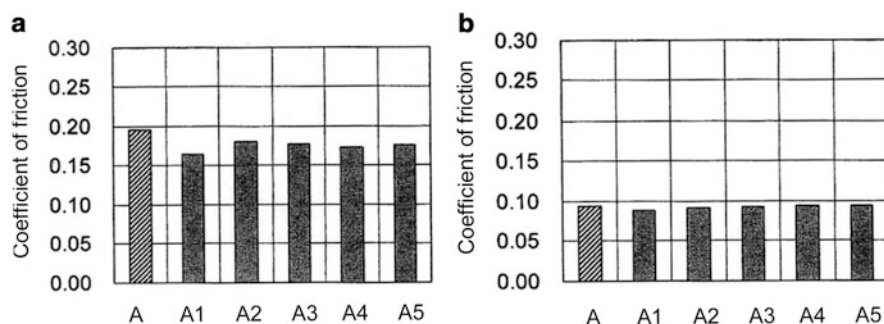


Fig. 5.84 Coefficients of friction for colza oils with additive agents of A1 to A5 at emulsion concentrations of 0.1 % (a) and 3.0 % (b)

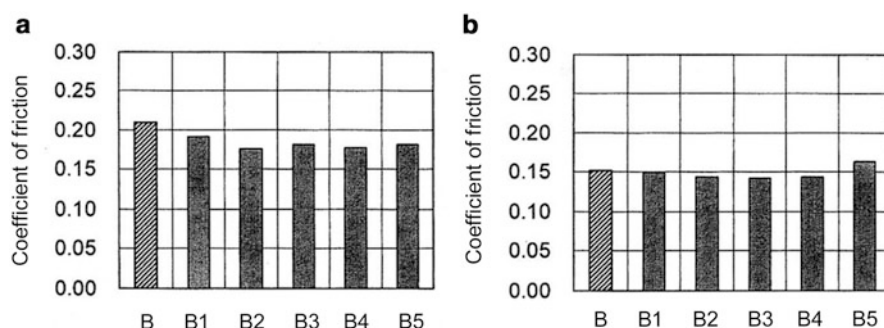


Fig. 5.85 Coefficients of friction for mineral oils with additive agents of B1 to B5 at emulsion concentrations of 0.1 % (a) and 3.0 % (b)

5.8.3 Development of Hot Rolling Oil for Stainless Steel

In order to develop the hot rolling oil for the stainless steel, the effect of the lubricant composition on the antiseizure property using the hot sliding-rolling type tribo-simulator was examined by Toriumi et al. [44]. From previous papers, it was reported that the Ca sulfonate and the sulfide ester were effective on the antiseizure property of stainless steel in hot sheet rolling. Therefore, the effect of the S additive in the colza oil on the friction pickup of SUS430 stainless steel is examined. The lubricants of 3 % emulsion of the colza oil with S additive contents at 20, 30, 50, and 80 % are used.

The experiments are carried out using the SUS430 stainless steel sheet and the HSS roll with a surface roughness of $0.2\ \mu\text{m}$ at roll speeds of 30, 50, and 70 m/min and at a temperature of $800\ ^\circ\text{C}$ in the rolling reductions from 0.2 to 1.4 mm. Figure 5.87 shows the photographs of the cross section of scale on the SUS430 stainless steel sheet surface after heating, and Table 5.14 summarizes the EDX analysis of the cross section of scale. The scale thickness of the SUS430 stainless steel is thinner compared to that of carbon steel.

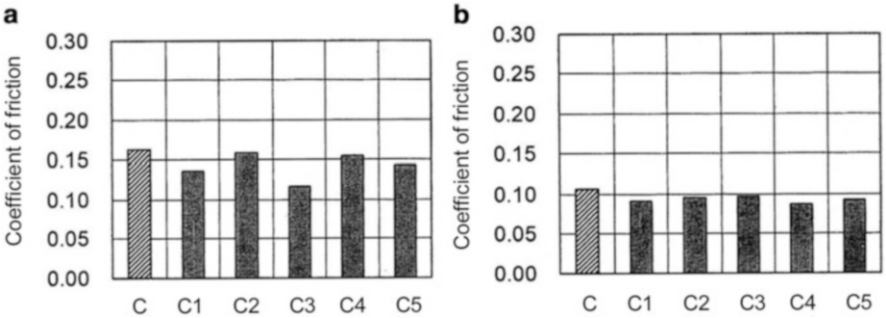


Fig. 5.86 Coefficients of friction for synthetic ester oils with additive agents of C1 to C5 at emulsion concentrations of 0.1 % (a) and 3.0 % (b)

Fig. 5.87 Photographs of cross section of scale on SUS430 stainless steel sheet surface after heating

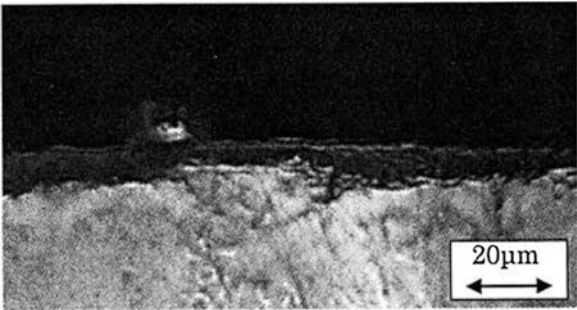


Table 5.14 EDX analysis of scale

O	Si	P	S	Cr	Mn	Fe	Mo
43.21	2.59	0	0.2	45.54	1.93	6.19	0.35

Figure 5.88 shows the occurrence of the friction pickup of the SUS430 stainless steel using the lubricants of the colza oil with S additive contents at 20 % (a), 30 % (b), 50 % (c), and 80 % (d), changing the rolling reduction. On the one hand, the critical rolling reduction decreases with increasing roll speed for each lubricant, and on the other hand, it increases with increasing S additive content.

Next, Fig. 5.89 shows the relationship between coefficient of friction and S additive content. In Fig. 5.89, the coefficient of friction increases with increasing S additive content. Even though the coefficient of friction increases with increasing S additive content, the critical rolling reduction increases with increasing S additive content. It is expected that this phenomena will be investigated chemically in the future.

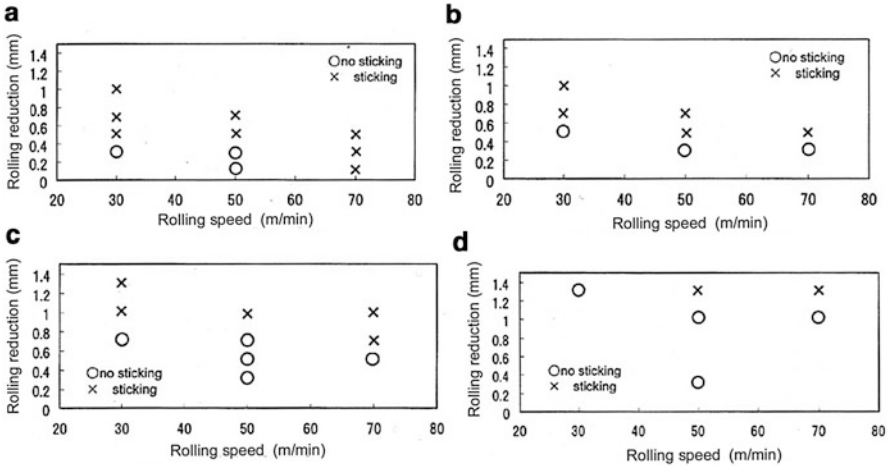
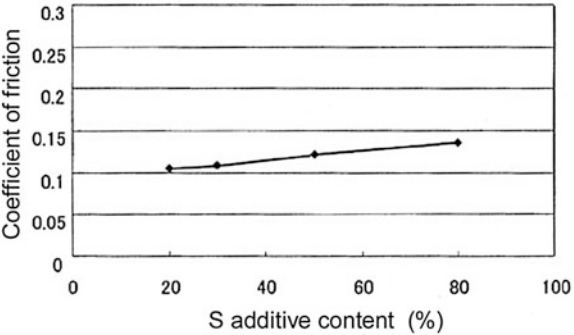


Fig. 5.88 Occurrence of the friction pickup of SUS430 stainless steel using lubricants of colza oil with S additive. (a) S additive content of 20 %, (b) S additive content of 30 %, (c) S additive content of 50 %, (d) S additive content of 80 %

Fig. 5.89 Relationship between coefficient of friction and S additive content



5.8.4 Development of Rolling Oil for Hot Rolling with Large Reduction

5.8.4.1 Previous Consideration

In order to manufacture the steel sheet with fine grain, it is necessary to carry out the hot sheet rolling with a large reduction. In order to carry out the hot sheet rolling with a large reduction, the hot rolling oil with high coefficient of friction must be used for the biting. However, when the hot rolling oils with high coefficient of friction are used, the rolling load becomes higher, so the rolling load may exceed the maximum load of mills. Therefore, the new hot rolling oil with properties that the coefficient of friction at the biting is high and the coefficient of friction during

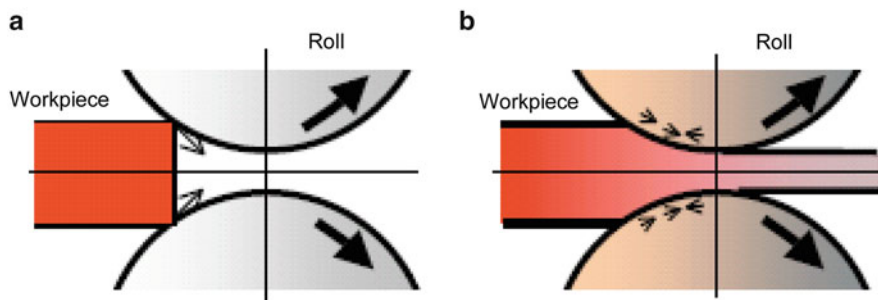


Fig. 5.90 Conceptual diagram of new hot rolling oil

rolling is low must be developed. Moreover, the hot rolling oils must also have an excellent antiseizure property.

Figure 5.90 shows the conceptual diagram of the new hot rolling oil. Figure 5.90a illustrates that the rolling process and the coefficient of friction at the biting must be high. Figure 5.90b illustrates that the rolling process and the coefficient of friction during rolling must be low.

In order to satisfy this demand of the coefficient of friction, the similar relationship between coefficient of friction and emulsion concentration in which the coefficient of friction decreases with increasing emulsion concentration as shown in Fig. 5.32 may be utilized. As a concrete image, the emulsion concentration is lower at the biting as shown in Fig. 5.90a and at the time the coefficient of friction remains high. Then, the emulsion concentration becomes higher during rolling as shown in Fig. 5.90b and at the time the coefficient of friction becomes lower.

In order to accomplish this phenomenon, the lubrication mechanism at the contact interface between roll and workpiece corresponding with the relationship between coefficient of friction and emulsion concentration shown in Fig. 5.32 may be used. In the region with lower emulsion concentrations, the contact interface consists of the region covered with the lubrication film and the region without the lubrication film. In this region, the coefficient of friction decreases with increasing ratio of the region with the lubrication film. If the emulsion concentration can be controlled in the actual tandem mill, the relationship between coefficient of friction and rolling distance can be obtained by the method wherein the emulsion concentration is controlled from the lower values at the biting to the higher values during rolling. However, it is difficult that this phenomenon cannot be accomplished by one lubricant in hot sheet rolling.

Since it is difficult to control the emulsion concentration in the actual tandem mill, another method must be developed. Ikeda et al. [45] proposed the new method in order to accomplish this phenomenon by one lubricant. Figure 5.91 illustrates the conceptual diagram of the new method using a new lubricant. The new hot rolling lubricant is made from a liquid colloidal lubricant with the silicate type inorganic compound. The silicate type inorganic compound becomes liquid at a temperature

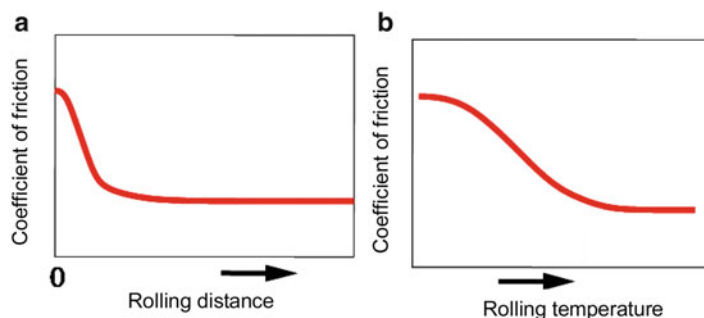


Fig. 5.91 Relationship between coefficient of friction and rolling distance (a) and coefficient of friction and temperature (b)

Table 5.15 Compositions (wt%) of lubricants used

	E-6	E-7	E-5	A-11
Metal soap	5	6.5	8	10
Silicate-type compound	5	3.5	2	2
Antiseizure compound	2	2	2	2
Colloid aids 1	10	10	10	1
Colloid aids 2	1.2	1.2	1.2	2
Colloid aids 3	1	1	1	1
Water	75.8	75.8	75.8	73

over the melting temperature, and the coefficient of friction decreases with increasing rolling temperature at the contact area as shown in Fig. 5.91b similar to the relationship in Fig. 5.91a.

5.8.4.2 Experiments and Results

The mixtures of metal soap and the silicate type inorganic compounds are used as developed hot rolling lubricants [45]. Table 5.15 summarizes the composition of lubricants evaluated. The metal soap is used in order to reduce the coefficient of friction at high temperature, and the silicate type inorganic compound is used in order to increase the coefficient of friction. In order to evaluate the antiseizure property and the coefficient of friction of the lubricants at high temperature, the hot Timken testing machine is used. The experiments of the antiseizure property are carried out using the SUS test piece and the HSS roll at revolutions of 150, 300, and 600 rpm and at a temperature 900 °C with loads from 0 to 500 N.

Figure 5.92 shows the experimental results of the antiseizure load of each lubricant. For the comparison, the antiseizure loads of hot rolling oils for mild steels (MS) and for stainless steels (SUS) are added in Fig. 5.92. The antiseizure loads of all the developed lubricants are better than that of the hot rolling oil for mild steels, and they are close to that for stainless steels.

Fig. 5.92 Antiseizure load of each lubricant

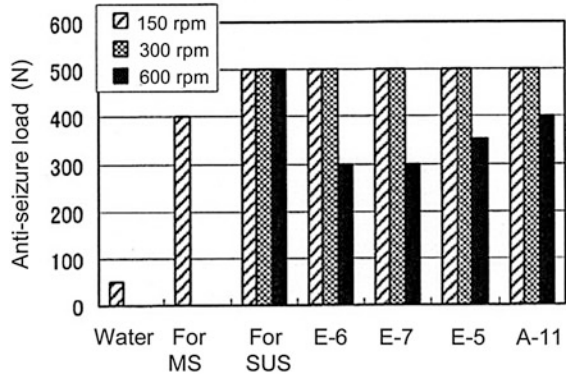
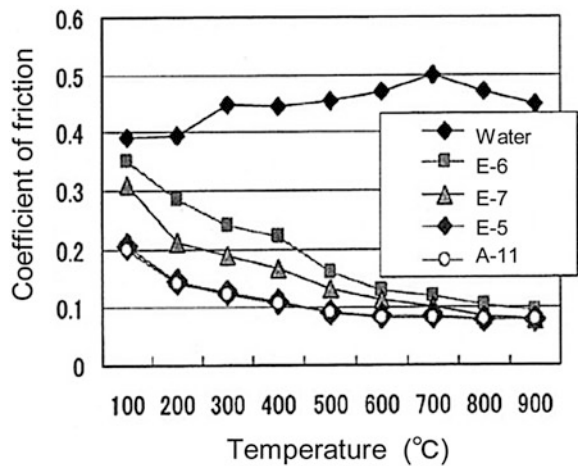


Fig. 5.93 Relationship between coefficient of friction and temperature of each lubricant



Then, the experiments for the coefficient of friction are carried out using the SS-400 test piece and the HSS roll at a revolution of 150 rpm and at a load of 200 N with temperatures from 100 to 900 °C using the hot Timken testing machine. Figure 5.93 shows the relationship between coefficient of friction and temperature. In Fig. 5.93, the relationship between coefficient of friction and temperature of the water is added. From the experimental results, it is found that the relationship between coefficient of friction and temperature changes by the composition ratio of metal soap to silicate type inorganic compound. The coefficient of friction decreases with increasing amount of metal soap and decreasing amount of silicate type inorganic compound.

Next, in order to evaluate the relationship between coefficient of friction and sliding distance at higher temperatures, the hot sliding-rolling type tribo-simulator is used. The experiments are carried out using SPHC sheet, the SKD61 roll, and the A-11 lubricant with an emulsion concentration of 15 % at a roll speed of

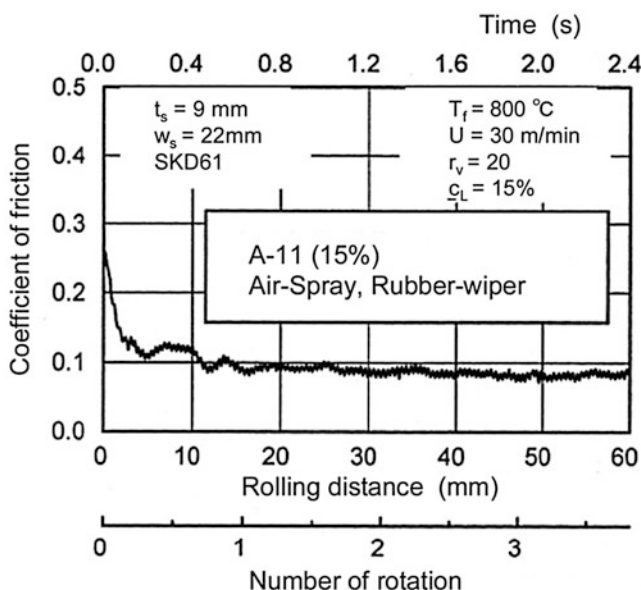
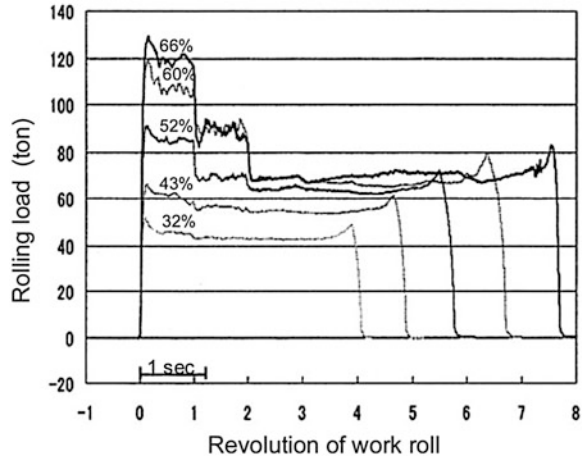


Fig. 5.94 Relationship between coefficient of friction and rolling distance of lubricant A-11 using hot sliding-rolling type tribo-simulator

30 m/min, at a velocity ratio of 20, at a rolling reduction of 0.15 mm, and at a temperature of 800 °C with an air-sprayer and a rubber-wiper. Figure 5.94 shows the relationship between coefficient of friction and rolling distance of lubricant A-11. It is found that the coefficient of friction decreases abruptly with increasing rolling distance from 0.25 to 0.1 by one rotation of roll. It is understood that the A-11 lubricant can become the new hot rolling lubricant with properties that the coefficient of friction at the biting of rolling is high and then the coefficient of friction during rolling is low.

Moreover, in order to evaluate the relationship between coefficient of friction and rolling distance in rolling process, the laboratory hot rolling mill is used. The rolling experiments are carried out using the SPHC sheet, the SKD roll, and the lubricant A-11 with an emulsion concentration of 30 % at a rolling speed of 50 m/min, changing the reduction in thickness from 30 to 70 %. Figure 5.95 shows the relationship between rolling load and work roll revolution changing the reduction. From Fig. 5.95, it is found that the rolling load decreases with increasing work roll revolution, and in particular, in higher reductions, the rolling load becomes significantly lower after two revolutions of work roll. From the results, it is confirmed that the new developed lubricant has the properties that the coefficient of friction at the bite of rolling is high and then the coefficient of friction during rolling is low.

Fig. 5.95 Relationship between rolling load and work roll revolution



5.9 Hot Roll

5.9.1 Hot Roll in History

In Japan, before the 1990s, the materials used for the hot work rolls in hot sheet rolling are summarized in Table 5.16. In particular, Fig. 5.96 shows the relationship between hardness and carbon content of the hot work rolls used widely at the present time [46].

For the work rolls in hot sheet rolling shown in Fig. 5.96, the range of the hardness is in HS35 to 85, and the contents of C% and Cr% are from 0.4 to 3.5 % and 0.5 to 20 %. There are the cast steel roll, the forged steel roll, the adamite roll, and the ductile cast steel roll. Figure 5.97 shows the transition of the work roll of hot sheet rolling [46].

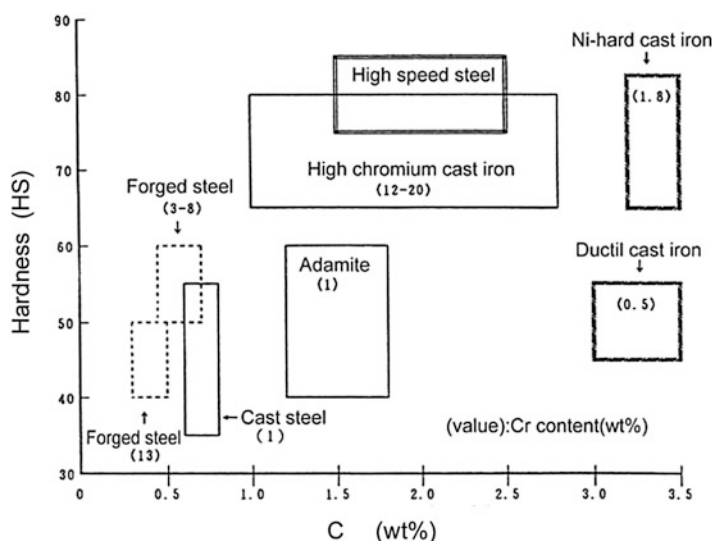
Before 1985, in the front stands in hot sheet rolling, the adamite roll was used, but the high-chromium cast iron roll with high anti-wear resistance property after 1985 was used. On the other hand, in the back stands in hot sheet rolling, the Ni-hard cast iron with high hardness and high anti-wear resistance property was used.

Figure 5.98 shows the relationships between wear losses of the adamite roll, the high-chromium cast iron roll, and the Ni-hard cast iron roll and total frictional work [46]. The vertical axis shows the wear loss per 1000 t. The wear loss for each stand becomes smaller in high-chromium cast iron roll, the adamite roll, and the Ni-hard cast iron roll.

After the 1990s in Japan, the tendency toward higher load and higher speed in hot sheet rolling was required, and the hot rolls with excellent wear resistance were developed. The high-speed steel (HSS) roll began to be used in the front and back stands in hot rolling. Figure 5.99 shows the depth of wear of the Ni-hard cast iron, the high chromium cast iron, and the HSS [47].

Table 5.16 Materials used for hot rolls in hot sheet rolling

	Materials	C/%	Symbol
Low carbon	Cast steel	0.5–1.4	S
	Forged steel	0.5–1.0	S-F
Mild carbon	Adamite	1.4–2.5	AD
	Forged adamite	1.4–2.5	AD-F
High carbon	Definite chilled cast iron	3.0–3.5	CH
	Indefinite chilled cast iron, Ni-hard cast iron	3.0–3.5	GR
	Ductile, nodular, spheroidal graphite cast iron	3.0–3.5	DC
High alloy	High-chromium steel	0.9–1.8	HC-S
	High-chromium cast iron	2.3–2.9	HC
	High-speed steel	1.5–3.0	HSS
Sintered	Sintered carbide, carbide	1.5–3.0	HSS-P
	Tungsten carbide	WC 70–90	WC

**Fig. 5.96** Relationship between hardness and C% of work roll in hot sheet rolling [46]

From Fig. 5.99, it is understood that the anti-wear resistance of the HSS roll is three times that of the Ni-hard cast iron and is five times that of the high chromium cast iron roll. At the beginning of the use of the high-speed rolls, there were problems as follows:

1. In the front stands, the surface roughening of the work roll occurred.
2. In the back stands, the accident of cluck of the work roll occurred.
3. The coefficient of friction is high, so the rolling load increased.

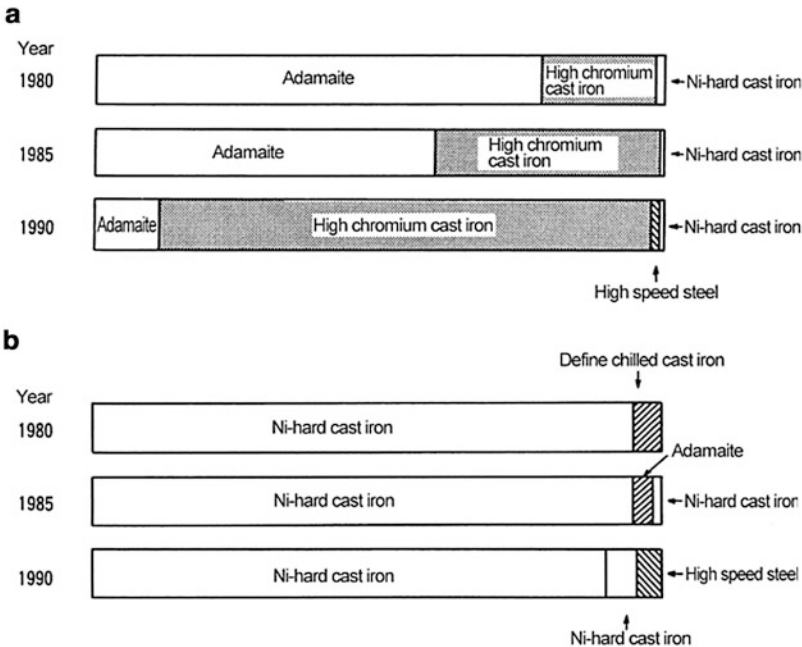


Fig. 5.97 Transition of work roll in hot rolling [46]. (a) Work roll of front stands in hot rolling, (b) work roll of back stands in hot rolling

Fig. 5.98 Relationship between wear loss of adamate roll, high-chromium cast iron roll, and Ni-hard cast iron roll and total frictional work [46]

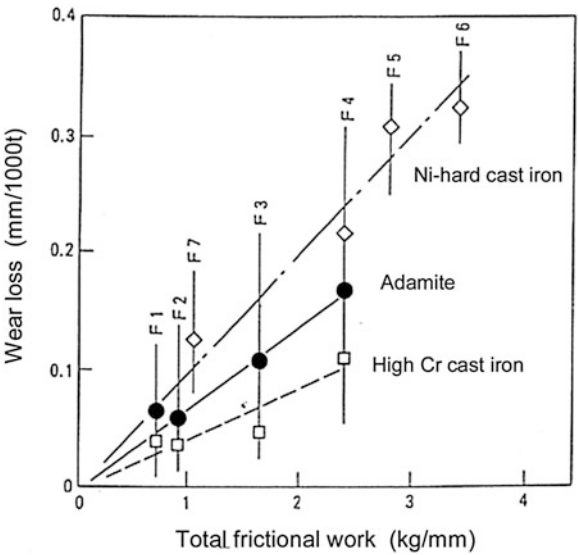


Fig. 5.99 Relationship between the depth of wear and unit load x rolling cycle of Ni-hard cast iron, high chromium cast iron, and high-speed steel [47]

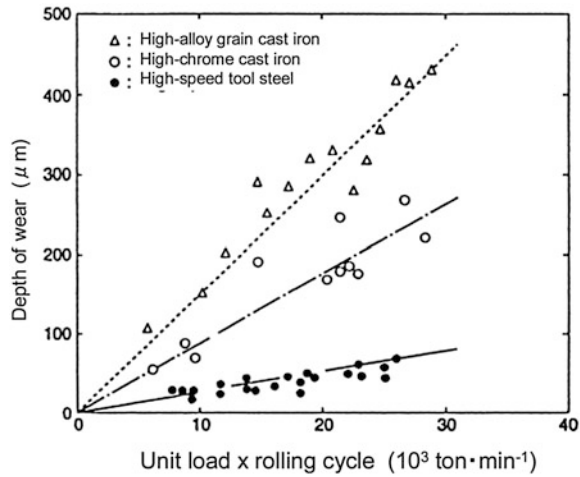
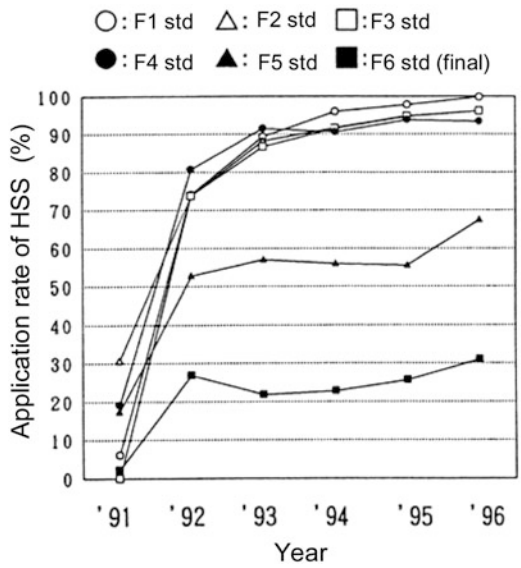


Fig. 5.100 Application rate of high-speed roll [48]



Concerning problem (1), the mechanism of the surface roughening was clarified and the problem was improved by the development of the roll material. Concerning problem (3), it was also improved by the development of the roll material.

Figure 5.100 shows the application rate of the high-speed roll in Hirohata Works of Nippon Steel Corp. The application rate in the front stands of Nos. 1–3 approached to almost 100 % by 1994. However, in the back stands, the application rate of No. 4 approached to almost 100 % by 1994 and Nos. 5–50 % and Nos. 6–30 % by 1995. Even now, the application rate of No. 6 remains at a low value by problem (2).

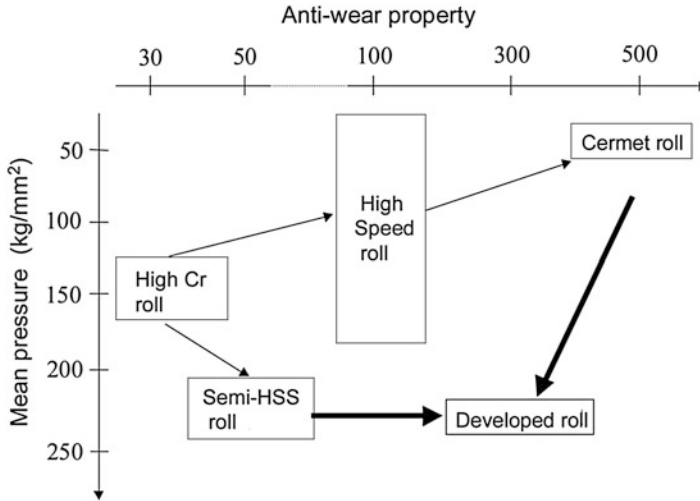


Fig. 5.101 Target of developed hot roll

5.9.2 Development of Hot Roll for Hot Sheet Rolling with High Reduction

5.9.2.1 Previous Consideration

In order to carry out the hot sheet rolling with high reduction, the hot rolls with high fatigue strength, high resistance for pressure, and high anti-wear resistance must be developed. Figure 5.101 shows the target of the developed hot roll for hot sheet rolling with high reduction. It is necessary that the developed hot roll has the same resistance property for pressure as the Semi HSS roll and the same anti-wear resistance property as the ceramic roll.

In order to satisfy these targets, the sleeve roll of cermet layer was designed as shown in Fig. 5.102 [49]. The designed hot roll consists of the outer layer made of cermet and the inner layer and the axis made of steel. In this designed hot roll, the bonding strength at the interface between cermet outer layer and steel inner layer must be maintained at a high value.

5.9.2.2 Results

Since the cermet roll has a superior anti-wear resistance property, the designed sleeve cermet roll must have a high fatigue strength and a high resistance for pressure. In order to carry out the hot sheet rolling with high reduction using this designed cermet roll, the tensile strength at the interface between cermet outer layer and steel inner layer must be over 1000 MPa and the fatigue strength must be also over 350 MPa.

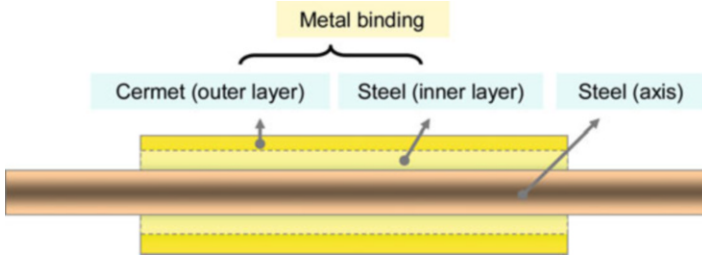


Fig. 5.102 Schematic representation of sleeve roll of cermet layer designed

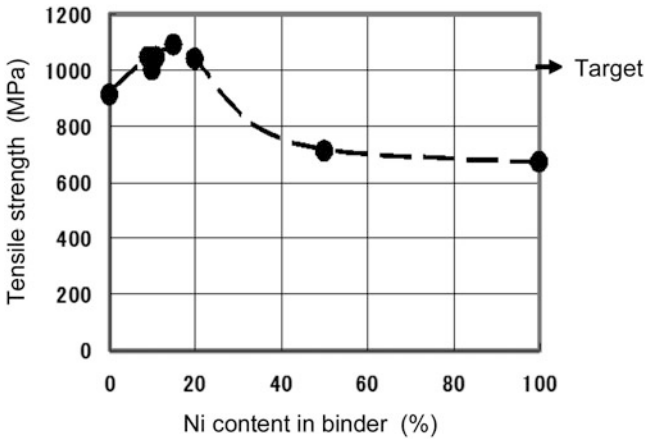


Fig. 5.103 Relationship between tensile strength and Ni content in binder

In order to increase the tensile strength at the interface, the composition of the intermediate layer is improved. The composition of the intermediate layer consists of WC (50 %) and binder (50 %). The binders consist of Ni with X % and Co with (100 – X)%. The tensile strength and the fatigue strength are measured. The tensile specimen has a diameter of 6 mm and a length of 90 mm, and the fatigue specimen has a diameter of 5 mm and a length of 60 mm. These specimens consist of a half of cermet, a half of steel, and the intermediate layer.

Figure 5.103 shows the relationship between tensile strength and Ni content in binder. From Fig. 5.103, it is found that when the Ni content of the binder is in the range of 15–20 %, the tensile strength exceeds over 1000 MPa.

Then, Fig. 5.104 shows the relationship between stress amplitude and number of cycles. From Fig. 5.104, it is found that when the specimen with a tensile strength of over 1000 MPa is used, the stress amplitude exceeds over 300 MPa which is the target value.

Next, in order to evaluate the antiseizure property of the cermet hot roll, the laboratory rolling mill is used. The rolling experiments are carried out using the SPHC sheet and the cermet and Ni-hard cast iron rolls without a lubricant, changing

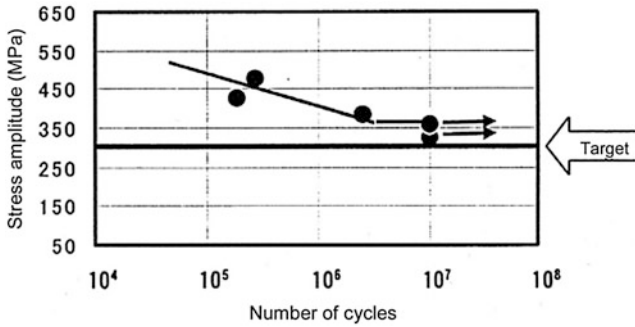
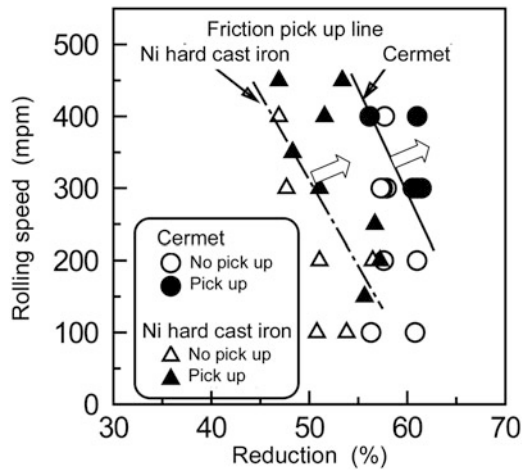


Fig. 5.104 Relationship between stress amplitude and number of cycles

Fig. 5.105 Relationship between rolling speed and reduction of cermet and Ni-hard cast iron rolls



the rolling speed and the reduction. Figure 5.105 shows the limitation line of the friction pickup of the cermet and Ni-hard cast iron rolls. From Fig. 5.105, it is found that the limitation line of friction pickup of the cermet roll is better than that of the Ni-hard cast iron roll. It is found that the cermet roll has a good antiseizure property.

References

1. R. Terakado, J. Jap. Soc. Mech. Engr., 81 (1978), 1069-1074. (in Japanese)
2. N. Kamii, R. Terakado, J. Jap. Soc. Technol. Plast. 17-182 (1976), 202-208. (in Japanese)
3. S. Itoh, K. Kobayashi, N. Asakawa, Testu-to-Hagane, 61 (1975), A81-A84. (in Japanese)
4. T. Mase, J. Jap. Soc. Lub. Engr., 24 (1979), 144-149. (in Japanese)
5. K. Nishizawa, N. Hase, T. Mase, T. Kohno, Testu-to-Hagane, 61 (1975), A77-A80. (in Japanese)

6. J. Kihara, T. Oguchi, K. Watabe, K. Douya, T. Watanabe, J. Jap. Soc. Technol. Plast. 17-189 (1976), 791-796. (in Japanese)
7. R. Ueda, K. Tanaka, T. Yoshida, Maruzen Petrochemical Technical Report, 21 (1976), 45. (in Japanese)
8. K. Tashiro, S. Izumi, T. Ashiura, Y. Itoh, Tetsu-to-Hagane, 61 (1976), S176. (in Japanese)
9. T. Hira, H. Abe, K. Nakagawa, S. Itoh, K. Kobayashi, Proc. Spring Conf. Technol. Plast., (1976), 25-28. (in Japanese)
10. T. Inoue, Symposium text in division of processing for quality products of ISIJ, (1997), 20-23. (in Japanese)
11. T. Hibi, J. Ikeda, Symposium text in division of processing for quality products of ISIJ, (1997), 32-35. (in Japanese)
12. T. Inoue, H. Yamamoto, M. Ataka, H. Takahashi, Y. Nishiyama, R. Kurahasi, J. Jap. Soc. Technol. Plast. 48-496 (2002), 411-416. (in Japanese)
13. T. Inoue, H. Katoh, S. Yamamoto, M. Araka, H. Takahashi, Proc. 41st Joint Conf. Technol. Plast., (1990), 191-194. (in Japanese)
14. A. Azushima, W. D. Xue, K. Aoki, J. Jap. Soc. Tribologists, 7 (2007), 532-538. (in Japanese)
15. A. Azushima, W. D. Xue, K. Aoki, Proc. 4th European Steel Rolling Conference, (2006), 103-108.
16. A. Azushima, W. D. Xue, Y. Yoshida, Annals of the CIRP, 56-1 (2007), 297-300.
17. A. Azushima, W. D. Xue, Y. Yoshida, Tetsu-to-Hagane, 94 (2008), 134-140. (in Japanese)
18. A. Azushima, W. D. Xue, Y. Yoshida, Tetsu-to-Hagane, 93 (2007), 681-686. (in Japanese)
19. A. Azushima, Y. Nakata, T. Toriumi, J. of Material Processing Technology, 210 (2010), 110-115.
20. A. Azushima, H. Utsunomiya, Tetsu-to-Hagane, 100 (2014), 1456-1466. (in Japanese)
21. T. Sasaki, Y. Imai, T. Kohn, T. Fukiage, Proc. 37th Joint Conf. Technol. Plast., (1986), 53-56. (in Japanese)
22. T. Inoue, H. Yamamoto, K. Watanabe, K. Nishida, T. Sugiura, J. Jap. Soc. Technol. Plast. 44-506 (2003), 266-270. (in Japanese)
23. K. Gotoh, T. Shibahara, K. Takeuchi, Tetsu-to-Hagane, 84 (1998), 502-509. (in Japanese)
24. J. Ikeda, J. Jap. Soc. Technol. Plast. 40-466 (1999), 1031-1036. (in Japanese)
25. T. Triumi, Master course thesis in Yokohama National University (Supervisor A. Azushima.), (2011). (in Japanese)
26. Y. Hidaka, T. Anraku, N. Otsuka, Oxidation of Metals, 59 (2003), 97.
27. P. A. Munther, J. G. Lenard, J. Materials Processing Technology, 88 (1999), 105-113.
28. Y. Yu, J. G. Lenard, J. Materials Processing Technology, 121 (2002), 60-68.
29. H. S. Luong, T. Heijkoop, Wear, 71 (1981), 93-102.
30. A. Azushima, Y. Nakata, ISIJ International, 50-10 (2010), 1447-1452.
31. Y. Satta, Master course thesis in Yokohama National University (Supervisor A. Azushima.), (2013). (in Japanese)
32. A. Azushima, Y. Satta, Proc. 62nd Joint Conf. Technol. Plast. (2011), 495-498. (in Japanese)
33. K. Hori, H. Tabe, Tetsu-to-Hagane, 55 (1969), 163. (in Japanese)
34. Y. Sekimoto, M. Tanaka, T. Yoshimura, Tetsu-to-Hagane, 61 (1975), 869-874. (in Japanese)
35. T. Ohnuki, K. Hasuka, O. Katoh, T. Kikuchi, T. Aritomi, T. Kawanami, Tetsu-to-Hagane, (1983), S1132. (in Japanese)
36. S. Araya, T. Inoue, S. Uchida, S. Hamauzu, S. Yamamoto, CAMP-ISIJ, 10 (1997). 1076, (in Japanese)
37. S. Araya, T. Inoue, S. Uchida, S. Hamauzu, L. Lanteri, C. Thomas, CAMP-ISIJ, 10 (1997). 397, (in Japanese)
38. T. Oohata, T. Hattori, G. Sano, J. Kihara, CAMP-ISIJ, 3 (1990), 422. (in Japanese)
39. A. Azushima, K. Nakazawa, Proc. 62nd Joint Conf. Technol. Plast. (2011), 493-494. (in Japanese)
40. A. Azushiam, K. Nakazawa, Proc. 5th ICTMP, (2012).

41. K. Nakazawa, Master course thesis in Yokohama National University (Supervisor A. Azushima.), (2013). (in Japanese)
42. T. Imae, S. Kanenari, Symposium text in division of processing for quality products of ISIJ, (1997), 15-19. (in Japanese)
43. A. Azushima, W. D. Xue, Y. Yoshida, ISIJ International, 49-6 (2009), 868-873.
44. T. Toriumi, A. Azushima, Tetsu-to-Hagane, 97 (2011), 388-392. (in Japanese)
45. J. Ikeda, S. Inagaki, A. Azushima, W. D. Xue M. Etou, Proc. 3rd ICTMP, (2007), 129-132.
46. T. Hara, Textbook of 148th Nishiyama Memorial Lecture, (1993), 135-161. (in Japanese)
47. A. Azushima, CAMP-ISIJ, 16 (2003), 1137-1140. (in Japanese)
48. T. Itoh, N. Kanaama, Masuda, T. Kawakami, K. Hashimoto, CAMP-ISIJ, 16 (1996), 964-967. (in Japanese)
49. A. Azushima, T. Hattori, T. Kudoh, H. Ihara, J. Ikeda, Proc. 3rd Symposium on PROTEUS Project, (2005), 28-39. (in Japanese)

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