Tribological properties of cemented carbide rolls in cold sheet rolling

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When high elastic modulus rolls are applied to cold rolling, roll flattening becomes smaller than with conventional steel rolls. This factor reduces the rolling load by decreasing the contact length between the roll and the sheet being rolled. Conversely, the smaller roll flattening radius increases the contact angle between the roll and the sheet, which reduces the thickness of the lubricating oil film carried into the roll bite. This factor increases the rolling load by increasing the friction coefficient in the contact area. The influence of the roll material on rolling load appears as the sum of these two factors. However, few studies have attempted to separate and evaluate their effects. To clarify the effect of the roll material on rolling load, a series of experimental cold sheet rolling tests was conducted with cemented carbide rolls and conventional steel rolls. The experimental results showed that the difference of the rolling load between cemented carbide rolls and conventional steel rolls varied with rolling conditions. To investigate the lubricant behavior in rolling, a numerical analysis of the oil film thickness was carried out. Based on the experimental results and the calculated oil film thickness, the effect of the roll material on rolling load was discussed.

Keywords: Cold sheet rolling - Rolling load - Roll material - Cemented carbide - Lubrication - Friction coefficient

INTRODUCTION

In the field of cold rolling, processing of thin and hard materials is increasing. Because the rolling load is higher with these materials, this trend has given rise to problems of reduced product quality and productivity. Among various methods of reducing the rolling load [1-2], application of work rolls with a high elastic modulus is one technique [3-6]. When cold rolling is performed with high modulus rolls, the radius of roll flattening decreases owing to the high elastic modulus, and this reduces the contact length between the roll and the steel sheet. Conversely, since the contact angle increases, the thickness of the lubricating oil film carried into the roll bite is reduced, and as a result, the friction coefficient increases. The rolling load in cold rolling is decided by the sum of these two effects. However, few studies have attempted to separate and evaluate the two effects.

In this report, a series of experimental cold sheet rolling tests was conducted with cemented carbide rolls and conventional steel rolls in order to clarify the effect of the roll material on rolling load, and a numerical analysis of the oil film thickness in rolling was carried out to clarify the difference of lubricant behaviors in cold rolling with cemented carbide rolls and conventional steel rolls. Based on the experimental results and the calculated oil film thickness, the effect of the roll material on rolling load was discussed.

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ROLLING EXPERIMENT

Experimental Procedures

Firstly, a rolling experiment was conducted in order to investigate the change of rolling load depending on the roll material. The conditions of the rolling experiment are shown in Table 1. Two work rolls were used in the experiment, one made of cemented carbide (WC85%-Co15%) and the other made of conventional steel SUJ-2 (2%Cr-steel). The elastic modulus of the two materials was 540GPa and 210GPa, respectively. The diameter of the work rolls was ϕ100mm. The surface roughness of the work rolls was 0.08 *μmRa*. The work material was a high strength steel with surface roughness of 0.54 *μmRa*. Mineral oil (72.5cst at 40°C) was used as the lubricating oil, and a sufficient amount of oil was applied to the work surface by neat oil. The rolling pass schedule is shown in Table 2. The work was rolled in six passes from an initial thickness of 1.5mm to a final thickness of 0.23mm. Experiments were performed at a rolling speed of 60mpm

Roll material	a) WC85%-Co15%, E=540Gpa b) SUJ-2 (2%Cr-Steel), E=210GPa
Roll diameter	ϕ 100mm
Rolling speed	60mpm
Lubricant	Neat mineral oil 72.5cst at 40°C
Roll roughness	0.08 μmRa
Work material	High strength steel
Workpiece size	1.5t×50w×150 L mm
Rolling temperature	Room temperature

Table 1. Experimental rolling conditions.

Tabella 1- Condizioni sperimentali di laminazione

at room temperature. The lubricating oil adhering to the roll surface and the steel surface after the end of each pass was removed by degreasing with petroleum benzene so that rolling could be performed with no influence of adhering oil in the following rolling pass. Lubricity was evaluated by comparing the coefficients of friction calculated from the measured rolling load and the deformation resistance of the cemented carbide and conventional steel. In order to investigate the change of the amount of oil carried into the roll bite during rolling, the surface roughness and gloss of the steel surface after rolling were measured.

Pass No	1	2	3	4	5	6
Inlet thickness /mm	1.50	1.01	0.75	0.55	0.39	0.28
Outlet thickness /mm	1.01	0.75	0.55	0.39	0.28	0.23
Total reduction /%	32.7	50.0	63.3	74.3	81.3	85.3

Table 2. Rolling pass schedule.

Tabella 2 – Programma dei passaggi di laminazione

Results of experiment

Fig. 1 shows the change of rolling load per width relative to total reduction. In the first two passes, when the thickness of the rolling material was large, there was no difference in the rolling load with the cemented carbide roll and conventional steel roll. However, after 3 rolling passes, when total reduction reached 63%, the rolling load of the cemented carbide roll was small compared with that of the conventional steel roll. Moreover, the amount of reduction of the rolling load with the cemented carbide roll became large in the passes in the second half of the rolling schedule, in which the thickness of rolling material was thin. Fig. 2 shows the change of the friction coefficient relative to total reduction. In all the passes, the coefficient of friction was larger with the cemented carbide roll than with the conventional steel roll. This is attributed to the fact that the amount of lubricating oil carried into the roll bite decreased due to the increase in the contact angle in rolling with the cemented carbide roll. In order to determine the amount of lubricating oil carried into the roll bite during rolling, the steel surface after rolling was investigated. Fig. 3 shows the results of measurements of the surface roughness and gloss of the steel surface after

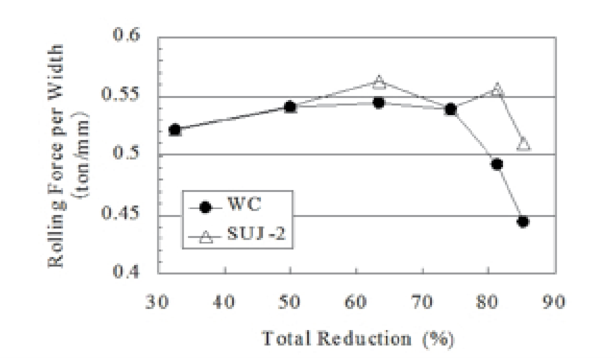

Fig. 1 - Comparison of change in rolling force relative to total reduction.

Fig. 1 – Confronto fra cambiamento nella forza di laminazione in riferimento alla riduzione totale.

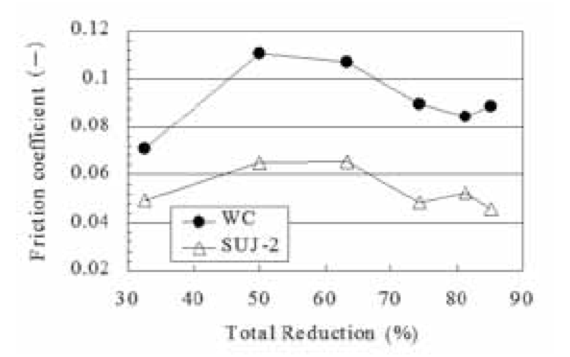

Fig. 2 Comparison of change of friction coefficient relative to total reduction.

Fig. 2 – Confronto fra cambiamento nel coefficiente di frizione in riferimento alla riduzione totale.

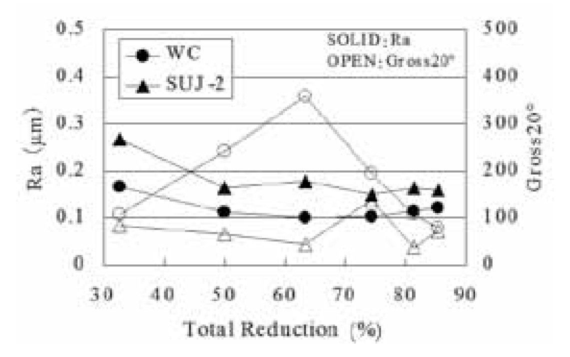

Fig. 3 Change of surface roughness and gloss after rolling.

Fig. 3 – Cambiamento nella rugosità superficiale e lucidatura dopo laminazione.

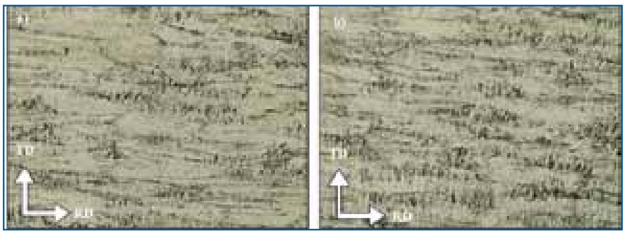

Fig. 4 - Optical micrographs of sheet surface after fifth rolling pass. a) WC, b) SUJ-2.

Fig. 4 - Micrografie ottiche della superficie della lamiera dopo il quinto passaggio di laminazione. a) WC, b) SUJ-2.

rolling. The surface roughness of the steel rolled with the cemented carbide roll was smaller than that of the steel rolled with the conventional steel roll, and the gloss of the steel rolled with the cemented carbide roll was larger. These differences are considered to be due to control of the formation of oil pits by reduction of the amount of lubricating oil carried into the roll bite. Fig. 4 shows optical micrographs of the steel surface after 5 rolling passes. The steel rolled with the cemented carbide roll has many oil pits on the surface. It was confirmed that the amount of lubricating oil carried into the roll bite actually decreased.

ANALYSIS

Analysis of inlet oil film thickness

In the above-mentioned rolling experiment, there is no difference in rolling load with the cemented carbide roll and conventional steel roll in the first two rolling passes, when the thickness of the rolling material is large. On the other hand, the rolling load with the cemented carbide roll is small compared with that of the conventional steel roll in the second half of the rolling schedule, when the thickness of the rolling material becomes thin. This reduction in rolling load with the cemented carbide roll is considered based on the balance of the reduction of the rolling load due to the decreased contact length, and the increase of the rolling load due to the decreased lubricant oil film carried into the roll bite, which changes with rolling conditions.

In order to clarify quantitatively the relationship between the lubricating oil film thickness carried into the roll bite and the rolling conditions, the inlet oil film thickness was verified in an analysis as proposed by Azushima *et al.* [7] In that analysis, the initial oil film thickness h_2 in Fig. 5 is sufficiently thick, when the pressure of the oil film reaches the yield stress of the test piece, and the inlet oil film thickness h_1 in the roll bite is given by Reynolds equation, as shown in Eq. (1), and the oil viscosity equation in Eq. (2).

$$\frac{dP}{dh} = -\frac{6\eta(U_1 + U_2)}{\tan\theta}\left(\frac{h - h_1}{h^3}\right) \tag{1}$$

$$\eta = \eta_0 \exp(\alpha P - \beta(T_m - T_0)) \tag{2}$$

where, P is the rolling pressure, h is the oil film thickness, U_1 and U_2 are the speed of the test piece and the speed of work roll, η_0 is the contact angle between the test piece and the work roll, T_0 is the reference viscosity of the lubricant oil at 40°C, α is the pressure coefficient, β is the temperature coefficient, T_m is the average temperature between the test piece and work roll, and T_0 is the reference temperature (40°C). The boundary conditions in Fig. 5 are given by

$$P = 0 \text{ at } h = h_2 \tag{3}$$

$$P = k_0 \text{ at } h = h_1 \tag{4}$$

where, k_0 is the yield stress of the test piece. The hydrodynamic oil film thickness h_1 can be calculated by solving the differential equation in Eq. (1). The parameter in Table 3 was used for the analysis of the inlet oil thickness.

Oil viscosity (Pa·s)	0.065 (40°C)
Oil kinematic viscosity (mm^2/s)	72.5 (40°C) 21.2 (70°C)
Pressure coefficient (GPa^{-1})	19.7
Temperature coefficient (°C^{-1})	0.044

Table 3 - Data used in inlet oil film calculation.

Tabella 3 - Dati utilizzati per i calcoli sul film di olio in ingresso.

In Table 3, the temperature coefficient β was calculated from the kinematic viscosity at the temperature of the two points, and the pressure coefficient α was calculated by the Wu and Klaus equation [8] expressed as follows:

$$\alpha = (0.1657 + 0.2332\log\nu_{Tm}) \times m \times 10^{-8} \tag{5}$$

$$m = \frac{\log(\log(\nu_{40} + 0.7)) - \log(\log(\nu_{70} + 0.7))}{\log(70 + 273.15) - \log(40 + 273.15)} \tag{6}$$

where, m is the temperature coefficient in the ASTM-Walther equation in Eq. (5), and ν_{TM} is the kinematic viscosity at the average temperature between the test piece and the work roll. ν_{40} and ν_{70} are the kinematic viscosities at 40°C and 70°C, respectively. Next, the contact parameter h_1/σ was calculated using the inlet oil film thickness h_1 and the synthetic surface roughness σ calculated by the equation in Eq. (7), where R_{qs} is the mean square roughness of the sheet, and R_{qr} is the mean square roughness of the roll. Generally, the lubrication condition of the roll bite in cold rolling is the mixed lubrication condition. The friction coefficient in the mixed lubrication theory is expressed by the equation in Eq. (8), where a is the contact rate, μb is the friction coefficient of the boundary lubrication part, and μ_f

is the friction coefficient of the hydrodynamic lubrication part. The contact parameter h_1/σ and the contact area a display a correlation, in that a becomes large when h_1/σ is small. As a result, the friction coefficient becomes large. That is, using h_1/σ, it is possible to compare quantitatively the change of the lubricant state in the roll bite depending on the rolling conditions and the roll material.

$$\sigma = \sqrt{R_{qs}^{\ 2} + R_{qr}^{\ 2}} \tag{7}$$

$$\mu = a\mu_b + (1 - a)\mu_f \tag{8}$$

Fig. 6 shows the change of the contact parameter h_1/σ relative to total reduction. In rolling with the cemented carbide roll, h_1/σ is smaller than that with the conventional steel roll. This result shows that the contact rate of the boundary lubrication part is increased by rolling with the cemented carbide roll. However, there is no difference between the cemented carbide roll and the conventional steel roll in the first two passes, i.e., when rolling thick material. From this result, there is a problem in thinking that the contact length reduction effect of the high modulus roll is offset only by the increase in the coefficient of friction resulting from reduction of the inlet oil film thickness.

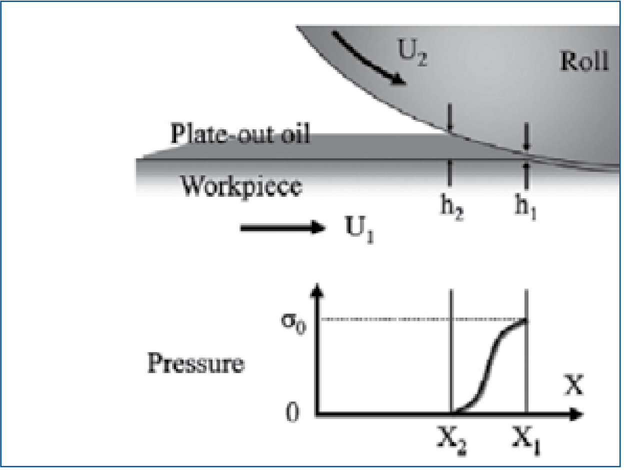

Fig. 5 - Schematic view of inlet region and pressure change.

Fig. 5 – Vista schematica della regione di ingresso e della variazione nella pressione.

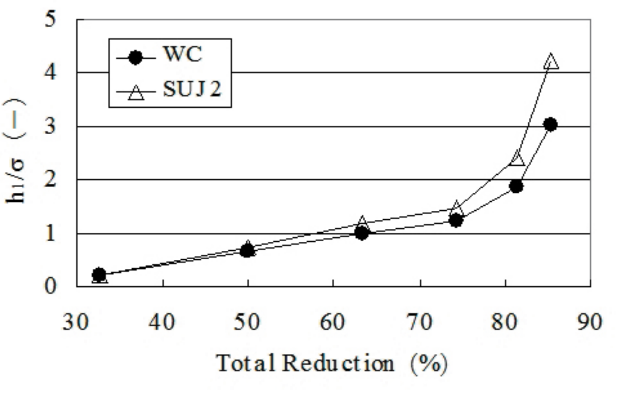

Fig. 6 - Comparison of change of parameter h_1/σ of WC and SUJ-2 relative to total reduction.

Fig. 6 - Confronto fra variazione del parametro h_1/σ di WC e SUJ-2 in relazione alla riduzione totale.

DISCUSSION

Separation of influence of contact length and oil film thickness

In order to clarify the tribological properties in cold rolling with cemented carbide rolls, the authors attempted to separate and evaluate the influence of the contact length and oil film thickness on rolling force by model calculation. In case 1, the rolling force was calculated for the elastic modulus of the roll as 540GPa of the cemented carbide roll using the coefficient of friction calculated from the rolling force in the experiment with the conventional steel roll. In this case, the reduction of rolling force by the contact length reduction accompanying the increased elastic modulus of the roll is evaluated. In case 2, for the increase in the coefficient of friction resulting from the increase in the contact angle, the rolling force was calculated assuming the coefficient of friction is in inverse proportion to h_1/σ. The elastic modulus of the roll at this time was 540GPa, and the coefficient of friction was calculated by multiplying the ratio of h_1/σ by the coefficient of friction calculated from the rolling experiment in which the conventional steel roll was used. This calculation estimates the sum of the increase in rolling force due to the increase in the contact angle and the decrease in rolling force due to the reduction in the contact length. The rolling force calculated by the above-mentioned method is shown in Fig. 7, together with the result of a rolling experiment. The rolling force in case 1 is the smallest. As for case 2, considering the reduction of the oil film thickness, the rolling force is larger than that in case 1. However, compared with the rolling force in the rolling experiment with the conventional steel roll, it is small in case 2. From this calculation result, if the coefficient of friction is decided only by the change of the inlet oil film thickness, the initial pass, when total reduction is still small, shows the load reduction effect by rolling with the cemented carbide roll. However, there is a large deviation between the calculated rolling force of case 2 and the rolling force of the cemented carbide roll in the rolling experiment, namely, the rolling force in the experiment is large. This shows that the increase in the coefficient of friction is larger than that predicted only from the reduction effect of the inlet oil film thickness in rolling with the cemented carbide roll. The following can be considered as a reason for this deviation: As shown in Eq. (8), when the coefficient of friction in a mixed lubrication state is decided by the contact area a, the friction coefficient of the boundary lubrication part μ_b, and the friction coefficient of the hydrodynamic lubrication part μ_f, under the rolling condition of the initial two passes, when the total reduction is small and there is no difference in rolling force between the cemented carbide roll and the conventional steel roll, h_1/σ of the cemented carbide roll and the conventional steel roll is comparable, and there is no large difference in the contact area. In order for the coefficient of friction of the cemented carbide roll to become larger than that of the conventional steel in this case, μ_b or μ_f of the cemented carbide roll must be large compared with that of the conventional steel roll. The viscosity of the lubricating oil may change due to differences in the pressure within the roll bite in the hydrodynamic lubrication coefficient of friction. However, as it is thought that the viscosity change of the lubricating oil within the roll bite of a cemented carbide roll and a conventional steel roll, as calculated from the measured rolling load and the pressure dependence of the lubricating oil, is 0.1% or less, this influence can be disregarded. On the other hand, the boundary lubrication coefficient of friction may change greatly with the roll material, and it is necessary to clarify this influence.

Change of boundary friction coefficient by roll material

In order to investigate the change of the boundary lubrication coefficient of friction by roll material, a Bowden test was performed. The experimental conditions of the Bowden test are shown in Table 4. In the experiment, sliding was performed on a high strength steel sheet with surface roughness of $0.1\mu mRa$ using steel balls made from cemented carbide (WC-Co) and conventional steel SUJ-2 (2%Cr-steel).The ball diameter is 5mm. The vertical load and the horizontal load were measured, and the coefficient of friction was calculated. Lubricating oil was applied as neat oil in sufficient quantity for the steel surface using the same mineral oil as that used in the rolling experiment. The sliding speed was 5mm/s, the sliding length was 50mm, and the pressure was changed in the range of 830-1530MPa, which is equivalent to the pressure in the roll bite in the rolling experiment. The test temperature was changed in the range from 25°C to 150°C. The interfacial temperature in the rolling experiment calculated by the method of Azushima *et al.* [9] is 100°C or more in all passes. Fig. 8 shows the change of the boundary coefficient of friction relative to the temperature and pressure as measured by the Bowden test. The pressure dependence showed a tendency in which the coefficient of friction decreased with increasing pressure with both the cemented carbide roll and the conventional steel roll. On the other hand, regarding temperature, the cemented carbide and conventional steel showed the opposite temperature dependency. That is, although the coefficient of friction decreases with rising temperature in WC, the coefficient of friction increases with rising temperature in SUJ-2. Furthermore, on the conditions that the temperature is high, the difference of the coefficient of friction of SUJ-2 and the coefficient of friction of WC *increases with decreasing pressure*. These results show that the coefficient of friction of WC increases in the initial pass with a high contact ratio and low pressure, and can explain why the rolling force of WC increased in the initial pass of the rolling experiment. As for the above result, in cold rolling using a cemented carbide roll, it is necessary to note that, as compared with conventional steel rolls, the rolling load also changes with rolling conditions and the desired load reduction effect may not be obtained, depending on rolling conditions.

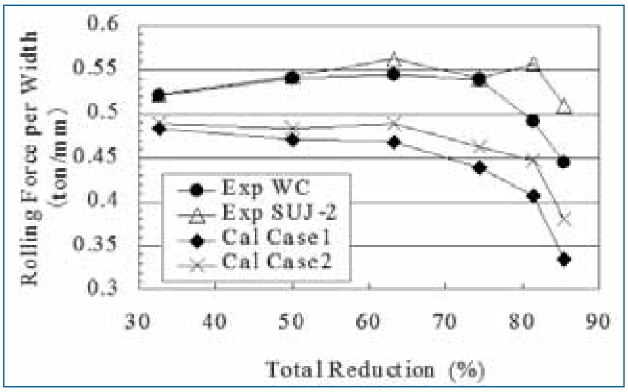

Fig. 7 - Comparison of rolling force of experimental data and model calculation.

Fig. 7 – Confronto fra dati sperimentali e dati calcolati da modello, per la forza di laminazione.

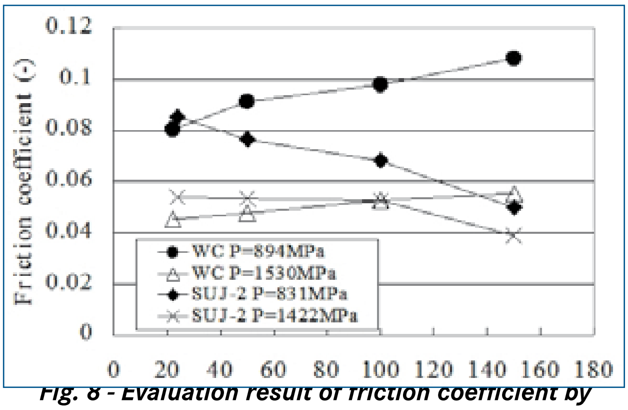

Fig. 8 - Evaluation result of friction coefficient by Bowden test.

Fig. 8 – Risultato della valutazione del coefficiente di frizione mediante prova di Bowden.

SUMMARY

A cold rolling experiment using a cemented carbide roll was conducted for the purpose of clarifying the tribological characteristics in cold rolling using a high modulus roll. A conventional steel roll was also used for comparison. The following knowledge was obtained.

The rolling force of the high modulus cemented carbide

Ball material	a) WC85% - Co15% b) SUJ-2 (2%Cr-Steel)
Ball diameter	ϕ 5mm
Sliding speed	5mm/s
Sliding length	50mm
Lubricant	Neat mineral oil 72.5cst at 40°C
Work material	High strength steel
Work surface roughness	0.1 μmRa
Pressure	830-1530MPa
Test temperature	25°C, 50°C, 100°C, 150°C

Table 4 - Experimental conditions of Bowden test.

Table 4 – Condizioni sperimentali della prova di Bowden.

roll varied depending on the balance of the effects of the decrease in contact length, which reduces the rolling load, and the reduction of the oil film thickness in the roll bite resulting from the increased contact angle, which increases the friction coefficient and thereby increases the rolling load. Moreover, it is also thought that the influence of the difference of boundary lubrication characteristic depending on the roll material is significant.

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Proprietà tribologiche di rulli in acciaio cementato nella laminazione a freddo di lamiere

Parole chiave:

Quando nella laminazione a freddo vengono applicati rulli con alto modulo elastico, la loro deformazione è minore rispetto a quella che si determina con rulli convenzionali in acciaio. Questo fattore riduce il carico di laminazione riducendo la lunghezza di contatto tra il rullo e il foglio in laminazione. Viceversa, il raggio minore di un rullo deformato aumenta l'angolo di contatto tra il rullo e il foglio, che riduce lo spessore del film di olio lubrificante trasportato nella linea di contatto. Questo fattore aumenta il carico di laminazione aumentando il coefficiente di attrito nella zona di contatto. L'influenza del materiale del rullo sul carico di laminazione dipende dalla somma di questi due fattori. Tuttavia, alcuni studi hanno tentato di separare i loro effetti e valutarli. Per chiarire l'effetto del materiale del rullo sul carico di laminazione, sono state condotte una serie di prove sperimentali di laminazione a freddo di lamiere con rulli di acciaio cementato e rulli convenzionali di acciaio. I risultati sperimentali hanno mostrato che la differenza del carico di laminazione fra rulli in acciaio cementato e rulli di acciaio convenzionale varia in base alle condizioni di laminazione. Per studiare il comportamento del lubrificante durante la laminazione, è stata effettuata un'analisi numerica dello spessore del film d'olio. Sulla base dei risultati sperimentali e dello spessore calcolato del film d'olio, è stato discusso l'effetto del materiale del rullo sul carico di laminazione.