PERFORMANCE OF LUBRICATING OIL FILM IN ALUMINIUM FOIL ROLLING①

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ABSTRACT The surface of the aluminum foil rolled has been observed with microscope on the basis of industrial experiments, and the structure of the surface adsorption film has been analyzed by means of low angle X-ray diffraction. It is advanced that the lubrication in aluminum foil rolling is in the state of thin film lubrication, surface adsorption film is an ordered multi-layered molecule film with more than 7 layers; and the layers of the ordered molecule film is influenced by the concentration of the additive in certain range; the concentration of the additive in oil is the main factor affecting the stability of rolling, controling the concentration of the additive can control the ratio of fluid friction, boundary friction, and local holding-on in deformation zone, thus obtaining good rolling deformation conditions.

Key words aluminum foil ordered multi-layer molecule film rolling deformation

1 INTRODUCTION

The application of technological lubricant in metal rolling can decrease the friction on the surface of contact arc in the deformation zone, increase the reduction in pass, decrease processing passes, increase rolling speed, decrease the attrition of rolls, and prevent metal from adhering to the rolls. Therefore, lubricants greatly affect the stability of rolling process and the quality of product. Usually, there are several different kinds of lubrication mechanisms existing at the same time in rolling process, which affect each other, thus complicates the study of it.

On the basis of the study of fluid lubrication theory, Hardy and some other researchers[1] first advanced the conception of boundary lubrication in 1919; Tomlinson[2] revealed the action between surface molecules in solid friction process, thus started the study of boundary lubrication mechanism, for example, Bowden and Leben[3] considered analyzing the lubricating state on metal surface by the size of molecule and the known thickness of lubricant film. In 1969, Allen and Drauglis advanced the conception of regular fluid film according to the result of Fuks' experiment[4]. But because boundary lubrication involves with the property and variation of a very thin surface layer, there's no unified theory on boundary lubrication mechanism now, and the application of it still depends on experience.

Whether the lubricating state in aluminum foil rolling is fluid lubrication or boundary lubrication, is still under discussion. This article studies the structure and the behavior of the lubricant film in metal foil rolling on the basis of industrial experiment and lab experimental analysis, and gives reference to oil adjusting and technological parameter choosing in commercial run.

2 INDUSTRIAL ROLLING EXPERIMENT

The typical technique of the rolling of 0.0065 mm aluminum foil by single d 660/254/210 mm × 1600 mm quadruple universal foil mill accorded with the rolling regulation of 0.5 mm → 0.25 mm → 0.12 mm → 0.06 mm → 0.031 mm →

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0.014 mm → 0.006 5 mm. In order to examine the influence of the concentration of lubricant additive on the performance of lubrication, in the 6^{th} pass, major parameters such as rolling speed, rolling pressure, roughness of roll's surface, oil temperature and tension were kept unchanged, while only the concentration of additive in the technological lubricating oil was changed. The result showed that, (1) when the concentration of lubricant additive CSA-B is 3.0 % ~ 3.5 %, the rolling process is steady, tension curve distributes homogeneously, and foil's surface is shiny; (2) when the concentration increases to 5.5 %, rolling slippage and whistle occur, the number of strip breaking increases obviously, at the same time the surface of aluminum foil presents the figure of orange peel, and gloss decreases obviously.

When rolling 0.007 mm aluminum foil on the production line equipped with two d 850/280 mm × 1 850 mm quadruple aluminum foil mills, the thickness of blank was 0.3 mm; from blank to product dimension five passes were needed, among which the former four passes were done by intermediate mill and the 5^{th} pass was completed by finishing mill.

The technological parameters of each pass and the value of friction factor calculated by advancing slippage method in normal rolling state are shown in Table 1. The rolling situation demonstrates that, under this technological conditions, aluminum foil's sheet shape is good, the number of strip breaking is small; this technoloical conditions can continue rolling 0.007 mm aluminum foil to more than 150 000 meter without breaking, and the number of pinhole remains at about 50 m^{-2}.

3 RESULTS AND DISCUSSION

3.1 Micrographs of Aluminum Foil's Surface

The observation by optical microscope of 0.006 5 mm aluminum foil rolled by d 660/254/210 mm × 1 600 mm universal foil mill shows that, when the concentration of lubricant additive CSA-B is 3.0 %, longitudinal scratches exist all over the aluminum foil's surface (Fig.1(a)); while the concentration rises to 5.5 %, the pattern of aluminum foil's surface changes so dramatically that there are less serious longitudinal scratches, and at the same time there're many orange peel like small pits (Fig.1(b)). The measuring of surface roughness confirms that, when the concentration of additive is 3.0 %, aluminum foil's surface roughness is very close to the rolls', and the upper foil surface's roughness is a bit smaller than the upper roll surface's, while the lower foil's surface roughness a bit bigger than the lower roll surface's. This phenomenon might be caused by the fact that the drag condition to lubricating oil between the upper foil surface and the upper roll surface is better than that between the lower foil surface and the lower roll surface (Table 2). But when additive's concentration increases to 5.5 %, the surface roughness of the aluminum foil rolled (0.23 μm) is quite obviously bigger than that of the roll (0.08 μm).

The result as above shows that there's aluminum foil's local inhomogeneous deformation when using lubricating oil containing 5.5 % additive. The main factor causing foil's inhomogeneous deformation is that in a certain range, the thickness of ordered molecule adsorption film increases with the increase of additive's content; and the molecules of the additive dissolved in base oil exist not as single molecules but mainly as micellae, the diameter of which is affected by temperature, pressure and concentration of additive[6]. When increasing external pressure or the concentration of the additive, the diameter of micelle increases, and the micelle with big diameter can cause additive's eduction. Both the two aspects' factors as above will cause over lubrication or local area's lubricant inhomogeneity.

According to the theory of fluid lubrication, when the thickness of oil film is bigger than the roughness of contact surface, complete insulating state will exist between the surfaces of aluminum foil and roll, and no scratch exists on the surface of aluminum foil at the time. The furrow on aluminum foil surface in Fig.1 shows that the lubricant film in foil rolling is quite thin, and its thickness should be smaller than the complex

Table 1 Main technological parameters of each pass and value of friction factor

Pass	Thickness/mm		Tension/MPa		Roll's roughness /μm	Value of advancing slip	Rolling force/kN	Friction factor
	H	h	σ_{back}	σ_{forth}	R_a	S	P	μ
1	0.3	0.142	20.4	29.0	0.18	0.08	154.6	0.036
2	0.142	0.068	32.1	37.9	0.18	0.12	156.0	0.045
3	0.068	0.0315	39.4	44.2	0.08	0.14	213.4	0.053
4	0.031 5	0.015	36.0	51.5	0.08	0.16	305.0	0.023
5	0.015	0.007	31.9	36.2	0.04	0.18	414.0	0.026

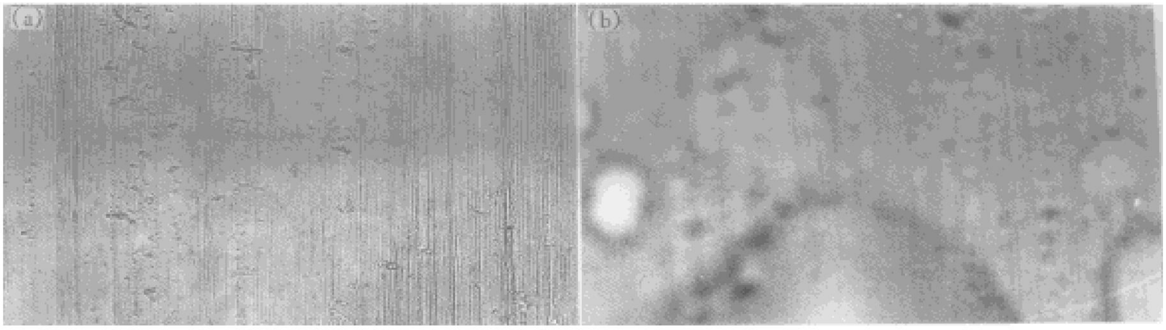

Fig.1 Surface shape of aluminum foil when lubricant additive concentration is 3.0% (a) and 5.5% (b), ×200

Table 2 Surface roughness of aluminum foil in normal rolling R_a(μm)

Pass	1	2	3	4	5	6
Surface roughness of upper roll	0.18	0.18	0.12	0.12	0.08	0.08
Surface roughness of upper foil	0.17	0.16	0.11	0.10	0.07	0.07
Surface roughness of lower roll	0.18	0.18	0.12	0.12	0.08	0.08
Surface roughness of lower foil	0.20	0.19	0.13	0.14	0.10	0.09

surface roughness of roll and entrance aluminum foil ($\sqrt{\sigma_{roll}^2 + \sigma_{foil}^2}$) .

3.2 Friction Factor and Lubricant Oil Film's Thickness

The data in Table 1 show that, when rolling 0.007 mm aluminum foil by d 850/280 × 1 850 quadruple aluminum foil mill, the friction factor of each pass falls in the range of 0.026 ~ 0.053. According to Masuta's stipulation on friction factor[7]:

μ = 0.1 ~ 1.0 for boundary friction state

μ = 0.01 ~ 0.1 for mixed state of fluid friction and boundary friction

μ < 0.01 for fluid friction state

Then, the friction of foil rolling is in the mixed state of fluid friction and boundary friction.

The present formulas for the calculation of lubricant oil film's thickness are all developed on the basis of the theory of hydrodynamic-pressure lubrication, so they can't thoroughly reflect the complicated lubrication mechanism in foil rolling, also their error is relatively large. In this article the method of weighting has been applied to measure the thickness of lubricant layer. The result of measuring shows that, when rolling under the technological condition listed in Table 1, the thickness of oil film in the 4^{th} pass is 0.096 μm, in the 5^{th} pass 0.069 μm, both separately larger than the roughness of roll's surface in corresponding pass, but smaller than the complex surface roughness of roll and aluminum foil.

In recent years, lubrication researchers discovered a new kind of lubricating state during the study of elasto-hydrodynamic lubrication's mechanism, i.e. thin film lubrication. According to the lubrication state described by the thickness of oil film[8]:

Hydrodynamic-pressure lubrication film thickness is 100 ~ 500 μm;

Elasto-hydrodynamic lubrication film thickness is 0.1 ~ 1 μm;

Thin film lubrication film thickness is 0.01 ~ 0.1 μm;

Boundary lubrication film thickness is 0.005 ~ 0.01 μm

Clearly, oil film thickness of the 4^{th} and 5^{th} pass fall in the range of thin film lubrication. In fact, thin film lubrication is also a mixed lubrication state consisted of lubricant oil film with different thickness. Therefore, the characteristics of thin film lubrication are a complex representation of different lubricant oil films.

3.3 Speed Effect

In aluminum foil rolling, when the thickness of rolled piece is less than 0.1 mm, the rolled condition of zero clearance between rolls occurs. In this thickness range, the effect of rolling pressure and tension's control of thickness decreases sharply. Fig.2 shows that the variation of thickness caused by rolling speed change in the 5^{th} pass ply rolling (15 ~ 7 μm) when tension and rolling pressure were kept unchanged.

From Fig.2 we can see that with the increase of rolling speed, the thickness of oil film increases while the exit thickness of rolled piece decreases. When rolling speed is lower than 70 m/min, the curve is relatively even, and the relationship between rolling speed and the exit thickness of rolled piece is relatively weak. But when rolling speed is higher than 75 m/min, the slope of the curve increases and the relationship between rolling speed and the exit thickness of rolled piece strengthens. The occurrence of the phenomenon as above shows that in the total oil film in aluminum foil rolling, there's non-flowing film besides the fluid film that is familiar to many people. Non-flowing film is an ordered adsorption film that does not flow, its thickness mainly depends on the strength of adsorption potential, polarity, induction force, the length of molecular chain, etc.[10] This orderly arrayed layer-like structure is not solid film, but relatively well-ordered liquid like liquid crystal (Fig.3). Because the proportion of adsorption film in total film thickness increases with the decrease of total film thickness, when rolling speed is lower than 70 m/min, speed index is small, and the curve is even; but when rolling speed is higher than 75 m/min, the curve is steep, and speed index increases, which shows that fluid film has become the major part of oil film.

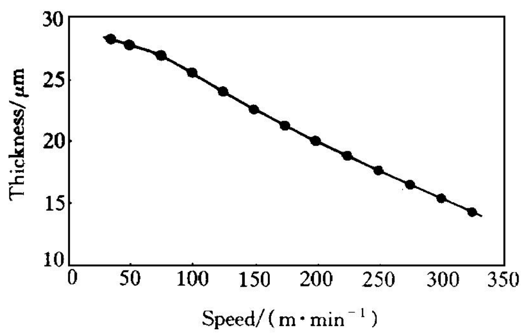

Fig.2 Relationship between rolling speed and aluminum foil's thickness at exit side of rolls

3.4 The Characteristics of Surface Adsorption Film

The technological lubricant oil in foil rolling is composed of base oil (narrow-distillated coal oil) and lubricant additives, in which the base oil is non-polar hydrocarbon; its molecules are in a disordered state, and only play a role of conveyer in the rolling lubrication process. Pure base oil's film intensity is so low that the oil film soon break under a quite small normal compressive stress, thus causes the direct contact of friction metals and big friction factor. Add a little bit of lubricant additive to base oil, then the intensity of oil film increases while the friction factor decreases dramatically. Therefore, the surface adsorption film constituted by polar molecules of lubricant additive plays a very important role in preventing metal surface from scratch, and in decreasing attrition and friction factor.

The foil rolling oil containing 3.0 % (a) and 5.5 % (b) additive CSA-B has been tested by Low Angle X-ray Diffraction. The result shows that, relatively weak non-crystal diffraction peak appears at $2\theta = 27.8°$ on the diffraction pattern of the oil with 3.0 % additive; while a much stronger one appears at the same angle on the diffraction pattern of oil with 5.5 % additive (Fig. 3). This confirms that in a certain concentration range, the thickness of adsorption molecule layer increases with the increase of additive's concentration.

The Low Angle X-ray Diffraction to the LB film of stearic acid confirms that there's no clear diffraction peak when the number of the ordered film's molecule layers is less than 7 (Fig.4). Therefore, we can deduce that in foil rolling the lubricant oil adsorption film is impossible to be mono-layered ordered molecule film, but a multi-layered one with more than 7 layers, and the thickness of the ordered molecule adsorption film is more than 177.9 Å.

In low concentration range lubricant additive has little influence on oil's viscosity. When the content of additive increases from 3.0 % to 6.0 %, the viscosity of technological lubricating oil increases from 1.75 cst to 1.8 cst. Therefore, in foil rolling the variation of viscosity caused by

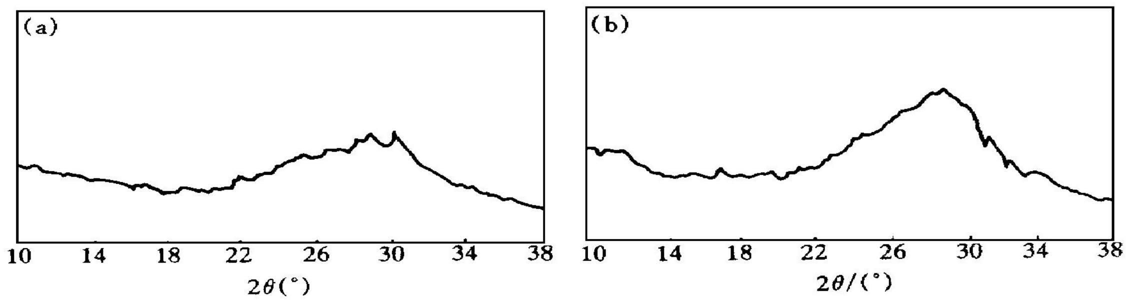

Fig.3 X-ray diffraction patterns of base oil with 3.0 % (a) and 5.5 % (b) lubricant additive (Cr target)

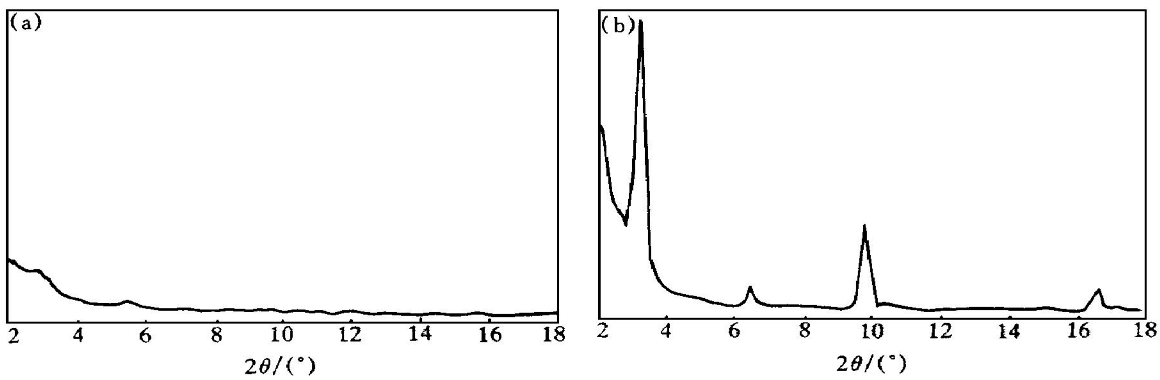

Fig.4 X-ray diffraction patterns of LB film of stearic acid on aluminum chip, with 7 layer (a) and 11 layer (b) (Cr target)

the change of additive's concentration can be ignored. According to the theory of hydrodynamic pressure, the formula for the calculation of lubricant film's thickness is as follows[11]:

$$h = \frac{3.17\eta_0^{0.75}\theta^{0.6}(V_w + V_b)^{0.75}}{P^{0.15}(\rho_w + \rho_b)^{0.4}} \quad (1)$$

where h—the thickness of lubricant film at the exit of deformation zone, η_0— dynamic viscosity under atm press, θ—compression coefficient of viscosity, V_w & V_b—the circle speed of working roll and back roll, P—the contact pressure on unit width, ρ_w & ρ_b—the curvature of the surface of working roll and back roll.

From formula (1) we can see that the thickness of oil film should be changeless in foil rolling passes, in which technological parameter, force and energy parameter and oil's viscosity are all kept unchanged. Then, quite obviously the slippage and the loss of stability in foil rolling caused by the variation of additive's concentration are closely concerned with the adsorption film of additive. Since adsorption film molecule layer could not be perfect, for example, it has isolated island[12] comprised of base oil's molecules, metal peak can easily penetrate these weak points. Therefore, fluid friction, boundary friction and local holding-on exist in foil rolling all at the same time. In a certain concentration range, with the increase of the concentration of additive, the thickness of adsorption molecule layer increases, and at the same time the looseness and empty bands among molecules of adsorption film decrease, which cause the decrease of holdings-on between the metal peak, thus has a certain adjusting effect on each friction state[13]. However, we must pay attention that too high a concentration will cause local inhomogeneous deformation and slippage.

4 CONCLUSIONS

(1) The lubricant film in foil rolling is comprised of ordered adsorption film and fluid film. Ordered molecule adsorption film is a multi-layered molecule film with more than 7 layers of molecules, and in a certain concentration range the thickness of the molecule layer of ordered adsorption film varies with the concentration of additive.

(2) There is looseness and isolated islands captured by base oil molecules in lubricant adsorption film. Therefore, in rolling process it is easy for metal peak to penetrate these weak points, and for rolling lubrication to constitute thin film lubrication state which is composed of fluid friction, boundary friction and local holding-on.

(3) The content of lubricant additive in lubricant oil is the main factor influencing the stability of rolling. Controlling lubricant additives concentration can curb the ratio of each friction state, thus obtain good rolling deforming conditions.

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