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Gloss Promotion of Aluminum Sheets by Tribology Model

YHU-JEN HWU*, WEI-JR LIN*, LEE-CHENG LIU* and MING-JEN WANG**

**Iron and Steel Research & Development Department*
China Steel Corporation
***Rolling Mill II Department*
China Steel Aluminum Corporation

To promote surface gloss of aluminum sheets for can ends, the effects of entry strip surface roughness and oil film entry thickness of lubricant of the last pass were investigated. Several experiments were planned and a tribological model was developed to calculate the oil film entry thickness. Results show that when roughness Ra of the entry strip of the last pass is low and oil film entry thickness is thick, surface gloss after the last pass always becomes low. When the values of Ra and oil film thickness reverse, surface gloss becomes high. Hence, a simple compound variable, fill ratio, is defined and it has a linear relation between fill ratio and gloss for all experimental data. When the fill ratio becomes large, lubricant can easily be trapped in between the roll and strip roughness valleys and it can easily induce high hydrostatic pressure to impede strip roughness peaks to be flattened further and also induce transverse fissures on the strip surface. The transverse fissure is a dominating factor to decrease surface gloss. Based on the results, a special rolling pass schedule with normal speed is designed and finally the surface gloss for can ends was promoted to reach the target and also maintain productivity.

Keywords: Oil file thickness, Gloss, Aluminum sheets, Surface roughness, Cold rolling, Fill ratio, Morphology

1. INTRODUCTION

Within the past 20 years, high surface qualities of cold strip were demanded by aluminum beverage can makers. The main purposes of the cold rolling process are to provide a high quality surface and generate the appropriate roughness for different customers. Gloss is one of the more important surface qualities for the production of the aluminum can end. Gloss will be determined by the surface morphologies of the aluminum sheets. Surface morphologies are described by many roughness parameters, such as average roughness (Ra), root mean square roughness (Rq), mean width of the roughness profile element (Rsm), root mean square slope (RΔa), skewness (Rsk), kurtosis (Rku), peak counter per centimeter (Rpc). Generally except Rku and Rsm, the increase in the values of all the above parameters will decrease gloss. From the point of view of the cold rolling processes, two factors, which are roll surface morphology and the medium in between rolls and strip, dominate the gloss of products, because only the roll and the medium are in contact with the strip surface. The former is determined by the roll grinding parameters, such as the properties of the grinding wheel, feeding speed of the grinder and roll speed(1). The latter is dominated by the chemical compositions of the lubricant, additives and oil film thickness which is determined by the viscosity of the lubricant, temperature in roll gap, flow rate of the lubricant and rolling variables such as roll speed, reduction and roll force(2,3). Factors which affect strip gloss are shown in Fig.1.

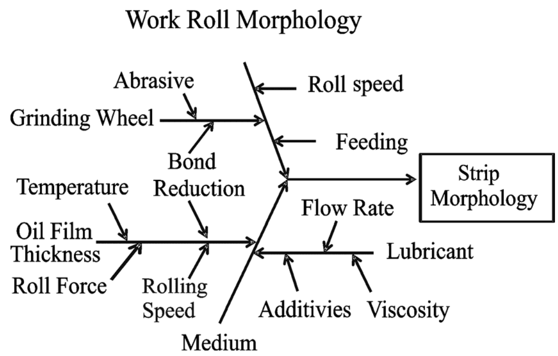


Fig.1. Affecting factors on strip morphology.

Can ends are made by aluminum alloy 5182 which is manufactured by a six high single cold mill in China Steel Aluminum Corporation (CSAC). The lubricant is mineral oil which is circulated and kept at 60 ^{o}C during rolling. For a long time, the gloss of CSAC aluminum sheet for can ends could not reach a high level (Gs20 > 200) as its competitor's product. In order to promote the gloss for can ends, the relation between gloss and roughness parameters should be identified first. Secondly, an operation window of variables should be determined in order to obtain desired surface roughness parameters. Theoretically, oil film thickness is a critical factor which affects the friction behavior in the roll gap and contact length between roll and strip surface[2,3]. When the thickness of oil film at the entry zone becomes thick, the friction behavior tends to become hydrodynamic lubrication and leads to low gloss. It reverses when entry thickness of the oil film becomes thin. It shows that increasing the viscosity of the lubricant, increasing the rolling speed and decreasing the roll pressure will increase the entry thickness of the oil film. But oil film thickness cannot be directly measured on line. Hence, a mathematical model to calculate entry thickness of the oil film should be developed. In this article, a mixed lubrication model was developed to predict entry thickness of the oil film. Several experiments also were designed to find appropriate rolling conditions to prompt the gloss of can end aluminum sheet.

2. TRIBOLOGY MODEL

In traditional rolling models developed by von Karman[4], Orowan[5], Bland and Ford[6], complicated tribological behaviors in roll bite cannot be considered. When emulsion was used as lubricant in cold rolling, mixed lubrication dominates in roll bite. In order to analyze mixed lubrication behaviors, Wilson and Chang[3] developed a mixed lubrication model for low speed rolling. Considering the effect of surface roughness, Christensen[7] used the averaged Reynolds equation to solve the pressure distribution in interface between roll and strip. Patir and Cheng[8] used the flow factor to handle complicate effects of surface roughness. Lo and Wilson[9] further improved the flow factor. Chang et al[3] considered asperity as a Gaussian distribution and used it in Reynolds equation. Wilson and Marsault[10] changed the flow factors into an empirical equation. Based on the results from Chang et al and considered work hardening effect, Qiu[11] used a second order Reynolds equation to solve mixed lubrication behaviors. Tieu[12] developed a mixed lubrication model including an inlet zone for cold strip rolling. In this article, a cold rolling model which integrates roll deformation and mixed lubrication in the inlet zone and biting area was developed.

2.1 Strip theory of flat rolling

Considering a small slab in the roll bite, the differential equation from force balance in horizontal direction is obtained:

$$\frac{y}{2}\frac{dF}{dx} + \sigma_y \tan\phi + q\frac{2}{\pi}\arctan\left(\frac{\Delta v_i}{\Delta v_o}\right)(1+\tan^2\phi) = 0 \quad (1)$$

where F is horizontal force, φ is angle, the arc-tangent function[13] is used to determine the directions of friction force before and after the neutral point. Δv_i is relative speed between strip and roll, Δv_o is a constant which is used to determine the width of the smoothing zone of shear stress near the neutral point. q is friction force in roll bite including solid friction in the asperity contact area, qa, and hydrodynamic friction, q_f. Hence, q can be expressed as:

$$q = Aq_a + (1-A)q_f \quad (2)$$

where A is fraction of contact area in roll bite. The relation between vertical pressure P, horizontal pressure F, and yield stress σ_y is obtained based on yield criterion as following:

$$p - F = \sigma_y \quad (3)$$

The work hardening effect of strip and elastic deformation of the strip were considered, and the deformed radius was calculated by Hitchcock Equation.

2.2. Tribology of roll gap

Combining the Average Flow Model developed by Patir and Cheng[8] and the Flow Factor, Φ, the pressure of the oil film between roll and strip can be calculated by the modified Reynolds Equation, as shown in the following equation:

$$\frac{\partial}{\partial x}\left(\Phi_x \frac{\rho h_t^3}{12\eta}\frac{\partial p_f}{\partial x}\right) + \frac{\partial}{\partial z}\left(\Phi_z \frac{\rho h_t^3}{12\eta}\frac{\partial p_f}{\partial z}\right) = -\frac{\partial\left(\Phi_{ux}\bar{u}\rho h_i\right)}{\partial x} - \frac{\partial\left(\Phi_{ux}\bar{u}\rho h_i\right)}{\partial z} + \frac{\rho d\left(\Phi_{ux}h_i\right)}{dt} + \Phi_{uz}\frac{h_i d\rho}{dt} \quad (4)$$

in which P_f is hydrostatic pressure in the lubricant pocket, η is viscosity of oil, ρ is density, h_t is average thickness of oil film, expressed as:

$$h_t = \sqrt{3\delta}(1-A)^2 \quad (5)$$

δ is surface roughness. Using the upper bound method, Chang and Wilson derived a differential equation for solid contact fraction A, shown as:

$$\frac{dA}{dx} = -\frac{x}{\theta_a Rl\left[(1-A) + yE/21\right]} \quad (6)$$

A can be obtained by the 4th Runge-Kutta integration.

2.3 Hydrodynamics in front of the roll gap

The thickness of the oil film at the inlet zone will affect the lubrication condition in roll bite. Tieu[11] developed a model, as shown in Fig.2, in which the inlet zone was divided into two parts: non-contact zone I and asperity contact zone II. Hydrostatic pressure in this zone can be calculated by average Reynolds Equation.

$$\frac{\Phi_X h_t^3}{12\eta}\frac{dp_f}{dx} = -\frac{v_R + v_w}{2}h_t + C \quad \text{.................................} (7)$$

where v_R is speed of work roll, v_w is speed of strip at entry into roll gap, Φ_x is flow factor, at zone I, $\Phi_x=1+3(\delta/h_t)^2$ and at zone II, $\Phi_x=2\sqrt{3}\,\delta/h_t$. Based on the geometry of roll bite, thickness of oil film can be estimated by:

$$h(x) = h(x_b) + \sqrt{R'^2 - x_b^2} - \sqrt{R'^2 - x^2} + y(x_b) - y(x) \quad \text{...} (8)$$

R is radius of work roll, x_b distance to asperity contact starting point, y is thickness of strip. Average thickness of oil film in front of the roll gap can be calculated by $h_t=h$ at zone I, and $h_t= (h+\sqrt{3}\,\delta)^2/4\sqrt{3}\,\delta$ at zone II.

At the inlet zone, the pressure on the contact area of asperities, P_a, is calculated by the upper bound method developed by Wilson[10]:

$$p_a = \frac{\sigma_y}{f_1 E + f_2} \quad \text{...} (9)$$

$$f_1 = -0.86A^2 + 0.345A + 0.515$$

$$f_2 = 1/[2.571 - A - 1\ln(1-A)] \quad \text{................................} (10)$$

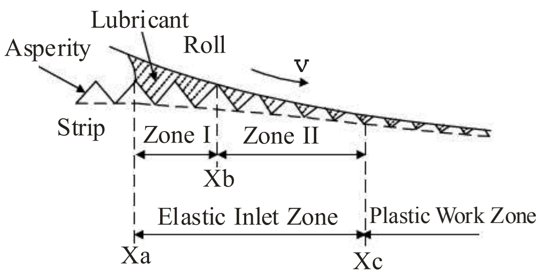


Fig.2. Geometry of inlet zone[12].

2.4. Numerical calculation procedure

At the beginning, an initial x_b was estimated and average thickness of oil film $h_t(x_c)$ at inlet zone was also estimated. An initial entry velocity of the strip was estimated and F can be solved by Eq. 1 and 2. And P was calculated by Eq. 3. Then total roll force, deformed roll radius R', fraction of contact area A, oil film thickness h_t, and pressure of oil film P_f can be calculated consequently. This procedure was iterated until P_f converged. Then based on Eq. 7 and 9, hydrodynamic pressure and pressure of contact area at the inlet zone were calculated by the 4th Runge-Kutta integration. Pressure distribution, elastic deformation of strip and thickness of oil film at the inlet zone were recalculated iteratively until elastic deformation of strip converges. The boundary condition, vertical pressure at x_c, which should satisfy strip yield criterion, $P(x_c)=\sigma_y-F_1$ was used to check correctness of x_b. If this boundary cannot be satisfied, x_b was modified and the above procedures were iterated.

3. EXPERIMENTAL METHOD

In order to promote the gloss of aluminum sheets for can ends, CSAC tried several experiments in which reductions in the last two passes and roll speeds of the last pass were changed to evaluate the effects on gloss. For case 1 with a small reduction of 23% in the last second pass and a higher reduction of 34% in the final pass, surface gloss decreased with increasing roll speed, as shown in Fig.3. But for Case 4 with the same reduction pattern and lower rolling speed in the last second pass, decreasing roll speed in the last pass causes surface gloss to increase significantly and the target for Gs20 with a value of greater than 200 is satisfied. For Case 2 and 3, when rolling speed of the last pass decreases lower than 1000mpm, surface gloss has a higher opportunity to reach higher values. Although low rolling speed can promote surface gloss, it causes low productivity and higher costs. Hence, a new way should be developed to promote surface gloss and avoid these disadvantages.

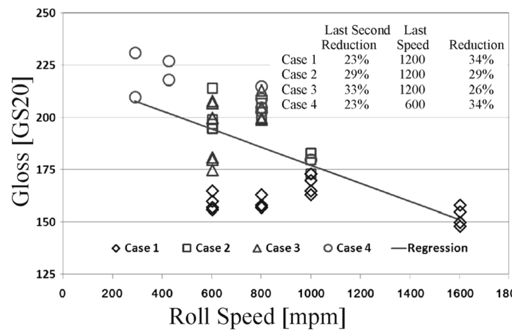


Fig.3. Relation between surface gloss and rolling variables.

During the above experiments, only surface gloss of the last pass was measured, but variations of surface morphologies from pass to pass was not investigated. In order to understand in more detail about the changes of surface morphology during the last two passes, another six experiments were planned and the rolling conditions are shown in Table 1. On those tries, it focused on the effect of entry strip roughness parameters of the last pass on gloss promotion. The difference of the last two cases from the others was that they had a higher entry thickness.

Before rolling, replicas of the roll surface were made and roughness parameters, including Ra, Rq, Rsk, Rpc, Rsm and RΔa, were measured by a 3D Measuring Laser Microscope. After rolling, same roughness parameters of the strip surface were measured and gloss also was measured by a Rhopoint Instruments.

4. RESULTS AND DISCUSSION

Results of roughness parameters of strip and work roll are shown in Table 2. For case A and B after a 35% reduction in the last two passes with rolling speeds of 600mpm and 1200mpm respectively, gloss reached 173 and 167. But gloss decreased to 104 and 108 respectively after the last rolling pass with a reduction of 23%. For case C and D, the last second pass with a low reduction of 23%, gloss reached 130 and 121, and the

Table 1 Rolling conditions

Case	Entry Thickness [mm]	Last Second Pass		Last Pass	
		Reduction [%]	Speed [mpm]	Reduction [%]	Speed [mpm]
1	0.285	35	600	23	1200
2	0.285	35	1200	23	1200
3	0.285	23	600	35	1200
4	0.285	23	1200	35	1200
5	0.33	35	600	35	1200
6	0.33	35	1200	35	1200

Table 2 Roughness parameters

Case	Ra [μm]	Rq [μm]	Rsk	Rpc	Rsm [μm]	R△a [μm]	Gloss [Gs20]	Oil film Thickness [μm]	Equi Ra [μm]
Roll	0.274	0.364	-0.61	209.0	48.1	0.105			
Strip Initial	0.449	0.571	0.24	139.7	71.9	0.100	112	0.00	0.68
Case A_1[*]	0.252	0.318	0.55	224.2	44.8	0.072	173	0.566	0.68
Case B_1	0.269	0.338	0.65	222.4	45.4	0.074	167	0.574	0.68
Case C_1	0.242	0.308	0.51	188.4	54.0	0.072	130	0.569	0.68
Case D_1	0.229	0.288	0.36	218.7	45.8	0.070	121	0.578	0.68
Roll	0.235	0.309	-1.13	187.0	53.7	0.075			
Case A_2[#]	0.197	0.254	0.24	182.5	56.2	0.059	104	0.389	0.44
Case B_2	0.206	0.264	0.48	169.0	60.3	0.060	108	0.401	0.46
Case C_2	0.244	0.310	0.43	160.0	63.4	0.067	132	0.377	0.44
Case D_2	0.251	0.321	0.62	173.0	58.8	0.069	135	0.364	0.42
Roll	0.286	0.37	-0.81	191.9	52.3	0.08			
Strip Initial	0.440	0.54	0.11	115.1	87.7	0.08	106		
Case E_1	0.336	0.42	0.37	171.6	59.9	0.08	188	0.550	0.66
Case F_1	0.333	0.42	0.28	152.3	66.1	0.07	161	0.557	0.66
Roll	0.286	0.37	-0.97	172.0	58.1	0.08			
Case E_2	0.325	0.41	0.25	128.3	78.3	0.07	165	0.473	0.56
Case F_2	0.297	0.38	0.45	152.9	65.6	0.07	163	0.480	0.56

[*] the Last two pass; [#] the Last pass

last pass with a high reduction of 35%, gloss could sustain above 130. For case E and F, after a 35% reduction of the last second pass, gloss reached 188 with a low rolling speed and reached 161 with a high rolling speed. Then using a higher reduction of 35% in the last pass, gloss could sustain a high value of about 160. The final product of case E and F had higher gloss finishes than that of the other cases. A significant difference was the values of strip entry roughness parameters, such as Ra, Rq and Rpc, were higher than that of the work rolls.

The relation between RΔa and gloss is shown in Fig.4. Except for the two strip initial data, when RΔa increases, gloss increases linearly. This phenomenon seems to violate the common concept that a higher RΔa, defined as the slope of root mean square of Ra, will reflect the incident lines more randomly and cause a low gloss. One probable reason is that the experimental conditions were in a very narrow range. Based on the definition of Rsm, the high Rsm, the higher the gloss value should be. Figure 5 shows that the strip gloss after the last pass increases significantly as Rsm increases. But this relation is not obvious for the strip surface gloss after the last second pass. From now on, it is difficult to find a clear relation between gloss and rolling variables and roughness parameters.

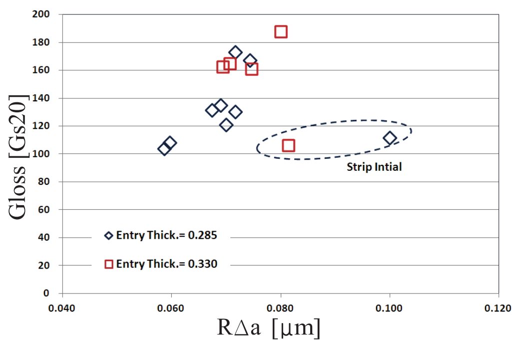


Fig.4. Relation between surface gloss and RΔa.

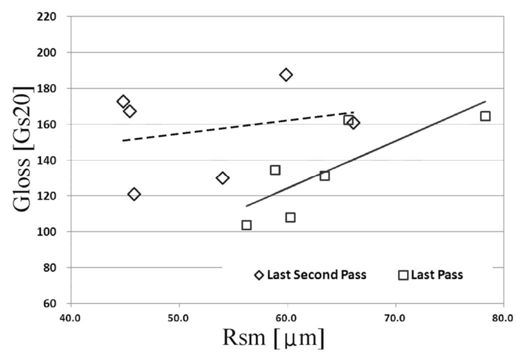


Fig.5. Relation between surface gloss and Rsm.

Based on tribological theory, a thinner entry oil film can cause a higher surface gloss. Experimental results also showed that low rolling speed induces thin entry oil film and causes high gloss. To investigate in more detail about the effect of entry oil film thickness on gloss, the model developed in Section 2 was used to calculate entry oil film thickness for each case and the results are shown in Table 2. It was observed that for each case, when entry oil film thickness increases, surface gloss shows a decreasing tendency, shown as Fig.6. In this study, two main rolling variables to cause changes of entry oil film thickness are reduction and rolling speed. Entry oil film thickness still is not the single parameter to describe the variation in the behavior of gloss.

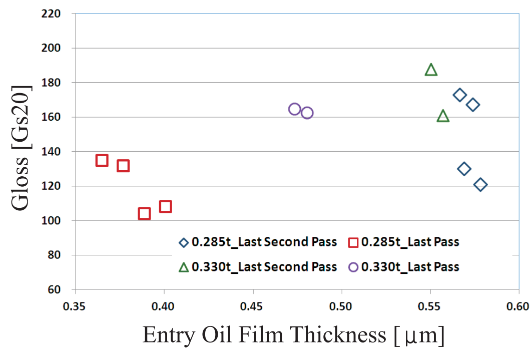


Fig.6. Relation between surface gloss and entry oil film thickness.

For case A and B, after the last second pass the strip surface achieves a high gloss, but roughness Ra was about 0.26μm, which was very close to the Ra of the work rolls used in the last pass, shown in Table 2. During the last pass rolling, entry oil film thickness (0.4μm) was greater than that of the strip entry roughness. This means that rolling condition tends to be a hydrodynamic lubrication condition, because lubricant has filled with the gap between roll and strip. It makes the contact area between the roll and strip become less and cause a very low gloss. For case E and F, after the last second pass, the strip surface reaches a very high gloss, and a high Ra (0.34μm), which was higher than that of the Ra (0.29μm) of the work rolls used in the last pass. Because the entry strip with a high Ra, rolling condition will tend to be mixed lubrication. It makes contact area between roll and strip become more and cause an insignificant reduction in gloss. Based on the above analysis, a simple model can be created as shown in Fig.7. If the equivalent roughness Rq_{eq}, defined by Eq.(11), is filled with lubricant, the contact area ratio between work roll and strip becomes small during rolling, because the hydrostatic pressure in roll bite is high and impedes the work roll to flatten roughness peaks further. The flattening area of the surface becomes

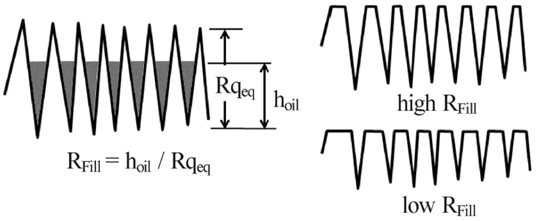


Fig.7. Scheme of oil film fill ratio.

small and causes a low gloss. If the ratio of oil film thickness to Rq_{eq}, called fill ratio and defined by Eq(12), is small, it will allow more strip roughness peak to be flattened by the work roll. Obviously, strip surface gloss will become higher. Effects of rolling conditions, such as roll force, rolling speed, reduction, and lubricant viscosity are considered in the numerator of this compound variable R_{FILL}. Effects of work roll roughness and strip roughness are considered in the denominator of R_{FILL}. Hence, it should be a variable having very strong physical meaning, and a linear relation between gloss and fill ratio as shown in Fig.8. When fill ratio decreases, gloss significantly increases. Photographs of surface conditions of samples with high gloss and low gloss are shown in Fig.9. Lots of defects, known as transverse fissures, were found on the surface of samples with low gloss. This defect is caused by high hydrostatic pressure of the lubricant which is trapped in between roll and strip roughness valleys. When fill ratio is high, lubricant is easily to be trapped and transverse fissures are easily formed. Transverse fissures are across to the rolling direction which is the direction to measure surface gloss. This is the main reason to cause a low gloss when transverse fissures appear on the strip surface. Transfer fissures have not been found on the surface of sample with high surface gloss.

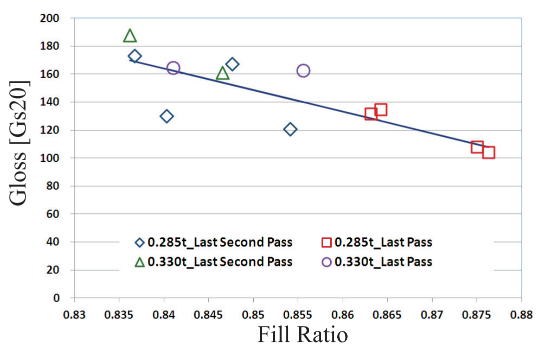
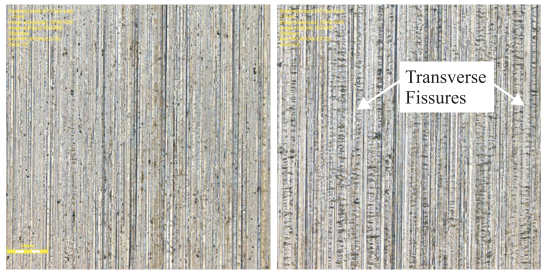


Fig.8. Relation between fill ratio and surface gloss.

$$Rq_{eq} = \sqrt{(Rq)^2_{roll} + (Rq)^2_{strip}} \quad \text{..................................(11)}$$

$$R_{Fill} = h_{oil} / Rq_{eq} \quad \text{.. (12)}$$



(a) (b)

Fig.9. Photographs of surface of (a) Gs20 =200, (b) Gs20=160.

Based on above results, a special rolling schedule with normal rolling speed was designed and finally a very high surface gloss over 250(Gs20) was obtained.

5. CONCLUSIONS

To promote gloss of aluminum sheets, a tribological model was developed to calculate entry oil film thickness and several experiments were conducted in this project. The following conclusions were obtained.

(1) Although decreasing rolling speed of the last pass can achieve high surface gloss over 200 (Gs20), it will reduce productivity seriously.

(2) It is difficult to find a single variable which shows a direct relation with surface gloss.

(3) Experimental data shows that when roughness Ra of entry strip of the last pass is low and oil film entry thickness is thick, surface gloss after the last pass always becomes low. When the values of Ra and oil film thickness reverse, surface gloss becomes high. Hence, a simple compound variable, fill ratio, is defined and it shows that a significant linear relation between fill ratio and gloss for all experimental data exists.

(4) When fill ratio becomes large, lubricant is easily trapped in between roll and strip roughness valleys and it is easy to induce high hydrostatic pressure which impedes strip roughness peaks to be flattened further and also easily induces transverse fissures on the strip surface. Transverse fissures are a dominating factor in decreasing surface gloss. This phenomenon is also proved by photographs the of strip surfaces.

(5) Based on above results, a special rolling pass schedule with normal speed is designed and finally the surface gloss for can ends was promoted to reach the target and also maintain productivity.

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