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Nominal friction coefficient in spread formulas based on lead rolling experiments

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Abstract: Friction coefficients in spread formulas were studied under low width-to-thickness ratio. The effects of all the factors on friction were considered as different roughness of surfaces. After lead rolling experiments in 5 different roughness grades, friction coefficients were obtained. With changing width-to-thickness ratio, reduction rate and ratio of diameter of roller to thickness, all the nominal friction coefficients which can be used in these formulas were calculated. Then, a fitting expression was proposed, comparing with the results measured in 232 times tests, the errors of the nominal friction coefficients calculated by the expression are mostly less than 12%. After a certain times self-learning, the errors are no more than 2%. With the varying nominal friction coefficients, the spread will be predicted more accurately. When the nominal friction coefficient is used to predict the spread under the real working condition, the results calculated are also in agreement with the measured ones, and the errors are less than 2%. This credible reference and solution about how to set the friction coefficient in spread formulas would also be used in practical industrial production.

Key words: spread; rolling; friction coefficient; fitting; self-learning

1 Introduction

In hot rolling process, knowledge of how the material is going to spread during a pass is the most necessary thing for shape controlling. An accurate prediction for spread in rolling process will make the increase of both quality and yield of work pieces. However, even today, there are still some problems to be researched about the spread [1].

The traditional spread formulas are applied more to the wide work piece. When the width-to-thickness ratio is less than 6 or as low as 1, the spread should be only calculated by empirical formulas [2]. This is because the theories of the rolling are almost concerned with the prediction of rolling force for wide slab and strip. Unfortunately, if the width-to-thickness ratio is larger than 10, the rolling process will be approximated to a plane deformation which sometimes makes the spread ignored in that situation.

The other one is friction coefficient, which is still confused in spread formulas [3]. Friction has the most complex effect, for example, when bars and small width slabs are rolled, increasing friction increases the spread; for wider slabs, sheets and strips, more friction means less spread. This is because friction disfavors flow in the longest direction: in bar rolling, the longest direction is in the rolling direction; in sheet rolling it is in the width direction. When it comes to the spread formulas; however, it should be emphasized that there are some traditional formulas independent of friction coefficient, but some other spread formulas are closely related to the friction coefficient. No matter that the formulas of spread are independent of or related to friction coefficient, there is no contradiction and both of the two kinds are valid in their range [4]. The first one is developed for slab/thick sheet rolling, influence of friction on spread is second order; the latter is valid for long products. Here, four of the latter ones which are functions of friction coefficient for spread are listed as follows:

Gubkin's formula,

$$\Delta B=\left(1+\frac{\Delta h}{H}\right)f\left(\sqrt{R\Delta h}-\frac{\Delta h}{2f}\right)\frac{\Delta h}{H} \tag{1}$$

Shuralev's formula,

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$$\Delta B = f\sqrt{R\Delta h}\ln\frac{H}{h} \tag{2}$$

Bakhchernoff's formula,

$$\Delta B = 1.15\frac{\Delta h}{2H}\left(\sqrt{R\Delta h}-\frac{\Delta h}{2f}\right) \tag{3}$$

Ekelund's formula,

$$B_\mathrm{h}^2 = 8m\sqrt{R\Delta h}\Delta h + B_\mathrm{H}^2 - 4m(H+h)\sqrt{R\Delta h}\ln\frac{B_\mathrm{h}}{B_\mathrm{H}},$$
$$m=\frac{1.6f\sqrt{R\Delta h}-1.2\Delta h}{H+h},\ f=0.8(1.05-0.0005t) \tag{4}$$

where B_H is the initial width of workpiece; B_h is the final width of workpiece; ΔB is the change in width of workpiece; H is the initial thickness of workpiece; h is the final thickness of workpiece; Δh is the change in thickness of workpiece; R is the radius of rollers; f is the friction coefficient; t is the rolling temperature.

In this work, a method is proposed to set f in spread formulas for long product with width-to-thickness ratio less than 10. In the past it was set as a constant value empirically [5], which obviously could not be used to give a precise solution of the spread. As it is shown above, in Ekelund's formula, f is expressed as f=0.8(1.05−0.0005t). However, the effects of temperature on f are not linear. Rolling temperature mainly influences the friction coefficient through the properties and quantities of oxidized scales which will make the surface of slab rougher. At low temperature, scale will appear on the surface of the slab because of the increasing temperature, f is also increased in this situation. On the contrary, at high temperature, heat will melt the scale, so f is decreased with increasing temperature [6]. As well known, f is complicated in spread formulas because it is also related to rolling speed and chemical composition of material [7,8]. Since f is important for the spread, it is necessary for us to propose a method for setting the value of a nominal friction coefficient in formulas.

Five conditions of roughness have been investigated. Considering the limited capacity of the experimental mill, it is difficult to heat and maintain the temperature during the rolling. Using hot steel in rolling tests seems to be impossible, pure lead has been used as the rolling materials because at room temperature it behaves in a similar manner with hot steel [9,10]. With Shuralev's and Gubkin's formulas, a new method is obtained to set the f_n in the spread formula. After fitting, an expression is received to calculate the f_n^* in spread formulas with low width-to-thickness ratio. The errors of expressions are no more than 12%. After a certain times self-learning the calculation errors will be lessened. With the f_n^*, spread will be accurately predicted under the real working condition and the errors are no more than 2%.

2 Experimental

Five conditions of roughness have been considered. They are perfectly rough, partially rough, normal, partially smooth and perfectly smooth. Since the same lead bars are used in the experiments, the only way to vary the roughness of the surfaces is to change the roughness of the rollers. A number of methods were tried. As it was described in Ref. [11], emery cloth is applied to roughing the rollers. The surfaces of the rollers are shown in Fig. 1 which also shows different image scales. The roughness of the rollers can be seen easily.

Emery cloth of No.1 standard was used to obtain partially rough rollers, and No.4 standard was considered as perfectly rough rollers. Normal rollers were lubricated with graphite, and they were considered as partially smooth. The oil was used to lubricate the normal rollers for achieving the perfectly smooth. All the roughness grades of the experiments are expressed in Table 1.

Pure lead was used in this experiment with different sizes shown in Table 2. After cutting to the required length, the material was annealed in boiling water. The diameter of rollers was 130 mm. The experiment materials were divided into two groups with different

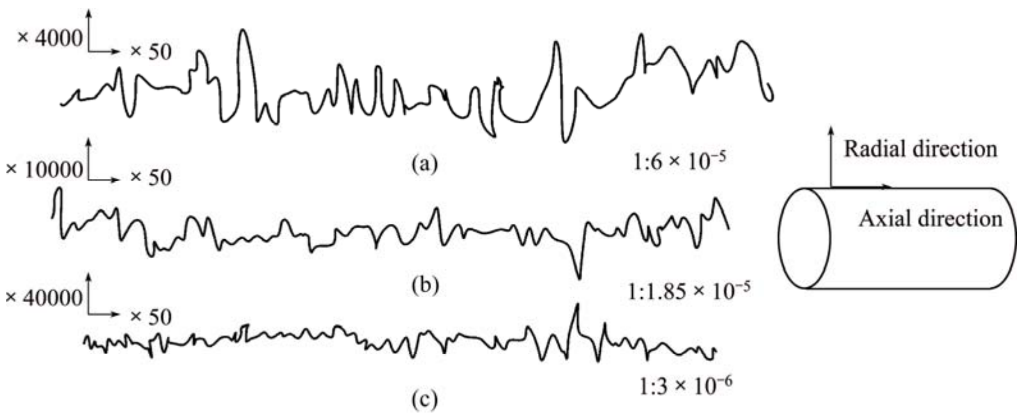

Fig. 1 Roughness of rollers including its image scale: (a) Perfectly rough rolls; (b) Partially rough rolls; (c) Normal rolls

Table 1 Roughness grades of experiments

No.	Roughness grade	Roller	Lubrication condition
1	Perfectly rough	Perfectly rough roller (No.4 standard emery cloth)	–
2	Partially rough	Partially rough rollers (No.1 standard emery cloth)	–
3	Normal	Normal roller	–
4	Partially smooth	Normal roller	Graphite
5	Perfectly smooth	Normal roller	Oil

Table 2 Size of lead in experiment

D/H=10.66		D/H=21.33	
$(H\times B_H)$/mm	B_H/H	$(H\times B_H)$/mm	B_H/H
12.2×12.2	1	6.1×6.1	1
12.2×24.4	2	6.1×12.2	2
12.2×30.87	2.53	6.1×18.3	3
12.2×40.63	3.33	6.1×24.4	4
12.2×48.8	4	6.1×30.87	5.06
		6.1×40.626	6.66

D is the diameter of roller.

D/H, one is D/H=10.66, the other is D/H=21.33. In each group, we designed 4 or 5 sizes with different B_H/H for the experiments, in order to let the experimental results perform well in most cases. When the lead bars are rolled, with different reductions applied the times of experiments are about 250.

After rolling, the sizes of the lead bars were measured by micrometers, and then mean value was taken. All of the results are shown in Figs. 2−6.

From Fig. 2, perfectly rough roller was used in the experiments, solid lines are for the experiments with D/H=21.33, while dotted lines are for the D/H=10.66. B_H/B_h increases with increasing D/H, because every solid

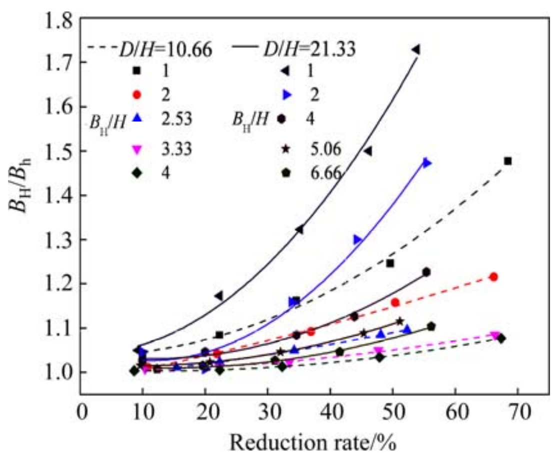

Fig. 2 Effect of roughness on spread (Grade 1, perfectly rough)

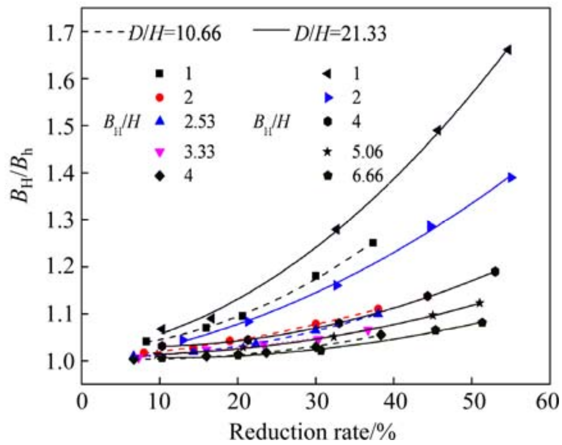

Fig. 3 Effect of roughness on spread (Grade 2, partially rough)

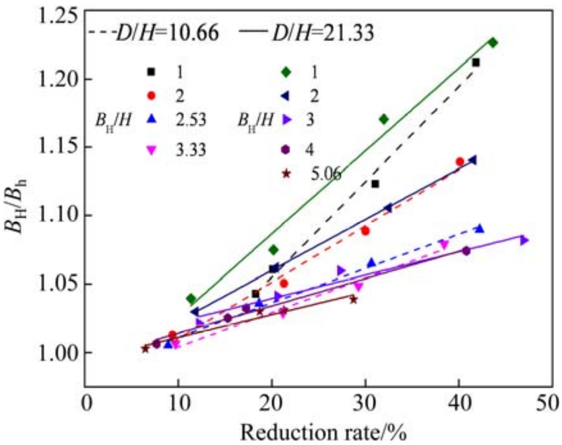

Fig. 4 Effect of roughness on spread (Grade 3, normal)

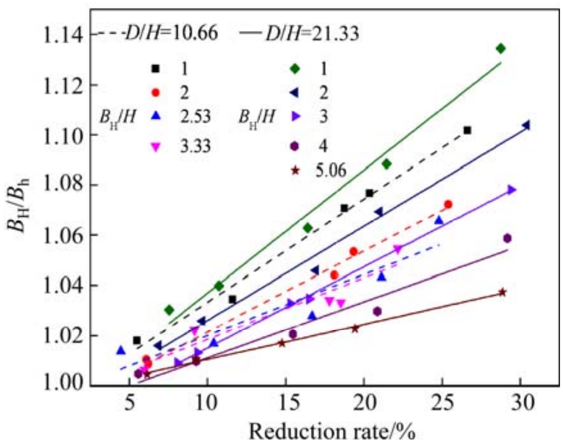

Fig. 5 Effect of roughness on spread (Grade 4, partially smooth)

line is higher than the dotted lines with the same B_H/H, e.g., B_H/H values are 1, 2 and 4. Also it can be seen in the figure, no matter solid lines or dotted lines the B_H/B_h decrease with increasing B_H/H.

From Fig. 3, partially rough roller was applied in the experiments, and the same conclusions are obtained as above. But comparing Figs. 2 with 3, B_H/B_h is higher

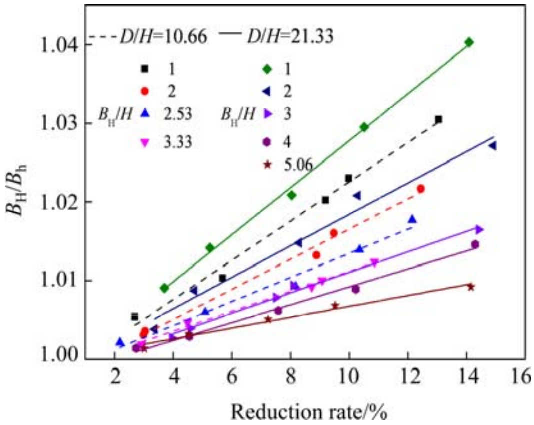

Fig. 6 Effect of roughness on spread (Grade 5, perfectly smooth)

in Fig. 2 than that in Fig. 3 under the same condition. This means that when bars and small width slabs are rolled, more friction means more spread.

From Figs. 4−6, when Grades 3−5 are put in experiments, the curves which represent the relationship between B_H/B_h and reduction will be changed from parabolas to straight lines. Also from Figs. 2 and 3, with the decrease of the roughness, the inclination angles of the curves will fall. If the surface of rollers is smoother, the curves will become straight lines as shown in Figs. 4−6. The inclination angle decreases with the decrease of roughness which also means that the rougher surfaces will make larger spread than the smooth ones. Under the same condition of width-to-thickness ratio the spread decreases with the decrease of D/H. As it is described above, the diameter of rollers is always 130 mm. This means that if the bars are thicker, the spread will become less. All the values of ΔB, Δh, R, H and h are recorded.

3 Nominal friction coefficients (f_n) in spread formulas

From Eqs. (1) and (2), Eqs. (5) and (6) are obtained as follows:

$$f_{n_1}=\frac{2\Delta BH+\Delta h^2\left(1+\dfrac{\Delta h}{H}\right)}{2\left(1+\dfrac{\Delta h}{H}\right)\Delta h\sqrt{R\Delta h}} \tag{5}$$

$$f_{n_2}=\frac{\Delta B}{\sqrt{R\Delta h}\ln\dfrac{H}{h}} \tag{6}$$

where f_n is the nominal friction coefficient.

Figures 7 and 8 show good examples for research. D/H is 21.33 with perfectly rough rollers in Fig. 7, while in Fig. 8, D/H is 10.66 with partially rough rollers. f_{n_1} is calculated through Eq. (5) obtained by

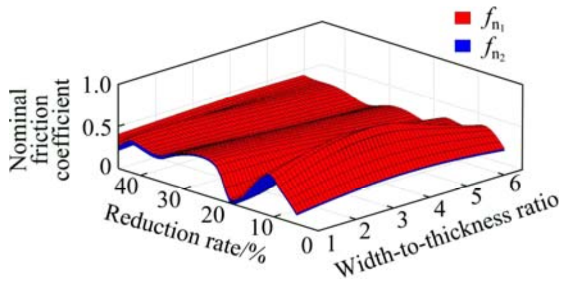

Fig. 7 Nominal friction coefficient at D/H=21.33 with perfectly rough rollers

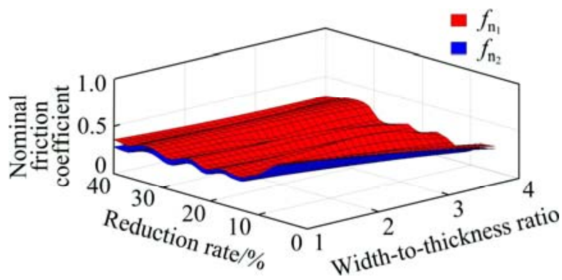

Fig. 8 Nominal friction coefficient at D/H=10.66 with partially rough rollers

Gubkin's formula. f_{n_2} is calculated by Eq. (6), which is obtained from the Shuralev's formula. From these equations it is known to us, the nominal friction coefficients f_n are in connection with B_H/H, $\Delta h/H$ and D/H. With changes of B_H/H and $\Delta h/H$, f_{n1} and f_{n2} are almost the same with each other. So, two conclusions can be obtained. One is that friction coefficients in Shuralev's and Gunkin's formulas are almost the same when the width-to-thickness ratio is lower than 10. The other is that the nominal friction coefficients change in the same roughness grade. This means that even the surfaces are the same, the nominal friction coefficient will also change with the width-to-thickness ratio and reduction rate. It should be emphasized that the Bakhchernoff's and Ekelund's formulas are also considered, but these two formulas cannot be used because based on these two formulas, some of the friction coefficients are larger than 1, and some of them are negative. It can be seen that these two formulas are not so suitable for the low width-to-thickness ratio.

So, as seen in Fig. 9, there is a method [12,13] to calculate the nominal friction coefficients in spread formulas. x_1 and x_2 are the values of width-to-thickness ratio (Table 2), they are 1, 2, 2.56, 3, 3.33, 4, 5.06, 6.66. y_1 and y_2 are reduction rates, as shown in Figs. 2−6, they are 2%−70%. With the results of the experiments, ΔB is acquired. Through Eq. (5) f_{n_1a}, f_{n_1b}, f_{n_1c} and f_{n_1d} are obtained. Also based on Eq. (6), f_{n_2a}, f_{n_2b}, f_{n_2c} and f_{n_2d} can be obtained. x^* is any value from x_1 to x_2. y^* is also an arbitrary value between y_1 and y_2. Since the number of

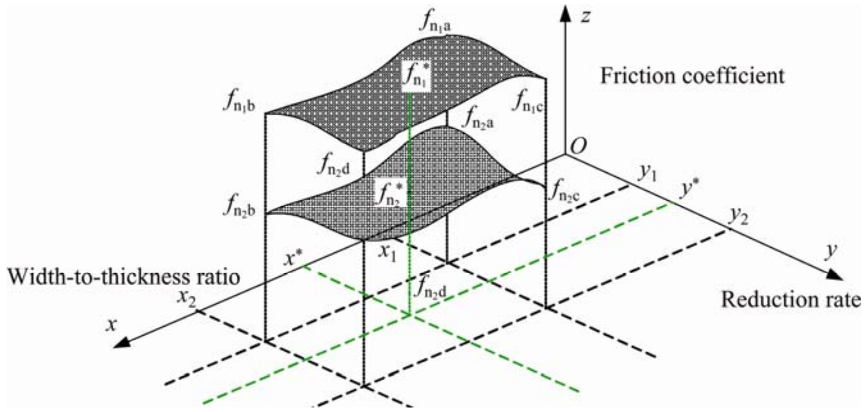

Fig. 9 Method for calculating f_{n1}^* and f_{n2}^*

experiments is limit, ΔB is not clear for any x^* and y^*. Equations (5) and (6) cannot be used to acquire every $f_{n_1}^*$ and $f_{n_2}^*$. So, $f_{n_1}^*$ is defined as a point which is the nearest to f_{n_1a}, f_{n_1b}, f_{n_1c} and f_{n_1d}.

$$F_1^* = \min\left(\overline{f_{n_1}^* f_{n_1a}} + \overline{f_{n_1}^* f_{n_1b}} + \overline{f_{n_1}^* f_{n_1c}} + \overline{f_{n_1}^* f_{n_1d}}\right) \quad (7)$$

$$F^*{}_1(x^*, y^*) = \sqrt{(f_{n_1}^* - f_{n_1a})^2 + (x^* - x_1)^2 + (y^* - y_1)^2} + \sqrt{(f_{n_1}^* - f_{n_1b})^2 + (x^* - x_2)^2 + (y^* - y_1)^2} + \sqrt{(f_{n_1}^* - f_{n_1c})^2 + (x^* - x_1)^2 + (y^* - y_2)^2} + \sqrt{(f_{n_1}^* - f_{n_1d})^2 + (x^* - x_2)^2 + (y^* - y_2)^2} \quad (8)$$

where $F^*{}_1$ is a function for calculating the distance among $\overline{f_{n_1}^* f_{n_1a}}$, $\overline{f_{n_1}^* f_{n_1b}}$, $\overline{f_{n_1}^* f_{n_1c}}$ and $\overline{f_{n_1}^* f_{n_1d}}$. The minimum value of F_1^* can be received in MATLAB as shown in Fig. 10. $f_{n_1}^*$ is the horizontal axis value in the parabola of F_1^*. In Fig. 10, when $f_{n_1}^*$ is 0.3025, with D/H=21.33, x^*=2.1707, y^*=13.8363, F_1^* will be the minimum 17.25314. So, $f_{n_1}^*$ can be gotten as the example above.

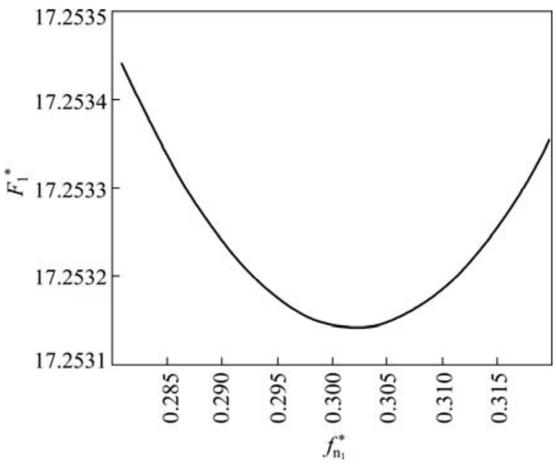

Fig. 10 Example for searching minimum value of F_1^* (D/H=21.33, x^*=2.1707, y^*=13.8363)

Then, with the same method, $f_{n_2}^*$ can be obtained.

$$f_n^* = \frac{1}{2}(f_{n_1}^* + f_{n_2}^*) \quad (9)$$

f_n^* is gotten by Eq. (9) which is based on both the Shuralev's and Gunkin's formulas. f_n^* is variational, comparing with a constant value, it will meet requirements in different real rolling working conditions. Also, it should be emphasized that this method is a new way which is based on the traditional formulas to calculate the friction coefficient in spread formulas, so we have good theoretical reasons to believe it.

From Figs. 11 and 12, different colors are used to represent different grade roughnesses of f_n^* calculated by Eq. (9), x, y and z axes are respectively width-to-thickness ratio, reduction rate and nominal friction coefficient. It can be seen that if a certain D/H is confirmed, f_n^* changes with width-to-thickness ratio and reduction rate. D/H is 21.33 in Fig. 11, while in Fig. 12, D/H is 10.66. So, D/H can be considered as a constant coefficient for f_n^*. The effect of width-to-thickness ratio can be described by a cubic curve which influences the nominal friction coefficient simply. This is because when width-to-thickness is lower than 10, the friction influences the spread in the same way. The friction exists along the width direction, and it is a uniform distribution value. In each per unit width, the effect of the width-to-thickness ratio is almost the same. So, only a

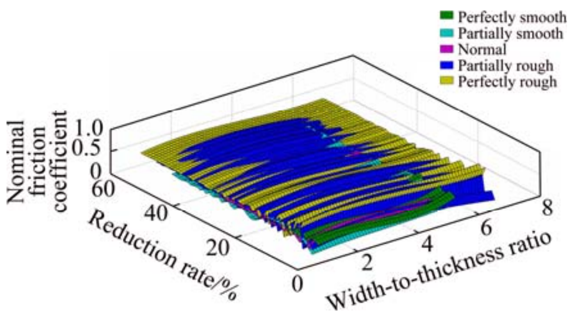

Fig. 11 Fitting expression for f_n^* with D/H=21.33

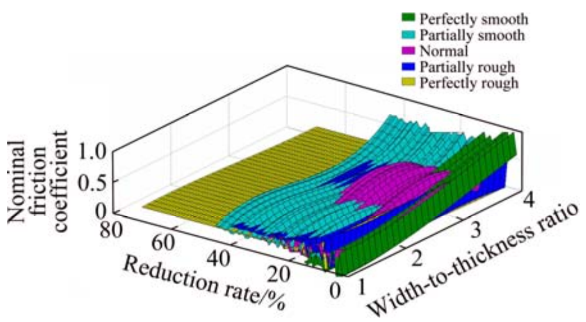

Fig. 12 Fitting expression for f_n^* with D/H =10.66

simple cubic curve is used to describe the influence of the width-to-thickness ratio. However, the effect of reduction rate is little different, which can be expressed as a sine function, because of its periodicity. It is known from Fig. 11 that, with high reduction rate, the friction coefficient is almost a content value. But with the decrease of reduction rate the amplitude of the sine function will increase. This is because when there is a high reduction rate, the contact surfaces between the rollers and work pieces are larger and the friction acts more sufficiently than that in low reduction[14]. So, Eq. (10) is shown as follows. It is a fitting expression for f_n^*.

$$f_n^* = (D/H)[a_1x^3 + a_2x^2 + a_3x + a_4 + a_5\exp(a_6y)\sin(a_7y^3 + a_8y^2 + a_9y + a_{10})] \quad (10)$$

where x is the width-to-thickness ratio, y is the reduction rate, a_1-a_{10} are coefficients in expression. In this model, a_1-a_{10} can be obtained for each roughness grade by the real experimental data. This means that if a roughness grade is approximately chosen from these 5 grades based on the real working conditions, a set of coefficients will be used in corresponding equation, according to a database and layers of these coefficients in Eq. (10), then f_n^* can be predicted accurately [15,16].

Equation (10) shows the value of f_n^* during the changing width-to-thickness ratio, reduction rate and D/H. To verify the expression, Figs. 13 and 14 are shown below.

From Fig. 13, the errors of f_n^* between fitting and experiment test points are almost less than 12%. In 232 tests only 18 of them do not meet this requirement. Also from Fig. 14, when the roughness grade is perfectly smooth and the D/H is 10.66, the error of fitting is described by a contour map. In Fig. 14, the largest error of the fitting is 9%, the error areas are shown by red lines, and the areas of blue lines represent lower errors. So, Eq. (10) can be used to calculate f_n^*. This means that if we choose a roughness grade according to the surface, the temperature of oxidized scale, the rolling speed and chemical composition of material, then f_n^* will be calculated with a certain width-to-thickness ratio, reduction rate and D/H. f_n^* is used in the Shuralev's and Gubkin's formulas. Comparing with just setting a constant value, the change of nominal friction coefficient will give a more accurate value for calculating the spread [17,18].

As shown in Fig. 15, we choose a kind of slabs with D/H=10.66 and the surface roughness between rollers

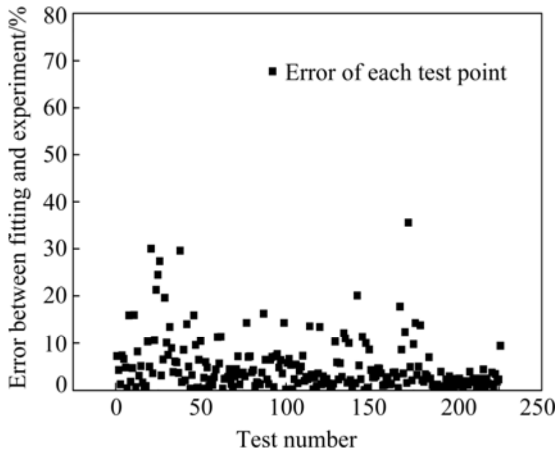

Fig. 13 Error of each test point (232 tests)

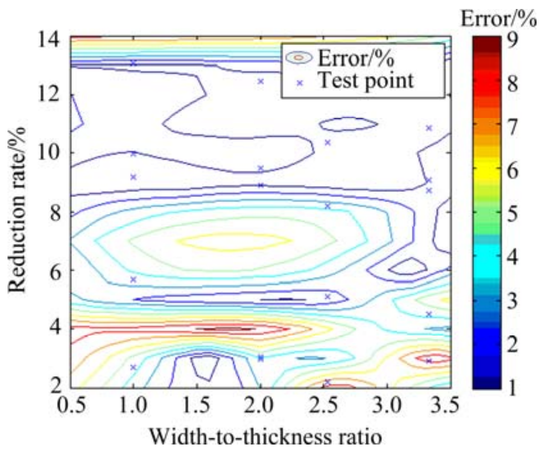

Fig. 14 Error of perfectly smooth roughness with D/H =10.66

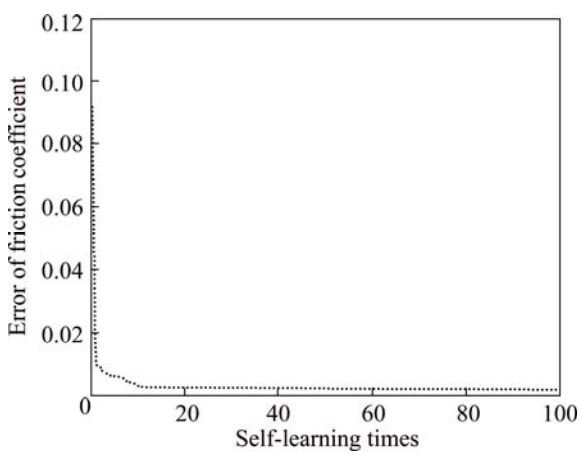

Fig. 15 Error of f_n^* after 100 times self-learning (partially smooth roughness with D/H=10.66)

and this kind of slabs are approximately as partially smooth. After a certain times of self-learning in the real working conditions, the errors of f_n^* will be lessened. The Eq. (10) will calculate a more precise value of f_n^*, after only 5 times self-learning the error of the f_n^* is lessened below 1%. When the self-learning times are over 20, the errors are almost the same.

From Fig. 16(a) slab is rolled under the real working condition, and the spread is measured after rolling process. Through Eq. (10), the prediction width is obtained as the red line in Fig. 16, the prediction error is no more than 2%. In order to compare the prediction width with measured width, right blue box is made to zoom in 8−12 s in left ones. From Fig. 16 we can also see that the black line is little higher than the red one. This means that the results calculated by Eq. (10) are little lower than those of the measured ones. The reasons for that may be measured under the real working conditions is not so precise, and many other reasons may let this happen such as impurities in steel and inhomogeneous deformations in edge of the slab [19,20].

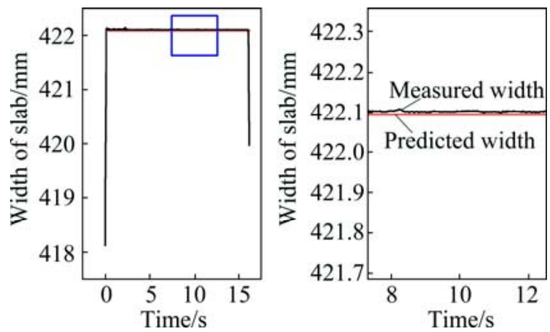

Fig. 16 Comparison of prediction width with measured one under real working condition (The blue box in the left figure is magnified in the right figure)

4 Conclusions

1) Friction coefficients in spread formulas are studied for low width-to-thickness ratio. There are many factors related to the friction coefficient, but all of them affect the friction coefficients through the roughness of surfaces. It is not only verified by the rolling theories, but also based on definition of the friction.

2) The roughness grades of surfaces are creatively defined. Based on the different roughness grades, the spreads are measured after rolling experiments. With the Shuralev's and Gubkin's formulas, a nominal friction coefficient is obtained. It should be emphasized that this is a new way to set a modified nominal friction coefficient in spread formulas. This method would propose a credible reference and solution about how to set the friction coefficient in spread formulas.

3) After fitting, an expression is proposed to calculate the nominal friction coefficients in spread formulas with low width-to-thickness ratio. The errors of the expressions are almost less than 12%. In addition, after a certain times self-learning under the real working condition, the expression can be used to calculate a more precise value of friction coefficient. The spreads are predicted by the expression accurately and the error is no more than 2%.

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基于铅轧实验宽展公式中的名义摩擦因数

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摘　要：在低辊径−厚度比下，研究摩擦因数在宽展公式中的作用，摩擦因数对展宽的作用主要体现在接触面的粗糙程度。经过 5 组不同的铅轧实验，获得不同等级的摩擦因数。随着宽厚比、压下率和辊径−厚度比的改变，可以得到不同的名义摩擦因数并应用在相应的公式中。随后提出一个拟合公式，通过与 232 次实验结果进行比较，验证拟合得到的名义摩擦因数的误差低于 12%。通过一定次数的自学习修正，该误差减少至 2%以下。最终实现通过可以变化的名义摩擦因数对宽展进行更加精确的预测。在真正的工作环境下使用名义摩擦因数，得到的宽展预测误差也小于 2%。在实际生产中验证，得到了一个能够对宽展公式中摩擦因数进行设置的参考和解决方法，从而满足工业生产的应用。

关键词：宽展；轧制；摩擦因数；拟合；自学习

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