DOI: 10.3901/CJME.2015.0310.027, available online at www.springerlink.com; www.cjmenet.com; www.cjme.com.cn

Control Method for Steel Strip Roughness in Two-stand Temper Mill Rolling

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Received June 16, 2014; revised January 6, 2015; accepted March 10, 2015

Abstract: How to control surface roughness of steel strip in a narrow range for a long time has become an important question because surface roughness would significantly influence the appearance of the products. However, there are few effective solutions to solve the problem currently. In this paper, considering both asperities of work roll pressing in and squeezing the steel strip, two asperity contact models including squeezing model and pressing in model in a two-stand temper mill rolling are established by using finite element method (FEM). The simulation investigates the influences of multiple process parameters, such as work roll surface roughness, roll radius and roll force on the surface roughness of steel strip. The simulation results indicate that work rolls surface roughness and roll force play important roles in the products; furthermore, the effect of roll force in the first stand is opposite to the second. According to the analysis, a control method for steel strip surface roughness in a narrow range for a long time is proposed, which applies higher work roll roughness in the first stand and lower roll roughness in the second to make the steel strip roughness in a required narrow range. In the later stage of the production, decreasing the roll force in the first stand and increasing the roll force in the second stand guarantee the steel strip roughness relatively stable in a long time. The following experimental measurements on the surface topography and roughness of the steel strips during the whole process are also conducted. The results validate the simulation conclusions and prove the effect of the control method. The application of the proposed method in the steel strip production shows excellent performance including long service life of work roll and high finished product rate.

Keywords: temper mill rolling, surface roughness, interface contact

1 Introduction

With the demand of better surface quality of steel strip, surface roughness in a narrow range was required due to the influence of surface roughness on glossiness of products and the appearance after painting[1–2]. How to control steel strip surface roughness in a narrow range for a long time has become a serious problem and attracted wide attention. It is well known that transfer of work roll roughness to steel strip plays an important role in the formation of surface topography of steel strip. Important experimental work[3–10] has been done to study the mechanism of transfer and the influence of process parameters on transfer ratio. Theoretical investigations were also carried out by simulating elastic-plastic contact between rough work roll surface and ideal smooth steel strip. SHI, et al[11], simulated the process that a serrated surface indented the strip and was subsequently removed using slip line theory. Recently, FEM has been successfully used to analysis elastic-plastic deformation of the materials[12]. YANG, et al[13], KIJIMA, et al[14–15], studied multi-asperity contacts between circular arc work roll surface and ideal smooth steel strip using FEM. KIJIMA[16–17] further studied the influence of roll radius on contact condition, material deformation and roughness transfer in skin-pass rolling of steel strip by using FEM. Some other kinds of profiles asperities were used in simulation work[18] by upper bound element theory (UBET). Besides, combining elastic-plastic contact between rough work roll and ideal steel strip by analytical method with plastic deformation during temper rolling, ZHANG, et al[19], built an integration model of work roll and strip.

Although significant results have been obtained in asperity contact between work roll and steel strip, most work focused on rough work roll surface and ideal smooth steel strip to investigate transfer. The cases that smaller work roll roughness than steel strip have not been treated, which might play a key role in surface roughness control. The aim of this paper was to study the formation of surface roughness in both situations, and illustrate the surprising effect of them on roughness control in a narrow range through simulation and experiment work. This work furthermore contributed a method for surface roughness control in two-stand temper mill rolling.

2 Simulation Model

Steel strip surface roughness depended on asperities

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Supported by National Natural Science Foundation of China (Grant Nos. 51174248, 51475039)

contact between work roll surface and steel strip surface. Asperities contact was influenced by roll force when asperity parameters were settled. As a result, the whole simulation process was composed of asperities contact simulation and roll force calculation. Then two kinds of models for roll force and asperity contact were established respectively. The value of roll force was input parameter of asperities contact simulation. The illustration of simulation process in one stand was shown as Fig. 1.

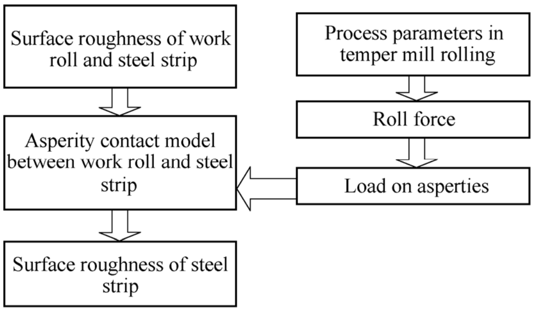


Fig. 1. Simulation process of surface roughness formation as steel strip passed through one stand

2.1 Roll force model

Fig. 2 illustrated work zone of temper mill rolling, which included elastic zone at the entrance, plastic deformation zone and elastic zone at the exit. Contact arc length was calculated using the method used by IKE[20]. Detailed calculation process was shown in Fig. 3.

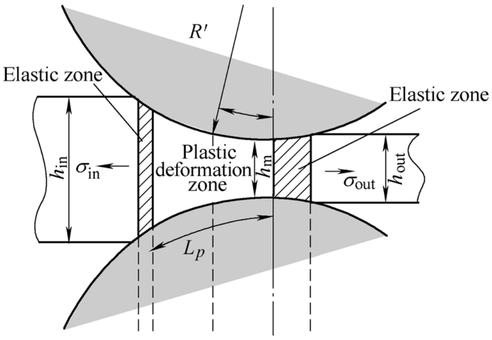


Fig. 2. Work zone in temper mill rolling

The roll forces of elastic zone at the entrance and at the exit were calculated according to usual way. The equations were expressed as follows[21]:

$$p_{a1}=\frac{1-\nu^2}{E}\frac{h_{\text{in}}\left[k(h_{\text{in}})-\sigma_{\text{in}}\right]}{4\sqrt{(h_{\text{in}}-h_{\text{out}})/R'}}, \tag{1}$$

$$p_{a4}=\frac{2}{3}\left[k(h_{\text{out}})-\sigma_{\text{out}}\right]^{3/2}\sqrt{h_{\text{out}}\frac{R'(1-\nu^2)}{E}}. \tag{2}$$

Tensile stress σ_{in}, σ_{out} was revised using Bryant revision. Classical empirical Bland-Ford equation was used to calculate the roll force in plastic deformation zone. The influence of strain rate was considered in calculating strain rate of steel strip using Ekelund equation, which was expressed as follows:

$$\dot{\varepsilon}=\frac{1000}{600}\frac{V}{\sqrt{R'h_{\text{in}}}}\frac{2}{2-\varepsilon}\sqrt{\varepsilon}. \tag{3}$$

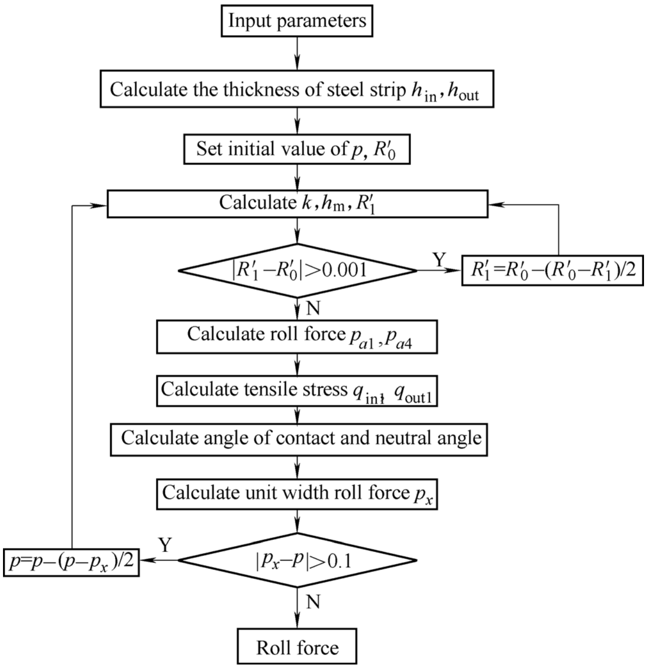


Fig. 3. Calculation process of roll force

The deformation resistance of steel strip k was expressed as follows:

$$k=k_m(1000\dot{\varepsilon})^{\alpha}, \tag{4}$$

$$\alpha=\begin{cases}\dfrac{5}{k_m/10+23}-0.046, & 15\leqslant k_m\leqslant 85,\\ \alpha=0, & k_m>85.\end{cases} \tag{5}$$

In the above, E is the elastic modulus of steel strip (MPa); ν is Poisson's ratio of steel strip; h_{in}, h_{out}, h_{m} are the thickness of steel strip at the entrance, at the exit and at the exit of plastic zone (mm); k, k_m are the dynamic and static deformation resistance of steel strip (MPa); p_{a1}, p_{a4} are the unit roll force in elastic zone at the entrance and at the exit (MPa); R', R'_0, R'_1 are the contact flattened radius (mm); V is the temper speed (m/s); σ_{in}, σ_{out} are the tensile stress at the entrance and at the exit (kN); ε is the deformation degree of steel strip

2.2 Asperities contact model

Considering one stand might not be enough to control steel strip surface roughness in a narrow range, we simulated a two stand temper mill rolling process. We considered the case that work roll roughness in 1# stand was much higher than 2# stand, which implied that both stands might influence steel strip roughness at the entrance. Then asperities contacts of 1# and 2# stand can be assumed rough work roll and ideal smooth steel strip, ideal smooth work roll and rough steel strip, respectively.

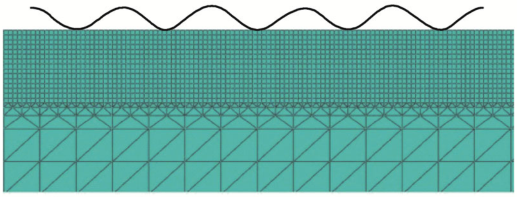
Equivalent roughness was calculated according to the equation

$$R_{\mathrm{a}}' = \sqrt{R_{\mathrm{a1}}{}^2 + R_{\mathrm{a2}}{}^2}.$$

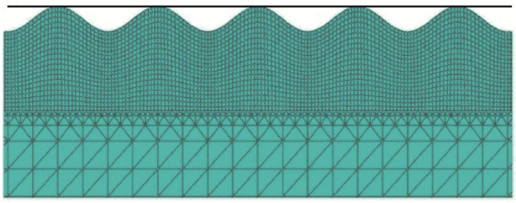
Given the much higher yield strength of roll, rigid roll and elastic-plastic steel strip were applied. After comparing several kinds of asperities including round, trapezoid, triangle and cosine profiles in a typical case, cosine asperity was finally applied because roughness was closer to the experimental measurement of steel strip using it. The cosine asperity was described by

$$y = A\cos\frac{2\pi x}{S_m}, \quad -\frac{S_m}{2} \leqslant x \leqslant \frac{S_m}{2},$$

where $A=\pi R_{\mathrm{a}}/2$, $S_m=Pc/10$ were derived from the definition of surface roughness. Then two models were established respectively, which included the rigid cosine profile work roll surface pressing in the ideal elastic-plastic smooth steel strip surface, the ideal rigid smooth work roll surface squeezing the elastic-plastic cosine profile steel strip surface. The illustrations of two simplified models using FEM were given in Figs. 4(a) and 4(b). When wok roll roughness was much larger than steel strip, the interaction between work roll surface and strip surface performed like the case in Fig. 4(a). In contrast, the case like Fig. 4(b) was dominant owing to small reduction in temper mill rolling.



(a) Pressing in



(b) Squeezing

Fig. 4. FEM models of asperities contact between work roll surface and steel strip

The whole simulation process was composed of loading and unloading. The pressure obtained from roll force model was applied in loading process. Unloading process was achieved by affording displacement in the vertical direction to roll surface to make it depart from strip. Fixed constraint was applied on symmetry planes of strip, and rigid roll only had one degree of freedom in vertical direction. The material properties of steel strip was Young's modulus 182.0 GPa, Poisson's ratio 0.3. Von Mises yield criterion and updated Lagrangian formulation were used. Contact problem between roll surface and steel strip was solved by applying penalty function. Fine rectangular mesh near the interface with the number of 2800 and sparse triangular far the interface were used considering accuracy and efficiency.

The detailed simulation parameters in roll force model and asperity contact models were given in Table 1.

Table 1. Simulation parameters

Parameter	Value	Parameter	Value
Thickness of supplied steel strip h/mm	0.2, 0.25, 0.3	Tensile stress in the back T/kN	100, 150, 200
Width l/mm	1000	Tension force in the back T/kN	30, 40, 50
Yield strengthσ/MPa	300, 400, 500	Reduction of 1# stand ε/%	0.5, 1, 1.5
Radius of work roll r/mm	200, 225, 250	Reduction of 2# stand ε/%	0.2, 0.4, 0.6
Temper speed v/(m • min^{-1})	400, 500, 600	Roughness of steel at the entrance R_{a}/μm	0.3, 0.35, 0.4
Tensile stress in front T/MPa	100, 150, 200	Roughness of 1#roll R_{a}/μm	1.2, 1.4, 1.6
Tension force in front T/kN	20, 30, 40	Roughness of 2#roll R_{a}/μm	0.35, 0.4, 0.45
Tensile stress in the middle T/kN	150, 200, 250	Pc of 1#roll Pc/mm^{-1}	20
Tension force in the middle T/kN	30, 40, 50	Pc of 2#roll Pc/mm^{-1}	20

3 Experiment

The samples for experimental measurement were the steel strips before 1# stand, between 1# and 2# stand and after 2# stand, which all came from one factory. The work rolls of 1# and 2# were electro-discharge textured and grounded, respectively. Their surface roughness was approximately 1.1 μm, 0.4 μm. The former was much larger than the latter. The samples parameters and corresponding process parameters were given in Table 2. Yield strength 328.3 MPa came from experimental measurement. Surface roughness of the sample was measured in production site by portable roughness instrument TR200. Three-dimensional surface topography of sample was observed by WYKO optic profiler.

Table 2. Sample parameters and corresponding process parameters

Parameter	Value			
Steel type	T-4	T-4	T-4	T-4
Width l/mm	740.2	738.4	759.1	834.6
Thickness h/mm	0.202	0.202	0.202	0.202
Roll force in 1#stand F/kN	9731	11 250	10 231	11 231
Roll force in 2#stand F/kN	4733	4792	5723	4792
Ra of 1# work roll R_a/μm	0.45	0.45	0.45	0.45
Ra of 2# work roll R_a/μm	1.50	1.50	1.50	1.50
Elongation μ/%	1.5	1.6	1.7	1.5

4 Results and Discussions

4.1 Theoretical results in the influence of parameters on steel strip roughness

4.1.1 Influence of supplied steel strip

The maximum roll force, Roughness of steel strip with thickness and yield strength of supplied steel strip were illustrated by Fig. 5 and Fig. 6, respectively. According to the curves, the maximum roll force decreased slightly with the thickness of steel strip. Roughness of steel strip showed similar trend. The reason was that the larger thickness led to more even distribution of force, which resulted in a larger decline of the maximum roll force than smaller roughness. Compared to the influence of thickness, the maximum roll force increased obviously with yield strength. Roughness of steel strip after 1# stand showed similar trend, however the roughness after 2# stand did not show obvious change. It was because higher pressing in force caused larger steel strip roughness at the exit of 1# stand, but higher squeezing force in 2# stand was helpful to reduce roughness. The combination of two stands made steel strip roughness at the exit only changed slightly.

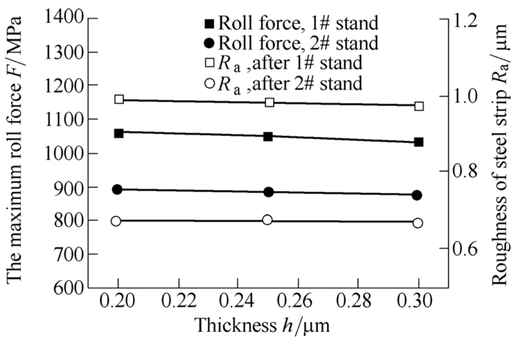


Fig. 5. The maximum roll force and roughness of steel strip with the thickness of supplied steel strip

4.1.2 Influence of work roll

Fig. 7 showed the curves of the maximum roll force and roughness of steel strip as radiuses of work rolls in two stands changed at the same time and only the radius of one stand changed each time. The results indicated the maximum roll force got rise as radiuses of work roll increased at the same time. Ra of steel strip at the exit of 2# stand only changed a little. However, when only the radius of one work roll changed, Ra at the exit of 2# stand showed significant change. According to the curves, the rise of radius of 1# work roll and decline of 2# work roll were both helpful to increase Ra of steel strip product at the exit of 2# stand. The reason was that larger radius of work roll influenced the roll force distribution, then led to larger pressure on the asperities. The results implied that the radius of work roll was an important factor for roughness control.

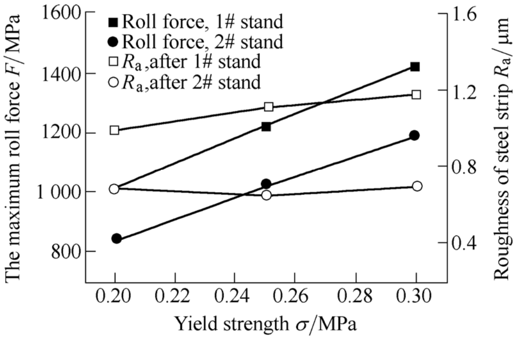


Fig. 6. The maximum roll force and roughness of steel strip with yield strength of supplied steel strip

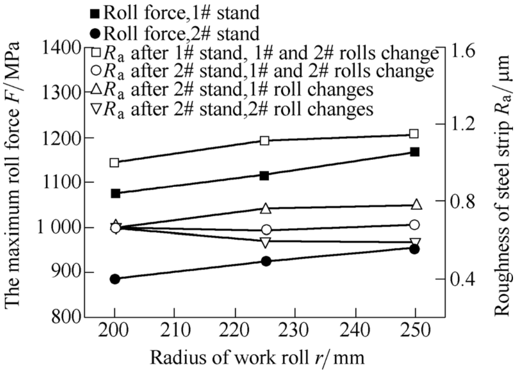


Fig. 7. The maximum roll force and roughness of steel strip with work rolls radiuses of 1# and 2# stand

4.1.3 Influence of process parameters

Fig. 8 showed the roughness of steel strip at the exit of 2# stand with the roughness of work roll. According to the curves, work roll roughness influenced steel strip roughness obviously. The influence of 1# stand was more obvious.

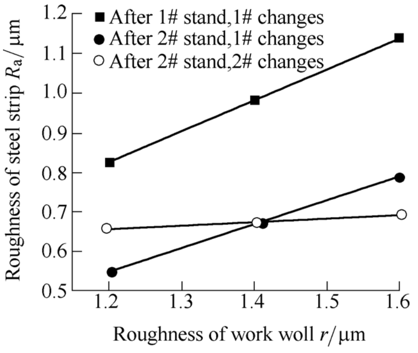


Fig. 8. Roughness of steel strip with roughness of work rolls of 1# and 2# stand

The process parameters adjustment also played an important role in surface roughness control. Fig. 9 and Fig.

10 showed the maximum roll force and roughness of steel strip with elongation and temper speed. The results indicated the maximum roll force increased obviously with elongation, and changed slightly with temper speed. Roughness of steel strip at the exit did not change a lot with elongation and temper speed. The maximum roll force and roughness of steel strip with tension forces were also calculated. The results indicated that the maximum roll force declined linearly with tension force. However, roughness of steel strip with tension forces showed different ways, as shown as Fig. 11. Roughness of steel strip at the exit declined with tension force in front and in the middle, but went up with tension force in the back. The reason was that the rise of tension force in front and in the middle reduced the roll force in 1# stand in contact arc area, which brought out smaller roughness of steel strip. However, the rise of tension force in the back reduced roll force in 2# stand, which led to smaller squeezing force to steel strip, then less change of roughness as steel trip passed through 2# stand, that is, surface roughness of steel strip product at the exit became larger.

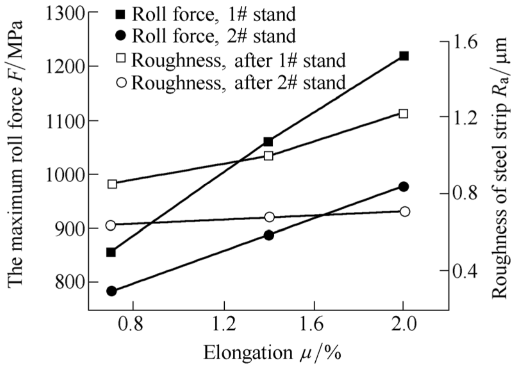


Fig. 9. The maximum roll force and roughness of steel strip with elongation

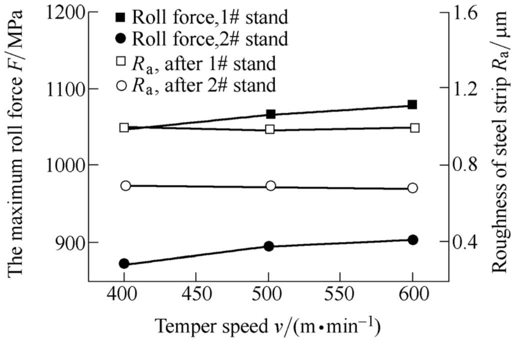


Fig. 10. The maximum roll force and roughness of steel strip with temper speed

4.2 Method for surface roughness control

According to the analysis above, there were two main factors that had significant influence on steel strip product roughness. One was work roll roughness, the other was roll force. Besides, the effect of roll force in 1# stand was opposite to 2# stand. All adjusting means that led to the change of the two factors could influence Ra of product. For example, initial work roll roughness, work roll radius, tension force, and so on. As we know, stable tension forces were required for steady production. Work roll radius only changed a little in production. The available ways to control steel strip roughness at the exit were to adjust initial work roll roughness and roll force directly.

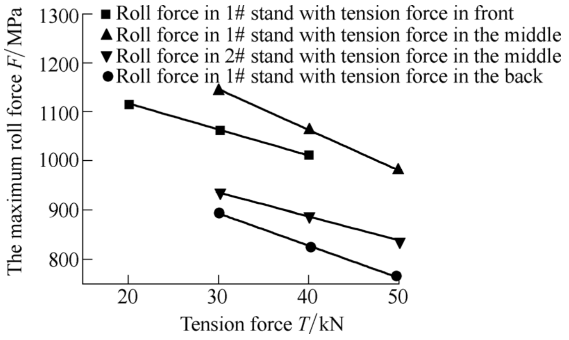


Fig. 11. Roughness of steel strip at the exit of 1# and 2# stand with tension force in front, in the middle and in the back

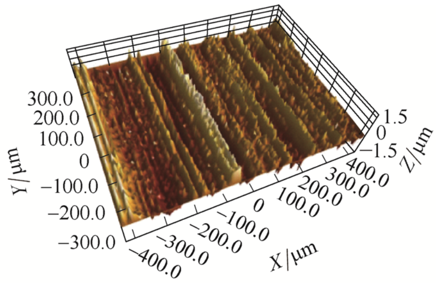
Here an effective method for steel strip surface roughness control was proposed with higher work roll roughness at 1# stand and lower work roll roughness at 2# stand. As time went by, work roll roughness in two stands decreased simultaneously. Given 2# work roll roughness decreased more owing to larger roughness, gradually increasing roll force in 1# stand and decreasing roll force in 2# stand in the later stage could be used. Finally, roughness in a narrow range for a long time was achieved. The effect of this control method was confirmed by experimental observation and the application in production.

4.3 Experimental results

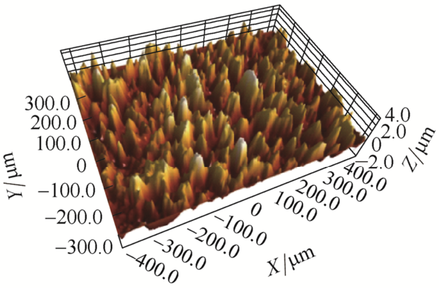
Process parameters in the experiments could be seen in Table 2, which was mentioned above. The surface topography of T-4 steel strip during the whole temper mill rolling process was shown as Figs. 12(a), 12(b), 12(c).

The texture of supplied steel strip was like ground surface. After electro-discharge textured roll of 1# stand, it changed completely owing to transfer of work roll surface, then appeared like the textured surface. However, after ground roll of 2# stand, the texture of steel strip looked like superposition of ground and textured surface, which implied pressing in and squeezing both occurred in 2# stand. Moreover, squeezing was dominant. Roughness of steel strip samples with roll number was given in Fig. 13. Roughness of steel strip increased to about 1 μm after 1# stand, and dropped to about 0.4 μm after 2# stand, which was consistent with the observation of surface topography.

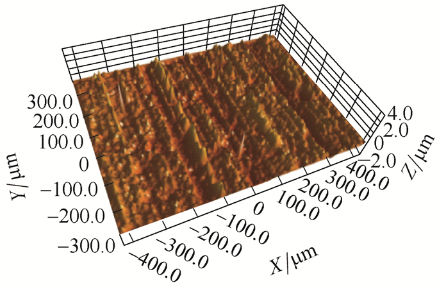
Roughness of steel strip product with roll force in 1# and 2# was given in Fig. 14. Because work roll asperities pressed in steel deeply in 1# stand, roughness of steel strip after 1# stand went up with roll force. However, the opposite trend was obtained after 2# stand. The reason was squeezing process was dominant relative to pressing in process in 2# stand. Higher roll force led to lower height of asperities, then smaller roughness. The results of surface topography and roughness both validated simulation conclusion. Furthermore, surface topography with superposition of ground and textured appearance was helpful to tinning and painting. But caution that the simplified simulation model was only suitable for analysis of one-dimensional surface roughness, not for surface texture analysis.



(a) The supplied



(b) After 1# stand



(c) After 2# stand

Fig. 12. Surface topography of steel strip

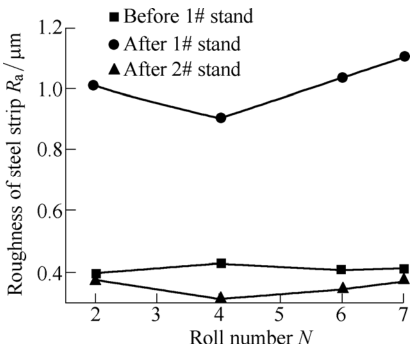


Fig. 13. Roughness of several steel strips before 1# stand, at the exit of 1# stand, at the exit of 2# stand

4.4 Industry application

The simulation and experiment conclusions have been applied to the production process of T-4 steel strip in one factory. Roughness of steel strip product between 0.37 μm and 0.47 μm was required. Initially it was so hard to control in this narrow range that many products did not confirm to the requirement. With the application of this method, after preliminary optimization of initial work roll roughness and the adjustment of roll forces of two stands in the later stage of temper rolling, the number of qualified products improved significantly. As shown as Fig. 15(b), range of roughness of steel strip lied within 0.3 μm to 0.5 μm, which was clearly better than before. The ratio between 0.37 μm and 0.47 μm got rise to 65.33% from 15%. Rolling miles also increased greatly, which improved production efficiency and reduced the cost. Moreover, better performance could be expected after further optimization.

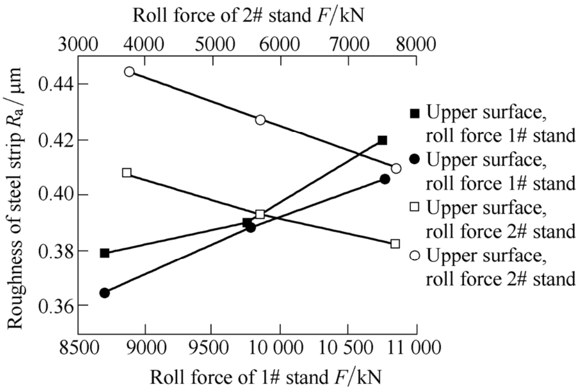
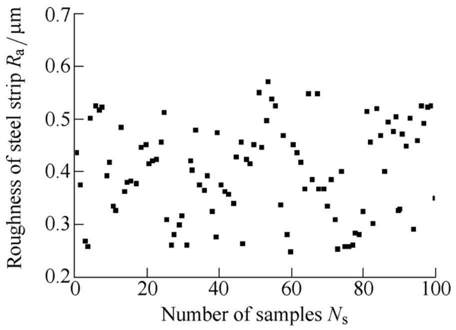
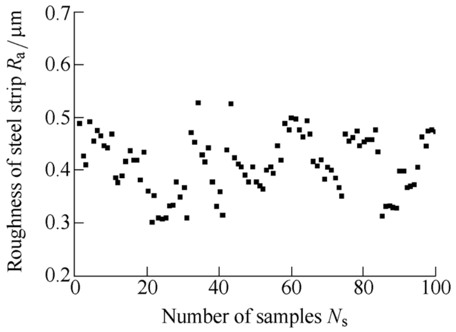


Fig. 14. Roughness of upper and under surface of steel strip with roll force in 1# stand and 2# stand



(a) Before optimization



(b) After optimization

Fig. 15. Roughness of steel strip product in production

5 Conclusions

(1) Asperity contact models considering pressing in and squeezing were established using FEM. The models

simulated the formation of surface roughness in two-stand temper mill rolling with higher work roll roughness in 1# stand and lower work roll roughness in 2# stand. The results indicated that several process parameters influenced steel strip roughness obviously, such as work roll roughness, radius of work roll, roll force, and tension force. For the stability of production, two factors were crucial to control steel strip roughness. One was work roll roughness, the other was roll force in two stands. The change of roll force in 2# stand showed an opposite effect to 1# stand. Experimental observation of surface topography and the measurement of roughness of steel strip validated the simulation results.

(2) A control method with higher work roll roughness in 1# stand and lower in 2# stand was proposed, in which optimization of initial work roll roughness and the adjustment of roll forces in different stages of production played important roles. After the preliminary optimization, the application of this method performed much better in finished product ratio and service life of work roll than before. Therefore excellent performance could be expected in the future.

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