Analysis of factors influencing the steel sheet surface waviness in cold rolling process

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Abstract. In order to study the influence factors of steel sheet surface waviness in cold rolling process, using coherence scanning interferometry, the surface waviness with different cold rolling processes had been investigated at room temperature, and without condensation according to relevant standard. The results show that the surface waviness of the typical steel was successfully evaluated, while the mill reduction rate, working roll cycle, and temper rolling elongation were found to be the most informative for surface waviness parameters $W_{a_{0.8}}$ and $W_{sa_{1.5}}$. It was found that the surface waviness parameters $W_{a_{0.8}}$ and $W_{sa_{1.5}}$ sharply increased with increasing rolling reduction rates in rolling process, and vice versa. Moreover, in the continuous annealing process, finish rolling temperature had almost no effect on the waviness. In temper rolling, the surface waviness parameters $W_{a_{0.8}}$ and $W_{sa_{1.5}}$ gradually increased with elongation and dropped with increasing working roll period. Ultimately, it was proved that the control measures to improve the surface waviness of steel plate in cold rolling process successfully improved the product surface quality.

1. Introduction

With increasingly strict requirements on environmental protection, the coating process in the automobile industry is developing towards the water-based midcoat-free coating process with low energy consumption, low emission, and low pollution. After free of medium coating process, the appearance quality of the whole paint layer is easy to produce defects, such as orange peel particles with poor reflecting property.

The visual appearance painted of steel sheet is of vital importance, which is often experienced as a direct indicator of the quality of the product towards the end user. Therefore, on the one hand, the quality of the paint process and automotive paint is required to study for automobile factories [1,2]. On the other hand, the quality of the paint appearance is determined by the surface topography of the bare steel sheet for steel mill [3-11].

While the automobile steel plate roughness can be smoothed by the painting process, its waviness remains. Therefore, it is crucial to keep waviness as low as possible in producing steel sheets. The surface waviness extensive research has been conducted [12-17].

Although many works were performed to mitigate the surface waviness, the research on influencing factors of steel sheet surface waviness in cold rolling process are scarce in literature. In this work, we studied the influence of various factors on the steel plate surface waviness in the cold rolling process by coherence scanning interferometry (CSI). Through testing the surface waviness of steel plate in different cold rolling processes, the influence rules of various factors were obtained. The effects of the rolling reduction rates, working roll period, finish rolling temperature on steel sheet
surface waviness have been analyzed in detail, which could guide industrial production and improve the surface quality of steel plate, so as to enhance the competitiveness of steel plate.

2. Experimental

2.1. Test principle

To gain more insight into surface waviness, the coherence scanning interferometry (CSI) was used to measure the smooth surface topography. The principles of measurement as good practice have been applied to much surface texture measuring field [18-21].

A schematic of a CSI is shown in figure 1. The illumination is divided into two beams by a beam splitter. One beam is directed towards the sample as a probe light, the path length varies with the surface height. Another beam is directed towards an internal reference mirror, and the length of its optical path is precisely monitored. The optical path to the reference mirror is adjusted to be equal to whom the focal plane of the objective lens, with the beam splitter as the starting point. The two beams recombine and the recombined light is sent to the digital image sensor. Interference fringes appear in the image would be taken by the camera, if the light path difference between the two beams is zero. The variation of interference fringes is directly related to the height of each point on the sample surface. As a result, the surface topography of the sample is generated by Z-direction scanning.

![Figure 1. A schematic of a CSI.](image1)

![Figure 2. A schematic representation of the sample size.](image2)

2.2. Experimental method

In order to ensure the accuracy of measurement, the full-range closed-loop scanning can continuously measure Z-direction rising and falling samples of 0.1 nm ~ 10 mm, with automatic focusing function and automatic light intensity adjustment function. Before the measurement, the sample surface with alcohol to wipe clean, at the same time the Measurement conditions are as follows: 20~30°C of ambient temperature, environment humidity less than 80% with no condensation, earthquake requirements with vibration isolation system, 4.2~7.0 kg/cm² of compressed air.

For the same influence factors of cold rolling processes, at least 5 specimens were prepared for accuracy of measurement. The arithmetic mean of the surface waviness of the 5 samples is the surface waviness of the process. The surface of the sample is clean and free from defects and bending deformation. A schematic representation of the sample size is shown in figure 2. The test sample size is 150 mm×100 mm. The test must be performed as per SEP 1941-2012 [22]. Measurement tracks must be carried out along the rolling direction, and at least three parallel lines measured for each specimen with a distance of about 15 mm. The average of the three test surface waviness was taken as the surface waviness of the sample.

In this paper, taking steel DC04 and DC06 as an example, the waviness characteristic values $W_{a_{0.8}}$ and $W_{s_{a1.5}}$ were calculated from the waviness profile. $W_{s_{a1.5}}$ is arithmetic mean waviness in the wavelength range between 1 mm and 5 mm. At the same time, $W_{a_{0.8}}$ is arithmetic mean waviness at
lower wavelength limits 0.8 mm. We measured the sample surface topography with the same measuring distance \( l = 50 \) mm.

2.2.1. **Evaluation of Wsa\(_{1,5}\).** Evaluation of Wsa\(_{1,5}\) for steel DC04 is shown in figure 3. Firstly, the surface topography of the sample was measured by the principle of CSI, as shown in figure 3(a). In figure 3(b), the sampling distance \( l_i = 30 \) mm, horizontal orientation by subtracting a 1st degree polynomial, primary profile \( Z(x) \) is shown in figure 3(c).

![Figure 3. Evaluation of Wsa\(_{1,5}\) for steel DC04.](figure3.png)

Then, through low-pass filtering with Gaussian filter and wavelength limit \( \lambda_f = 5 \) mm, in figure 3(d), removal of the run-in and run-out sections \( \lambda_f/2 = 2.5 \) mm, the processing results are shown in figure 3(e). High-pass filtering by Gaussian filter with wavelength limit \( \lambda_c = 1 \) mm, \( Z_m(x) \) of the entire sampling distance is shown in figure 3(f).

Finally, \( Wsa\(_{1,5}\) can be written as:

\[
Wsa\(_{1,5}\) = \frac{1}{l_m} \int_{l_m}^{l_i} \left| Z_m(x) - Z_m \right| dx
\]

(1)

where \( l_i \) is the traverse length, \( \lambda_f \) is the cut-off wavelength, \( l_m \) is the evaluation length, \( Z_m \) is the Mean line of waviness, \( Z_m(x) \) is the waviness profile as a function of the spatial coordinate \( x \). As a result, surface waviness \( Wsa\(_{1,5}\) of DC04 is 0.193 \( \mu m \).

2.2.2. **Evaluation of Wa\(_{0.8}\).** Evaluation of Wa\(_{0.8}\) for steel DC04 is shown in figure 4. In figures 4(a) and 4(b), the test result of surface topography and primary profile \( Z(x) \) is shown with profile measuring traverse length \( l_i = 50 \) mm, by subtracting a 1st degree polynomial.

In entire sampling distance, form removal by 5th order polynomial regression, the results is shown in figure 4(c). Removing roughness components by Gaussian filtering using \( l_i = 0.8 \) mm, waviness profile \( Z_m(x) \) is shown in figure 4(d).

Next, \( Wa\(_{0.8}\) can be written as:

\[
Wa_{0.8} = \frac{1}{l_m} \int_{l_m}^{l_i} \left| Z_m(x) - Z_m \right| dx
\]

(2)

where \( l_i \) is the traverse length, \( l_m \) is the evaluation length, \( Z_m \) is the mean line of waviness, \( Z_m(x) \) is the waviness profile as a function of the spatial coordinate \( x \). As a result, our test result of surface
waviness $W_{a0.8}$ of DC04 is 0.309 µm.

3. Results and discussion

According to the above test method, after a large amount of tests, the surface waviness curves of different process parameters were drawn respectively according to the test results.

3.1. Cold rolling process effect on surface waviness

3.1.1. Effect of mill reduction rate. The surface waviness $W_{sa1.5}$ and $W_{a0.8}$ varied with the mill reduction rate comparison results are shown in figure 5. The waviness characteristic values of $W_{a0.8}$ is higher than $W_{sa1.5}$. It can be seen that both characteristic values increase with the increase of rolling rate.

![Figure 5. Surface waviness with different rolling mill reduction rates.](image)

As can be seen from figure 5(a), for DC04, when mill reduction rate was 75.768%, $W_{sa1.5}$ was 0.184 µm. When mill reduction rate increased to 76.836%, $W_{sa1.5}$ increased to 0.213 µm. The result is that with the reduction rate of rolling mill increased by 1.41%, the waviness parameter $W_{sa1.5}$ increased by 15.76%. Similarly, when mill reduction rate increased to 75.768%, $W_{a0.8}$ increased to 0.287 µm. When mill reduction rate increased to 76.836%, $W_{a0.8}$ increased to 0.318 µm. The result is that with the reduction rate of rolling mill increased by 1.41%, the waviness parameter $W_{sa1.5}$ increased by 10.80%.

Therefore, with an increase in the rolling mill reduction rate, both waviness parameters $W_{sa1.5}$ and $W_{a0.8}$ also increase. The waviness parameters are positively correlated with rolling mill reduction rate, but rolling mill reduction rate has a greater impact on $W_{sa1.5}$.

For DC06, as can be seen in figure 5(b), that waviness parameters $W_{sa1.5}$ and $W_{a0.8}$ increase with the reduction rate of rolling mill, and have the same change regularity as DC04. When mill reduction rate was 78.162%, $W_{sa1.5}$ was 0.186 µm. When mill reduction rate increased to 79.586%, $W_{sa1.5}$ increased to 0.223 µm. The results indicate that with the reduction rate of rolling mill increased by 1.82%, the waviness parameter $W_{sa1.5}$ increased by 19.89%. At the same time, when mill reduction rate was 78.162%, $W_{a0.8}$ was 0.292 µm. When mill reduction rate increased to 79.586%, $W_{a0.8}$ increased to 0.319 µm. The result is that when the reduction rate of rolling mill was increased by 1.82%, the waviness parameter $W_{a0.8}$ increased by 9.25%.

Obviously, the reason of characteristic values increase with the rolling rate is that the steel sheet deflection increases as well, so that it can be anticipated that the characteristic values increase in the end. Therefore, in order to improve the surface quality of steel plate, on has to reduce mill reduction rate and, thus, reduce the surface waviness.
3.1.2. Effect of working roll cycle. Moreover, in rolling process, working roll period also has a strong effect on surface waviness, as shown in figure 6.

![Figure 6. Surface waviness with different working roll period.](image)

Figures 6(a) and 6(b) show the variations trend of the waviness as a function of the working roll period for DC04 and DC06. It can be seen that the $W_{s1.5}$ and $W_{0.8}$ decrease dramatically with working roll period. The waviness of DC06 and DC04 has the same change rule.

In figure 6(a) for DC04, the working roll period increased from 38.45 to 57.69 km, while waviness $W_{0.8}$ decreased from 0.301 to 0.281 $\mu$m and waviness $W_{s1.5}$ decreased from 0.229 to 0.189 $\mu$m. This analysis implies that, with an increase in the working roll period by 50.03%, the waviness parameters $W_{s1.5}$ and $W_{0.8}$ dropped by 17.47 and 6.64%, respectively. Thus, working roll period has a greater impact on $W_{s1.5}$ than on $W_{0.8}$. In figure 6(b) for DC06, the working roll period ranged from 5.71 to 80 km, while $W_{s1.5}$ dropped from 0.221 $\mu$m to 0.192 $\mu$m, and $W_{0.8}$ dropped from 0.328 $\mu$m to 0.291 $\mu$m. As a result, with an increase in the working roll period from 5.71 to 80 km, $W_{s1.5}$ and $W_{0.8}$ dropped by 11.28 and 13.12%, respectively. The working roll period also had a greater impact on $W_{s1.5}$ for DC06.

In working roll period, the surface topography of steel is copied from the roller texture in certain attenuation. The waviness of steel sheets always has positive correlation with surface roughness for electrical discharge texturing, whereas waviness decreased with working roll period. Therefore, the working roll cycle should be reduced as far as possible to ensure the surface waviness of steel plate.

3.2. Continuous annealing process effect on surface waviness

Next, in continuous annealing process, finish rolling temperature dependent surface waviness of steel DC04 and DC06 have also been investigated in this work.

Surface waviness with different finish rolling temperature is shown in figure 7. It can be seen in figure 7(a) that, in case of DC04, waviness characteristic values of $W_{s1.5}$ and $W_{0.8}$ rise and drop with temperature increases, but exhibit no particular trends. In figure 7(b) for DC06, the same situation is observed. Therefore, the finish rolling temperature has no obvious effect on the waviness.

In the continuous annealing, the vertical annealing furnace is composed of preheating section, heating section, insulation section, slow cooling section, fast cooling section, over-aging section, and final cooling section. The above lack of the finish rolling temperature effect on the waviness is that after continuous annealing and high-temperature treatment, the steel plate is softened. The surface waviness of the steel inherited the previous process, so finish rolling temperature has no obvious influence on the waviness.
3.3. Temper rolling effect on surface waviness

3.3.1. Effect of elongations. Finally, in order to analyze the temper rolling effect on surface waviness, we have taken a large number of test samples of DC04 and DC06. The relationships between elongations and surface waviness in the temper rolling are shown in figure 8.

In figure 8(a) for DC04, $W_{sa_{1.5}}$ increased from 0.193 to 0.197 μm, and $W_{a_{0.8}}$ increased from 0.301 to 0.315 μm with the elongation variation from 71.9 to 72.2% in figure 8(a). When the elongation was increased by 0.42%, the waviness parameters $W_{sa_{1.5}}$ and $W_{a_{0.8}}$ rose by 2.07 and 4.65%, respectively. Thus, elongation has a greater impact on $W_{a_{0.8}}$.

In figure 8(b) for DC06, the waviness has the same change rule for DC04. $W_{sa_{1.5}}$ increased from 0.176 to 0.185 μm, and $W_{a_{0.8}}$ increasing from 0.258 μm to 0.263 μm with elongation ranging from 60.1 to 61.9%. When the elongation was increased by 1.49%, the waviness parameter $W_{sa_{1.5}}$ increased by 5.11% and $W_{a_{0.8}}$ increased by 1.94%. The elongation variation has a greater impact on $W_{sa_{1.5}}$.

3.3.2. Effect of working rolls period. Ultimately, the working roll period was found to influence the surface waviness in temper rolling. The results prove that the waviness characteristic values changed along with different working roll period in temper for DC04, as shown in figure 9.
When the working roll period increased from 11.36 to 96 km, $W_{sa1.5}$ dropped from 0.213 to 0.189 $\mu$m (i.e., reduced by 11.27%), while $W_{a0.8}$ also decreased from 0.32 4 to 0.293 $\mu$m (i.e., reduced by 9.57%). This implies the working roll period has a greater impact on $W_{sa1.5}$ than on $W_{a0.8}$.

The same pattern was observed in the test: the surface waviness parameters $W_{sa1.5}$ and $W_{a0.8}$ with lower working rolls period exceeded their values for a 5%–higher working rolls period. This indicates that the working rolls period has a negative correlation with the surface waviness parameter $W_{sa1.5}$.

4. Conclusions
An experimental procedure for steel sheet surface waviness assessment was developed. Influencing factors of steel sheet surface waviness in cold rolling process were investigated by the coherence scanning interferometry. The main findings can be summarized as follows:

- The waviness characteristic values of $W_{a0.8}$ were higher than those of $W_{sa1.5}$.
- $W_{sa1.5}$ and $W_{a0.8}$ increased with the rolling rate for both DC04 and DC06. For DC04, when the reduction rate of rolling mill increased by 1.41%, the waviness parameter $W_{sa1.5}$ increased by 15.76% and the waviness parameter $W_{sa1.5}$ increased by 10.80%. For DC06, when the reduction rate increased by 1.82%, $W_{sa1.5}$ increased by 19.89% and $W_{a0.8}$ increased by 9.25%. The rolling mill reduction rate variation has a greater impact on $W_{sa1.5}$ for DC04 and DC06.
- In rolling process, the working roll period increase resulted in a drop of waviness parameters $W_{a0.8}$ and $W_{sa1.5}$. For DC04, with the working roll period increased by 50.03%, $W_{sa1.5}$ and $W_{a0.8}$ dropped by 17.47 and 6.64%, respectively. For DC06, with an increase in the working roll period from 5.71 to 80 km, $W_{sa1.5}$ and $W_{a0.8}$ dropped by 11.28 and 13.12%, respectively. The working roll period also has a greater impact on $W_{sa1.5}$ for DC04 and DC06.
- The finish rolling temperature had almost no effect on the waviness.
- Waviness parameters $W_{a0.8}$ and $W_{sa1.5}$ increased with elongation in temper rolling and dropped with working roll period.

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