Analysis of surface roughness of cold-rolled aluminium foil

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Abstract

This paper describes a detailed analysis of the surface finish of aluminium foil which has been cold-rolled under industrial conditions in the mixed lubrication regime. The foil was rolled with freshly ground rolls at a constant speed for the first pass and at a wide range of speeds for the second pass. Samples were collected after the second pass. For comparison, samples were also collected after rolling with worn rolls. Surface replicas of the rolls were taken with surface replicating tape. The surface roughness of the strip samples and roll surface replicas was measured with a three-dimensional non-contact interferometric profilometer. The spectrum of the surface roughness was analysed by the fast Fourier transform method to identify the way in which different wavelengths of roughness behave. Theory suggests that longer wavelengths of roughness should be crushed more easily. This was confirmed by results. A new image analysis technique has been developed to identify and quantify the area of the micro-pits. To differentiate between these pits and grind marks transferred from the rolls, the height information was first filtered in the rolling direction using a digital filter. The low-frequency component of the surface roughness, which represents the contribution from the roll marks, was subtracted off to leave the pits. Results showed a significant decrease in pit area during the pass schedule, while there was a significant increase in pit area with increasing rolling speed during a single pass.

Keywords: Roughness; Surface finish; Surface spectrum; Hydrodynamic pitting; Mixed regime; Lubrication; Metal rolling

1. Introduction

Modelling of the metal rolling process is currently an active theme of research as the high tonnage of metal rolled means that better understanding can have a significant economic impact. Particular interest has arisen in modelling friction and modifications of surface roughness during rolling, both to improve product quality and mill productivity.

Friction and the surface quality of the rolled strip are closely related to the amount of oil drawn into the bite and the surface roughness on the rolls and the in-going strip [1]. The lubrication regime can be characterised by $A_s$, the ratio of the lubricant film thickness $h_w$ to the combined surface roughness on the strip and roll, $\sigma_t = \sqrt{\sigma_s^2 + \sigma_r^2}$. The film thickness $h_w$ can be estimated, using the results of Wilson and Walowit for smooth rolls and strip [2] as,

$$h_w = \frac{6\eta U}{\theta_0(1 - \exp(-aY))}$$

where $U$ is the average entraining velocity, $\theta_0$ the inlet angle between the strip and roll, $Y$ the plain strain yield strength of the strip, $\eta$ the viscosity of the lubricant at ambient pressure and $\alpha$ the oil’s pressure viscosity coefficient. For thick oil films with $A_s$ greater than about 1, surface roughening occurs due to the unconstrained deformation of different grains [3]. The resulting poor surface quality is unacceptable for most products. To achieve an appropriate surface finish, rolling must operate in the mixed lubrication regime, where the oil film thickness is smaller than the surface roughness. In this regime, asperities on the strip are flattened and tend to conform to the bright surface finish of the rolls [4–7]. Measurements of friction coefficients in mixed regime on an experimental mill by Tabary et al [8] show that the friction coefficient is also correlated with $A_s$.

Details of the surface roughness topography may influence the behaviour of the strip both during rolling and in subsequent use. Moreover, they often give clues as to the tribological behaviour in the bite. The effect of wavelength of roughness has been explored using measurements of the surface spectrum on strip rolled in the mixed lubrication regime on an experimental mill [9]. It is shown that short wavelength components persist more than the long wavelength components. This is confirmed by a new model of surface...
The purpose of this paper is to look at the details of the surface of aluminium foil rolled under industrial conditions, to confirm the results of the laboratory-scale tests and to provide benchmarks for the theoretical models currently being developed. The spectral analysis of surface roughness described in Ref. [16] is applied to the measured surface data. Section 2 of this paper describes the details of the strip samples and measurements of surface roughness. Observations of the surface feature are described in Section 3. The methodology of spectral and hydrodynamic pit analysis is described in Section 4. Section 5 presents the results, and conclusions are given in Section 6.

2. Experimental procedure

2.1. Collection of samples

A coil of 1200 aluminium alloy of initial strip of thickness 0.4 mm was rolled under industrial conditions at a constant speed for the first pass and at a wide range of speeds for the second pass using freshly ground rolls. The reduction in strip thickness during both passes was ≈50%. Lubricant was applied abundantly on both sides of the strip. Samples of the initial strip were collected from the end of the coil. After the first pass, a sample was taken from a region where the coil was being rolled at speed. Changes in speed during the second pass were marked on the side of the coil. These were used to identify the rolling speed of samples that were collected from the middle of the coil, which was scrapped after this pass. Samples rolled with worn rolls under similar conditions were collected for comparison. Replicas of the roll surface were taken before the second pass using Press-O-Film surface-replicating tape supplied by Testex.

2.2. Measurements of surface roughness

Surface roughness was measured in a Zygo non-contacting three-dimensional interferometric profilometer. The equipment has a lateral resolution of 0.5 μm and vertical resolution of 0.1 nm.

2.2.1. Preparation of samples

It is very important to use flat samples, a problem that is especially relevant for thin foil and the replica tape. To ensure this, the samples are carefully cut, trimmed and stuck onto a glass slide. The surfaces of the strip samples were cleaned with acetone to remove residual lubricant before measurements were taken.

2.2.2. Measurements

A 20× objective lens was used to ensure that the field of view and depth of field are sufficient to take in the relevant surface features. For surface roughness measurements, a magnification of 200 is used. Normally, 10 areas are measured and averaged to give the average r.m.s roughness.
Table 1
Details of the measurements

<table>
<thead>
<tr>
<th>Magnification</th>
<th>Field of view (mm)</th>
<th>Depth of view (µm)</th>
<th>Sampling distance (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.71 × 0.53</td>
<td>3.5</td>
<td>2.2</td>
</tr>
<tr>
<td>400</td>
<td>0.35 × 0.26</td>
<td>3.5</td>
<td>1.1</td>
</tr>
<tr>
<td>800</td>
<td>0.17 × 0.13</td>
<td>3.5</td>
<td>0.55</td>
</tr>
</tbody>
</table>

and standard error. For spectrum and hydrodynamic pit analyses, a magnification of 400 or 800 is used. Details of the measurements are listed in Table 1.

3. Observations of surface features

In order to analyse the surfaces, the surface heights on a two-dimensional grid are exported from the profilometer to a computer for analysis in Matlab. The columns of the height matrix $H$ correspond to changes in surface height in the rolling direction and the rows correspond to the transverse direction. Surface maps of the initial strip are shown in Fig. 1. The surface height is shown on the grey scale at the side of the figure. On both the top and bottom surfaces, the surface topography is dominated by roll marks running in the rolling direction, but there are also a number of isolated micro-pits. Clearly the roll marks are transferred directly from the roll topography. However, the origin of these pits is unclear. Suggestions that they may arise from unconstrained deformation, in the regions where there is an oil film between the surfaces [3], seem to be confirmed by the way that the pits in Fig. 1a are strung along in rows running in the rolling direction. Once created, these pits may persist for several passes before they can be eliminated (c.f. Ref. [14]). It is interesting to note that the bottom surface is much rougher than the top surface, with more closely spaced and much higher ridges but fewer pits. These differences presumably arise from differences in roll roughness and lubrication conditions between the top and bottom surfaces in the previous passes. The roll marks seem to be widely spaced on the initial strip with a wavelength of about 100 µm. The surface maps of the first and second passes are shown in Fig. 2. It appears that, during these subsequent passes, the wavelength of roll marks becomes less uniform and that micro-pits on the surface are smaller than those on the initial strip.

4. Surface analysis

In this section, the change in surface topography during rolling, which can clearly be observed from the surface...
maps, Figs. 1 and 2, will be quantified, both to help characterise these surface changes and to provide a more objective definition of the changes in surface topography. In Section 4.1, a spectral analysis of the surfaces is described, while Section 4.2 outlines a method for identifying micro-pits.

4.1. Spectrum analysis

For a given one-dimensional discrete data array of the surface heights, \(h_i, (i=1, \ldots , n)\), the single-sided power spectral density \(S(1/\lambda)\) can be found using a fast Fourier transformation (FFT) [17,18] with a Hanning window [19].

\[
S\left(\frac{1}{\lambda_j}\right) = \frac{2 F_j \bar{F}_j}{n \bar{w} f}, \quad j = 0, \ldots , \frac{n}{2} - 1
\]  

where \(F_j\) is a FFT coefficient of the data array, \(\bar{F}_j\) the conjugate of \(F_j\), \(\bar{w}\) the mean square of the window factor, \(\bar{w} = (\sum w_j^2)/n\), and \(f\) the sampling frequency, \(f=1/\Delta\). The corresponding frequency is \(1/\lambda_j=jf\Delta\), \((j=0, \ldots , n/2-1)\).

Now, \(S(1/\lambda_j)\) represents the contribution to the variance of heights of the component with wavelength \(\lambda_j\). Therefore, the contribution between wavelengths \(\lambda_1\) and \(\lambda_2\) is given by

\[
s^2(\lambda_1, \lambda_2) = \int_{1/\lambda_2}^{1/\lambda_1} S\left(\frac{1}{\lambda}\right) d\left(\frac{1}{\lambda}\right)
\]

Taking a fixed upper cut-off at the value of 200 \(\mu m\) to eliminate waviness in the strip, \(\sigma^2(\lambda) = s^2(\lambda, 200 \mu m)\) represents a cumulative roughness variance including all wavelengths \(>\lambda\), but less than the upper cut-off.

For each row of data, the one-dimensional FFT is used to find the spectrum of the surface roughness across the rolling direction. Spectra for all the rows in the measured area are averaged to give an average spectral density across the rolling direction and the corresponding cumulative variance \(\sigma^2\).

4.2. Identification of roll marks and micro-pits

Although the surface roughness is mainly characterised by longitudinal roll marks, micro-pits become more prevalent at high rolling speeds. To identify these features, a zero-phase forward and reverse digital filter (\texttt{filtfilt} in Matlab [19]) is applied to each column of the height matrix \(H\), using a 4th-order low-pass Butterworth filter, with a cut-off wavelength of \(\lambda_r\), typically of 25–50 \(\mu m\). The filtered height signal \(\tilde{H}\), containing wavelengths longer than \(\lambda_r\), is taken as corresponding to the roll marks. This is illustrated in Fig. 3a which shows the roll marks corresponding to the surface map of Fig. 1a. The roll marks are then subtracted from the height array \(H\) to essentially leave the micro-pits. To discriminate between the pits and any ‘noise’ in the signal, only regions which are deeper than a critical value \(\delta\) are identified as pits. Typically, \(0.1<\delta<0.25 \mu m\). The pits corresponding to the surface map of Fig. 1a are identified using different \(\delta\) and shown in Fig. 3b and c, respectively. It is noted that some small areas in Fig. 3b are probably due to noise in the height signal rather than being hydrodynamic pits. Therefore, it is more appropriate to identify the pits with \(\delta=0.25 \mu m\). The fraction of pitting area is quantified by dividing the total pixel area of the measurement by the pixel area of the pits.

5. Results

5.1. Roughness amplitude

The r.m.s. surface roughness of the initial strip and foil samples taken after the first and second passes is shown in Fig. 4a. The roll roughness \(\sigma_r\) is indicated by an arrow on the graph. Each point represents an average of 10 measurements. Error bars indicate the standard deviation of measurements within this sample. Results show that the roughness on the
bottom surface of the initial strip is significantly greater than on the top surface, as observed in Fig. 1. Nevertheless, both sides of the surface have nearly conformed to the roll surface after the first pass, so that the difference between the two sides is then negligible. In the second pass, the surface roughness is further reduced slightly. The high degree to which the strip conforms to the roll surface reflects the small value of lubrication parameter $\lambda_s$, which is about 0.04 for the first pass and varies between 0.015 and 0.08 for the second pass.

Fig. 4b shows the effect of $\lambda_s$, which is proportional to rolling speed, on the r.m.s surface roughness after the second pass. Since the surface roughness on both the incoming and outgoing strip is close to that of the rolls, any effect of $\lambda_s$ on surface roughness is overshadowed by scatter in the measurements. Nevertheless, there appears to be a slight increase in the surface roughness at very small $\lambda_s$, which may be associated with a breakdown of lubrication.

**5.2. Surface spectrum**

Fig. 5 shows the change in the surface spectrum during the pass schedule. The contribution of long wavelength components to the surface roughness falls through the pass schedule as these components are crushed. The increase in the high-frequency components (30–100 mm$^{-1}$) in the first pass arises as the strip conforms to the fresh rolls used for this pass, which contain large high-frequency components. Presumably worn rolls were used to produce the initial strip surface, giving only a small high-frequency component to the ingoing strip. Although the surface roughness amplitude of the strip after the first pass approaches that of the roll surface, there is an increase in the relative composition of short wavelength components during the second pass, as the long wavelengths are crushed more readily. This is in line with the results of laboratory experiments [9] and predictions from theory [10]. Fig. 5b shows that, for the second pass, there is no significant effect of rolling speed on the surface spectra. By this pass the actual changes in roughness are slight, and any effect due to differences in hydrodynamic oil entrainment at these small values of $\lambda_s$ is too small to be detectable.

Fig. 6 illustrates the change in surface spectrum from fresh to worn rolls. Fig. 6a plots the spectral density and
Fig. 6. The effect of roll roughness on strip surface spectrum: (a) spectral density; and (b) cumulative surface variance, normalised by the strip roughness variance.

Fig. 6b plots the cumulative variance, normalised by the r.m.s. roughness of each roll replica. Fig. 6a shows that short wavelength components are most rapidly reduced in amplitude as the roll wears. The way in which the roll surface imprints on the strip surface can be seen from the change in shape of the curves, Fig. 6b. The relative contribution from wavelengths $<5 \mu m$ (1/λ>200 mm$^{-1}$), given by the difference between one and the cumulative variance at this frequency, is significantly greater for the strip rolled with a fresh roll than for the strip with the worn rolls. This reflects the reduction in short wavelength components on the roll surface as the rolls wear.

5.3. Variation of hydrodynamic pits

Fig. 7 shows the results of the pitting analysis for the first pass at a single speed and for the second pass at two rolling speeds. The dark regions on the maps shown in Fig. 7 identify the pits. The corresponding map of pits for the initial strip is given in Fig. 3c. The fraction of the total area taken up by pits is quantified and plotted against pass number in Fig. 8a and against $A_s$ in Fig. 8b, for two values of pit depth tolerance $\delta$. Each point represents an average over an area of 0.35×0.25 mm$^2$. The estimated area of pitting is larger for the smaller value of $\delta$. Also including shallower pits using the smaller $\delta$, some points are spuriously identified as pits. The curve for $\delta=0.25 \mu m$ is, probably, to be preferred, unless the smaller pits are expected to play a significant role in subsequent operations. A value of $\delta$ equal to 0.25 $\mu$m corresponds to about 60% of the $R_q$ roughness of the rolls. Ahmed and Sutcliffe [14] come to similar conclusions about the appropriate choice of pit tolerance parameter using their
The earlier analysis of Le and Sutcliffe [15] gave quantitatively similar results for the pitting analysis as those presented here for \( \delta = 0.25 \mu m \). Their method, which uses a linear least-squares fit to data in the rolling direction to eliminate the roll marks, falls half-way between the approach described in this paper and the ad-hoc and more complicated approach described by Ahmed and Sutcliffe [14] for considering local differences in surface height to identify pits. For the aluminium foil surfaces seen in practice, the filtering method described in this paper is effective in eliminating the roll marks and is to be preferred to the earlier approaches as being both simpler and more accurate. Conversely, it is likely that the method described here may be less successful for the more broken surfaces that Ahmed and Sutcliffe find on stainless steel sheet.

6. Conclusions

1. Surface roughness measurements on aluminium foil rolled under industrial conditions show that the surface of the strip nearly conforms to the roll surface after the first pass. Subsequent passes slightly reduce the surface roughness on the strip.
2. Spectral analysis confirms the results of laboratory-scale trials, that long wavelength components on the strip surface are flattened more rapidly than short wavelength components.
3. A program has been developed which successfully identifies the micro-pits on the strip surface. Results show that both the area and size of deep pits are reduced during rolling. Deep pits are eliminated more effectively during the second pass at smaller values of speed parameter \( \Lambda_s \).

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References


