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Quantification of roping intensity on aluminium sheets by Areal Power Spectral Density analysis

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ABSTRACT

To quantify the roping level on strained AA6xxx sheets, a new automatic procedure is introduced and applied. The method calculates the Areal Power Spectral Density (APSD) from digitized surface images and determines the separate contributions of isotropic and unidirectional components using their spatial dimensions. To deal with mixed roughness morphologies, the overall roping grade is given by the ratio of these two individual contributions.

An analysis of the surface appearance of 16 different samples of AA6016 shows that the roping grade is in good agreement with the three groups of roping level (Low, Intermediate and High) determined previously by visual judgment. The procedure appears robust and versatile if some data constraints are respected.

1. Introduction

For autobody applications, aluminium sheets made from 6xxx series alloys are a solution of choice due to their low weight, good formability, corrosion resistance and strengthening potential during paint-baking. However, in particular cases, strain-induced roughness can lead to roping, a well-known macroscopic surface roughening defect [1–8]. Roping is characterized by visible lines (several centimeters) along the rolling direction (RD) and appears when the material is stretched along the transverse direction (TD). This surface distribution of ridges and valleys can limit their use as outer panels in vehicle applications for cosmetic reasons.

In current industrial practice, the roping level is given by a manufacturer's visual assessment after sheet forming and painting. This evaluation is binary (surface quality accepted or not) and quite subjective because it depends on a global human appreciation. However, this visual roping evaluation is still considered the benchmark for setting up any other ranking methods.

In the past, numerous parameters have been proposed for the quantification of roughness heights and spatial distributions, e.g. R_a (Arithmetic Average Roughness) or R_q (Root-Mean-Square Roughness) [9,10]. However, Baczynski et al. [5] found no correlation between the visual roping level and some of these surface roughness parameters. Moreover, Stoudt and Hubbard [11] have observed two very different rough surfaces that give the same R_q magnitude. This problem may be a consequence of parameters based on a single linear profile instead of a large area of surface roughness. It appears that these parameters give too much weight to the amplitudes of height and do not take sufficiently into account the 3D morphologies.

For these reasons, some authors have tried to set up customized methods to evaluate the roping phenomena. In particular, Wu et al. [2] have proposed to characterize roping tendency by a surface profile plotted against TD but defined by a normalized average variation along RD. Our own R_a calculations on these modified profiles still fail to adequately predict the roping level. Choi et al. [12] have introduced a

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modified roughness parameter $N\%\text{-}R_{pv}$ for the deformation-induced surface roughness morphology of Al sheets. This is defined as the difference between the average heights of the upper $N\%$ of peaks and the lower $N\%$ of valleys. The authors showed a relation between the magnitude of N and the contribution of the high wavelength roughness components. But in our experience, this quantity often suffers from a lack of generalization because it seems to depend too much on data dimensions and step size.

Frequency methods appear to be very powerful for morphological analysis of roughness features. Thus, the Areal Auto Correlation Function (AACF) has been used by several authors [6,13–15] to highlight periodical phenomena embedded in an input signal, such as the alignments of surface roughness or crystallographic orientations. Another possibility is the Areal Power Spectral Density (APSD) which quantitatively describes how the power of a 2D signal is distributed with its frequencies. After some preliminary tests with both the AACF and APSD methods, it turns out that the latter has much potential for roping characterization. The APSD method has recently been applied to the characterization of machined surfaces, e.g. [16], but to our knowledge, there is no published work on its application to roping. This paper briefly describes the method and its constraints and then applies it to the comparison of roping in a wide range of alloy sheets.

2. Experimental Method

2.1. Materials and Roping Intensity

In this study, 16 AA6016-T4 sheets were produced to a thickness of 1 mm by different processing routes. It is recalled that the standard AA6016 alloy has a composition of (0.3–0.6 wt.%) Mg and (1.0–1.5 wt.%) Si. The sheets were cut to 50 (RD) × 200(TD) mm² samples and stretched 15% along TD. They exhibit a wide variety of strain-induced surface roughness morphologies. Roping levels were then evaluated by visual inspection, and materials were classified into three groups depending on roping intensity: Low, Intermediate and High.

2.2. Surface Roughness Acquisition

Two different techniques were used to record experimental strain-induced surface roughness.

Laser Scanning Confocal Microscopy (LSCM) gives a non-contact 3D image of the sample surfaces with a high spatial resolution. Using a NanoFocus μSurf CF4 device, 15 × 15 mm² area images were acquired by scanning with a 30 μm step size. However, a post-processing operation was needed to deal with sample surface distortion. Sample flatness was corrected by removing a polynomial approximation (5th order) from the initial surface.

On the same samples, roughness features were highlighted by the "stoning" technique which artificially increases the contrast between valleys (dark) and peaks (bright). This consists of manually grinding the ink-blackened surface of the stretched samples (a single pass along TD with a grade P800 abrasive paper). The surface appearance is then digitalized to grayscale (value range of [0; 255]) by a scanner to a 240dpi (9.4pixels/mm) spatial resolution. In order to avoid edge effects, the images are finally cropped to obtain surfaces of 42.4(RD) × 84.8(TD) mm² that are then characterized (dimensions of all the images shown here).

3. Principles of the Numerical Procedure

3.1. Definition of the Areal Power Spectral Density

The analysed data for grayscale intensity x_{ij} are transformed into Fourier space X_{ij} by the use of a discrete fast Fourier transformation. But, in order to avoid artifacts created by the transformation, the data x_{ij} are previously modified to x'_{ij} by shifting their average value to zero and by applying a Hann window H_{ij} described in Eqs. (1–3) where ⊗ represents the dyadic product, N the size of the data, and with M set to the value of 16.

$$H_i = \begin{cases} \frac{1}{2}\left[1-\cos\frac{M4\pi i}{N}\right] & \text{if} \quad 0 < i < \frac{N}{M} \\ 1 & \text{if} \quad \frac{N}{M} < i < \frac{N(M-1)}{M} \\ \frac{1}{2}\left[1-\cos\frac{M4\pi i}{N}\right] & \text{if} \quad \frac{N(M-1)}{M} < i < N-1 \end{cases} \tag{1}$$

$$H_{ij} = H_i.H_j \tag{2}$$

$$x'_{ij} = x_{ij} \otimes H_{ij} \tag{3}$$

The two-dimensional Areal Power Spectral Density (APSD) is then calculated from Eq. (4) where X^*_{ij} is the complex conjugate of X_{ij}, and X_{size} and Y_{size} are the TD and RD data dimensions. The denominator of the expression normalizes the APSD function and makes it independent of data dynamics or sizes.

$$APSD_{ij} = \frac{X_{ij} \otimes X^*_{ij}}{X_{size} Y_{size} \sum_{ij} X^2_{ij}} \tag{4}$$

The APSD function has the same dimensions as the initial data, and can be plotted in 2D as a function of spatial frequencies.

3.2. Application of APSD to Strain-induced Surface Roughness Features

Fig. 1 depicts the APSD function for two idealized structures, one of which is purely linear and the other is globular or

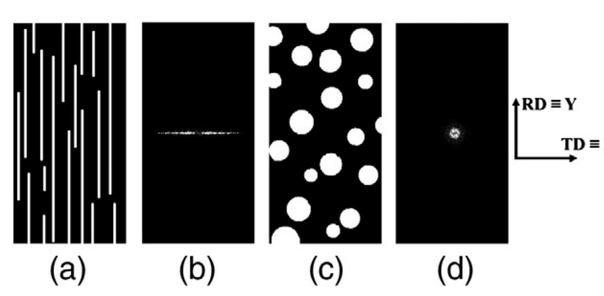

Fig. 1 – (a,c) Idealized roughness features and (b,d) corresponding APSD functions (arbitrary values).