Detection and classification of orange peel on polished steel surfaces by interferometric microscopy

M L Miranda-Medina, P Somkuti and B Steiger
AC²T Research GmbH
Viktor Kaplan Strasse 2, Wiener Neustadt 2700, Austria
E-mail: medina@ac2t.at

Abstract. In this work, we provide a general description of the so-called orange peel defect produced on polished steel surfaces. By characterizing a prototype set of samples with various degrees of orange peel, we attempt to create a simple model that allows the classification of additional samples through the study of surface parameters. On those surfaces, the orange peel structure has roughness amplitudes in the nanometer range. Detecting surface features on that range requires the implementation of a high-precision technique, such as phase shifting interferometry (PSI). Therefore, we can contribute to the improvement of the manufacturing of polished steel surfaces as well as to the quality control by using optical techniques.

1. Introduction

Recently, the manufacturing steel industry has increased the use of optical techniques in their respective quality monitoring schemes. Such optical systems are favourable due to the high speed in detection as well as the non-destructive measuring principle. In particular, highly polished metallic surfaces are easily damaged through contact with even very low load.

However, during polishing processes, different physical and chemical parameters are involved, and some of them can lead to specific artefacts on the surface. Unlike the orange peel texture in paints, which is usually produced on purpose, we focus on orange peel on metal that is an undesirable roughening on the surface. Consequently, the reflection of the light is not homogeneous on the surface, affecting the functionality of polished surfaces for particular applications such as the production of mirrors, where specular reflection is a quality criterion.

Commercial devices are currently available for the evaluation of orange peel in paint, plastic or even mirror-like metals [1], however the most of these devices measure orange peel structures with amplitudes in the micron range. Nevertheless, under specific conditions most chemical-mechanical polishing techniques produce an orange peel texture with amplitudes in the nanometer range.

Despite this, such types of orange peel are still detected by visual inspection performed by experts in the field. Thanks to the fact that the human eye is sensitive enough to perceive visual effects such orange peel, the appearance of polished surfaces is evaluated and classified according to levels of quality. Due to the subjective nature of this method, the support of additional techniques is needed for the standardization of the quality control process, independently of sample position, evaluator or lighting conditions. Hence, we propose the topography characterization of polished samples by means of interferometrical measurements.

Interferometry is a well-known technique that associates shapes of produced fringes (circular, elliptical, straight, irregular) to the shape of surface. Phase shifting interferometry (PSI) allows the
measurement of the surface topography at high accuracy and is thus the method of choice to obtain
topographies of polished steel surfaces. State of the art 3D interferometrical microscopes include a PSI
mode, where sequence of images is obtained and processed by computational methods to extract
information of the sample surface. Measurements done by PSI have a vertical resolution of less than 1
nm independent of the field size. The common feature of PSI instruments is that, unlike differential or
phase contrast methods, surface heights are directly proportional to interference phase [2].

2. Detection and evaluation of orange peel
In collaboration with steel industry¹, we performed the evaluation of two sets of polished steel
samples. The first set, composed of six samples, has been classified by visual inspection as prototypes
degrees of orange peel, and the second set, which contains ten samples, are unclassified specimens.
In the set of prototypes, three degrees of orange peel are identified with the classifiers “strong”,
“intermediate” and “weak”. In section 2.1 we provide detailed information about the methodology as
well as the relevant results for each set. Afterwards, in section 2.2 we develop a simple model to
classify the second set of samples according to their surface parameters.

2.1. Experimental details and results
A total of 16 samples were provided to us with the initial information summarized in table 1. The
samples are made of stainless steel and have a lateral size of 10 cm x 10 cm.

| Degree of orange peel (visual) | Set 1                  | Set 2                  |
|-------------------------------|------------------------|------------------------|
| Weak                          | W1, W2                 |                         |
| Intermediate                  | I1, I2                 |                         |
| Strong                        | S1, S2                 |                         |
| Unclassified                  |                         | Ui¹                    |

¹For these samples i = 1, 2….10

The topographies of the samples have been determined by means of a commercial 3D
interferometric microscope in the PSI operational mode, where the focused sample is scanned
vertically in steps that are very accurate fractions of the wavelength. The profiling algorithms produce
a phase map of the surface, which is converted to the corresponding height map via an unwrapping
procedure [3]. The magnification of the selected Mirau objective is 10x, measuring a field of view
(FOV) of 1270 µm × 950 µm, and uses a blue LED of 460 nm wavelength as light source. In order to
increase the size of the evaluated area, we stitched 12 × 12 single images with 10 % of overlap by
using a proper software [4] to achieve a total area of 11.8 mm × 8.7 mm. Afterwards, the full
evaluated area of each sample was levelled via subtraction of a least-squares plane and subsequently
the main shape was removed by subtracting a least-square second order polynomial. In figure 1, as an
example of orange peel degrees, the topographies corresponding to samples W1, I1 and S1 are shown
respectively.

¹ Berndorf Band GmbH, Leobersdorfer Strasse 26, A-2560 Berndorf, Austria.
Figure 1. Three different degrees of orange peel: W1 (weak), I1 (intermediate) and S1 (strong).

In figure 1, the sample referred to as W1 exhibits the lowest grade of orange peel on the surface. On this area, the orange peel texture is manifested without any predominant orientation. In contrast, the samples I1 and S1 are perceived by the microscope as a pebble pattern with a specific orientation, which is created during the treatment of the base material. In addition, a peculiar characteristic that distinguishes degrees of orange peel is the amplitude of the surface (see color bar in figure 1) measured from a reference plane. For samples W1 it is in the range between 0 nm to 10 nm, while for S1 it can be between 20 nm to 50 nm. Therefore, in order to provide a quantitative description of orange peel topography, surface parameters are calculated from the measured data. These evaluate diverse characteristics of the surface, such as amplitude of peaks and valleys, spatial distribution of structures, texture orientation, slopes of on a surface, etc. Surface parameters are calculated according to ISO 25718 [5] and a full description of these can be found in reference [6]. To characterize the degrees of orange peel for the prototype samples, we have selected 20 surface parameters from the categories: areal height parameters ($Sq$, $Sa$, $Ssk$, $Sku$), areal spacing parameters ($Sal$, $Str$), areal hybrid parameters ($Sdq$, $Sdr$), functional parameters ($Sk$, $Svk$, $Spk$, $Vm$, $Vv$, $Vmp$, $Vmc$, $Vvc$, $Vvv$) and feature parameters ($S5p$, $S5v$, $S10z$). In figure 2, the corresponding normalized surface parameters of the two sets of samples are shown.

Figure 2. Surface parameters of samples with specific (Set 1) and unclassified (Set 2) degrees of orange peel.
For the calculation of feature parameters (Sk, Svk, Spk), a Gaussian filter with a cut-off wavelength of 1.5 mm was used, and the rest of the parameters were calculated with the standard variables defined in reference [6]. Additionally, in figure 2, degrees of orange peel in the samples of set 1 are well distinguished for most of the surface parameters, and this distinction agrees with the visual inspection criterion. On the other hand, parameters such as Sal, Ssk, Sku and Str cannot classify degrees of orange peel, since those parameters give us information regarding periodicity, skewness, kurtosis and orientation of the samples respectively. For example, the sample S1 exhibits the lowest Str parameter, which indicates that the texture of this sample is highly orientated as is confirmed from figure 1. Moreover, the sample U7 is the only one that can be distinguished from the rest of the samples according to the chosen surface parameters (figure 2, set 2), however we can not a priori assume that this sample has strong degree of orange peel, since the normalization of the parameters was done independently.

2.2. Classification of samples by feature recognition

Surface parameters corresponding to Set 1 have been adopted as an arrangement of descriptors represented by a prototype vector for each class or degree of orange peel. For example, weak degree of orange peel is denoted by \( \mathbf{w} = (w_{Sp}, w_{Sa}, w_{Sdp}, w_{Spd}, w_{Fv}, w_{Fvs}, w_{Fnc}, w_{Fve}, w_{Vmc}, w_{Vmc}, w_{Vmc}, w_{Vmc}) \) and similar notation has been assigned for intermediate \( \mathbf{i} \) and strong \( \mathbf{s} \) orange peel. Therefore, an unclassified sample is assigned to the class to which the surface parameters of the corresponding vector is closest to a prototype vector. So, as a first step, we calculate the mean vector of the two samples assigned to each degree of orange peel, which is given by

\[
\bar{m}_z = \frac{1}{2} \sum_{j=1}^{2} \bar{z}_j, \quad z = w, i, s \text{ and } j=1, 2. \tag{1}
\]

Afterwards, we calculate the Euclidian distance between an unknown vector sample \( \mathbf{x} \) and the mean vector \( \bar{m}_z \) to each class of orange peel. From reference [7], we know that the smallest distance between an unclassified sample and a prototype sample is equivalent to calculate a decision function given by

\[
d_z(\mathbf{x}) = \mathbf{x}^T \bar{m}_z - \frac{1}{2} \bar{m}_z^T \bar{m}_z. \tag{2}
\]

In order to define the class membership of sample \( \mathbf{x} \), one of the following conditions has to be satisfied:

1) \( \mathbf{x} \in \) weak orange peel class if: \( d_u(\mathbf{x}) > d_i(\mathbf{x}) \) and \( d_u(\mathbf{x}) > d_s(\mathbf{x}) \),
2) \( \mathbf{x} \in \) intermediate orange peel class if: \( d_i(\mathbf{x}) > d_u(\mathbf{x}) \) and \( d_i(\mathbf{x}) > d_s(\mathbf{x}) \),
3) \( \mathbf{x} \in \) strong orange peel class if: \( d_s(\mathbf{x}) > d_i(\mathbf{x}) \) and \( d_s(\mathbf{x}) > d_u(\mathbf{x}) \).

The boundary function between 2 degrees of orange peel, for example strong and intermediate, can be determined by calculating

\[
d_{st}(\mathbf{x}) = d_s(\mathbf{x}) - d_i(\mathbf{x}) = 0. \tag{3}
\]

Therefore, if the vector \( \mathbf{x} \) is composed of either two or three elements, we can represent this boundary as a line and plane respectively, but if it has more than three elements the boundary is given by a hyperplane.
By using this method we classify the samples $U_i$ according to the degree of orange peel estimated from surface parameters (see table 2).

| Degree of orange peel (visual) | Set 1 (prototypes) | Set 2 |
|--------------------------------|-------------------|-------|
| Weak                           | W1, W2            | U3, U8|
| Intermediate                   | I1, I2            | U1, U2, U4, U5, U6, U9, U10 |
| Strong                         | S1, S2            | U7    |

In addition, as a representative way to depict the boundaries between degrees of orange peel, we selected the parameters $S5p$ and $Spk$ to illustrate it in figure 3.

3. Conclusions
Based on the findings, we can conclude that phase shifting interferometry is an appropriate technique to characterize the orange peel topography of polished metallic surfaces in agreement with the visual classification. In addition, by using a method of recognition of features, as well as the surface parameters calculated from PSI measurements, it is possible to classify samples into the corresponding category of orange peel. Therefore, the implementation of this method in the quality control inspection of polished surfaces can improve and contribute to the standardization of these processes.

4. Acknowledgements
This work was funded by the Austrian COMET Programme (Project K2 XTribology, no. 824187) and carried out at the “Excellence Centre of Tribology”. In addition, we thank Berndorf Band GmbH for providing the polished samples.
5. References

[1] Byk additives and instruments, April 30 (2013) www.byk.com/en/instruments
[2] De Groot P 2011 Optical Measurement of Surface Topography, ed Leach R (Berlin, Verlag and Heidelberg: Springer) pp 167-185
[3] Leica DCM 3D, “3D Optical Surface Metrology System”, January 15 (2011). www.leica-microsystems.com/products
[4] MountainsMap Premium, Digital Surf, France, January 20 http://digitalsurf.com (2011).
[5] ISO 13565-2:1996 Geometrical Product Specification Surface texture Part 2: Height characterization using linear material ration curve.
[6] Leach R 2010 Fundamental Principles of Engineering Nanometrology. (UK: Elsevier) 211-258.
[7] Gonzalez R.C 2001 Digital Imaging Processing. (New Jersey: Prentice Hall) 693-701.