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## IDENTIFICATION OF LOCAL LUBRICATION REGIMES ON TEXTURED SURFACES BY 3D ROUGHNESS CURVATURE RADIUS

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### ABSTRACT

This paper proposes a new method of 3D roughness peaks curvature radius calculation and its application to tribological contact analysis as a characteristic signature of tribological contact. This method is introduced through the classical approach of calculation of radius of asperity in 2D. Actually, the proposed approach provides a generalization of Nowicki's method [1], depending on horizontal lines intercepting the studied profile. Here, the basic idea consists in intercepting the rough surface by a horizontal plane and to calculate the cross section area without including “islands into islands”, *i.e.* the small peaks enclosed in bigger ones. Then, taking into account the maximal value of the height amplitude of the roughness included into this area, an appropriate algorithm is proposed, without requiring the classical hypothesis of derivability, which may be unstable when applied to engineering surfaces. This methodology is validated on simulated surfaces, and applied to engineering surfaces created experimentally, with a laboratory aluminium strip drawing process. The regions of the textured and lubricated specimens surface are analysed, and the results gives interesting prospects to qualitatively identify the local lubrication regimes: regions with high curvature radii correspond to severe contact (boundary/mixed lubrication regime) while regions with low curvature radii correspond to hydrodynamic lubrication regime.

*Keywords: Roughness, Drawing, Lubrication, Texturation.*

### 1. INTRODUCTION

The texturation of surfaces in metal forming processes has recently attracted considerable attention due to enhanced lubrication, resulting in lower friction and wear. Also, better control of the tool/workpiece interface can be achieved and the resulting surface finish can be controlled by adapting hydrodynamic and/or mixed lubrication regimes. The lubricant trapped in a texturation pocket can act as a fluid reservoir during the deformation process, intensifying the so called “Plasto Hydrodynamic Lubrication” (PHL) introduced by Mizuno and Okamoto [2]. Azushima et al. [3] investigated plane strip drawing with lubricant pockets,

created by indentation and showed the phenomenon of fluid escape. Bech et al. [4] characterised the lubricant escape mode and direction as a function of process parameters such as the lubricant viscosity, the drawing speed, the thickness reduction ratio or the back tension. Based on the experiments carried out by Dubar et al. [5], and using the methodology developed by Bigerelle et al. [6], Hubert et al. [7] defined different zones of lubrication regimes inside on regularly textured surfaces. They also introduced the concept of roughness signature in tribological contact by estimation of peaks radii on 2D profiles.

The methodology developed by Bigerelle et al. [6] to estimate the peaks (and valleys) curvature radii was particularly reliable since it was based on the hypothesis of plane strain drawing, leading to analyse a 3D surface as a sequence of multiple 2D profiles. But in the case of a purely 3D lubrication phenomenon, such as specimens used by Bech et al. [4], where lubricant pockets were pyramidal indentations, this method cannot be applied.

In this paper, the method of peaks curvature radius estimation on textured surfaces is extended to 3D, where, for instance, the peaks orientation and radius distribution can be considered.

## 2. DEFINITION AND CALCULATION OF 3D PEAKS CURVATURE

In this study, the definition of the radius of 3D peaks  $r_a$  is based on the method proposed by Nowicki [1] and its extension presented in the Bigerelle et al. [6] work. It reads:

$$r_c = \frac{l_z}{2} + \frac{l_{eq}^2}{8l_z}, \quad (1)$$

where  $l_{eq}$  is the equivalent diameter of a peak calculated as the diameter of the circle with the same area  $S$  as the ellipsoidal region, defined by its minor ( $r_{mi}$ ) and major ( $r_{ma}$ ) radii, resulting in the interception of a given peak by a plane  $M$ .  $l_{eq}$  is thus calculated as

$$l_{eq} = \sqrt{4A/\pi}. \quad (2)$$

Finally,  $l_z$  corresponds the distance between the centre  $O$  of the equivalent circle and a crest  $A$  of the profile, included in the region of the equivalent circle. These parameters are detailed in Figure 1.

The numerical algorithm to detect peaks curvature consists of the following steps:

- the vertical height of a given 3D surface is divided into an arbitrary number of levels (255 in this study, which has been found sufficient to obtain an acceptable number of peaks radii);
- the surface is cut at each level by a plane  $M$  (Figure 1), and only the top remaining part is considered;
- the peaks will be detected only if an enclosed region is found, and their radii will be calculated according to Equation 1.

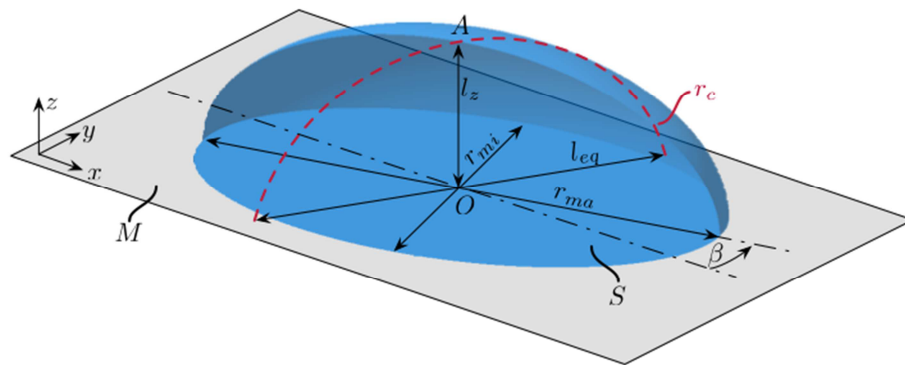


Figure 1: Schematic diagram of 3D roughness peak represented by an ellipsoidal cap.

The numerical algorithm was written in MATLAB®, and the function used to detect the enclosed regions was 'regionprops'.

To validate the developed algorithm, several surfaces have been created numerically with peaks simulated by spherical and sinusoidal caps with known radius. In the example below, illustrated in Figure 2, the surface has  $3 \times 3$  peaks, their radius is  $r_c = 80\text{pt}$  and the surface size is  $512\text{pt} \times 512\text{pt}$ .

After application of the algorithm described above, the detected peaks radii can be plotted as a function of their equivalent diameter  $l_{eq}$  and the distance between the maximum height and the intercepting plane ( $l_z$ , Figure 1).

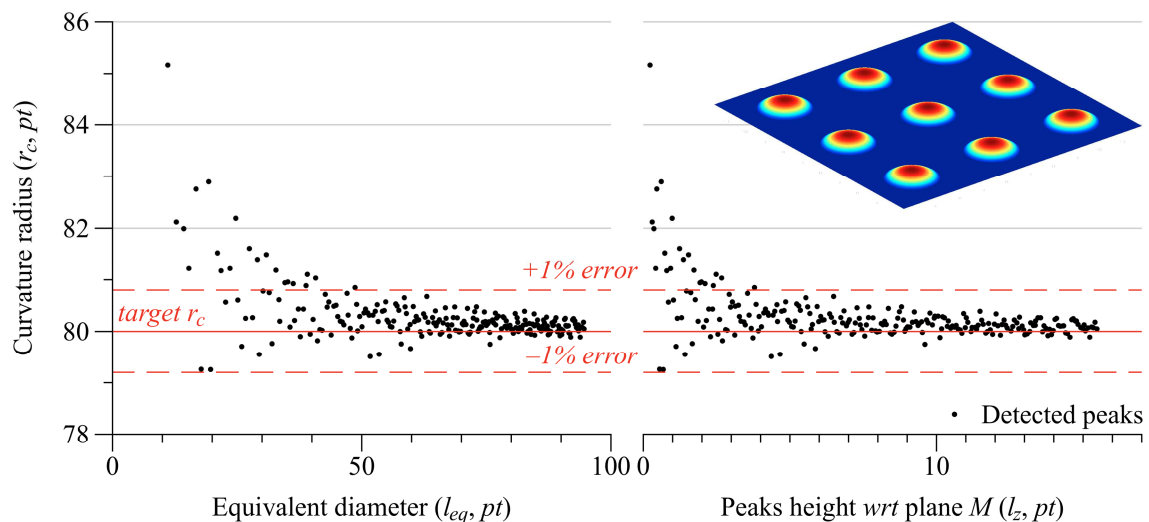


Figure 2: Curvature radii of peaks detected on a surface simulated numerically, with spherical caps with  $80\text{pt}$  radius.

It can be noted that the algorithm is more precise for large values of  $l_{eq}$  (or  $l_z$ ), which is due to the discretization of the surface: if the value of  $l_{eq}$  (or  $l_z$ ) decreases, it becomes closer to the sampling length, affecting the peak radius calculation. In the case presented in Figure 2, if  $l_{eq} > 50\text{pt}$  (or  $l_z > 4\text{pt}$ ), the error of peaks radii estimation is less than 1%.

### 3. EXPERIMENTAL PROCEDURE

The experimental testing device used in this study has been developed by Bech et al. [4] for thickness reduction of aluminium strips. The strips are drawn by means of a hydraulic jack between two dies. The upper die is made of hardened glass so the lubricant behaviour can be observed during thickness reduction. The lower die is made of steel, with an inclined plane with an angle  $\beta = 3^\circ$  to apply the thickness reduction. The hardened glass is used as delivered in a shape of a circular disc with dimensions  $\varnothing 50\text{mm} \times 11\text{mm}$ . The lower die is 80mm long and 50mm wide, with a polished contacting surface to reduce friction. A high speed video camera is used to record the lubricant behaviour for subsequent analysis, *i.e.* identification of the occurrence of Micro Plasto Hydrodynamic Lubrication (MPHDL) and Micro Plasto Hydrostatic (MPHSL) [4], location of the onset and direction of escape or front wave speed. The testing device is illustrated on Figure 3.

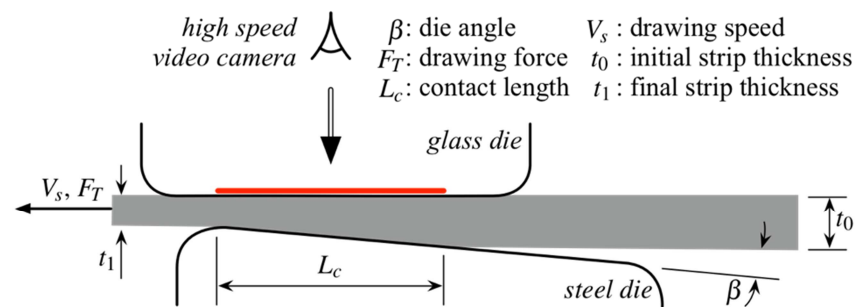


Figure 3: *Experimental testing device with its intrinsic parameters, after [5].*

The dimensions of the strips are  $l_0 \times L_0 \times t_0 = 450 \times 20 \times 2\text{mm}$  and their material is a semi-hardened aluminium AISI 1050 H24. Macro lubricant pockets are manufactured by Electro Discharge Machining to reduce the local residual stresses and to avoid the formation of banks on the indentation edges, that would change the tribological contact properties and fluid escape, as observed in a prior study [8]. The shape of the lubricant pockets is a groove normal to the drawing direction with triangular cross section. The grooves are 10mm long and 1mm wide, with an angle to the edge  $\alpha = 5^\circ$ . The spacing between each cavity centre is 2mm, so that the plateaus are 1mm wide. The strips are obtained from cold rolling and their raw roughness is preserved all along the specimens preparation process. An illustration of the manufactured strips and an illustrative picture are given in Figure 4.

The aluminium strips have been subjected to a reduction of about 15% during the drawing process. In this paper, we investigate the curvature radius of surfaces peaks to qualitatively correlate it with the lubrication regime. Thus, two conditions have been selected, one favouring a mixed lubrication regime (Testing Condition 1, TC1), and a second one favouring a hydrodynamic lubrication regime (Testing Condition 2, TC2). The strips surfaces resulting of these two drawing conditions will be compared with an initial surface. The drawing conditions were as follows:

- mixed lubrication regime (TC1): drawing speed  $V_s = 5\text{mm/s}$ , lubricant viscosity (at  $40^\circ\text{C}$ )  $\eta = 60\text{cSt}$  ( $\eta = 0.0537\text{Pa}\cdot\text{s}$ );
- hydrodynamic lubrication regime (TC2): drawing speed  $V_s = 50\text{mm/s}$ , lubricant viscosity (at  $40^\circ\text{C}$ ) is  $\eta = 660\text{cSt}$  ( $\eta = 0.5954\text{Pa}\cdot\text{s}$ ).

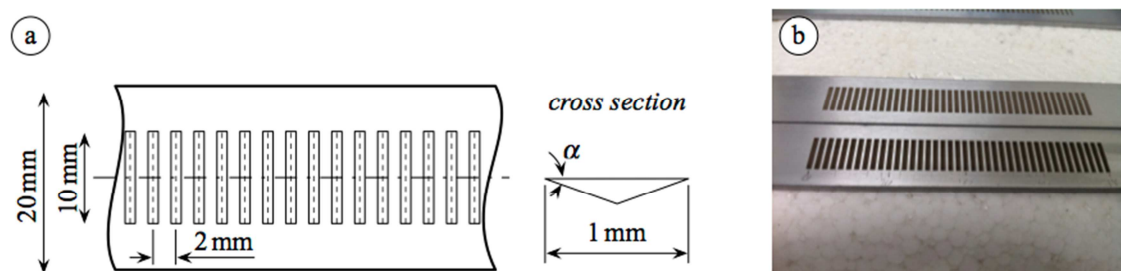


Figure 4: Groove shaped pockets pattern (a) and picture (b) of an EDMed strip, after [5].

#### 4. RESULTS AND DISCUSSION

The surface topography was acquired using a Zygo NewView 7300 profiler, which is a Vertical Scanning Interferometer (VSI). The measurement principle is based on unfiltered white light beam that is split in two: half of the beam is directed through a microscope lens and reflected from the surface, and the other half is reflected from the reference mirror. When the reflected beams recombine they produce interference fringes, where the best-contrast fringe occurs at best focus. In a VSI, the objective moves vertically to scan the surface at various heights. A 3D surface is then reconstructed by analysis of fringes at every pixel. A VSI uses an algorithm to process fringe modulation data from the intensity signal to calculate the surface heights. The obtained resolution will therefore depend on the precision of the  $z$ -axis positioning. In the case of the Zygo NewView 7300 instrument, a piezoelectric stage with range of  $160\text{ }\mu\text{m}$  is used to refine the height resolution going down to  $0.1\text{nm}$ .

The developed algorithm of 3D peaks detection and peaks curvature radius estimation described in Section 2 is applied to surfaces before and after a lubricated drawing process. Two examples of initial and processed surfaces with cavity pockets are presented in Figure 5.

The curvature radius of peaks for two selected surfaces obtained with the drawing conditions mentioned above (TC1 and TC2) are presented in Figure 6. It can be noted that in the case of



the initial surface, the curvature radius of the surface peaks  $r_c$  inside the cavities, obtained by means of Electro Discharge Machining, are very small in comparison to  $r_c$  on the “plateaus”, where the biggest detected radius is about 10 000  $\mu\text{m}$ . These regions correspond to almost flat surfaces (Figure 6b), which is consistent with surfaces obtained from a cold rolling process.

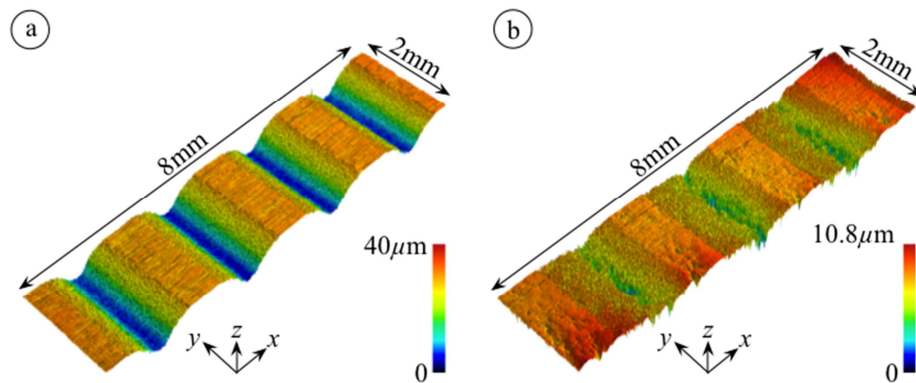


Figure 5: Illustration of strips surfaces before (a) and after (b) drawing, after [7].

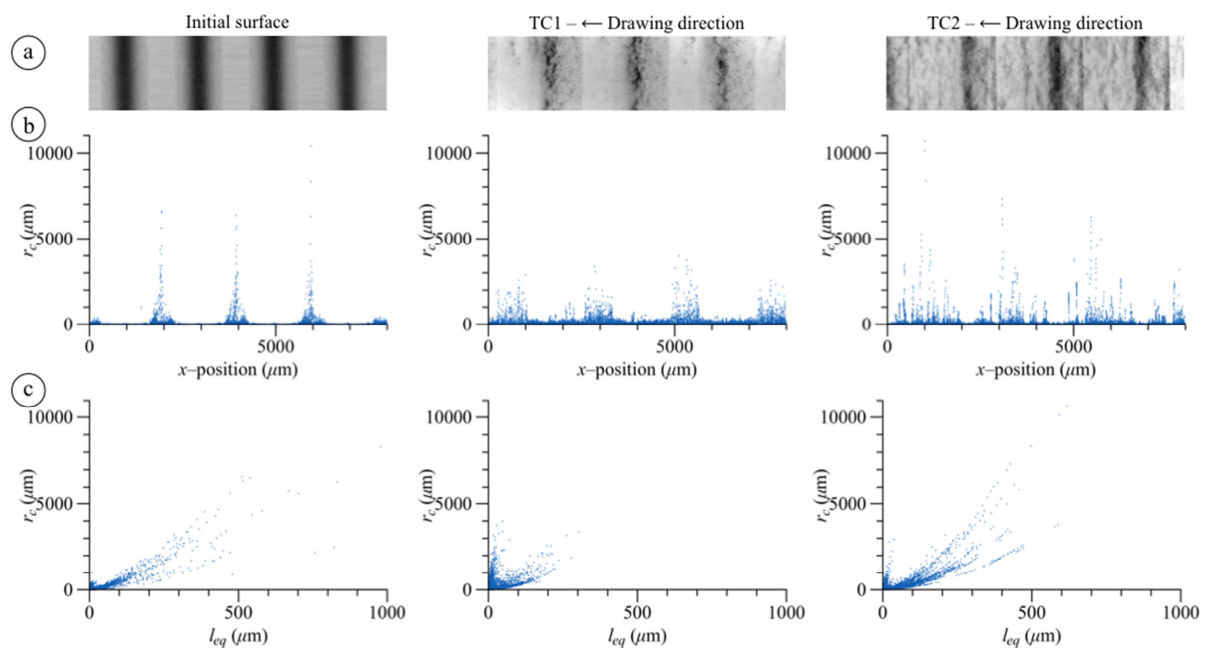


Figure 6: Distribution of peaks curvature radii on an initial surface and after drawing process in mixed lubrication regime (TC1), and in hydrodynamic lubrication (TC2).

Radii of peaks plotted as a function of the equivalent diameter  $l_{eq}$  (Figure 6c) for the initial surface and for testing condition TC2 shows distinctive lines where the same peak has been detected several times, at different interception levels. Concerning the initial surface, this shows that there are some large and relatively flat areas. These areas are conserved after the drawing process with testing condition TC2 (that favours a hydrodynamic lubrication



regime), however they are removed in testing condition TC1 (that favours a mixed lubrication regime). For this testing condition, the contact conditions were more severe with a higher pressure of lubricant, which led to more local peaks deformation, and therefore the initial large flat areas are more localised.

In both cases, after the drawing process, the majority of detected peaks have higher curvature radius, which suggests that during the drawing process the peaks were flattened.

The proposed methodology can be used to analyse the lubrication regime of the surface subjected to plastic deformation by comparing initial and final surface morphology. However further analysis will be required to take full advantage of the developed method of 3D peaks curvature radii estimation, and to analyse the anisotropy of the detected peaks.

## 5. CONCLUSIONS

A new method of peaks curvature radii estimation of 3D surfaces was developed and applied to drawing process analysis. The 3D surface is intercepted by a flat surface and top part of the profile is analysed. If a peak is detected, the spherical cap with radius  $r_c$  is fitted at point corresponding to the highest point inside the detected peak. Radius  $r_c$  calculation is based on area of cross section of detected peak with cutting surface.

This methodology allows to qualitatively analyse the effects of the lubrication regime in drawing process based only on measured surface. The proposed method shows clearly the differences in deformation in cavity pockets and on “plateaus” surfaces of aluminium strips used in this study. This method is also independent from the phenomena direction (2D or pseudo-2D), which means that the effect of lubricant escape could be analysed in any direction and can be linked to the surface anisotropy. This point, as well as the qualitative nature of the lubrication regimes identification, will be investigated in future works.

## 6. ACKNOWLEDGEMENTS

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