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DISTINGUISHING THE PLATEAU AND VALLEY COMPONENTS OF PROFILES FROM VARIOUS TYPES OF TWO-PROCESS TEXTURES

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Abstract

This paper presents methods of separating the plateau part for various types of two-process profiles, having the traces of two processes. The traditional method based on the plateau-valley threshold, according to the ISO 13565-3 standard, is not always sufficient, since the valley portion can include plateau roughness. Starting and finishing points of each plateau in the measured profiles should be determined. The procedure found in the technical literature depends on setting not only the plateau-valley threshold but also a lower threshold. This approach was a little modified for profiles that contain both random and deterministic topography components. A new procedure of determination of the lower threshold was proposed for stratified profiles containing two deterministic parts. The valleys can be characterized by their widths and the distance between them. In addition, a description of the material probability curve is proposed.

Keywords: surface topography, two-process texture, material ratio.

1. Introduction

Surface roughness is important in many tribological problems [1]. Most publications were related to surfaces of approximately Gaussian ordinate distributions. However, multi-process topographies, having traces of two or more processes, are becoming more important from functional points of view. Plateau honed cylinder surfaces, with tracks of two-step honing (coarse honing followed by plateau honing), are practical examples of two-process textures, having good sliding properties of smooth surfaces and a great ability to keep oil by porous topographies. It was found that the functional properties of plateau honed surfaces were better than those of classically honed surfaces with Gaussian ordinate distributions [2–6].

Plateau honed cylinder surfaces are the first examples of textured surfaces with networks of micro-reservoirs, called dimples, oil pockets or cavities. The dimples can act as micro-bearings to enhance full lubrication, cause decrease of friction under boundary (mixed) lubrication or can be traps for wear debris, minimizing abrasive wear [7–9]. Two-process surfaces can be also created as the results of a low wear process (within the limits of original surface topography).

Characterization of two-process surfaces is difficult. Using only the Ra parameter is not sufficient, since it does not distinguish portions of these textures. Two texture parts: the plateau and valley ones ought to be characterized independently. Control of such surfaces requires a complementary response from surface metrologists. Two competitive standards, originated from the automobile industry, exist. They have been dedicated for plateau-honed cylinder surfaces. According to the ISO 13565-2 standard, a three-part model of the surface (the shape of the Abbott-Firestone curve is similar to the letter S) is the basis of material ratio assessment using the portions of: peaks, core and valleys. Consequently, there are 5 parameters describing

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the material ratio curve: the reduced peak height – Rpk, the reduced valley depth – Rvk, the core roughness depth – Rk, and material ratios determined by a straight line separating the core roughness from the *material side* (Rmr1) and the *free-from-material side* (Rmr2). It is believed that the Rk parameter is a measure of roughness height after a running-in process, the Rvk parameter measures the capacity of oil accumulated in the honing valleys and the Rpk is related to the running-in duration. Nielsen found that the honing process could be monitored by the Rk parameter family [10]. In Zipin's opinion [11], this approach can be misleading because it can be used not only for stratified textures, but also for surfaces of a symmetric ordinate distribution, where it is difficult to distinguish the valley part.

However, another method of describing the material ratio curve can be used, presenting the material ratio in a Laplace-normal system (ISO 13565-3). This method with a sound theoretical basis, conceptually simpler and more elegant than that described in the ISO 135565-2 standard, can be applied only to two-process textures [12–14]. In this approach, two regions of roughness exist. If the material ratio curve of a random two-process surface is plotted on a normal probability scale, it will show two straight lines of different slopes. The Rpq (*plateau root-mean square roughness*) parameter is the slope of a linear regression performed through the plateau region, whereas the Rvq (*valley root-mean square roughness*) – through the valley portion. The intersection point on the normal probability graph of the abscissa Rmq (material ratio of plateau-to-valley transition) defines the separation of plateau and valley textures. The parameters from the ISO 13565-3 standard can be obtained in a different way [15].

Because of the sound theoretical basis, it is possible to computer generate two-process random surfaces by superposition of two textures with Gaussian ordinate distributions [16]. The probability description of a two-process texture can be used to assess progress of low wear or abrasive machining [17]. It was found that in a regime of starved lubrication the coefficient of friction was proportional to the Spq parameter (3D equivalent to the Rpq parameter) of two-process random isotropic surfaces [18, 19]. It is believed that contact characteristics of two-process random textures are governed by the Rpq parameter [20, 21].

The ISO 13565-3 standard is mainly concerned with two-process surfaces of a random type. A comprehensive approach to analysing the material probability curve was developed for a specific (random) class of two-process surfaces, for which heights of plateau and valley parts follow a Gaussian distribution, and may not necessarily extend successfully onto other types. Random textures are typically created by abrasive machining, like grinding, polishing, honing, lapping, vapour blasting, superfinishing (material removal by action of hard, abrasive particles). Deterministic topographies are created by machining using cutting edges of specified geometry (turning, milling *etc*.). In some cases the plateau part of two-process texture has a deterministic, whereas the valley part – a random character, or both of them have a deterministic character. There are problems with separation of surface portions of these types of two-process textures.

This paper presents methods of distinguishing the plateau part for various types of two-process profiles. Proper separation of this profile portion is functionally important; the plateau surface part decides about either lubrication or contact of two-process textures [6, 18, 19, 21].

2. Study of random two-process surfaces

In the ISO 13565-3 standard the following equation is used for description of the material ratio curve probabilistic plot of a two-process profile:

$$y = Ax^2 + Bxy + Cy^2 + Dx + E\,, \tag{1}$$

where: y – the profile ordinate; x – the material ratio expressed in standard deviations.

In this curve two linear regions and three non-linear parts exist. The three non-linear portions are: non-statistical peaks, non-statistical valleys (of heights not following a Gaussian distribution) and a transition region between straight lines. Two limits of the plateau linear part exist: the *upper limit of the plateau region* (UPL) and the lower *limit of the plateau region* (LPL). There are also similar limits for the valley linear part portion: the upper *limit of valley region* (UVL) and the lower limit of valley region (LVL). These four limits are presented in Fig. 1b. As a result of analysing many two-process profiles, it was found that application of a conical curve (1) was difficult in numerical implementation. The authors of paper [24] obtained similar findings.

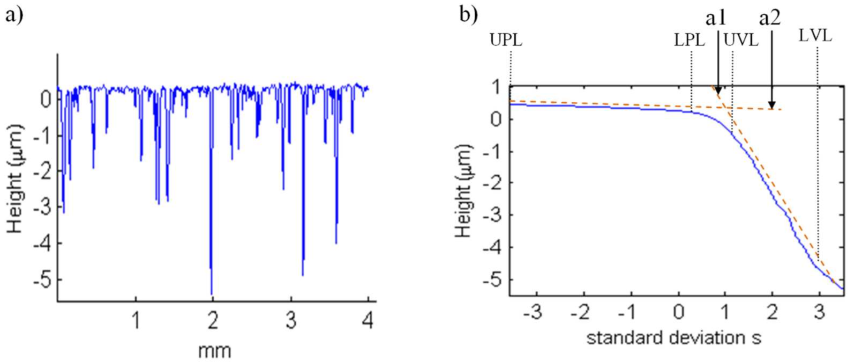

Fig. 1. a) The profile after 2processes; b) the probability plot of its material ratio curve; a1, a2: asymptotes.

Therefore, we analysed the technical literature in order to find a better curve describing the material probability curve of profile from a two-process random surface. As a result, an alternate model, originated from the paper [25], was used for hyperbola approximation. In this model:

- the dependent variable y is a function of only one independent variable x;
- the left asymptote has inclination θ_1 and right θ_2;
- the asymptotes intersect at a point of coordinates (x_0, β_0);
- the angle of curvature at the point of abscissa $x = x_0$ is proportional to δ value;

The following equation describes a branch of the hyperbola:

$$y = \beta_0 + \beta_1 \left(x - x_0\right) + \beta_2 \left[\left(x - x_0\right)^2 + \delta^2 / 4\right]^{\frac{1}{2}}, \tag{2}$$

where: $\beta_1 = \left(\theta_1 + \theta_2\right)/2$ and $\beta_2 = \left(\theta_2 - \theta_1\right)/2$.

When $\beta_2 < 0$ then $\theta_1 > \theta_2$ and the hyperbola is located under asymptotes; when $\beta_2 > 0$ then $\theta_1 < \theta_2$ and the hyperbola is positioned above asymptotes. The radius of curvature of the hyperbola at the point $x = x_0$ is:

$$R = \delta\left(1 + \beta_1^{\,2}\right)^{\frac{3}{2}} / \left(2\left|\beta_2\right|\right). \tag{3}$$

All the used parameters $(\beta_0, \beta_1, \beta_2, \delta, x_0)$ have clear geometrical interpretations, making their estimation easy. A special software was elaborated by the authors, in which (2) was used. Many simulated and measured two-process profiles were analysed. It was found that use of the formula (2) assured similar results to those achieved after application of a commercial software. In some cases better results were obtained with application of the new software, compared with the commercial one [26].

Godi *et al.* developed – for profiles of textured surfaces with a deterministic pattern – a method recognizing the starting point (left) and the finishing point (right) of each plateau (this approach cannot be applied for 3D surface topography). These points (starting and finishing) are located on the actual measured random-deterministic profile. After initial setting the plateau-valley transition point (the upper threshold), the lower threshold is determined on the basis of an arbitrary procedure. First, the points above the lower threshold (x_i; i = 1,…, n) are detected, then the points below the lower threshold are discarded. Next, all the points between several x_i and the last point below the upper threshold are discarded, as follows. When the profile is climbing up – all the points following x_i, when profile is stepping down – all the points preceding x_i are erased till the plateau-valley (upper) transition point is reached. As a result of this procedure, a correct plateau separation is achieved. The details are given in [22, 23]. This approach can be promising also for two-process profiles of a random character. In this case, the ordinate of the intersection point of two approximating straight lines defines the upper threshold, of the Rmq abscissa, according to the ISO13565-3 standard. A problem arises in determining the lower threshold. Godi *et al.* [22, 23] recommended a special procedure for random-deterministic two-process surfaces.

We propose a different approach to stratified profiles of a random character.

a)

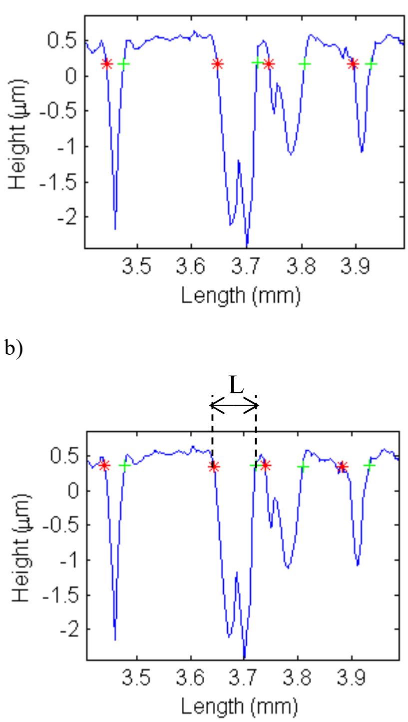

Fig. 2. a) The lower threshold of a random profile; b) the valley edges with a width of the second valley L.

After application of the new software on the basis of (2), the following limits were determined: UPL, LPL, UVL, LVL, according to the ISO 13565-3 standard (see Fig. 1b). The lower threshold has the ordinate of the UVL point. No additional calculations than those contained in the standard are required for determining the lower threshold. Fig. 2 presents the lower valley threshold and valley edges as well as the width of the selected valley. It is possible to calculate a width of each valley *L* (see Fig. 2b) and the number of valleys. It was found that the average distance between the deep valleys was a very important tribological parameter [3].

3. Analysis of random-deterministic textures

Surfaces with a deterministic valley part and a random plateau portion are called random-deterministic textures, because the plateau part of an approximately Gaussian ordinate distribution is created by an abrasive process and the valley part by a tool of known geometry. Initially turned piston skirts after a low wear process (wear within the limits of the original surface topography) or surfaces after abrasive machining (grinding, polishing) containing separate oil pockets after burnishing can be examples of these textures, because burnishing or turning created the deterministic part, whereas wear or abrasive machining – the random portion. The profile, as well as the material ratio curve from this type of two-process texture consist of the random and deterministic parts because the plateau has typically a random and the valley portion – a deterministic character.

There is a problem of implementing the ISO 13565-3 standard for random-deterministic textures, since the valley component of a deterministic character cannot be described by the Rvq parameter. The problem is to establish the transition point between the plateau and valley surface portions. Grabon *et al.* [27] proposed a method of obtaining this threshold. Since the plateau part of a random-deterministic texture has a random character, the material probability curve should be used. It is rotated counter-clockwise by an angle being the slope of the line passing through the first and last points of the material probability curve, then the point of the maximum ordinate of this curve can be treated as the plateau-valley transition point [27]. Godi *et al.* [22, 23] modified marginally this method. In their proposal the transition point has the largest perpendicular distance to the straight line connecting the first and finishing points of the material probability curve. The lubrication capability of valleys was evaluated on the basis of a new parameter called EQF (*equivalent film thickness*), being the ratio of the linear volume of oil pockets and the profile evaluation length [22, 23].

Selection of the lower threshold is not so easy as for random stratified profiles. Godi et al. determined the lower threshold as 25−50% of the total profile height from the lowest profile point depending on irregularity of the valley distribution [22, 23]. We propose a different method of determining this threshold. The height of the roughness profile of a normal ordinate distribution is similar to Rq (standard deviation of roughness heights). It can be assumed that the maximum height of the plateau portion of a two-process profile is equal to 6 Rpq (or 6 Ppq when the primary profile is analysed). The upper threshold (point A) ordinate yA (see Fig. 3a) is located at a vertical distance smaller than 6 Rpq from the highest profile point, excluding non-statistical peaks. Therefore, the lower threshold should be positioned at a distance little longer than 7 Rpq from the highest profile point after eliminating outliers. In practice, it is necessary to approximate the plateau part of the material probability curve by a straight line and find its crossing with the vertical axis of 4 s abscissa. The ordinate of the crossing point is the proposed ordinate of the lower threshold B.

After analysis of a lot of measured and simulated two-process profiles it was found that the lower threshold was determined correctly (plateau profile parts were accurately separated) using this method, providing that the plateau height was much smaller than the valley amplitude. The degree of arbitrariness of this method is smaller than that of the proposal of Godi *et al.* The method of determining the lower threshold proposed by us is therefore more precise. Fig. 3b shows the lower threshold obtained in the new way. After determining the lower threshold, the procedure developed by Godi *et al*. [22, 23] should be used. The plateau roughness of random and random-deterministic profiles can be assessed by the Rpq parameter.

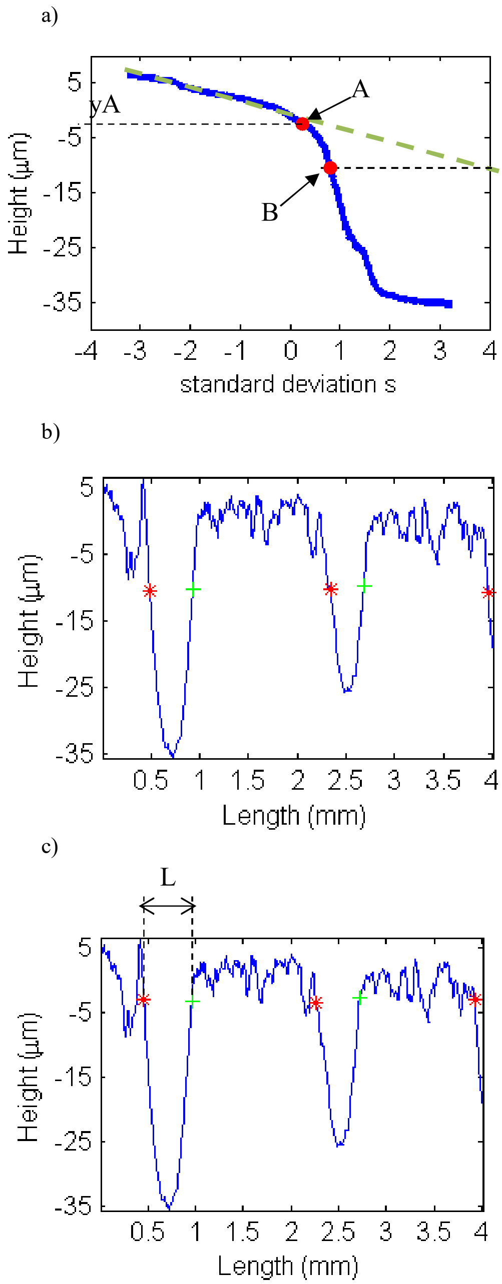

Fig. 3. The material probability curve with the upper threshold A, a) a straight line approximating the plateau region and the lower threshold B; b) the lower threshold of profile; c) the valley edges with a width of the first valley L.

4. Study of deterministic two-process surfaces

A two-process texture with both deterministic components is the third type of stratified surface. In this case, two parts of profile have a deterministic character. A precision turned surface with burnished oil pockets is an example of two-process deterministic texture. A probabilistic plot of the material ratio curve cannot be used for such a topography, because it does not have Gaussian parts. Instead, the usual material ratio curve can be rotated counter-clockwise [28]. Fig. 4 shows a measured profile, its normalized material ratio curve (NH – *normalized height*, MR – *material ratio*) with a straight line connecting its first and finishing points, the material ratio curve rotated by an angle β and the transition point B (of ordinate yB) between the plateau and valley parts, being the upper threshold. The angle β in Fig. 4b is 45°.

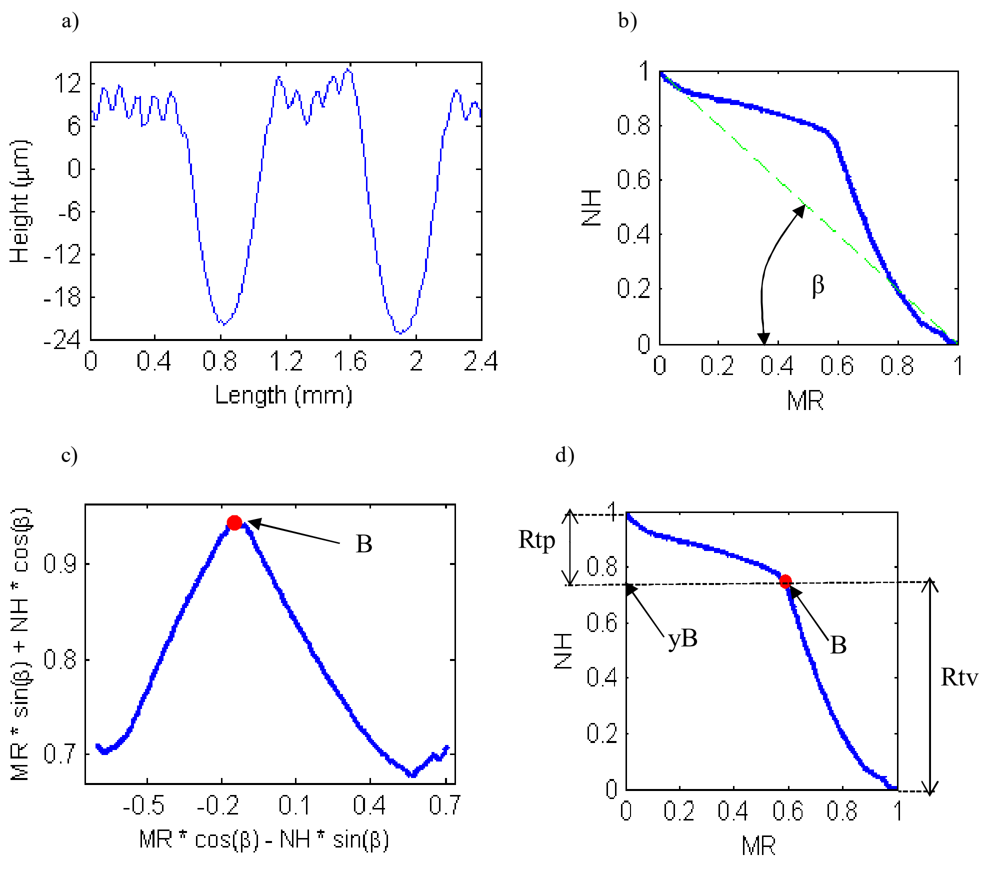

Fig. 4. a) A deterministic two-process profile; b) its normalized material ratio curve with a straight line passing the first and finishing points; c) the normalized material ratio curve rotated by β angle; d) the transition point B with heights of plateau and valley parts, Rtp and Rtv, respectively.

Another method of determining the transition between the plateau and valley parts is finding the point of maximum curvature of the normalized material ratio curve [28].

The authors propose the following method of establishing the lower threshold for such a type of profile. In Fig. 4d Rtp is the estimated height of the plateau part and Rtv is that of the valley portion. For this type of profile the lower threshold is set to 0.25–0.5 Rtv below the point B. Then, the procedure of finding edges of valleys should be carried out (see Fig. 5). Similarly to other types of two-process profiles, the number of valleys and their widths can be determined. This procedure can be used also for two-process profiles of a non-clear character of the plateau and valley parts, assessed on the basis of the material probability curve.

The oil capacity can be also determined for two-process surfaces of various characters [28]. The plateau roughness can be described by the Rq parameter in profile details free of oil pockets.

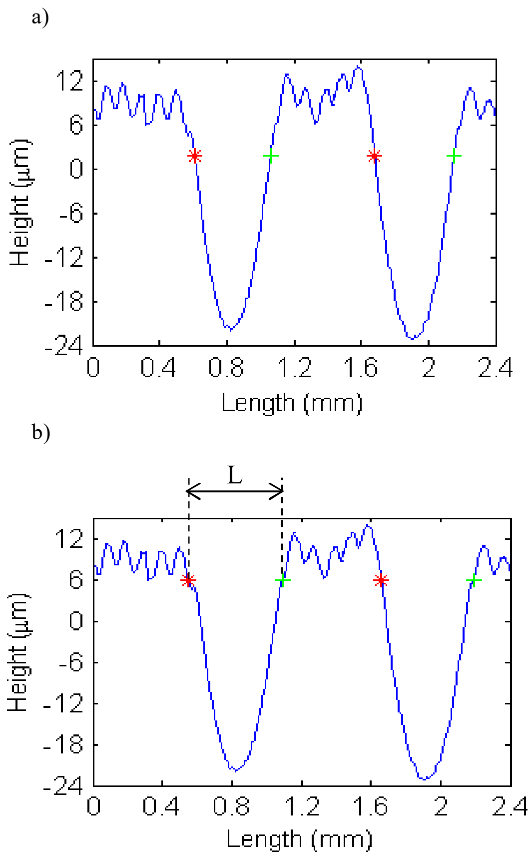

Fig. 5. a) The lower threshold of a deterministic two-process profile;
b) the valley edges with a width of the first valley L.

5. Conclusions

This paper presents methods of separating the plateau part from two-process textures for various types of profiles. These methods are based on a procedure, presented in the technical literature, that finds the starting and finishing points of each plateau of a textured profile with a deterministic pattern. For its aim it is necessary to find the plateau-valley (upper) threshold and the lower threshold, which seems to be difficult.

Correct separation of the plateau part is also possible for a random two-process profile, after approximation of its probability plot by a hyperbola. An equation of a branch of the hyperbola, different in comparison with that of the ISO 13565-3 standard, is proposed. The lower threshold is determined on the basis of the upper valley limit UVL.

Modification of the existing method of plateau part separation for a random-deterministic profile is suggested. It consists of a different method of estimating the lower threshold belonging to the valley part. A procedure of plateau part separation for profiles with a deterministic character of both plateau and valley parts is also proposed.

The valleys can be characterized by their number (or mean distance between them), their average width and oil capacity. The plateau roughness can be assessed by a height parameter, Rpq, which is suggested for random and random-deterministic profiles.

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