Problems of surface topography with oil pockets analysis

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Abstract. The present paper presents method of description of two-process surfaces of random (load-bearing plateau structure) and deterministic (oil pockets) character on the basis of the probabilistic approach of material ratio curve. Examples of this method usage for textured surfaces are shown. The other application of material ratio curve for estimation of pit-area ratio of textured surfaces is discussed. Distortion of surface topography with oil pockets measurement by improper selection of areal reference plane is taken into consideration.

1. Introduction
Surfaces with a dominant deterministic feature pattern are termed “structured” or “textured” surfaces. Structured surfaces have numerous applications ranging from optics to automotive, from aerospace to biomedical and from micro-fluidics to power generation. The key feature that determines a structured surface is that its topography is not just an artifact of the process used to generate the surface, i.e. it has been engineered for a specific function. Thus, for a structured surface, typical parameters such as Ra or Rq do not adequately characterize its properties. Therefore, such surfaces are a challenge to manufacture and a challenge to measure. However, their function is by definition profoundly affected by their geometrical characteristics. Example includes surfaces to control the tribological characteristics of mating components. Method of this surface type creation is termed as surface texturing.

Recently, surface texturing attracted the attention of tribologists since it can be used to improve tribological properties of sliding elements without changing the materials and the lubricants. The dimples can serve either as a micro-hydrodynamic bearing in cases of full or mixed lubrication, a micro-reservoir for lubricant in cases of starved lubrication conditions or a micro-trap for wear debris in either lubricated or dry sliding [1, 2]. Various techniques can be employed for surface texturing including laser texturing, etching techniques and machining. It seems that laser surface texturing offers the most promising concept, because the laser is extremely fast and allows short processing times, is clean to the environment and provides excellent control of the shape and size of the texture, which allows realization of optimum designs [2]. A burnishing (embossing) technique is very promising in the creation of textured surfaces [3]. The applications of texturing include: cylinder liners [4, 5, 6], piston ring [7, 8], piston pin, disk brakes, thrust bearings, journal bearings [3], mechanical face seals, gas seals, hard disk sliders, magnetic tapes, machine tools guideways and other elements. The textured surface topography is functionally important in tribology, but it is notoriously difficult to characterize. Characterization of it entails analysis and identification of the departure from the nominal geometry of the basic repeat unit and analysis of the distribution and spacing of the repeat unit [9, 10]. The approach used to these surfaces is analyzing the surface autocorrelation function and then applying...
pattern analysis (segmentation) to the autocorrelation function. The segments around the origin of the autocorrelation function provide information on the average basic repeat unit and the relationship of the origin segment with its neighbouring elements of the tessellation pattern. The mean distances as well as the maximum, minimum and average depth, diameter of the holes and pit-area ratio were computed. The diameter is calculated as the best fit least square circle fitted to the segmentation boundary of the holes.

In this paper some problems of measurement and analysis of surface topography with oil pockets is discussed. The authors focused on the application of material ratio curve for determination of tribologically important surface topography parameters and on selection of reference plane for cylindrical surfaces with oil pockets.

2. Application of material ratio curve

Two scales of roughness can be found on textured surface: a relatively rough valley structure containing dimples and comparatively smooth finer plateau structure. When plateau surface part was created by honing or grinding or arose during wear it had random character, but valley structure, created by burnishing technique deterministic character. The random character of plateau part was confirmed by the analysis of the surface details free of dimples and by the fact, that the fine part of textured surfaces can be approximated by a straight line in material probability plot. Material probability curve is a representation of material ratio curve in which the surface material ratio is expressed as Gaussian probability in standard deviation values, plotted linearly on the horizontal axis. This scale is expressed in standard deviation s. For stratified (two-process) surfaces, composed of two Gaussian distributions, the material probability curve exhibits two linear regions. Ppq parameter is the slope of a linear regression performed through the plateau region, but Pvq – through the valley region. The intersection point on normal probability graph of abscissa Pmq defines the separation of plateau and base textures. These parameters were defined in ISO 13565-3 standard. Since this approach independently characterises the components of the multi-process texture, process control can be much more specific. However ISO 13565-3 standard is devoted only to stratified surfaces composed of two Gaussian distributions. Therefore for the analyzed textured surfaces of random-deterministic character Pq parameter (height standard deviation) of surface details free of dimples equalled to Ppq parameter of worn textured surface can be determined from the analysis of surface fragments between dimples. However this procedure is time consuming. One of the present authors developed the method of Pqp and Pmq parameters determination for this type of surface. This problem is of great practical importance because standard deviation of height in areas free of dimples can affect tribological properties of sliding pairs. The main problem is determination of transition point between random and deterministic regions. This point was determined by rotation of material probability plot of ψ angle anticlockwise according to the following equation:

\[
\begin{align*}
  x &= x \cos \psi - y \sin \psi \\
  y' &= x \sin \psi + y \cos \psi
\end{align*}
\]

ψ angle is the slope of straight line passing by the first and the finishing point of the material ratio curve (see Figure 1). In rotated diagram C point of the highest ordinate was determined (see Figure 2). This point is treated as transition between deterministic and random regions. The regression line passing by points lied on point C left side was determined (see Figure 3). Slope of this straight line is equal to the Pqp parameter, but abscissa of C point is equal to transition Pmq parameter. Figure 4 shows example of the presented method application. Areal Spq or Smq parameters can be also determined in this way. After the analysis of many surfaces it was found that this method is useful.
Figure 1. Material probability plot with straight line passing by the first and the finishing point and ψ angle

Figure 2. Material probability plot rotated by ψ angle

Figure 3. Material probability plot with regression line passing by random region and transition point between random and deterministic regions

Figure 4. Profile of shaft surface with oil pockets (a), profile ordinate distribution (b), material probability plot (c): Ppq = 2.91 μm, Pmq = 66.85%
Oil pockets density (pit-area ratio) is tribologically important parameter characterizing textured surfaces. It is calculated as ratio of surface area occupied by dimples to the total area. However calculation of pit-area ratio is time consuming. It is necessary to measure area occupied by each dimples (when holes are of spherical shape, determination of mean diameter is sufficient). When the total area is larger than measured area one should determine average area occupied by each dimple, multiply it by the number of holes and divide it by the total area. It is possible to estimate pit-area ratio on the basis of shape of material ratio curve (see Figure 5).

This method is quicker than presented above. Because valley part is of deterministic character, therefore it presents straight line on usual (not probabilistic) material ratio curve. Therefore oil pockets density is obtained basing on determination of the point of this straight line finishing. Pit-area ratio $S_p$ is equal 100% - $t_p$, where $t_p$ is material ratio (abscissa) of this point. The real area covered by dimples is equal to $S_p$ multiplied by measured area. It is also possible to estimate average area occupied by each dimple. Differently to developed method of the $P_{pq}$ parameter determination, it can be used for surfaces of various character of plateau part (deterministic or random). However there are some problems with estimation of dimples density higher than 70% using the proposed method. Two presented above methods of pit-area ratio $S_p$ estimation were compared for some surfaces with oil pockets created by burnishing technique. The mean difference was 0.44% (the highest was 0.8%). Figure 5 presents examples of oil pockets density determination on the basis of material ratio curve.

3. Selection of reference plane

The initial, but very important operation during analysis of areal surface topography is selection of the reference plane. For improper its choice serious errors in parameter calculation can arise. Only a few technical publications were found in this subject ([11] is the example). The present authors analyzed the effect of degree of a polynomial on areal surface parameters on cylindrical textured elements. The
polynomials of degrees from the range 1-12 were analysed. Parameters from standard ISO 25178-2 and oil pockets sizes were studied.

Increase of degree of a polynomial caused decrease of average height parameters Sa and Sq (sometimes the values of these parameters increased when polynomial degree was higher than 10). Peak density Spd and auto-correlation length Sal also decreased when polynomial degree increased. No tendency of texture parameter Str changes was found. However parameters describing maximum surface height St, S10z as well as the core roughness depth Sk, the maximum surface peak height Sp and the lowest valley of the surface Sv initially decreased and increased when the degree of a polynomial was higher than 2 or 3 (depending on the surface) during increase of the degree of a polynomial. Similar tendency of the Sk parameter changes was observed during the analysis of plateau honed surfaces [12]. When the polynomial degree was higher than 2 or 3, areal surface parameters can be improper calculated, and, more importantly the dimples depth could be underestimated, and, as a consequence, the tribologic properties could be falsely assessed (see Figure 6). Therefore the 2nd and 3rd degree of polynomial was recommended.

![Figure 6. Contour plot of textured surface (a), the shape of oil pocket (b), after application of polynomial of 3rd degree (upper graph) and polynomial of 7-th degree (lower graph) as reference planes.](image)

This analysis was done for cylindrical elements of the same diameter. However for textured surfaces the following procedure is proposed: computing parameters for increase of the polynomial degree and selection of this degree, from which the parameters St, S10z, Sp, Sv and Sk started to increase. The information that oil pockets depth if highly correlated (proportional) to St, S10z and Sv parameter values [13] is also important.

Change of the reference element did not affect value of the parameter Std, changes in Sdq, Spd and Sdr parameters were negligible. Figure 6 shows example of false estimation of oil pocket depth as a result of improper selection of the degree of a polynomial (7th).

4. Concluding remarks

Material ratio curve can be applied for determination of tribologically important parameters of two-process textured surface topography.
Material probability curve is useful in determination of standard deviation of plateau height \( P_{pq} \) and abscissa of transition point between deterministic and random part \( P_{mq} \) of surface profiles with oil pockets. The originally developed method for these parameter obtaining is basing on the rotation of material probability plot. Areal extension of the \( P_{pq} \) and \( P_{pq} \) parameters (\( S_{pq} \) or \( S_{mq} \)) can be also determined in this way. After the analysis of a lot of surfaces it was found that proper parameter values can be obtained using this method.

One can estimate pit-area ratio on the basis of shape of the usual plot of material ratio curve. The oil pockets density can be obtained by determination of the point of finishing the straight line describing deep valley part of deterministic character. This method assures very similar values of pit-area ratio and is much quicker than that commonly used.

After improper selection of textured surface reference plane serious errors in parameter calculation can arise. More importantly, dimple sizes can be assessed falsely. The procedure of increase in the degree of polynomial is proposed, according to it this degree should be chosen, from which the parameters \( S_{t} \), \( S_{10z} \), \( S_{p} \), \( S_{v} \) and \( S_{k} \) started to grow up. For the analyzed surfaces from cylindrical elements of the same diameter the 2nd and 3rd degree of polynomial was recommended. When the polynomial degree was higher the dimples depth could be underestimated. Generally increase of degree of a polynomial caused decrease of the parameters: \( S_a \), \( S_q \), \( S_{al} \) and \( S_{pd} \), however the changes of \( S_{td} \), \( S_{dq} \), \( S_{pd} \) and \( S_{dr} \) were negligible.

5. References

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