Calculation of plasticity index of honed cylinder liner textures

P Pawlus, W A Grabon and D Czach
Rzeszów University of Technology, Poland

E-mail: ppawlus@prz.edu.pl

Abstract. The fundamental objective of this work is to develop method of plasticity index calculation for honed and especially plateau honed cylinder textures. Cylinder liner surface topographies were measured by white light interferometer Talysurf CCI Lite. Honing angle was in the range: 15-70°. For each identified summit the ratio of the smaller and the larger radii in the axial and circumferential directions $\gamma_1$, was computed. Then the ratios of the radii in orthogonal directions for different orientations ($9^\circ$ resolution) were computed and the smallest value, $\gamma_2$ was recorded. Average values of these ratios were compared and errors of plasticity index estimation were computed. It was found that for both honed and plateau honed liners only a tolerable level of error is introduced in plasticity index calculations by taking the cylinder axis and circumference as the principal axes. These errors were larger when the honing angles are bigger.

Keywords: surface topography, cylinder liners, plateau honing, plasticity index

Nomenclature

- $E'$ - Hertz elastic modulus
- $H$ - Hardness of the softer material
- PP - Plateau part
- VP - Valley part
- $R$ - Mean radius of summits curvature
- $R_e$ - Equivalent radius of curvature
- $S$ - Standard deviation
- $Spq$ - Standard deviation of plateau height
- $Sq$ - Root-mean-square value of the surface deviations
- $\alpha$ - Honing angle
- $\Gamma$ - Degree of anisotropy
- $\gamma_1$ - Ratio of the smaller and the larger radii in axial and circumferential directions
- $\gamma_2$ - The smallest value from the ratios of the radii in orthogonal directions for different surface orientations
- $\sigma_s$ - Standard deviation of asperity height
- $\Delta$ - Error in the plasticity index estimation using $\gamma_1$ than $\gamma_2$
- $\phi(\gamma)$ - Correction factor
- $\Psi$ - Plasticity index
1. Introduction

Wear regimes are a function of a plasticity index, first introduced by Greenwood and Williamson [1], which determines the mode of deformation of an array of asperities of varying heights. The plasticity index has the form:

\[ \psi = \frac{E'}{H} \left( \frac{\sigma_s}{R} \right)^{1/2} \]  

(1)

where: \( H \) – hardness of the softer material, \( E' \) – Hertz elastic modulus, \( \sigma_s \) – standard deviation of asperity height, \( R \) – mean radius of summits curvature.

According to Greenwood and Williamson the contact should be plastic for plasticity index larger than 1.0 and elastic for smaller than 0.6, but for the plasticity index between 0.6 and 1 the mode of deformation is in doubt. The mode of surface deformation is important in understanding contact mechanics of rough surfaces. A boundary from safe to unsafe sliding depends on the plasticity index [2, 3].

The initial version of plasticity index can be calculated on the basis of surface profiles. However, the importance of areal characterization of surface topography is being increasingly recognized. In this model, all asperity summits have the same radius but their height varied randomly. For isotropic surfaces of Gaussian height distribution, parameters characterizing surface topography can be predicted based on profile analysis using Nayak’s predictions [4, 5]. Anyway, they can be calculated directly on the basis of analysis of areal surface topography [6]. However, most real surfaces are anisotropic, so there were several attempts to develop a modern version of the plasticity index, for instance for strongly anisotropic (one-directional) random surfaces [7]. The contact deformation is strongly dependent on the ratio of the principal curvature radii of asperities (degree of anisotropy) \( \gamma \).

Thus a general expression was developed [8] for plasticity index, taking the degree of anisotropy into consideration by assuming that all asperities are ellipsoidal near their summits:

\[ \Omega = \frac{E'}{H} \left( \frac{\sigma_s}{R_e} \right)^{0.5} \]  

(2)

where \( R_e \) is an equivalent radius of curvature, the geometric mean of the principal radii, and \( \phi(\gamma) \) is a correction factor of near unity if \( \gamma > 0.2 \).

Typically it is assumed that measurements can be taken along and across the lay (main surface direction). However, for honed cylinder liners this is not possible since they have cross-hatched structure with a two-directional lay.

There then arises a need to estimate the degree of anisotropy for cross-patterned cylinder surfaces. The other problem is that cylinder liner surface after plateau honing is a kind of two-process surfaces [9, 10, 11, 12, 13, 14] consisting of two parts: plateau and valley. The plateau honed cylinder liner surface texture is a composition of relatively smooth plateau areas ensuring low wear intersected by valleys with great ability to maintain lubricant, improving tribological performance of a piston ring pack. The quantitative assessment of two-process structures is contained in ISO 13565-3 standard, basing on the cumulative distribution plot on normal probability graph. Greenwood and Williamson [1] thought that non-Gaussian worn surfaces can be characterized by a Gaussian distribution of summit height. Leefe [15] also believed that because contact was related to the behavior of plateau surface portion, the contact behavior is governed by the Gaussian distribution of summit heights from this surface part. However it was found that the valley part affected contact properties of the stratified surface. The method of calculation of plasticity index of two-process surfaces was proposed [16]. However, this work was restricted only to isotropic textures.

The main aim of this work is to develop method of plasticity index calculation for honed and particularly plateau honed cylinder surfaces. This would help to better predict the ability of cylinder to plastic deformation and hence wear. The other aim is to find if the calculation of the plasticity index by taking the cylinder axis and circumference as the principal axes leads to tolerable errors.
2. Materials and methods

Twenty five honed (one-process) and plateau honed (two-process) cylinder liner surface topographies were measured by white light interferometer Talysurf CCI Lite (1024 x 1024 points, sampling intervals 3.3 µm in perpendicular directions, measurement area 3.28 x 3.28 mm). Honing angle α (see figure 1) of one process surfaces was in the range: 15°-70°, but of two-process textures 50°-60°. The height of one-process textures, determined by the Sq parameter (the root-mean-square value of the surface deviations) was between 0.5 and 2.8 µm. The values of the Sq parameter of two-process textures were smaller, up to 1 µm. These surfaces are better characterized by the root-mean-square value of the surface deviations Spq [17]. This parameter was in the following range: 0.1 – 0.4 µm. The form was removed by a polynomial of the 2nd degree. Digital filtration was not used.

![Figure 1. Honing angle α](image)

In both analyzed methods the plasticity index was calculated using equation (2). The equivalent radius of curvature in the traditional method was calculated in the axial and circumferential directions, while in the proposed method for principal curvature radii of individual asperities.

For measured surfaces, summits were identified on the basis of their eight neighbors [5, 18], which means that a surface point was classified as a summit when its ordinate was higher than ordinates of eights neighboring points. For each summit, the ratio of the smaller and the larger radii of curvature in the axial and circumferential directions $\gamma_1$ was computed using a three-point Lagrangian formula [19]. Then the ratios of the radii in orthogonal directions for different orientations (9° resolution) were computed and the smallest value, $\gamma_2$ was recorded. Average values of these ratios were stored.

The error in the plasticity index estimation using $\gamma_1$ (traditional method) rather than the true value $\gamma_2$ (proposed method) was computed. Taking the sum of any two orthogonal curvatures as equal to the sum of the principal curvatures [4] leads to an error estimate of:

$$\Delta = \left(1+\gamma_2\right)^{-0.5} \left(\frac{\gamma_1}{\gamma_2}\right)^{0.25} - 1$$

(3)

The method of calculation of plasticity index of two-process surfaces is proposed in Reference [16]. In this approach, only the summits which taking part in contact were taken into consideration.

3. Results and discussions

One-process surfaces

Hybrid and spatial properties of surfaces and hence the values of plasticity index depend on the sampling interval [5, 20, 21, 22]. The smallest sampling interval was 3.3 µm, while the sampling...
Intervals used in calculating various radii varied with angular orientation, but were always the same in the orthogonal directions. The $\gamma_1$ values were larger than 0.3; in most cases the $\gamma_2$ values were similar or greater than 0.2, so the correction factor [8] is of little significance. Similar results were obtained previously [23]. Figure 1 presents an example of the analysed cylinders with values of the degrees of anisotropy $\gamma_1$ and $\gamma_2$ as well as of errors of the plasticity index calculations $\Delta$.

$\gamma_1 = 0.3$, $\gamma_2 = 0.2$, $\Delta = 6.2\%$  
$\gamma_1 = 0.46$, $\gamma_2 = 0.23$, $\Delta = 8.9\%$  
$\gamma_1 = 0.48$, $\gamma_2 = 0.2$, $\Delta = 12.2\%$  
$\gamma_1 = 0.57$, $\gamma_2 = 0.2$, $\Delta = 13.5\%$

**Figure 2.** Contour plots of one-process measured cylinder liners with values of $\gamma_1$, $\gamma_2$ and $\Delta$.

The errors of the plasticity index estimation using $\gamma_1$ than $\gamma_2$ led to an overestimation of the plasticity index. These errors (equation 2) were between 6 and 15.5%. Such errors are reasonably acceptable bearing into mind the large uncertainties in the measurement of some surface topography parameters and the assumption that circumference and axis define the major axes suffices. However, it is not difficult to compute more correct $\gamma_2$ instead of $\gamma_1$. From the analysis of cylinder liners contour plots, one can assume that the errors should be larger for larger honing angles. These assumptions were confirmed (see figure 3).
Figure 3. Dependence between honing angle and error of plasticity index calculation

Two-process surfaces
Calculation of the plasticity index of the whole surface by can seriously overestimate its value. In order to compute the plasticity index of the two-process surface in a correct way, the special procedure was developed. All summits should be recognized. The heights of all summits should be stored. Then the special profile containing heights of asperities was obtained. This profile was analysed using probability approach [9, 10, 11, 12, 13], in which material ratio is expressed as Gaussian probability in standard deviation (s) values, plotted linearly on the horizontal axis (-3s = 0.13%, -2s = 2.28%, -s = 15.8%, 0 = 50%, s = 84.13%, 2s = 97.72%, 3s = 99.87%). For profiles composed of two Gaussian distributions, the material probability curve exhibits two linear regions. There are two parts of the profile obtained from heights of summits – plateau and valley. There are 3 kinds of summits on the two-process surface (see figure 4). For summits of type 1, both the summit and its neighbouring points belong to the plateau part PP. A summit of type 2 belongs to the plateau part, while its neighbouring points to valley part VP. However, a summit of type 3 belongs entirely to the valley part. To calculate the standard deviation of asperity height and mean radius of summits curvature only summits of types 1 and 2 should be analysed. Therefore only summits positioned vertically between the highest summit and the horizontal line visible in figure 4 were taken into consideration. The procedure of the plasticity index calculation for two-process surfaces is detailed described in Reference [16].
For identified summits, degrees of anisotropy $\gamma_1$ and $\gamma_2$ were computed. The anisotropy ratios were calculated for all summits and only for summits belonging to plateau parts. The analysis of only summits of types 1 and 2 led to an increase in the degree of anisotropy $\gamma_2$ calculated for all summits. Smaller but similar changes in calculating the $\gamma_1$ ratio occurred. In all analysed cases the $\gamma_2$ values were greater than 0.2, so it is not necessary to use the correction factor $\varphi(\gamma)$. However, after study of all summits, this correction would be needed. The errors of the plasticity index calculation were between 10.5 and 11.9%. Similar values of the honing angle may be the most probable reason of stable errors. Figure 5 shows an example of the analysed cylinders with values of the degrees of anisotropy $\gamma_1$ and $\gamma_2$ as well as of errors of the plasticity index calculations $\Delta$.

However, the most important difference in plasticity index calculation for all summits and summits belonging to the plateau part is the standard deviation of asperity height $\sigma_s$. This parameter is much higher after considering all summits existed on the surface, leading to overestimation of the plasticity index.
\[ \gamma_1 = 0.55, \gamma_2 = 0.22, \Delta = 11.2\% \]
\[ \gamma_1 = 0.22, \gamma_2 = 0.5, \Delta = 10.9\% \]

**Figure 5.** Contour plots of two-process measured cylinder liners with values of \( \gamma_1, \gamma_2 \) and \( \Delta \)

Greenwood and Williamson [1] in 1966 developed a basic contact model of isotropic surface, in which all asperity summits have the same radius but their height varied randomly. The interaction of asperities was not taken into consideration. From this time, new better models were developed. For example, the Boundary element method-BEM in a half space is well established and used method for contact simulations. Also BEM does not have problems with the definition of a summit. However, no alternatives to plasticity index have not been developed yet.

4. Conclusions
Only a tolerable level of error is introduced in plasticity index calculations by taking the cylinder axis and circumference as the principal axes when the honing angle of one-process textures is between 15 and 70°. The errors are larger when the honing angles are larger. However, a procedure for calculating the anisotropy degree in a better way can be easily developed. Similar and even smaller errors were obtained when two-process cylinder liners are analysed for the honing angles between 50 and 60°. The analysis of only summits which might take parting contact led to an increase in the degree of anisotropy \( \gamma_2 \) calculated for all surface summits.

It is not necessary to use the correction factor for plasticity index calculation of honed and plateau-honed cylinder surfaces because the correction factor \( \gamma_2 \) was typically higher than 0.2.

The errors of the plasticity index estimation calculating the equivalent radius of curvature in the axial and circumferential directions led to an overestimation of the plasticity index.

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