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METHODS OF SURFACES QUALITY COMPARISON IN MECHANICAL ENGINEERING APPLICATIONS

L. SOLECKI✉

Széchenyi Istvan University, Department of Materials- and Vehicle Manufacturing Engineering
9026 Győr, Egyetem tér 1. HUNGARY
✉E-mail: solecki@sze.hu

The macro- and micro-geometric properties featuring the boundary surfaces of machine components are important for quality reasons. The comparison of surfaces is needed if the machined surface is to be matched to preset requirements or the same surface can be manufactured with different manufacturing processes or various measurement and surface testing methods are available, or the time variation of the surface is to be assessed. After the comparison, surface deviations must be numerically evaluated in relation to size, shape, position, and surface irregularity. Nowadays, surface irregularity tends to represent not only the unevenness of the surface but also the comparison of the real surface to a favourable micro-geometric structure. Information on the actual surface is obtained through perception (optical or mechanical), and the nominal surface can be a mathematical model, a sample, or a previous condition of the surface in the form of any previous perception, or a previously made print of the surface (replica). During comparison, similarities and differences must be evaluated in terms of the key properties of the surface related to the operation of the given component. Comparison based on visual inspection is a suitable and acceptable method for a quick inspection, for identification of the parts of the component, and for detection of significant deviations. A technically more advanced method is image processing. Three dimensional properties of the surfaces can be evaluated with 3D geometric calculation methods and methods developed for surface roughness. The presentation introduces a method for comparing cylinder surfaces of an internal combustion engine and presents an example of the method currently used in automotive engineering applications.

Keywords: surface comparison, cylinder liner, replica

Introduction

Particular points are measured with 1-2 or 3 coordinates in the length measurement technique in mechanical engineering (along a straight line, in plane or space). Based on the measurements, dimensional, shape and position accuracies, and the surface irregularities of the parts are concluded. If the distance between two bores on the connecting rod given in *Fig. 1* is to be determined then, in theory, it is sufficient to measure the outer (O) and inner (I) dimensions of the bores and to calculate the centre distance (D) based on this with the following formula:

$$D = \frac{(I + O)}{2}, \qquad (1)$$

where:

D – centre distance
O – outer dimension of the bores
I – inner dimension of the bores

This formula is valid for two parallel cylinders. In fact, we try to approach parallelism of the cylinders and the axes of the two bores as far as possible in relation to the shapes of the bores, but this is possible only with the accuracy that is allowed by our production processes.

Figure 1: Connecting rod of an internal combustion engine

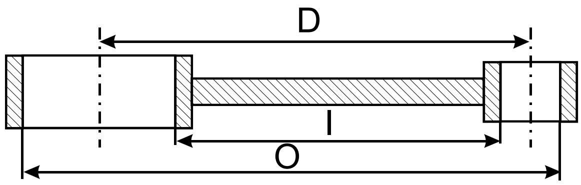

Figure 2: Theoretical determination of the centre distance on the connecting rod

The profile of a real bore surface measured in one section and its approximate circle are presented on *Fig. 3*, its profiles measured in several sections on *Fig. 4*.

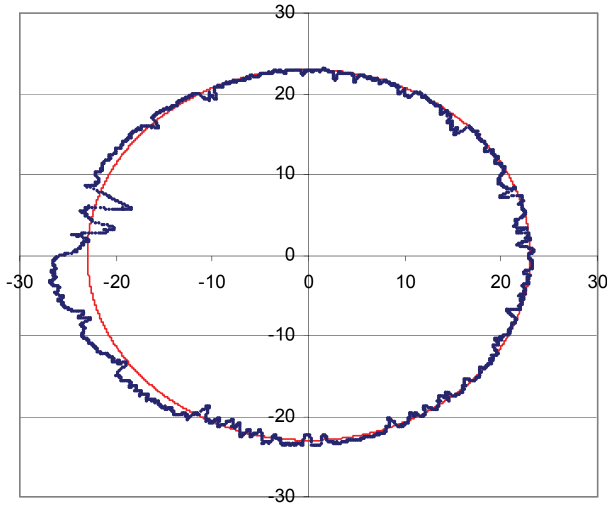

Figure 3: Profile of bore in 1 section and its approximate circle (shape distortion, 100x zoom)

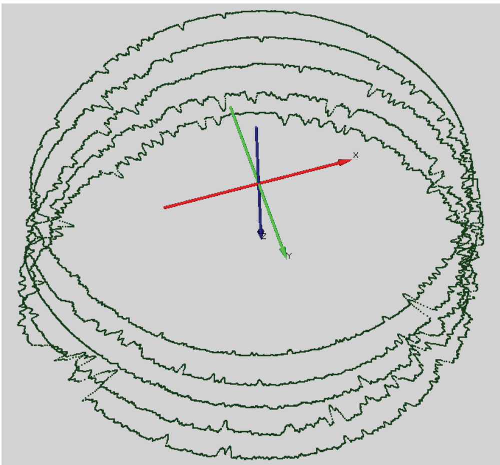

Figure 4: Measured profiles of bore in 5 sections

The centre distance between real bores of irregular geometry can be considered a two-dimensional problem in a simple case. The bore profiles in the mid-pane of the connecting rod, and their approximate circles and their distances are determined.

If the issue is considered a spatial problem then the profile of each bore is measured in several sections, and then the cylinders approaching the profiles measured for the individual bores are determined. The approximate cylinders are likely not to have parallel axes, and as a result, we could not use their distances in a mathematical sense either. In techniques, the minimum and maximum values of the centre distances are determined for one piece in such cases, and the centre distance is interpreted to be located between these two values.

To be able to use the above formula (1), first we have to determine either the approximate circle of the measured profiles of the circles, or the approximate cylinders of the profiles. This means fitting of a circle to the measured profile in plane, and a cylinder to the measured profile in space.

This simple example proves that whether a size, or a shape or a position is determined in length measurement technique, surfaces must be compared in space and profiles in plane, and they must be properly fitted to compare the surfaces.

Perception of surfaces

Spatial surfaces are perceived by touch or in an optical way. Perception by touch is the determination of the spatial position of a finite or a preliminarily defined point or a point in a system (touching along a line or a circle). Optical perception is possible from point to point, similarly to mechanical touching, but several points may be taken within one shot. Optical perception does not use force (suitable for elastic parts and it is easy to fasten the piece), there is no wear, and generally more points can be taken in a shorter time than in the case of perception by touch. Visibility of the surface is required for optical perception. Inner surfaces can be also perceived if X-rays are used (CT technique). Coordinate measuring machines are used basically for the measuring of regular geometries in the orthogonal coordinate system, circularity testing units are used for the measuring of rotational-symmetric parts in the cylindrical coordinate system, optical surface digitalisation systems may be used also for the perception of surfaces of regular but free geometry (orthogonal coordinate system), shape testing units make several sections (plane orthogonal coordinate system), surface-roughness testers make plane sections, but the spatial pattern of the measured surface can be given by the parallel sections. [1]

Principle of surfaces comparison

To determine a geometric dimension, distance between nominal surfaces approaching the real surfaces must be determined in accordance with the example given in the introduction. To determine the shape distortion of the surface, the nominal surface most approaching the surface must be determined again, and the shape distortion will be the greatest deviation of the actual surface from the most approaching nominal value. In the example, the shape distortion of the connecting rod bore is the distance of the point perceived at the greatest distance from the cylindrical shell most approaching the bore. To determine the position fault of a surface, determination of the nominal surface most approaching the real surface is the first step again, but then the position of the real surface is identified with the position of the approximate nominal surface. The parallelism fault of the connecting rod bores is the distance differential of the axes of the cylinders most approaching the bores within the volume of the connecting rod. Surface irregularity is the deviation between the real surface and the most approaching nominal surface (plane or cylinder), but the difference from shape distortion is that surface irregularity is examined not on the whole surface but on its basic length involved in irregularity. To determine the surface irregularity of the connecting rod, a line and a plane are fitted not onto the whole surface but onto its small socalled basic length section, and the distance measured between the measured points is the irregularity.

Perception is followed by the determination of the nominal surface most approaching the perceived points. The most approaching profile or surface may be situated basically in two ways: delimiting the measured points from a direction (contact plane of spatial points, greatest circle that can be drawn in the bore, or the smallest circle that can be drawn around points of a stud), or passing between the points so that the resulting division is the least (principle of least squares). [DIN EN ISO 14660-2 [DIN EN ISO 14660-2, DIN ISO 1101, DIN ISO 8015]

In case of simple geometries (line, circle, plane, cylinder, sphere) the surface most approaching the measured points can be calculated in a closed form, and in case of complex surfaces (involute, thread profile, fee surface) approximate iteration methods can be used [2].

Wear analysis of cylinder surfaces of internal combustion engines

On the cylinder surface, the wear is less measurable for the change of the surface dimension or shape than for the change of the micro-geometry (irregularity) of the surface. The starting cylinder surface is of a special pattern to make the surface the smoothest, and thereby to provide a surface less resistant to motion, requiring a thin lubricant film, subject to less wear, having good bearing properties, but allowing lubricant adhesion. The shape of the cylinder surfaces (cylinder) is provided by honing after drilling. The honing pattern is typical for the whole surface, and the bidirectional linear traces including a specific angle to the movement direction of the piston are evenly spaced. Since honing is made in several steps using tools with various granulation sizes, therefore deeper and shallower traces alternate in the pattern. In addition to traditional honing, surface treatment procedures, such as surface laser treatment, providing sufficient lubricant film also over minor surface irregularities and – as in the case of laser treatment – making the surface material layer more resistant to wear are also more and more widely used today [3, 4].

Silicon prints were taken of the starting cylinder surface [5, 6]. There are special optical measuring instruments (white light interferometer) able to image the cylinder surface without cutting it. Though it is indirect and therefore a disadvantageous method from a point of view of measurement technique, surface evaluation made on the basis of the print has the advantage of preservation of the surface as the wear itself will subsequently determine the places relevant for the evaluation. The engine assembled after the print had been taken was operated for 350 hours under various loads on a test-bench. After disassembly of the engine, the cylinder block was cut so as to be able to take direct micro-geometric and microscopic measurements on the surface, but prints were taken also of the worn cylinder surface so as to be able to evaluate the accuracy of transfer from the surface pattern to the print.

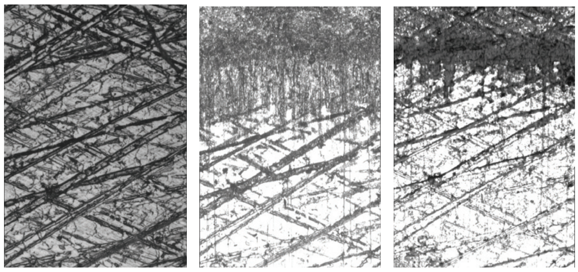

Figure 5: Optical images of the same point: starting condition of the cylinder surface, worn condition on the silicon print, and the worn condition directly on the cylinder surface

The left image on *Fig. 5* shows the silicon print taken in the starting condition of the cylinder surface, the middle image shows the silicon print of the worn condition, the right one shows the cylinder surface, and they are vertically mirrored to show the patterns in the same position as on the prints. The pistons move vertically, the images show 0.5 mm x 0.8 mm surfaces. The images show the honing pattern, the dark spot on the top of the images of the worn surfaces is the spot above the upper dead point of the upper piston ring. In this area, nothing contacts the surface and coke adheres to it in the explosion chamber. On the starting surface, only the deeper and shallower patterns of honing are visible, wear is represented by two phenomena: vertical scratches appear and the depth of the original pattern decreases. This will disappear in the case of fine patterns - and surface parts with fine patterns become bright.

Optical examination is necessary since the whole surface can be examined with 200 times magnification, on 1.2 mm x 0.9 mm images. Surface parts to be evaluated for wear can be chosen and their positions can be determined with optical examination. The optical examination is made with coordinate measuring apparatus type MAHR PMC800. The examination was based on the worn print, and spots preliminarily chosen on the worn print were searched on the print of the original surface and the worn cylinder surface with the optical examination. The optical examination does not give wear figures.

Scanning of the chosen surface parts with surface-roughness tester type Talysurf CLI2000 is the next step of the examination. The prints were digitalised with confocal optical scanning, and the worn surface with needle scanning. As a result, the surface height was obtained in 0.5 μm x 0.5 μm grid points, in 10 nm resolution.

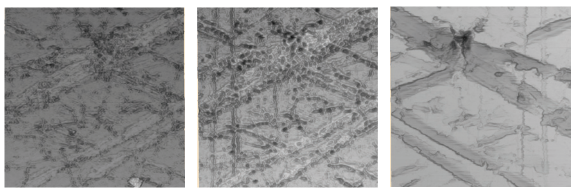

Figure 6: Illustration of bivariate point distribution after surface scanning

The image of bivariate point distribution obtained via spatial scanning of a 0.3 mm x 0.3 mm part of areas shown on the previous images is illustrated on *Fig. 6*. Point clusters obtained with surface digitalisation were fitted using the surface digitalisation evaluation system of GOM-ATOS, GOM-Inspect, in two steps, first in a three point rough fitting procedure then by fine fitting of all points, with the best fit method. Fitting the bottom points of the deep honing grooves would have been more favourable from one aspect; since they are not worn, the wear points would have been directly obtained by fitting the point clusters here. The benefit of fitting all points is that if fitting is made to chosen points then the choice of the fitting points must be correct, and the measuring fault of the fitting points may distort the result.

Results and Conclusions

Fig. 7 shows the silicon print of the original surface and comparison of the silicon print of the worn surface. Image colours on the basis of the height difference: green: approximately identical height, blue: the print of the worn surface is deeper, red: the print of the worn surface is higher than the print of the original surface.

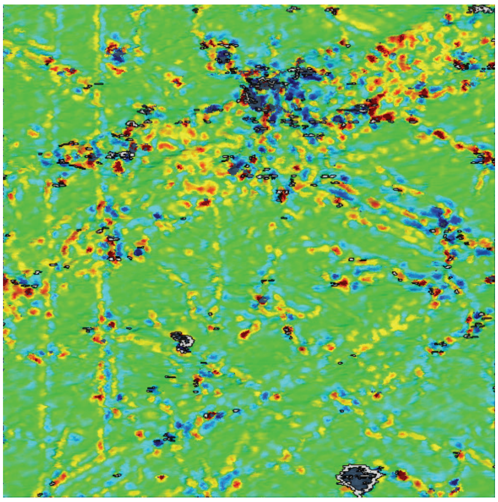

Figure 7: Comparison of the prints of the original surface and the worn surface

Choosing 10 yellow points, their average height is 1.2 μm, this is the height difference of the cylinder surface against the bottom of the honing grooves after wear.

Fig. 8 shows the comparison of the print of the worn surface and the direct needle scanning of the worn surface.

Since in this examination only small surface parts can be compared it is very important to be able to find the same maximum 1 mm x 1 mm surface parts in surface spatial perception. Another precondition is that the surfaces must definitely fit to each other, which is possible on the basis of the surface pattern, however the approximate position determination is still subjective and only fining is made with the best fit method.

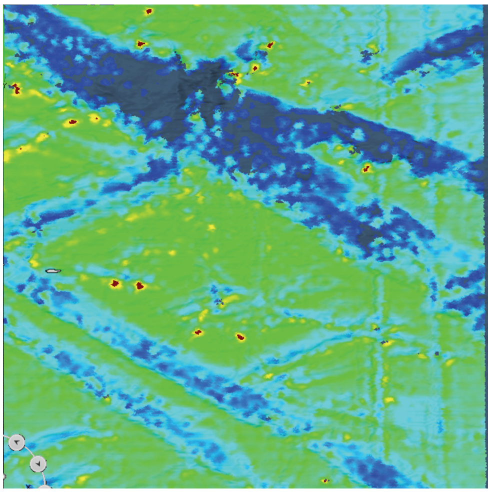

Figure 8: Comparison of the print of the worn surface and the direct needle scanning of the worn surface

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