Mechanical Engineering

DESCRIPTION OF SURFACES HAVING STRATIFIED FUNCTIONAL PROPERTIES

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***Abstract**: The article presents the characteristic of surfaces having functional properties. It discusses the parameters used to describe the roughness of this type of surfaces. It proposed the method of constructing software which calculates probability parameters.*

***Keywords**: two-process surfaces, roughness parameters.*

***ACM Classification Keywords**: Algorithm, Measurement.*

Introduction

During friction in the presence of a lubricant too smooth surfaces hold lubricating oil poorly (it can lead to erosion of a coupling), whereas too rough surfaces are worn away intensively. The opposing influence of small and large heights of surface roughness of a cylinder liner on the functional properties of the piston-rings-cylinder assembly caused that the researches began to conduct studies in order to find surfaces combining sliding properties of smooth surfaces with the oil storage capacity which is typical of porous surfaces. Thanks to those works, in the 1980s structures of cylinder liner surface achieved after two processes (plateau honing surfaces) came into being. They should be similar to the geometrical structure of cylinder liner surfaces which is created during running-in period, then the time of running-in process and wear should be smaller. The example of these kinds of surfaces is the surface of a cylinder liner after plateau honing. The basic tasks of this surface are: to ensure leak-tightness as well as to provide the piston-rings-cylinder assembly with optimal greasing of gear. The most difficult functioning conditions among all of tribological systems of an internal combustion engine are precisely in piston-rings-cylinder assembly [Niewiarowski, 1983]. In this system the particularly difficult conditions are found in the area of the top dead centre position of the first piston ring, where the thickness of an oil film between a packing ring and smooth surface of a cylinder comprises 0-3 µm. The coefficient of friction between the packing ring and a cylinder comes to 0.1-0.15. The piston-rings-cylinder assembly should assure mileage up to 500000 km with reference to personal cars and 1500000 km to trucks. Between the smooth surface of a cylinder and the surface of piston rings there are various greasing conditions from the boundary lubrication up to hydrodynamic lubrication in the middle of the piston's distance line [Shin, 1983], [Sudarshan, 1983]. To the dominant types of wearing-out of cylinders in an internal combustion engine the researches include: abrasive wear, corrosive wear, adhesive wear and from time to time fatigue wear.

According to the author [Kozaczewski,1986] of the research articles, the geometrical structure of cylinders surface influences engine properties, mainly in the initial stage of its functioning (the period of running-in). It is considered that the rough surface of cylinders causes little tendency to erosion, whereas smooth surface ensures their little wear in the period of running-in. At first, the researches stated that little wear in the period of running-in was found in cylinders characterised by great smoothness. As a result, this kind of cylinders was recommended. However, as progression in engine construction was marked (most of all in the load growth), erosions of cylinders' smooth surface happened. The author of publication [Wiemann, 1971] claimed that the bigger height of roughness of cylindrical liner which does not have additional surface treatment is, the greater its erosion resistance. It appeared that considerable increase of roughness height is also unfavourable because it causes acceleration of chromium plated piston rings wear. The researches [Sreenath, 1976] proved that above the optimal roughness height of Ra=0.8 μm parameter, the linear wear of cylinder rises. Duck [Duck, 1974] determined the advisable value range of parameter Rt for spark-ignition engines: 2-5μm, whereas for diesel engine 4.7 μm. The authors of the review work [Day, 1986] came to the similar conclusions. The advisable greater roughness in diesel engine results probably from the greater loads in this kind of engine. The difference in functioning conditions of various types of engine is the cause of discrepancy with regard to honing cross-hatch angle α (fig.1), usually smaller in spark-ignition engines in comparison to diesel ones.

a) b)

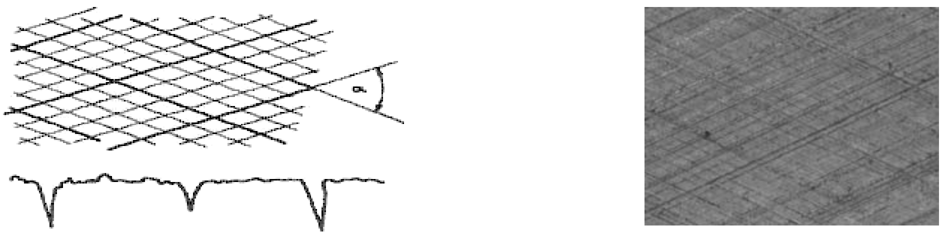


Fig.1 Schematic diagram of a cylinder after honing (a) [Zwierzycki, 1990] and a photograph of the surface of a cylinder liner (b)

The smaller honing cross-hatch angle affects the decrease in consumption of oil which is particularly aimed at in spark ignition engines, but in the case of compression-ignition engines more important issue is to eliminate the galling. Decreasing of the honing cross-hatch angle causes oil film thickness reduction which leads to greater loss of energy and increasing of wear.

The authors of the publications [Pawlus, 1994], [Willis, 1986] confirmed that plateau honing provides lesser linear wear during running-in period and the time of this process might be shortened in comparison to one process honing. In his work [Campbell, 1972], Campbell affirmed that the achievement of linear wear corresponding to 30% of bearing ratio requires two times less of volumetric consumption in the case of plateau honing cylinders in comparison to the similar surface of the same roughness height after one process honing. The usage of plateau honing caused significant reduction of running-in time [Willis, 1986]. Santochi and Vignale [Santochi, 1982] employed plateau honing with reference to air cooled motorcycle engines. They reached geometrical structure od surface characterized by Ra=1μm, Rz=12 μm, Rv/Rp=2 parameters, however traditional structure was characterised by the following parameters: Ra=2.4μm, Rz=18 μm, Rv/Rp=1.1. One obtained faster stabilization as well as improvement of functional parameters of engine after running-in by replacing the traditional honing with the plateau honing (fig. 2). Dolecki et al. in their research [Dolecki, 1983] proved smaller oil consumption (at about 20%) by engine in the case of equipping it with plateau honing cylinders. The research conducted on Polonez engine shows that the plateau honing has a positive influence on the linear wear of cylinders during running-in. It allowed to conclude that the linear wear in the period of running-in is proportional to roughness height as well as to emptiness coefficient Rp/Rt [Pawlus, 1999]. The evidence for the supremacy of plateau honing over one-process honing are also works [Essig, 1990], [Barber, 1987]. One of a few comprehensive works concerning the influence of two processes surface on fricative tribological properties is Jeng's work [Jeng,1996]. He highlighted that the research described in literature was not able to grasp only the influence of microgeometry of surface on the wear, therefore he was not sure about the need of using additional process of honing.

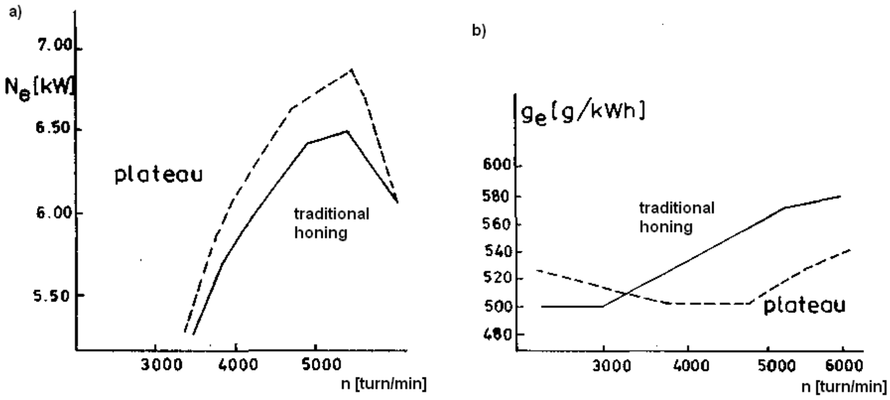


Fig.2 The influence of geometrical structure of surface on power output Ne (a) and individual fuel consumption ge (b) [Santochi, 1982]

He studied the one process honing surfaces and plateau honing surfaces, both kinds of the surfaces had the same values of the Rq parameter. On the basis of experiments carried out on the special simulation stand he found that the two processes surfaces have a shorter running-in period and less galling resistance in relation to the one process surfaces (the resistance may be increased by the use of oil additives).

The initial wear of these surfaces during the running-in period was greater, however they quickly attained a constant intensity of wear. Therefore, during the work of piston-rings-cylinder assembly they ensure less wear in comparison with surfaces after one process honing. He also performed friction coefficient test and found that in the course of the work in a homogenous hydrodynamic lubrication conditions, the coefficient of friction two-process surfaces is the same as the one-process surfaces. However, the two-process structures of surface are more advantageous from the point of view of the influence on the mixed friction coefficient.

Nosal considers [Nosal, 1998] that the increase in resistance of galling of the plateau honing structure is caused by the increase of oil surface capacity (which causes lubricating layer thickness increase, the reduction of friction resistance and temperature in the contact zone), and frequent interruptions of two surfaces being in contact caused by valleys (which reduces the probability of a galling centre).

The authors of the publications [Sudarshan, 1983] paid attention to the possibility of accumulation of abrasive particles in valleys created during honing process. It should lead to reduction of intensity of abrasive wear. The considerable deterioration in lubrication conditions since the disappearance of valleys was observed by the authors of the publications [Stout, 1990]. This kind of situation causes possibility of intensification of the abrasive wear or generation of galling danger. The specific danger appears in the high loaded diesel engines, in this case on the cylinder liner a very smooth texture comes into existence, it resembles bore polishing surface of a significant tendency to galling. This is the case when together with the increase of smoothness friction increases as well. The authors of the publications [Michalski, 1994] studied the influence of roughness of cylinders liner surfaces on the value of abrasive wear which significantly exceeds the initial roughness height. As a result of the conducted studies, they claimed that the abrasive wear of the cylinder liner is proportional to the distance between the honing valley and to the value of the emptiness coefficient Rp/Rt. Excessive increase of height roughness causes oil consumption increase in the engine [Kozaczewski, 1986]. Figure 3 shows an example of the impact of roughness height of the cylinder liner on the oil consumption.

During recent years there have been a few changes in requirements relating to cylinder liner roughness: from very smooth, mirror-surface (Ra = 0.20 mm), by changing the roughness to higher one (Ra in range 0.8-1.2 mm) caused by the increase in power of an engine, up to plateau structure which is now almost universally applicable.

The increased roughness diminishes the ability to galling, however, it causes the increased consumption of oil and increased toxicity of exhaust gases.

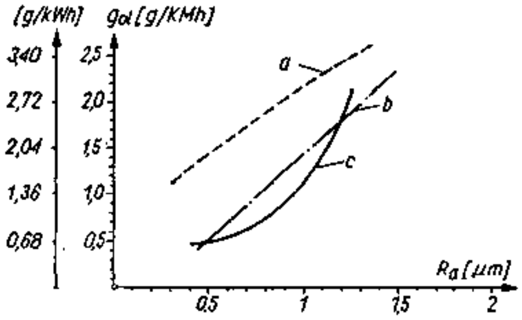


Fig. 3. Influence of cylinder liner roughness on the oil consumption in internal combustion engine [Kozaczewski, 1986]: a) compression-ignition engine, Vs (engine cubic capacity) = 6 dm3, b) spark ignition Vs = 1.3 dm3, c) compression-ignition, V s = 4 dm3

We can also find the opposite statement. For example, Gruszka [Gruszka, 1983] in his doctoral thesis maintains that too low roughness increases the consumption of oil.

During the construction process of new engines manufacturers of trucks must take into consideration very stringent requirements which are constituted by the European Union standards included in the series EU III/IV/V relating particularly to toxicity of exhaust gases. Therefore, they strive to reduce the roughness of cylinder liner, which leads to reduction of oil film thickness and consequently to smaller oil consumption and exhaust gases emissions. Currently, there are the following ways of honing development of cylinder liner surfaces:

- glide or slide honing,
- honing using laser beams to cracks cutting,
- manufacturing of lubricating pockets on the smooth honing surface.

There are two types of glide honing due to the honing cross–hatch angle:

- measuring 60° angle,
- measuring 140° angle, so called – spiral [Cieślak, 2008].

In currently manufactured (according to plateau standard) cylinder liners , cylinder bearing surface is described by the following roughness parameters: Rpk < 0.3 µm, Rk = 0.8-1.4 µm, Rvk = 1.7-3.2 µm. In order to decrease the thickness of oil film and reduce oil consumption as well as exhaust gases emissions it has been proposed to reduce the roughness to the following parameter levels: Rpk < 0.2 µm, Rk = 0.2-0.5 µm, Rvk = 1.4 to 3.0 µm. New requirements focus on even greater reduction of parameter Rk value.

The researchers from the Volvo and the University of Halmstad (Sweden) followed the program Piston Simulation for the analysis of impact of the geometrical structure of cylinder liner surface on the oil film thickness and friction force. It was found that the increase of the value of the Rk parameter has an impact on increasing both analysed values in a top dead centre position of the piston [Johansson, 2008].

The authors of the article [Ohlsson, 2003] explored the correlation between roughness parameters of a cylinder liner and consumption of oil by the engine. Oil consumption is proportional to the value of many parameters of geometrical structure of cylinders liner surface, but only Rq, Rvk and Rk parameters in 2D and 3D correlation coefficients are included within the limits of 0.9-1.

The Authors of the articles [Hassis, 1999], [Schmid, 2006], [Schmid, 1999] from Nagel company think that producers should aim at minimizing the value of the parameters Rk and Rpk in order to reduce oil consumption.

They presented the results of the studies in accordance with which the change of the classical plateau honing (Rpk < 0.2 μm, Rvk = 1.4 to 2.0 μm, Rk = 0.6-0.8 μm) to the glide honing (Rpk < 0.1 μm, Rvk = 0.8-1.2 μm, Rk < ¼ Rvk) leads to the reduction in consumption of oil by the engine (over 60%). The reduction of oil consumption is even more affected by the application of spiral honing.

It is essential to modify the honing cross-hatch angle by the application of spiral honing. Application of angle less than 90 degrees counteracted too easy blow-by of oil into the combustion chamber. However, the increase of the honing cross-hatch angle (fig. 1) leads to the decrease of abrasive wear of cylinder liner. The applied honing cross-hatch angle less than 180 degrees allows rotations of the piston rings. The laser honing process is a perspective technology, since it allows to reach the geometrical surface structure with the guarantee of small oil consumption and adequate lubrication surface of cylinder liner at the most loaded place - in piston's top dead centre position. The remaining surface of cylinder liner can have small height of roughness. For example, Klink [Klink, 1997] received the cracks with a width of 40-80 μm, depth 5-25 μm, and the mutual distance of 300 μm. Figure 4 shows examples of cylinder liner surfaces made by different methods.

a)

b)

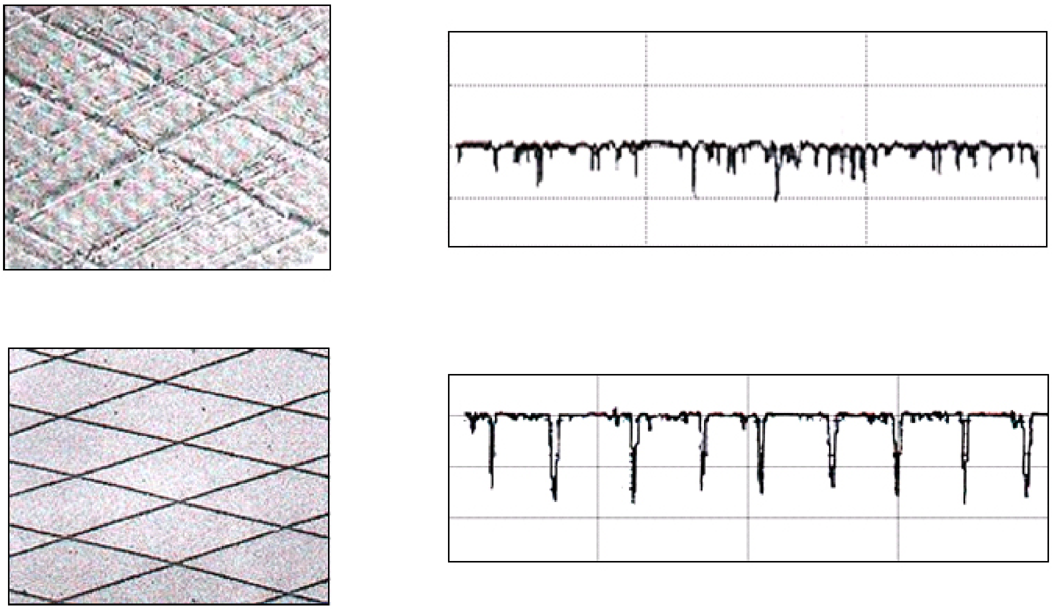


Fig.4. The surface of cylinder liner after glide honing (a) and laser honing (b) [Cieślak, 2008]

As a result of literature analysis it can be concluded that the topography of the cylinder liners' surfaces formed by honing process has a significant impact on the operating parameters of the combustion engines, particularly in the early period of their work.

Description of two-process surfaces

In accordance with the information contained in the works of [Chusu, 1975], [Nowicki, 1991] the profiles of cylinder liner surfaces after plateau honing are irregular, they usually have random character. When on this kind of profiles periodical irregularity appears then we can qualify them to the mixed profiles. Periodic irregularities depending on oscillation and kinematics of machining process may be a consequence of the earlier boring process of cylinders. Due to the explicit directionality of cylinders' patterns the authors [Wieczorowski, 1996] rated the cylinders' surfaces after honing to the mixed surfaces. According to the author of the work [Michalski, 1998] waviness of surface of honing cylinders has the random characteristics.

In connection with an important impact of the geometrical structure of surface of cylinder liner on the combustion engines exploitation properties, their producers have high requirements concerning the roughness parameters of plateau honing surfaces.

These requirements are mainly related to the proper determination of material ratio curve (so called bearing curve or Abbot Firestone curve) of roughness profile, the profile height and the distance between the deep valleys. The requirements of Berliett company from the 1970s (see fig. 5.) are typical example.

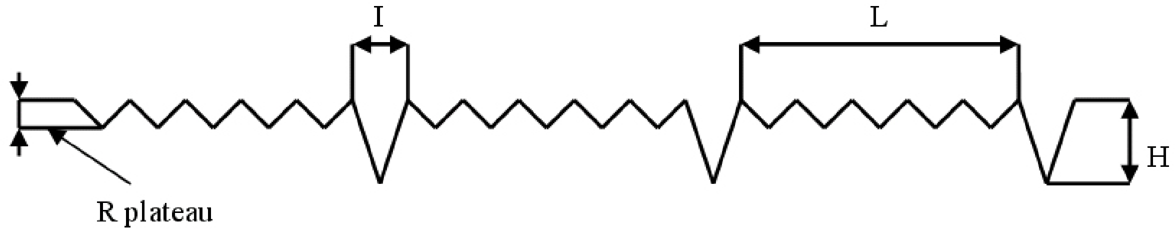


Fig 5. Roughness parameters describing the cylinder liner surface profile [Cieślak, 2008]

Parameters should take the following values:

- average roughness depth: 2.5 μm ≤ R ≤ 6.5 μm

- "plateau" roughness depth: 1 μm $_{plateau}$ ≤ R ≤ 3 μm

- depth of valleys: 6 μm ≤ H ≤ 16 μm

- width of the plateau: 125 μm ≤ L ≤ 600 μm

- width of valleys: 10 μm ≤ I ≤ 65 μm

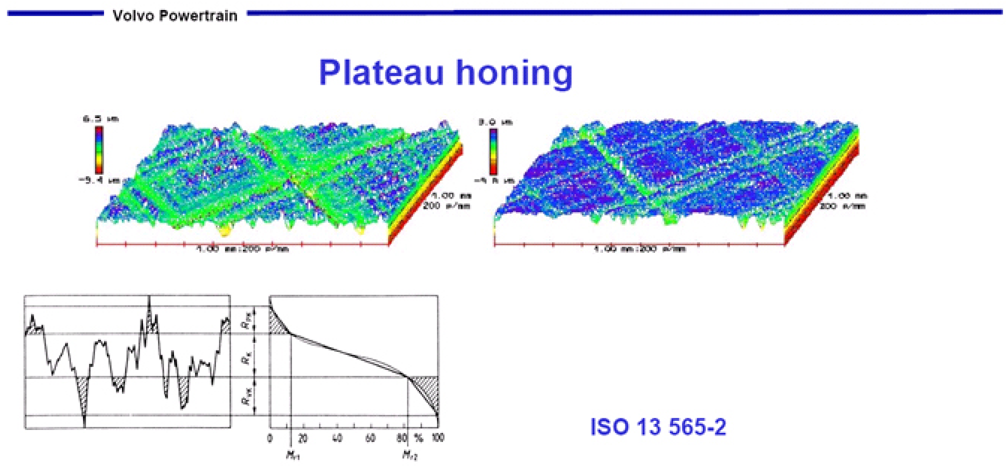
Important parameters are the horizontal ones, it is demonstrated by the fact that the average distance between valleys and their dimensions are often included in the requirements of engine manufacturers.

The method of determining the width of the valleys previously required by the GOETZE company was subjective. More objective manner, similar to the method described in the article [Michalski, 1994], is shown in the work [Lenhof, 1997]. It is based on the number of intersections of profile with the line described in DIN 4776 standard. Other parameters, used by researchers because of their statistical significance are the statistical moments of the third and fourth order: Rsk (skewness or asymmetry) and Rku (eksces or kurtosis). Willn [Willn, 1972] said, however, that these parameters are correlated with each other, therefore, he proposed additional parameters based on analysis of distribution of the number of peaks or distribution of cross sections of the profile lines parallel to the geometric mean line.

Many researchers associated with automotive companies use bearing area curve to cylinder liner surface analysis. In this curve we can distinguish 3 basic parts: peak, central and valley area, responsible for the different properties of surface. Abbott and Firestone [Abbott, 1993] considered that part of the peak corresponds to 2-5% of the bearing ratio, the central 25-75%, valley 75-98%.

German researchers proposed the profile roughness description method described in DIN 4776 (and later ISO 13565-2). Nielsen thought that honing process can be controlled by changing of Rk parameter value [Nielsen, 1988]. Authors of the work [King, 1994] tried to determine the value of the five parameters from the group "Rk" on the basis of the value of the parameters Rsk, Rku Rq. It is possible only for certain types of ordinate distributions, which are characterized by small asymmetry.

Criticizing the method defined in DIN 4776, Zipin in his work [Zipin, 1983], discredited its usage for analysis of surface's profiles having Gaussian's ordinates distribution. Also the authors of the work [Malburg, 1993] express doubts as to the correctness of the determination of Mr2 parameter. It depends on the slope of the material bearing ratio curve in its middle area. The parameters contained in ISO 13565-2 are used by most European manufacturers of internal combustion engines.



	P3108	HDEP	Gleid Old	Gleid New
Rpk <	0.3	<0.3	<0.3	<0.2
Rk =	0.8-1.4	0.5-1.1	0.2-0.5	0.2-0.5
Rvk =	1.7-3.2	1.4-2.4	0.6-1.8	1.4-3.0

Fig 6. The values of cylinder liner surface parameters used by the Volvo company [Cieślak, 2008]

Figure 6 shows the requirements applied by the VOLVO company for compression ignition engines used in trucks. Authors in the work [Michalski, 1992] suggested a method based on the analysis of approximated material ratio curve. They applied the following equation (1):

$$R = 0.35[1 + (2/\pi)arctg(A\{tg[(\pi/2)(2tp-1)] - tg[(\pi/2)(2X0-1)]\})] + 0.3tg(Btp)/tg(B) \quad (1)$$

where A, X, B-independent parameters, R - standardized height of the roughness , tp - bearing ratio.

This approach allows you to specify the minimum and maximum curvature of the coordinates (xrk1, yrk1, xrk, yrk), coordinates of a point of inflexion bearing curve (xpp, ypp) and tangent of slop of this curve at that point (del).These parameters and the ones resulting from ISO 13565-2 are shown in Figure 7. The parameter yrk1 is analogous to yr1, yrk-yr2, ypp-pp, xrk1-Mr1, xrk- Mr2, del-Rk/Rt, Vok-Vo2.

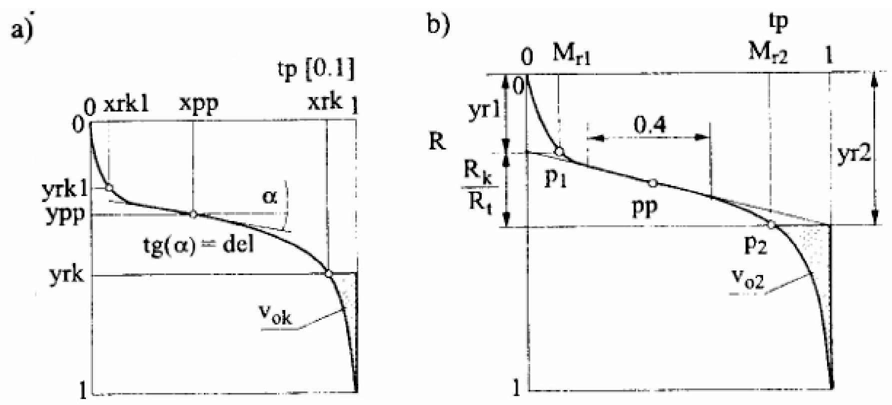


Fig 7. Some parameters of roughness resulting from the approximation of the Abbott curve, (a) and ISO 13565-2 standard (b) [Pawlus, 1999]

The authors of the publications [Malburg, 1993], [Sanna-Reddy, 1997] proposed a method of analysis the surface obtained after many processes. It was used in the American company Cummins producing internal combustion engines. This method is described in ISO 13565-3 standard (fig. 8).

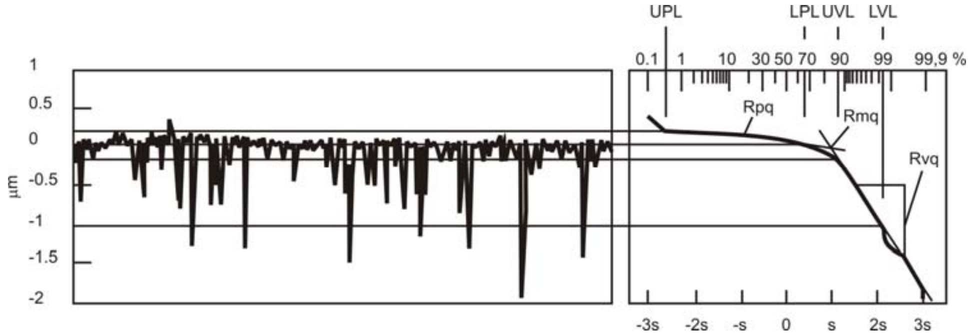


Fig. 8. Graphical interpretation of parameters contained in PN-EN ISO 13565-3: 2002 standard [Jakubiec, 2004]

This method called the probabilistic one, is based on an analysis of the data becomes from the bearing area curve plotted on normal probability paper. In this co-ordinate system, surface which has the Gaussian ordinate distribution is described by a straight line, but the surface after two-process honing, both of them having Gaussian ordinate distribution too, is described by two straight lines of different slopes. The intersection point of those lines in this graph according to the authors of the work [Malburg, 1993] separates the plateau and base texture.

In this graph the abscissa of this intersection point is defined as Rmq parameter (see fig.8) which is important feature of the model because it depends on the honing time. Rpq parameter is the slop of a regression line drawn through the plateau region, but Rvq – through the walleyes region. Rpq, Rvq and Rmq are three parameters independently characterizing each area of plateau honed surfaces, therefore the honing process controlled with their use should be precise.

This method was recommended in the work: [Whitehouse, 1985] [Zipin, 1983], it was also used for the analysis of the zero wear process and to study running-in process. It is conceptually simpler and more elegant than the method described previously (ISO 13565-2), but the practical difficulty of the parameters Rpq, Rvq and Rmq computations exists [Pawlus, 2009].

The method has been used to model the geometrical surface structure after two processes. The authors of the works: [Rosen, 2004], [Anderberg, 2009] analyzed the connections between parameters from ISO 13565-2 (Rk) and ISO 13565-3 (Rq) standards with honing process parameters. However, the conclusive answer to the question which group of parameters is more associated with the manufacturing process was not found. Parameters contained in ISO 13565 standard make a major contribution to an analysis of profiles after several processes. These parameters can be used also in 3D system. The analysis of the relative differences between parameters contained in the standards ISO 13565-2 and ISO 13565-3 and their three-dimensional counterparts is interesting. It can give the answer to the question whether these parameters describe the statistics (average) properties of the surface or they are susceptible to the presence of accidental valleys and peaks. In order to find the intersection point between plateau and valley areas, methodology described in ISO 13565-3 standard and other methods (for example [Sannareddy, 1998]) used different curves to the approximation probability plot of cumulative distribution. Those methods have some imprecisions which were noticed by the authors of the works [Jakubiec, 2004], therefore, the author proposes a different way of solving the problem. This method will be presented in the following subsection.

Implementation

To automatize the determination process of parameters Rq in plateau and valley area, computer program was created. This program was partly based on algorithm described in ISO 13565-3 standard. The main problem is to determine transition point between two random regions. To find this point material probability curve graph was rotated by ψ angle anticlockwise according to the following equation:

$$x' = x\cos\psi - y\sin\psi$$

$$y' = x\sin\psi + y\cos\psi$$

ψ angle is the slope of straight line passing by the first and the finishing point of the material ratio curve (see Figure 9).

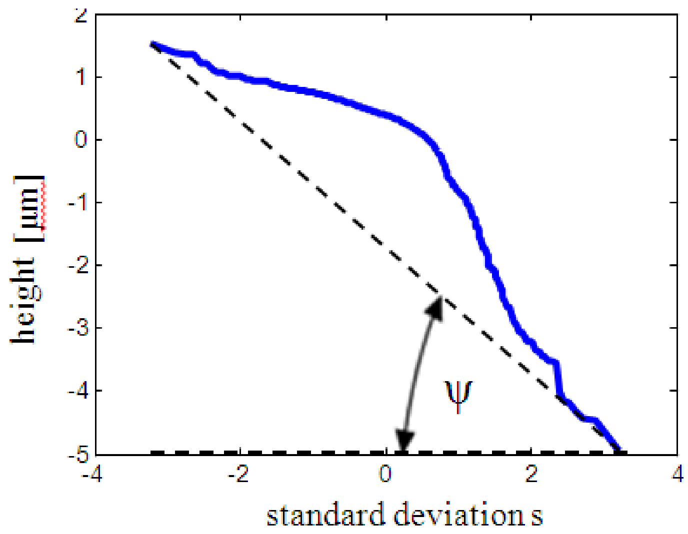


Fig.9. Material probability plot with straight line passing by the first and the finishing point and ψ angle In rotated diagram C point of the highest ordinate was determined (see Figure 10). This point is treated as transition between two random regions.

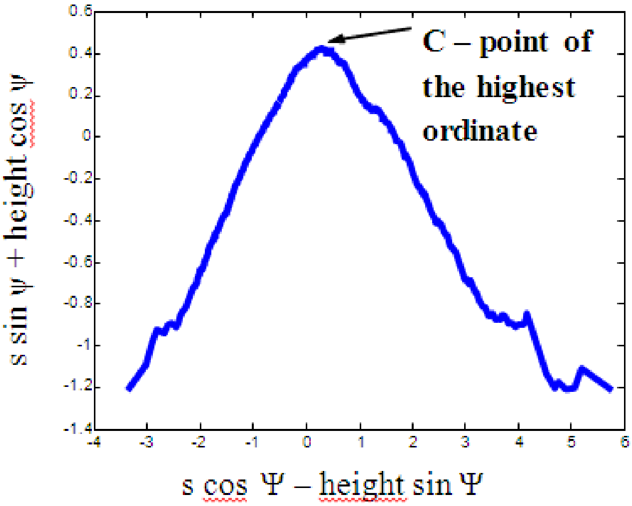


Fig.10. Material probability plot rotated by ψ angle

According to methodology which is recommended in ISO 13565-3 standard, nonlinear material probability curve graph regions were eliminated and Upper Plateau Limit (UPL), and Lower Valley Limit (LVL) points were assigned.

In material probability curve graph the lower boundary of the region plateau (LPL) and upper region valley (UVL) were determined by elimination of a few points which are situated partly right and partly left from transition point. The number of eliminated points was determined from the value of curvature material ratio curve in transition area. Afterwards, linear regression lines between points UPL and LPL and between points UVL and LVL were determined. The values of directional coefficients of these lines were assigned as values Rpq and Rvq. Parameter Rmq was assigned as value of abscissa in intersection of regressions lines drown in plateau and valley region - Fig.11. Areal Spq, Svq or Smq parameters can be also determined in this way.

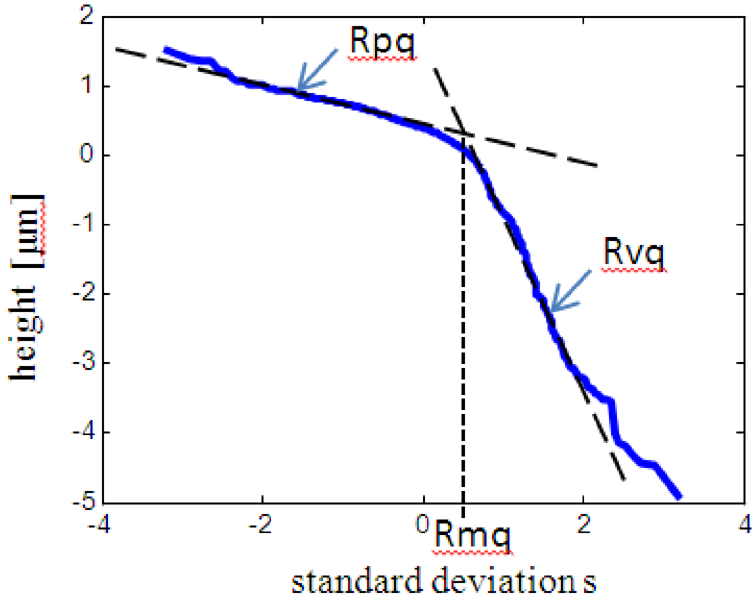


Fig.11. Material probability plot with regression lines passing through random regions and transition point between those regions

Conclusion

Parameters describing roughness profiles of surfaces having stratified functional properties were proposed in the standards ISO 13565-2 (Rk) and ISO 13565-3 (Rq). Parameters from Rq group can be used to profile simulation and zero-wear evaluation or to control of manufacturing process. The number of those parameters is lesser than parameters from Rk group and they are not determined arbitrarily as in ISO 13565-2 standard. However, in European industry the parameters from ISO 13565-2 are used. Methodology of determining the parameters included in ISO 13565-3 standard is imprecise, therefore its incorrect usage can lead to significant mistakes. That is why different methodology to determine those parameters was suggested. After the analysis of many surfaces it was found that this method is useful.

Bibliography

[Abbott, 1993] E.J.Abbott, F.A.Firestone: Specifying surface quality. Mech. Eng., 55, 1993, 556-572.

[Anderberg, 2009] C.Anderberg, P.Pawlus, B.G.Rosen, T.R.Thomas: Alternative descriptions of roughness for cylinder liner production. Journal of Materials Processing Technology 209, 2009, 1936-1942.

[Barber, 1987] G.C.Barber, J.Lee, K.C.Ludema: Materials and surface finish effects in the breaking-in process of engines. ASME Journ. of Eng. for Gas Turbines and Power, 109, 1987, 380-387.

[Campbell, 1972] J.C.Campbell: Cylinder bore surface roughness in internal combustion engines: its appreciation and control. Wear, 19, 1972, 163-168.

[Cieślak, 2008] T.Cieślak: Wpływ wybranych parametrów procesu gładzenia na strukturę geometryczną powierzchni cylindrów. Rozprawa doktorska, Politechnika Rzeszowska, Rzeszów 2008.

[Chusu, 1975] A.P.Chusu, Ju.R.Witenberg, W.A.Palmow: Szerochowatost powierchnostiej. Moskwa, Nauka 1975.

[Day, 1986]R.A.Day, T.J.Reid, D.C. Evans: Developments in liner technology. AE Technical Symp, paper 2, New York, USA, 1986.

[Duck, 1974] G. Duck: Zur Laufflachengestaltung von Zylindern und Zylinderlaufbahnen. MTZ, 35 (10), 1974, 339-340.

[Dolecki, 1983] W.A.Dolecki, W.N.Buntów, A.K.Argusow, B.A.Opoczyński, M.A.Grigorjev: Zwiększenie trwałości maszyn metodami technologicznymi. WNT, Warszawa 1983.

[Essig, 1990] G.Essig, H.Kamp, E.Wacker: Diesel engine emissions reductions - the benefit of low oil consumption design. SAE, paper 900591, 1990.

[Gruszka, 1983] J.Gruszka: Badanie wybranych cech warstwy wierzchniej żeliwnych tulei w oparciu o próby zużyciowe. Rozprawa doktorska, Politechnika Poznańska, Poznań 1983.

[Hassis, 1999] G.Hassis, U-P.Weigmann: New honing technique reduces oil consumption. Industrial Diamond Review, 3/99, 205-211.

[Jakubiec , 2004] W.Jakubiec , J.Malinowski: Metrologia wielkości geometrycznych. PWN, Warszawa 2004.

[Jakubiec , 2004] W. Jakubiec, M. Brylski: Validation of software for calculation the surface roughness parameters according to ISO 13565-3. Proceedings of 9th International Conference on Metrology and Properties of engineering Surfaces, Halmstad University, Sweden 2004, 77-84.

[Jeng,1996] Y.Jeng: Impact of plateaued surfaces on tribological performance. Tribology Transactions, 39/2, 1996, 354-361.

[Johansson, 2008] S.Johansson, P.H.Nilsson, R.Ohlsson, C.Anderberg, B.-G.Rosen: New cylinder liner surfaces for low oil consumption. Tribology International, 41, 2008, 854-860.

[King, 1994] T.G.King, N.E.Houghton: Describing distribution shape: Rk and central moment approaches compared. Proceedings of the 6-th Conference on Metrology and Properties of Engineering Surfaces, Birmingham, UK, 1994, 110-118.

[Klink, 1997] L.Klink: Laserhonen fur Zylinderlaufbagnen. MTZ, 58/9, 1997, 554-556.

[Kozaczewski,1986] W.Kozaczewski: Konstrukcja złożeń: tłok-cylinder silników spalinowych. WKŁ, Warszawa 1986.

[Lenhof, 1997] U.Lenhof, A.Robota: Assessment of honed cylinder bore surfaces for IC engines. AE GOETZE GmbH, Braunschweig 1997.

[Malburg, 1993] M.C.Malburg, J.Raja: Characterization of surface texture generated by plateau-honing process. CIRP Annals, 42/1, 1993, 637-640.

[Michalski, 1992] J.Michalski, P.Pawlus: Description of the bearing length curve of the inner surface of piston engine cylinders. Wear, 157, 1992, 207-214.

[Michalski, 1994] J.Michalski, P.Pawlus: Effects of metallurgical structure and cylinder surface topography on the wear of piston ring-cylinder assemblies under artificially increased dustiness conditions. Wear, 179, 1994, 109-115.

[Michalski, 1998] J.Michalski: Badania poprawności odwzorowania nierówności powierzchni cylindrów po gładzeniu płasko-wierzchołkowym. Materiały konferencji: „Mechanika '98", część 2, Rzeszów 1998, 149-158.

[Michalski, 1994] J.Michalski, P.Pawlus: Description of honed cylinders surface topography. Int. J. Mach. Tools Manufact., 34/2, 1994, 199-210.

[Nielsen, 1988] H.S.Nielsen: New approaches to surface roughness evaluation of special surfaces. Precision Engineering, 10, 1988, 209-213.

[Niewiarowski, 1983] K. Niewiarowski: Tłokowe silniki spalinowe. WKŁ, Warszawa 1983.

[Nosal, 1998] S.Nosal: Tribologiczne aspekty zacierania się węzłów ślizgowych. Rozprawy nr 328, Wydawnictwo Politechniki Poznańskiej, Poznań 1998.

[Nowicki, 1991] B.Nowicki: Struktura geometryczna. Chropowatość i falistość powierzchni. WNT, Warszawa 1991.

[Ohlsson, 2003] R. R.Ohlsson, B.-G.Rosen: Surface texture knowledge – ISM. In: Advanced Techniques for Assessment Surface Topography. L. Blunt, X. Jiang (Eds.), Kogan Page, London and Sterling 2003, 325-336.

[Pawlus, 1994] P.Pawlus: A study on the functional properties of honed cylinder surface during running-in. Wear, 176, 1994, 247-254.

[Pawlus, 2009] P. Pawlus , T. Cieslakb, T. Mathia The study of cylinder liner plateau honing process Journal of Materials Processing Technology 209.

[Pawlus, 1999] P.Pawlus: Struktura geometryczna powierzchni cylindrów podczas eksploatacji silnika spalinowego. Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów 1999.

[Rosen, 2004] B.G.Rosen, C.Anderberg, R.Ohlsson, Characterisation of cylinder roughness for manufacturing control and quality assurance. Addendum to Proceedings of XI International Colloquium on Surfaces, Chemnitz (Germany) 2004.

[Sannareddy, 1998] H. Sannareddy, J. Raja, K.Chen: Characterization of surface texture generated by multi-process manufacture. Int. J. Mach. Tools Manufact. Vol 38. Nos 5-6, pp.529-536, 1998.

[Sanna-Reddy, 1997] H.Sanna-Reddy, J.Raja, K.Chen: Characterization of surface texture generated by multi-process manufacture. Transactions of the 7th International Conference on Metrology and Properties of Engineering Surfaces, Gothenburg, Sweden, 1997, 111-118.

[Santochi, 1982] M.Santochi, M.Vignale: A study on the functional properties of a honed surface. CIRP Annals, 31, 1982, 431-434.

[Schmid, 1999] J.Schmid: Honing technology for optimal cast-iron cylinder liners. Engine Technology International, 1(2), 1999, 108-109.

[Shin, 1983] K.Shin, Y.Tateishi, S.Furuhama: Measurement of oil film thickness. SAE, paper 830068, 1983.

[Sudarshan, 1983] T.S.Sudarshan, S.B.Bhaduri: Wear in cylinder liner. Wear, 91, 1983, 269-277.

[Sreenath, 1976] A.V. Sreenath, N.Raman: Running-in wear of a compression ignition engine: factors influencing the conformance between cylinder liner and piston ring. Wear, 38, 1976, 271-289.

[Sudarshan, 1983] T.S.Sudarshan, S.B.Bhaduri: Wear in cylinder liner. Wear, 91, 1983, 269-277.

[Stout, 1990] K.J.Stout, EJ.Davis, P. I.Sullivan: Atlas of machined surfaces. Chapman and Hall, London 1990.

[Schmid, 2006] J.Schmid: Optimized honing process for cast iron running surfaces. VDI Symposium "Piston running surfaces, pistons and conrods". Boblingen, Germany, Schmid.

[Willis, 1986] E.Willis: Surface finish in relation to cylinder liners. Wear, 109, 1986, 351-366.

[Wieczorowski, 1996] M.Wieczorowski: Stereometryczna ocena porównawcza powierzchni przy zastosowaniu różnych układów odniesienia profilometrów. Rozprawa doktorska Politechnika Poznańska, Poznań 1996.

[Willn, 1972] J.E.Willn: Characterisation of cylinder bore surface finish: a review of profile analysis. Wear, 19, 1972, 143-162.

[Whitehouse, 1985] D.J.Whitehouse: Assessment of surface finish profiles produced by multi-process manufacture. Proceeding of the Inst. Mech. Engrs, 199/4, 1985, 263-270.

[Wiemann, 1971] L.Wiemann: Die Bildung von Brandspuren auf den Laufflachen der Paarung Kolbenring - Zylinder in Verbrennungsmotoren. MTZ, 32/2, 1971, 43-49.

[Zipin, 1983] D.J.Zipin: The analysis of profile strata for surface texture specification. Appl. Surface Science, 15, 1983, 334-360.

[Zwierzycki, 1990] W.Zwierzycki: Wybrane zagadnienia zużywania się materiałów w ślizgowych węzłach tarcia. PWN, Warszawa 1990.

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