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porosity,
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DIAGNOSING THE POROSITY AND LIQUID PERMEABILITY OF LARGE-PORE GRINDING WHEELS

The paper presents a new method of diagnosing the porosity and liquid permeability of large-pore grinding wheels, consisting in the application of computer tomography, image analysis and finite elements method. This method was developed at the Faculty of Mechanical Engineering, Cracow University of Technology in 2006, and is covered by patent protection (P-382829). The method enables diagnosing the grinding wheel porosity not only as regards the percentage share of pores in entire grinding wheel capacity but also their number, shape, length and net of small ducts made by them. It also makes it possible to diagnose permeability of a large-pore grinding wheel without the need to run labour- and cost-consuming experiment tests.

1. INTRODUCTION

The use of lubricant-coolant liquids (LCL) in industry constitutes a serious technological, economic and ecological problem. From the technological point of view, total elimination of LCL as an agent in the machine tool-fixture-object-tool-liquid arrangement would be the most appropriate solution. It succeeded, partially, in many areas of machining, while in the case of grinding it was possible to the small extent only, since in grinding processes, as compared to machining processes the specific energy is significantly higher. This is mainly due to the application of grinding grains of negative rake values and often zero clearance angles, which is related to the increased work done by friction, as well as the work done by plastic and elastic strains in the material being machined. Moreover, an increased power of grinding results from the increased number of kinematic cutting edges which participate at the same time in the machining process. In view of the greater share of work done by friction, a smaller part of heat energy is carried away together with chips, which means that more and more heat penetrates into the machined material. Previous attempts at introducing dry grinding technologies through increasing the grinding wheel speed in relation to the object being machined and reducing the time of contact of particular abrasive grains with the worked material did not solve the issue of total elimination of LCL from grinding. Approaching the issue from the economic point of view, one should note that

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in average grinding conditions, the share of LCL cost amounts to 17% of total machining costs. Pointing to the ecological aspect of the problem, one should consider burdening the natural environment and the related legal issues. Burdening the natural environment concerns, on the one hand, a huge consumption of water from its natural resources (e.g. in Germany in 1996 more than 1 million tons of water a year), and a high consumption of mineral or synthetic oils and the necessity to recycle or neutralize them, on the other [5,6]. In particular, the latter issue has been conditioned by a number of stringent regulations, existing and valid not only in the European Union, but also in many civilized countries worldwide. In such a situation, we have considered the option of grinding under conditions of an effective supply and a limited consumption of LCL. Those methods were discussed by us in detail in our previous publications of that series of papers [1], as well as in other publications on the subject [3]. The method of an effective supply of LCL to the grinding zone that is used more and more often consists in supplying it through the pores of large-pore grinding wheel. When compared with classic grinding, where lubricant and coolant liquid is supplied gravitationally, that method of grinding, which involves the supply of LCL through the pores, yields a decrease in the specific wear of a grinding wheel by ca. 25%, a reduction of the number of honing operations by ca. 22%, an improvement in the quality of top layers in worked surfaces, an increase in dimension and shape accuracies of machined surfaces by ca. 24%, and a reduction of labour-consumption of the grinding process by almost 35% [1,2,4]. Also the consumption of the LCL itself is lower by 32%. It should be mentioned that many manufacturers classify as large-pore grinding wheels not only those of structures above structure number 14, but also certain grinding wheels of open structures (structure numbers 12,13, and 14). Permeability of grinding wheels is an essential parameter, which characterizes the quality of large-pore grinding wheels in conditions of LCL flowing though their pores. It determines not only the wear of the grinding wheel, the number of honing operations required, the volume of LCL consumed, but also the quality of machined surface and the possibility of avoiding the so-called grinding burns.

2. POROSITY AND PERMEABILITY OF LARGE-PORE GRINDING WHEELS AND CURRENT METHODS OF DETERMINING THEM

The capacity of every grinding wheel includes abrasive, adhesive, and pores. The sum of capacities of those components makes up 100% of the grinding wheel capacity. The porosity of a grinding wheel is the percentage share of pores in the capacity of the entire grinding wheel. In grinding wheels of a defined structure, that is of a defined capacity of adhesive, the ratio of the adhesive capacity and the pore capacity is therefore not free, but it strictly depends on the anticipated hardness of the grinding wheel. The dependence of grinding wheel porosity on its hardness is established experimentally, since the volumetric percentage of increase in the adhesive quantity, which causes the increase of the grinding wheel's hardness by one degree, depends on the type and kind of abrasive and adhesive. In manufacturing practice, the grinding wheel porosity is determined based on empirically established linear equations, in which hardness appears as the unknown. For example, in the case of grinding wheels of normal alundum with ceramic adhesive, such equation shall have the following form:

$$V_p = 46.5 - 1.5t \ \% \quad (1)$$

where:
t - indicator of grinding wheel hardness degree, according to Tab. 1.

Table 1. Subjection of grinding wheel porosity from its hardness

Grinding wheel hardness	G	H	I	J	K	L	M	N	O
Hardness indicator *t*	0	1	2	3	4	5	6	7	8
Grinding wheel porosity *p* %	46.5	45.0	43.5	42.0	40.5	39.0	37.5	36.0	34.5

The only problem is that grinding wheels of the same porosity may contain a high number of small pores, or a small number of high pores. In the first case, such grinding wheels will have a compact structure, while in the second case an open, or a large-pore one. The permeability of a large-pore grinding wheel means its capacity to let in through it the LCL under the influence of LCL pressure gradient applied. 1 darsi is a unit of measure of that quantity. A large-pore grinding wheel has the permeability of 1 darsi, when the drop of LCL pressure by 101,325 Pa is caused by an outflow of 1 cm3 of LCL during 1 second through the surface area of a cube of 1 cm side, and LSL has the dynamical viscosity of 10^{-3} Pa·s [1]. Therefore 1 darsi has dimensions of 1 cm^2. The permeability of large-pore grinding wheel can be determined by the following experimental and analytical methods:
- directly from the Darcy's formula, which makes it dependent on a number of characteristic features of a grinding wheel,

$$K = \frac{Q \bullet \mu}{A \bullet (\Delta p / L)} \qquad cm^2 \quad (2)$$

where: Q - volume of outflowing machining liquid,
μ - dynamic viscosity of machining liquid,
A - active surface of the grinding wheel opening,
Δp/L - pressure drop at the L length of a porous material

- analytically, using the Regusz-Jaszczericyn formula, depending on the canal porosity K_K and conventional diameter of pores d_y (Fig. 1) [1],

$$K = \frac{K_K \bullet d_y^{\;2}}{32} \tag{3}$$

The canal porosity K_K is determined as per the following equation [1]:

$$K_K = \frac{\sum N_j \bullet L_j}{\sum N_j \bullet L_j + \sum N_i \bullet d_i} \tag{4}$$

where: *Nj* - number of ducts on the tested surface,
Lj - length of ducts on the tested surface,
Ni - number of pores on the tested surface,
di - diameter of pores on the tested surface.

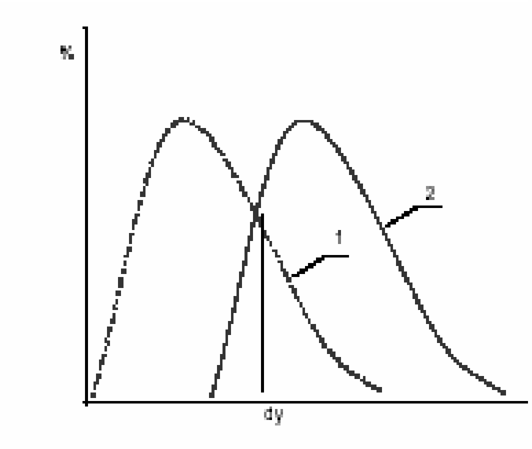

Fig. 1. Distribution curves of pore diameter dimensions d_i and duct length L_i , and way of determining conventional diameter of pores d_y in the Regusz-Jaszczericyn method [1]

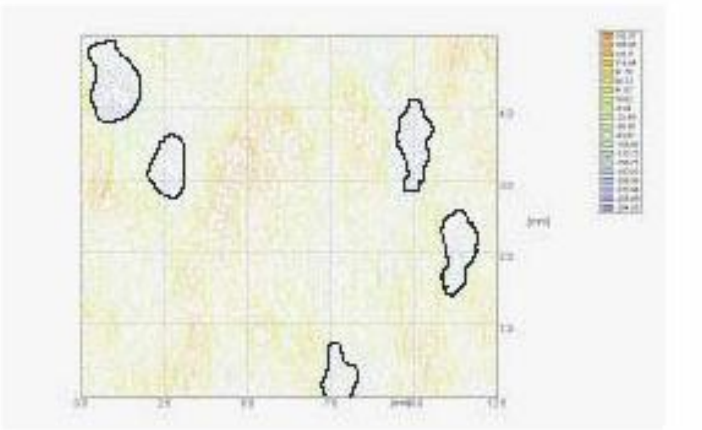

Fig. 2. Contour-line view of the grinding wheel active surface (contours indicate pores) in the Skrzypiec – Regusz method [2]

- from the Regusz's formula, as modified by M. Skrzypiec, depending on the active porosity and the expected values of equivalent diameters of pores [6,2]. When determining the permeability of large-pore grinding wheel with the use of that third method, the statistical analysis of microgeometry of the grinding wheel active surface was applied. That technique consisted in measuring the grinding wheel active surface topography, followed by computer analysis of images. The equivalent diameters of pores were determined as diameters of circles, with areas equivalent to pore areas, determined from the contour-line chart of the grinding wheel active surface. The active porosity of large-pore grinding wheel was determined on the basis of profiles of grinding wheel active surface in relation to technological porosity of the grinding wheel [Fig. 2].

3. CONCEPT OF THE NEW METHOD TO DIAGNOSE POROSITY AND LIQUID PERMEABILITY OF GRINDING WHEEL

The concept arises out of the use of computer tomography image analysis and the finite element method to determine permeability of large-pore grinding wheel. That new method is marked by high diagnosing efficiency in comparison to methods discussed in Section 2 above. Instead of measuring the consumption of machining liquid at the machine tool and the drop of pressure along the grinding wheel radius (the first method), analysing transparent films with spider's webs, or possibly measuring the microgeometry of grinding wheel active surfaces by means of topography (the second method), it is enough to take (within less than a minute) the characteristics of any large-pore grinding wheel with the use of a computer-aided tomography [Fig. 3], next transfer the bitmapped images of that characteristics [Fig. 4] to a proper FEM model of the grinding wheel, use relevant computer programs (e.g. Flotran ANSYS or Fluid ALGOR), perform numerical simulation of the LCL through the large-pore grinding wheel, and – using the Darcy's formula – determine the permeability of the large-pore grinding wheel. The method has been covered by patent protection (P-382829). Most convenient for the computer topography are Philips Sensation Cardiac 64 computer-aided tomographs, which allow for the acquisition of minimum 64 images during a single, complete rotation of the lamp around the grinding wheel. In that specific case, the Workstream technology is most useful to assess the obtained images. As a result of x-ray scanning of the grinding wheel in relation to its entire capacity, one obtains a series of images of that tool's microstructure. After adequate marking of images according to grey or colour scales and calibrating them according to their resolution, standard software for 3D image reconstruction and analysis by filtration, binarisation, and measurement is used. Due to those actions with pixels, we receive accurate information about the size, shape, number and three-dimensional location of pores in the examined grinding wheel. This method enables visualisation of small ducts made by the grinding wheel pores. Knowing the density of scanning and basic geometrical parameters of quantitative image analysis, it is also possible to determine the grinding wheel porosity. Very deep analysis of images in the grinding wheel cross-section can be effected by using Aphelion software (e.g. to determine relative errors in pore surface measurements or to establish the pore edge sharpness).

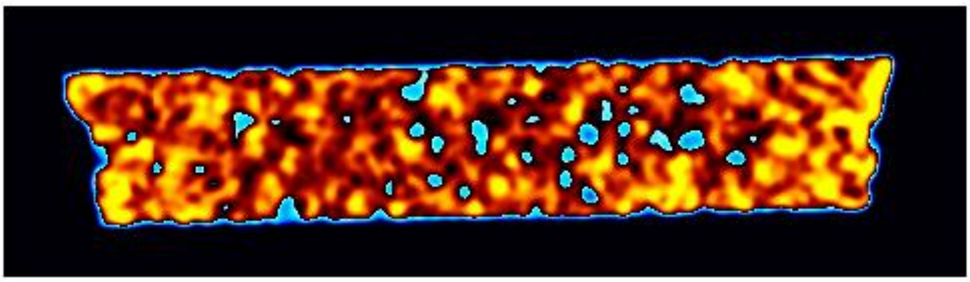

Fig. 3. Fragment of a tomographic cross-section of a large-pore grinding wheel [4]

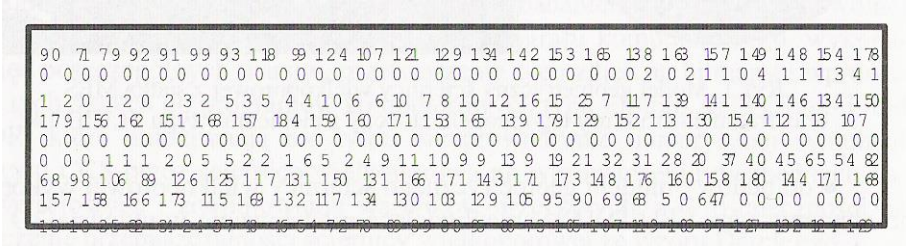

Fig. 4. Example of bitmapped images of a tomograph [6]

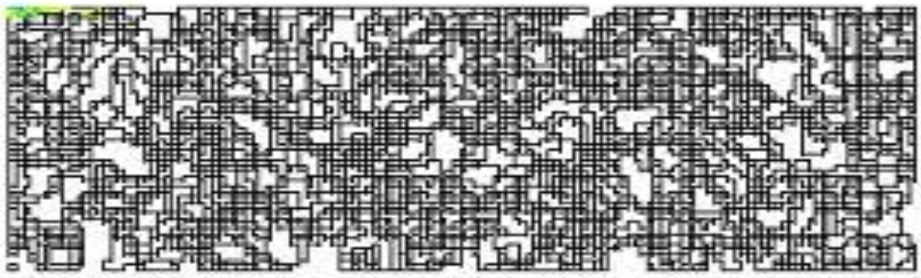

Fig. 5. Pores in a tomographic cross-section of a large-pore grinding wheel

4. DIAGNOSING THE POROSITY OF A LARGE-PORE GRINDING WHEEL

Diagnosing the porosity of a large-pore grinding wheel with the use of a computer-aided tomography and image analysis was presented on the example of a grinding wheel, with the characteristics of 1A 200x32x20 99A 60 40-20 V, manufactured by Grinding Wheel Factory in Grodzisk Mazowiecki, Poland. Accurate observing of pores and counting the number of them is possible due to the option of enlarging the selected fragments of the tomographic cross-section of the grinding wheel, and manual and automatic determining the number of pores enclosed within the frame area Fig. 6- Fig.10.

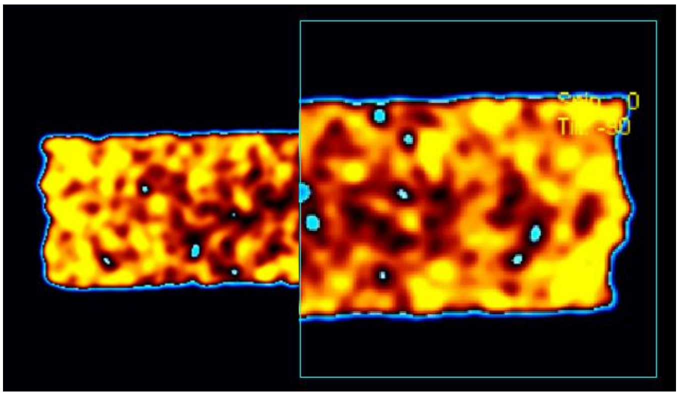

Fig. 6. Enlargement of a fragment of tomoghraphy cross-section image of a large-pore grinding wheel (e.g. the number of pores in the fragment is 12)

In the same way it is possible to determine the percentage share of the pores' area in the entire grinding wheel cross-section area. The size of pores is normally described with the use of Feret diameters.

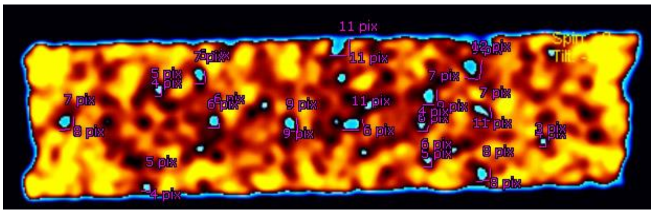

Fig. 7. Horizontal and vertical Feret diameters marked for grinding wheel cross-section pores

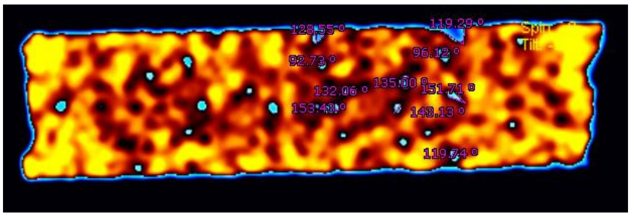

Fig. 8. Angle-oriented Fered diameters marked for grinding wheel cross-section pores

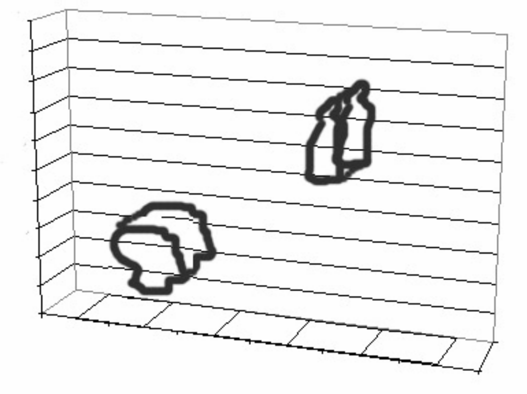

Fig. 9. Schematic diagram of determining the capacity of pores in the grinding wheel capacity layers (e.g. depth of 0.3 mm)

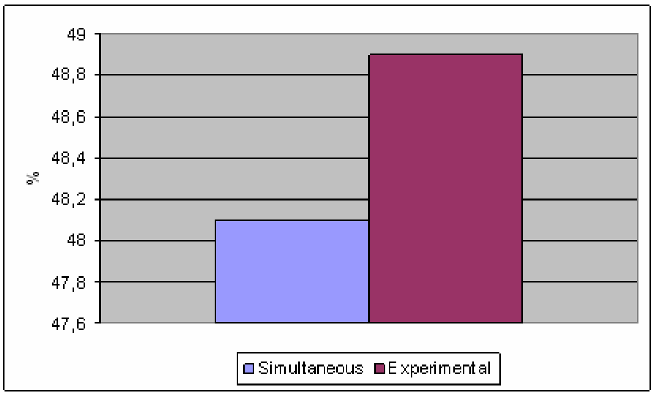

Fig. 10. Histograms of simulation and experiment comparative tests concerning porosity of large-pore grinding wheels

5. DIAGNOSING THE LIQUID PERMEABILITY A LARGE-PORE GRINDING WHEEL

Diagnosing the liquid permeability of a large-pore grinding wheel was made with the use of the new method presented herein, on the example of a grinding wheel, with the characteristics of 200x32x20 99A 60 40–20V, manufactured by Grinding Wheels Factory in Grodzisk Mazowiecki, Poland. Numerical simulation of the flow of the lubricating and cooling liquid through the pores of a large-pore grinding wheel was made with the use of ANSYS Flotran program, Fluid Flow module and Gambit pre-processor. The input data to perform simulation were as follows:

- ✓ large-pore grinding wheel, grain size 60,
- ✓ dimensions: 200x20x32,
- ✓ hardness and structure numbers: 20 – 40,
- ✓ liquid pressure Δp=0.3 [MPa],
- ✓ liquid specific weight γ = 9982 [N/m^3] (in 20°C),

- ✓ rotational speed n=2240 [r.p.m.],
- ✓ kinematic viscosity ratio $\eta = 1.005 \cdot 10^{-3}$ [$N \cdot s/m^2$] (in 20°C),
- ✓ gravity acceleration g = 9.81 [m/s^2],
- ✓ surface area of a single element $S_{op}=1.2*10^{-7}[m^{-2}]$,
- ✓ iteration number i = ca. 6000,
- ✓ liquid flow time t=50 s,
- ✓ character of liquid flow: a laminar flow.

Results of numerical prediction of a large-pore grinding wheel permeability obtained during simulation were verified during tests at a custom-designed test stand (Fig. 11d). [4,6].

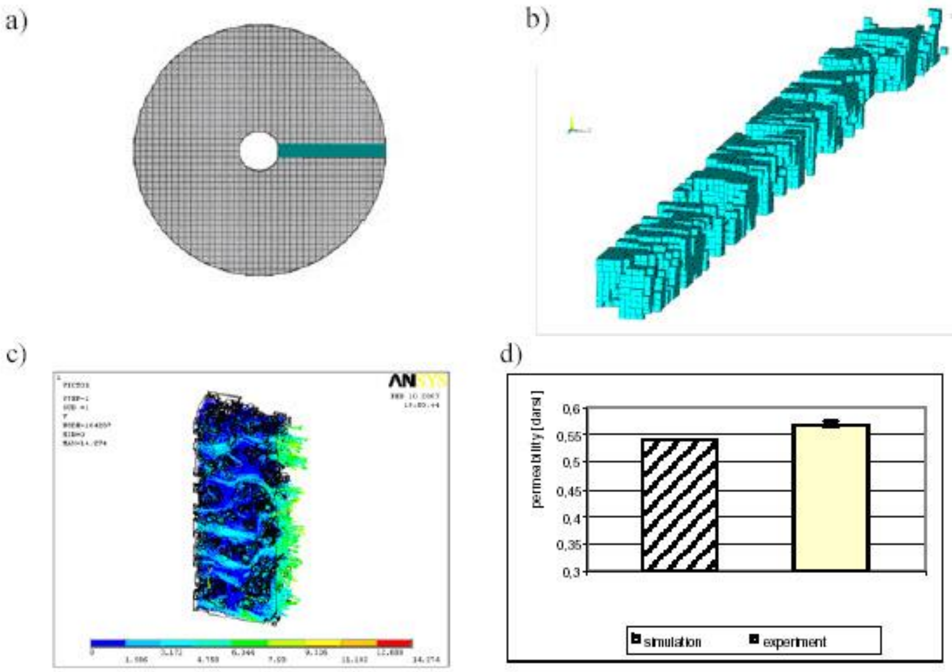

Fig. 11. Model of a large-pore grinding wheel, with superimposed finite element net (a), sector of the grinding wheel volume model, composed of Fluid 142-type elements, (b) resolution of speed vectors of LCL flows in the analysed fragment of the large-pore grinding wheel capacity (c), histograms of simulation and experiment results of comparative tests of permeability of large-pore grinding wheel under same operating conditions (d). [6]

5. SUMMARY

We have proved a full usefulness of the new method of diagnosing the porosity and permeability of large-pore grinding wheel, consisting in the serial application of computer tomography, image analysis and FEM software in the process of numerical simulation of porosity and permeability. The numerically simulated porosity and permeability of a large-pore grinding wheel was 48,1 % and 0.54 darsi, whereas the permeability of large-pore grinding wheel of same characteristics, tested experimentally at a test stand under same operating conditions, was 48,9 % and 0.58 ±0.02 darsi.

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