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The Influence of External Conditions on the Mechanical Properties of Resin-bonded Grinding Wheels

Albin Matavz[1] – József Mursics[2] – Ivan Anzel[3,*] – Tina Zagar[4]
[1]MAMUT TIM, Ltd., Slovenia
[2]FALCO Zrt. Hungary
[3]University of Maribor, Faculty of Mechanical Engineering, Slovenia
[4]Ministry of Economic Development and Technology, Slovenia

The paper presents the ageing effects on mechanical and functional properties of resin-bonded grinding wheels with Aluminium oxide and Silicon carbide. The measurements provided the basis for the design of a temporary model of changes. Furthermore, the influence of humidity as the most likely cause for a steep downgrade in the mechanical properties of grinding wheels was examined and identified. Within that context, the system of forced, i.e. accelerated ageing of grinding wheels (additional humidification) was used under special atmospheric conditions.

The model mechanisms for changing microstructures during ageing are presented and are based on the microstructural characterisation of grinding wheels that were exposed to different thermo-mechanical impacts. These mechanisms confirm the most likely cause for ageing, as established empirically, and therewith related changes of the mechanical properties of grinding wheels. Furthermore, the findings are useful in the process of manufacturing grinding wheels, helping to improve mechanical properties and most of all, considerably slowing down the ageing process, and providing higher added value to such products.
Keywords: resin-bonded grinding wheels, mechanical properties, ageing, microscopic analysis

Highlights
- *Mechanisms for changing microstructures during ageing of grinding wheels are presented.*
- *The suggested process of manufacturing of grinding wheels, with the aim of helping to improve mechanical properties.*
- *Influence of humidity downgrades the mechanical properties of grinding wheels.*
- *Slowing down the ageing process provides a higher added value to such products.*

0 INTRODUCTION

When we check the quality of grinding or cutting abilities of grinding wheels with corundum or SiC grains, it can be seen that their quality tends to alter over time. This time-dependent ageing processes or changes of mechanical properties occur gradually over the period of two or three months from the date of production, especially because of atmospheric conditions (humidity), affecting the microstructure of grinding wheels and their alterations during grinding.

When we searched for causes of the change of mechanical properties of resin-bonded grinding wheels during a specific period, we have not been able to find any scientific article or source in the database dealing with the issue. Different producers or researchers connected with them have dealt with a similar issue, but due to confidentiality of data and findings (significantly unfavourable technological information for grinding wheels producers with respect to uncontrolled fall of quality of grinding wheels), their findings are not accessible to a wider circle of users, or the technological information are owned by the producers.

It should however be mentioned that many authors have dealt with the issue of the change in mechanical properties of certain other types of grinding wheels (e.g. metal – bonded Cubic Boron Nitride (CBN) and diamond grinding wheels) [1] to [6], and have shed light on processes during grinding, depending on the type of binder, the shape and type of grains, and the changes of their micro and macro structures during the process of their use. Some of the findings from researches may be connected to such recognitions and findings. The wear behaviour of abrasive tools can greatly affect the machined surface quality and integrity, which is the reason why different wear status of the abrasive tools could produce different material removal behaviour during grinding. Generally, the classification of wear behaviour in grinding includes the wear of abrasive tools and the wear of abrasive grains. In recent years, more attention has been paid to the research on wear behaviour of abrasive tools from the macro and micro perspective [1] and [2].

At the same time, a lot of investigations on the influence of the porosity on the mechanical strength of the porous composite matrices of grinding wheels were made [3].

*Corr. Author's Address: University of Maribor, Faculty of Mechanical Engineering, Smetanova ulica 17, 2000 Maribor, Slovenia, ivan.anzel@um.si

Newest literature also mentioned numerical simulation and experimental studies on the mechanism of grain fracture based on the analysis of brazing-induced residual stress and the resultant stress in grinding; as such, the grain fracture wear could be predicted and controlled effectively [4].

On the basis of scientific and research methods it has been established how the ageing affects the mechanical properties of grinding wheels and how downgrade in the functional properties can be prevented by appropriate production procedures.

With this objective, the following activities have been carried out:

- test samples of resin-bonded grinding wheels were made within the series production of grinding wheels under realistic production and technological conditions and parameters, applied in the industry;
- the influence of humidity on mechanical properties of grinding wheels has been determined;
- the research of what causes the downgrade in the cutting abilities of a grinding wheel (hydroscopic moisture from the atmosphere, pores and cracks in grinding wheels);
- analysis of how moisture content in resin-bonded grinding wheels affects the downgrade in the quality and the related ageing process of grinding wheels;
- the weighting factor determined by tests was eliminated, as it causes ageing of resin-bonded grinding wheels and reduction of cutting abilities;
- cutting ability factor values of grinding wheels were identified over a time-defined ageing process;
- influence of ageing was determined on the rotational speed in disintegration of grinding wheels during ageing;
- the findings were confirmed by the microstructural analysis of samples and the created model of the course of ageing in polymeric matrix of grinding wheel.
- On the basis of the results, the course or intensity of the influence of ageing on the properties of resin-bonded grinding wheels was determined, and the obtained data and findings enabled an improvement in production procedures or defining the method of quality control in the production of resin-bonded grinding wheels.

1 THEORETICAL BACKGROUND

1.1 Grinding Products

Grinding products may be used for cutting or grinding metals, as well as organic and inorganic materials. There are conventional (classic), flexible grinding wheels (emery cloth and paper) and super abrasive wheels (CBN and Diamond wheels) [5] and [6]. Their properties and efficiency depend on the microstructure and components they are made of, the mechanical properties or the loads they can bear, circumferential speed of the grinding wheel, and the heat generated during use [7].

Conventional grinding wheels are made of grain aggregates, fillers (additives) and binders (phenol-formaldehyde resins), which provide the grinding wheel with strength and uniform design.

In order to create a strong and stable bond between grains and the bearing material, we need a high quality phenol-formaldehyde resin and the correct ratio between liquid (resole) and powdered (novolak) resin. The composition of the polymer matrix of a resin-bonded grinding wheel must be such that the operating temperature ranging between 700° C and 1000° C generated during grinding doesn't significantly alter the mechanical properties.

The key properties of phenol-formaldehyde resins are their ability to crosslink and form infinite polymer chains and their irreversible thermal strengthening in the thermal process phase of grinding wheel production.

Phenol-formaldehyde resins are obtained by reaction of phenol (P) and formaldehyde (F) in the presence of a catalyst, which may be acid, base or metal salt. The result is a liquid or hard dispersed product, which may be thermo-plastic (novolak) or duro-plastic (resole) [8].

Fig. 1 shows the molecular structure of phenol-formaldehyde resins with regard to the F/P molar ratio and pH.

P and F are the most important raw materials for industrial production of phenol resins.

The key factors, which affect what type of resin is obtained, are:

- molar ratio between F and P;
- type of catalyst, which is used in polymerization.

When a catalyst is alkaline, we obtain resoles (liquid resins) with the addition of formaldehyde and phenol and the formation of oligomers, with a molar ratio of F to P ≥ 1, which is the most frequently used binder on water basis for grain wetting in the grinding industry [9].

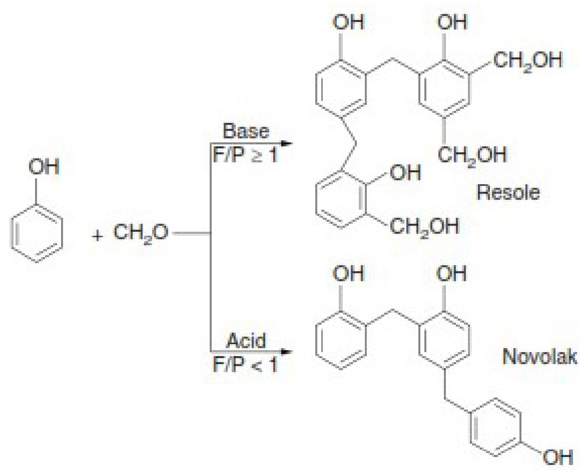

Fig. 1. *Molecular structure phenol-formaldehyde resin*

However, if an acidic catalyst is used, novolak (powdered resins) is obtained by the addition of formaldehyde and phenol and the formation of oligomers in an acidic environment, with a molar ratio of F to P < 1, which is useful for impregnation of meshes. In addition, together with hexamethylenetetramine (HMTA or Hexa) it is also useful in the grinding industry.

1.2 Abrasive Grains

Grains are made of inorganic materials and are distinguished by high strength and appropriate toughness. The basic function of grains is grinding of processed material (workpiece) [10].

Grains are most often composed of Aluminium oxide (Al_2O_3) and Silicon carbide (SiC), which are produced synthetically.

Grains with high hardness are usually fragile, so such grains are used for fine and end grinding [11]. A type of phenol resin is used as a binder, since it is more flexible, whereas resistance to higher temperatures is not that important. Quite the opposite, grains with lower hardness usually possess a higher degree of toughness, and are less fragile, so they are used for intensive, rough grinding. Because high quantities of heat are released during such grinding, phenol resins must be used as a binder, since they are more resistant to high temperatures and serve as a strong binder of abrasive grain particles [12] and [13].

The choice in the size of grains is also important and depends on the processed material and grinding conditions. The surface roughness of the processed material directly depends from size of abrasive grains [14]. As a rule, larger grains are used for rougher materials, and smaller grains are used for less rough materials.

1.3 Fillers

Fillers have been used in the production of grinding wheels from the very beginning. The use of fillers delivered the findings that various fillers, which are usually inorganic, in powdered or fibre form, may improve and add some properties to the basic composition of polymer or grinding wheel.

The added fillers may influence the density of grinding wheel, optical features, colour and change of surface qualities. They may also retain the shape of product during drying (shrinking), reduce bending, reduce thermal conductivity, change magnetic properties and essentially contribute to improvement and achievement of wanted mechanical properties of grinding wheels. Their ability of chemical reaction is particularly important, which means they can facilitate or inhibit chemical reactions of polymerisation, drying time and heat treatment, and the related degree of crosslinking.

The most frequently chosen fillers in the production of resin-bonded grinding wheels are pyrite, cryolite (fluoroaluminates), calcium carbonate, potassium fluoroaluminates (PAF), Wollastonite, and an inorganic pigment like "C-soot".

Fillers, such as Calcium carbonate and Wollastonite, increase the toughness (strengthen the grinding wheel) and contribute to higher efficiency and durability of grinding wheels at high temperatures and mechanical loads during the grinding process. When the heat is released during grinding, fillers react with the workpiece, and contribute to a more efficient grinding and thus protect the grains [8].

1.4 Impregnated Glass Cloth

In cutting discs and convex cutting discs with glass cloth only the mechanical structure of a grinding wheel is reinforced. Glass cloth is impregnated with phenol resins. The maximum rotational force the wheel can endure depends on the properties of the glass cloth fibres. Especially important properties are the endurance or tensile strength, and quality of the interweaving of fibres.

1.5 Microstructural Composition of Resin-Bonded Grinding Wheels

The basic composition of a grinding wheel is made of grains, binder, filler, pores and cracks, and glass-fibre nets as additional reinforcement. Grains are used for grinding, binder holds grains together, and pores are responsible for the removal of chips. Grinding grains are capable of self-restoration (self-sharpening) and new grains appear on places, where worn grain falls out of the structure. This is a very important property of resin-bonded grinding wheels. If resin holds grains too tight, the restoration of the working surface of the grinding wheel is slow and pores get clogged, which reduces the efficiency of a grinding wheel. However, a grinding wheel is worn out too fast, if grains fall out, because resin failed to hold the grains together well.

2 EXPERIMENTAL PART

In the experimental part, analytical and statistical methods were applied in obtaining and evaluating the results. In order to determine the reliability of results, the Weibull statistical method and the calculated module, which is actually a quality criterion of resin-bonded grinding wheels have been used in the past **[15]**.

The experimental part of the research was performed in the following way:

- an experimental part was prepared and executed with the purpose of determining the repeatability of results and comparability;
- a whole spectre of samples was prepared by implementing the procedure of determining the changes of functional properties of grinding wheels in a natural environment and under specific atmospheric conditions (humidity);
- a synthesis of findings was implemented and a model was created of time influence on mechanical features during ageing of grinding wheels in a natural environment under forced conditions;
- findings and conclusions have been made.

To obtain the results the following was applied:

- routine procedures in the industry, like internal technological rules and norms (preparation of samples and measurements of functional properties);
- procedures prescribed by standards (preparation of samples and measurements of mechanical properties and statistical data processing);
- procedures that have been designed by the authors (preparation of samples for the microstructural analysis).

For various types of grinding wheels of equal dimensions and quality, using the prescribed method of the grinding wheel manufacturer, we carried out tests of maximum rotational speed (disintegration) and defined the cutting ability factors.

The microstructural analysis of samples was made on the basis of the imaging of samples on the scanning electron microscope in high vacuum. On the basis of the characterization of microstructures of grinding wheel samples, which were exposed to various thermo-mechanical impacts, we set a hypothesis (model) and determined the reasons for the downgrade in mechanical properties during ageing of grinding wheel.

For the purposes of the experimental study of the impact of ageing on mechanical and functional properties over a longer period, and due to easier traceability in the production, various types of samples have been prepared (six), separated by trademarks (label or TYPE 0X), which are presented in more detail in Table 1, where codes PL260, PL340 and PL380 suggest a different grammage of glass impregnated cloth, as a grinding wheel reinforcement.

Table 1. *Basic types of grinding wheel samples*

Sample no.:	Grinding wh. code:	Product composition (type and quality of reinforcement):
01	TYPE 01	No reinforcement, non-reinforced product
02	TYPE 02	2 pieces PL 340
03	TYPE 03	1 piece PL 340 and 1 piece PL 380
04	TYPE 04	2 pieces PL 380
05	TYPE 05	2 pieces PL 260
06	TYPE 06	2 pieces PL 380, grinding wheel heat processed again at 190 °C in the time of 6 hours

2.1 Disintegration

The concept of disintegration defines the rotational speed, where a grinding wheel is torn apart due to extreme centrifugal forces. Testing was performed on the machine, which continually increases rotational speed of the attached wheel to the value, at which the disc disintegrates.

The disintegration ability was tested on the machine PVM30, 50 Hz: rotational speed variation: Min/Max rpm: 4,500 min^{-1} to 30,000 min^{-1}, drive system: variable frequency unit, wheels diameter: 100 mm to 400 mm, spindle drive: motor-belt. each individual testing was undertaken on 1 piece of wheel. Tests were performed with 10 disintegration repetitions of grinding wheels.

Measurements or testing of maximum rotational speeds of grinding wheels were performed for basic types of grinding wheels (T01, T02, etc.).

In all cases, the same type of grinding wheel was used, F41 230 × 3(3.1) × 22 A30S. The average values of rotational speeds of grinding wheels where disintegration occurred are given in Table 2.

The results of measurements of rotational speeds of disintegration show that the lowest values of rotational speed and, consequently, of disintegration are around the 15th day of wheel ageing. Then, by the day 60, the values started growing again.

Table 2. *Average values of rotational speeds [min^{-1}] of wheel disintegration*

Type of gr. wh.:	Day 1:	Day 15:	Day 60:
TYPE 01	9,860	9,610	9,693
TYPE 02	13,600	13,460	13,630
TYPE 03	13,690	13,650	14,020
TYPE 04	13,380	13,450	13,840
TYPE 05	13,340	12,930	13,230

With regard to the comparison of test results of various types of samples (different composition of glass cloth grammage), it has been determined that the downward trend of disintegration by day 45 is constant, after that the repeated growth was present in all types of grinding wheels.

2.2 Cutting Ability

The measurement of mechanical properties (cutting factor) of resin-bonded grinding wheels is a practical procedure (method), used for decades by all producers of resin-bonded grinding wheels [8]. The method was developed on the basis of practical experience of leading world producers of grinding wheels and is still used in a modified way by all the producers of grinding wheels (even though it is not standardised). The testing of cutting factor is carried out on automated machines of the biggest Italian producer, which enables making a comparison of products (grinding wheels) when the data is accessible.

The cutting ability of grinding wheel is actually its ability to cut off and remove material from the surface of a workpiece. It is defined by the cutting factor (f) and the number of possible cuts of the grinding wheel on the test workpiece.

The cutting factor is the ratio between a chip (ΔM_{ml}) in grams of ground-off workpiece and the wear of grinding wheel (ΔM_{gw}) in grams of wheel wear, Eq. (1)

$$f = \frac{\Delta M_{ml}}{\Delta M_{gw}}. \tag{1}$$

The cutting factor was determined for all types of grinding wheels on ten samples. In all cases the sample type of grinding wheel F41 230 × 3(3.1) × 22 A30S was used. The cutting factor was calculated on the basis of the data obtained with the test method of 30 cuts with a wheel.

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The cutting ability check procedures are defined in the internal standards of the manufacturer and are used for regular testing of grinding wheels in the production (monitoring and ensuring the stability of grinding wheels' quality).

To understand the concept better and to assess changes, more frequent measurements (from 1 day to 83 days) were initially performed on the sample TYPE 04 and a time diagram of cutting factor dependence was drawn, Fig. 2.

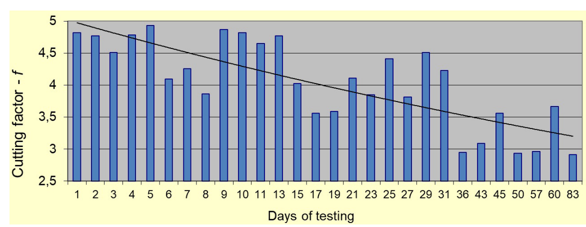

Fig. 2. *Cutting factor by days for sample TYPE 04*

As can be seen from Fig. 2, there is a great dispersion of value by individual days. For that reason and for easier interpretation of results and monitoring of time dependence, the diagrams of cutting factor dependence were made for the 1st, 2nd, 15th, 45th and 60th day for all samples, Figs. 3 to 6.

On the basis of the experimental preparation of samples, the results of measurements and calculations for a time period of 60 days, the following points were established:

- measurements confirm the actual impact of ageing during a time period and a direct impact on mechanical features of grinding wheels, i.e. cutting factor in grinding wheels;
- the implementation of more frequent measurements in fact somewhat distorts the entire image of monitoring the downgrade in the cutting ability of wheel, but it does not change

the trends shown by comparisons of results of the same grinding wheel in longer intervals during individual testing days;

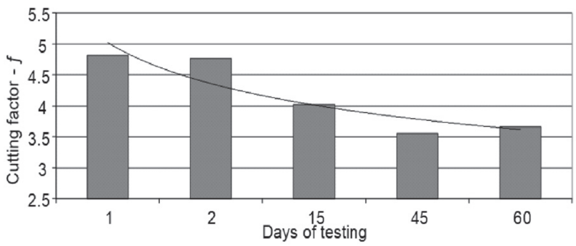

Fig. 3. *Cutting factor by days for sample TYPE 04*

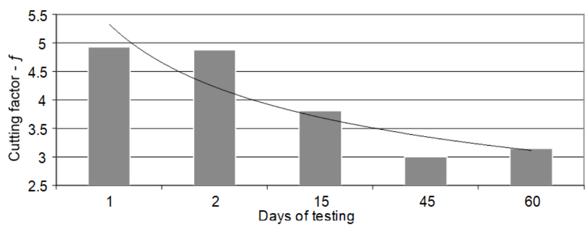

Fig. 4. *Cutting factor by days for sample TYPE 03*

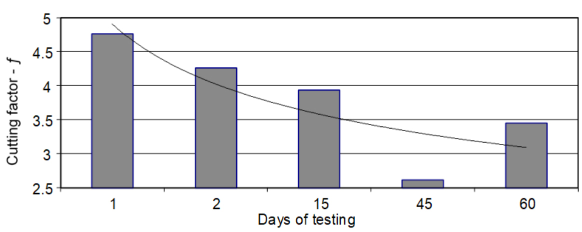

Fig. 5. *Cutting factor by days for sample TYPE 02*

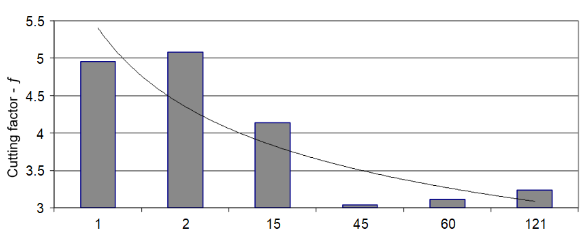

Fig. 6. *Cutting factor by days for sample TYPE 05*

- cutting factor in a time period of 45 days achieves the lowest value in all types of grinding wheels and is about 40 % lower;
- as the time period extends over 45 days, the ageing process stops and stabilizes, and the cutting ability slightly improves;
- repeated heat processing – i.e. drying of grinding wheels at an appropriate work temperature results in the mechanical properties (cutting ability) reversibly returning to original production values, Fig. 7;
- the results and findings in the paper are a result of monitoring of simultaneously measured samples of grinding wheels during a longer period of time, with the same technological processes of the same batch of prepared mixture (raw material). The measurements of mechanical properties (the measurements of the cutting factor and rotational speed) have shown that significant changes of mechanical properties of grinding wheels have occurred during the monitored period. From the findings it is evident that the mechanical changes do not occur as a result of in-built raw materials and changes in the geometry of the grain during the grinding wheel use, but as a consequence of what happens in the matrix of the composite due to the exposure of the composite matrix to the environmental influence where the grinding wheels have been stored;
- atmospheric conditions of storage (humidity and temperature) certainly have a decisive impact on the mechanical properties of grinding wheels.

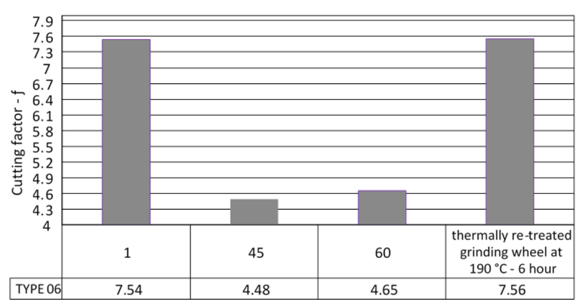

Fig. 7. *Cutting factor by days for sample TYPE 06 (repeated heat processing)*

2.3 Microstructure of Grinding Wheels

Microstructural analysis of samples was based on the imaging of samples on a scanning electron microscope (Quanta 200 3D) with wolfram cathode as the source of electrons in high vacuum. The microscope has an installed detector for bounced off electrons, which obtains the contrast between the areas of sample with a different chemical composition (Z-contrast).

On the basis of the characterisation of the microstructures of grinding wheel samples, which were exposed to various thermo-mechanical impacts, the authors designed the models of mechanisms of changes in the microstructure of grinding wheels during ageing.

In search of the answers for possible causes for the change of mechanical properties of grinding wheels during their use in a longer period, the metallographic analyses of samples of microstructure of matrix composite of resin-bonded grinding wheels had been carried out. By using and analysing different magnifications of samples, we determined what is happening to the microstructure or the binding matrix of the samples, the changes of pores in the matrix, the occurrence of pores, their migration through the composite matrix, the performance of grains, their deviation from the binding matrix and the falling out of matrix connected with that. Consequently, the result are findings on the change of mechanical properties of the monitored samples, thermally treated with cutting in relation to the compared etalon of the same sample that was not exposed to usage, that is to cutting. In all cases, the same type of grinding wheel was used, F41 230 × 3(3.1) × 22 A30S.

In order to confirm the actual reasons for the downgrade in the functional properties of wheels throughout the measured period, we prepared samples of test pieces for the microstructural analysis, Table 3.

Table 3. *Preparation of samples for the microstructural analysis* [15] *and* [16]

Sample code / meas. date	Sample description	Sample processing
Sample A /07.02	Sample analysed 5 days old	Wheel not used – measurement standard
Sample B /07.02	Sample analysed 5 days old	5 cuts with grinding wheel
Sample C /03.03.	Sample analysed 30 days old	Additional force humidification 30 days and 5 cuts – 1 % humidity
Sample D /03.03	Sample analysed 140 days old (containing 1 % moisture)	Stored under normal conditions (40 % humidity and 15 °C) and 5 cuts

Figs. 8 to 10 show images of different magnifications of the microstructure of grinding wheel sample A that was 5 days old. Grinding wheel had not yet been used. Images of the microstructure of grinding wheel served as a comparable measurement standard in observing the changes in the microstructure of grinding wheel samples, which are intended for cutting.

Figs. 11 and 12 show the images of the microstructure of grinding wheel sample B, 5 days old. Grinding wheel is shown at different magnifications and had already been used.

Figs. 13 and 14 show images of the microstructure of grinding wheel sample C, 30 days old, at different magnifications. The grinding wheel was additionally aged (content of 1 % moisture) and already in use.

Figs. 15 and 16 show the images of the microstructure of grinding wheel sample D, 140 days old, at different magnifications. The grinding wheel was stored under normal conditions (~40 % humidity and ~15 °C, moisture content of 1 %). The grinding wheel had already been used.

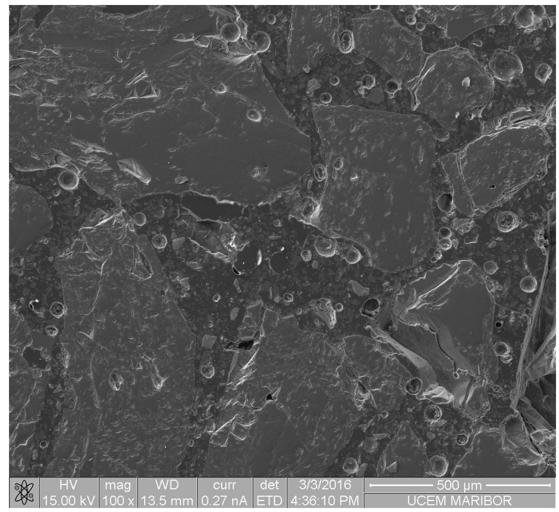

Fig. 8. *Microstructure of grinding wheel sample A/07.02* [15]

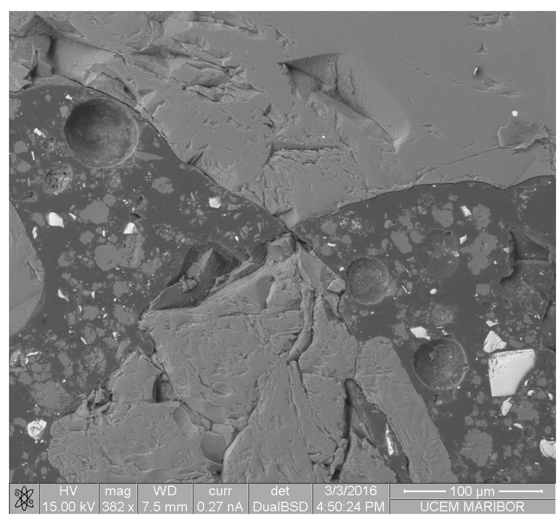

Fig. 9. *Microstructure of grinding wheel sample A/07.02* [15]

On the basis of the method of cross-observation, comparison and analysis (Figures 8 to 16) of the microstructure of grinding wheels, which were exposed to various thermo-mechanical impacts, the following conclusions can be given:

- microstructure of the grinding wheel matrix that was not used for cutting is significantly different from the grinding wheel matrix that was used for cutting (Figs. 8 and 15);

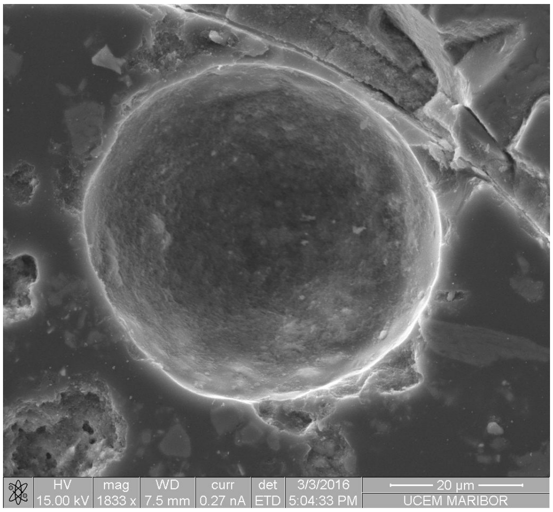

Fig. 10. *Microstructure of grinding wheel sample A/07.02* **[15]**

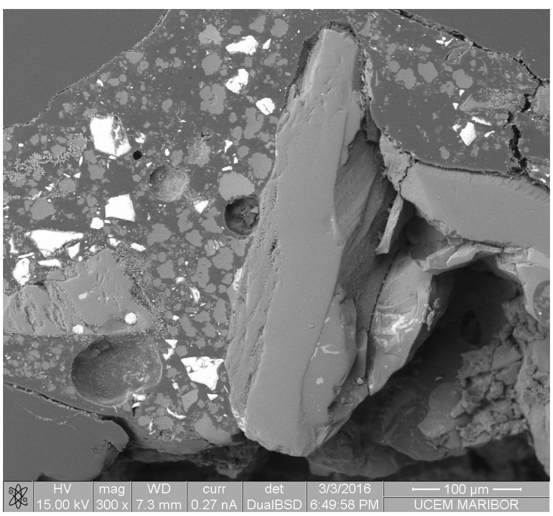

Fig. 11. *Microstructure of grinding wheel sample B/07.02* **[15]**

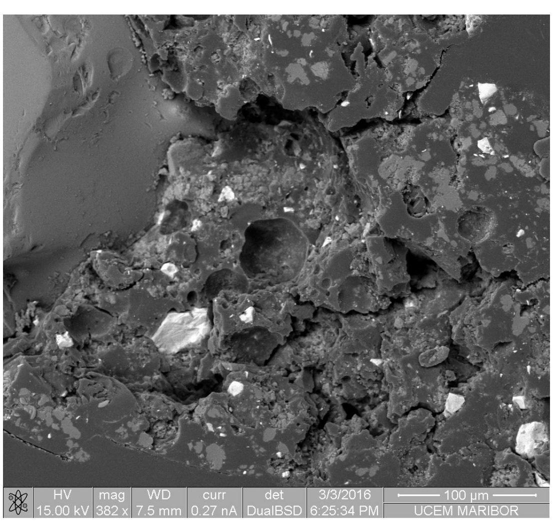

Fig. 12. *Microstructure of grinding wheel sample B/07.02* **[15]**

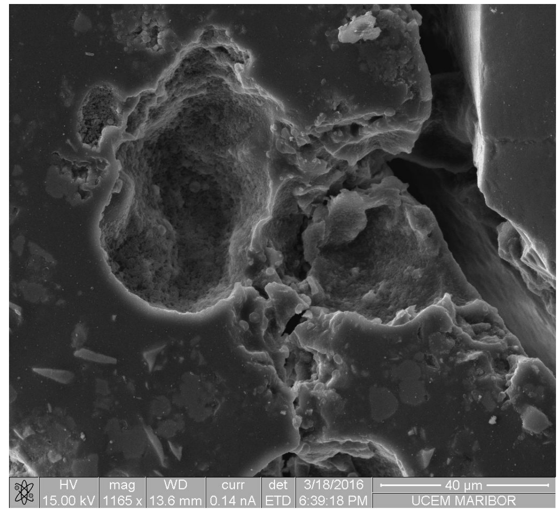

Fig. 13. *Microstructure of grinding wheel sample C/03.03.* **[15]**

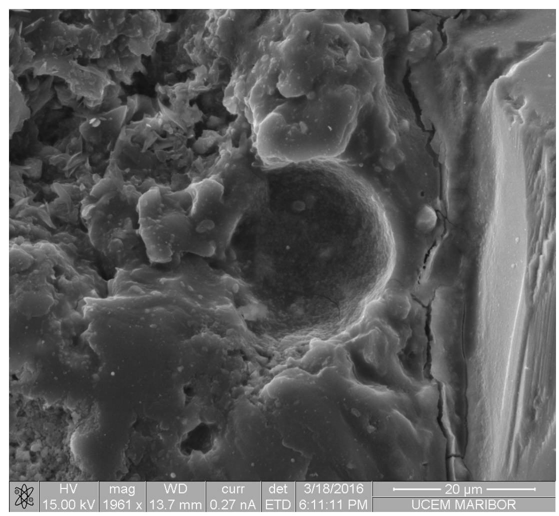

Fig. 14. *Microstructure of grinding wheel sample C/03.03* **[15]**

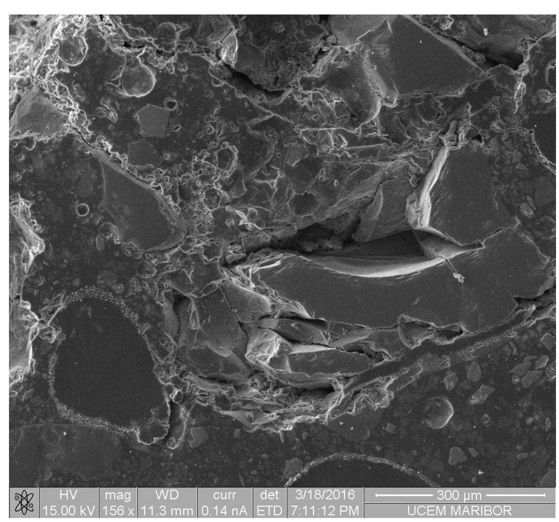

Fig.15. *Microstructure of grinding wheel sample D/03.03* **[15]**

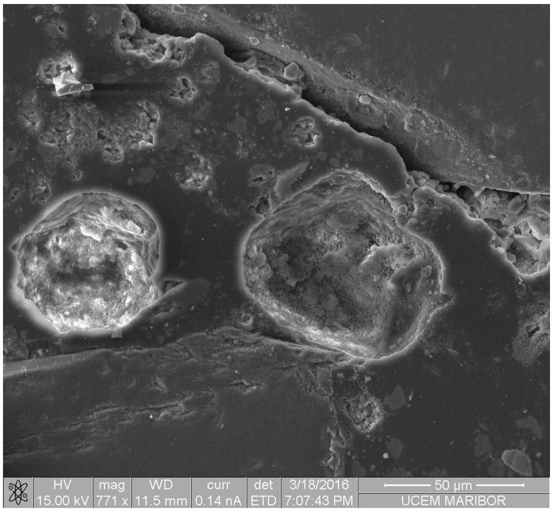

Fig. 16. *Microstructure of grinding wheel sample D/03.03* [15] *and* [16]

- with the accelerated ageing method, the authors successfully inserted a quantity of water (1 % of moisture) into the grinding wheel pores, which is similar to that of the grinding wheel, which is stored under normal conditions for a much longer period, but such procedure has a negative effect on the internal structure of polymer matrix (microstructure) of grinding wheel (Figs. 13 and 16);
- the effect of ageing of grinding wheel is essentially related to the number and size of pores, which are caught in the polymer matrix of phenol-formaldehyde resin (Figs. 11 and 15);
- heat is generated during grinding and heats the water (atmospheric humidity), which is present in grinding wheel pores. It is transformed into a gas phase – water vapours, which causes a rise or increase of hydrostatic pressure of water vapours in pores (Figs. 10 and 16);
- in critical threshold values of the increased hydrostatic pressure in grinding wheel pores, it was first noticed that the internal deformation of pores occurs and in the next phase the destruction of the material across the circumference of pores caught in the polymer binder matrix (Fig. 16);
- water vapour, which penetrates the wall and travels through the matrix, causes cracks in polymer binders. Cracks travel over the matrix and stop on the edge of grain (Figs. 13 and 16);
- a dilatation crack is formed between the structurally homogenous grain and matrix, which first results in the downgrade of hardness of polymer matrix and after that also in faster fall-off of abrasive grains of the phenol-formaldehyde matrix and thereby in a significant downgrade in the grinding wheel cutting ability in the first 45 days from the date of production (up to 40 %) (Figs. 2, 12 to 14);
- phenol-formaldehyde resin (duromer) in grinding wheel cross-binds individual abrasive grains. By nature, duromer is very hard and fragile, so the formation of cracks in the matrix contributes to a much faster reduction of grinding wheel hardness and, consequently, to the downgrade in functional and mechanical properties of grinding wheel (Figs. 11 to13);
- increased presence of water vapours in pores of the polymer matrix of wheel increases internal tensions between the matrix, grain and glass impregnated cloth, which strengthens the microstructural matrix of wheel, which has a positive impact on the process of material destruction due to centrifugal forces, which occur when examining the maximum rotational speed of grinding wheel (disintegration testing) (Table 2).

Table 4 presents a comparison of characterisation based on the cross-observation, comparison, and analysis of the grinding wheel microstructural images.

3 DISCUSSION

The research of the cutting factor and maximum rotational speed of resin-bonded grinding wheels with corundum and SiC grains was performed within a period of 60 days with the purpose of determining the influence of ageing on their functional properties. The following conclusions can be drawn based on the results of experimental measurements:

- Results of measurements of rotational speeds of disintegration indicate that the lowest values of rotational speeds and thereby of disintegration are around the 15th day of grinding wheel ageing. After that, the values of rotational speeds start slowly growing again up to the 60th day.
- Trend in growth of rotational speeds of grinding wheels continues also in the later period and can actually exceed the original values.
- Results of measurements of the cutting factor confirm the actual influence of ageing during the monitored period and a direct influence on the mechanical properties of grinding wheels, i.e. the grinding wheel cutting factor.
- The implementation of more frequent measurements in fact somewhat distorts the entire image, but it does not change the trends shown

Table 4. *Comparison of characterisation of grinding wheel microstructures*

Sample code/Date of measurement:	Description of sample microstructure	Comment/notes:
Sample A/07.02./ grinding wheel analysed, 5 days old / grinding wheel not used – comparison measurement standard to other samples.	Microstructure of grinding wheel is quite homogeneous; pores are spherical, polymer well crosslinked and bonded to grains. The sample serves as a comparison measurement standard to other observed samples.	Pores have proper shapes, relatively well distributed throughout the polymer matrix there, are no present cracks and fractured grains, grains are fused along edges, and grain fractures run on proper planes. Pores themselves are highly spherical shape; on the surface of the pores is no indication of any plastic deformation or cracks. Polymer matrix around grains is unchanged, inclusions of fillers are well seen, and there is still no change of the microstructure.
Sample B/07.02./ grinding wheel analysed 5 days old / 5 cuts done with grinding wheel.	Microstructure of grinding wheel is still homogeneous, pores are slightly deformed over circumference, tears of binder parts are presents around grains and minor deformities are also present. Spherical pores are still clearly seen.	Pores already have partly improper shapes, cracks are present around grains and binder is separating from grain. The structure of polymer binding has also changed and is more homogenous (aggregates of fillers are not visible any more). The process of destruction of the polymer matrix already started, which results in a partial breakdown of the matrix strength, but due to the small quantity of air humidity content of the moisture, the process of destruction is not so pronounced and noticeable. Also, the size and length of the cracks in the matrix is not so clearly visible.
Sample C/03.03./ grinding wheel analysed 30 days old / additional forced humidification 30 days and 5 cuts (content of 1 % moisture).	Microstructure of grinding wheel has changed the most in this sample, pores have completely lost their original shape and many grains are torn. Very pronounced and branched cracks appear throughout the matrix, the grains are removed from the polymer matrix. Polymer structure is completely ruined. Cracks between grain and matrix are clearly seen. Due to the process of breakthrough of water vapor through the wall, the appearance of eruptive lunches, from which the cracks are spreading in the direction of breakthrough through the bonding matrix to the abrasive grains, where they stop. In the sequel, the water vapor, which spreads and travels through the cracks, deflects and drains abrasively grain from the binding matrix. Critical change of microstructure, many stripped-off grains and the most damaged microstructure.	Due to the forced addition of moisture into the polymer matrix, the most pronounced process of destruction of the polymer matrix is present here and its large deviation from the ideal structure, which results in a breakdown of the matrix strength (the size and length of the cracks in the matrix is clearly visible, the grains are moving away from the binding matrix itself) in accordance with this process the mechanical strength and durability of the resinoid grinding wheel during use is dropped extremely quickly. Destruction of homogeneity of binders due to changes in pores, the changes are a result of hydrostatic overpressure of water vapour in pores, penetration in the walls of pores can be seen in the weakest part. Deformation continues through the cracks in the matrix, which lead to edges of grains. Grains are eliminated from the matrix. Eruptive fields are present in places, where pores used to be. Penetration occurred in the weakest part of the pore wall, water vapour injects cracks in the matrix, cracks travel to the edges of the grains.
Sample D/03.03./ grinding wheel analysed 140 days old / Normal storage (40 % humidity and 15 ºC) and 5 cuts (content of 1 % moisture).	Microstructure is worse than the sample B, but much better than sample C. Pores are partly deformed, grains are already separating from the binder matrix, but there are not so many eruptive fields present around the pores in the matrix as in the sample C. The process of destruction of the pores is also present here, as in sample B and C, but due to the lower amount of moisture in the matrix, the process is not as intense as in the sample C. The pores are less damaged, the eruptive zones are smaller, the cracks are less intense and branched, the deviation polymer matrix grain is not as pronounced as in the case of sample C.	Pores are deformed in the sample D more than in the sample B, destruction of binder matrix is clearly present. There are deformations around grains, but the matrix itself is not that extremely damaged as in the case of sample C. In pores, there is already an ongoing process of hydrostatic pressure of water vapour on walls. In pores, which are the closest to grains, there is already the same process of wall penetration; there are visible expansions of water vapour through the cracks in polymer matrix. Crack stops at the edge of grains, but in this case cracks around grains are smaller, and still bigger than in sample B. For that reason, less grains fall off the polymer matrix.

by comparisons of results of the same grinding wheel in longer intervals between individual testing days.

- Cutting factor achieves the lowest value in a period of 45 days in all tested types of grinding wheels. The downgrade in cutting factor may amount up to 40 %.
- As the period is extended above 45 days, the ageing process stops and stabilises, and the cutting ability somewhat improves.

- Slight growth in the cutting factor of the grinding wheel continues also in the subsequent period, but it does not achieve the original properties.
- Repeated heat processing – thermal treated(drying) of grinding wheel under original conditions leads to the initial mechanical properties of grinding wheel (cutting factor values).
- Atmospheric storage conditions (humidity and temperature) certainly have a decisive impact on the mechanical features of resin-bonded grinding wheels.

On the basis of the findings it can be concluded that, during the observed period, atmospheric humidity has a positive influence on the disintegration of a grinding wheel and thereby on the increase of rotational properties and a much stronger negative influence on the cutting properties of grinding wheels during ageing.

4 CONCLUSIONS

The research explores the impact of ageing in specific time sequences on the mechanical and functional properties of grinding wheels. On the basis of the results, it can be seen that the ageing process happens much faster than predicted. The highest downgrade in the mechanical properties of resin-bonded grinding wheels occurs in the first 45 days after the production.

Simultaneous comparisons of results of the measurements of the wheel cutting factor and the maximum rotational speed have shown that the ageing process has a negative impact on both functional properties in the first phase, but then the trend is reversed.

The measurements of mechanical tensile strengths of grinding wheels have confirmed the findings on a very dynamic and fast ageing of grinding wheel, that the method of determining tensile strength is very useful, reliable and repeatable, and that the statistical processing of measurement results by means of the Weibull model delivers the answer about the correct method of execution of measurements [15].

Cross characterisation of microstructure of grinding wheel samples, which were exposed to different thermomechanical influences has shown how and in what way the ageing process in grinding wheels takes place and what is the extent of impact of the moisture caught in pores of polymer matrix. The size and quantity of pores caught in the polymer matrix of grinding wheel have an indisputably high influence on the course and speed of ageing.

Reduction and control of the occurrence of pores is related to how and in what way the producers of grinding wheels master the entire production process. It is important that the raw materials used are well monitored, technologically verified and controlled so that the process of substance preparation and stabilisation is of good quality and repeatable. The occurrence and quantity of pores and, consequently, the change of properties of grinding wheel during ageing is highly influenced also by the proper selection of the length, inclination of thermal diagram and control during the total thermal procedure of heating and cooling of the grinding wheel.

Consequently, the conditions under which the grinding wheel was stored have a very high impact on the speed of ageing. Therefore, the producers of artificial resin-bonded grinding wheels are faced with a challenge ofhow to protect the wheel from unnecessary atmospheric impacts.

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