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Evaluation of the Influence of the Cooling Method Used During Grinding on the Operating Properties of Ceramic Grinding Wheels Made with Different Abrasives

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ABSTRACT

This article presents the results of a study of the performance characteristics of ceramic grinding wheels during peripheral grinding of flat surfaces carried out using different methods of supplying cooling and lubricating fluid (coolant). In the study, T1 type grinding wheels were used, differing in the type of abrasive used in their construction. The abrasive consisted of mixtures with different volume percentages of: 1) grains of conventional white electro-corundum, 2) grains of submicrocrystalline sintered corundum produced by sol-gel technology, 3) microcrystalline sintered ceramic grains with RECERAMAX™ RT microclasters from RECKEL. Specimens made of 145Cr6 tool steel (60±1 HRC) were ground using coolant feeding by flood method and MQL (Minimum Quantity Lubrication) method. During the study, the components of grinding force (F_n, F_t), radial loss of the grinding wheel and roughness of the ground surface were measured, which made it possible to determine the volumetric wear of the grinding wheel V_s, the total grinding power P, and then calculate the grinding indicators G and K_s. The obtained values of the G index indicate that, regardless of the type of grinding wheel used, a higher relative grinding efficiency was obtained during grinding with the delivery of coolant by the MQL method. The highest values of this index were obtained in the case of the grinding process carried out with a grinding wheel containing RECERAMAX™ RT abrasive. The K_s index confirmed the best performance of the mentioned grinding wheel. Since its value also depends on the total grinding power P and the surface roughness parameter Ra, the grinding process carried out with this grinding wheel is additionally characterized by a better quality of the obtained surface and lower energy consumption.

Keywords: coolants, MQL method, grinding wheel wear, G-ratio, K_s indicator.

INTRODUCTION

Grinding is a commonly used finishing process for hardened workpieces that enables the achievement of high dimensional and shape accuracy, low surface roughness, and favorable compressive stresses in the surface layer of the workpiece [1, 2]. In order to achieve the desired grinding results, it is necessary to ensure the right machining conditions, properly selecting all input quantities affecting the grinding process. In this context, the following are of key importance: the juxtaposition of the characteristics of the two elements of the grinding wheel/workpiece tribological pair, the selection of the type of cooling and lubricating fluid and its application method, and the selection of grinding parameters [3].

When selecting a grinding wheel for a specific machining task, it is necessary to take into account many variables, concerning the properties of the material to be ground, the type of surface to be ground, the required geometric structure and the accuracy of the shape and dimension of the surface after machining, as well as the grinding variety used. The selection of the grinding wheel should be complemented by the determination of its operating conditions, i.e., the value of grinding parameters, the method of cooling the machining zone and the method of dressing. Each of these factors has a significant impact on the final machining result, as it affects the phenomena occurring in the contact zone between the grinding wheel and the surface of the material being ground [4].

The heat and cutting forces generated in the contact zone lead to physical, chemical and mechanical interaction of the contacting surfaces. As a result, the active surface of the grinding wheel is worn down, changes in its micro and macro geometries occur, negatively affecting the course and result of the grinding process.

The development of wear on the active surface of a grinding wheel is the result of four phenomena occurring singly or simultaneously, i.e., grain abrasion, grain fracture and crushing, grain pull-out, and chip space sealing.

Abrasive wear causes the blunting of cutting edges and the development of quasi-flat surfaces at the grain tips. Cracking and shattering of grains is caused by increasing load on them, for example, as a result of progressive dulling or fatigue of the abrasive material resulting from varying mechanical and thermal loads. This phenomenon can have a positive effect on the grinding process - fractured or crumbling grains expose new sharp cutting edges - the grinding wheel becomes self-sharpening. Grain pull-out occurs when the bonding forces of the grains to the binder are exceeded, when the strength of the binder bridges is exceeded, or when the restraint of the grains in the grinding wheel weakens as a result of intensive binder erosion. Sealing of the chip space of the grinding wheel surface occurs as a result of adhesion of the workpiece material to the abrasive grains and progressive filling of the pores. The phenomenon of bonding of the grinding wheel can be accompanied by the pulling out of abrasive grains. This occurs in the case of the formation of layered chips, which, welding to the surface of the workpiece material, are torn out of the grinding wheel together with the surrounding abrasive grains.

The effect of the wear process on the grinding wheel is a progressive change in its shape and cutting ability, resulting in a decrease in grinding efficiency and deterioration in the quality of the workpiece [4, 5, 6]. It should be noted that the progressive wear of the grinding wheel, especially abrasive wear and that resulting from the sealing of the wheel, is the cause of increasingly intense heat generation. If the heat flux cannot be effectively dissipated into the grinding wheel, into the material or into the environment then it can cause adverse changes in the physical and mechanical properties of the surface layer of the workpiece. The negative effect of heat on the surface layer manifests itself in scorching, structural changes, the occurrence of micro-cracks and residual stresses. Prevention of these changes involves taking measures to reduce the amount of heat generated and to remove excessive heat from the contact zone between the grinding wheel and the workpiece. Very important in this matter is the correct choice of coolant and the method of its application to the machining zone [3, 7].

Accordingly, research work is constantly being carried out to improve grinding wheels in terms of their performance characteristics. Such research is carried out by both abrasive tool manufacturers and research centers. The work concerns the components that make up grinding wheels (i.e., abrasive materials and the abrasives produced from them, bonding and reinforcing materials), and at a later stage, the properties of the wheels themselves, which are composites of the aforementioned components. Intensive work is also being carried out in the area of cooling and lubricating fluids [8]. This applies both to their types and methods of delivery into the machining zone. In this regard, research work has been carried out for years on minimizing the expense of coolants by using the MQL (Minimum Quantity Lubrication) method [9, 10, 11]. In this method, which involves the continuous generation of an oil mist and feeding it directly into the grinding zone, synthetic esters or fatty alcohols are most often used as a lubricant, and for some time, mainly for environmental reasons, vegetable oils have also been used [12, 13, 14]. Literature data indicate that in the MQL method, the lubricating medium is supplied in the amount of 10-500 mL/h [15, 16, 17]. In comparison, aqueous oil emulsions supplied during grinding by the flood (WET) method are used, depending on the variation of the process, at a rate of 300,000 to 1,200,000 mL/h.

It is worth to note, that one of the significant disadvantages of using the flood method is the occurrence of the phenomenon of the so-called airbag around the rotating grinding wheel. The air stream swirling around the periphery of the grinding wheel surrounds it, causing deflection and atomization of the emulsion stream, which, as a result, severely restricts the emulsion's access to the grinding zone and hinders its contact with the abrasive grains on the wheel's active surface [18]. Studies indicate that the MQL method provides better penetration of oil particles and allows lubrication at a higher level than the flood method [19]. The use of the MQL method can contribute to reducing wear phenomena on the active cutting tips causing them to retain their sharpness over a longer period of working time with respect to dry grinding and, when grinding hard steels, also with respect to grinding with coolant feed by the flood method. The use of the MQL method can have the effect of reducing the cross-sectional area of the chips [20]. The results of a study on the grinding of 100Cr6 steel reported in paper [21] indicate that the use of the MQL method allows the chips to glide more freely over the surface of the grinding wheel, which can reduce the friction between the chips formed during grinding and the work surface, as well as facilitate the removal of grinding products from the cutting zone. In addition, from the description of the research in the paper [22], it can be seen that the use of the MQL method avoids significant sealing of the grinding wheel, and lubrication takes place around the entire circumference of the wheel, which provides better sliding at the contact between the grain and the machined surface.

Despite the advantages of the MQL method, no description of comprehensive operational tests of grinding wheels made of various abrasive grains and working in the conditions of coolants application with this method was found in the available literature. Available test descriptions are usually limited to testing one grinding wheel with known characteristics. Their mutual comparison is difficult due to different machining conditions (e.g. type of grinding process, type of workpiece material, grinding parameters, flow of coolants) used by different researchers. Therefore, it is justified to undertake research in this area for cognitive reasons. In addition, such a comparison of grinding wheels with different characteristics can influence the decision to use conventional (with conventional electro-corundum grains) or so-called premium (with e.g. submicrocrystalline sintered corundum grains) grinding wheels in a particular machining task.

It is worth mentioning that in the studies of the grinding process aimed to evaluate the suitability of new grinding wheel designs, cooling and dressing methods and conditions, the suitability of grinding wheels for machining new materials, etc., a very important role is played by the adoption of a method according to which it will be possible to objectively perform this evaluation. The most common solution is the use of grinding indices, suggestions for which can be found in the literature [23, 24]. Depending on the form in which they are formulated, these indices take into account performance, energy and quality aspects of the grinding process based on, for example: force, power, grinding wheel wear, or surface roughness parameters [25, 26]. It should be remembered that in order to obtain information about the process under study, several indicators are most often used, properly selected according to the adopted evaluation criteria.

Therefore, this paper describes the course and results of a study aimed at evaluating the effect of the cooling method used during grinding on the performance of ceramic grinding wheels with different abrasives. The study was carried out using three types of ceramic grinding wheels, the abrasive of which were mixtures with different volume percentages of grains of conventional white electro-corundum, grains of submicrocrystalline sintered corundum produced by sol-gel technology and microcrystalline ceramic grains. In the study, two cooling methods were evaluated: standard flood method and with minimum MQL. Two grinding indices were chosen to evaluate the machining process - the basic G index and the K_s index capturing a wider range of process quantities. The paper presents the conditions and methodology of the experimental tests, along with a description of the test stands, as well as the results and conclusions of the tests carried out.

MATERIALS AND METHODOLOGY

Machine tool and workpiece

Experimental tests were conducted during peripheral grinding of flat surfaces on a site equipped with a conventional SPG 30/80 surface grinder (Jotes S.A., Poland). Samples made of 145Cr6 (1.2060) tool steel with dimensions of 100×20×50 mm hardened by quenching and tempering to a hardness of 60±1 HRC were ground. Table 1 summarizes the chemical composition of 145Cr6 steel.

Table 1. Chemical composition of the 145Cr6 steel

Content of elements (wt. %)						
C	Si	Mn	P	S	Cr	V
1.30–1.45	0.15–0.40	0.40–0.70	Max 0.030	Max 0.030	1.30–1.65	0.10–0.25

Grinding wheels

Three T1-type ceramic grinding wheels with dimensions of 350×40×127 mm from Molemab (Italy) were used during the tests, characterized by the same hardness, structure and binder type, but differing in the type of abrasive used in their construction. Three types of abrasive grains were used in the same proportion in each grinding wheel, i.e.:

- in the grinding wheel with the symbol 09A60L8V40, there were grains of various sizes of conventional white electro-corundum, designated by the manufacturer as HUNGAKOR EKF (MOTIM Electrocorundum Ltd., Hungary). The abrasive grains used were of the following granularity according to FEPA: 54 (32.3%), 60 (35.4%), 70 (32.3%);
- in the grinding wheel with the symbol 3SA60L8V40, HUNGAKOR EKF grains of grain size 60 were replaced with TREIBACHER ALODUR® SGK2 grains (IMERYS FUSED MINERALS VILLACH GmbH, Austria). These are grains of submicrocrystalline sintered corundum produced by sol-gel technology. The grains obtained by this method are characterized by higher ductility compared to all types of electrocorundum and at the same time have the ability of submicrovolumetric self-sharpening [27];
- in the grinding wheel designated 3NA60L8V40, RECERAMAX™ RT grains (RECKEL GmbH, Germany) were used instead of HUNGAKOR EKF grains of 60 granulation. According to the manufacturer, RECERAMAX™ RT abrasive consists of microcrystalline ceramic grains with a shape similar to a triangle. The abrasive is resistant to fracture and can be used for machining, characterized by high grinding forces, such as stainless steels, alloys based on Ni, Co, Cr, Ti. The abrasive grains, thanks to their microcrystalline structure, are prone to self-sharpening.

The manufacturer's declared grinding wheel structure number is $N = 8$, which means that the volume proportion of the abrasive in the wheel is 46%. The volume proportion of the binder and pores was 12.5% and 41.5%, respectively. The grinding wheels were fired at 960 °C. In addition, the manufacturer determined the specific gravity and modulus of elasticity of each grinding wheel in the process of quality control, these data are summarized in Table 2. In order to simplify the designation of grinding wheels for the purpose of testing, they were given individual symbols: GW-1, GW-2 and GW-3.

Methods of supplying the coolants to the grinding zone

Grinding of the samples was carried out with coolant supplied to the machining zone by two methods: flood and minimum MQL. In the flood method, an aqueous oil emulsion based on AQUAMET 104 oil (5%) was used and fed into the grinding zone through a single nozzle with a flow rate of $Q_{WET} = 12$ L/min (Figure 1a).

An external Ecolubric MQL Booster (Accu-Svenska AB, Sweden) was used to generate oil mist in the MQL method. The oil mist was directed into the machining zone through two nozzles positioned tangentially to the active surface of the grinding wheel as shown in Figure 1b. The total output of the two nozzles was $Q_{MQL} = 100$ mL/h. Ecolubric E200L canola oil, supplied by the machine manufacturer, was used as the coolant in the MQL method.

Grinding and dressing conditions

The values of the grinding process adjustment quantities that were used during the tests were assumed to be at the level typical for finishing peripheral grinding of flat surfaces. A

Table 2. Specification of grinding wheels used during the study

Description	Symbol	Specific gravity, g/cm^3	Elastic modulus E, GPa
GW-1	09A60L8V40	2.170	49.74
GW-2	3SA60L8V40	2.168	49.20
GW-3	3NA60L8V40	2.161	48.00

constant value of peripheral grinding wheel speed v_s = 27.2 m/s and workpiece speed v_w =10 m/min was assumed for the tests. The machining allowance a = 1 mm was removed in 200 work cycles using an infeed a_e = 0.005 mm in each working pass (concurrent direction).

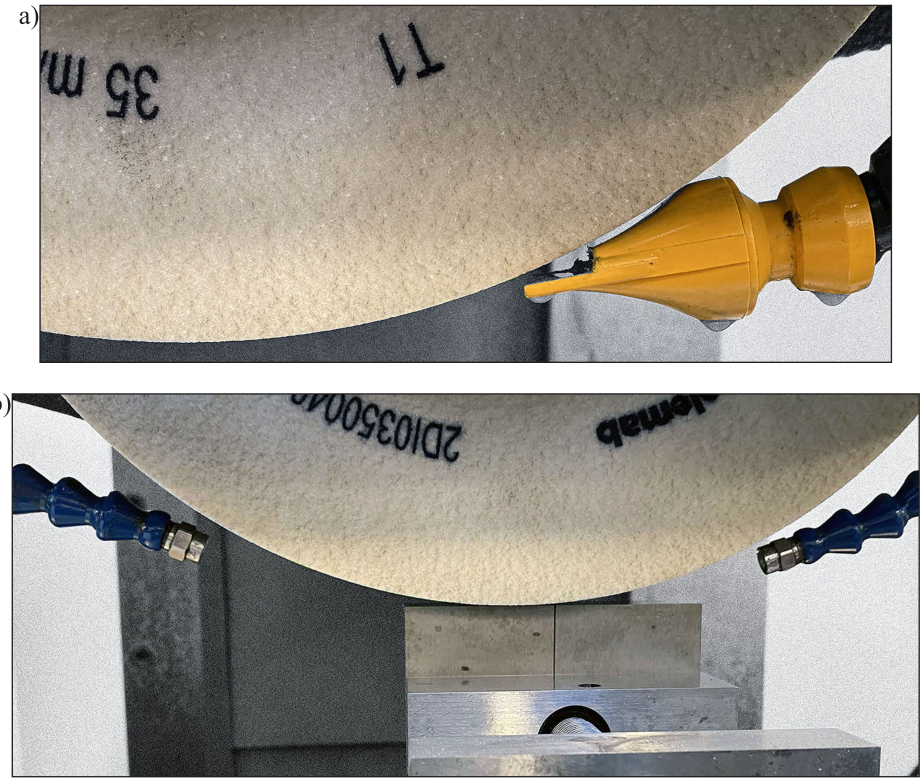
a)
b)


Figure 1. Alignment of coolants feeding nozzles using the method: (a) WET; (b) MQL

Table 3. Grinding conditions used in the study

Parameter	Description/Value
Grinding mode	Longitudinal circumferential surface grinding
Grinding machine	Flat-surface grinder SPG 30/80 by Jotes S.A. (Poland)
Grinding parameters	Grinding wheel peripheral speed v_s = 27.2 m/s
	Workpiece feed speed v_w = 10 m/min
	Working engagement a_e = 0.005 mm
	Machining allowance a = 1 mm
Dressing parameters	Multi-grain diamond dresser
	Axial table feed f_{ad} = 0.625 mm/rev
	Overlap ratio k_d = 2
	Grinding wheel rotational speed n_s = 1490 rev/min
	Dressing allowance a_d = 0.01 mm
	Number of dressing passes i_d = 5
	Dressing with flood method using water emulsion as coolant with flow rate Q_{WET} = 12 L/min
Cooling conditions	Flood method (WET) using water emulsion as coolant: • AQUAMET 104 oil in a 5% concentration • Flow rate Q_{WET} = 12 L/min
	Minimal Quantity Lubrication (MQL) method: • Ecolubric MQL Booster – oil-mist generator with two external nozzles • Ecolubric E200L – cold-pressed rapeseed oil with additives • Air supply pressure p = 0.6 MPa • Flow rate Q_{MQL} = 100 mL/h

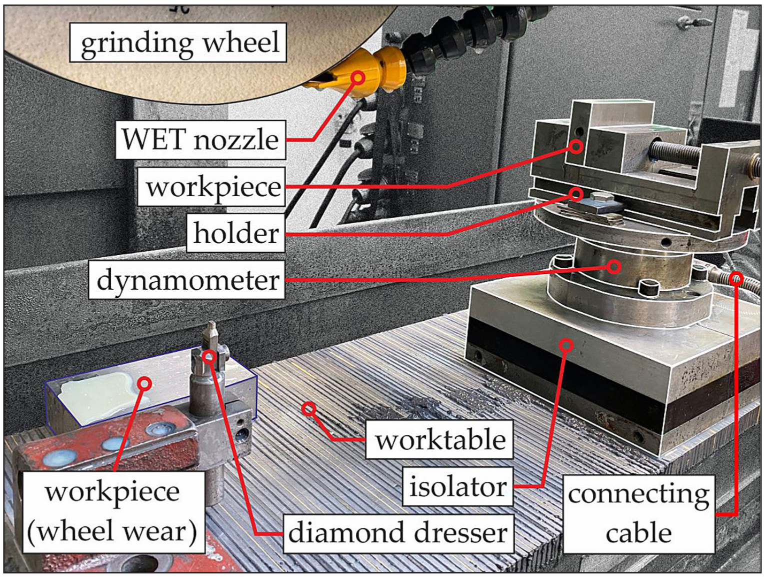


Figure 2. View of the processing zone of the SPG-30/80 surface grinder

Before grinding, the grinding wheels were conditioned with an MCD diamond rod dresser, cooled with an aqueous oil emulsion. The use of this type of dresser was intended to ensure uniform dressing conditions for all grinding wheels. Diamond rods, in contrast to single-grain diamond dressers, maintain a constant shape and active width of the tip in contact with the grinding wheel throughout the service life. This guarantees uniform splitting conditions of the abrasive grains and binder on the active surface of the grinding wheel, as well as maintaining a constant value of the overlap index k_d in subsequent operations, without having to change the dressing feed.

Table 3 summarizes the grinding wheel dressing and grinding conditions used during the tests.

Measurement of cutting force components

During the tests, two components of the grinding force were measured - the normal component F_n and the tangential component F_t. Figure 2 shows the working space of the SPG 30/80 grinder with the components of the measurement track of the components of the grinding force. A 4-component piezoelectric force gauge type 9272 (Kistler, Switzerland) was attached to the magnetic table of the grinder, separated from the table by a layer of insulator. A vise, in the jaws of which the ground sample was placed, was attached to the upper plane of the force meter. The measurement signal from the force meter was routed to a four-channel Kistler 5019 amplifier, and then to a KUSB-3108 measurement card (Keithley Instruments, USA) connected to a PC. Keithley quick DAQ computer software was used to record the measurement signal. The software was also used to determine the normal force F_n and the tangential force F_t.

As already mentioned, the machining allowance was removed in 200 work cycles. The components of the grinding forces were measured periodically by recording their values in two consecutive cycles at an interval of 25 cycles, with the values of the forces F_n and F_t corresponding to the last working pass of a given cycle being taken for subsequent analysis.

Grinding wheel macro-wear assessment

After each of the 25 machining cycles, the volumetric wear of the grinding wheel V_s was determined. Macro-wear was evaluated on the basis of the change in the shape of the profile of the wheel's active surface. Since measuring the profile directly on the grinding machine is a difficult task, it was mapped on a specially prepared sample. The sample, measuring 130×75×40 mm, was made of C45 steel with a hardness of 20±1 HRC and was placed on the grinding machine table before testing at the location shown in Figure 2. By pushing the rotating grinding wheel to a depth of 0.05 mm, a trace of the width of the wheel could be obtained, which was then measured. A Hommel Tester T8000 stationary contact profilometer (Hommelwerke GmbH, Germany) was used for the measurement. Analysis of the shape of the measured profile allowed determining the difference in height between the part of the profile representing the grinding wheel surface not involved in grinding and the part of the profile corresponding to the active width of the grinding wheel b_w (involved in grinding). The resulting value of the depth of wear a_s was used to calculate the volumetric wear of the grinding wheel V_s based on the formula [4]:

$$V_S = b_W \cdot a_S \pi \cdot d_S \quad (1)$$

where: b_W – active width of the grinding wheel equal to 20 mm;
d_S – diameter of the wheel equal to 350 mm.

Surface roughness measurement

Measurements of the surface roughness of the samples after grinding were made with a Hommel Tester T8000 profilometer. The measurement conditions were established on the basis of PN-EN ISO 3274 and PN-EN ISO 4288 and are summarized in Table 4. The value of the arithmetic mean of the ordinates of the roughness profile *Ra* (according to PN-EN ISO 4287) was used to describe the roughness of the ground surface. The value of the *Ra* parameter for each sample was calculated as the arithmetic mean of three measurements.

RESULTS AND DISCUSSION

Volume of wheel wear V_s and *G*-ratio

Table 5 summarizes the values of volumetric wear of the grinding wheel V_s calculated from formula (1), the values of the volume of workpiece loss V_w and the grinding index *G*, which is the quotient of V_w and V_s. In the case of the index *G*, the higher its value, the better the grinding process is considered. The volume of workpiece loss V_w was taken as its nominal value determined from the formula:

$$V_W = b_W \cdot a_{e\text{-}s} \cdot L_W \quad (2)$$

where: $a_{e\text{-}s}$ – total machining allowance removed in successive working cycles (for 25 cycles equal to 0.125 mm, for 50 cycles equal to 0.250 mm, etc.);
L_w – grinding distance corresponding to the length of the sample equal to 100 mm.

The grinding time t_s was determined from the grinding distance L_w and the workpiece speed v_w.

Figure 3 shows a graphical interpretation of the obtained results of volumetric wear of the grinding wheel V_s. Figure 3a presents a graph of the course of wear of the grinding wheel used for grinding with the application of coolant feeding by the flood method, and Figure 3b for grinding with a minimum amount of coolant by the MQL method.

As can be seen from Figure 3, for both methods of feeding coolant, the highest values of volumetric wear of the grinding wheel V_s over the entire period studied were observed for the GW-1 wheel containing 100% grains of conventional white electro-corundum. For the other two grinding wheels (GW-2 and GW-3), the V_s wear patterns are similar to each other, with the difference between the two being evident when grinding using the flood method, averaging about 20% (V_s for GW-2 < V_s for GW-3), while when using the MQL method, the difference is smaller, averaging about 7% (V_s for GW-2 > V_s for GW-3).

Attention is drawn to the first stage of the wear course V_s (up to t_s = 30 s), in which for both cases of feeding coolants the wear of the GW-1 grinding wheel increases rapidly, while for the other grinding wheels the wear course increases

Table 4. Conditions for measuring surface roughness

Parameter	Description/Value
Profilometer	Hommel Tester T8000 by Hommelwerke GmbH
Stylus	TKU 300
Tracing length *lt*, mm	4.8
Evaluation length *ln*, mm	4.0
Sampling length *lr*, mm	0.8
Stylus tip radius r_{tip}, μm	2
Tracing speed v_t, mm/s	0.05
Long-wave profile filter (cutoff) λ_c, mm	0.8
Measuring range, μm	±80

Table 5. Calculated values of volumetric wear of the grinding wheel V_s, volume of workpiece loss V_w and grinding index G

Flood method (WET)								
a_{e-s}, mm	t_s, s	V_w, mm³	GW-1 (09A60L8V40)		GW-2 (3SA60L8V40)		GW-3 (3NA60L8V40)	
			V_s, mm³	G	V_s, mm³	G	V_s, mm³	G
0.000	0	0	0.000	-	0.000	-	0.000	-
0.125	30	250	107.405	2.328	18.264	13.688	19.770	12.645
0.250	60	500	137.522	3.636	36.439	13.721	56.583	8.837
0.375	90	750	159.095	4.714	56.935	13.173	71.867	10.436
0.500	120	1000	161.635	6.187	78.245	12.780	89.570	11.164
0.625	150	1250	185.209	6.749	81.323	15.371	97.399	12.834
0.750	180	1500	189.047	7.935	100.214	14.968	117.499	12.766
0.875	210	1750	203.451	8.602	118.565	14.760	144.636	12.099
1.000	240	2000	213.633	9.362	128.846	15.522	151.893	13.167
MQL method								
a_{e-s}, mm	t_s, s	V_w, mm³	GW-1 (09A60L8V40)		GW-2 (3SA60L8V40)		GW-3 (3NA60L8V40)	
			V_s, mm³	G	V_s, mm³	G	V_s, mm³	G
0.000	0	0	0.000	-	0.000	-	0.000	-
0.125	30	250	77.585	3.222	34.900	7.163	25.972	9.626
0.250	60	500	83.852	5.963	38.375	13.029	26.653	18.759
0.375	90	750	84.490	8.877	42.949	17.463	40.178	18.667
0.500	120	1000	88.866	11.253	52.317	19.114	47.193	21.190
0.625	150	1250	92.407	13.527	59.046	21.170	53.614	23.315
0.750	180	1500	98.762	15.188	61.245	24.492	59.794	25.086
0.875	210	1750	108.262	16.164	76.573	22.854	67.711	25.845
1.000	240	2000	119.610	16.721	82.951	24.111	80.004	24.999

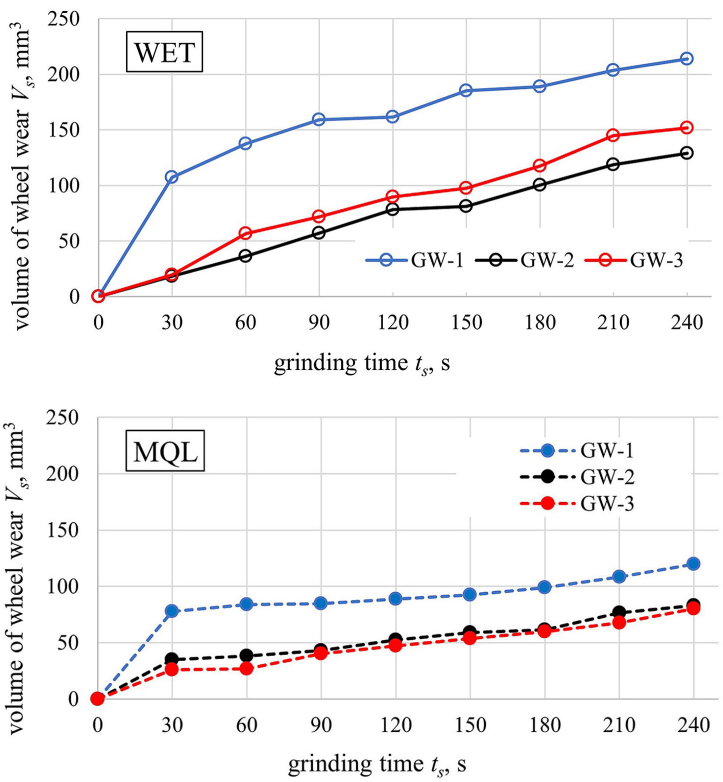


Figure 3. Diagram of the course of volumetric wear of the grinding wheel V_s during grinding with the application of coolants feeding by: (a) WET flood, (b) MQL method

in a more or less linear manner (especially when using the WET method).

The above observations result from the use of different types of abrasive grains in individual grinding wheels. In the case of white electro-corundum (GW-1), under the influence of machining loads, especially in the initial phase of grinding, grain cracking occurs parallel to the crystallographic planes. This results each time in the loss of a significant part of the grain weight through chipping. In the case of submicrocrystalline sintered electro-corundum grains, they exhibit a submicrocrystalline structure. Such a structure results in a greater value of the critical coefficient of grain stress intensity, which enables the phenomenon of self-sharpening of abrasive grains. This is due to the chipping of their macromolecules from the grains, which promotes the discovery of new sharp corners and cutting edges. As a result, a grinding wheel containing this type of ceramic grains (GW-2) has a longer life and retains its shape longer. In the case of microcrystalline ceramic grains (GW-3), their fracture toughness is determined by the polyhedral shape similar to a triangular profile, obtained in the grain crushing process. Furthermore, the grain was modified in a refining production process in such a way that microcrystalline clusters are formed in the line-shaped structure. This structure causes that a dull grain creates new cutting edges when it fractures down. Thus a self-sharpening effect is resulting in a very long tool lives with high stock removal rates.

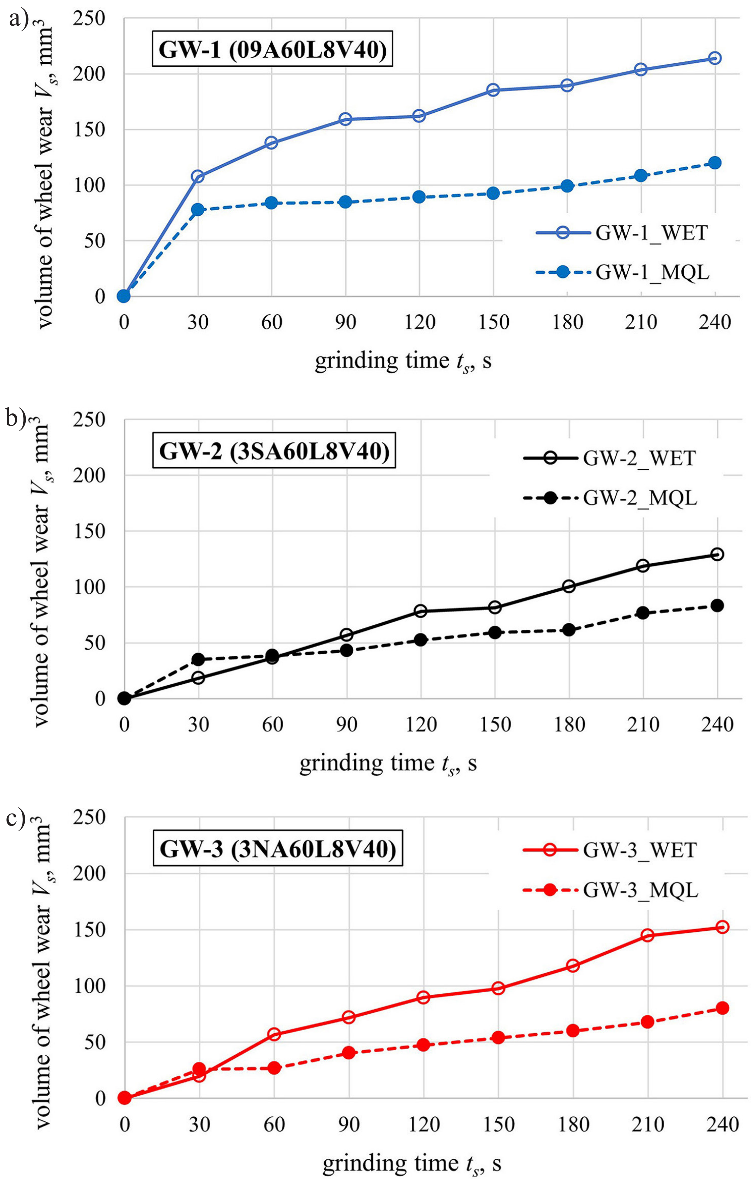


Figure 4. Diagram of the course of volumetric wear of the grinding wheel V_s during grinding with two methods of feeding coolants for the wheel: (a) GW-1, (b) GW-2, (c) GW-3

Figure 4 shows graphs of volumetric wear V_s obtained for grinding wheel GW-1 (Fig. 4a), GW-2 (Fig. 4b) and GW-3 (Fig. 4c). Each of the graphs includes the wear course obtained during grinding with coolant feeding by the WET method and the MQL method.

As can be seen from Figure 4, for all the tested grinding wheels after the initial period (to t_s between 30 s and 60 s), lower values of V_s wear were observed when the coolant was fed with the minimum output by the MQL method compared to the coolant feed by the flood method. At the final stage of the wear course, the largest difference in V_s values occurred for the GW-3 grinding wheel and was 90%, for the GW-1 grinding wheel the difference was 79%, while for the GW-2 grinding wheel it was 55%.

The above observation may result from the fact that, according to the literature [20], the use of the MQL method contributes to the reduction of phenomena related to the wear of active cutting tips, causing them to retain their sharpness over a longer period of time in relation to grinding using the WET method at grinding of hard steels.

Figure 5 shows the graphical interpretation of the results obtained for the grinding index *G*. Figure 5a presents the graph obtained for grinding using the WET method, while Figure 5b shows the MQL method.

The *G* index courses in Figure 5 show that the smallest, least favorable values of it over the entire period under study were obtained during grinding with an electro-corundum grinding wheel marked GW-1. This means that the grain used in it and the selected grinding conditions provide a low relative grinding efficiency in relation to the other grinding wheels. It is worth to note that the largest, most favorable values of the *G* index during grinding with the use of the flood method were obtained for the GW-2 grinding wheel, while with the use of the MQL method for the GW-3 grinding wheel. As already mentioned, microcrystalline ceramic grains are present in the abrasive of the latter grinding wheel, the properties of which in this case caused the smallest volume loss of this grinding wheel to remove the same amount of the allowance. However, a necessary condition is to carry out grinding in conditions of good lubrication, which is possible thanks to the MQL method.

Figure 6 shows graphs of grinding index *G* obtained for grinding wheel GW-1 (Fig. 6a), GW-2 (Fig. 6b) and GW-3 (Fig. 6c). Each graph shows the course of changes in the grinding index *G* values obtained during grinding with

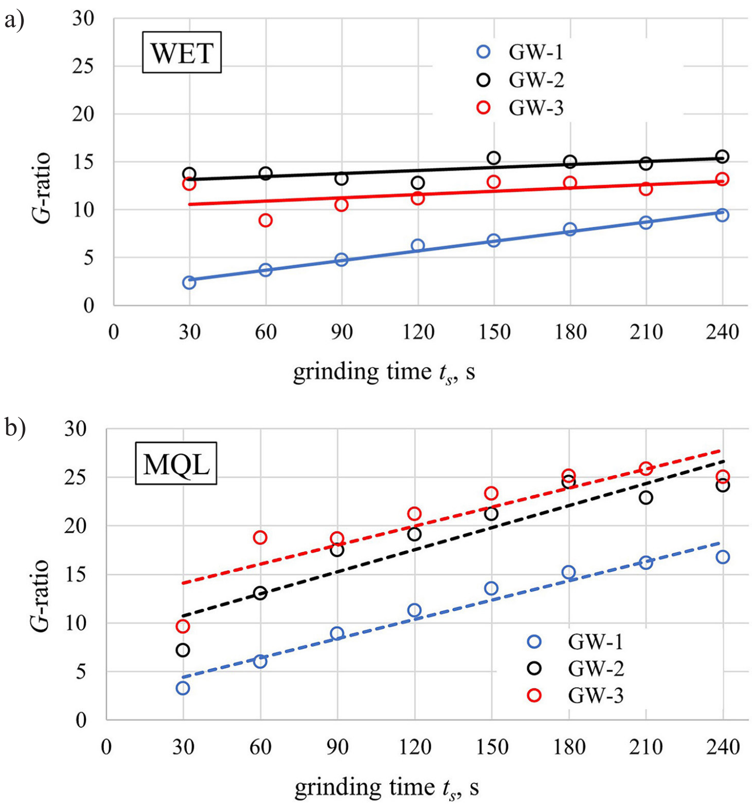


Figure 5. Graph of the course of changes of the grinding index *G* during grinding with the application of coolants feeding by: (a) WET, (b) MQL method

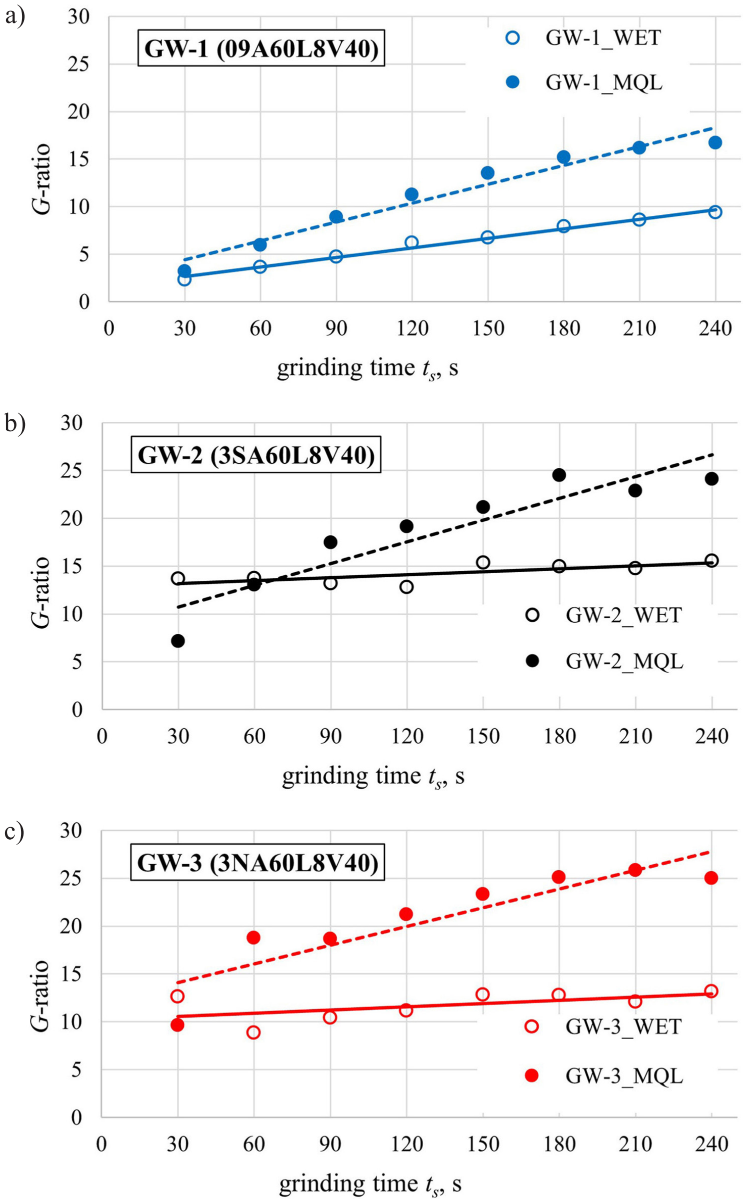


Figure 6. Graph of changes in grinding index *G* values obtained during grinding with two methods of feeding coolants for the grinding wheel: (a) GW-1, (b) GW-2, (c) GW-3

coolant feeding using the WET method and the MQL method.

As can be seen from Figure 6, for each of the three grinding wheels, throughout the wear course, higher values of the grinding index *G* were obtained when using the coolant feed with the minimum MQL method. Only in the initial period of grinding wheel GW-2 operation (up to $t_s \leq 60$ s) this feature was not preserved. It should be noted that in the case of the value of the *G* index attributed to grinding wheels operating under minimum lubrication conditions, the difference in value with respect to the *G* index during flood operation increases with the working time. In the final stage of the study period, the largest difference in value occurred for the GW-3 grinding wheel and amounted to 11.8, for the GW-2 grinding wheel the difference was 8.6, while for the GW-2 grinding wheel it was 7.4.

It is worth noting that from the very beginning of the grinding wheel's operation, the most favorable values of the *G* index were obtained using the GW-3 grinding wheel when feeding coolant using the MQL method. Considering only the grinding wheels operating using the flood method, the grinding wheel GW-2 deserves similar attention.

Tangential grinding force F_t, total grinding power *P*, surface roughness *Ra*, grinding indicator K_s.

Compared to the grinding index G, the K_s index covers a wider range of grinding process quantities. This index was determined based on equation (3), which takes into account the previously calculated G index, the total grinding power P and the surface roughness defined by the parameter Ra.

$$K_S = G / (P_S \cdot Ra) \tag{3}$$

The numerator of the formula includes the index G, which takes on large values when the grinding process is highly efficient and the grinding wheel wear is low. The denominator, on the other hand, takes smaller values when the grinding result is a surface with lower roughness and the machining requires low energy input. Accordingly, the higher the value of the K_s index, the better the grinding process is considered to be.

Table 6 summarizes the values of the tangential component F_t of the grinding force necessary for the calculation of the total grinding power P, obtained for the three tested grinding wheels during grinding with the application of coolant feed by the flood method and with the minimum output by the MQL method.

Table 6. Values of the tangential component F_t of the grinding force

t_s, s	GW-1 (09A60L8V40)		GW-2 (3SA60L8V40)		GW-3 (3NA60L8V40)	
	WET	MQL	WET	MQL	WET	MQL
	F_t, N					
30	32.1	31.1	33.7	31.7	46.9	43.2
60	37.7	35.1	36.6	31.5	53.5	43.7
90	40.9	37.5	44.3	32.1	56.5	50.5
120	46.9	40.8	46.1	37.2	61.7	51.4
150	50.6	42.5	53.9	37.3	62.3	53.3
180	61.8	46.9	54.4	36.8	70.0	55.7
210	50.3	47.9	53.6	38.5	74.3	58.3
240	56.3	50.5	62.4	40.7	83.8	60.2

Table 7. Determined values of total grinding power P, roughness parameter R_a and grinding index K_s

Flood method (WET)									
t_s, s	GW-1 (09A60L8V40)			GW-2 (3SA60L8V40)			GW-3 (3NA60L8V40)		
	P, W	Ra, μm	K_s	P, W	Ra, μm	K_s	P, W	Ra, μm	K_s
30	877.01	0.31	0.009	922.04	0.38	0.039	1271.12	0.39	0.025
60	1030.01	0.33	0.011	1001.39	0.35	0.039	1450.00	0.35	0.017
90	1117.44	0.34	0.012	1212.06	0.35	0.031	1531.31	0.32	0.021
120	1281.37	0.33	0.015	1261.31	0.33	0.031	1672.24	0.32	0.021
150	1382.46	0.32	0.015	1474.72	0.31	0.033	1688.51	0.37	0.021
180	1688.46	0.32	0.015	1488.40	0.31	0.032	1897.20	0.40	0.017
210	1374.26	0.31	0.020	1466.51	0.31	0.032	2013.74	0.42	0.014
240	1538.19	0.32	0.019	1707.28	0.31	0.030	2271.22	0.41	0.014
MQL method									
t_s, s	GW-1 (09A60L8V40)			GW-2 (3SA60L8V40)			GW-3 (3NA60L8V40)		
	P, W	Ra, μm	K_s	P, W	Ra, μm	K_s	P, W	Ra, μm	K_s
30	845.57	0.31	0.012	862.37	0.40	0.021	1170.84	0.36	0.023
60	954.32	0.30	0.021	856.93	0.40	0.038	1184.39	0.32	0.049
90	1019.57	0.31	0.028	873.26	0.40	0.050	1368.69	0.34	0.040
120	1109.30	0.33	0.031	1012.00	0.43	0.044	1393.09	0.33	0.047
150	1155.52	0.32	0.036	1014.72	0.45	0.047	1444.58	0.34	0.047
180	1275.15	0.32	0.038	1001.12	0.45	0.055	1509.63	0.35	0.048
210	1302.34	0.34	0.037	1047.36	0.46	0.048	1580.10	0.31	0.054
240	1373.03	0.37	0.033	1107.21	0.46	0.047	1631.59	0.34	0.045

Table 7 shows the calculated values of the total grinding power P, the measured values of the roughness parameter R_a and the calculated values of the index K_s.

Figure 7 shows the graphical interpretation of the obtained results of the grinding index K_s. Figure 7a presents a graph for grinding using the WET method, while Figure 7b shows the MQL method.

As in the case of the G index, the K_s index courses in Figure 7 also show that the smallest, least favorable value of the index throughout the study period was obtained when grinding with an electro-corundum grinding wheel marked GW-1. Analogous to the G index, when using the flood method, the most favorable K_s index values were obtained for the GW-2 grinding wheel. When using the MQL method, the K_s values for the GW-2 and GW-3 grinding wheels are similar to each other.

As noted earlier, the most efficient grinding took place using the GW-3 grinding wheel, which resulted from the fact that the grinding index G was at the highest value at that time. Since the value of the K_s index is directly proportional to the value of G and inversely proportional to Ra and P, it means that grinding with the GW-2 grinding wheel had to be performed with lower power consumption and/or generate lower roughness of the machined surface, so that the K_s index had a similar value in both cases. As shown in Table 7, this factor was lower power consumption. The lower energy demand of this grinding can be explained by the sub-micro-volume self-sharpening ability of the sintered corundum grains being a component of the abrasive of the GW-2 grinding wheel. The continuous exposure of new, sharp cutting edges on the grains ensures that the specific resistance of the microcutting process is low.

Figure 8 shows graphs of grinding index K_s obtained for grinding wheel GW-1 (Fig. 8a), GW-2 (Fig. 8b) and GW-3 (Fig. 8c). Each graph shows the course of changes in the grinding index K_s values obtained during grinding with coolant feeding using the WET method and the MQL method.

As can be seen from Figure 8, throughout the lifetime of each of the three grinding wheels, the K_s values obtained during grinding with coolant feeding by the MQL method take on larger values than those obtained with the flood method. This is mainly due to the smaller values of the tangential component F_t of the grinding force, and, consequently, the smaller values of the total grinding

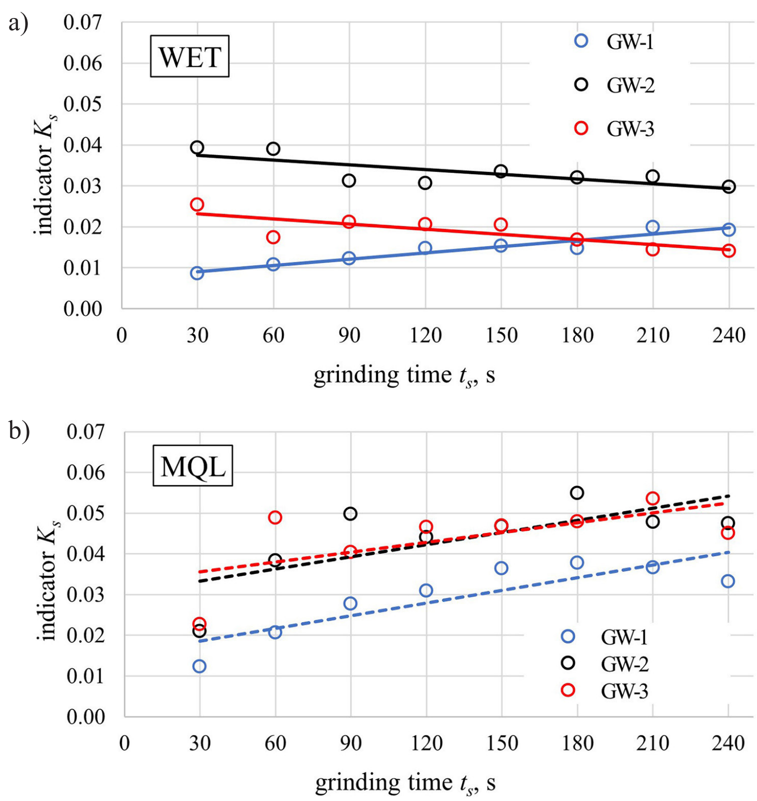


Figure 7. Graph of the course of changes in the grinding index K_s during grinding with the application of coolants feeding by: (a) WET, (b) MQL method

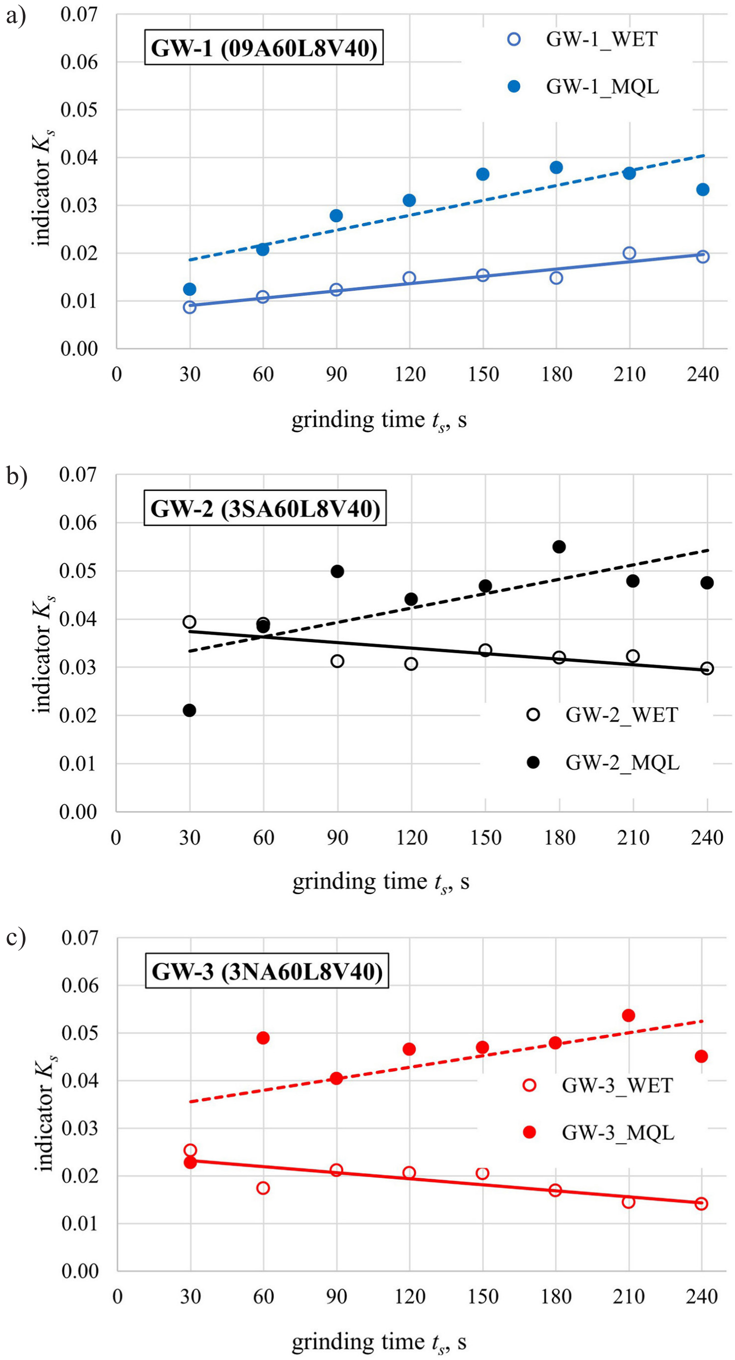


Figure 8. Graph of changes in grinding index K_s values obtained during grinding with two methods of feeding coolants for the grinding wheel: (a) GW-1, (b) GW-2, (c) GW-3

power P, which were recorded in the tests with coolant feeding with a minimum output.

Obtaining lower values of the force F_t results from the high efficiency of lubrication of the contact zone between the surface of the workpiece and the active grinding wheel surface using the MQL method. Lubrication by this method provides better glide and reduces friction between the grain and the surface of the workpiece.

When the grinding process is carried out with GW-2 and GW-3 grinding wheels using an aqueous oil emulsion, the course of changes in the K_s index tends to decrease. This means that grinding under these conditions requires significantly higher energy expenditure compared to the process with the supply of oil with a minimum output by the MQL method. As indicated by the data in Table 7 and shown in Figure 9, in the final period of machining, the energy demand is always higher for the grinding process with the supply of coolant by the WET method than when using the MQL method. This demand for grinding with

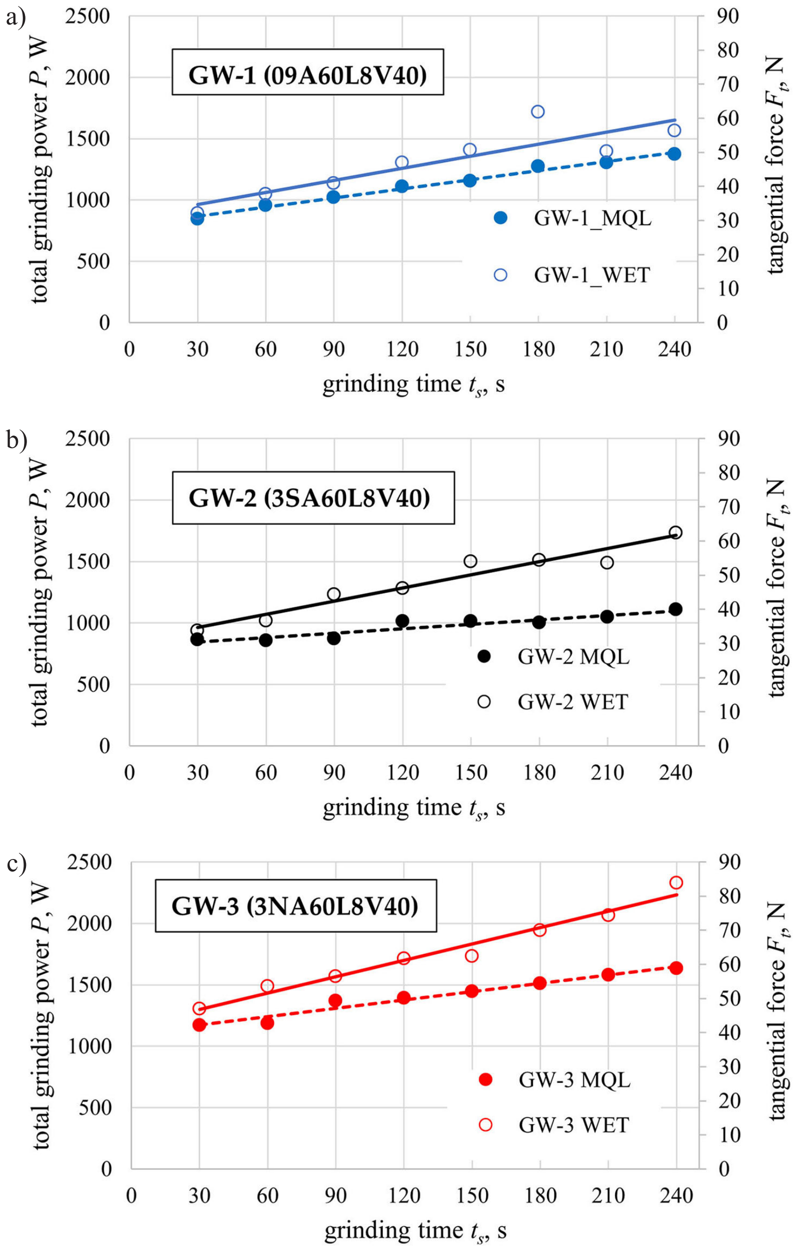


Figure 9. Diagram of the course of total grinding power P and tangential force F_t during grinding with two methods of feeding coolants for the wheel: (a) GW-1, (b) GW-2, (c) GW-3

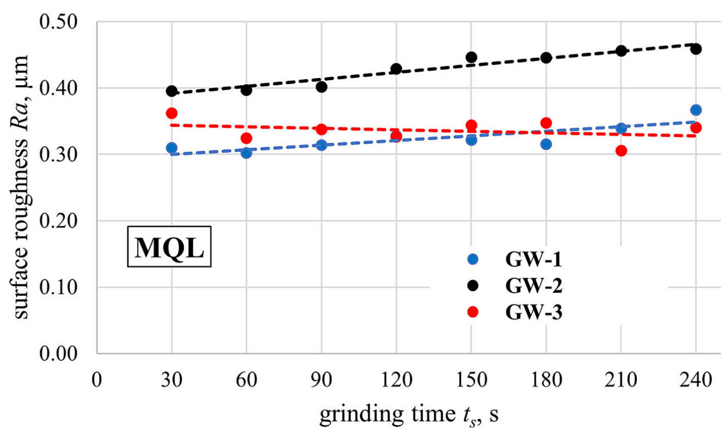


Figure 10. Graph of the course of changes in the surface roughness parameter Ra during grinding with the application of coolants feeding by MQL method

the GW-2 grinding wheel is 54% higher, with the GW-3 grinding wheel 39% higher, and for the GW-1 grinding wheel it is only 12% higher.

Another fact worth an attention is the similar course of the K_s index characterizing the operation of GW-2 and GW-3 grinding wheels under conditions of minimum lubrication by the MQL method (Fig. 7b). However, this similarity is not due to similar energy output (the power *P* for the GW-3 grinding wheel is on average 45% higher than that of the GW-2 wheel), but to the achievement of different values of the *Ra* parameter of surface roughness (Fig. 10). In the case of the GW-2 grinding wheel, the *Ra* parameter is on average 30% greater than the *Ra* parameter corresponding to the surface ground with the GW-3 grinding wheel.

CONCLUSIONS

The research carried out within the framework of this work made it possible to evaluate the influence of the cooling method used during grinding on the performance of ceramic grinding wheels with different abrasives. This evaluation was made on the basis of two grinding indices - the basic *G* index and the K_s index, covering a wider range of process quantities. Grinding was carried out by supplying coolant to the grinding zone by the flood method and with minimum output by the MQL method. Three types of ceramic grinding wheels were used, whose abrasive was a mixture of different volume percentages: 1) grains of conventional white electro-corundum, 2) grains of submicrocrystalline sintered corundum produced by sol-gel technology, 3) microcrystalline ceramic grains RECERAMAX™ RT.

The results obtained in the adopted range of treatment conditions allowed the following conclusions to be drawn:

For each grinding wheel, higher (more favorable) values of the grinding index *G* were obtained when using the coolant feed with minimum output by the MQL method. It follows that the MQL method allows for a higher relative grinding efficiency and thus a lower contribution of tool costs to the cost of grinding operations.

The highest *G* index values were characteristic for grinding performed with the GW-3 grinding wheel with coolant feeding using the MQL method. The abrasive of this grinding wheel contains RECERAMAX™ RT microcrystalline ceramic grains. The manufacturer's indicated use of this abrasive for grinding hard-to-machine materials with high grinding forces was confirmed in this study. The smallest volumetric loss of this grinding wheel to remove the same amount of allowance indicates the high wear resistance of RECERAMAX™ RT grains. A prerequisite, however, is to conduct grinding under the conditions of good lubrication made possible by the MQL method.

For each grinding wheel, larger (more favorable) values of the grinding index K_s were obtained using the MQL method. This is mainly due to obtaining smaller values of the tangential component F_t of the grinding force compared to the use of the flood method and thus providing less energy input for machining. At the same time, this results in greater efficiency of the grinding process when using minimum lubrication with the MQL method compared to the WET method.

The highest K_s index values were obtained in grinding tests in which GW-2 and GW-3 grinding wheels were used and coolant was fed into the MQL machining zone. In both cases, the K_s index took on similar values. As noted earlier, the most efficient grinding took place with the GW-3 grinding wheel - the grinding index *G* had the highest values then. Since the value of the K_s index is directly proportional to the value of *G* and inversely proportional to R_a and *P*, it means that grinding with the GW-2 grinding wheel had to be carried out with lower power consumption and/or generate lower roughness of the machined surface in order for the K_s index to have similar values in both cases. As demonstrated in Table 7, this factor was lower power consumption. The lower power requirements of this grinding can be explained by the ability of the sintered corundum grains, which are a component of the GW-2 grinding wheel, to sub-microvolumetric self-sharpening. The continuous exposure of new sharp cutting edges on the grains ensures that the specific resistance of the micro-grinding process is low.

In summary, it should be concluded that in the studied range of machining conditions, the application of the MQL method had a favorable effect on the grinding process - the grinding indices *G* and K_s took on more favorable values compared to the cooling carried out by the flood method. The best relative grinding performance was achieved by a grinding wheel containing microcrystalline ceramic grain RECERAMAX™ RT, slightly worse, but with a similar energy input, by a wheel containing grains of submicrocrystalline sintered corundum produced by sol-gel technology.

It should be borne in mind that a high value of *G* indicates that the adopted grinding wheel characteristics and grinding conditions provide high relative grinding efficiency.

With reference to the available literature, the obtained results confirmed the validity of the use of the MQL method in the grinding process, extending them to the case of surface grinding of a hard material considered difficult to machine. In this aspect, the MQL method can be an alternative to the WET method. At the same time, the comparison of grinding wheels with different characteristics of abrasive grains included in this article (which was not the subject of previous research) indicated the important role of premium grains in increasing the durability of the grinding wheel, both when using the MQL method and the WET method.

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