SOME REMARKS ON GRINDING WHEEL WEAR AND WHEEL LIFE

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Nomenclature

C, C_w, C_G	constants in various formulae
D	wheel diameter (mm)
e	feed (mm/rev.)
ε	exponent of time in empirical formulae
η	statistical parameter: ratio of hypothetical ball radius to nominal grit diameter
f	depth of cut (mm)
G	grinding ratio: G_{kr} maximum grinding ratio during wheel life
g	nominal grit diameter (mm)
k	constant, power of time in wear function
m	Taylor exponent
n	wheel revolutions (r.p.m.)
r	radius of hypothetical grain ball (mm)
ϱ	power of wheel diameter ratio
t	grinding time: t_{kr} critical time during wheel life when changes occur (min)
T	wheel life (min)
V	specific volume of removed metal [mm^3/mm, min]
v	speed in general: v_m speed of the workpiece, v_f table speed (m/min)
W	volume wear of wheel in general: W_T volume wear of wheel during wheel life (mm^3)
x, y	constants in empirical formulae

1. Introduction

Grinding plays an increasingly important part in every-day workshop practice in the production of components requiring great accuracy and ready interchangeability. Provided that the correct wheel is used, the grinding machine can play an effective and efficient part in any machine workshop. To prove the economical effect of grinding operation is, however, not quite simple due to the lack of theoretical formulae such as the Taylor equation in metal cutting [1].

A series of investigations has recently been carried out at the Department of Production Engineering, Technical University, Budapest, to find the factors governing wheel life. It is generally known that a number of factors have influence on wheel life such as grinding wheel, speed, grade, diameter and width, table speed, working speed and grinding lubricant. But assuming that all grinding factors are constant, except wheel wear, the question arises: what are the main parameters defining wheel life and whether it is possible to establish a wheel life equation in function of these parameters.

In the Soviet literature several empirical formulae are available [2, 3] expressing relationship between working speed v_m, wheel diameter D, depth of cut f, table speed e and wheel life T, such as

$$v_m = \frac{CD^\delta}{T^m f^x e^y} \tag{1}$$

where C, δ, m, x and y are constants to be determined experimentally. According to data in [2] for internal grinding of steels with aluminum oxide, vitrified bonded wheels, these constants are as follows:

$$\delta = 0{,}5 \qquad m = 0{,}6 \qquad x = 0{,}9 \qquad y = 0{,}9$$

Formulae like in Eqn. 1 give the idea to investigate the possible relationship between the specific volume of removed metal in terms of

$$V = f \cdot x \cdot v_m \left[\frac{\mathrm{mm}^3}{\mathrm{mm,\ min}}\right]$$

and the wheel life T (min) for a given wheel diameter D (mm). Thus, the following function may be assumed:

$$T = \Phi(V) \tag{2}$$

where $\Phi(V)$ represents the relationship to be determined.

The aim of this paper is to examine this wheel-life function and to find its possible determination, taking into consideration some unexpected effects.

2. Basic assumptions

2.1. *Hypothetical wheel structure*

It has earlier been proved by KOLOC [4] that statistical evaluation of various phenomena in connection with wheel performance is possible when considering the wheel as a body consisting of ideal average size balls, as shown in Fig. 1. On basis of this assumption Koloc derived a formula for the theoretical time of self-dressing. In practice the use of Koloc's formula is impossible because there exists no ideal ball diameter of grains. But this assumption is of use for estimating how long a newly dressed wheel can work.

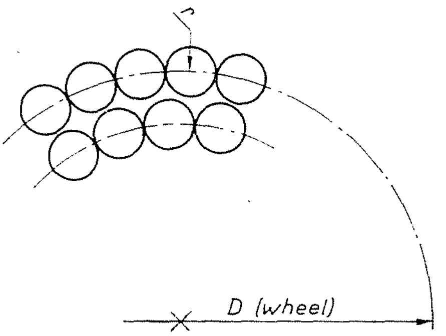

Fig. 1. Hypothetical wheel structure [14]

2.2. *Change in grinding ratio characterizing wheel life*

Our finding that the grinding ratio G will be constant (or decreasing) after a critical grinding time t_{kr} (see Fig. 2) is in conformity to the results of other investigators. This t_{kr} mainly depends on the metal removal rate

$$V\left[\frac{\text{mm}^3}{\text{mm, min.}}\right].$$

For a given V, the grinding ratio G can be determined by the following equation:

$$G = C_G t^{\varepsilon} \qquad (3)$$

where C_G and ε are constants and depend on other conditions, too.

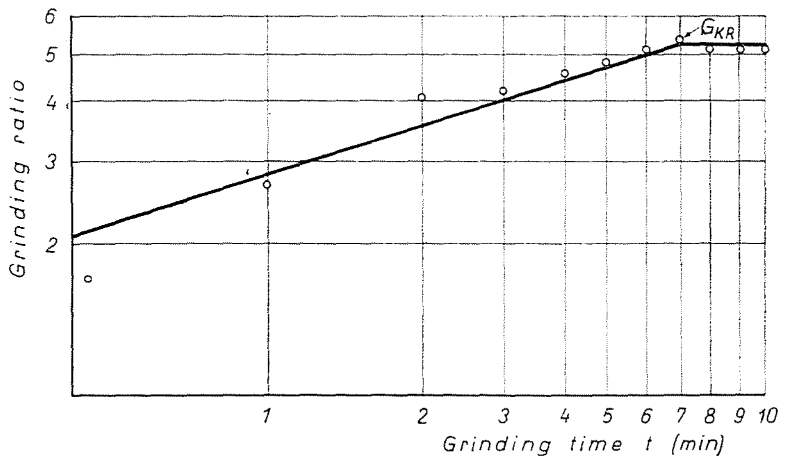

Fig. 2. The grinding ratio has a slope-change after a critical grinding time t_{kr}. Wheel type: Ka 32 I (Gránit Co.). Metal removal rate V = 300 mm³/mm, min

According to Fig. 2, Eqn. 3 will be constant at t_{kr} which can be characterized as follows:

$$G = C_G t_{kr}^{\varepsilon} = G_{kr} = \text{constant.}$$

Assumably, this is the occurrence of self-dressing, provided that the correct wheel is used. After time t_{kr} grinding is possible, but not preferable due to the chatter and the poor surface finish. If the wheel used is harder than needed, il will be impossible to continue grinding after time t_{kr}. Therefore t_{kr} may practically be taken as wheel life.

2.3. *Relationship between volume of wheel wear and grinding ratio*

Determining experimentally the volume of wheel wear as a function of grinding time, it is found that the wheel volume worn in time is as follows:

$$W = C_w t^k \tag{4}$$

where C_w and k are constants and $k < 1$, while the grinding ratio will reach the G_{kr} value at t_{kr}. After this grinding time t_{kr}, k will be equalling or exceeding the unit. In Fig. 3 it is shown that at time t_{kr}, G is constant and W as a function of grinding time has also an inflection near that time.

According to the above, it may be assumed that a newly dressed wheel will wear in small increments up to that time, if the size of the ideal hypothetical grain decreases to half diameter. During this period of wheel wear, the wear-rate $\mathrm{d}W/\mathrm{d}t$ is small and it may be determined by the known (or measured) wear function characterized by Eqn. 4. Assuming that the hypothetical ball radius is r, wheel volume W_T worn on the unit width of the wheel surface during wheel life, may be computed as

$$W_T = \int_{t=0}^{t_{kr}} \frac{dW}{dt}\, dt = D\pi r \tag{5}$$

where D is the wheel diameter after re-dressing.

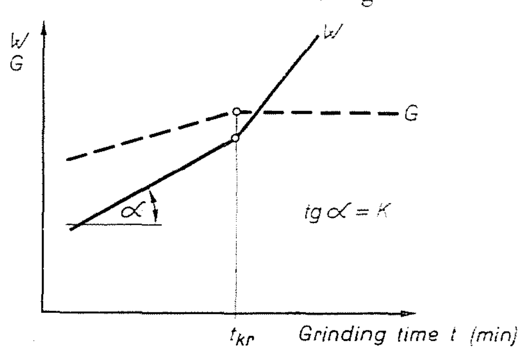

Fig. 3. The wheel volume worn W and the grinding ratio G have an inflection approximately at the same grinding time t_{kr} (schematic diagram)

On the contrary, if t_{kr} value is known and W_T is the wheel volume worn, the radius r may be determined by grinding experiments. This hypothetical ball radius may be a new statistical parameter describing the given wheel structure. Thus, it is a parameter helping to determine wheel life for a given wheel diameter D, provided the other conditions are constant. It is more convenient to introduce a ratio η for calculating r, as it will be shown in the next chapter.

2.4. *Ratio η for calculating r at a given nominal grit size*

As it is known, a given wheel is characterized by a mean grit size determined by a statistical method prescribed in several standards [5, 6]. It means that a grinding wheel of mean grit size g consists of grits coarser or finer than g. The relationship between the hypothetical ideal ball radius r and the mean grit size g is assumed to be:

$$\frac{r}{g/2} = \eta \tag{6}$$

where η is a factor depending on the grain size distribution and the wheel dressing method.

For example, 60% of grits in a vitrified wheel KA 32 complying with the Hungarian Standards [6] of nominal mean grit size $g = 320\ \mu m$ are between 250 and 320 μm size, 15% grits are coarser than 400 μm and 3% are very fine, like powder. Knowing that the very large grits fracture earlier than the time of self-dressing, it may be assumed that this wheel would act as one consisting of 160 μm ($r = 80\ \mu m$) hypothetical ball size only. In this instance, the η ratio would be: $\eta = \frac{60}{160} = 0.5$. However, this η would be unduly high and due to other effects and the real geometrical form of the grains it would be in fact lower (0.25 to 0.4).

3. Computing wheel life

On the basic assumptions mentioned in Chapter 2 and knowing the wear function, wheel life can be computed as follows. If in a given wheel, the mean grit size is g (μm) and the η is known from preliminary grinding experiments, then the hypothetical ball radius will be

$$r = \eta \frac{g}{2000}\ (\mathrm{mm}). \tag{7}$$

Knowing the wheel diameter D (mm) after re-dressing, the volume of the unti wheel-width to be worn up to t_{kr} will be

$$W_T = D\,\pi\,r \qquad (\mathrm{mm}^3/\mathrm{mm}) \tag{8}$$

Graphically plotting the wheel wear function given by Eqn. 4, the constant C_w and k will be:

$$C_w = W \qquad \text{at } t = 1, \text{ and } k = \mathrm{tg}\,\alpha \tag{9}$$

where α is the slope of the wear function in log-log diagram.

Applying the values of C_w and k, the critical time when self-dressing occurs, is found by re-arranging Eqn. 4, as follows:

$$t_{kr} = \left[\frac{W_T}{C_w} \right]^{1/k}. \tag{10}$$

Varying the metal removal rate $V \left[\frac{\mathrm{mm}^3}{\mathrm{mm,\ min}} \right]$ several $V = \varnothing(t)$ functions and several t_{kr} values will be obtained which can be plotted in a log-log diagram taking as axis x the parameter V and as axis y the parameter $t_{kr} = T$ (see Fig. 5).

This diagram delivers the relationship

$$V = \frac{C}{T^m} \tag{11}$$

similar to the Taylor equation used in metal cutting. But in Eqn. 11 V represents the metal removal rate on unit width of wheel and T is the starting time of self-dressing. The constant m may be checked by the usual graphical method (slope of the curve) [7].

4. Experimental results

All the tests were carried out on a Hungarian-made surface grinder type KSU-250. Work material was carbon steel, normalized with $HB = 200 \pm 10$. The test pieces were made in size 10×100 mm, set up in a 600 mm long fixture. The grinding was arranged according to the in-feed method, with a wheel $\varnothing\ 220 \times 70 \times 20$ mm. This way the wheel wore out to U-shape and the actual radius wear was checked by rasor-blade method, with a tolerance $\pm 2\ \mu$m. The grinding spindle had a constant speed of 2960 r.p.m. To vary the metal removal rate, the wheel speed was changed only and the table speed kept constant, $v_t = 10$ (m/min).

The grinding wheel was type KA 32, Hungarian-made (Gránit Co.), hardness I, structure 11, vitrified bonded. Special care was taken to re-dressing the wheel by diamond. Before beginning each life test, the accurate wheel diameter was checked.

Various grinding fluids were used to investigate their effect on the wear functions. Grinding fluid "A" was a water solution recommended by ISO [8] and "B" was a Hungarian made emulsion (solution ratio: 1 : 30). The rate of fluid was 7.25 lit/min in each case.

Test series helped to determine the η value characterizing the ratio between the ideal ball diameter and nominal grit size. For the given grinding wheel it was found: $\eta = 0.3$ (as the mean of four series).

Table I

Work material: carbon steel, normalized
Grinding fluid: Type "A" 7.25 (lit/min)
Wheel: Ka 32, I, 11, Ke; $n = 2960$ rpm; Table speed: 10 m/min; Feed: 0.03 mm

Wheel diameter D (mm)	t (min)	Radial wear (μm)	W $\left(\frac{mm^3}{mm, min}\right)$ Volume of wheel wear	G ratio	Constants of wear function		η	t_{kr} (min)	
					C_w	k		measured	computed
185.1	0.43	9.0	5.81	18.0					
	1.01	15.0	8.72	31.8					
	2.02	37.6	21.80	36.8					
	3.03	40.3	23.50	38.0	12	0.70	0.3	2.8	3.36
	4.03	67.0	39.0	30.4					
	5.05	108.6	63.2	22.3					
183.9	0.43	9.0	5.17	19.8					
	1.01	23.0	13.60	20.7					
	2.02	35.6	20.6	27.5	13	0.70	0.3	2.2	2.85
	3.03	80.0	46.6	18.3					
	4.03	118.0	68.0	16.7					
	5.05	175.0	101.0	14.1					
182.3	0.43	12.0	6.85	17.3					
	1.01	30.6	17.50	15.8					
	2.02	51.3	29.40	19.0					
	3.03	100.0	57.2	14.7	15	0.70	0.3	1.8	2.36
	4.03	119.0	67.5	16.6					
	5.05	188.3	116.0	12.2					

In Tables I and II data are given to illustrate the method described. All test-runs consisted of three sets. The period of one set was so adjusted that the grinding time was a few minutes only. Between every two sets the wheel diameter changed by 1.2 to 1.6 mm due to wear and re-dressing. The data of

Table II

Work material: Carbon steel normalized
Grinding fluid: Type "B" 7.25 lit/min

$n = 2960$/min; Wheel: KA 32 I 11 Ke; Table speed: 10 m/min; Feed: 0.03 mm

Wheel diameter D(mm)	t (min)	Radial wear (μm)	Volume of wheel wear W $\left(\frac{mm^3}{mm, min}\right)$	G ratio	Constants of wear function		η	t_{kr} (min)	
					C_w	k		measured	computed
181.4	0.43	14.3	8.1	16					
	1.01	18.6	10.5	28.3					
	2.02	20.6	11.6	50.5					
	3.03	43.3	24.5	37.0	14	0.40	0.3	4.2	5.31
	4.03	48.6	27.5	43.5					
	5.05	65.3	27.0	40.6					
179.4	0.43	15.0	8.45	14.6					
	1.01	31.0	17.5	16.9					
	2.02	37.0	20.8	18.6					
	3.03	42.6	24.0	31.0	15	0.40	0.3	4.0	4.35
	4.03	46.0	26.0	45.3					
	5.05	59.0	33.2	44.6					
178.4	0.43	14.6	8.15	14.5					
	1.01	29.0	16.3	17.0					
	2.02	41.0	23.0	15.3	17	0.40	0.3	3.0	3.16
	3.03	51.6	28.0	31.0					
	4.03	69.0	38.9	30.4					
	5.05	90.0	50.7	29.0					

Table I for $D = 185.1$ mm are plotted in Fig. 4, to illustrate how C_w, k, t_{kr} (measured) were obtained. It is to be seen that the function of $G = \Phi(t)$ has an inflection at $t_{kr} = 2.8$ min. The function $W = \Phi(t)$ has a slope $\text{tg}\,\alpha = 0.7$ in the interval between $t = 0.43$ and $t_{kr} = 2.8$. At grinding time $t = 1$ min the value of C_w may be checked graphically as 12. This way, all the data necessary for computing t_{kr} are available, such as:

$$W = 12\, t^{0.7} \text{ and } t_{kr} = 2.8 \text{ min.}$$

For computing the t_{kr} value, knowing that $r = \frac{320}{2000} = 0.048$ mm with $\eta = 0.3$, first the W_T is to be determined:

$$W_T = D\,\pi\,r = 185.1 \cdot \pi \cdot 0.048 = 27.9$$

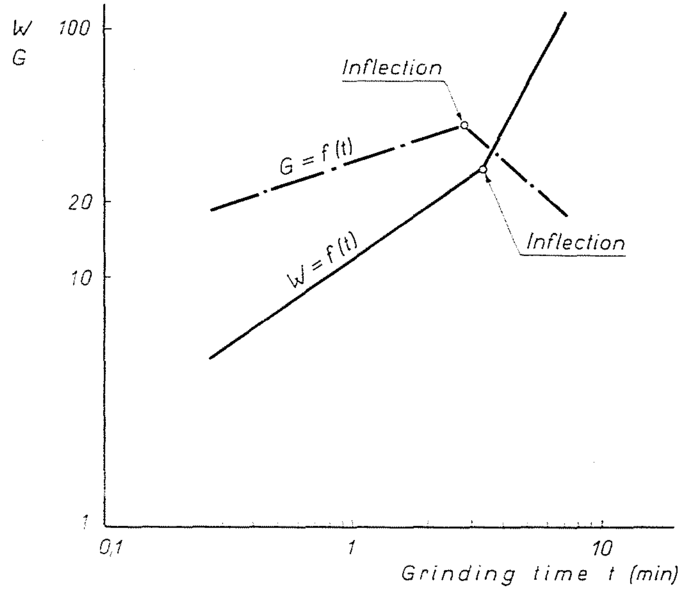

Fig. 4. Functions $G = f(t)$ and $W = f(t)$. Grinding conditions: see Table I

and the t_{kr} (computed) will be:

$$t_{kr} = \left[\frac{W_T}{C_w}\right]^{1/k} = \left[\frac{27{,}9}{12}\right]^{1/0{,}7} = 3{,}36(\text{min})$$

All the similar data of Tables I and II were computed by the illustrated method. It is to be noted that the function $W = \Phi(t)$ may be determined either by graphical or by Gaussian method. The deviation from this curve is due mainly to redressing.

Analyzing these data it may be observed that wheel life computed on basis of the assumption given in Chapter 2.4 is in good agreement with the experimental results. It should be noted that the diameter change has a great effect on wheel life. When applying grinding fluid "A" (which has no lubrication effect), the wear is greater, i.e.

$$W = 12\, t^{0{,}7} \text{ (taking } D = 185.1 \text{ from Table I)}$$

and in case of grinding fluid "B" with some lubrication effect due to its oil content:

$$W = 14\, t^{0{,}4} \text{ (taking } D = 181.4 \text{ from Table II)}$$

It is to be seen that the power of the wear function alters when other fluid type is used. The effect of wheel diameter change is worth of consideration. From Tables I and II the power ϱ of the diameter ratio can also be computed by the following equation:

$$\frac{T_1}{T_2} = \left[\frac{D_1}{D_2}\right]^{\varrho}$$

Using water solution (fluid "A") $\varrho \cong 30$ (mean value) while for fluid "B" $\varrho \cong 20$ (mean value) which are reasonable at first sight.

Ignoring this effect, the results gained on wheel-life tests were in contradiction with each other in Table III. During the investigation the wheel diameters ranged between 209 mm and 192 mm. By correcting the measured wheel life points the contradictions were eliminated. In Fig. 5 the wheel-life function is seen. The dashed curve is plotted from the measured points, the

Table III

Wheel-life test
Work material: Carbon steel, normalized
Grinding fluid: Type "A" 7.25 (lit/min)

Wheel: Ka 32, 1, 11 Ke; $n = 2960$ (rev/min); Table speed: variable; Depth of cut: variable

Wheel diameter D (mm)	Table speed V_t (m/min)	Depth of cut (mm)	Metal removal rate V $\left[\frac{mm^2}{mm, min}\right]$	Wheel life (min)		Remarks
				measured	corrected*	
202.2	10	0.02	200	6.8	16	
195.5	8	0.03	240	6	12	
209.3	10	0.03	300	3.4	3.4	Chosen as reference
203.5	10	0.04	400	1.1	2	
192.0	15	0.03	450	0.2	1.1	Uncertain, due to insufficience of measured points

Note: (*) Correction was carried out with a mean power value of 25 (See text and Fig. 5)

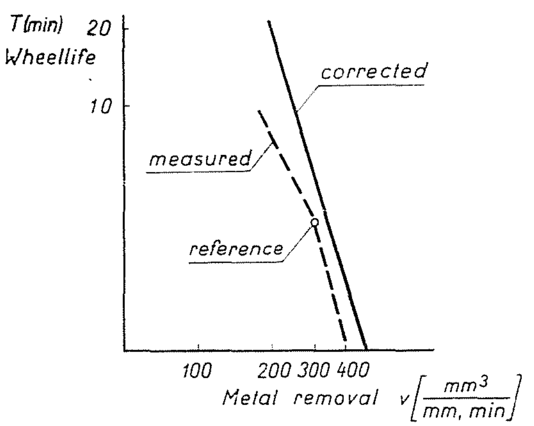

Fig. 5. Wheel-life function corrected by the author's method. Grinding conditions: see Table III

straight line represents the function after correction. In the latter case the wheel life equation was determined graphically, that is

$$V = \frac{480}{T^{0,30}} \left[\frac{\text{mm}^3}{\text{mm, min}}\right] (\text{when } D = 209 \text{ mm})$$

which shows that in the given conditions $T = 1$ min wheel life will be observed if the metal removal rate exceeded 480 mm^3/min on the unit width of the wheel. Of course, as in every case of empirical formulae, this formula gives an average value of wheel life only. The limits of uncertainty need extra determination.

But the wheel-life equation obtained is suitable in practical cases. For example, if it is known how long the wheel of $D = 209$ mm diameter works when the metal removal rate equals 300 mm^3/mm, min, the result will be

$$T_{D=209} = \left[\frac{480}{300}\right]^{1/0,30} = 4,6 \text{ min}.$$

If wheel diameter is below $D = 200$ mm, the following correction will have to be introduced with a mena power of 25:

$$T_{D=200} = T_{D=209} \cdot \frac{1}{\left[\frac{209}{200}\right]^{25}} = \frac{4,6}{3} = 1,54 \text{ min}.$$

When grinding with less metal removal and greater wheel diameter, the wheel change does not affect the wheel life to such a large extent. This rule has been well known to all operators for a long time.

But this fact has to be considered when experiments are carried out in laboratories.

5. Conclusions

The results described lead to the following conclusions:

a) The wheel-wear process can simply be modelled by introducing the ratio η as a parameter of a given wheel controlled by statistical rules of grinding. This parameter depending on grain size distribution and the conditions of wheel dressing can be determined by wear experiments.

b) If the wheel-life is defined as the grinding time needed to reach critical time t_{kr} (when the grinding ratio is constant or begins to decrease), then $t_{kr} = T$ may be computed by the help of the wheel-wear function and η. This method is more convenient than that proposed by Koloc earlier.

c) The wheel life depends not only on the wear characteristic for a given wheel, but also on the wheel diameter. From the η ratio and knowing the wheel diameters after re-dressing, it is possible to compute the wheel-volume to be worn up to time $t_{kr} = T$.

d) This way it may be proved that wheel diameter has a tremendous effect on the wheel life. Analyzing the measured and computed t_{kr} values it is shown that wheel-life varies with the power of diameter ratio ranging from 20 to 30, depending on the type of grinding fluid. Therefore special care is needed when determining wheel-life equations for practical purposes in laboratories.

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Summary

Among the several factors affecting grinding wheel life, wheel diameter is discussed. A new parameter is introduced as a statistical feature of wheel structure which can be determined by wear measurings and permits the time t_{kr} to be defined. By the t_{kr} values obtained at various metal removals, Taylor wheel life equations can be achieved. At last, the author discusses the corrections which — owing to the varying wheel diameters — are needed for setting up wheel life equations.

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