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# Selected Relationships between Process Magnitudes during Surface Grinding with and without Cooling

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The paper contains a comparison of surface grinding process run and its outcomes contingent on cooling and greasing lotion used. On this basis relationships were established between process magnitudes and a new way of predicting their values during grinding processing with cooling was proposed.

*Keywords*: Grinding, parameters, correlations, functional dependencies

## 1. Introduction

Grinding is the most commonplace finishing process. Its usage rate in highly efficient processes is also high. Abrasive treatment is featured by a marked domination of heat produced in process energy balance over volume of chip formation [1], which is translated into high temperature existing in the process zone. Hence comes a routine use of cooling and greasing lotions, which can remove much of the heat produced and not allow for a significant temperature increase of grinded details and for a deterioration of processing accuracy level. The evaluation of cooling lotion's influence can be made by determining the energy separation coefficient Rw, which is defined as the portion of heat transferred to the processed detail [2]. A range of publications referred to in [3] suggests the conclusion, that dry grinding with conventional grinding wheels containing alundum or silicon carbide as the abrasive, results in a transfer of 50-85% heat to a detail, whereas grinding with cooling and greasing lotion – 20-50% of generated heat. Such a cooling process has an ecologically negative aspect however, and attempts are made toward its limitation.

On the other hand research conducted on the grinding process often is performed without the use of any cooling lotion, thereby limiting the influence of additional disturbances and enabling measurement by gauges and apparatus sensitive to liquids. Often it is said that the cooling liquid does not reach the contact zone between the wheel and detail. The liquid turns into vapor, which is caused by the thermal conditions prevailing in the contact zone, so that research investigations can be conducted without cooling lotion. It cools mostly the vicinity of the contact zone by transferring heat from the surface layer and the cutting surface of a grinding wheel. Greasing components in the liquid play an important role here, however, as even after it turns into vapor, they can deposit on the detail, cutting surface and reach the contact zone thereby changing its tribological conditions and chip formation.

This paper attempts to indicate possibilities to combine research results obtained from the grinding process conducted without the cooling and greasing lotion with prediction of such results obtained with cooling. The possibility enables a fuller conduct of laboratory tests using greater number of measured variables (also by means of transducers sensitive to liquid cooling). It also makes it easier to transfer the results to practical applications by using established functional relationships.

## 2. The methodology and research range

In order to handle the task plunge grinding of flat steel surfaces was used with samples made of C45 steel and hardened up to 46–50 HRC. Two grinding wheels dedicated in manufacturer's catalogue for such a material were selected both made of pure alundum and having following characteristics:

1. I–350x20x127–99A60K7VE01–35 – further referred to as "60K",
2. I–350x20x127–99A46L7VE01–35 – further referred to as "46L",

manufactured by Andre Abrasive Articles, Co. from Koło. Grinding made by two wheels allowed a more reliable inference. The range of settings for grinding was selected so as to obtain the desired capacity for evaluation and comparison. Research conditions are contained in Tab. 1.

**Table 1** Conditions of research experiments

| Research stand | Grinding machine SPG 30x80 |
|---|---|
| Grinding wheel dressing: | |
| Depth of dressing [mm/rot] | 0.01 |
| Contact ratio | 1.5 |
| Cooling | Depending on stage in grinding |
| Grinding settings: | |
| Depth of grinding [mm] | 0.005; 0.0125; 0.02 |
| Feed [m/sec] | 0.15; 0.225; 0.3 |
| Grinding wheel's velocity [m/sec] | 26 |
| Cooling: | |
| Lotion type | Oil emulsion 5% |
| Output [l/sec] | 0.11 |
| Grinding wheel working time [sec] | 60 |

Evaluation of the grinding process performance was based on measurement and recording of force components by means of piezoelectric dynamometer Kistler 9275A, surface layer temperature of a grinded detail and cutting surface of a grinding wheel by means of point pyrometers Rayomatic LT20. Temperatures were measured during grinding without cooling. Temperature measurement at a grinding wheel was continuous. Temperature measurement at a grinded sample was interrupted, as soon as the sample left the grinding zone. Detailed description of the measurement process is provided in [4].

Grinding outcomes were evaluated by surface roughness parameter Ra at a sample's surface, and measured by mobile profile measurement gauge Hommelwerke Tester T1000 as well as by radial wear of the of a grinding wheel, determined by Hommelwerke Waveline$^{TM}$ measuring instrument from traces made by a grinding wheel's generating line on a control sample.

The tests were carried out during one–minute work of grinding wheels in contact with a sample. The removed allowance was thus different and dependent on grinding settings. The outcomes were registered by data acquisition card Keithley KUSB3208 and a PC computer software. Research was conducted by repeating tests three times in two series – without cooling and with a cooling lotion, ending in fifty four research cycles in total.

For an analysis of research results the measured values from every five latest grinding passes were subsequently averaged. Next an average was calculated from three sampling repetitions obtained with the same parameters. The obtained values of parameters for grinding process run and its outcome were subsequently used to find relationship between grinding process with cooling and without it.

## 3. Analysis of research results

In the first stage, results were shown in a form of graphical values of recorded parameters as a function of volumetric grinding efficiency, examples of which were shown in Fig. 1 and 2.

Functional responses underline the character of changes in parameters depended on efficiency changes in grinding process and were marked with the use of a well fitted Harris model in a form:

$$y = 1/(a + bx^c) \tag{1}$$

The character of changes in measured magnitudes corresponds with general knowledge, namely that with an increase of allowance removal intensity the grinding force, process temperature, wear of the grinding wheel as well as grinded surface roughness also increase. However, it is worthwhile to look closer at these dependencies.

As can be seen in Fig. 1 and 2, functional responses of force components within one type of grinding, as well as between grinding with and without cooling are quite similar. Functional responses of temperature also share much similarity to them. Also some similarity is born by responses of surface roughness parameter Ra and radial wear between grinding runs with and without cooling.

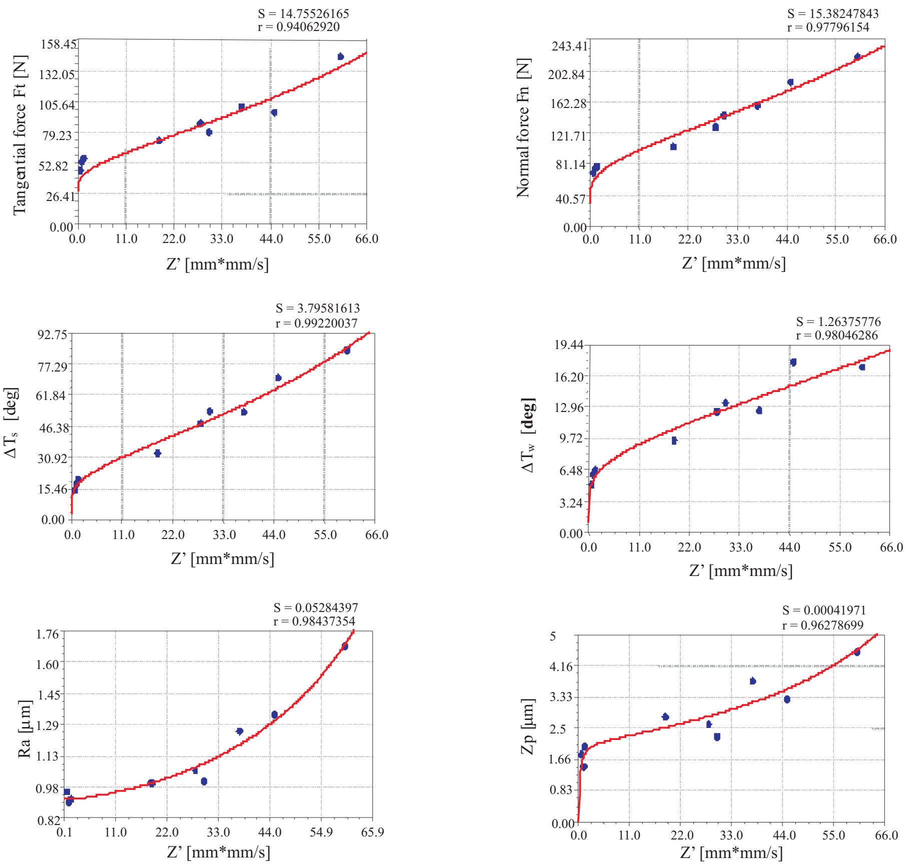


**Figure 1** Comparison of functional values for: force components (A, B), temperature increment in the sample's surface layer (C) and grinding wheel's cutting surface (D), roughness (E) and radial wear of grinding wheel (F), as a function of specific efficiency of grinding without cooling for grinding wheel "60K"

Evaluation of this probability has been achieved by determining correlation between the measured magnitudes in Statistica ver. 7. Results are presented in Tabs 2 and 3.

Preliminary comparison of values indicate a higher correlation between measured variables during grinding with grinding wheel "60K". This grinding wheel had much higher number of abrasive grains than grinding wheel "46L", and consequently offered more stable and repeatedly available work conditions.

Among comparable magnitudes the specific friction coefficient had the lowest correlation to other measured magnitudes. It is defined as the ratio of grinding force components Ft/Fn, ranging about 0.3–0.4 for grinding wheel "46L" and about 0.5–0.6 for grinding wheel "60K". Also temperature at the cutting surface showed low correlation: for grinding wheel "46L" it was about 0.55, but for grinding wheel "60K" was about 0.85.

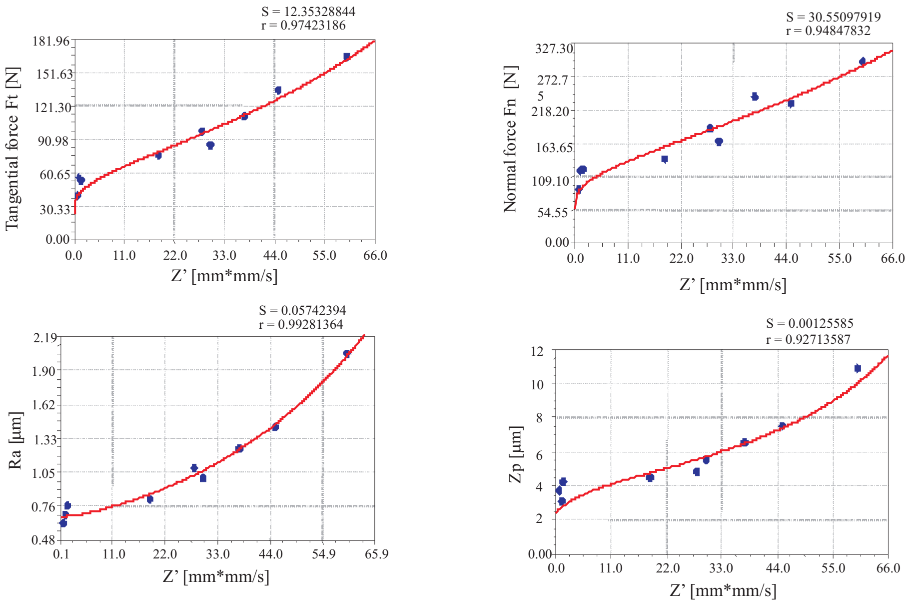


**Figure 2** Comparison of functional values for: force components (A,B), roughness (C) and radial wear of grinding wheel (D) as a function of specific grinding efficiency with cooling for grinding wheel "60K"

**Table 2** Values of correlation coefficient between magnitudes measured in grinding tests with grinding wheel "46L"

| Variable | $Ft_d$ | $Fn_d$ | $Ft_d/Fn_d$ | $Ra_d$ | $Zp_d$ | $\Delta Ts_d$ | $\Delta Tw_d$ | $Ft_w$ | $Fn_w$ | $Ft_w/Fn_w$ | $Ra_w$ | $Zp_w$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $Ft_d$ | - | 0.90 | 0.20 | 0.92 | 0.96 | 0.90 | 0.37 | **0.96** | 0.91 | 0.40 | 0.94 | 0.98 |
| $Fn_d$ | 0.90 | - | 0.60 | 0.85 | 0.90 | 0.99 | 0.68 | 0.97 | **0.94** | 0.39 | 0.97 | 0.92 |
| $Ft_d/Fn_d$ | 0.20 | 0.60 | - | 0.18 | 0.25 | 0.59 | 0.87 | 0.44 | 0.46 | 0.21 | 0.47 | 0.28 |
| $Ra_d$ | 0.92 | 0.85 | 0.18 | - | 0.92 | 0.79 | 0.30 | 0.86 | 0.75 | 0.51 | **0.86** | 0.95 |
| $Zp_d$ | 0.96 | 0.90 | 0.25 | 0.92 | - | 0.89 | 0.50 | 0.94 | 0.85 | 0.49 | 0.93 | **0.95** |
| $\Delta Ts_d$ | 0.90 | 0.99 | 0.59 | 0.79 | 0.89 | - | 0.69 | 0.98 | 0.96 | 0.32 | 0.97 | 0.90 |
| $\Delta Tw_d$ | 0.37 | 0.68 | 0.87 | 0.30 | 0.50 | 0.69 | - | 0.58 | 0.54 | 0.35 | 0.58 | 0.42 |
| $Ft_w$ | **0.96** | 0.97 | 0.44 | 0.86 | 0.94 | 0.98 | 0.58 | - | 0.97 | 0.39 | 0.99 | 0.95 |
| $Fn_w$ | 0.91 | **0.94** | 0.46 | 0.75 | 0.85 | 0.96 | 0.54 | 0.97 | - | 0.18 | 0.96 | 0.87 |
| $Ft_w/Fn_w$ | 0.40 | 0.39 | 0.21 | 0.51 | 0.49 | 0.32 | 0.35 | 0.39 | 0.18 | - | 0.43 | 0.51 |
| $Ra_w$ | 0.94 | 0.97 | 0.47 | **0.86** | 0.93 | 0.97 | 0.58 | 0.99 | 0.96 | 0.43 | - | 0.94 |
| $Zp_m$ | 0.98 | 0.92 | 0.28 | 0.95 | **0.95** | 0.90 | 0.42 | 0.95 | 0.87 | 0.51 | 0.94 | - |

The remaining measured magnitudes had good correlation to other ones, except for the cases mentioned above, and typically had values exceeding 0.9.

Meaning of symbols: $Ft$ – tangential component of the grinding force. $Fn$ – normal component of the grinding force. $Ra$ – surface roughness parameter. $Zp$ – radial wear of the grinding wheel. $\Delta Ts$ – temperature increment in the

**Table 3** Values of correlation coefficient between magnitudes measured in grinding tests with grinding wheel "60K"

| Variable | $Ft_d$ | $Fn_d$ | $Ft_d/Fn_d$ | $Ra_d$ | $Zp_d$ | $\Delta Ts_d$ | $\Delta Tw_d$ | $Ft_w$ | $Fn_w$ | $Ft_w/Fn_w$ | $Ra_w$ | $Zp_w$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $Ft_d$ | - | 0.95 | 0.39 | 0.95 | 0.95 | 0.94 | 0.88 | **0.97** | 0.98 | 0.62 | 0.98 | 0.96 |
| $Fn_d$ | 0.95 | - | 0.64 | 0.93 | 0.90 | 1.00 | 0.97 | 0.98 | **0.96** | 0.72 | 0.96 | 0.95 |
| $Ft_d/Fn_d$ | 0.39 | 0.64 | - | 0.40 | 0.34 | 0.66 | 0.74 | 0.53 | 0.46 | 0.62 | 0.43 | 0.46 |
| $Ra_d$ | 0.95 | 0.93 | 0.40 | - | 0.93 | 0.90 | 0.82 | 0.95 | 0.94 | 0.59 | **0.98** | 0.98 |
| $Zp_d$ | 0.95 | 0.90 | 0.34 | 0.93 | - | 0.87 | 0.81 | 0.92 | 0.94 | 0.57 | 0.92 | **0.92** |
| $\Delta Ts_d$ | 0.94 | 1.00 | 0.66 | 0.90 | 0.87 | - | 0.98 | 0.98 | 0.95 | 0.75 | 0.95 | 0.93 |
| $\Delta Tw_d$ | 0.88 | 0.97 | 0.74 | 0.82 | 0.81 | 0.98 | - | 0.95 | 0.90 | 0.81 | 0.88 | 0.86 |
| $Ft_w$ | **0.97** | 0.98 | 0.53 | 0.95 | 0.92 | 0.98 | 0.95 | - | 0.98 | 0.73 | 0.97 | 0.95 |
| $Fn_w$ | 0.98 | **0.96** | 0.46 | 0.94 | 0.94 | 0.95 | 0.90 | 0.98 | - | 0.59 | 0.96 | 0.93 |
| $Ft_w/Fn_w$ | 0.62 | 0.72 | 0.62 | 0.59 | 0.57 | 0.75 | 0.81 | 0.73 | 0.59 | - | 0.63 | 0.61 |
| $Ra_w$ | 0.98 | 0.96 | 0.43 | **0.98** | 0.92 | 0.95 | 0.88 | 0.97 | 0.96 | 0.63 | - | 0.98 |
| $Zp_w$ | 0.96 | 0.95 | 0.46 | 0.98 | **0.92** | 0.93 | 0.86 | 0.95 | 0.93 | 0.61 | 0.98 | - |

detail's surface layer. $\Delta Tw$ – temperature increment in the cutting surface of a grinding wheel. The "d" index indicates dry grinding (without cooling), whereas "w" grinding with cooling and greasing lotion (wet).

The highest mutual correlation showed increases of temperature in the surface layer of a detail in comparison to normal component of the grinding force. It amounted to 0.99 for grinding with grinding wheel "46L" and 1.00 for grinding with grinding wheel "60K".

This is comprehensible because this component generates main deformations in the surface layer and friction of abrasive grains and the binder against the grinded detail, which produces heat.

Relationship between these two magnitudes however is quite combined and no function has been matched which meets the physical requirements of this problem. However another applicability of temperature measurement was noticed.

Despite lower correlation of grinding force component ratios compared to other magnitudes under analysis. The temperature measurement in the surface layer of a grinded detail can be used to model dependencies which determine relationship between tangential and normal grinding force component of a form:

$$Fn_d = a * Ft_d * \Delta Tp^b \tag{2}$$

where $a$ and $b$ are function parameters.

This made possible to determine the normal component of the grinding force having values of the tangential component and the increment of the temperature in the surface layer of a detail. Fig. 3 shows a comparison of values for this function in measurement points with results of direct measurements of the normal component. Good concordance is visible of the predicted functional relationship with verifying values.

From practical point of view interesting are correlations between registered magnitudes during dry grinding. without cooling and with cooling and greasing lotion applied. Appropriate excerpt from the Tabs 2 and 3 has been presented in Tab. 4.

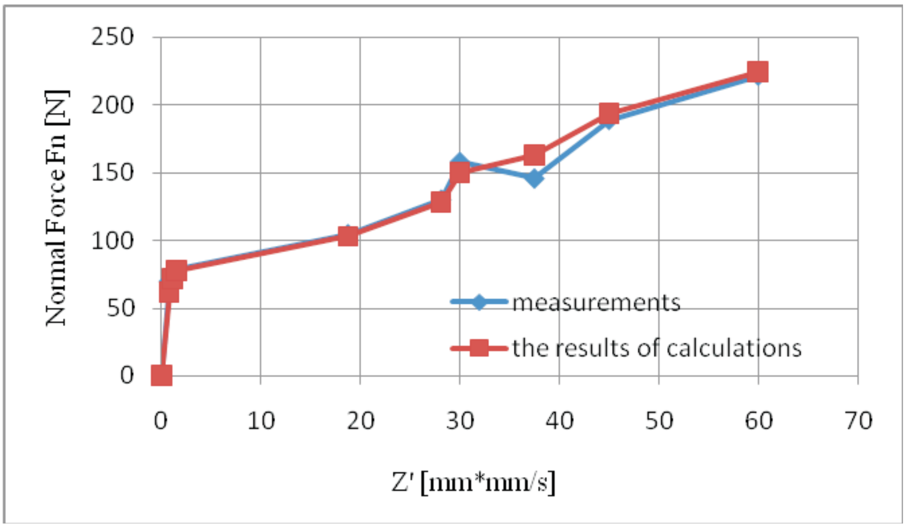


**Figure 3** Comparison of calculated and recorded values of a grinding force's normal component as a function of efficiency of processing for "60K". Functional parameters: a=1[1/ $^\circ$ C], b=0.1

**Table 4** Correlations of magnitudes measured during grinding without cooling and with cooling

| Correlated magnitudes | Values of the correlation coefficient | |
|---|---|---|
| | Grinding wheel "46L" | Grinding wheel "60K" |
| $\mathrm{Ft}_s$ — $\mathrm{Ft}_m$ | 0.96 | 0.97 |
| $\mathrm{Fn}_s$ — $\mathrm{Fn}_m$ | 0.94 | 0.96 |
| $\mathrm{Ra}_s$ — $\mathrm{Ra}_m$ | 0.86 | 0.98 |
| $\mathrm{Zp}_s$ — $\mathrm{Zp}_m$ | 0.95 | 0.92 |

They are on acceptable levels which allows to undertake efforts to build prognostic relationships for grinding with the use of cooling and greasing lotion having registered results obtained without it. Such a forecasting is made possible only in strictly determined research conditions available on the same grinding machine.

Sample relationships between values of grinding force components are shown in Fig. 4. Such sample relationships between surface roughness of a grounded detail and radial wear of a grinding wheel are shown in Fig. 5.

In Figs 4 and 5 there are equations of a function which represents relationships between variables across the whole range of applied grinding intensity. ranging from thorough grinding ($a_c = 0.005$ mm. $v_{ft} = 0.15$m/s) to rough grinding ($a_c = 0.02$mm, $v_{ft} = 0.30$m/s). In three cases proportional dependencies between corresponding magnitudes have been assumed: between grinding force components and radial wear of grinding wheels; in fourth. for surface roughness an exponential model has been applied in a form of $y = a * \exp(b)$. Values of correlations are higher than 0.95.

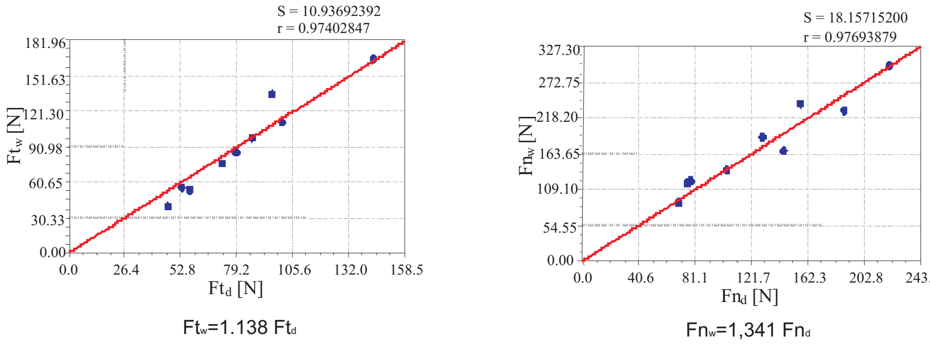


**Figure 4** Relationships between tangential and normal forces during grinding with cooling and without it for grinding wheel "60K"

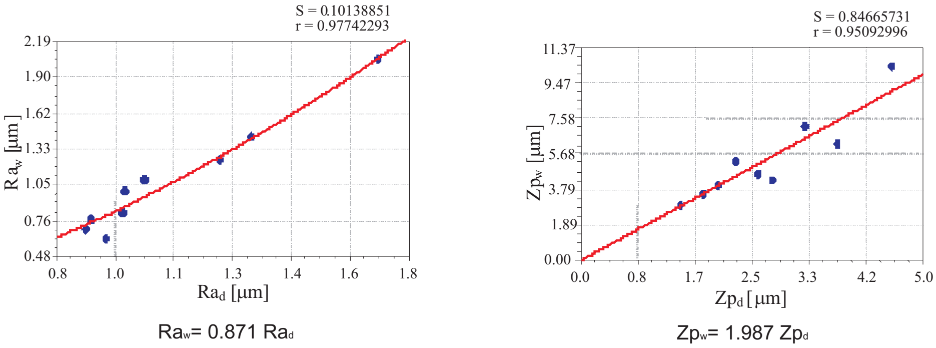


**Figure 5** Relationships between surface roughness of a grounded detail and radial wear of grinding wheel after grinding with cooling and without it for grinding wheel "60K"

The use of exponential function has significantly improved correlation of variables in this case.

A slightly worse results were obtained for grinding wheel "46L" and shown in Tab. 5.

**Table 5** Relationships between measured magnitudes for grinding with grinding wheel "46L"

| Measured magnitude | Relationships | Correlation coefficient |
|---|---|---|
| Tangential force | $Ft_w = 1.133\ Ft_d$ | 0.972 |
| Normal force | $Fn_w = 1.408\ Fn_d$ | 0.963 |
| Surface roughness | $Ra_w = 0.986\ Ra_d$ | 0.845 |
| Radial wear | $Zp_w = 1.710\ Zp_d$ | 0.958 |

Also here high correlation between values of force components and wear was obtained. Worse results appear at comparisons of values of surface roughness. Exponential function of similar form but fitted for grinding wheel "60K" grinding wheel gave an effect worse. than proportional function. Therefore such a function has been given in the table.

## 4. Conclusion

1. The analysis of research results supports a high qualitative similarities of values for grinding force components, surface roughness of a detail and radial wear of grinding wheels within the whole range of the grinding process intensities both with cooling and greasing lotion and without it.

2. Quantitative evaluation of relationships between twelve magnitudes recorded during grinding processes under comparison, showed high correlation in most of the investigated ranges. The lowest correlation to other magnitudes appeared for the ratio of force components called *specific friction coefficient*.

3. High correlation of temperature increments in the detail's surface layer and the normal component of a grinding force allowed for determining the relationship between tangent and normal component of the grinding force.

4. High correlation between values of magnitudes measured during grinding with cooling and greasing lotion and without it made it possible to propose functional relationships. Mostly proportional relationships were accepted; this allows one to infer linear influence of cooling on process magnitudes with correlation level higher than 0.95. Only the relationship of values of the Ra parameter for surface roughness does not correspond with the above proposition. because the parameter relationship appears to be less stable than other measured magnitudes.

5. The proposed procedure can be successfully used in significant research labor intensity cuts owing to the defined functional relationships. In order to prepare them, a preliminary cycle of experiments is needed to establish the functional form. Next, research tests conducted without cooling and greasing lotion are likely to become a base for determining process conditions and outcomes carried out with cooling, which becomes necessary in practical applications of research results.

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