Forecasting the Reliability of Automated Grinding Systems on
the Basis of Young’s Modulus of Grinding Wheels∗

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The paper presents the model of procedure and the results of forecasting the operational
reliability of conventional grinding wheels applied to automated production systems. The
forecasting was issued on the basis of Young’s modulus of these tools obtained from preoper-
ational acceptance inspection. The model was verified during the process of internal grinding
of bearing rings. Investigations were applied to 100 ceramic grinding wheels with the same
characteristics. As a criterion for operational reliability were assumed: the grinding wheels
radial wear Δrs, the maximum spindle power demand Prs and the arithmetical mean devia-
tion of the roughness profile Ra. It was demonstrated that the operational reliability of tools
under investigations was strictly interrelated the modulus E. Therefore; it can be used as a
prognostic criterion for reliability of the system including these tools.

Key Words: Forecasting, Reliability, Internal Grinding, Ceramic Grinding Wheels, Young’s
Modulus

1. Introduction

The global demand for increasing the productivity,
accuracy and efficiency is a main reason for a more and
more wide industrial automation of production systems.
It also concerns abrasive machining, especially applied
to automotive and bearing industry. Respecting serious
losses due to downtime of machine tools and in-line trans-
fer machines, it should be scheduled and reduced to mini-
mum. Particularly disadvantageous is unscheduled down-
time as a result of premature tool wear. In this connection,
the abrasive tools applied to these kinds of machines are
marked by high operational reliability expressed by near-
unity probability value of efficient operation at determined
error-free running time. Since after performing the spe-
cified machining operation the abrasive tools usually need
to be dressed to restore the cutting ability of the tool and
then the process is continued.

If we assume that the intrinsic conditions of deter-
mined, reproducible production are created in the process
of automated abrasive machining, then it will be linked
with stable input and output of the system. The stability
at the output means the production of uniform products.
However, the stability at the input means the necessity of
using the abrasive tools with uniform structure properties.
And yet lack of this uniformity is a natural characteristic
of these tools. It has a destabilizing influence on the ma-
chining operation and impairs the operation reliability of
the system.

2. Essence of Research Problem

The reliability R constitutes the particular property
of all functioning systems (process characteristic), deter-
mined by degree (probability) of satisfying the require-
ments at determined time and under determined condi-
tions(1). The operational system reliability of abrasive ma-
chining Re is a characteristic of its operational use on the
assumption that the time of operational use t is a constant
random variable. A degree of reliability for this system
is the probability that it will be working according to re-
quirements at the time not shorter than the machining time
tm, determined by work task.

Assuming the independency of main states of opera-
tional chain components: a machine, a tool and an opera-
tor, it can be expressed by the relation(2):

\[
R_e(t_m) = R_M(t_m)R_N(t_m)R_0(t_m),
\]

where:

- \( R_M \): man’s reliability (an operator),
- \( R_N \): reliability of technological means (an abrasive tool),
- \( R_0 \): reliability of a machine tool (equipment).

Assuming that the automation reduces with positive
effect the instability of the machine tool and operator, it
is possible to put forward the assumption that \( R_{01}(t_m) = R_{02}(t_m) = 1 \). In this case we can neglect the operator and machine tool effect, and the operational reliability of the system is identified with the operational reliability of the abrasive tool:

\[
R_{0}(t_m) = R_{0}(t_m) = P(t|t_m) = R(t_m), \quad \text{for} \quad t_m > 0 \quad (2)
\]

where:

\( P(t) \): reliability of tool’s real operation.

Therefore, the problem of instability of the whole operational system is connected with the instability of the abrasive tool. The present research problem applies to this issue—Fig. 1.

It is quite difficult to maintain the stable operational properties in case of abrasive tools with conventional structure (\( Al_2O_3 + \) modifications). These requirements are positively satisfied by super-hard grinding wheels made of cubic boron nitride (CBN). Their common use is still limited due to high purchase price \( (3) \). The alternatives to CBN tools are “hard” grinding wheels made of sintered corundum (SG). It is mainly due to the fact that these tools are definitely cheaper and easier for processing \( (4) \). However, it is anticipated that regardless of these innovative achievements in the field of abrasive tool design, the conventional grinding wheels still will find the wide applications \( (3) \).

It results from at least three reasons: low price, high experience in their operational use and by force of habit (mental inertia). Therefore, the issue of assessment of these abrasive tools aimed at their further improvement still seems to be topical.

The research problem generally stated can be brought to the model describing the probability of efficient operation of these tools (taken from a lot of products with specified characteristics) at determined time \( t_m \) and specified operating conditions.

Respecting the design for these models, the following three trends could be distinguished \( (2) \):

1. The course of the whole manufacturing process, taking into consideration both the variances of operational properties, process parameters and the properties of workpieces, is forecast.
2. The operation of respective tools with a low variance of life at variable operational conditions is forecast (This model would be proper e.g. for grinding wheels made of CBN).
3. The operational correctness of a specified lot of tools (with an essential variance of life) under assumed operational conditions. If at the first two cases it is necessary to determine the possible range of process parameter variability and the behaviour of the tool being tested in each range of these parameters, so at the third case the indeterminacy of operational properties of tools from a given lot would occur and the forecasting applies to the essential factors influencing its life \( T \). This third case is adequate to consider abrasive tools applied to automated grinding machines.

The formal, mathematical notation of a survival function for such tools is be presented as follows \( (5) \):

\[
R(t_m) = R(0) \cdot \int_{C_1} dC \int_{T_0} P_0(C/T) \cdot P_0(T) \cdot dT, \quad (3)
\]

where:

\( P_0(T) \): probability of changes in tool life,
\( P_0(C) \): probability of changes in distinguished tool characteristics,
\( P_0(C/T) \): conditional probability.

The function \( R(t_m) \) is not increasing, in general monotone-decreasing, from the initial reliability \( R(0) \) to zero at the machining time \( t_m \) approaching infinity.

Requirements imposed on the reliability may apply to the initial reliability \( R(0) \) and the course of variation of the function \( R(t_m) \) at the time interval \( [0, t_m] \).

Analysing the general model expressed by Eq. (3), one can observe it describes both the tool design (with the characteristics \( c_i \)) and its resistance to the reaction of input factors at the discriminated time interval \( [0, t_m] \). Therefore, the conditional probability \( P_0(C/T) \) describing the interrelations of the tool design characteristics with the course of changes in life is particularly favourable feature apart from the course of changes in characteristics \( P_0(C) \) and the probability of the course of changes in life \( P_0(T) \) at the time interval \( [0, t_m] \).

Usually, it is assumed \( (1) \) in most issues applied to the reliability of technological objects that at the beginning of operational use all the items of the object are fitted for use, that is \( R(0) = 1 \). This assumption in case of abrasive tools (especially with conventional structure) despite the same operating characteristics is not performed \( (2) \). As a result of the reaction of many process variables they obtain randomly the variable values of characteristics \( c_i(0), i = 1, 2, \ldots, n \). Each function \( c_i \) is a random function, and therefore the initial tool reliability \( R^{(0)}(0) \) respecting the
The operational reliability is determined by the probability that values of all the characteristic are contained in acceptable limits. In this case the reliability criterion is a logical basis for the determination of the quality characteristics for tools. However, as opposed to quality, one can determine it mathematically for the whole operational system on the basis of tests on specimen tools from a lot of products with the same characteristics.

3. Experimental Procedure

One of the most important design characteristics of conventional abrasive tools determining the grinding performance is their hardness. It follows from the specific volume fraction of pores $V_p$ and is described symbolically according to Norton’s literal scale (E, F, G, ...). Nowadays, these characteristics are determined by acoustic methods on the basis of Young’s modulus (E). It follows from Author’s investigations in this field that the general relation connecting the modulus $E$ with the volume fraction of pores $V_p$ for abrasive tools with ceramic bonds is given by the expression:

$$ E = 165 - 3V_p \text{[GPa]} . $$

At the difference of the arithmetic sequence $\varphi = 1.5\%$, for the normative variation $V_p$ at a change in hardness according to Norton’s scale, the acceptable variation range for the modulus $E = 4.5 \text{ GPa}$ falling to one class of hardness according to the historically formed scale is obtained.

So one can assume that such the variation of the parameter being tested should not exert the notable effect on operating properties of abrasive tools taken from a specified production lot, and by the same the operational reliability of tools from this lot. However, it was judged necessary to verify this assumption experimentally. So, we decided to carry out investigations on a large group of grinding wheels ($n = 100$ pcs) from the same production lot operated under strictly repeatable operational conditions. Research was aimed to establish the correlation between the modulus $E$ and the service life $T_k$. Since it forms the basis for forecasting the operational reliability $R_c$ for these tools.

Experimental investigations were carried out on the 1-35x20x10-CrA/F80J7V (ISO 525: 1999) grinding wheels applied to the internal grinding of the bearing inner rings. Before starting the operational tests, the modulus $E$ was determined for each grinding wheel by acoustic method according to methodology described in Ref. (6).

Operational tests were carried out on an automatic grinding machine Nova (Italy). The process parameters were set to grind off the material volume $V_m = 410 \text{ mm}^3$ at the specified time $t_m = 48 \text{ s}$. This material removal rate was obtained at standard grinding parameters for this operation, applied to grinding industry. The service life $T_k$ of
Fig. 2 Results of operation tests on a lot of grinding wheels: a) Young’s modulus $E$; b) radial wear $\Delta_r$; c) maximum spindle power $P_c$; d) arithmetical mean roughness value $R_a$

grinding wheels subjected to testing was connected with the critical limitation $k_p$ for this operation. Three types of this service life are distinguished:

1. $T_R$: considering the acceptable roughness of the machined surface ($R_a)_p = 0.63 \mu m$,

2. $T_P$: considering the requirement of maximum spindle power, $P_g = 3.6 kW$,

3. $T_\Delta$: considering the acceptable grinding wheel radial wear, $\Delta_g = 0.03 mm$.

While testing the following measurements were taken: the grinding wheel radial wear $\Delta_r$, the maximum spindle power $P_c$ and the machined surface roughness $R_a$. Measurements of the maximum spindle power $P_c$ were taken from sensors built in the structure of the electro-spindle applied. Measurements of the grinding wheel radial wear $\Delta_r$, were taken with the use of Abby’s vertical length measuring instrument accurate to 0.001 mm. The arithmetical mean roughness value $R_a$ was measured using a profilographometer connected with a computer (measuring errors were within the limits $\pm 4\%$).

4. Experimental Results

The grinding wheels subjected to operational tests were sorted out according to the growing modulus $E$ (No.1—a grinding wheel with the lowest value of the modulus $E$ in a given lot, No.100—a grinding wheel with a highest value of this parameter)—Fig. 2 (a). It illustrates the variability of a tested hardness criterion in one and in the same lot of grinding wheels manufactured under the same conditions and by the same producer. It shows that despite the same marking of the grinding wheels in a given lot, there were grinding wheels with diversified mechanical properties. According to the normative values of the modulus $E$ (Eq. (6)), the hardness of these tools was not within one but three classes of hardness (according to Norton’s scale). It results from extensive investigations on tools of this type obtained from different producers in the world that the standard scatter of the modulus $E$ was within two classes of hardness according to Norton’s scale. So one may expect that this will markedly affect the grinding performance. This conclusion was totally confirmed by investigations. The diagrams of grinding parameters being under consideration in Fig. 2 (b)–(d) constitute a proof of that.

The course of relations in Fig. 2 (b) shows that particularly large differences in the wear $\Delta_r$ occurs if during the grinding process the hardness of grinding wheels is too low in relation to the load applied. The wear of such the grinding wheels (numbers from 1 to 20) is significantly higher than in case of the others. An influence of grinding wheels on the process of grinding is also affected by remaining grinding parameters—Fig. 2 (c) and (d). Despite
they were manufactured under identical conditions as the others, the hardness of the first 20 grinding tools is inappropriate for a given operation. They have damaging effect on the quality coefficients of the whole lot of tools subjected to the assessment. So, they should be eliminated during the acceptance inspection.

The statistic analysis revealed that there is a very close correlation between the modulus $E$ of grinding wheels subjected to testing and the accepted assessment coefficients. Coefficients of the multidimensional correlation for individual functions have the following values:

$$
\Delta_g = f(E); \quad r = -0.965, 1
$$

$$
P_g = f(E); \quad r = 0.964, 3
$$

$$
R_g = f(E); \quad r = -0.794, 3
$$

The functions on examination at a 5% significance level of results can be described by the models of regressive relations presented in Fig. 3 (a)–(c).

Introducing the boundary values ($\Delta_g$, $P_g$, $R_g$) to individual functions described by these models the conversion line $LW$ was obtained. It is a criterion line ($+/-$), which divides the whole domain of the modulus $E$ variation into two subdomain: satisfying (+) the imposed boundary requirement and not satisfying this condition. In the case being analysed, the essential critical limitations include the limiting radial wear $\Delta_g$ and the maximum spindle power demand $P_g$. They determine the acceptable variation (tolerance) of the modulus $E$ for a given operation ($50.0 < E < 61.8$) — Fig. 3 (d).

After introducing the obtained distribution of the modulus $E$ plotted at a 99% confidence level into this range, one may determine the probability of efficient operation for a lot of these tools under assumed operational conditions. In this case it amounts only $p = 0.07$. Therefore, the operational reliability of this order ($R_e \approx 0.07$) could be expected from a given lot of grinding wheels.

The allowable grinding wheel radial wear $\Delta_g$ constitutes a critical limitation of the reliability. Taking it into consideration the real service life $T_o$ of grinding wheels in this process was calculated. The obtained reliable functions respecting this limitation are illustrated by the plot in Fig. 4.

The operational reliability of the system being examined at the assumed time of operation $t_m = 48$ s amounted to $R(T_o) = 0.23$. So it exceeded the anticipated value. However, the obtained, real life distribution $T_o$ is not a standard distribution (which was used for forecasting), but an asymmetric gamma distribution with its maximum at the left side of average value. It is a favourable system, because due to the asymmetry of the life distribution curve $T$ (generally always existing) the reliability in practice is higher than it follows from the forecasting made on the basis of the modulus $E$ variation distribution.

Both the process “$E$” and the process “$T$” are ran-
dom processes. While forecasting the following question arises: what is the conditional probability $P_\Theta(C/T)$ of these two correlated random processes? This problem was solved\(^{(2)}\) by Bayes’ theorem on the probability a posteriori. It follows from the results obtained, that its value for a given system of variables is lesser than 80% (therefore the accuracy of forecasting the service life $T_\Delta$ was estimated on the basis of preoperational investigations on the modulus $E$). It means that at least 80% conformity of the foreseen life $T_\Delta$ was obtained on the basis of preoperational investigations on the modulus $E$ with the real life. So it goes without saying that the dynamic Young’s modulus of grinding wheels determined by acoustic methods is a good coefficient of forecasting the operational behaviour of these tools.

5. Conclusion

The reliability, or limited to possible minimum the probability of not realisation of tasks imposed by any element of this system, is crucial for the optimum implementation of the production targets. In practice the sense of talking about optimisation gathers significance only under condition of stable production. This stability, to a great extent, is provided by automated manufacturing without any participation of human being. Since man is the least reliable member of any system. After eliminating him by the automation of the working cycle, the stability of the system mainly depends on the stability of operational properties of tools applied. It is particularly important in case of ceramic abrasive tools with conventional structure. Since they are characterised by heterogeneity of their structure resulted from the essence of the manufacturing process.

The paper proves that Young’s modulus is a good factor characterising the heterogeneity of these tools. It is well correlated with coefficients characterising operational properties of ceramic grinding wheels, especially abrasive wear. It can be considered as a service life coefficient and at the same time it can be used as a factor for forecasting the operational reliability of these tools.

References


