ISSN 1068-798X, Russian Engineering Research, 2016, Vol. 36, No. 1, pp. 67–70. © Allerton Press, Inc., 2016.
Original Russian Text © A.A. D'yakonov , 2015, published in STIN, 2015, No. 6, pp. 27–30.

Abrasive-Tool Wear and the Machinability of High-Speed Tungsten-Free Steels

A. A. D'yakonov

South Ural State University, Chelyabinsk
e-mail: sigma-80@mail.ru

Abstract—The physics of grinding is considered in order to explain the difference in machinability of tungsten-free and tungsten steels. The strength of the most common steels and alloys is studied over a broad range of strain rate and temperature. Analysis of the results established the variation in strength of high-speed tungsten-free and tungsten steels in typical grinding conditions and permits explanation of the difference in machinability of the steels in physical terms. The relation between the machinability of steel and wear of the abrasive tool is investigated in experiments with individual grains (plane angle $\varphi = 90°$) of different abrasive materials: electrocorundum (24A), zirconium corundum (38A), and Elbor (Borazon). That permits the derivation of a regression equation reflecting the qualitative characteristics of the process, such as the starting point, the presence of an extremum, and the asymptotic behavior.

Keywords: machinability, wear, abrasive material

DOI: 10.3103/S1068798X1601010X

In tool production today, manufacturers of cutters, chisels, mills, broaches, bits, and other cutting tools are switching from high-speed tungsten steels (P18, P6M5, P6M5K6, P10K10M4Ф3, etc.) to less expensive high-speed tungsten-free steels (11M5Ф, 11M5Ф-Ш, and 11M7X2Ф-Ш) [1].

However, their introduction is being held back by the lack of any recommendations regarding optimal finishing operations—in particular, grinding. In fact, the first high-speed tungsten-free steels available in Russia were imported—for example, S412 steel from Böhler (Germany)—and were subjected to the abrasive machining usually employed for traditional high-speed steels.

This approach led to numerous problems, including rapid wear of the grinding wheel (geometric distortion, clogging) and cracking of the machined surface. As a result, the productivity was reduced by a factor of 1.5–2.

The standard strength characteristics (HRC_e, HB) provide no information regarding the different machining properties of high-speed tungsten-free and tungsten steels, since they fall within a narrow range: for example, for P6M5 steel, the hardness after quenching is 65 HRC_e, as against 65.5 HRC_e for 11M5Ф steel. The same pattern is seen for the strength σ_u [2].

To explain the difference in machinability of tungsten-free and tungsten steels, we consider the physics of grinding. In grinding, metal is removed by a set of individual abrasive grains. The contact time of a single grain in the wheel and the machined surface is 1.2–3.4 s. Accordingly, the strain rate is 10^3–10^8 s^{-1} [2]. In addition, grinding generates considerable heat: the temperature in the contact zone is 200–1050°C. Thus, when investigating the strength of materials in the course of grinding, we should consider appropriate temperatures and strain rates.

Existing theoretical approaches do not permit precise description of the change in strength of the workpiece with considerable increase in the temperature and strain rate. Therefore, we must formulate empirical relations on the basis of experimental data. The first such research on the temperature and strain rates in grinding was based on the modification of the stress in static tests [3]. Subsequently, in order to eliminate the considerable error in stress modification, a method was developed for direct determination of the temperature and strain rates of material in grinding [4].

On that basis, we have developed a special test bench containing an inertial dynamometer, which measures the work of cutting by an abrasive grain. That permits determination of the strength of the material by means of a familiar physical formula [5].

Experiments on this bench yield strength plots for the two most common steels and alloys at strain rates of 10^3–10^8 s^{-1} and temperatures of 20–1000°C. In Fig. 1, we present examples of such curves.

Analysis of the results reveals the variation in the strength of high-speed tungsten-free and tungsten steels in typical grinding conditions and permits explanation of the difference in machinability of tungsten-free and tungsten steels in physical terms. For example, in external wheel grinding at a mean temperature of

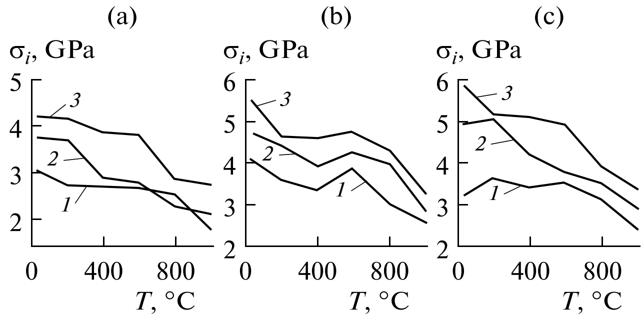


Fig. 1. Strength σ_i of high-speed P6M5 (a), 11M5Φ (b), and 11M7X2Φ-Ш (c) steel as a function of the temperature T at strain rates of 10^3 (*1*), 10^5 (*2*), and 10^8 (*3*) s^{-1}.

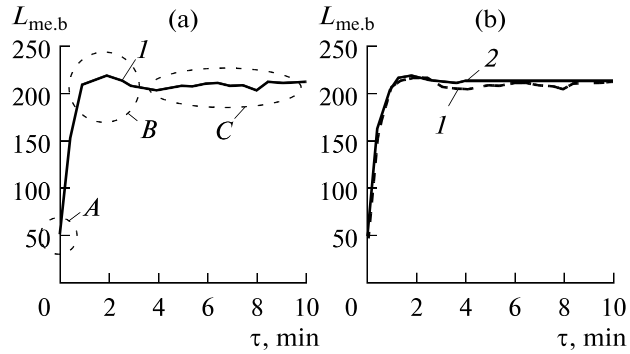


Fig. 2. Experimental wear curve for a grinding wheel (a) and wear curve according to Eq. (3) (b): $L_{me.b}$ is the mean length of the blunting area; τ is the time of wheel operation; areas *A*, *B*, and *C* are described in the text.

600°C, the ratio of the effective resistance to deformation σ_i for P6M5, 11M5Φ, and 11M7X2Φ-Ш steel is 1 : 1.2 : 1.5 at a cutting speed of 50 m/s, as against 1 : 1.5 : 0.8 when the cutting speed is 35 m/s.

Hence, knowing the dependence of the steel strength on the temperature and strain rate, we may not only explain the difference in machinability of tungsten-free and tungsten steels in physical terms but also identify the optimal ranges of temperature and strain rate corresponding to maximum productivity. Thus, for tungsten-free 11M5Φ steel at a cutting speed of 50 m/s (about 10^5 s^{-1}), there are three optimal machining zones at 400, 800, and 1000°C (Fig. 2a), corresponding to minimal resistance to deformation by an abrasive grain (minimal σ_i).

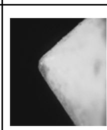
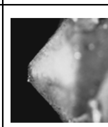
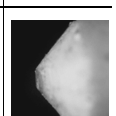
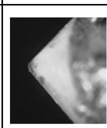
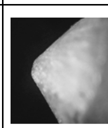
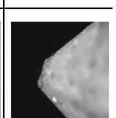
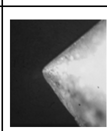
These ranges and the type of grinding may be regarded as physical parameters determining the outcome of the process. In other words, for final grinding of high precision, producing satisfactory surface quality, the optimal temperature is 400°C, corresponding to the absence of scorch marks (when using lubricant) and minimal stress (thanks to the low σ_i value), which implies high machining precision. Grinding at 1000°C is optimal in roughing, when maximum removal of material is required. That corresponds to minimal σ_i (Fig. 1).

If we regard grinding as an interaction between two basic objects (the grinding wheel and the workpiece surface), we also need information regarding the best operating conditions for the wheel, corresponding to minimum cutter wear.

Once again, we may use the test bench proposed in [5]. In this case, however, instead of the workpiece, we study newly sharpened abrasive grains (plane angle φ = 90°) of various materials: white electrocorundum (24A), zirconium corundum (38A), and Elbor (Borazon).

Grains are cyclically loaded in cutting workpieces preheated to different temperature and then inspected under a microscope. The table presents the test results for zirconium corundum (38A) as a function of the number of contact cycles and the temperature, when the machined material is 11M5Φ steel: increasing the temperature and the number of loading cycles increases the wear of a single abrasive grain by a factor of 90.

Wear of abrasive grains in tests

Material	Temperature, °C	Number of cycles		
		1	10	18
Zirconium corundum 38A	400			
	600			
	800			

The results in the table show that the wear of the grain is greatest at 600°C: 0.18 mm, other conditions being equal. This is consistent with the strength plot of 11M5Φ steel, since an extremum of σ_i is observed at 600°C (Fig. 1a). Hence, in this case, zirconium corundum (38A) may effectively be used at 400 and 800°C. The selection of a specific value depends on the requirements on grinding quality and precision.

As yet, our understanding of the physics of abrasive-tool wear is still very basic [6]. At this point, accordingly, the development of mathematical models of wear is based on the analysis of experimental results, with the derivation of regression equations. However, such regression equations must reflect the key properties of the process: the presence of extrema and the behavior at the limits of the region of definition.

Experiments on the wear of grinding wheels in final grinding yield wear curves (illustrating the formation and growth of blunting areas on the abrasive grains) with the characteristic form shown in Fig. 2a.

Analysis of the experimental results show that the following characteristics of the curves must be taken into account in selecting the regression equation (Fig. 2a): the fixed point of onset of the process, determined by the granularity of the wheel (point *A*); the presence of an extremum (point *B*); and the presence of a horizontal asymptote reflecting stable dynamic equilibrium between two wear processes: blunting of the abrasive grains; and tearing of the blunt grains from the binder (region *C*).

Thus, the model must describe the wear characteristics of the grinding wheel's cutting profile, which depends on the wheel's characteristics, the shaping of the working surface after dressing, and the presence of a horizontal asymptote (the possibility of predicting the process).

The standard models in regression analysis do not permit the description of the specified parameters. In addition, they are only applicable in the immediate vicinity of the working points employed in the experiment.

That results in a fundamentally new problem for regression analysis: description of the characteristics of the object being studied. This implies a new approach in the formulation of mathematical models.

Analysis of existing mathematical formulas shows that the requirements on the wear curve of a grinding wheel satisfy a family of exponential polynomials

$$Z = a_1 e^{\Delta_1 t} + a_2 e^{\Delta_2 t} + C, \tag{1}$$

where a_1, a_1, and C are coefficients of the regression equation; and $\Delta_1 t$ and $\Delta_2 t$ are increments in the wheel's operating time.

In terms of regression analysis, the selection of the coefficients in this family of functions is a significantly nonlinear problem, which cannot be reduced to linear form by familiar functional transformations.

Accordingly, we propose constraints on the measurement method: the measurements will be made at equal time intervals h. That poses no experimental difficulties. Then, in Eq. (1), it is expedient to introduce the following notation: $\mu_1 = e^{\Delta_1 t}$ and $\mu_2 = e^{\Delta_2 t}$.

As a result, the regression equation will take the form

$$Z_k = a_1 \mu_1^k + a_2 \mu_2^k + C, \tag{2}$$

where $k = 0, 1, ..., n$.

In Eq. (2), we need to determine a_1, a_2, μ_1, μ_2. The determination of μ_1 and μ_2 is the most difficult. We write the equations

$$\left.\begin{aligned} &\Delta Z_k = Z_{k+1} - Z_k = a_1\mu_1^k(\mu_1 - 1) + a_2\mu_2^k(\mu_2 - 1);\\ &\Delta Z_{k+1} = Z_{k+2} - Z_{k+1}\\ &= a_1\mu_1^{k+1}(\mu_1 - 1) + a_2\mu_2^{k+1}(\mu_2 - 1);\\ &\Delta Z_{k-1} = Z_k - Z_{k-1} = a_1\mu_1^{k-1}\\ &= a_1\mu_1^{k-1}(\mu_1 - 1) + a_2\mu_2^{k-1}(\mu_2 - 1). \end{aligned}\right\} \tag{3}$$

Linear transformations

$$\Delta Z_{k+1} - \mu_1 \Delta Z_k = a_2\mu_2^k(\mu_2 - \mu_1)(\mu_2 - 1);$$
$$\Delta Z_k - \mu_1 \Delta Z_{k-1} = a_2\mu_2^{k-1}(\mu_2 - \mu_1)(\mu_2 - 1),$$

yield the relation

$$\Delta Z_{k+1} - (\mu_1 + \mu_2)\Delta Z_k + \mu_1\mu_2 \Delta Z_{k-1} = 0,$$

where the coefficients may be interpreted as roots of some quadratic equation. In Eq. (3), three successive measurements are taken into account. By analogy with the least-squares method, we obtain the following system from Eq. (3) (by shifts to the right and left and summation over all the points)

$$\left.\begin{aligned} &\sum_{k=1}^{n-1} \Delta Z_{k+1}\Delta Z_k - (\mu_1 + \mu_2)\\ &\times \sum_{k=1}^{n-1} (\Delta Z_k)^2 + \mu_1\mu_2 \sum_{k=1}^{n-1} \Delta Z_k \Delta Z_{k-1} = 0,\\ &\sum_{k=1}^{n-1} \Delta Z_{k+1}\Delta Z_k - (\mu_1 + \mu_2)\\ &\times \sum_{k=1}^{n-1} \Delta Z_k \Delta Z_{k-1} + \mu_1\mu_2 \sum_{k=1}^{n-1} (\Delta Z_{k-1})^2 = 0. \end{aligned}\right\} \tag{4}$$

This is a linear system with respect to $(\mu_1 + \mu_2)$ and $(\mu_1\mu_2)$. By solving Eq. (4), we obtain their values, which may be regarded as the roots of the equations

$$\mu^2 - (\mu_1 + \mu_2)\mu + \mu_1\mu_2 = 0.$$

Solution of this quadratic equation yields the unknowns μ_1 and μ_2. The roots may be equal and may also be complex. Thus, instead of Eq. (3), we may have the equations

$$Z_k = \mu_0^k(a_1 \cos k\alpha + a_2 \sin k\alpha) + C;$$
$$Z_k = \mu_0^k(a_1 + a_2 k) + C.$$

Since μ_1 and μ_2 are now known, Eq. (2) is linear in terms of the arguments $x_k = \mu_1^k$, $y_k = \mu_2^k$. The coefficients of this linear regression are found by the least-squares method.

The significance level of the regression is then assessed by conventional statistical methods. If it is not significant, then Eq. (2) is rejected.

Given the time consumed by manual linearization and determination of the coefficients in Eq. (2), corresponding computer software has been developed. In Fig. 2b, we show the results of computer analysis of experimental data.

The regression equation obtained reflects all the qualitative characteristics of the process, such as the starting point, the presence of an extremum, and the asymptotic behavior.

Calculations on the basis of the proposed model for other wear characteristics of the abrasive grain also prove successful.

The proposed model may be used to describe any wear characteristics of grinding wheels (such as the formation and growth of blunting areas on the abrasive grains and wear along the grain axis).

Thus, by the interpretation of grinding in terms of the physics of wheel–workpiece interaction, we may predict the optimal grinding conditions with sufficient accuracy at the design stage.

ACKNOWLEDGMENTS

Financial support was provided by the Russian Foundation for Basic Research (project 14-08-31064 mol_a).

REFERENCES

1. Gordeev, A.V. and Vostroknutov, D.V., Grinding of chip grooves in the axial cutting tool of tungsten free fast cutting steels, *Metalloobrabotka,* 2004, no. 6, pp. 2–6.
2. D'yakonov, A.A., The theory of material treatment during implementation of abrasives. Part 1: Definition and formal description, *Vestn. Yuzh.-Ural. Gos. Univ., Ser. Mashinostr.,* 2015, vol. 15, no. 1, pp. 54–68.
3. Korchak, S.N., *Proizvoditel'nost' protsessa shlifovaniya stal'nykh detalei* (Efficiency of the Grinding of Steel Parts), Moscow: Mashinostroenie, 1974.
4. Koshin, A.A., Klochko, V.I., Akanovich, V.A., and Butorin, G.I., The direct measurement of integral parameters of high-speed interrupted grinding, in *Vses. nauchno-tekhn. konf. "Covremennoe sostoyanie i perspektivy vysokoskorostnoi fotografii i metrologii bystroprotekayushchikh protsessov," Tezisy dokladov* (All-Union Sci.-Tech. Conf. "Modern Status and Prospects of the High-Speed Photography and Metrology of Rapid Processes," Abstracts of Papers), Moscow: Vseross. Nauchno-Issled. Inst. Opt.-Fiz. Izmer., 1975, p. 53.
5. D'yakonov, A.A., Blank-cutter interaction in high-speed cutting, *Russ. Eng. Res.,* 2014, vol. 34, no. 12, pp. 775–777.
6. Ardashev, D.V., The mechanical wear of abrasive grains at grinding, *Vestn. Yuzh.-Ural. Gos. Univ., Ser. Mashinostr.,* 2014, no. 4, pp. 55–65.

Translated by Bernard Gilbert