Estimation of cutting ability of cubic nitride boron wheels by surface microhardness criteria for pendulum grinding of high-speed steel plates

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Abstract. The grinding wheel LKV50 B107 O V K27 100 KF40 is chosen as preferable according to the statistical interpretation of cases of surface microhardness of high-speed steel plates W6Mo5.

1. Introduction

Grinding is a major process that determines endurance and workability of machine tools, therefore grinding is often a completion phase of an engineering tool production. In mechanical engineering, high-speed steels (HSS) are referred to hard-to-machine materials due to the high content of carbide-forming elements. Therefore, in order to ensure optimal grinding conditions, it is essential to take into account not only a reserve strength coefficient of an abrasive wheel but high heating temperatures as well. In real-time grinding, more than 80% of power transforms into heat. The heat sources are abrasive grains which can be classified into cutting, pressing and non-cutting ones by their different radial orientation. The most projecting grains first cause an elastic deformation of metals, then – a plastic one, and achieving the ultimate strength - chipping. The instantaneous heating of a workpiece surface reaches a temperature of 700-800 °C, in case of intensive grinding - 1200-1500 °C. Heat rate reaches 10000 °C/s, and temperature decreases in a split second as well, as most heat passes to the underlying metal. It causes phase conversions in metal surfaces increasing or decreasing microhardness.

Microhardness of a metal surface is a complex thermal physics and dynamics criterion of cutting characterizing surface hardening and caused by plastic deformation.

Grinding wheels made from traditional abrasives cause such major surface defects as burns (a surface area with a low microhardness and a changed structure). Use of cubic nitride-boron (CBN) abrasive wheels might solve the problem. CBN has a high hardness that exceeds the hardness of traditional abrasives several times. Moreover, CBN has a high thermal resistance: grain oxidation begins only at temperature of 1100-1200 °C. As HSS is high alloyed steel, another advantage of CBN is their chemical resistance that makes it possible to grind avoiding adhesive and diffusion grain abrasive wear [1;6].

For example, in [2;3], the authors having estimated the grinding abilities of W6Mo6 test samples concluded that nitride-boron wheels showed better results than wheels made from fused alumina. Major structural changes in the metal surface were observed when grinding with fused alumina wheels as evidenced by decreasing microhardness. On the other hand, CBN-wheel grinding did not cause...
visible structural changes in the steel surface and microhardness by grinding depth remained unaltered. We have estimated cutting abilities of CBN grinding wheels to provide the highest microhardness and grinding stability.

2. Statistical analysis methods of experimental data

Surface microhardness parameter is estimated statistically using software Statistica 6.1.478.0. Applied statistics makes it possible to analyze the sequences being the sets $e = 1, \ldots, k$ where $v = 1, \ldots, n$.

$$\{y_{ev}\}$$

There are two statistical methods - parametric and non-parametric ones. Each of these methods has more stability zero-hypothesis «on the home court» [4]. To present and analyze output data, homogeneous distribution parameters [4] have been used. Among them, one can mention position measures (State Standard GOST R ISO 5721-1-2002): averages and medians for parametric and non-parametric methods respectively; dispersion (precision): measures: deviation standards (variances) and ranges - for a parametric statistical method; quartile latitude - for a non-parametric statistical method. Distribution asymmetry (skewness) based on the following equation:

$$A_{Se} = \left[ 3 \left( \bar{y}_e - \overline{y} \right) / SD \right]_e$$

where $A_{Se}$ is a positive value when $\bar{y}_e < \overline{y}$, otherwise, skewness is negative.

For a parametric statistical method «on the home court» we assumed the conditions when (1) is a normal distribution with homogeneous variances of deviations. In this case, their criteria are robust to an insignificant random variables (RV) distribution violation. However, it cannot be applied to the homoscedasticity of distributions (1). The violation of distribution laws can cause accepting a wrong hypothesis, because maximum permissible deviation values are not stipulated anywhere. In these cases, a non-parametric method which does not depend on the properties of any distribution family is the most suitable. Kolmogorov-Smirnov (D) and Shapiro-Wilk (W) test statistics can be used to prove Ho for the normal distribution in software. D-test is widely used in technical applications. However, in [6], the authors have revealed the weakness of the criterion. Therefore, in our paper $H_0$ for (1) has been tested according to W-statistics which satisfies the inequality:

$$\alpha > 0.5$$

There are three tests for homogeneity variance ($q=1, \ldots, 3$): 1 – Hartley, Cohran and Bartlett’s tests; 2 – Levene’s tests; 3 – Brown-Forsythe’s tests. In all cases, they satisfies the inequality ($\alpha$ – acceptance reliability for $H_0$):

$$\alpha > 0.05.$$  

Stochastic nature of hypotheses assumes that decisions $f$, based on criteria $q=1, \ldots, 3$, may differ. Thus, final results on homogeneity ($H_0$) and heterogeneity ($H_1$) deviations variances have been accepted for following reasons:

$$H_0 \text{ at } f_e \in [2;3];$$  

$$H_1 \text{ at } f_1 \in [2;3].$$

Predicted averages and medians have been obtained by multiple comparison [4,5] and designated as $\tilde{y}_{ev}$ and $\tilde{m}_{y_e}$ respectively.

3. Methodology

The experiments have been carried out under the following conditions: plan grinding-machine 3E11V and 3G71M; HSS plates made from steel W6Mo5 (63-64 HRC); grinding scheme – by the side of a wheel without nursing courses; cutting parameters: cutting speed $v_w=28$ m/s, traverse motion $s_{tr} = 7$ m/min, cross-feed motion $s_{cf} = 4$ mm/double pass, cutting depth $t=0.01$ mm, stock allowance $z=0.10$ mm. The lubricoolant is a 5 % Akvolo-6 emulsion (Technical Specifications TU 0258-024-00148845-98) supplied by watering to the workpiece at a rate of 7-10 l/min. The wheel is being lowered at depth
When the bench with HSS plate is being displaced fully to the left relative to the operator. Its movement from left to right is a working stroke. Otherwise, it is a nursing stroke with a final formation of a HSS plate surface micro-relief according to the wind grinding scheme as the spindle rotates clockwise. HSS plates are samples sized $D \times H = 40 \times 50$ mm. They are fixed on the magnetic bench and undergone face grinding. The number of repetitions of experiments is $n = 30$. Microhardness parameter $HV$ (State Standard GOST R ISO 6507-1: 2007) is measured by instrument PMT-3. Output process data are presented as $y_{ev}$, where $e = 1, \ldots, 3$ is a code of high-porous CBN wheels (HPCBNW): 1 - for CBN50 B107 O V K27 100 KF40 (the basic wheel), 2 - for LKV50 B107 O V K27 100 KF40, 3 - for CBN50 B126 O V K27 100 KF40. The original microhardness of HSS plate surface is $HV_o = 9000$ MPa [3].

For a quantitative analysis of process stability, we use:

$$K_{SD} = \frac{(SD)}{(SD)}_e, e = 2, 3.$$

The value $K_{SD} < 1$ corresponds to the higher process stability for the basic wheel ($e = 1$), the value ($K_{SD} > 1$) – for wheels $e = 2, 3$.

Additionally, we have analyzed the process stability according to the ranges of experimental cases and obtained:

$$K_p = \frac{R_e}{R_e}.$$ (8)

### 4. Result and Discussion

The results in table 1 prove the hypothesis $H_o$ for the homogeneity of variances for all wheels $e = 1, \ldots, 3$, and the decision (5) is made for all three tests. However the distribution normality condition is fulfilled only for wheel LKV50 B107 ($e = 2$). Therefore, a non-parametric method based on Kruskal-Wallis and Dunn’s range criteria is the most suitable.

| Inequality | CBN50 B107 ($e = 1$) | LKV50 B107 ($e = 2$) | CBN50 B126 ($e = 3$) |
|------------|----------------------|----------------------|----------------------|
| (3)        | $H_1$                | $H_0$               | $H_1$               |
| (4)        | $H_0$                |                      |                      |

Fig. 1 illustrates case results of (1) based on parametric (figure 1A) and nonparametric (figure 1B) statistics methods for $HV$ parameter at grinding with $e = 1, \ldots, 3$ wheels where “square” means position measure for $HV_e$ (figure 1A) and $HV_e$ (figure 1B). The other marks have different meanings. In figure 1A, “rectangle” means dispersion borders for error standards ($\pm SD_e$) and “moustache” means deviation standards ($\pm SD_e$) for. In figure 1B, the quartile latitude $|y_{0.75} - y_{0.25}|_e$ and ranges $R = |y_{max} - y_{min}|_e$ are shown. Median and ranges in figure 1B show a form of a distribution curve (2).
First, let us analyze the results for microhardness position measures. As seen from table 2, the wheels \( e = 2,3 \) showed the best W6Mo5 steel grinding results with a minimum hardness loss \((HV_o = 9000 \text{ MPa})\) for expected medians of \( HV \) parameter. At the same time, the wheel showed the worst result.

Nevertheless, there is a positive asymmetry of distributions for LKV50 B107 \((e = 2)\) and CBN50 B126 HPCBNW. It has a negative impact on process reliability as it reduces position measures. The asymmetry is negative for CBN50 B107 wheels. However, the worst is when cases (1) are located below the medians. For example, while CBN50 B107 wheel grinding \((e = 1)\), 26 cases from \( n = 30 \) turned out to be smaller than an experiment median with the same \( n = 30 \), the majority of cases turned out to be bigger than experiment medians - 20 with \( \tilde{HV}_2 8147 \) and 19 with \( \tilde{HV}_3 8033 \) for LKV50 B107 HPCBNW respectively (figure 1, table 2).

Wheel grinding stability analysis \( e = 1, \ldots, 3 \) showed that reproducibility ratios (7), (8) coincided (table 2). Wheel LKV50 \((e = 2)\) demonstrated the highest level of stability of deviation standards and ranges. The lowest level of stability of deviations standards was found in CBN50 160/125 wheel \((e = 3)\). The lowest level of stability of ranges was found in CBN50 100/80 wheel \((e = 1)\).

According to our experiment, grinding wheel LKV50 B107 O V K27 100 KF40 \((e = 2)\) is preferable.

### Table 2. Prediction results and wheel influence on position and dispersion measures for \( HV \) parameter

| Grinding wheels | \( \hat{\mu}_e \) [MPa] | \( m\hat{\mu}_e \) [MPa] | \( SD_e \) [MPa] | \( As_e > 0 \) \((2) \) | \( (K_{SD})_e \) \((7) \) | \( y_{emin} \) [MPa] | \( y_{emax} \) [MPa] | \( K_{Re} \) \((8) \) |
|-----------------|------------------------|------------------------|-----------------|------------------|------------------|-----------------|-----------------|------------------|
| CBN50 B107 \((e = 1)\) | 7067.34 | 7190.38 | 949.39 | – | 1.00 | 4515.60 | 9158.20 | 1.00 |
| LKV50 B107 \((e = 2)\) | 8226.09 | 8090.31 | 831.74 | + | 1.14 | 6646.62 | 9902.50 | 1.42 |
| CBN50 B126 \((e = 3)\) | 8226.09 | 8090.31 | 985.94 | + | 0.96 | 6158.22 | 10055.00 | 1.19 |

### 5. Conclusion
1. The rationale of grinding high-alloyed tool steels using HPCBNW instead of traditional abrasives has been proved.
2. It has been proved that the cutting ability of abrasive wheels in assumed technological conditions should be estimated using non-parametric statistical method «On the home court».

3. CBN-grains influence on the process stability has been established. CBN50 wheels have lower reproducibility coefficients than LKV50 wheels.

4. LKV50 B107 O V K27 100 KF40 has shown the best results according to position measures and precision of microhardness when grinding HSS plate W6Mo5.

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