Size Influence of High Pores on Cutting Ability of Cubic Nitride Boron Wheels for Pendulum Grinding of High-Speed Steel W9Mo4Co8 Plates by Surface Roughness Criteria

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Abstract. The grinding wheel CBN30 B126 100 L V K27 KF40 is chosen as preferable according to the statistical interpretation of cases of surface roughness of high-speed steel plates W9Mo4Co8.

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. In order to ensure optimal grinding conditions, it is essential to take into account not only a reserve strength coefficient of an abrasive grains but high heating temperatures as well [1]. 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 [2], and temperature decreases in a split second as well, as most heat passes to the underlying metal. Traditional grinding is often used for machining of HSS, but the high grinding forces and micro cracks on a workpiece surface are major problems [3, 4]. 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;8].

In the pores of a grinding wheel, vacuum is created under the action of centrifugal forces. As a result, the lubricant and coolant fluid is sucked through the pores to the ends of the wheel, with subsequent release into the grinding zone. The pore size has the primary influence on the permeability
(corresponds to the ability of the wheel to pass through the material; under the action of the applied pressure gradient), as established in [5]. We have estimated cutting abilities of CBN grinding wheels with different pore-forming agents (PA) to provide the lowest roughness and highest grinding stability.

2. Statistical analysis methods of experimental data

Surface microhardness parameter \( R_{d,l} \) is estimated statistically using software Statistica 6.1.478.0 (where \( d \) is a direction of roughness). Applied statistics makes it possible to analyze the sequences being the sets \( l = 1, \ldots, k \) where \( v = 1, \ldots, n \).

\[
\left\{ Y_{d,l} \right\}
\]

There are two statistical methods - parametric and non-parametric ones. Each of these methods has more stability zero-hypothesis \( (H_0) \) «on the home court» [6]. To present and analyze output data, homogeneous distribution parameters [6] have been used. Among them, one can mention:

- position measures (State Standard GOST R ISO 5721-1-2002):
  - averages \( \bar{Y}_{d,l} = \bar{y}_{d,l} \),
  - medians \( \tilde{y}_{d,l} \),

which defines the cutting ability of wheels;

- dispersion (precision) measures:
  - deviation standards \( SD_{d,l} \),
  - ranges \( R_{d,l} = (y_{\text{max}} - y_{\text{min}})_{d,l} \),
  - quartile latitude \( QL_{d,l} = (y_{0.75} - y_{0.25})_{d,l} \),

which defines the process stability.

We use (2), (4), (5) and (3), (6) for parametric and non-parametric methods respectively. Asymmetry (skewness) based on the following equation:

\[
A_{sd,l} = \frac{3(\bar{y} - \tilde{y})}{SD_{d,l}},
\]

where \( A_{sd,l} \) is a positive value when \( \tilde{y}_{d,l} < \bar{y}_{d,l} \), 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 \( H_0 \) for the normal distribution in software. D-test is widely used in technical applications. However, in [8], the authors have revealed the weakness of the criterion. Therefore, in our paper \( H_0 \) for (1) has been tested according to Shapiro-Wilk test statistics which satisfies the inequality:

\[
\alpha_{sl,l} > 0.5
\]

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 \( (\alpha – \text{acceptance reliability for } H_0 \text{ when } d,l – \text{const.}) \):

\[
\alpha_{sl,l} > 0.05.
\]
Stochastic nature of hypothesizes assumes that decisions \( f \), based on criteria \( q=1,...,3 \), may differ. Thus, final results on homogeneity (\( H_0 \)) and heterogeneity (\( H_1 \)) deviations variances have been accepted for following reasons:

\[
\begin{align*}
H_0 & \text{ at } f_0 \in [2;3]; \\
H_1 & \text{ at } f_1 \in [2;3].
\end{align*}
\]

Predicted averages and medians have been obtained by multiple comparison \([6,7]\) and designated as \( \hat{y}_{de} \) and \( m_{de}^{\hat{y}} \) respectively.

3. Methodology

The experiments have been carried out under the following conditions: plan grinding-machine 3E711V; form and sizes of wheels (State Standard GOST R 53923-2010): 1A1 200×20×76×3; HSS plates made from steel W9Mo4Co8 (63-64 HRC); grinding scheme – by the side of a wheel without nursing courses; cutting parameters: cutting speed \( v_c=28 \) m/s, traverse motion \( s_r = 7 \) m/min, cross-feed motion \( s_{c,f} = 4 \) mm/double pass, cutting depth \( t=0.01 \) mm, stock allowance \( z=0.10 \) mm. The lubricant is a 5 % Akvol–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 \( t \) 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 \( n=30 \). Roughness parameter \( R_{ade} \) is measured by profilograph-profilometer 252 “Kalibr”. Output process data are presented as \( y_{dev} \), where \( d = 1,2 \) is a code of direction of roughness: 1 – corresponds to cross-feed motion \( s_{c,f} \), 2 – corresponds to traverse motion \( s_r \); \( e = 1,2 \) is a code of high-porous CBN wheels (HPCBNW): 1 - for CBN30 B126 100 L V K27 KF25 (the basic wheel), 2 - for CBN30 B126 100 L V K27 KF40. The direction of roughness \( d = 1 \) has chosen as general to regulate quality of HSS plate surface.

For a quantitative analysis of cutting ability of HPCBNW according to predicted analogues of medians (3), we use

\[
K_{le} = (m_{2}^{\hat{y}} / m_{1}^{\hat{y}})_{le}.
\]

Grinding is a stochastic process, which often don’t satisfies the normal distribution with homogeneous variances of deviations. Therefore we have analysed its stability according to the deviation standards (\( SD_e \)), ranges (\( R_e \)) and quartile latitude (\( QL_e \)) of experimental cases (1), and obtained:

\[
\begin{align*}
(K_{SD})_{le} &= (SD)_1 / (SD)_2, \\
(K_{R})_{le} &= R_1 / R_2, \\
(K_{QL})_{le} &= (QL)_1 / (QL)_2.
\end{align*}
\]

The value of (12)-(14) < 1 corresponds to the higher process stability for the basic wheel \( e=1 \), otherwise – for wheels \( e = 2 \).

4. Result and Discussion

The results in table 1 prove the hypothesis \( H_1 \) for the homogeneity of variances for all wheels \( e = 1,2 \), and the decision (11) is made for all three tests. Moreover the distribution normality condition is not fulfilled only for both wheels. Therefore, a non-parametric method based on Kruskal-Wallis range criteria is the most suitable.
Table 1. Results of tests for homoscedasticity and normality of distributions for a $R_{a1}$ parameter.

| Inequality | CBN30 KF25 ($e = 1$) | CBN30 KF40 ($e = 2$) |
|------------|----------------------|----------------------|
| (8)        |                      |                      |
| (9)        | $H_1$                |                      |

Figure 1 illustrates case results of (1) based on parametric (figure 1A) and nonparametric (figure 1B) statistics methods for $R_{a1}$ parameter at grinding with $e = 1, 2$ wheels where “square” means position measure for $R_{a1e}$ (figure 1A) and $R_{d1e}$ (figure 1B). The other marks have different meanings. In figure 1A, “rectangle” means dispersion borders for error standards ($\pm SDE_{ie}$) and “moustache” means dispersion of deviation standards ($\pm SD_{ie}$). 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 (7). Categorical values (CV) (State Standard GOST 2789-73) has shown in the baskets.

First, let us analyze the results for roughness position measures. As seen from table 2, the wheels $e = 2$ showed the best W9Mo4Co8 steel grinding results for expected medians of $R_{a1}$ parameter. At the same time, the wheel $e = 1$ showed the worst result greater than 2 CV than $e = 2$: $mR_{a11}, 0.43(0.50)$ for KF25 PA and $mR_{a12}, 0.29(0.32)$ for KF40 PA with higher permeability. Thus, increasing the permeability changes the thermal conditions in the grinding zone, as indicated by contact-temperature data for the grinding of W6Mo5 steel. Thus, the grinding of AEROBOR wheels with A40 filler (correspond to KF40) reduces the temperature greater then grinding of wheel with smaller pores (with A25 filler) and correspondingly with smaller permeability [5].

![Figure 1](image_url)

**Figure 1.** Parametric (A) and nonparametric (B) statistics of wheel characteristic influence to $R_{a1}$ parameter.
There is a positive asymmetry of distributions for both HPCBNW (e=1,2). It has a positive impact on process reliability as it reduces position measures. However, the best is when cases (1) are located below the medians. For example, while CBN30 KF25 wheel grinding (e = 1), only 1 case 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 smaller than experiment medians - 29 with $\overline{Ra}0,28(0,32)$ for CBN30 B126 100 L V K27 KF40 (figure 1, table 2).

**Table 2. Prediction results and wheel influence on position measures for $Ra_i$ parameter**

| Grinding wheels | $Ra_{ie}$ | $\overline{Ra}_{ie}$ | $\overline{Ra}_i$ | $m\overline{Ra}_{ie}$ | $A_{S_{ie}} > 0$ | $K_{ie}$ |
|-----------------|----------|-------------------|------------------|-----------------|----------------|---------|
| CBN30 KF25 (e = 1) | 0.44(0.50) | 0.43(0.50) | 0.44(0.50) | 0.43(0.50) | + | 1.00 |
| CBN30 KF40 (e = 2) | 0.29(0.32) | 0.28(0.32) | 0.29(0.32) | 0.28(0.32) | + | 0.66 |

Wheel grinding stability analysis $e = 1,2$ showed that reproducibility ratios (12)-(14) coincided (table 3). Wheel CBN30 KF40 (e = 2) demonstrated the highest level of stability of deviation standards, ranges and quartile latitude.

**Table 3. Prediction results and wheel influence on dispersion measures for $Ra_i$ parameter**

| Grinding wheels | $SD_{ie}$ | $R_{ie}$ | $QL_{ie}$ | $(K_{SD})_{ie}$ | $(K_{R})_{ie}$ | $(K_{QL})_{ie}$ |
|-----------------|----------|---------|----------|----------------|----------------|----------------|
| CBN30 KF25 (e = 1) | 0.06 | 0.24 | 0.08 | 1.00 | 1.00 | 1.00 |
| CBN30 KF40 (e = 2) | 0.03 | 0.12 | 0.05 | 1.88 | 1.99 | 1.64 |

According to our experiment, grinding wheel CBN30 B126 100 L V K27 KF40 (e = 2) is preferable.

**5. Conclusion**
1. The rationale of grinding high-speed 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. PA of HPCBNW influence on the process stability has been established. KF25 PA has lower reproducibility coefficients than KF40 PA.
4. CBN30 B126 100 L V K27 KF40 has shown the best results according to position measures and precision of roughness when grinding HSS plate W9Mo4Co8.

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