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The effect of the grinding method on the grain shape coefficient of black silicon carbide

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ABSTRACT

Introduction. JSC Volzhsky Abrasive Plant is the sole producer of silicon carbide in Russia and the largest producer in Europe. The company employs various methods, equipment, and technologies for grinding abrasive materials, which influence the geometric parameters of the grains. The most prominent and widely used methods for grinding silicon carbide in current production are roller-press grinding and rotary grinding. **The purpose of this work** is to study the effect of the roller-press and rotary methods of grinding black silicon carbide, which are used at the JSC Volzhsky Abrasive Plant, on the shape factor, length, and width of the grains in the sample fractions. **Research methods.** The initial material obtained in accordance with the current technological process was selected after crushing in a rod mill. One sample was crushed using the roller-press method, and the other was crushed using the rotary method. The crushed silicon carbide was sieved into fractions using a *Ro-Tap* sieve analyzer. The geometric parameters and grain shape were determined in five fractions, and 800 grains were measured in each fraction. The horizontal projection of the grain profile was obtained using an *Altami SM0870-T* optical stereoscopic microscope. Special software was used to process the projections and determine the geometric parameters. **Results and discussion.** It has been established that the shape factor and grain length follow the maximum value law, while the width follows the normal distribution law. The strength of the correlation between geometric parameters ranges from weak to strong, and the direction of the relationships varies from positive to negative. Graphical dependencies are presented, demonstrating the correlation and regression relationships between the geometric parameters of the grains in the fractions. Rotary grinding results in an average increase of 5% in the number of isometric grains compared to roller-press grinding, while the number of needle-like grains decreases by a factor of 3. The research findings are intended for optimizing the formulation and manufacturing technology of abrasive and refractory products.

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Introduction

The grain shape of grinding powders has a significant effect on the properties of abrasive tools and the quality of the machined surface of parts [1–3], and is a determining indicator in the manufacture of refractory products [4, 5]. Isometric grains contribute to reducing wear, increasing the durability of abrasive tools, and improving machining performance [6–9].

The grains attain the desired size and shape through a technological process involving multi-stage crushing and grinding of the abrasive material. These operations are performed using various equipment

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and crushing methods, such as jaw, ball, cone, rod, roller (roller press), and rotary crushers [10–16]. If sorting the crushed grains by shape is required, they undergo additional treatment [17–21].

The most common quantitative criterion for the shape of abrasive grains is the shape factor, defined as the ratio of the length ***l*** of the grain projection on a horizontal plane to the width ***b***. Length is defined as the largest distance between perimeter points (the maximum *Feret* diameter). Width is calculated as the sum of the maximum distances from the length line to the left and right sides of the perimeter, divided by the length line (*ISO 9276-6-2008*, *GOST R 70336-2022*). In effect, the grain projection is inscribed in a rectangle where the longest side corresponds to the length of the grain, and the shortest side corresponds to the width.

The crushing and grinding methods of abrasive materials significantly affect the shape and properties of the resulting particles. For example, studies have shown that when crushing corundum using roller, cone, and ball crushers, a ball crusher yields the greatest isometricity [11, 12].

The influence of grinding methods on the geometric parameters and shape of grains within the current technological process for producing abrasive materials at JSC Volzhsky Abrasive Plant, a leading enterprise in the industry, is of particular interest. The relevance of this research is further supported by the fact that JSC Volzhsky Abrasive Plant is "the only producer of silicon carbide in Russia and the largest in Europe" [22].

Silicon carbide is used to manufacture grinding powders and micro-powders, a wide range of abrasive tools, refractories, and specialized products. These diverse applications, encompassing abrasive machining of various parts and the production of a wide range of items, preclude the establishment of uniform requirements for geometric parameters and grain shape. Consequently, it is essential to consider the specific characteristics of the machined surface and the properties of the target product.

For example, in cutting operations where the objective is to increase productivity, cutting wheels made of grinding powders with a shape factor $kf = l/b = 2.2$ are employed, where ***l*** and ***b*** represent the length and width of the grain, respectively. Conversely, if minimizing abrasive tool consumption is the primary concern, isometric grains with a shape factor of $l/b = 1.3$ are preferred [23].

To grind silicon carbide, the plant employs various methods, equipment, and processing parameters that influence the geometric characteristics and properties of the grains. Roller press grinding and rotary grinding are among the most common methods implemented at JSC Volzhsky Abrasive Plant.

Grain sizes exhibit significant variation. For instance, *GOST R 52381-2005* specifies a range of grain and fraction sizes spanning from 4,750 μm, to 45 μm. Furthermore, based on grain composition, grinding powders are categorized into 30 grain sizes, each containing 5 distinct fractions.

The ***purpose of the paper*** is to investigate the effect of roller press grinding and rotary grinding of black silicon carbide, as implemented at JSC Volzhsky Abrasive Plant, on the grain shape factor of fraction samples.

Tasks:

– to determine the distribution patterns of black silicon carbide grain shape factors, along with the geometric parameters influencing them (grain length and width);

– to analyze correlation and regression relationships between grain shape factors and geometric parameters;

– to identify trends in geometric parameters of grains within fraction samples produced by roller press grinding and rotary grinding.

Research Methodology

The input materials for roller press and rotary grinding were produced under identical conditions following the current technological process. Black silicon carbide feedstock was sequentially processed using a cone crusher and a rod mill.

Following drying, a portion of the abrasive material was ground using a roller press, while the remaining portion was subjected to rotary grinding.

The *PVI 800/150* roller press used at JSC Volzhsky Abrasive Plant is characterized by: adjustable hydraulic pressure applied to only one roll, which avoids over-grinding; and material crushing within an adjustable layer between the rolls. The grinding parameters were: rotational speed – 50 Hz, pressure – 28 kg/cm^3, roll gap – 2 mm.

The *VSI Barmac 5100SE* vertical shaft impact (*VSI*) crusher operates on a stone-on-stone principle, with a rotor speed of 3,000 rpm and a throughput of 4 tons per hour. The crushing chamber's lining pockets are filled with compacted silicon carbide, which significantly reduces metal-on-metal abrasion and promotes the formation of more isometric grains. During typical operation, grinding generates a substantial amount of fine silicon carbide particles (dust). Therefore, a dust extraction system is integrated into the crushing chamber to ensure compliance with the abrasive grain quality requirements of *GOST R 52381*.

Input material fractions were obtained by sieving powders using a *Ro-Tap* machine. Five fractions were selected for analysis, with the nominal cell sizes of the upper and lower control sieves presented in Table 1. The average nominal cell size (*Wmi*) of the upper (*Wui*) and lower (*Wli*) sieves was used as the primary parameter characterizing the grain size of each fraction, calculated as: *Wmi* = (*Wui* + *Wli*)/2. In accordance with *GOST R 52381*, the ratio *Wui/Wli* should fall within the range of 1.18–1.21.

Table 1

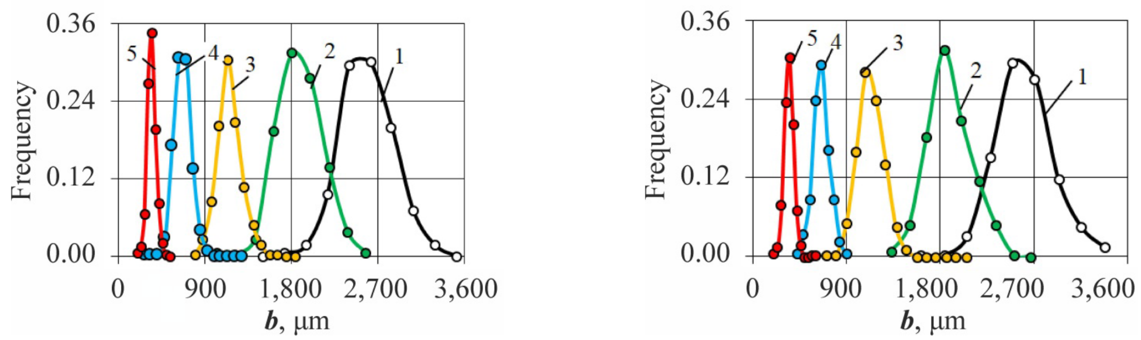
Grinding powder fractions *(GOST R 52381)*

Fraction designation	Nominal size of sieve cells		
	Upper sieve *Wu*, µm	Lower sieve *Wl*, µm	Average value *Wmi* = (*Wu*+*Wl*)/2, µm
1	2,360	2,000	2,180
2	1,700	1,400	1,550
3	1,000	850	925
4	600	500	550
5	300	250	275

Grain profile images were captured using an *Altami CM0870–T* optical stereoscopic microscope. Image processing and geometric parameter calculations were performed using dedicated software [24]. A total of 800 grains were measured within each fraction. The following geometric parameters were determined and analyzed: grain length (***l***), grain width (***b***), and shape factor (***l/b*** ratio).

Research Results and Discussion

Based on the empirical grain size distribution patterns (Figs. 1–3), four distribution models were evaluated to determine the theoretical distribution: normal, lognormal, gamma, and the law of maximum value. The normal distribution is typically used to model distributions exhibiting symmetrical right and left branches on graphs [25].



a *b*

Fig. 1. Experimental distributions of grain width ***b*** for fractions after roller-press (*a*) and rotary (*b*) grinding methods

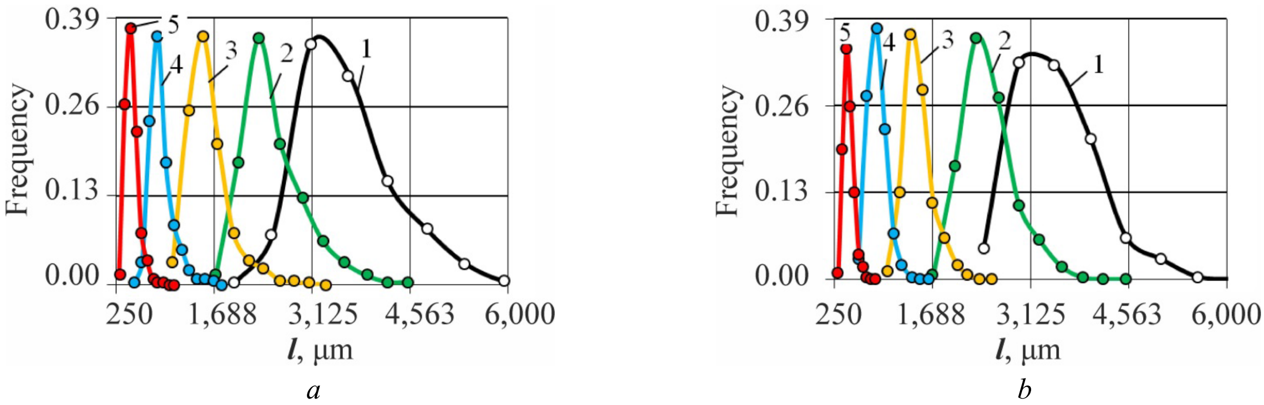


Fig. 2. Experimental distribution of grain length ***l*** for fractions after roller-press (*a*) and rotary (*b*) milling methods

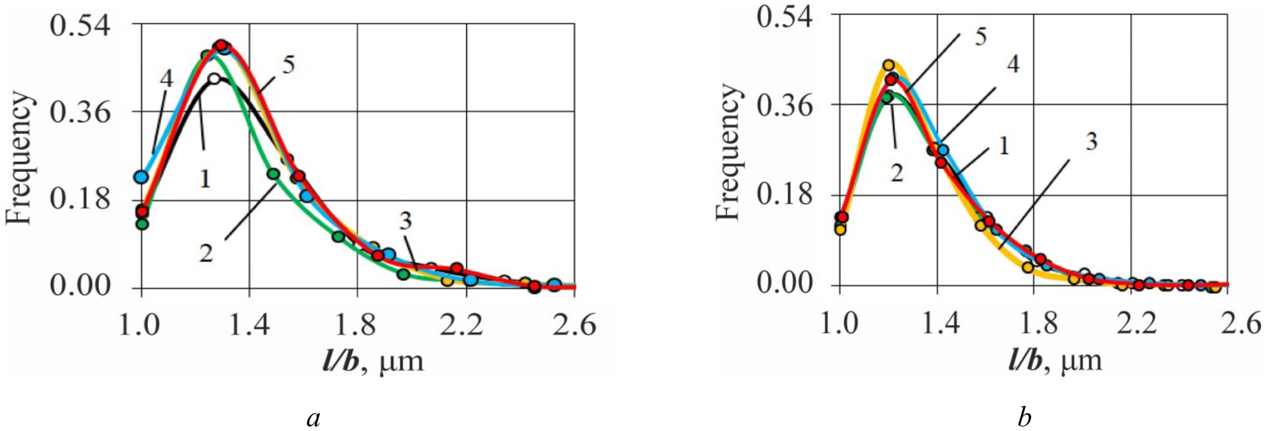


Fig. 3. Experimental distribution of the aspect ratio ***l/b*** for fractions after roller-press (*a*) and rotary (*b*) milling methods

In Table 2, the observed and critical values of the *Pearson's* chi-squared test statistic satisfying the condition $\chi^2_{obs} < \chi^2_{crit}$ are highlighted in bold. This indicates that the sample data conforms to the distribution model under consideration. The grain length distribution in nine out of ten fractions aligns with the gamma distribution (90 %) and the law of maximum value (90%). The lognormal distribution provides a better fit for the grain length distributions resulting from rotary grinding (in four out of five fractions). The grain length of the roller-ground material does not conform to the lognormal distribution.

Grain width in all considered fractions follows a normal distribution (Table 3). The observed values of the *Pearson's* chi-squared test statistic in these fractions are less than the critical values. The grain shape factor in nine out of ten fractions adheres to both the gamma distribution and the law of maximum value (90 %). Based on these findings, the following distribution models were adopted: grain width follows a normal distribution, while grain length and shape factor adhere to the law of maximum value.

The *Pearson* correlation coefficient is a widely used statistical measure that quantifies the strength of the linear relationship between two variables. Its application requires that both variables are normally distributed and derived from the same sample. Given that the grain width follows a normal distribution, while grain length and shape factor adhere to the law of maximum value, any selected pair of geometric grain parameters will not satisfy the condition of the normal distribution law. Therefore, *Spearman's* rank criterion was used to estimate the strength of the relationship between the parameters [25]. This involved converting the natural values of the geometric parameters into ranks. Specifically, the numerical values of the geometric parameters were ranked in ascending order, and each value was assigned an ordinal number (rank) accordingly.

Fig. 4 presents a graphical representation of the correlations between the geometric parameters of grains obtained through roller press and rotary grinding. The ***x***-axis displays the arithmetic mean of the nominal

Table 2

The reliability of the correspondence of the observed grain length distribution to the theoretical one according to *Pearson's* chi-squared test χ²

Grinding method	Fraction	Lognormal		Gamma distribution		Length maximum value	
		χ^2_{obs}	χ^2_{crit}	χ^2_{obs}	χ^2_{crit}	χ^2_{obs}	χ^2_{crit}
Roller-press	1	53.5	11.1	**5.8**	**11.1**	**16.7**	**16.9**
	2	37.4	11.1	**5.5**	**9.5**	**1.7**	**11.1**
	3	36.9	11.1	**11.1**	**18.3**	**8.9**	**12.6**
	4	54.7	11.1	**8.0**	**18.3**	**9.3**	**11.1**
	5	18.2	9.5	**8.5**	**11.1**	**3.8**	**12.6**
Rotary	1	**7.9**	**9.5**	**3.5**	**9.5**	14.4	11.1
	2	**7.4**	**9.5**	11.1	9.5	**9.3**	**11.1**
	3	15.1	9.5	**6.4**	**18.3**	**8.6**	**11.1**
	4	**6.2**	**9.5**	**8.2**	**9.5**	**11.8**	**14.1**
	5	**6.6**	**9.5**	**8.2**	**18.3**	**9.1**	**11.1**
Reliability, %		40		90		90	

Table 3

Reliability of the correspondence of the observed distributions of grain width and shape factor according to *Pearson's* test

Method	Fraction	Width		Shape coefficient			
		Normal		Log-normal		Maximum value	
		χ^2_{obs}	χ^2_{crit}	χ^2_{obs}	χ^2_{crit}	χ^2_{obs}	χ^2_{crit}
Roller-press	1	**5.8**	**5.8**	34.0	7.8	**6.0**	**11.1**
	2	**5.5**	**5.5**	68.9	11.1	**7.6**	**7.8**
	3	**11.1**	**11.1**	40.1	7.8	**3.1**	**7.8**
	4	**8.0**	**8.0**	54.6	11.1	**9.4**	**11.1**
	5	**8.5**	**8.5**	66.9	14.1	**8.3**	**11.1**
Rotor	1	**3.5**	**3.5**	30.2	12.6	**4.6**	**12.6**
	2	**11.1**	**11.1**	52.4	12.6	**11.3**	**12.6**
	3	**6.4**	**6.4**	30.4	9.5	**5.4**	**12.6**
	4	**8.2**	**8.2**	29.9	9.5	**4.3**	**9.5**
	5	**8.2**	**8.2**	62.5	12.6	**3.3**	**9.5**
Reliability. %		100		0		100	

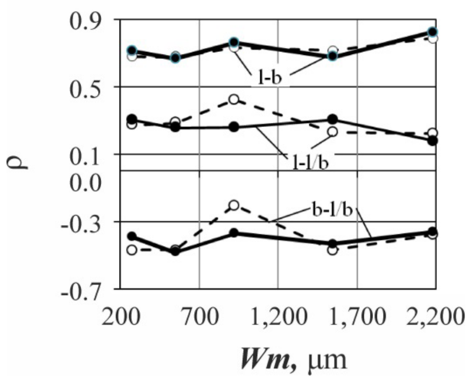


Fig. 4. Spearman's rank correlation coefficient **ρ** between geometric parameters of grains in different fractions:
● – roller-press grinding; **○** – rotary grinding

cell sizes of the upper and lower sieves (*Wm*) for each fraction (refer to Table 1). The strength of the correlation coefficients was evaluated using the *Chaddock* scale.

The *Spearman's* rank correlation coefficient (**ρ**) between grain length (***l***) and grain width (***b***) does not exceed 0.3. The average **ρ** value for the ***l-b*** relationship is 0.21 for roller-press grinding and 0.25 for rotary grinding. The correlation strength between the grain shape factor (***l***/***b***) and grain length (***l***) is significantly higher, with an average ***ρ*** value exceeding 0.7. The strength of the relationship between the shape factor (***l***/***b***) and grain width for the selected fractions ranges from −0.35 to −0.50, indicating an inverse relationship where the shape factor decreases as grain width increases.

Based on the absolute values of the correlation coefficients, the strength of the relationship between grain length (***l***) and width (***b***) falls into the "weak" category, while the relationship between grain width (***b***) and shape factor (***l***/***b***) is categorized as "moderate". The correlation coefficients between grain length (***l***) and shape factor (***l***/***b***) are at the lower end of the "strong" relationship category, ranging from 0.69 to 0.84 with an average of 0.76. In accordance with the established scale for **ρ**, this indicates a strong correlation. The grinding method does not appear to have a significant effect on the correlation strength.

We explored the feasibility of modeling the relationships between geometric parameters using a standard set of functional dependencies within *Microsoft Excel*. Table 4 presents the constant values and coefficients of determination (R^2) for the approximations of the relationships between the geometric grain parameters, based on the following dependencies:

$$l = a_1 b; \quad (1)$$

$$l/b = a_2 b + c_1; \quad (2)$$

$$l/b = a_3 l; \quad (3)$$

$$l/b = a_4 l + c_2. \quad (4)$$

Table 4

Constant coefficients and confidence coefficients for approximating the relationship between geometric parameters of grains

Roller-press grinding										
Fraction	$l = a_1 b$		$l/b = a_2 b + c$			$l/b = a_3 l$		$l/b = a_4 l + c_2$		
	a_1	R^2	a_2	c	R^2	a_3	R^2	a_4	c_2	R^2
1	1.39	0.10	–0.00044	2.54	0.16	0.00054	0.65	0.00037	0.065	0.72
2	1.34	0.10	–0.00046	2.25	0.17	0.00053	0.55	0.00044	0.247	0.57
3	1.37	0.10	–0.00079	2.30	0.13	0.00087	0.69	0.00078	0.141	0.70
4	1.35	0.20	–0.0017	2.49	0.22	0.0015	0.55	0.00135	0.145	0.56
5	1.37	0.15	–0.0029	2.41	0.19	0.0029	0.55	0.00255	0.176	0.54
$\boldsymbol{R^2 m}$	–	0.13	–	–	0.17	–	0.58	–	–	0.63
Rotary grinding										
Fraction	$l = a_1 b$		$l/b = a_2 b + c$			$l/b = a_3 l$		$l/b = a_4 l + c_2$		
	a_1	R^2	a_2	c	R^2	a_3	R^2	a_4	c_2	R^2
1	1.33	0.15	–0.00037	2.31	0.17	0.00038	0.64	0.00035	0.138	0.64
2	1.32	0.21	–0.00051	2.30	0.21	0.00053	0.56	0.00046	0.188	0.57
3	1.29	0.13	–0.00075	2.16	0.20	0.00089	0.47	0.00070	0.277	0.51
4	1.32	0.25	–0.0015	2.32	0.24	0.0015	0.49	0.00129	0.219	0.51
5	1.31	0.21	–0.0029	2.31	0.24	0.0029	0.45	0.00238	0.243	0.48
$\boldsymbol{R^2 m}$	–	0.19	–	–	0.21	–	0.52			0.54

For grains produced by roller-press and rotary grinding, the accuracy of the approximation using the linear dependence $l = a_1 b$ (1) does not exceed 0.25, indicating a weak correlation. Similarly, modeling the dependence of the shape factor (***l*/*b***) on grain width (***b***) using equation (2) yielded low approximation accuracy. A significant improvement in $\boldsymbol{R^2}$ was achieved using a direct proportional relationship (3), with average approximation reliability coefficients of 0.58 and 0.52 for grains produced by roller-press and rotary grinding, respectively. Replacing the proportional relationship with a linear one (4) resulted in only a marginal increase in approximation reliability.

As an illustration, fig. 5 depicts the regression relationships between the geometric parameters of fraction 3 grains produced by roller-press grinding (figs. 5, *a*; 5, *b*) and rotary grinding (figs. 5, *c*; 5, *d*). The data points in figs. 5, *a* and 5, *b* were approximated using a direct proportional relationship ($l = a_1 b$), while those in figs. 5, *b* and 5, *c* were approximated using a linear relationship ($l/b = a_2 b + c$).

It is worth noting that following roller-press grinding, the relative proportion of grains with a length exceeding, for example, 4,650 µm (fig. 5, *a*), is significantly higher than that after rotary grinding (fig. 5, *c*), which affects the shape factor. The number of grains with a shape factor ***l*/*b*** > 2 is 3.5 times greater after roller-press grinding than after rotary grinding (figs. 5, *b* and 5, *d*). Similar trends are observed in other fractions.

Fig. 6 illustrates the dependence of the shape factor on grain length for each of the five fractions. Within the range of ***l*/*b*** values from 2 to 4, the distribution density of needle-shaped grains obtained by roller-press grinding (fig. 6, *a*) is substantially higher than that of those produced by rotary grinding (fig. 6, *b*). In the larger fractions (1–3) obtained by roller-press grinding (fig. 6, *a*), grains with a shape factor exceeding 3 are absent. Grains with a shape factor exceeding 3 are absent in all fractions produced by rotary grinding (fig. 6, *b*).

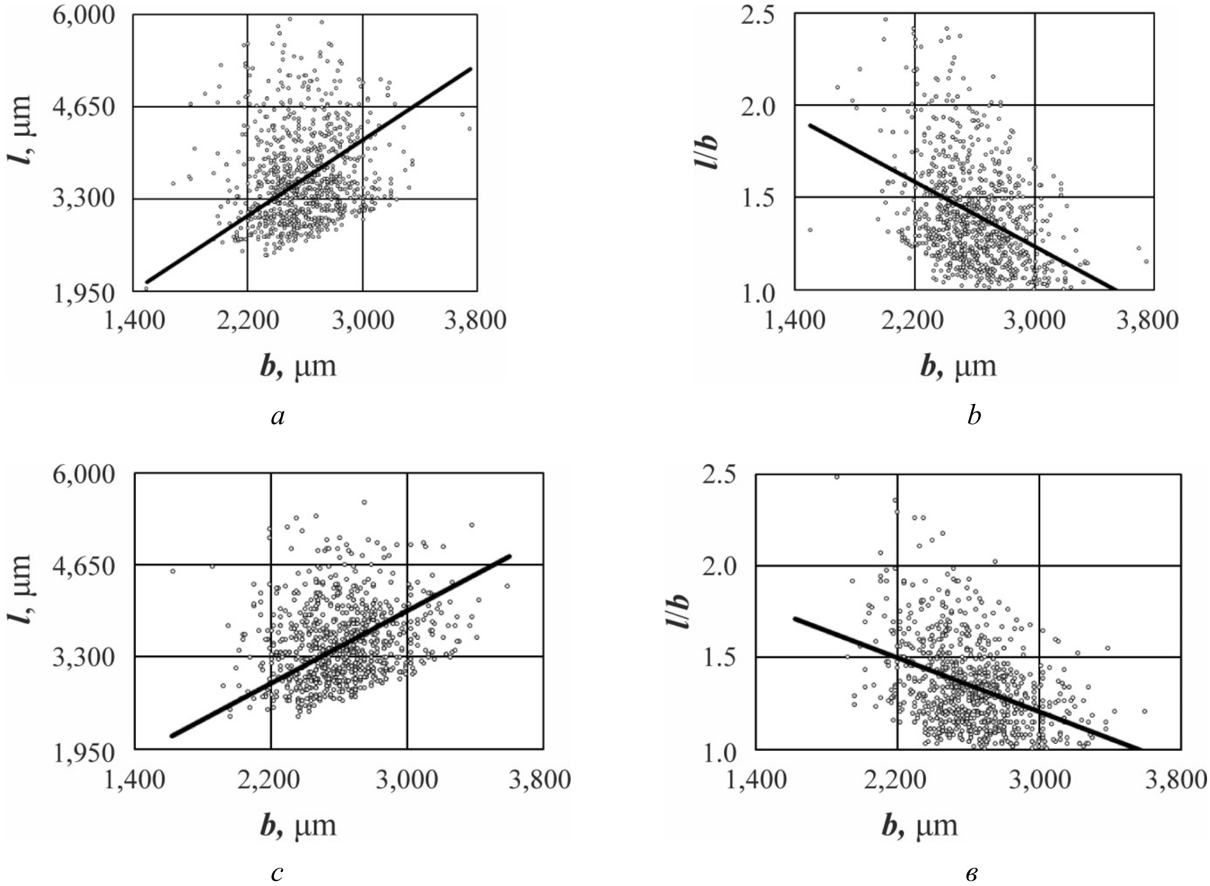
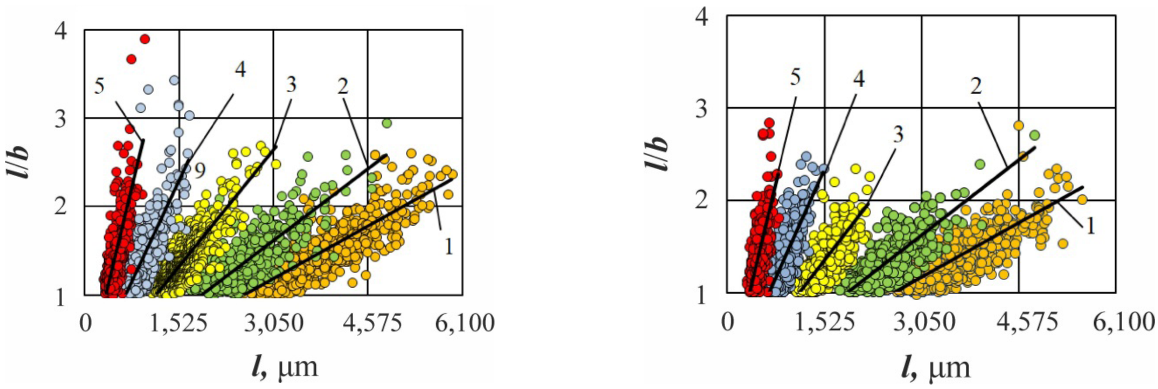


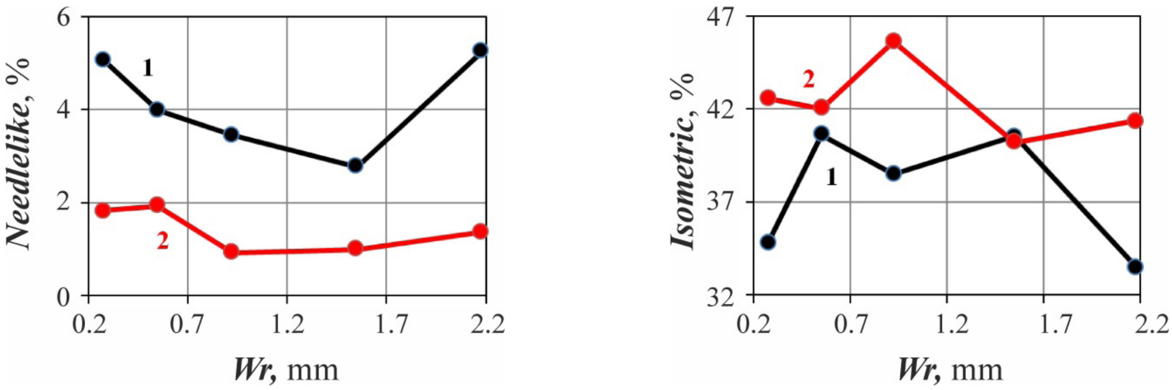
Fig. 5. Regression relationships between geometric parameters of grains in fraction **2**:
a, *b* – roller-press grinding; *c*, *d* – rotary grinding



a *b*

Fig. 6. Dependence of the aspect ratio ***l/b*** on grain width ***b*** for five fractions after roller-press (*a*) and rotary (*b*) grinding

A quantitative evaluation of the content of needle-shaped and isometric grains obtained by roller-press and rotary grinding is presented in fig. 7. Following roller-press grinding, the content of needle-shaped grains (***l***/***b*** > 2) in the five fractions ranges from 2.8 % to 5.2 %, while following rotary grinding, it ranges from 0.9 % to 1.9 %. On average, the number of needle-shaped grains in the five-fraction samples is reduced threefold after rotary grinding compared to roller-press grinding.



a *b*

Fig. 7. Content of needlelike (*a*) and isometric (*b*) grains after roller-press (1) and rotary (2) grinding, depending on the average cell size of the upper and lower sieves of the ***Wm*** fraction

The proportion of isometric grains (***l***/***b*** ≤ 1.3) after both roller-press and rotary grinding ranges from 33 % to 46 % (fig. 7). Rotary grinding yields the highest proportion of isometric grains, ranging from 40 % to 46 %. Following roller-press grinding, the proportion of isometric grains ranges from 33 % to 41 %. The average proportion of isometric grains is approximately 42 % after rotary grinding and 37 % after roller-press grinding, representing a 5 % decrease.

Conclusions

1. The grain shape factor distributions after roller-press and rotary grinding adhere to the law of maximum value. The geometric parameters used to calculate the shape factor follow these distribution models: grain length – the law of maximum value, grain width – the normal distribution.

2. Given that, of the three geometric parameters analyzed, only grain width follows the normal distribution, it is impossible to meet a prerequisite for using the *Pearson* correlation coefficient: the analyzed datasets of geometric parameters must conform to a normal distribution. Consequently, *Spearman's* rank criterion was employed to assess the relationship strength.

3. The following *Spearman's* rank criterion (**ρ**) were obtained: between grain length (***l***) and width (***b***), **ρ** does not exceed 0.3, indicating a weak, direct correlation; between grain width (***b***) and shape factor (***l/b***), **ρ** ranges from −0.35 to −0.50, indicating a moderate, inverse correlation; and between grain length (***l***) and shape factor (***l/b***), **ρ** exceeds 0.7, indicating a strong, direct correlation.

4. Using graphical examples of the relationships between geometric parameters in fraction 2, it is demonstrated that the number of grains with a length approaching the upper size limit (***l*** ≥ 4,650 μm) is significantly higher after roller-press grinding compared to rotary grinding.

5. Rotary grinding increases the proportion of isometric grains by an average of 5 % compared to roller-press grinding and by 8 % in the largest fraction. Roller-press grinding is characterized by a higher content of needle-shaped grains. The average content of needle-shaped grains across the five fractions is approximately 4 %. Rotary grinding reduces the number of needle-shaped grains threefold. The content of needle-shaped grains increases from larger fractions to smaller fractions and from rotary grinding to roller-press grinding.

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Conflicts of Interest

The authors declare no conflict of interest.