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Fractal analysis of surface topography evolution in homogeneous and dual ZrB_2-TaB_2-SiC composites during abrasive wear

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The evolution of the surface fractal dimension in ZrB_2-TaB_2-SiC composites subjected to abrasive wear was studied. The composites had two types of structural organization: with a homogeneous volume distribution of components, and a dual architecture consisting of the composite matrix with composite inclusions. It was found that the composite with homogeneous structure and dual composites show different abrasive wear behavior, which is reflected by the change in the dependence of fractal dimension on volume loss. The fractal dimension of the homogeneous composite surface was shown to grow with wear, while the fractal dimension of the dual composites decreases until a critical volume loss is reached. Further, the abrasive wear resistance decreases, the volume loss rate increases, and the behavior of the fractal dimension curve changes to opposite.

Keywords: fractal dimension, roughness, abrasive wear, ceramic, dual composite.

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The complexity of composite material surface can be measured by a characteristic number of the fractal dimension. The fractal dimension value is a measure of the rate of adding new details when moving from one scale to the next. It is accepted that the fractal dimension is a coefficient describing geometrically complex shapes, for which details are more important than the complete pattern [1]. The fractal dimension is a quantitative measure of the non-ideality of objects, including surface structures of real composites. It is sensitive to the interphase boundaries, cracks, pores, etc. Unlike the topological dimension of ideal objects, the fractal dimension is more sensitive to imperfections of real objects, due to which they can be distinguished and characterized. The use of fractal dimension to numerically characterize the surface changes of materials as a result of mechanical effects can be considered as an addition to the widely used methods of surface analysis. Shugurov et al. [2] applied fractal analysis to quantify the worn surface profile at different experimental stages and the failure mechanism of AuNi electroplated coatings. Horovistiz et al. [3] used fractal analysis to describe the fracture surface along the stretch zone front in an aluminum alloy characterized by complex morphology and inhomogeneous grain structure.

In this work, the fractal dimension is used as a characteristic describing the surface changes of complex structured ceramic composites under abrasive wear. It is known that the abrasive wear of ceramics occurs mainly by surface microcracking under the influence of impact loads exerted by abrasive particles [4]. The surface of wear-resistant ceramics subjected to abrasive wear can have high roughness with relatively low volume loss, whereas low wear resistance can lead to the formation of well-defined cavities, but with low roughness. An increase in the complexity and heterogeneity of the structure and phase composition of ceramics can cause an inhomogeneous behavior during wear, and a critical microdamage accumulation can lead to a jump-like loss of macrostructural stability.

Quantitative assessment of the abrasive wear of ceramics can be performed by measuring the mass or volume loss and surface roughness, or by analyzing the cross-sectional profile of the worn surface. At the same time, it is interesting to apply fractal analysis to the study of the abrasive wear of ceramics. The aim of this work is to study the abrasive wear behavior of ZrB_2-TaB_2-SiC composites fabricated with a homogeneous distribution of components and with a dual composite architecture [5], in which the composite matrix is filled with composite inclusions. The study is carried out by analyzing the evolution of the surface fractal dimension as an integral morphological characteristic.

Ceramic composites with a homogeneous volume distribution of components (HC) were obtained by mechanical activation of powder mixture in a planetary ball mill followed by sintering in vacuum at a temperature of 1800°C under a pressure of 150 MPa. Dual composite samples (DCx, where x reflects the volume content of inclusions in the matrix) were filled with composite inclusions obtained by spray drying and vacuum sintering at a temperature of 1600°C. TaB_2-SiC inclusions after sintering had an average size of $167.3 \pm 11.5\,\mu$m. The mixture of the matrix and inclusion powders was sintered under conditions similar to those for HC. The composition of the samples is presented in the table. A more detailed procedure of fabricating the studied materials is presented in [6].

Abrasion tests were conducted with silica sand as non-fixed abrasive, fed into the contact area of the ceramic sample pressed against a rotating rubber roller, according

Composition and properties of the studied ceramics

Sample	Composition					K_{IC} MPa·m$^{1/2}$ [6]	E, GPa
	vol.%		ZrB_2, vol.%	SiC, vol.%	TaB_2, vol.%		
HC	100	Matrix	72	20	8	3.22 ± 0.16	480.9 ± 24.0
DC10	90 10	Matrix Inclusions	80 –	20 20	– 80	4.16 ± 0.1	480.9 ± 24.0 525.5 ± 26.3
DC20	80 20	Matrix Inclusions	80 –	20 20	– 80	5.2 ± 0.1	480.9 ± 24.0 525.5 ± 26.3
DC30	70 30	Matrix Inclusions	80 –	20 20	– 80	9.3 ± 0.2	480.9 ± 24.0 525.5 ± 26.3
DC40	60 40	Matrix Inclusions	80 –	20 20	– 80	10.8 ± 0.3	480.9 ± 24.0 525.5 ± 26.3
DC50	50 50	Matrix Inclusions	80 –	20 20	– 80	11.2 ± 0.2	480.9 ± 24.0 525.5 ± 26.3

Note. K_{IC} — fracture toughness, E — Young's modulus.

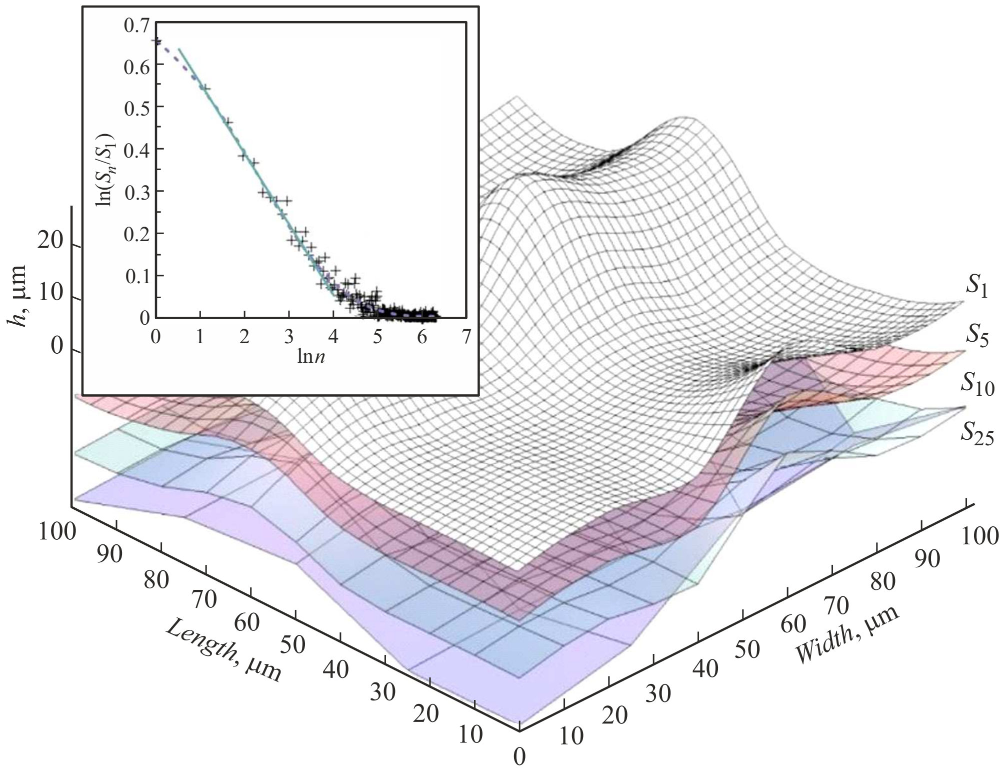

Figure 1. Three-dimensional surface of HC constructed with different scaling step n.

to ASTM G65-04. The roughness (R_a) was measured using an OSP100A (Uniscan) laser profilometer. The fractal dimension (D) was estimated by scanning a $100 \times 100\,\mu$m surface area with a laser profilometer. The result of the profilometric study was a table of 100×100 cells, where the number in each cell corresponded to the height. The table was represented as a three-dimensional surface (Fig. 1). To minimize the error introduced by the criterion for selecting the linear section of the S-curve, a region occupying 60% of the curve height, equidistant from the upper and lower points of the curve for all materials studied, was selected for linearization. This surface was constructed with different scaling step size n. The surface fractal dimension was defined as the coefficient of approximation of the linear portion of a reverse S-curve, which describes the dependence of the ratio of the area defined with scaling

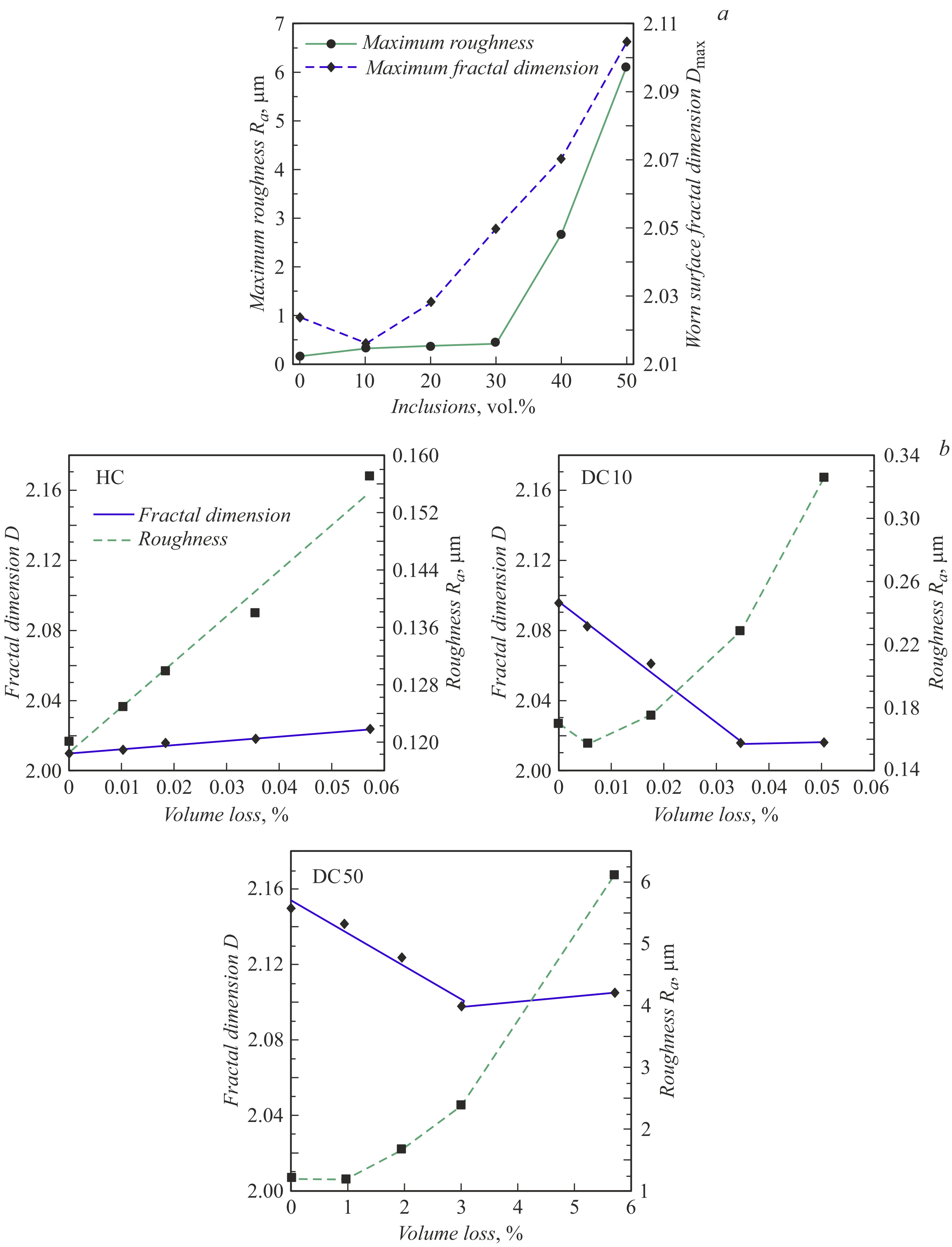

Figure 2. Plots of the worn surface roughness and fractal dimension vs the amount of composite inclusions (*a*); plots of roughness and fractal dimension vs volume loss at different stages of wear (*b*).

step n to the projection area of this surface $\ln(S_n/S_1)$, where S_1 is equal to $100 \times 100\,\mu$m, versus $\ln n$.

The worn surface studies showed that the roughness of the worn surface of HC and DCx grows markedly with increasing content of composite inclusions. However, despite the similar behavior of both curves in Fig. 2, *a*, the fractal dimension curve of the worn surface has a minimum corresponding to DC10. An increase in the content of inclusions is also accompanied by a decrease in the overall wear resistance. Nevertheless, despite the greater local wear depth on the DC*x* surface compared to HC, DC10 shows the highest wear resistance with lowest volume loss. Analysis of the variation of the surface fractal dimension during wear revealed that the fractal dimension of HC grows rather slowly (Fig. 2, *b*).

Despite the lower abrasion resistance of HC compared to DC10, the wear of HC [7] is accompanied by the formation of a large cavity with sufficiently low roughness. The fractal dimension of the DC*x* surface changes in a different manner. Initially, the high fractal dimension of DC*x* can be a consequence of residual porosity in inclusions and higher initial roughness after preliminary polishing of the samples, which is due to significantly different hardness and polishability of the matrix and inclusions. The initially high, relative to HC, fractal dimension, may be a consequence of the residual porosity in the inclusions, which was discernible in the initial profilograms, and the larger initial roughness after preliminary grinding of the samples, due to the significant difference in the hardness value of the matrix and inclusions. Apparently, the impact of abrasive particles during abrasive wear has a polishing effect on the DC*x* surface [8]. However, after reaching a critical volume loss, the behavior of the fractal dimension versus volume loss curves changes. Despite the fact that the fractal dimension and volume loss were measured after every 1000 m of linear distance during contact wear of the sample on the rotating roller, the most intensive wear was observed in DC20–DC50 at the last part of the distance (3000–4000 m), which led to the growth of fractal dimension. It was shown in [6] that for ZrB_2–TaB_2–SiC composites with a „dual" structure, the matrix is more intensively subjected to abrasive wear. However, when a certain critical value of the inclusion-matrix contact area is reached in the process of wear, a noticeable volume loss occurs, associated with the detachment of composite inclusions.

SEM studies of surface evolution during abrasive wear revealed that the wear of HC occurred by microcracking and detachment of particles from the surface, while the wear of DC*x* was characterized by dry erosion. The matrix, which was less hard than the inclusions, was more prone to wear, which continued until the contact area between the inclusion and the matrix reached a minimum critical value and the inclusion detached (Fig. 3, *a*). It can be seen that the wear of HC is accompanied by the formation of a cavity over the entire contact area of the composite with the rubber roller, while the DC*x* samples show small but rather deep wear pits.

In [6,7] it was shown that DC*x* exhibit a higher fracture toughness compared to HC, and data on Young's modulus for matrix and inclusions calculated by the mixture rule, using the literature data on the Young's modulus of ZrB_2, SiC, TaB_2 — 489, 423.5, and 551 GPa [9–11], respectively (see the table).

The higher fracture toughness is caused by two factors: residual elastic stress fields arising due to the CTE difference between the matrix and inclusions, and different stiffness of the matrix and inclusions. This creates favorable conditions for the propagation of cracks near inclusions and thus increases the crack propagation work. The combination of the two factors provided DC*x* with higher fracture toughness and different abrasive wear behavior and surface evolution scenario during wear.

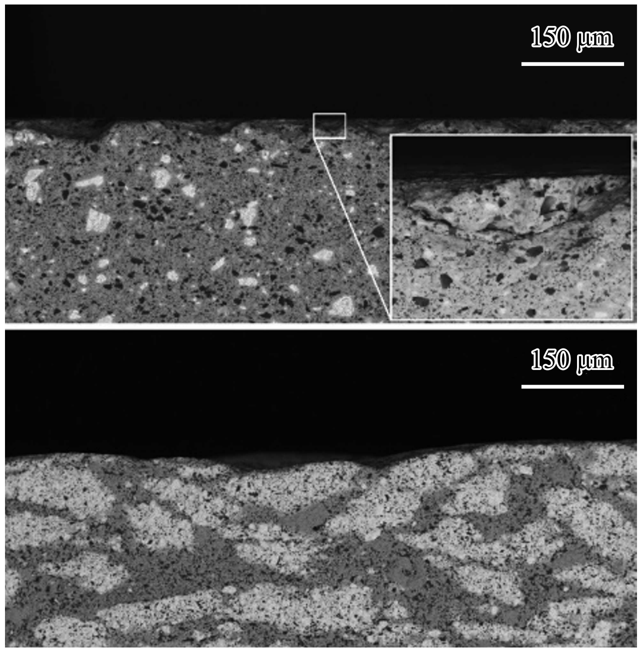

Figure 3. Cross-sectional view of the worn surface.

Thus, composites with dual and homogeneous structure show different abrasive wear behavior, which is reflected by the change in the dependence of fractal dimension on volume loss. The surface fractal dimension of the homogeneous composite increases with wear, while the fractal dimension of the dual composites decreases until a critical volume loss is reached. Further, the abrasive wear resistance decreases, and the behavior of the fractal dimension curve changes to opposite. The change in the surface fractal dimension depending on volume loss reflects the wear behavior of the composite: from polishing and smoothing by abrasive particles to active formation of cavities and pits.

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Conflict of interest

The authors declare that they have no conflict of interest.

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