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The use of graded coatings, with elastic moduli decreasing gradually from the contact surface to the substrate, is shown to result in considerably reduced stresses at the coating–substrate interface under indentation and friction [11] and sliding contacts subjected to surface loading [12].

When solving a contact problem, the researchers [13–14] have demonstrated that the stress distribution pattern, including stresses at the substrate–coating interface, as well as the coating thickness parameters and elastic characteristics depend on the contact plane and relative surface area of the loading zones.

The case under study here differs fundamentally from those discussed in the available publications, not so much in considering a coated tool as in the fact that the contact discontinuity depends also on the dimensions of the discrete coating segment. This requires taking up and considering a problem of contact loading of a discrete coating segment on a tool.

The objective of the present work is to minimize stresses in the substrate–coating adhesive contact under contact loading with friction.

2. EXPERIMENTAL, RESULTS, AND DISCUSSION

The up-to-date numerical methods, such as the finite element method (FEM), allow SSS calculations for coated workpieces and tools in view of operating loads [15]. The model design and calculation were performed using a licensed FEM software package MSC VisualNastran for Windows, which had been chosen for its relative simplicity and versatility. This package contains everything necessary to prepare and carry out a complete cycle of modeling. An element of a solid model of WC-8Co carbide tool with a discrete vacuum–plasma-deposited coating was taken to be studied. We considered one of the symmetric portions of the substrate–discrete coating model which was split into hexagonal finite elements that have smaller dimensions in the region of direct substrate–coating. The coating was produced by means of special masks with variously shaped and sized openings; this method enabled us to prepared coatings with preset geometrical parameters using a Mod. NNV-6,6-I1 apparatus [16].

For the purpose of calculating a stress–strain state in a coated surface segment, we took a carbide tool's coated square-shaped element with a side D and thickness h under contact loading q (Fig. 1).

The calculation has demonstrated that at the adhesive contact surface the tangential stresses τ_{adh} responsible for the coating peeling off the substrate are maximum at the discrete segment edges and depend on the segment dimensions (Fig. 2). At first, the values of maximum tangential stresses on the adhesive contact surface increase with the discrete segment size and then, upon some peak, start decreasing.

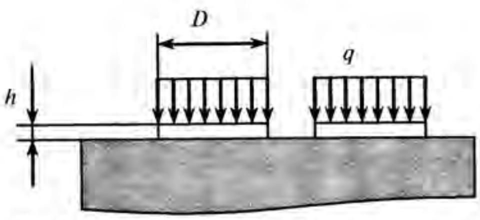


Fig. 1. Contact loading conditions for a discrete-coated element.

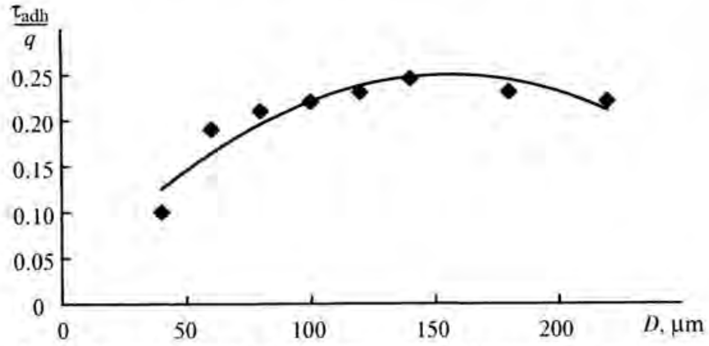


Fig. 2. An optimal level of maximum tangential stresses τ_{adh} as a function of a discrete segment size D.

This tendency is attributable to the fact that maximum tangential stresses arise at some depth proportional to a contact zone size. The larger the coated area, the deeper these maximum stresses penetrate into the substrate; as the discrete segment reaches a certain size, the level of stresses on the adhesive contact surface starts descending. In this case, the maximum coated segment size is limited to a value corresponding to ultimate equivalent stresses for a substrate material (a peak of the equivalent stresses as calculated by the fourth theory of strength is observed at the same depth as is that of tangential stresses). Conversely, a reduction of the discrete segment size leads to a situation where the peak of stresses approaches the adhesive contact surface and can be observed both on this surface as well as in the coating proper (Fig. 3). Analysis of the above findings enables us to define an upper and lower limits of the discrete segment. This is turn will make it possible to prevent adhe-

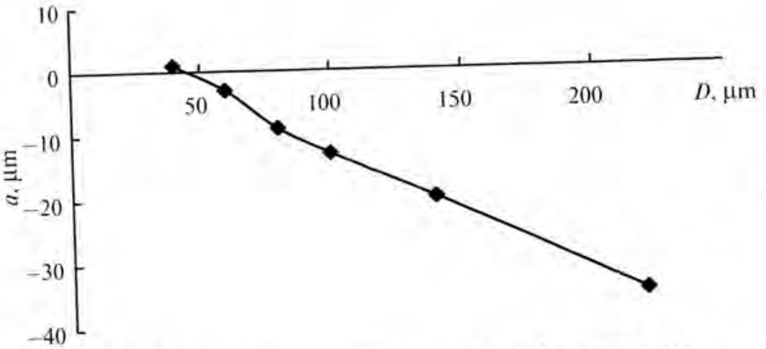


Fig. 3. Spacing between discrete segments vs. the segment size.

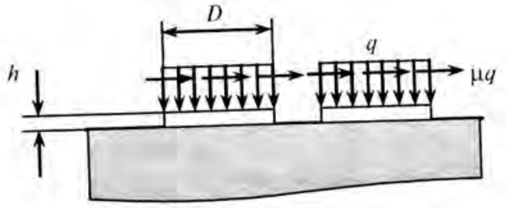


Fig. 4. Contact loading conditions with a tangential component for a discrete-coated element.

sive fracture (peeling) by reducing the level of tangential stresses on the adhesive contact surface and to preclude the substrate material fracture by decreasing the peak of equivalent stresses in the substrate.

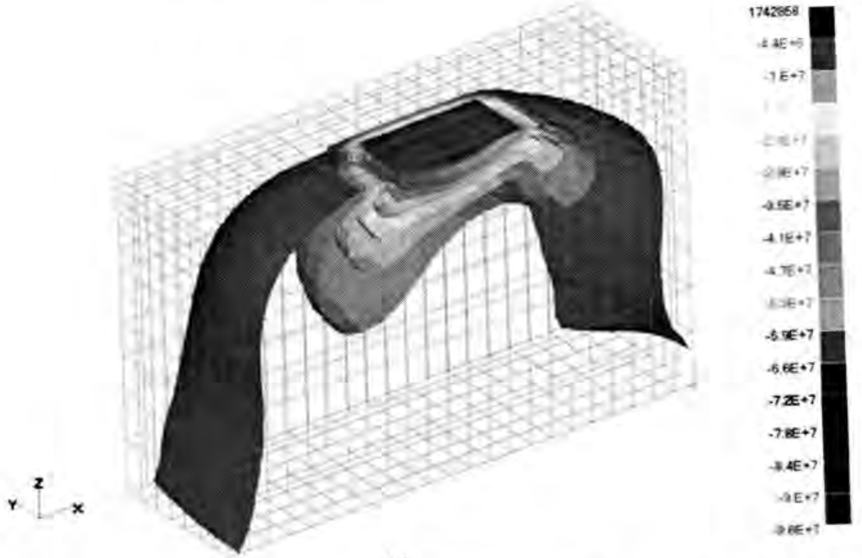
We have also looked at the influence of a discrete segment's dimensions and friction coefficient values on the stress level in the adhesive contact surface in the case of a tangential loading component (friction force) allowing for a friction coefficient μ (Fig. 4).

Discussion of the results obtained (Fig. 5) shows that an increase in the friction coefficient results in a redistribution of tangential stresses. Specifically, as the friction force grows, the maximum tangential stresses come from deep inside the substrate material towards the adhesive contact surface, enter the discrete segment of coating, and then reach its surface.

With the friction coefficient increasing, the peak of tangential stresses shifts in the direction of the friction force and the tangential stresses in the adhesive contact plane become distributed along the entire contact surface.

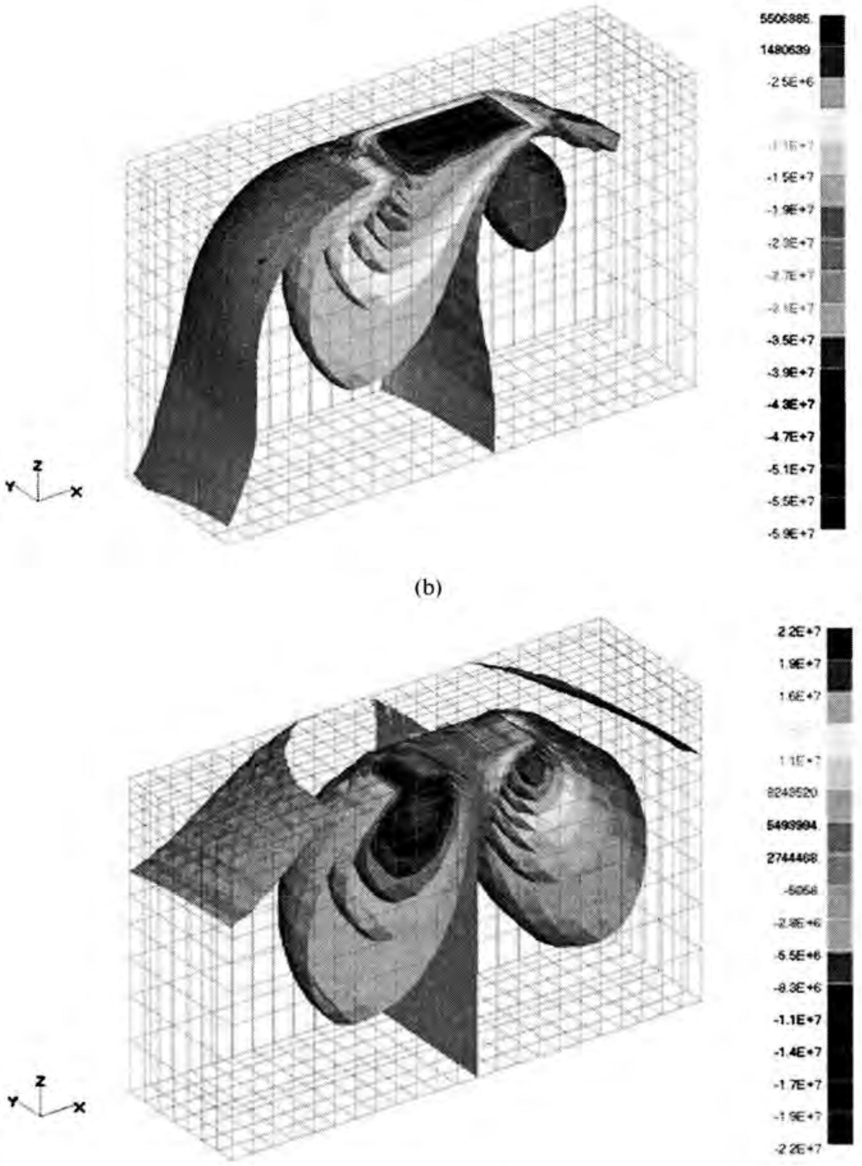
Using the calculated data we have plotted the functions of a ratio of maximum tangential stresses on the adhesive contact surface τ_{adh} to the intensity of applied load q for variously sized discrete segments and different friction coefficients (Figs. 6, 7). The friction coefficient itself depends on the type of coatings and the counterbody material [17–21].

Analysis of the functions plotted demonstrates that the geometrical parameters of a wear-resistant discrete surface should be chosen in view of the materials to be in frictional contact. The adhesive contact stress for coated areas up to 40 μm in size is shown to be almost independent of the friction coefficient, while for larger discrete segments the influence of the friction coefficient on the adhesive contact stresses becomes more significant.



(a)

Fig. 5. Isosurfaces of a tangential stress field due to the action of a normal and tangential loads on a discrete segment of size $D = 120$ μm under intensive contact loading $q = 100$ MPa: $\mu = 0.7$ (a), 0.5 (b), 0 (c).



(b)

(c)

Fig. 5. (Contd.)

Considering that titanium-based compounds, such as titanium nitrides and carbonitrides, are widely used as coatings for friction–pair components and cutting tools, we studied the dependence of the values of tangential stresses on the substrate–coating adhesive contact surface on the size of discrete segments for TiN- and Ti(C, N)-coated tools in machining structural materials (see Fig. 7). We dealt with particular coating–counterbody friction contacts with peculiar values of friction coefficient (Table 1) [18, 19, 21].

The calculated results enable us to establish the dependence of the stress level in an adhesive contact surface on the discrete coating segment size and friction coefficients. Thus, it becomes possible to predict the level of stresses in the substrate–coating interface for various types of coatings and various sizes of discrete coating segments and to ensure the required substrate–coating adhesion strength.

Note that we used friction coefficient values for continuous coatings. The preliminary findings show that as the contact conditions in the discrete coating–counterbody system change, so does the value of the friction coefficient. In particular, the use of discrete coatings has been found to result in a 1.3 times lower friction coefficient of TiN coatings against 40Kh steel. Clearly, this fact should be given due consideration in the SSS calculations for a coated working surface; for this purpose, further tests are to be carried out in order to measure the coefficient of friction of discrete-coated surfaces against counterbodies made of various materials.

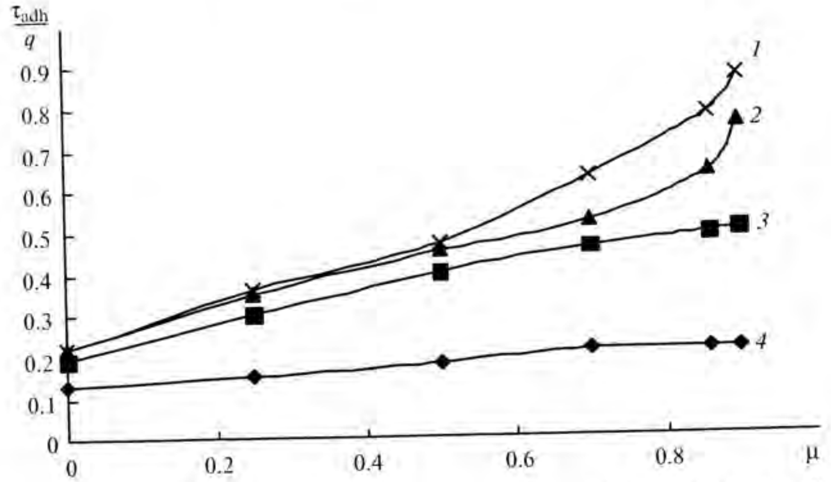
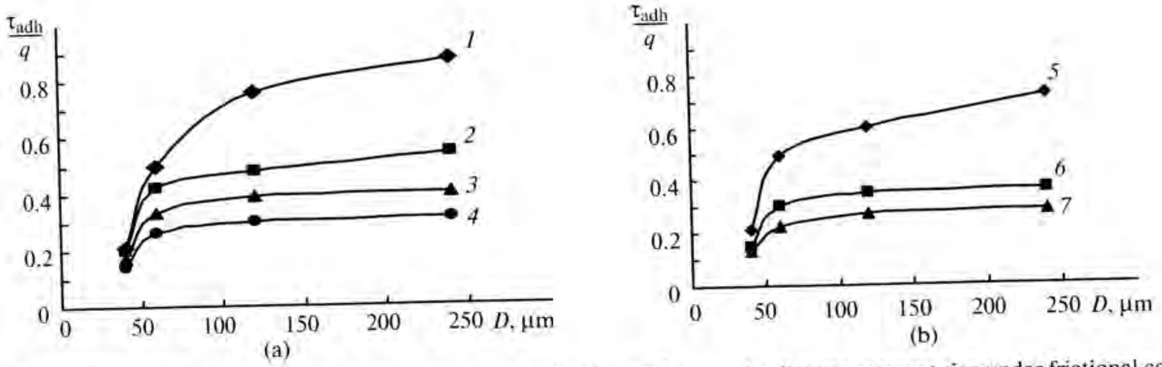


Fig. 6. Tangential stress ratio on the adhesive contact surface as a function of the friction coefficient for discrete segments with a size $D = 240$ (*1*), 120 (*2*), 60 (*3*), and 40 μm (*4*).



(a)

(b)

Fig. 7. Tangential stress ratio on the substrate–coating adhesion surface vs. the discrete segment size under frictional contact conditions: TiN (*a*) against a counterbody made of a carbon steel (*1*), chromium steel (*2*), alumina (*3*), chromium steel with MoS_x in a coating (*4*); Ti(C, N) (*b*) against a counterbody of a carbon steel (*1*), WC83Co17 cemented carbide (*2*), and alumina (*3*).

Table 1. Friction Coefficients for Coating–Counterbody Friction Contacts

Coating	Counterbody					
	Steel 45	Steel 40Kh	Chromium steel	WC83Co17	Al_2O_3	Steel 45 with MoS_x
TiN	0.9		0.6	NA	0.35	0.15
Ti(C, N)	0.8		NA	0.25	0.12	NA

3. CONCLUSIONS

The present calculations have revealed an influence of the discrete coating segment size and coating type on the level and pattern of distribution of tangential stresses in the substrate–coating system for a carbide cutting insert with a discrete vacuum-plasma-deposited coating.

The results of this research make it possible to choose optimal geometrical parameters and type of coatings in order to prevent the cutting tool failure due to the coating peeling off.

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