Related problems of designing heat-loaded structures from ceramic matrix

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Abstract. The paper presents a method of mathematical modeling of the mechanical and thermal state of the contact pairs on the example of contact between two composites. The algorithm of the study including the preparation of profilograms roughness of the contacting surfaces of the samples (identification roughness parameters), construction of a three-dimensional model of the surface roughness, mechanical interaction analysis microroughness contacting surfaces, determining the thermal contact resistance and the calculation of thermal fields in the contact zone. The technique was tested on a contact pair of ceramic-matrix composites for various values of mechanical and thermal loading. The obtained calculated data are verified according to the experimental study.

Key words: composite materials, contact pair, surface roughness, mathematical modeling

1. Introduction

The development of technological capabilities of modern materials has led to a significant amount of composite materials with radically new properties. The rapid growth of the spectrum of such materials leads to the need to develop methods for the rapid and reliable analysis of the contact properties of pairs of composite materials under their mechanical and thermal loading.

The performance characteristics of the contacting parts are directly determined by the contact properties of the mating surfaces. The processes of friction and wear occur on the actual contact area and depend not only on the material properties, but also on the pressure on this area, since the actual pressure determines the destruction of surface films and the occurrence of adhesive bonds in the contact. The flow of high-intensity heat fluxes through the contact of two materials is a rather complicated process that requires reliable determination of contact properties in a wide range of temperatures and pressures.
The study of the properties of new materials is carried out in the form of complex tests, on the basis of which it can be concluded that different materials are compatible in contact pairs. The program of complex tests is quite time consuming and is associated with known material costs. Conducting preliminary numerical studies based on a mathematical model of contact using the minimum set of known characteristics of the materials constituting the contact pair should allow a significant reduction in material and time costs by optimizing the test program. At the same time, to obtain the necessary contact parameters as a result of a numerical study, it is possible to formulate requirements for both the contacting materials themselves and the state of their surface.

The study of the contact properties of materials is devoted to a variety of works [1-10]. It should be noted that most authors conduct research in fairly local ranges of mechanical and temperature loads and a limited range of materials under study. As a rule, such an approach is caused by the need to solve an urgent, but narrowly specialized task. The tasks of contact interaction are often focused on specific aspects of contact interaction: separately on tribology issues, separately on modeling contact interaction of rough surfaces, separately on calculating the actual touch area and contact volume, separately on contact thermal resistance and thermal interaction of surfaces. The most common methods of calculating contact properties today are based on various analytical dependencies obtained as a result of generalization of experimental data. Unfortunately, such approaches, when used for a wide range of contacting materials, have extremely low accuracy, i.e. existing analytical dependencies are applicable only for a certain range of materials and fixed ranges of variation of mechanical and thermal loading of the contact zone.

In this paper, the authors attempted to calculate the comprehensive thermomechanical characteristics of contact surfaces, based on the influence of roughness on the contact parameters.

2. Algorithm of the study
To solve the problems of thermal interaction in the contact zone, the authors developed a technique [8, 9, 11], which allows, based on microgeometry of surface roughness, to simulate contact interaction of irregularities for subsequent thermal analysis. The variation of the geometrical parameters of the surface roughness profile made it possible to optimize the surface microgeometry in accordance with the necessary conditions of contact thermal interaction. This technique also makes it possible to simulate the introduction of a film into the contact zone and to evaluate its influence on the contact properties.

The algorithm for conducting research according to the existing methodology is as follows:
2.1. Obtaining profilogram of surface roughness of specific samples or determination of surface roughness parameters by known profile parameters from existing databases.
To determine the location and contact area of the surfaces of real connections, it is necessary to remove the profilogram of the surface under study. Then, as a result of processing the profilogram, its three-
dimensional model can be built, from which the characteristic contact spots can be distinguished. To implement this item, it is necessary to obtain the surface data as an array of points (x, z) in electronic format. This can be done using any modern profilometer.

If it is impossible to obtain an array of profilogram points in electronic form, you can use the base of the surface roughness profiles, from which you can select the most suitable profile based on the values of the average height of the irregularities and the step of the microprojections.

2.2. Construction of a three-dimensional model of surface roughness.

Building a three-dimensional model is possible only if there is a three-dimensional array of points with coordinates (x, y, z). A three-dimensional array of points can be obtained using the Fortran program [12], which allows, based on one surface roughness profile, to obtain an array of data with coordinates of points (x, y, z) of the surface asperities.

The resulting array of points is processed in the SolidWorks three-dimensional design environment, where the surface roughness geometry is modeled using the method of constructing a spline surface using points.

2.3. Mechanical analysis of interaction between asperities of contacting surfaces.

To perform a mechanical analysis of the interaction of asperities, a computational mesh model is constructed. As a result of the mechanical analysis of the asperity of asperities, the amount of convergence of the contacting surfaces, the area of the actual contact and the contact volume are determined.

2.4. Thermal analysis of the interaction of the contacting surfaces.

On the basis of the deformed model obtained, a thermal calculation is made of the contacting parts under given thermal loads. The temperature field of the contacting surfaces obtained as a result of thermal analysis allows determining the thermal state of the entire contact (intensity of heat fluxes and contact thermal resistance).

The obtained values of the thermal state of the contact allow you to make the necessary adjustments to the roughness of the contacting surfaces due to changes or improvements in the technological process of processing the contacting parts.

The data on the roughness parameters obtained as a result of such an analysis can later be used to develop design and technological documentation, and the data itself is recorded in the database of contact pairs of materials.

3. Testing methods
Testing of the technique was carried out on a contact pair of samples of composite materials KMK-MS - KMK-MS with an arithmetic average deviation of the profile $R_a = 12.27 \, \mu m$. The prototypes were cylinders with a length of 50 mm and a diameter of 30 mm. Samples were in contact with their ends and placed one above the other. The upper sample was heated from the side of the free end, heat was removed from the free end of the second sample. Samples were insulated from the surrounding space. It was possible to apply and control the clamping pressure.

At the first stage, profilograms of the contacting surfaces were determined using a Surftest SJ-210 profilometer. According to the results of roughness measurement, an average value was obtained for the three measurements made. The profilogram of one of the contacting surfaces is shown in Figure 1.

![Fig.1. Surface roughness of KMK-MS.](image)

$R_a = 12.27 \, \mu m$ at the base length $L = 14 \, \text{mm}$.

On the basis of an array of surface roughness profile points obtained using a profilometer using the program [12], a three-dimensional array of surface microrelief points was obtained (Fig.2).
Fig. 2. An array of profilogram points (left) and an array of surface microrelief points (right).

Based on the array of points of the surface microrelief, a three-dimensional model of the surface and a calculated finite element mesh model were constructed. The result of building a mesh model based on a three-dimensional model of surface roughness is presented in Figure 3.

Fig. 3. Mesh model of surface roughness.

\[ R_a = 12.27 \text{ microns (isometric)}. \]

For the mechanical analysis, the following boundary conditions were specified:

- pressure \( P \) (load \( A \)) is applied to the upper boundary, which varies in the range from 10 to 100 atm.,
- boundary conditions of the sliding seal without friction (load C, D) are applied to the lateral borders of the samples,
- to the lower boundary the boundary conditions of rigid fitting are applied (load B) (Fig. 4).

![Fig. 4. Boundary conditions.](image)

According to the results of mechanical analysis, the values of equivalent stresses and inter-contact pressure, the magnitude of the penetration of the surface of one part into the surface of another part were obtained. The field of equivalent stresses on the surface of the KMK-MS sample for an applied pressure of $10^6$ Pa is presented in Figure 5.
Fig. 5. The field of equivalent stresses on the surface of the KMK-MS sample for an applied pressure of $10^6$ Pa.

For each value of the pressure applied to the sample (10, 20, 30 ...), at least 10 calculation sub-steps were performed, based on the results of which, by moving the pressure of the upper surface of one sample, the displacement coordinates of the upper surface of one sample were calculated to find the value of its penetration into the surface of the other sample.

The field of equivalent stresses on the surface of the KMK-MS for a pressure of $10^7$ Pa is presented in Figure 6.
Fig. 6. The field of equivalent stresses on the surface KMK-MS for an applied pressure of $10^7$ Pa.

The presented figures make it possible to notice that the number of contact points and their area depend on the applied pressure: the number of contact areas and their area increase with increasing pressure applied.

As a result of the performed strength calculation, the magnitude of the displacement of the surface of the upper sample relative to the surface of the lower sample was obtained, which is necessary to determine the actual area of contact in the contact pair of two rough surfaces. The magnitude of the displacement for the considered contact pair, depending on the applied pressure are given in table 1.
Table 1. Dependence of the displacement of the pressure applied to the pair of materials.

| Applied pressure, MPa | Displacement, mm |
|-----------------------|------------------|
| 1.00                  | 7.21·10⁻⁶        |
| 2.00                  | 8.60·10⁻⁶        |
| 3.00                  | 9.77·10⁻⁶        |
| 4.00                  | 1.06·10⁻⁵        |
| 5.00                  | 1.13·10⁻⁵        |
| 6.00                  | 1.21·10⁻⁵        |
| 7.00                  | 1.27·10⁻⁵        |
| 8.00                  | 1.34·10⁻⁵        |
| 9.00                  | 1.40·10⁻⁵        |
| 10.00                 | 1.46·10⁻⁵        |

The determination of the parameters of the temperature field, depending on the magnitude of the heat flux, was made by dividing one calculation step into 10 substeps. As a result of the thermal analysis, the temperature field, the direction and magnitude of the heat flux in the contacting surfaces were obtained. Figure 7 shows the temperature field distribution on the contacting surface.

The values of the calculated contact thermal resistance $R_K$ and the surface temperature of the samples for the considered contact pair, depending on the applied pressure, are given in Table 2.

![Fig. 7. Distribution of the temperature field on the surface of the KMK-MS at an intercontact pressure of 5·10⁶ Pa.](image-url)
Table 2. Values of contact thermal resistance $R_k$ and temperature in the contact pair KMK-MS - KMK-MS

| Applied pressure, MPa | $R_k \times 10^4$, K-m$^2$/W | Top sample temperature, °C | Bottom sample temperature, °C |
|-----------------------|-----------------------------|-----------------------------|-----------------------------|
| 1.00                  | 187.03                      | 625.78                      | 438.75                      |
| 2.00                  | 148.88                      | 673.43                      | 524.55                      |
| 3.00                  | 131.65                      | 719.14                      | 587.49                      |
| 4.00                  | 119.09                      | 728.34                      | 609.25                      |
| 5.00                  | 111.05                      | 735.13                      | 624.08                      |
| 6.00                  | 105.09                      | 739.56                      | 634.46                      |
| 7.00                  | 100.48                      | 742.99                      | 642.51                      |
| 8.00                  | 96.40                       | 745.31                      | 648.92                      |
| 9.00                  | 93.60                       | 748.50                      | 654.90                      |
| 10.00                 | 90.52                       | 751.95                      | 675.57                      |

The conducted test calculation showed good (within 6%) agreement with the results of an experimental study of the properties of a KMK-MS-KMK-MS contact pair under power and thermal loading.

4. Conclusions

The use of the presented technique allows determining by the method of mathematical modeling contact thermal resistances for any contact pair in the permissible pressure range. And having the value of contact thermal resistance for the considered pairs of materials in a wide range of pressures, it is possible with certain reliability to calculate the thermal state of the structure under actual operating conditions of contact pairs of materials.

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