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Study of Thermal State of Powder Metal-Polymer System During Electrical Contact Sintering

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Abstract
Structural schemes and finite element models of mesofragments of powder metal-polymer composite materials have been developed. The thermal state of the initial components in the process of electrical contact sintering was investigated. The technological modes of the sintering process have been optimized. Electric current with a density of 400 A/mm^2 is the optimal sintering mode for a composite material based on a metal-polymer dispersed system "copper – PTFE".

Keywords: polytetrafluoroethylene, temperature field, numerical modeling, metal matrix, composite material, design scheme, metal-polymer system, copper.

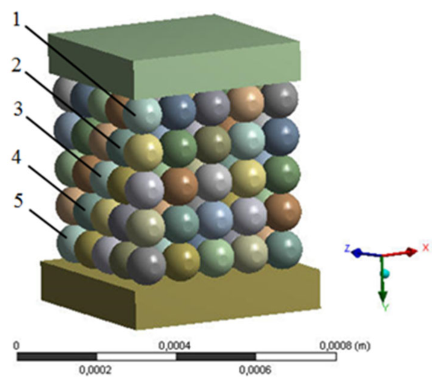
1. Introduction

Metal-polymer composites are promising types of composite materials for friction units without lubrication. Powder metallurgy is a promising technology for producing such materials. Self-lubricating materials make it possible to abandon the lubricant supply system, simplify the design and reduce the material consumption of machines and mechanisms [1 – 5].
Copper has high antifriction properties, corrosion resistance and thermal conductivity [2]. Copper and copper-based alloys have found wide application as matrixes of powder composites. Polytetrafluoroethylene (PTFE) has extremely high antifriction properties. The friction coefficient of PTFE without lubrication is 0,04 – 0,06 [6].
The classical methods of sintering a metal matrix during the formation of composite materials do not allow maintaining the high tribotechnical properties of the polymer filler. At the same time, the use of high-energy methods with a sintering duration of 1 – 2 s is justified.
However, the study of physical processes during the formation of the structure of a material under high-energy impact is limited by the current state of research methods. Modern research equipment does not allow one to see the picture of the formation of the structure of a powder composite material when a high-density electric current flow. Understanding the mechanisms of structure formation could significantly speed up the development of new materials.
To date, computer modeling methods have become widespread in solving natural-scientific and technical problems. Computer experiment is one of the main methods for studying complex systems and physical processes in modern science. Computer simulation has a number of advantages over real experiments. In particular, a computer experiment can be performed when carrying out a full-scale experiment is difficult or impossible.

The purpose of the work is to study the thermal state of the metal-polymer powder systems "copper – PTFE" in the process of electrical contact sintering. The study of temperature fields is a non-trivial task due to the presence of internal sources of heat caused by the passage of current in the initial components of the composite. At the same time, numerical modeling allows predicting the nature of structure formation and optimizing the properties of composite materials at the development stage.

2. Calculation schemes and Finite element 3-D model

Design schemes and finite element models have been developed to study the thermal state of metal-polymer composite materials (Figure 1).



1 – first layer of particles; 2 – second layer of particles; 3 – third layer of particles; 4 – fourth layer of particles; 5 – fifth layer of particles

Figure 1. Calculation schemes of the mesofragment of the metal-polymer system "copper – PTFE" indicating the numbers of the considered layers of particles in the XY plane

Design schemes have an elastic hypothetical layer to take into account the contact interaction of neighboring mesofragments of the powder composite.
The generated mesh of the mesofragment model is shown in Figure 2. The models are divided into finite elements in the automatic mode of the ANSYS [7].

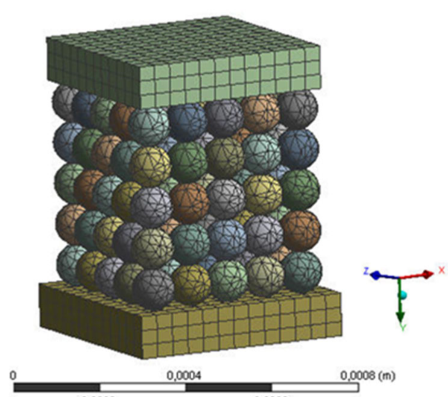
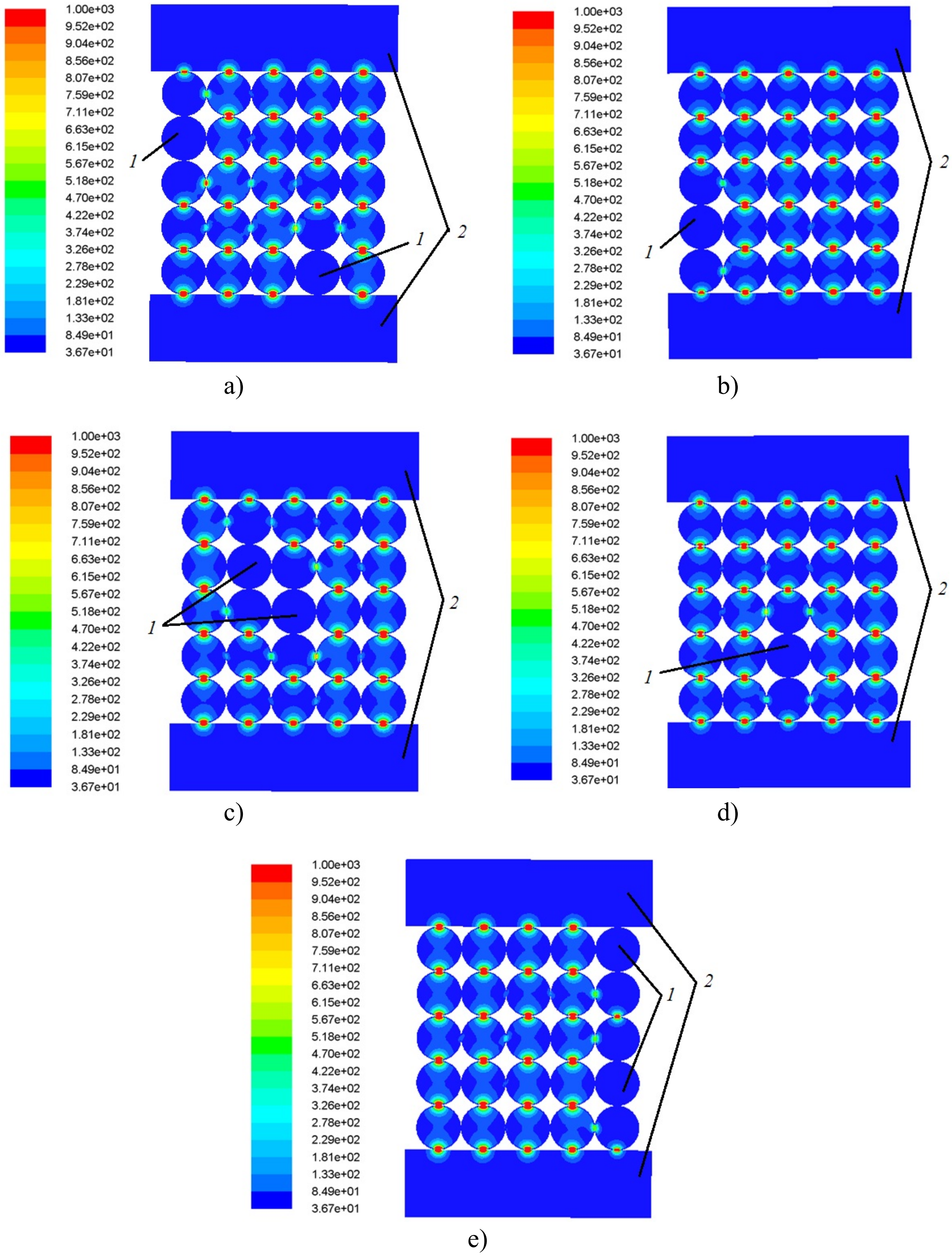


Figure 2. Finite element 3-D model of a mesofragment of a metal-polymer powder system "copper – PTFE"

The accuracy of the finite element method depends on the correct choice of type and size element. For example, a more frequent mesh is used in places with a high temperature gradient. The influence of the electric current on the thermal state of metal-polymer powder systems during the formation of hybrid composites using computer modeling approaches has been investigated. The thermal state of the sintered powder system has a significant effect on the process of obtaining high-quality powder materials by the method of electrocontact sintering. The sintering current and the sintering duration are the main tools for changing the mode of electrical contact sintering. In this case, the generated heat is a useful part of the supplied energy.
The amount of heat generated during sintering of the powder system by electric current is determined by the sum of the contact resistance between the particles and the intrinsic resistance of the matrix metal. It can be noted that the release of heat at the initial stage of electrical contact sintering occurs mainly in the regions of contact interaction of the particles of the metal matrix due to the presence of oxide films on their surface. Over time, oxide films are destroyed and heat generation on the matrix metal increases. The metal matrix partially transforms into a molten state. Strong interparticle metal contacts are formed.

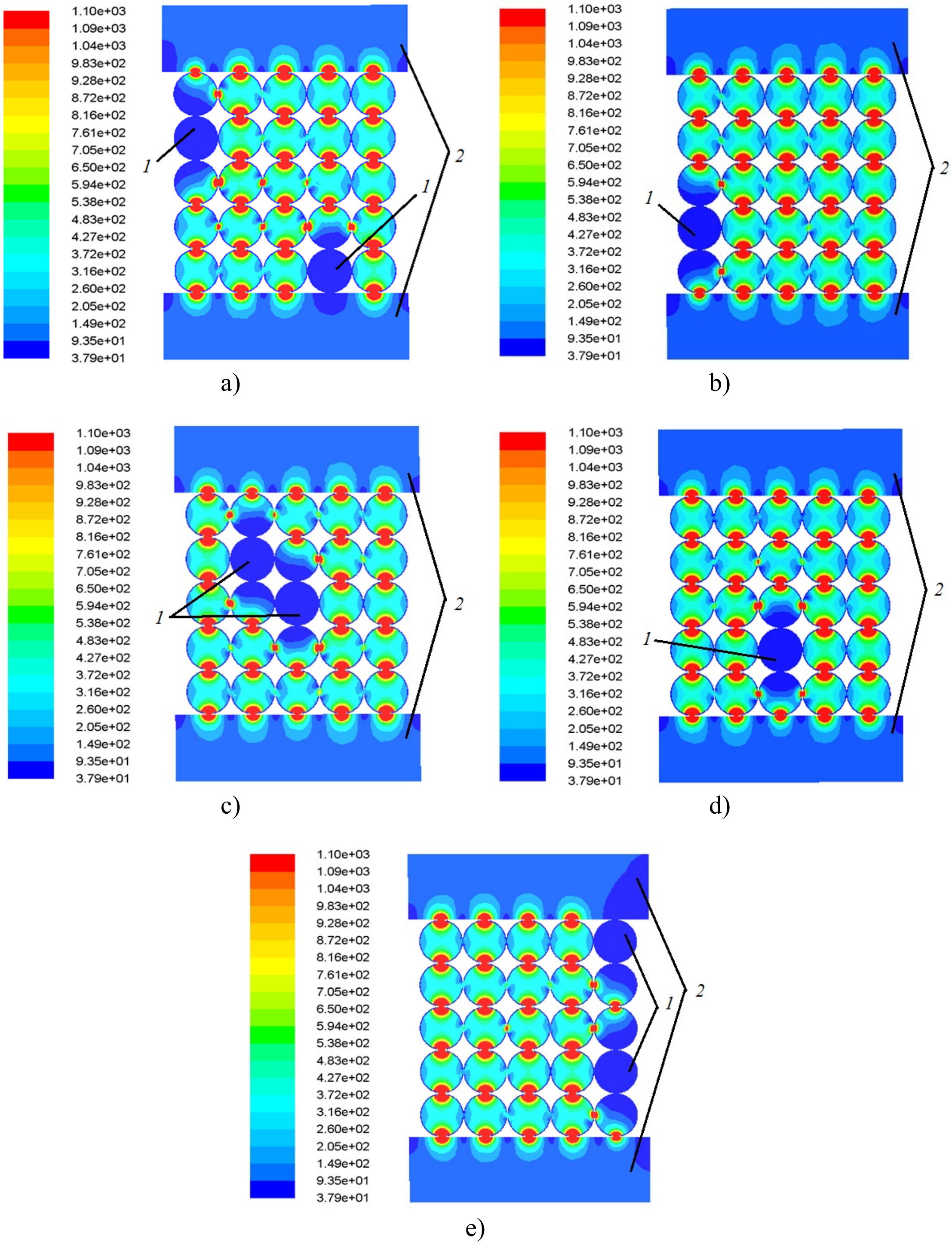
3. Results and discussion

The study of the effect of the sintering current on the thermal state of a mesofragment of a composite powder material based on a powder metal-polymer system is presented below. The distribution of temperature fields in a composite material with a polymer filler content of 6 wt. % at a sintering current density of 200 – 600 A/mm^2 is shown in Figures 3 – 5. Analysis of the thermal state of a mesofragment of a powder material during sintering with an electric current with a density of 200 A/mm2 made it possible to note the following features (Figure 3).
A local increase in temperature to 900-1000°C is observed in the areas of contact interaction of particles of the metal matrix. The formation of a liquid metal phase and the formation of strong metal contacts at these temperatures is not possible. The metal does not go into a softened state. The particles of the metal matrix do not move relative to each other. This makes it difficult to obtain a material with low porosity. Oxide films are not destroyed. Strong metal contacts when sintering a powder composite metal-polymer system with an electric current of 200 A/mm^2. It can be concluded that it is impossible. The average temperature of the metal matrix is about 300-400°C. The temperature in the polymer filler is 40-60°C.
The picture of the thermal state of a mesofragment of a powder material during sintering with an electric current with a density of 400 A/mm^2 is shown in Figure 4. The temperature in the metal matrix reaches 800°C. The predominant heat release is observed in the regions of contact interaction of the particles of the metal matrix. The metal temperature in these areas rises to 1100°C. A strong metal framework is formed by partial melting of matrix particles and the formation of liquid metal contacts. The temperature of the polymer filler particles does not exceed 100°C. There is no thermal oxidative degradation of PTFE. The maximum temperature at the contacts of the metal particles of the matrix is 1250°C. In this case, the oxide films melt. The uneven heating of the matrix particles is caused by the lines of electric current flow. Electric current travels along the paths of least resistance. As a result, some areas of the matrix with a higher electrical conductivity are subject to intense heating than less electrically conductive ones.
Analysis of the patterns of the distribution of temperature fields during sintering with an electric current with a density of 600 A/mm^2 allows us to note the following (Figure 5). The average temperature of the particles of the metal matrix is 1000-1083°C. Melting of the matrix metal and thermal-oxidative destruction of the polymer filler particles occur. The PTFE temperature in the contact interaction zones is 360-400°C.



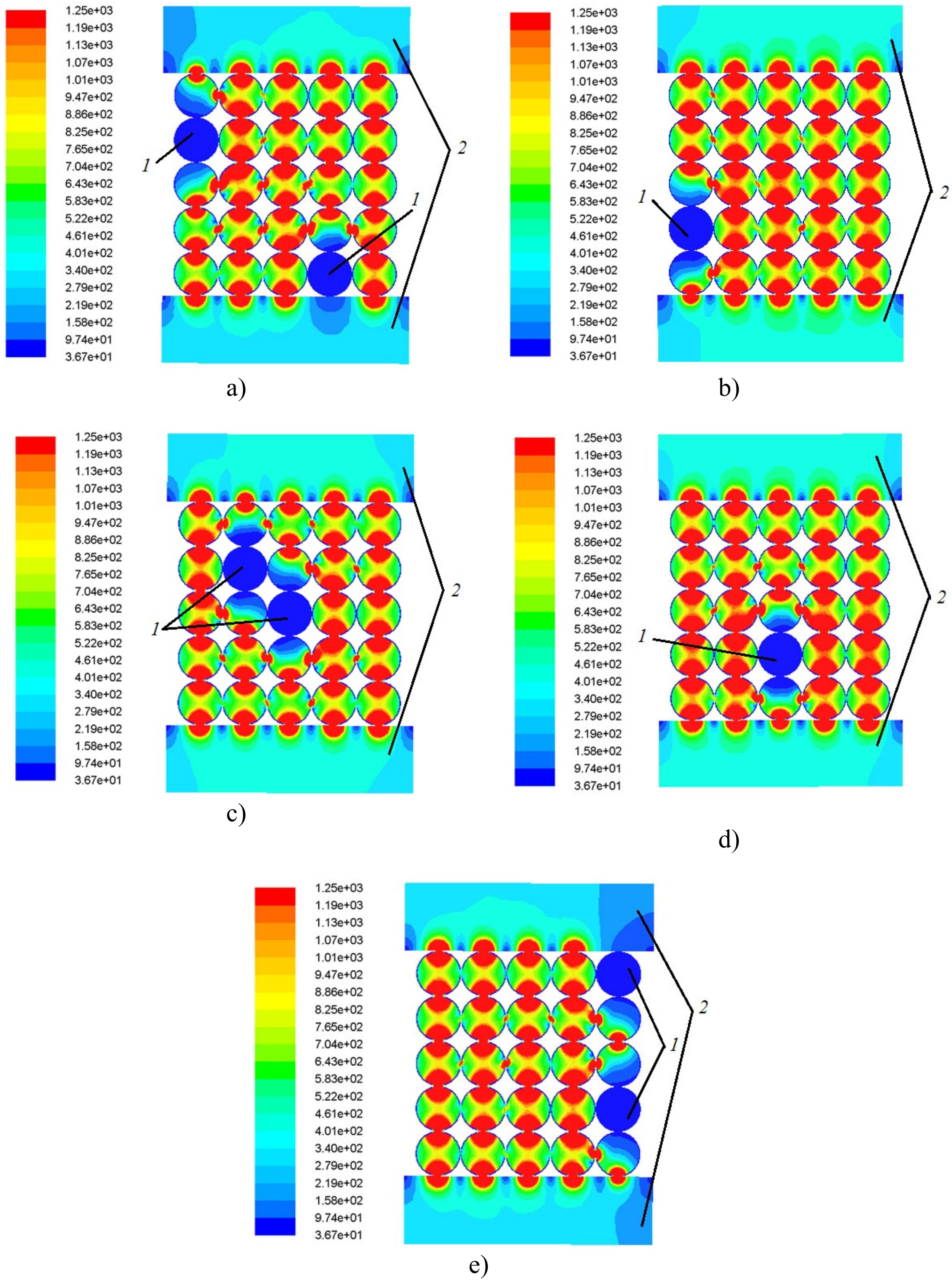
1 – PTFE particle, copper – other particles; 2 – electrodes

Figure 3. – Temperature distribution in the mesofragment of the dispersed-filled nanostructured metal-polymer powder system at a current density of 200 A/mm^2, °C:
a – first row of particles, b – second row of particles, c – third row of particles,
d – fourth row of particles, e – fifth row of particles



1 – PTFE particle, copper – other particles; 2 – electrodes

Figure 4. – Temperature distribution in the mesofragment of a dispersed-filled nanostructured metal-polymer powder system at a current density of 400 A/mm^2, °C:
a – first row of particles, b – second row of particles, c – third row of particles,
d – fourth row of particles, e – fifth row of particles



1 – PTFE particle, copper – other particles; 2 – electrodes

Figure 6. – Temperature distribution in the mesofragment of a dispersedly filled nanostructured metal-polymer powder system at a current density of 600 A/mm^2, °C:
a – first row of particles, b – second row of particles, c – third row of particles,
d – fourth row of particles, e – fifth row of particles

4. Conclusions

Thus, the complex of studies of powder dispersed-filled metal-polymer systems showed that sintering of the initial components with a current with a density of 200 A/mm2 does not allow generating the necessary amount of heat for the formation of strong metal contacts of matrix particles. Sintering of the initial components of the metal-polymer system with a current of 600 A/mm2 leads to melting of the metal matrix, thermal oxidative destruction of the polymer filler, and disruption of the material continuity.

The optimum, from the point of view of the formation of the structure of the material, is its sintering with an electric current with a density of 400 A/mm2. In this case, strong metal contacts are formed between the particles of the metal matrix. The processes of complete thermo-oxidative destruction do not occur. The hereditary structure of PTFE is maximally preserved.

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