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Numerical Simulation and Forecasting of Mechanical Properties for Multi-Component Nonferrous Dispersion-Hardened Powder Materials

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Abstract. A new mathematical simulation technique for physico-mechanical properties of multi-component powder materials is proposed in this paper. The main advantage of the technique is that finite elements representing different components are placed into a common mesh and may exchange their properties. The input data are properties of components and specified value of porosity. The output data are properties of material after sintering. The technique allows us to investigate the influence of each component of a material on the properties and distribution of properties inside the sample. The comparative analysis of materials with different compositions is based on simulation results that are well concordant with the results of the laboratory experiments.

Introduction

The functional powder materials refer to the most perspective materials which have specified physico-mechanical properties. The antifriction multi-component powder materials refer to functional materials, in which the required complex of physico-mechanical properties is reached by optimization of the volume fractions of components in the material at a specified porosity value [1].

At the same time, the development of new materials with given density and mechanical properties, that ensure high dimensional accuracy and quality of surfaces of details is impossible without a detailed analysis of phenomena which is taking place during the densification process. The existing analytical methods are simulations of the deforming processes based on the equations of mechanics of continua which require a formulation of boundary value problems, the drawing up differential equation systems and do not fully take into account the discontinuity in the structure of the powder materials.

Among the discrete mechanics methods, the most widespread are the large particles method, boundary element method and finite element method. There is a great deal of agreement in the opinion that one solution for such problems is the sequential application of analytical methods based on mechanics of continua and discrete mechanics for the prediction of properties of powder materials. The most essential drawback of such an approach is the appreciable decrease of simulation accuracy in the case of an increasing number of components in the material, and also great difficulties with taking into account the mutual influence of components on the material's properties [2].

The necessity of physico-mechanical properties prediction, while taking into account the mutual influence of all the components and porosity, required the development of more adequate and reliable methods for multi-component powder materials.

The enhanced technique for physico-mechanical properties simulation of multi-component nonferrous powder materials was developed on the basis of the finite element method by using the LS-DYNA solver.

Mathematical model

The mathematical model of multi-component material and mechanical test is a system of constitutive equations, which define the physical and mechanical properties of components. The finite elements that describe different components of material are placed in a common mesh. It

allows the possibility of taking into account interactions between components. The input data are volume fractions of components, their property in compact state, and also specified value of porosity. The elasto-plastic model of material is applied to all components. The following thermomechanical coefficients: temperature k_t, strain k_υ and deformation k_ε, are implemented to reproduce the effects of strain and deformation hardening [2]. Such an approach allows the analysis of the influence of each technological parameter onto the material properties. The independent parameters are nodal displacements [2].

The strain intensities ε_i and strain rates $\dot{\varepsilon}_i$ inside each element are defined through projections of the nodal displacements onto the coordinate axes [3]:

$$\varepsilon_{ix} = \frac{\sum_{\lambda=1}^{N} \frac{\partial u_x^\lambda}{\partial x}}{N}, \varepsilon_{iy} = \frac{\sum_{\lambda=1}^{N} \frac{\partial u_y^\lambda}{\partial y}}{N}, \varepsilon_{iz} = \frac{\sum_{\lambda=1}^{N} \frac{\partial u_z^\lambda}{\partial z}}{N}, \varepsilon_i = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_{ix}-\varepsilon_{iy})^2 + (\varepsilon_{iy}-\varepsilon_{iz})^2 + (\varepsilon_{iz}-\varepsilon_{ix})^2}, \dot{\varepsilon}_i = \frac{d\varepsilon_i}{dt}. \quad (1)$$

where λ – is the node number;
N – is the number of nodes in a finite element;
u_x^λ, u_y^λ, u_z^λ – are projections of nodal displacements onto the coordinate axes;
ε_{ix}, ε_{iy}, ε_{iz} – are relative strains of a finite element onto the coordinate axes.

Taking into account the thermomechanical coefficients, the Cowper and Symonds equation for stress intensity σ_i inside a finite element looks like [3]:

$$\sigma_i = \left[1 + \left(\frac{\dot{\varepsilon}_i}{C}\right)^{\frac{1}{p}}\right](\sigma_0 + \beta E \varepsilon_i). \quad (2)$$

where σ_0 – is the initial yield stress of a component;
E – is the Young modulus;
$\beta = k_t k_\upsilon k_\varepsilon$ – is the hardening coefficient of a component;
C, p – are arbitrary constants.

The values of σ, ε, E, Poisson's ratio v and density ρ in a given area of a sample may be expressed in the following way [3]:

$$\sigma = \frac{\sum_{j=1}^{n}\sigma_j}{n}, \quad \varepsilon = \frac{\sum_{j=1}^{n}\varepsilon_j}{n}, \quad E = \frac{\sigma}{\varepsilon}, \quad v = \frac{\varepsilon_{xy}}{\varepsilon_z}, \quad \rho = \frac{\sum_{j=1}^{n}\rho_j}{n\sum_{i=1}^{m}\delta_i}. \quad (3)$$

where n – is the number of finite elements in a given area;
ε_{xy}, ε_z – are the radial strain and the axial strain respectively;
m – is the number of components in the material;
δ_i – is the volume fraction of each component.

Porosity is also a component of the powder material and zero-elements are used for its modelling in the proposed model. The volume fraction of zero-elements is equal to the given porosity of the material. The proposed mathematical model is tested during the compression test of samples.

Finite element simulation

The results of the prediction of physical and mechanical properties are presented for the investigation of samples from a copper-nickel powder material with porosity 10–30 %. The technology for obtaining the samples consists of the following operations: moulding of powder mixture, sintering at 950 ^{0}C into the synthesis-gas medium for 3.5 hours, repeated moulding up to porosity 10–30 %, homogenizing annealing into the synthesis-gas medium at 960 ^{0}C for 1 hour, hardening in water. The input data are properties and volume fractions of the components, and also the specified value of the porosity (Table 1). The finite element model of the multi-component material, the analytical model of mechanical tests and density distribution are presented at Fig. 1 a, the numbers of positions correspond to the numbers of components in Table 1.

For each of the investigated materials the density, Young's modulus, Poisson's ratio, yield stress and ultimate stress were calculated during mathematical experiments. The laboratory experiments of compression tests are planned and carried out on the basis of numerical simulation results. The stress-strain dependences are drawn using the simulation and experimental results. The results of the simulation and experimental dependences are in concordance (Fig.1 b).

TABLE 1. Components of material and their initial properties

	Component	Volume fraction, [%]	Density, [kg/m^3]	Young's modulus, [MPa]	Poisson's ratio	Yield stress, [MPa]	Ultimate stress, [MPa]
1	Copper	70-90	8940	$1.20 \cdot 10^5$	0.33	120	220
2	Nickel	10–30	8897	$2.03 \cdot 10^5$	0.31	210	450
3	Cobalt	5	8900	$2.09 \cdot 10^5$	0.31	200	350
4	Iron	2	7850	$2.10 \cdot 10^5$	0.28	200	280
5	Manganese	1	7470	$1.98 \cdot 10^5$	0.22	210	430
6	Titanium	3	4505	$1.10 \cdot 10^5$	0.34	160	530
7	Graphite	1	1800	$0.85 \cdot 10^5$	0.43	100	120
8	Porosity	10–30	0	0.00	1.00	0	0

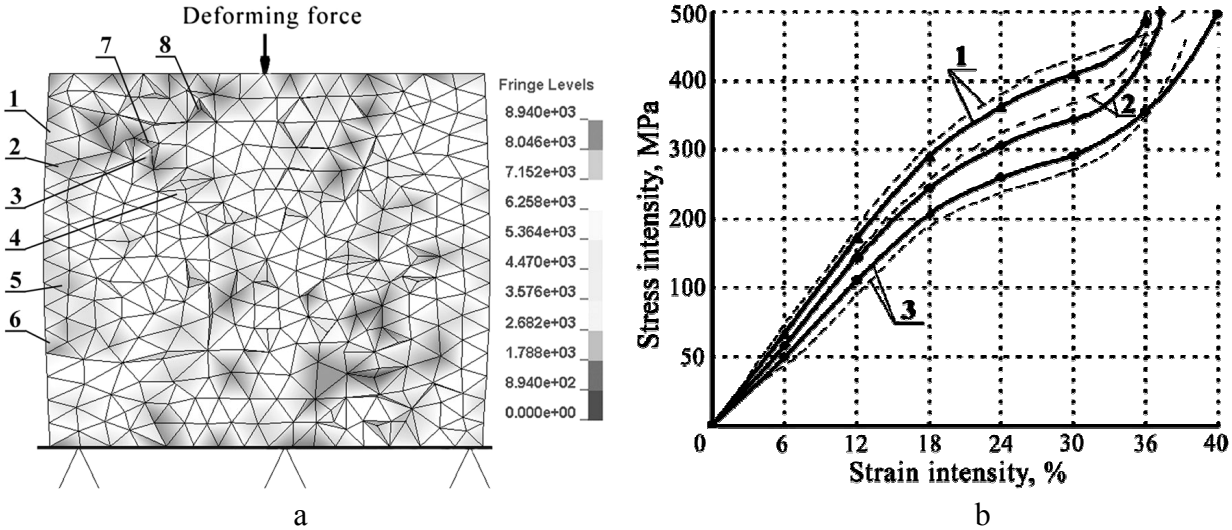

Fig. 1. The finite element model of the multi-component material, analytical model, density distribution (a), stress-strain dependences (b): 1 – is material 1; 2 – is material 2; 3 – is material 3: ——— – the numerical simulation results; - - - - - – the experimental results

The mechanical properties of the investigated materials obtained as a result of the finite element simulation and laboratory testing of samples are presented in the Table 2.

TABLE 2. Calculated and experimental properties of materials

Material	Volume fraction, [%]		Type of data	Porosity, [%]	Density, [kg/m^3]	Young's modulus, [MPa]	Poisson's ratio	Ultimate strain, [%]	Yield stress, [MPa]	Ultimate stress, [MPa]
	Copper	Nickel								
Material 1	90	10	S	10	8046	$1.53 \cdot 10^5$	0.42	34	320	430
			E	8	8110	$1.65 \cdot 10^5$	0.40	36	340	460
Material 2	80	20	S	20	7152	$8.75 \cdot 10^4$	0.38	30	280	370
			E	17	7350	$9.15 \cdot 10^4$	0.35	33	300	390
Material 3	70	30	S	30	6560	$5.86 \cdot 10^4$	0.35	30	250	300
			E	32	6245	$5.56 \cdot 10^4$	0.31	28	230	270

S – the numerical simulation results; E – the experimental results.

The analysis of data from Table 2 shows that the relative accuracy of the mathematical and experimental investigation of physical and mechanical properties does not exceed 10%. The highest level of mechanical properties is shown by material 1 due to its lowest porosity. Material 3 has the lowest mechanical properties. It has the highest porosity and at the boundaries between components copper–nickel interparticle cracks are possible, because of the great difference in their strength properties. Consequently, a porosity decrease down to 20% promotes a strength property increase up to 40%.

Summary

The new technique for forecasting the properties of multi-component dispersion-hardened nonferrous powder materials was proposed on the basis of physico-mechanical properties of its initial components by using the finite element method and LS-DYNA solver. The distribution of density inside a sample of the multi-component material was obtained. The influence of copper, nickel and porosity on mechanical characteristics was investigated. The porosity increase led to a significant decrease in mechanical properties. Increasing the volume fraction of nickel in the material improved the strength properties. The content of other components and their influence on properties was taken into account at interactions of finite elements. The results of the prediction are well concordant with the results of the laboratory experiments.

References

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[3] LS-DYNA Theoretical Manual (Livermore Software Technology Corporation, May, 1998).