Simulation of volumetric deformation in the process of hot compaction of composite infiltrated Fe-Cu

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Annotation. To describe the regularities of the compaction of an infiltrated Fe-Cu composite material in the process of hot compaction, a criterion is proposed that is determined by the volumetric deformation of the pores of a refractory metal (iron) frame associated with plastic deformation of a compact material surrounding the pore. In this work, a multiplicative model of the influence of the values of technological factors (the content of the infiltrate, the initial relative density of the refractory base, the reduced work of compaction) on the volumetric deformation of the pores of the iron frame in the process of hot compaction of the infiltrated composite material is built. A hypothesis is formulated for compaction of an iron frame by accommodation of powder particles in the process of hot compaction of a Fe-Cu composite material with an increased content of infiltrate. It has been established that the volumetric deformation of the iron base is determined by the course of competing processes - decompaction due to the effect of "copper growth" of the Fe-Cu composite material, as well as the disintegration of the powder base associated with the squeezing out of the liquid phase of the infiltrate along the unformed interparticle surfaces, and compaction due to the suppression of decompaction under the action of external pressure during hot compaction of the infiltrated composite material.

Introduction
Infiltration is an effective technology for producing low-porosity composite materials operating at elevated temperatures and stresses. Impregnation of porous refractory bases with metal melts expands the range of powder materials in comparison with the “mixing-pressing-sintering” technology. The technology ensures the production of pseudo-alloys based on W, Fe, Mg, Ti, Ni, etc. A necessary condition for infiltration is the creation of physical contact and the implementation of physical and chemical interaction of the components of the composite material (CM). At the initial stage, adhesive bonds are established, under the influence of which the melt propagates on the "base-infiltrate" interface. CM is obtained by spontaneous infiltration by dipping, pouring and melting the infiltrate on the surface of the base in the process of heating bimetallic blanks "infiltrate-base" obtained by overlaying, pressing or spraying [1].

At SRSPU (NPI), methods of infiltration, combined with sintering of cold compacted bimetallic molding, have been developed. The technology makes it possible to use low-porosity powder bases. In this case, infiltration is carried out through communicating pores and unformed surfaces of the fusion between the powder particles of the base during the initial period of sintering. Technologies for cold compaction of bimetallic infiltration-base molding include pressing the infiltrate material onto a pre-pressed powder mixture of the base or pressing the powder base material onto a pre-compressed infiltration briquette, and when obtaining long tubular products, thermal spraying of the infiltrate is carried out onto the outer cylindrical base molding surface. Pressing the infiltration briquette onto the base molding makes it possible to establish physical contact between low-melting and refractory components at the stage of cold compaction of a bimetallic workpiece and to reduce the time delay in the start of impregnation associated with the incubation period. Carrying out cold and hot compaction of infiltrated CM provides an increase in physical and mechanical properties [1-4]. Incompressible volumes of the liquid phase of the infiltrate restrict the plastic flow of the base material during hot compaction, causing increased stresses and local fracture. The penetration of the infiltrate melt along the grain-boundary and interparticle surfaces during hot compaction promotes decompaction of the base material with an increase in the degree of hot deformation and the concentration of the infiltrate.

Purpose of work
Construction of a model for hot compaction of infiltrated composite materials.

Research methodology
The manufacturing technology of the samples included: preliminary pressing (100 MPa) of iron powder (PZhV 3.160.28 GOST 9849 - 86); pressing (200 - 704.6 MPa) copper powder (PMS - 1 GOST 4960 - 75) infiltrate ($C_{Cu}$ = 1.99 - 24.43% of the weight of the iron base); heating (1423 K; 1.2 ks) in dissociated ammonia, combined with infiltration by molten copper from a pressed infiltration briquette, and hot compaction with the reduced work of compaction $w_{hc}$, equal to 37.4-200.8 MJ/m$^3$ on a head with a falling mass parts 50 kg. The influence of the pressure $p$ of cold compaction on the relative density $\theta_0$ of the iron powder of the base can be described by dependence (1) obtained using the TableCuve 2D mathematical package with an increased value of the coefficient of determination $r^2 = 0.999$

$$\theta_0 = 0.359 + 0.059 \cdot p^{0.327} .$$  

Construction of a 3D model of hot compaction of the infiltrated Fe-Cu composite material was carried out in the Statistica.

**Results of experimental studies**

To describe the processes of compaction-decompaction of a porous powder material during its consolidation, a criterion is proposed, determined by the volumetric deformation $\varepsilon_{v,por}$ of the pores associated with plastic deformation of the compact material surrounding the pore [5]. Volumetric deformation of pores $\varepsilon_{v,por}$, calculated considering the initial relative density $\theta_0$ of the porous material and after its consolidation $\theta_C$ by the formula (2)

$$\varepsilon_{v,por} = \ln \left( \frac{V_{por}}{V_0} \right) = \ln(K_i) = \ln \left( \frac{\theta_C(1-\theta_C)}{\theta_0(1-\theta_0)} \right),$$  

where $K_i = \frac{V_{por}}{V_0}$ – is a coefficient characterizing the activity of the powder.

The pore volume of the infiltrated composite material $V_{por}$ is determined considering the volume of the infiltrate $V_i$ and the pore volume of the refractory metal (iron) frame $V_{Fe}^{por}$ (3)

$$V_{CM}^{por} = V_{Fe}^{por} - V_i$$  

The volumetric deformation of the pores of the iron frame $\varepsilon_{v,Fe}^{por}$ pores is determined by the formula (4) considering the pore volume of the iron base after cold $V_{Fe,CP}^{por}$ pores and hot compaction $V_{Fe}^{por}$ pores of the infiltrated Fe-Cu composite material, as well as expressions for the pore volume of the iron base (5)

$$\varepsilon_{v,Fe}^{por} = \ln \left( \frac{V_{Fe}^{por}}{V_{Fe,CP}} \right),$$  

$$V_{Fe}^{por} = V_i + V_{CM}^{por} .$$  

Based on the results of calculating the values of $\varepsilon_{v,Fe}^{por}$, a multiplicative model (6) was built in the Statistica environment (with an increased value of the correlation coefficient $r = 0.911$) of the volumetric deformation of the pores of the iron frame, which depends on the initial relative density of the cold compacted base $\theta_0$, the content of the infiltrate $C_{Cu}$, and the reduced work of hot compaction $w_{hc}$, as well as a graphical 3D model $\varepsilon_{v,Fe}^{por}(C_{Cu}, \ln w_{hc})$ (Figure 1) for the main level of values of the initial porosity of the iron base ($\theta_0 = 0.795$; $\ln \theta_0 = -0.23$)

$$\varepsilon_{v,Fe}^{por} = a_0 \cdot F_1 \cdot F_2 \cdot F_3$$  

where $a_0 = 0.465$;

$F_1 = -0.123 - 1.155 \cdot \ln \theta_0 - 2.124 \cdot (\ln \theta_0)^2$;

$F_2 = -43.518 + 4.724 \cdot C_{Cu} - 0.139 \cdot (C_{Cu})^2$;

$F_3 = -7.792 + 1.762 \cdot \ln w_{hc} + 0.108 \cdot (\ln w_{hc})^2$. 


Figure 1. Graphic 3D model of the volumetric deformation of the pores of the iron frame $\varepsilon^{v\,Fe}$, built based on the multiplicative model (6) with the value of $\ln \theta_0$ equal to (-0.23), showed the following. The dependence $\varepsilon^{v\,Fe}(C_{Cu})$ has an extreme character. The minimum degree of compaction is observed at a copper content $C_{Cu} \sim 18\%$. The revealed regularities can be explained by the increased mobility of particles of the iron base with an infiltrate content of more than 18%, which contributes to the compaction of the powder base material by the mechanism of accommodation. An increase in the copper content to 18% leads to a decrease in the degree of compaction of the pores of the iron base for all investigated values of the reduced work of hot compaction $w_{hc}$ of the infiltrated composite material. The revealed regularities can be explained by the occurrence of two competing processes - compaction under the influence of external pressure of hot compaction and decompaction due to disintegration of the powder base associated with the squeezing out of the liquid phase of the infiltrate along the unformed interparticle fusion surfaces. An increase in the reduced work of hot compaction $w_{hc}$ leads to an increase in the degree of compaction of the pores of the iron frame for the entire range of values of the infiltrate content $C_{Cu}$. At minimum values of $w_{hc}$, decompaction of the pores of the iron base is observed due to the occurrence of two competing processes - decompaction because of "copper growth" for the Fe-Cu composite material at minimal external pressures and compaction due to suppression of decompaction with an increase in the reduced work of hot compaction. To assess the effect of the relative density $\theta_0$ of the cold-compacted iron base on the hot compaction of the Fe-Cu composite material, a graphical dependence $\varepsilon^{v\,Fe}(\theta_0, \ln w_{hc})$ was constructed at a copper content of 18% of the mass of the iron base (Figure 2).
Analysis of the graphical model (Figure 2) showed that the dependence $\varepsilon_{\nu, Fe}^{\text{nop}}(\ln \theta_0, \ln w_{hc})$ is extreme. The maximum compaction of pores is observed when using cold compacted iron bases with a relative density of 0.76, characterized by the transition from open to closed porosity of the framework.

**Conclusions**

Based on the studies carried out, the dependence of the influence of the pressure $p$ of cold compaction on the relative density $\theta_0$ of the powder iron base and the multiplicative model of the volumetric deformation of the pores of the iron frame $\varepsilon_{\nu, Fe}^{\text{nop}}$ depending on the content of the infiltrate $C_{Cu}$, the initial relative density of the base $\theta_0$ and the given work compaction of the infiltrated composite material. A hypothesis is formulated for the compaction of an iron frame by the accommodation mechanism in the process of hot compaction of a Fe-Cu composite material with an increased infiltrate content (more than 18%). It is shown that the volumetric deformation of the iron base is determined by the course of competing processes - decompaction because of "copper growth" for the Fe-Cu composite material, as well as the disintegration of the powder base associated with the squeezing out of the liquid phase of the infiltrate along the immature interparticle surfaces of the coalescence, and compaction due to suppression of decompaction under the action of external pressure of hot compaction. The transition from open to closed porosity of the cold-compacted iron base reduces the degree of compaction of the pores of the base material (frame).

**References**

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