Modeling of volumetric deformation during compaction of Al-SiC composite materials based on mechanically activated batch

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Annotation. A 3D Spline model of the effect of the silicon carbide content $C_{SiC}$ and the cold compaction pressure $p$ on the bulk deformation of the powder molding $\varepsilon_v$ during the cold compaction of the Al-SiC charge was constructed. The nonlinear character of the dependence $\varepsilon_v(p)$ is established for the studied values of the silicon carbide content. The two-stage nature of the cold compaction of the Al-SiC powder mixture was revealed, which is characterized by intensive compaction at the initial stage. A sigmoidal model of cold compaction of a powder mechanically activated Al-SiC charge, which takes into account the initial stage of lightweight structural compaction, is constructed. The dependences of the influence of the SiC powder content on the coefficients of the sigmoidal cold compaction equation are established. A logistic model of the influence of $C_{SiC}$ on the coefficients of the sigmoidal equation of cold compaction and the average size of agglomerates formed during the mechanical activation of a mixture of Al-SiC composite powder material is proposed. The energy equation of hot compaction is obtained, the value of the compressibility coefficient is determined, and a linear equation is constructed that relates the relative densities before and after hot compaction of the Al-SiC composite material.

1. Introduction
To solve the urgent problem of manufacturing valve seats of internal combustion engines, promising technologies for producing powder and cast Al-SiC composite materials have been proposed [1]. The physicomechanical properties of Al-SiC materials are determined by the content and average particle size of silicon carbide [2, 3]. The possibility of producing hot-compacted Al-SiC composite materials based on mechanically activated powder mixtures in an aqueous H3BO3 solution was studied at SRSPU (NPI). The increased efficiency of mechanical activation is shown, in comparison with the mixing technology for the production of hot-compacted materials. It was established that an increase in the relative density of the cold compacted molding and a decrease in the SiC content in the charge reduces the residual porosity of the hot compacted Al-SiC powder composite material [4]. As a result of previous studies, the hereditary effect of mechanical activation on the processes of compaction and formation of the mechanical properties of sintered and hot-compacted powder materials was established [4-25].

2. Purpose of work
Construction of models of cold and hot compaction of mechanically activated powder mixture of Al-SiC composite material.

3. Research Methodology
The manufacturing technology of the samples included mechanical activation of the Al-SiC powder mixture, its cold compaction with a pressure of 47-140 MPa, heating (t = 823 K; \( \tau = 0.12 \) ks) in an air atmosphere, followed by hot compaction on a copra with reduced (specific) work \((w)\), equal to 130 MJ/m³. The powder mixture was mechanically activated (3.24 ks) in a SAND-1 planetary ball mill with a rotational speed of 4.8 s⁻¹ and a mass ratio of balls \((db = 10 \text{ mm})\) and a charge of 20 in a saturated aqueous solution of boric acid \((20\% \text{ of the mass of the charge})\). Moreover, the formed protective layer on the surface of the powder particles prevents oxidation during short-term heating of the molding in an air atmosphere. Powders of aluminum PA-4 and silicon carbide (black) SiC \((5-20 \text{ wt.\%})\) With an irregular, fragmented form of particles were used as starting materials [4]. The construction of a 3D Spline model of cold compaction of a powder mixture of Al-SiC composite material was carried out in a Statistica medium.

4. The results of experimental studies

Based on the results of experimental studies [4], the values of volumetric strain \( \varepsilon_v \) (1) were determined taking into account the relative density \( \theta_0 \) of the charge in the bulk state \((p = 0)\) and the cold-compacted molding \( \theta \) at pressure \( p \)

\[
\varepsilon_v = \ln \frac{\theta_0}{\theta}
\]

(1)

Analysis of the 3D Spline model \( \varepsilon_v(p, C_{SiC}) \) of the effect of the silicon carbide content \( C_{SiC} \) and pressure \( p \) on the volumetric strain \( \varepsilon_v \) of the powder molding during cold compaction of the Al-SiC charge (Figure 1) showed that the dependences \( \varepsilon_v(p) \) are nonlinear for all studied SiC values. The dependence of the cold compaction \( p(\varepsilon_v) \) of an Al-SiC powder mixture \((10 \text{ wt\%})\) can be described by the nonlinear model \((SDSCum) \) (2) \((a = -146.39; b = 146.03; c = -0.357; d = 0.216; e = 0.0002)\), built in the Table Curve 2D environment, with an increased value of the coefficient of determination \((r^2 = 0.996)\)

\[
p = a + \frac{b}{2} \left( 2 \cdot e \cdot \left[ \ln \left( \exp \left( \frac{\varepsilon_v + 0.5d}{e} \right) + \exp \left( \frac{c}{e} \right) \right) - \ln \left( \exp \left( \frac{c + 0.5d}{e} \right) + \exp \left( \frac{\varepsilon_v + 0.5d}{e} \right) \right) \right] + d \right)
\]

(2)

As a result of a joint analysis of the 3D Spline model (Figure 1) and the resulting equation (2), the two-stage nature of the cold compaction of the Al-SiC powder mixture was revealed. At the first stage \((p<47 \text{ MPa})\), intense compaction is observed, associated with structural deformation, characterized by facilitated displacement of powder particles and their redistribution. With a further increase in the cold compaction pressure \((p>47 \text{ MPa})\) (in the second stage), the dependence \( p(\varepsilon_v) \) can be described by linear equation (3) by analogy with the rheological equation for a compressible medium

\[
p = K \cdot \varepsilon_v.
\]

(3)

where \( p \) is the pressure of cold compaction, MPa;
K-compressibility coefficient during cold compaction, MPa;
\( \varepsilon_v \)-is the logarithmic volumetric deformation calculated taking into account the calculated value of the relative density of the powder material \( \theta_\ell \) characterizing the completion of the stage of lightweight structural compaction \((p \approx 0)\) and taken as the initial one \((\theta_0 = \theta_\ell; \varepsilon_\ell \approx 0)\).

Transforming equation (3) taking into account dependence (1), it was found that \( \theta \) affects the pressure \( p \) for the second stage of cold compaction (4) when the relative density changes from the initial values \( \theta_\ell \) \((p \approx 0)\) to the current \( \theta \)

\[
p = K \cdot \ln \theta_\ell - K \cdot \ln \theta = K \cdot \varepsilon_\ell - K \cdot \ln \theta = p_{\text{max}} - K \cdot \ln \theta,
\]

(4)

where \( p_{\text{max}}, \varepsilon_\ell = \ln \theta_\ell \) are the calculated values of the cold compaction pressure and the ultimate volumetric deformation, which ensure the production of a non-porous (compact) powder composite material \((\theta = 1)\), respectively.
Figure 1. 3D Spline model $\varepsilon_v(C_{SiC}, p)$ of the effect of SiC content and cold compaction pressure $p$ on the volumetric strain $\varepsilon_v$ of the Al-SiC composite material

In the general case, during compaction of a compressible porous body, the dependence $p(\varepsilon_v)$ is nonlinear. To establish the relationship between the pressure of unilateral compression $p$ and volumetric strain $\varepsilon_v$, Professor Reiner M. proposed nonlinear equations $p(\varepsilon_v)$ (5) and (6)

$$p = K \cdot \varepsilon_v \cdot \exp(\varepsilon_v),$$

(5)

$$p = K \cdot \frac{1 - \psi}{\exp(\varepsilon_v) - \psi} \cdot \varepsilon_v \cdot \exp(\varepsilon_v),$$

(6)

where $\psi$ is the coefficient of the limiting relative volume.

When studying the cold compaction of Al-SiC composite material for the entire compaction stage, taking into account the initial stage of lightweight structural compaction, the sigmoid equation $p(\varepsilon_v)$ was proposed (7)

$$p(\varepsilon_v) = a + \frac{b}{1 + \exp(-\frac{\varepsilon_v-c}{d})},$$

(7)

The values of volumetric strain $\varepsilon_v$ of the compressible powder material during cold compaction were determined taking into account the relative molding density $\theta_0$ in the bulk state ($p = 0$) according to formula (1). Cold compaction of the charge of the Al-Si composite material is characterized by a continuously sequential compaction – decompression – re-compaction process, depending on the Si
content [4]. Based on the results of experimental studies (table 1) for the stage of continuous compaction (0-140 MPa), we determined (table 2) the parameters \((a, b, c, d)\) of the sigmoid equation (7) and the determination coefficients \(r^2\) using the standard package Table Curve 2D.

| \(C_{\text{SiC}}, \text{ wt.\%}\) | The values of \(\varepsilon_v\) at the investigated pressure \(p, \text{ MPa}\) |
|-------------------------------|----------------------------------|
| \(p = 0\)                     | \(p = -47\)                     | \(p = -94\)                     | \(p = -140\)                     |
| 5                             | 0                               | -0.268                          | -0.347                          | -0.396                          |
| 10                            | 0                               | -0.320                          | -0.389                          | -0.447                          |
| 15                            | 0                               | -0.295                          | -0.373                          | -0.481                          |
| 20                            | 0                               | -0.257                          | -0.297                          | -0.350                          |

An analysis of the results (table 2) showed that the content of SiC powder affects the values of the coefficients \((a, b, c, d)\) of the sigmoid equation (7) of cold compaction of the charge of the Al-SiC composite material. Dependences \(c, d(C_{\text{SiC}})\) are described by linear equations (8), and \(a, b(C_{\text{SiC}})\) logistic \((\text{LgstcDoseRsp})\) (9) with increased values of the determination coefficient \(r^2\) (table 3).

An analysis of the effect of \(C_{\text{SiC}}\) on the mean size \(d_0\) of agglomerates formed during the mechanical activation of the Al-SiC mixture [4] showed that the dependence \(d_0(C_{\text{SiC}})\) can be described by logistic equation (10) with an increased value of the determination coefficient \((r^2 = 0.999)\)

\[
d_0(C_{\text{SiC}}) = 128 + \frac{325.5}{14(\frac{C_{\text{SiC}}}{10.5})^{0.74}}. \quad (10)
\]

The values of the parameter \(c_2\) (table 3, equation 10) represent the critical value of the silicon carbide content in the charge \((C_{\text{SiC}} = 10 \text{ wt.\%})\). Characterizing the transition to the formation of large agglomerates (~ 450 μm), as well as an abrupt change in the values of the parameters \(a, b\) (table 2) of the sigmoidal equation (7) of cold compaction of the Al-SiC composite material. It was shown in earlier work that when an optimal SiC content (10 wt.%) is introduced into an Al-based charge, extreme values...
of the parameters of the nonlinear model of particle size distribution of mechanically activated powder powders are observed [4, 25].

When describing the hot compaction of Al-SiC composite material by the linear model (3), we obtain the energy equation of compaction (11) taking into account the relative density of the cold-compacted molding $\theta$ and the hot-compacted workpiece $\theta_1$

$$ w = 0.5 \cdot K_1 \cdot \varepsilon_0^2 = 0.5 \cdot K_1 \cdot (\ln \theta - \ln \theta_1)^2, \quad (11) $$

where $w$ is the reduced (specific) work of hot compaction of a unit volume of a compact (non-porous) composite material, MJ/m$^3$;

$K_1$ - compressibility coefficient during hot compaction of the composite material.

Transforming equation (11) for a fixed value of the reduced work ($w = 130$ MJ/m$^3$), we obtain a linear (12) dependence $\theta_1(\theta)$ connecting the relative density values before ($\theta$) and after hot compaction ($\theta_1$) of composite material Al-SiC

$$ \theta_1 = \theta \cdot \exp \left( \frac{2w}{K_1} \right)^2. \quad (12) $$

Based on the analysis of the results of studies [4] of hot ($t = 823$ K; $\tau = 0,12$ ks; $w = 130$ MJ/m$^3$) compacting of the Al-SiC composite material (15 wt.%), we obtained linear regression equation $\theta_1(\theta)$ (13) with an increased determination coefficient ($r^2 = 0.984$) and the value of the compressibility coefficient ($K_1 = 2000$ MPa) was calculated

$$ \theta_1 = 1,433 \cdot \theta. \quad (13) $$

5. Conclusions

Based on the studies, a 3D Spline model of cold compaction of a mechanically activated mixture of Al-SiC composite material was constructed. A nonlinear sigmoidal model of the effect of cold compaction pressure on volumetric deformation is proposed. Logistic models of the coefficients of the sigmoidal equation of cold compaction and the average size of agglomerates formed during mechanical activation, depending on the content of silicon carbide in the mixture, are constructed.

An energy equation of compaction is obtained that describes the effect of volumetric deformation of a composite material on the reduced work of hot compaction. A linear model is constructed that relates the relative densities before and after hot compaction of the Al-SiC composite material for a fixed reduced (specific) work $w$.

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