SAND-SODIUM-SILICATE MIXTURES STRUCTURED
IN STEAM-MICROWAVE ENVIRONMENT EFFECTIVE VALUES
OF THERMO-PHYSICAL PROPERTIES

**Purpose.** Sand-sodium-silicate mixtures, structured by steam-microwave solidification, thermo-physical properties integral-effective values during Al-Mg alloy and graphite cast iron pouring determination. Sand-sodium-silicate mixture apparent density changing according to quartz sand, cladded with sodium silicate solute, fractional composition and its influence on BrA9Zh3L bronze microstructure establishment.

**Methodology.** Quartz sand with 0.23 mm average particle size, sodium silicate solute, aluminum alloy with 8.5 % Mg, flake graphite cast iron SCh200 (DSTU 8833:2019), bronze BrA9Zh3L (GOST 493-79) were used. Mixtures structuring was carried out in 700 W magnetron power microwave furnace. Sand-sodium-silicate mixture thermos-physics integral-effective values were calculated by G.A. Anisovich method, using castings results and molds thermography. Structured mixtures apparent density was determined on samples $50 \times 120$ mm dimension. Metallographic studies were realized using Neophot-21 optical microscope.

**Findings.** It was found that with sodium silicate solute, used for sand cladding, amount increasing from 0.5 to 3 % mold material apparent density decreases and thermal activity lowers. This leads to castings grains size increasing. Mixture sodium silicate solute content was recommended limiting 1.5 % for fine-grained microstructure castings obtaining and cladded sand using, which particles pass through mesh side less 0.315 mm sieve. Sands with sodium silicate solute content more than 1.5 %, which don’t pass through sieve 0.4 mm mesh side, were recommended as casting molds heat-insulating material using.

**Originality.** For the first time, when aluminum-magnesium alloy and graphite cast iron pouring, quartz sand cladded with sodium silicate solute in amount from 0.5 to 3.0 % (weight, over 100 % quartz sand), steam-microwave radiation structured, thermo-physical properties integral-effective values were determined.

**Practical value.** Data obtained using will improve castings solidification time and rate analytical calculations accuracy, forecast level and residual stresses sign in them, shrinkage defects locations. This will reduce casting technology developing time and costs and castings manufacturability.

**Keywords:** sand-sodium-silicate mixture, steam-microwave solidification, thermo-physical properties, mold, casting, microstructure

---

**Introduction.** Cast alloys mechanical and exploitation properties are structurally sensitive. That is, they depend both on alloy chemical composition [1] and on its solidification rate [2, 3]. Alloy solidification rate changing leads to its dendritic structure dispersion changing, its phase components distribution and morphology [4, 5], distance between dendrites secondary axes, quantity of secondary phases [6, 7], etc. All these changes, finally, have a corresponding influence on mechanical, technological and exploitation properties of the cast part.

Solidification rate of almost any casting is largely related to the level of molding and core mixtures thermo-physical properties [8]. These mixtures properties include: specific heat ($c_\text{p}$), thermal conductivity ($\lambda$), thermal diffusivity ($\alpha$), heat storage capacity ($b_\text{p}$) and specific density ($\rho$). These parameters have been widely used in analytical calculations and computer modeling of casting solidification processes [9, 10], in cast parts quality and material properties prediction [11, 12], etc. At the same time, such forecasts accuracy largely depends on adequacy of casting molds and cores material thermo-physical parameters used values.

At present, data on molds and cores materials thermo-physical parameters are fragmentary, approximate and, as a rule, unregulated. Such data using leads to significant discrepancies between predicted and actual (experimental) results. That is, such data using as information support for modeling systems is not only unreasonable, but also unacceptable.

**Literature review.** Any material thermo-physical properties feature is their dependence on temperature and, for granular materials, on material apparent density. As a result, under unsteady heat transferring conditions, continuous changing in these parameters consideration is possible only at mixtures thermo-physical properties locally-effective values presence and numerical calculation methods using.

Computation analytical methods give fundamental ideas about complex influence of molds and cores sands thermo-physical parameters on analyzed process, but only for castings of simple configuration (plate, sphere, cylinder, etc.).

For solidification duration and castings in molds cooling analytical calculations, mixtures thermo-physical properties integral-effective values have been used [13, 14]. At the same time, these parameters values are characteristics of mixture only under those solidification conditions and only the casting alloy that has been used in research.

This, in particular, has been evidenced by the data of work [15], given in Tables 1 and 2, for castings with different thicknesses ($\delta$) and with different crystallization temperatures of their material ($t_{cST}$).

Among above-mentioned thermo-physical parameters for casting in mold solidification duration determination is coefficient $b_2$, which A. I. Veinik (1960) calculates by the formula
Influence of iron casting thickness ($\delta$) on molding mixture thermo-physical properties

<table>
<thead>
<tr>
<th>$\delta$, mm</th>
<th>$\rho_s$, kg/m$^3$</th>
<th>$c_s$, J kg$^{-1}$ deg$^{-1}$</th>
<th>$\lambda_s$, W m$^{-1}$ deg$^{-1}$</th>
<th>$\rho_2$, kg/m$^3$</th>
<th>$\lambda_2$, W m$^{-1}$ deg$^{-1}$</th>
<th>$b_2$, W kg$^{-1}$ deg$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1700</td>
<td>992</td>
<td>1.100</td>
<td>0.400</td>
<td>1372</td>
<td>1320</td>
</tr>
<tr>
<td>20</td>
<td>1760</td>
<td>963</td>
<td>1.380</td>
<td>0.500</td>
<td>1450</td>
<td>1460</td>
</tr>
<tr>
<td>30</td>
<td>1720</td>
<td>1030</td>
<td>1.550</td>
<td>0.530</td>
<td>1660</td>
<td>1680</td>
</tr>
<tr>
<td>50</td>
<td>1670</td>
<td>1063</td>
<td>1.640</td>
<td>0.560</td>
<td>1708</td>
<td>1730</td>
</tr>
</tbody>
</table>

Molding mixture thermo-physical properties for aluminum, cast iron and steel castings

<table>
<thead>
<tr>
<th>Metal, alloy</th>
<th>$T_{crt}$, °C</th>
<th>$\rho_s$, kg/m$^3$</th>
<th>$c_s$, J kg$^{-1}$ deg$^{-1}$</th>
<th>$\lambda_s$, W m$^{-1}$ deg$^{-1}$</th>
<th>$\rho_2$, kg/m$^3$</th>
<th>$\lambda_2$, W m$^{-1}$ deg$^{-1}$</th>
<th>$b_2$, W kg$^{-1}$ deg$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>660</td>
<td>1400</td>
<td>1070</td>
<td>0.400</td>
<td>775</td>
<td>1320</td>
<td>1372</td>
</tr>
<tr>
<td>Cast Iron</td>
<td>1147</td>
<td>1400</td>
<td>1300</td>
<td>0.732</td>
<td>1157</td>
<td>1210</td>
<td>1140</td>
</tr>
<tr>
<td>Steel (C = 0.3 %)</td>
<td>1487</td>
<td>1400</td>
<td>1425</td>
<td>0.898</td>
<td>1340</td>
<td>1340</td>
<td></td>
</tr>
</tbody>
</table>

where $V_{CAST}$ - volume of casting; $F_{CAS}$ - contact area of casting with mold; $r$ - specific heat of metal (alloy) crystallization; $t_{crt}$ - metal (alloy) crystallization temperature; $\rho_1$ - density of casting solid metal (alloy); $t_M$ - mold initial temperature; $\tau_{SOL}$ - casting solidification time.

According to G. A. Anisovich (1960, 1979) data (2)

$$b_2 = \frac{V_{CAST}}{F_{CAS}} \cdot \frac{\rho_1 r}{(t_{crt} - t_M) \sqrt{\tau_{SOL}}},$$

(1)

$$q_{SOLH} = \frac{q_{OHEAT} + r + \frac{2}{3}(\theta_{SOL} - \theta_{ET})}{2n + 1}$$

(2)

where $q_{SOLH}$ - solidification heat; $n$ - parabola degree; $q_{OHEAT}$ - melt overheating heat; $c_1$ - specific heat of solid metal; $\theta_{SOL}$ - metal crystallization excess temperature; $\theta_{ET}$ - metal overheating excess temperature; $t_{OHT}$ - metal overheating temperature.

From formulas (1, 2) analysis it follows that casting solidification time is inversely proportional to $b_2$ square and (Tables 1 and 2) can vary within fairly wide range due, in particular, to structured mixture apparent density changes. That is, by structured mixture only apparent density changing, it is possible to significantly change the values of $\lambda_2$, $b_2$ and, accordingly, casting solidification time and rate.

Purpose/Problem statement. Currently, there are no data on integral-effective values of sand-sodium-silicate mixtures (SSSM), structured by of steam-microwave solidification process (SMS-process), thermo-physical properties. Therefore, studies aimed at determining them are relevant.
where \( m \) – mass of cladded mixture; \( V \) – volume occupied by cladded mixture.

BrA9Zh3L bronze samples microstructure investigations have been carried out on optical microscope Neophot-21 after their chemical etching in 0.5 % hydrochloric acid aqueous solution. For microstructure investigation, specimens of \( 16 \times 130 \) mm have been used, which have been poured into steel chill mold, as well as into SSSM structured according to SMS-process.

Specific heat of structured mixtures \( (c_2) \) has been calculated by formula

\[
c_2 = \frac{R_p r (n+1)}{2X_2p_g \sqrt{\lambda_{ET}}} \tag{3}
\]

where \( R \) – radius of casting; \( X_2 \) – depth of heat penetration into mold body; \( \rho_1 \) – alloy specific density in solid state; \( \lambda_{ET} \rightarrow \) metal overheating excess temperature.

Structured mixtures thermal conductivity has been calculated by formula

\[
\lambda_2 = \frac{R^2(n+2)}{4n \lambda_{ET}^2} \left[ \frac{n+2}{n+1} \right] \left[ \left( \frac{1}{n+2} \right) \left( \frac{\rho_1 r}{\rho_2 c_2 \lambda_{ET}} \right)^2 - 1 \right] \tag{4}
\]

Calculated value of integral-effective thermal conductivity coefficient has been used for temperature drop in casting determination, and correction has been carried out for values of \( \lambda_{ET} \) and \( r \) changing.

Coefficient of mold heat storage capacity \( (b_i) \) has been calculated by formula

\[
b_i = \frac{\lambda_2}{c_2 \rho_2}, \tag{5}
\]

and thermal diffusivity \( (a_2) \) has been calculated by formula, \( \text{m}^2/\text{s} \)

\[
a_2 = \frac{\lambda_2}{c_2 \rho_2}. \tag{6}
\]

Thermo-physical parameters values of alloys and their melts overheating during pouring into molds adopted for calculations are given in Table 3.

Results. In accordance with accepted research methodology, each cylindrical casting has been thermographed and temperature fields’ distributions in molds have been plotted by the time of their solidification completion. As an example, in Fig. 2, a shows thermogram of cylindrical casting made of Al + Mg alloy \( (8.5 \%) \) and temperature distribution in SSSM wall (Fig. 2, b), structured by SMS method with \( 3 \% \) SSS.

From thermogram (Fig. 2, a) it analysis follows that heat removal duration of superheat from melt into mold was \( \approx 40 \) s, melt undercooling value \( \approx 3 \) °C, alloy liquidus temperature \( t_L = 623 \) °C, solidus temperature \( t_S = 540 \) °C, solidification duration \( T_{SOFT} = 400 \) s, and mold heating depth \( X_2 = 0.047 \) m.

Using thermocouples readings and data on their distance from casting surface, temperature distribution curve in form has been built (Fig. 2, b). Mold working surface temperature values \( (t_{surf}) \) and depth of mold heating \( (X_2) \) have been determined from results of temperature distribution curve in the mold extrapolation.

Fig. 2. Thermogram of cylindrical casting made of Al + Mg alloy \( (8.5 \%) \) solidification \( (a) \) and temperature distribution in SSSM mold wall with \( 3 \% \) SSS, structured by SMS method \( (b) \)

Parabola degree \( (m) \) has been calculated as ratio of image area above \( (S_1) \) and below \( (S_2) \) temperature curve. Images areas have been determined from results of their planimetry.

Calculated and experimental parameters values, adopted for computation by formulas (3–6), of thermo-physical properties integral-effective characteristics for structured mixtures, when pouring Al + 8.5 % Mg alloy and gray cast iron SCh 200 into them, are given in Table 4.

Calculating results of structured mixtures thermo-physical properties integral-effective values are given in Tables 5 and 6. According to Tables 5 and 6 data, dependences \( E_a = f(m_{SSS}) \) (Fig. 3, a) and \( T_{SOFT} = f(m_{SSS}) \) (Fig. 3, b) for semi-infinite castings \( \varnothing 30 \) mm have been plotted.

Thermal conductivity and specific heat dependences on apparent density of casting molds material are shown in Fig. 4.

Molds integral-effective thermal diffusivity and heat storage capacity dependences on apparent density of its material are shown in Fig. 5.

Mold material heat storage capacity integral-effective coefficient dependences on mass of SSS (mSSS) used for cladding are shown in Fig. 6, a. Semi-infinite cylindrical casting \( \varnothing 30 \) mm solidification duration dependences on mold material heat storage capacity coefficient value are shown in Fig. 6, b.
Curves of dependences $\tau_{SOL} = f(b_2)$, shows in Fig. 6, $b$. Plots in Fig. 6, $b$ analysis shows that both functions agree with formula (2) in terms of casting solidification duration dependence on $b_2$ value.

Let us represent formula (2) in following form

$$
\tau_{SOL} = R \left( \frac{R}{b_2} \right)^2;
$$

(7)

Using formula (7) at $B = 84 \cdot 10^{10} (W \cdot s^2)/(m^4 \cdot \text{deg})$ for aluminum alloy and $B = 10^3 \cdot 10^{10} (W \cdot s^2)/(m^4 \cdot \text{deg})$ for gray cast iron with relative error no more than 5%, solidification time of semi-infinite cylindrical casting in SSSM, structured by SMS-process, can be calculated. It has been evidenced by Table 7 data, which shows error ($\Delta t$) values between calculated and experimental values of castings solidification duration.

For data obtained practical using, most acceptable is dependence of structured molding mixture solidification time on specific gravity, shown in Fig. 7, $a$.

### Table 4

<table>
<thead>
<tr>
<th>$m_{SSS}$, % (weight)</th>
<th>$\tau_{SOL}$, s</th>
<th>$X_2$, m</th>
<th>$n$</th>
<th>$t_{OFF}$, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting from alloy Al + 8.5 % Mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>195</td>
<td>0.028</td>
<td>2.9</td>
<td>511</td>
</tr>
<tr>
<td>1.5</td>
<td>280</td>
<td>0.036</td>
<td>3.0</td>
<td>507</td>
</tr>
<tr>
<td>3.0</td>
<td>400</td>
<td>0.047</td>
<td>3.4</td>
<td>487</td>
</tr>
<tr>
<td>Casting from gray cast iron SCh 200</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>137</td>
<td>0.029</td>
<td>3</td>
<td>965</td>
</tr>
<tr>
<td>1.5</td>
<td>215</td>
<td>0.04</td>
<td>3.3</td>
<td>960</td>
</tr>
<tr>
<td>3.0</td>
<td>317</td>
<td>0.05</td>
<td>3.5</td>
<td>950</td>
</tr>
</tbody>
</table>

### Table 5

Thermo-physical properties integral-effective values of structured mixtures, when pouring Al + 8.5 % Mg alloy into them

<table>
<thead>
<tr>
<th>$m_{SSS}$, % (weight)</th>
<th>$\rho_2$, kg/m$^3$</th>
<th>$c_2$, J/kg·deg</th>
<th>$\lambda_2$, W/m·deg</th>
<th>$a_2 \cdot 10^5$, m$^2$/s</th>
<th>$b_2$, W·s$^{0.5}$/m$^2$·deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1758</td>
<td>1047</td>
<td>0.526</td>
<td>0.286</td>
<td>984</td>
</tr>
<tr>
<td>1.5</td>
<td>1503</td>
<td>923</td>
<td>0.465</td>
<td>0.335</td>
<td>803</td>
</tr>
<tr>
<td>3.0</td>
<td>1380</td>
<td>848</td>
<td>0.414</td>
<td>0.353</td>
<td>696</td>
</tr>
</tbody>
</table>

### Table 6

Thermo-physical properties integral-effective values of structured mixtures, when pouring gray cast iron SCh 200 into them

<table>
<thead>
<tr>
<th>$m_{SSS}$, % (weight)</th>
<th>$\rho_2$, kg/m$^3$</th>
<th>$c_2$, J/kg·deg</th>
<th>$\lambda_2$, W/m·deg</th>
<th>$a_2 \cdot 10^5$, m$^2$/s</th>
<th>$b_2$, W·s$^{0.5}$/m$^2$·deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1758</td>
<td>1220</td>
<td>0.801</td>
<td>0.373</td>
<td>1311</td>
</tr>
<tr>
<td>1.5</td>
<td>1503</td>
<td>1037</td>
<td>0.689</td>
<td>0.442</td>
<td>1036</td>
</tr>
<tr>
<td>3.0</td>
<td>1380</td>
<td>902</td>
<td>0.605</td>
<td>0.486</td>
<td>868</td>
</tr>
</tbody>
</table>

### Fig. 3

Dependences of $\rho_2$ (a) and $\tau_{SOL}$ (b) on SSS mass used for quartz sand cladding:
1 – castings from alloy Al + 8.5 % Mg; 2 – castings from gray cast iron SCh 200

### Fig. 4

Dependences of $\lambda_2$ (a) and $c_2$ (b) on structured mixture apparent density:
1 – castings from alloy Al + 8.5 % Mg; 2 – castings from gray cast iron SCh 200

It should be taken into account that structured SSSM by SMS method apparent density value also depends on cladded sand particles conglomerates size (dPCS), as evidenced by dependence in Fig. 7, $b$.

Dependence in Fig. 7, $b$ analysis shows that, with pure sand apparent density of 1642 kg/m$^3$, sand-sodium-silicate conglomerates size increasing from 0.1 to 0.8 mm leads to structured mixture apparent density in 2-time decreasing – from ~1610 to ~810 kg/m$^3$. Accordingly, such changes will lead to change in thermo-physical properties of structured mixture. That is, by SSS mass changing in cladded sand or using different sand-sodium-silicate mixture conglomerates fractions, it...
is possible to predictably change casting solidification time and, accordingly, alloy structure. This, in particular, is evidenced by microstructures of BrA9Zh3L bronze castings, prepared in various molds, and presented in Fig. 8, and by data in Table 8.

Conclusions. For the first time, the thermo-physical properties integral-effective values of quartz sand cladded with sodium silicate solute in amount of 0.5 to 3.0 % (by weight, in excess of 100 % quartz sand) and structured by SMS method when pouring aluminum-magnesium alloy and gray cast iron into it have been determined.

<table>
<thead>
<tr>
<th>Casting mold</th>
<th>Steel chill mold</th>
<th>SSSM, structured by SMS-process with weight SSS content</th>
</tr>
</thead>
<tbody>
<tr>
<td>D, µm</td>
<td>0.12</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 8
Average micrograin size in samples Ø18 × 100 mm made of BrA9Zh3L bronze cast into various molds.
Using bronze castings example contained 9 % Al and 3 % Fe, it has been found that sodium silicate solute amount for quartz sand cladding increasing from 0.5 to 3 % leads to castings material microstratum size increasing approximately in ~2.0 times. This regularity is due to intensity of heat removal from solidifying casting into mold decreasing, as evidenced by mixture heat storage capacity value decreasing with amount of silicon silicate solute used for cladding increasing.

To obtain castings with fine-grained structure, SSS content in cladded quartz sand should not exceed 1.5 %, and clad sand should pass through sieve with mesh of up to 0.315 mm. Sands with cladding sodium silicate solute content more than 1.5 % and with conglomerate size more than 0.4 mm can be used for casting molds heat-insulating elements manufacturing.

When creating refractory heat-insulating materials, it should not be more preferable so much reduce their thermal conductivity integral-effective coefficient, but to decrease their heat storage capacity integral-effective coefficient.

References.