Hybrid technology for manufacturing lightweight products with a cellular structure made of aluminum alloys

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Abstract. This article is devoted to one of the new directions of creating and obtaining porous materials. The cellular material part is a new element that provides high specific strength of the structure in combination with low density. An urgent task is to develop and obtain a cellular structure with optimal geometric parameters to ensure maximum manufacturability of the structure. The obtained data can be used in the development of technological processes of hybrid casting technologies, as well as for the manufacture of new lightweight parts with increased specific strength characteristics.

Keywords: hybrid technology, cellular material, aluminum alloys, die casting, FDM technology, investment casting

1. Introduction

Increasing the efficiency and reliability of aircraft is inextricably linked with the possibility of reducing the weight of the structure while maintaining or even increasing the strength. The solution of problems in this direction is associated with the development of new types of lightweight structures.

The cellular material part is a new element that provides high specific strength of the structure in combination with low density.

An urgent task is to develop and obtain a cellular structure with optimal geometric parameters to ensure maximum manufacturability of the structure.

Parts with a uniform cellular structure have been manufactured using the technology of direct laser sintering of metal powder, the advantages of which are providing higher accuracy and porosity of the product, manufacturing parts of complex geometry with thin walls (less than 2 mm) [6]. The main drawback is the inability to obtain a monolithic product, which means that it is not possible to provide the strength corresponding to cast copies.

The introduction of new hybrid technologies (additive + foundry) into production allows us to fulfill this task.

The technology consists in creating a burnable plastic model using FDM printing and then pouring the gypsum mold with molten metal using vacuum suction with solidification under pressure in a special filling chamber.
By casting using a burnt-out plastic model, a material with a given adjustable cellular structure of a metal product with a given strength and rigidity is obtained. The cast material will provide an extended service life, increased reliability, specific strength and energy efficiency of the part. In addition, the cost of production will be significantly reduced in comparison with foreign analogues.

2. Mathematical model for calculating the filling of a gypsum molds

The filling capacity of the mold is an important factor that ensures the production of a suitable casting using a thin-walled casting mold. The reproduction of the internal cavity of the mold is determined by sufficient cooling of the flow front during the casting process. The cooling of the flow front is a function of the filling rate, the filling mode, the material properties of the mold surface and the geometry of the mold cavity.

The optimal speed of filling the mold is affected by the cooling of the flow front by the previously listed factors.

Gypsum and ceramic molds have a relatively low thermal conductivity and sufficient gas permeability, which makes it possible to obtain thin-walled (up to 3 mm thick) castings with complex configuration. Casting in gypsum or ceramic molds ensures high accuracy and cleanliness of the surface.

Generalization of the research results [1, 4] allowed us to formulate a mathematical model (1) of the filling capacity of the gypsum mold.

$$
Y = \frac{cp}{a} \omega \left( 1 + \frac{b_m}{b_f} \right) \ln \frac{T_z - T_f}{T_l - T_f},
$$

- \(c\) – heat capacity, J/(kg·K);
- \(p\) – density, kg/m³;
- \(l_0\) – the reduced jet size, m;
- \(\alpha\) – the heat transfer coefficient, W/m²·K;
- \(\omega\) – the average flow rate of the metal, m/s;
- \(b_f\) and \(b_m\) – the heat storage capacity of the mold and metal, W·s^{1/2} / m²·K;
- \(T_z\) – the casting temperature of the alloy;
- \(T_l\) – liquidus temperature;
- \(T_f\) – the initial temperature of the mold.

To assess the adequacy of the obtained theoretical solution, an experimental test was carried out. The heat transfer coefficients of the mold were determined using the stretched thermocouple method. The filling was carried out in special plaster molds. The filling rate of the mold cavity was regulated by a measuring hole in the bowl (diameter 4 mm; 6 mm; 8 mm; and 10 mm). The filling rate varied in the range (0.02 – 0.13) m/s. The molds were dried in air at a temperature of (20-25) ºC for a day, then calcined at a temperature of (200-250) ºC for (20-24) hours. The filling temperature was 677 ºC. The method of a stretched thermocouple was used to measure the temperature of the flow front. [2]

The results of experiments are shown in Table 1.

| Head height, N, m | Hole diameter, d, m | Speed, \(\omega\), m/s | Heat transfer coefficient, \(\alpha\), W/m²·K | \(Nu_{80k}\) | \(Pe_{80k}\) |
|------------------|---------------------|---------------------|---------------------------------|----------|----------|
| 0.07             | 0.004               | 0.022               | 8316                            | 0.2      | 1.5      |
| 0.07             | 0.006               | 0.05                | 8999.6                          | 0.22     | 3.4      |
| 0.07             | 0.008               | 0.09                | 10308.6                         | 0.25     | 6.2      |
| 0.07             | 0.01                | 0.13                | 12284.4                         | 0.3      | 9.0      |

The \(Nu–Pe\) dependence for the lower metal supply (2) was obtained using the experimental data obtained and the application "Statistica 6.0":

$$
Nu_{80k} = 0.173 \cdot Pe_{80k}^{0.23}, \quad Pe_{80k} \leq 10, \quad R = 0.95
$$

(2)
A comparison of the calculated and experimental values of the parameters is shown in Figure 1.

![Graph showing comparison of calculated and experimental values of the Nusselt numbers](image-url)

**Figure 1.** Comparison of calculated and experimental values of the Nusselt numbers

The analysis of the obtained data shows that the proposed similarity equation significantly adequately describes the process of heat exchange between the metal flow front and the mold surface, therefore, a mathematical model can be recommended to describe the process of filling the cavity of gypsum and ceramic molds with a lower metal supply to determine the temperature of the flow front.

The developed mathematical model allows determining the dimensions of the gating system.

3. **Calculation of the filling of a gypsum mold with thin cavities**

To determine the heat transfer coefficients and the fillability of thin walls with a thickness of 2 mm and 4 mm with aluminum alloy AISi 12, the fillability of the sand-gypsum mold was calculated for $T_f = 20 \, ^\circ C$ and $T_f = 200 \, ^\circ C$.

The simulation results showed that heating the gypsum mold to a temperature of $200 \, ^\circ C$ increased the occupancy of the plate cavity with a thickness of 2 mm by 28.5 %.

The numerical values of the calculated and experimental data are summarized in Table 2.

**Table 2.** Comparison of experimental and calculated values of the height of castings samples.

| Aluminum alloy | $T_z, ^\circ C$ | $T_f, ^\circ C$ | Thickness of the plates, mm | Experimental height, mm | Calculated height, mm |
|----------------|----------------|----------------|-----------------------------|------------------------|-----------------------|
| AISi 12        | 677            | 20            | 2                           | 63.251                 | 62                    |
|                |                | 200           | 4                           | 212.798                | 210                   |
|                |                | 2             | 88.402                      | 87                     | 87                    |
|                |                | 4             | 293.922                     | 297                    | 297                   |

The analysis of the obtained data shows a good coincidence of the calculated and experimental values of the height of the filled cavities of the plate-type casting. It proves the adequacy of the theoretical solutions.
Modeling of the process of filling and solidification of castings in the LVM Flow 3D software package using experimental results made it possible to assess the filling capacity of a 2 mm thick plate-type casting cavity in a gypsum molds calcined to 200 °C in a vacuum from 0.2 atm to 2.0 atm.

The results of modeling the casting filling process under low pressure are summarized in Table 3.

**Table 3.** Peight of samples solidified under pressure.

| Aluminum alloy | Tz, ºC | Tf, ºC | Vacuum, atm | Experimental height, mm |
|---------------|--------|--------|-------------|-------------------------|
| AISi 12       | 677    | 200    | 0.2         | 97.24                   |
|               |        |        | 0.4         | 106.08                  |
|               |        |        | 0.7         | 113.21                  |
|               |        |        | 0.9         | 132.60                  |
|               |        |        | 2.0         | 300.0                   |

The simulation results showed that casting at a low pressure of 2.0 atm into a gypsum mold heated to a temperature of 200 °C filled a plate cavity with a thickness of 2 mm.

4. **Influence of geometric parameters of the cellular structure on the mechanical properties of the structure**

4.1. **Static calculation for structures made of aluminum material with different geometric cellular structure**

The properties of porous materials depend on both the volume and the structure of the porous space. The most preferred method for assessing the influence of the shape of the cellular structure on the strength of the material is the direct modeling method. This method is based on considering the matrix material as a continuous medium and does not take into account structural defects. [3, 5]

The parameters of the sample models are presented in Table 4.

**Table 4.** Characteristics of sample models with different geometric cellular structures.

| Without cellular structure | Square | Circle | A hexagon. The load is applied to the face | A hexagon. The load is applied to the corner |
|----------------------------|--------|--------|------------------------------------------|------------------------------------------|
| Wall thickness, mm         | -      | -      | 2.5                                      | 2.5                                       |
| Cell size, mm              | -      | -      | 5.0                                      | 5.0                                       |
| Sample dimensions, mm      | -      | -      | 55x16x10                                 | 55x16x10                                 |
| Sample material            | AISi7  | AISi7  | AISi7                                    | AISi7                                    |
| Sample weight, kg          | 23.76  | 16.93  | 17.93                                    | 17.93                                    |
| Sample surface area, mm²   | 3180   | 5054.25| 4476                                     | 4476                                     |
| Sample volume, mm³         | 8800   | 6271   | 6640                                     | 6640                                     |
| Estimated porosity, %      | 0      | 28.75  | 24.54                                    | 22.14                                    |

The mechanical characteristics of the samples after a pressure of 1 MPa are presented in Table 5.
Table 5. Mechanical characteristics of sample models with different geometric cellular structures.

| Without cellular structure | Equivalent voltage according to Mises, MPa | Linear displacement, mm | Turnover margin ratio | Safety margin factor |
|----------------------------|---------------------------------------------|-------------------------|----------------------|---------------------|
|                            | Min 0.07  Max 12.7                          | Min 0  Max 0.0007       | 10                   | Min 0.07  Max 12.7  |
| Square                     | Min 0.194  Max 34                           | Min 0  Max 0.0024       | Min 0.07  Max 12.7   | 10                   |
| Circle                     | Min 0.233  Max 13.7                         | Min 0  Max 0.0012       | Min 7.5  Max 10      | Min 9.7  Max 10     |

A hexagon. The load is applied to the face

A hexagon. The load is applied to the corner

The static calculation is performed both for the object as a whole and for each point of its arbitrary cross-section. The calculation results are presented in the form of various isosurfaces.

The stresses on deformed samples with a cellular structure of different geometries after simulation of mechanical tests are shown in Figure 2.

![Figure 2. Iso stress regions on deformed samples with a cellular structure of different geometries after simulation of mechanical tests.](image)
Based on the obtained results of the simulation of mechanical tests, the advantages of an aluminum block with a hexagonal cellular structure is that it has the highest degree of shock absorption. There are the smallest minimum equivalent stresses according to Mises in the fixed plane.

4.2. Strength characteristics of an aluminum alloy with multi-dimensional honeycomb cellular structures

Compression and shear tests were carried out to determine the influence of the size of the hexagonal shape of the cells (honeycombs) on the strength characteristics of the material. The test samples are made of aluminum alloy AW-5052.

The test results are shown in the Table 6.

**Table 6.** Determination of strength characteristics of aluminum material AW-5052 with a multi-dimensional cellular structure.

| Cell size, mm | Sample density, kg/m³ | Compressive strength, MPa | Shear strength in the plane in the Length-direction, MPa | Shear strength in the plane in the Wight direction, MPa |
|---------------|------------------------|----------------------------|--------------------------------------------------------|-------------------------------------------------------|
| 4.77±0.48     | 507±5.1                | 65.8                       | 30.9                                                    | 16.9                                                  |
| 6.35±0.64     | 127±12                 | 67.4                       | 32.1                                                    | 19.1                                                  |
| 9.52±0.95     | 37±3.7                 | 66.6                       | 31.5                                                    | 18.0                                                  |
|               |                        | 7.17                       | 4.43                                                    | 2.74                                                  |
| 11.21±1.12    | 25±2.5                 | 0.897                      | 0.691                                                   | 0.355                                                  |

The smaller the cell size, the higher the value of the compressive strength and when the material is shifted in different directions.

The specific strength is the ratio of the average value of the tensile strength of a cellular structure of the same size to the density of the test sample. The results of calculations of the specific strength characteristics of samples made of aluminum material are summarized in Table 7.

**Table 7.** The results of calculations of the specific strength characteristics of samples made of aluminum material.

| Cell size, mm | Specific compressive strength, MPa | Specific shear strength in the plane in the Length-direction, MPa | Specific shear strength in the plane in the Wight direction, MPa |
|---------------|------------------------------------|------------------------------------------------------------------|---------------------------------------------------------------|
| without cellular structure | 0.063 | 0.04 | 0.04 |
| 4.77±0.48     | 0.13 | 0.06 | 0.036 |
| 6.35±0.64     | 0.058 | 0.035 | 0.021 |
| 9.52±0.95     | 0.024 | 0.019 | 0.011 |
| 11.21±1.12    | 0.021 | 0.011 | 0.005 |
Analysis of the calculation results shows that a structure made of aluminum material with a cell size (4.77±0.48) mm will be 51.5% stronger than a cell-free structure.

5. Conclusion
The control of the hydrodynamic parameters of the metal flow allows filling the mold with minimal heat loss, especially for complex thin-walled large-sized castings. The form occupancy rate increases by 1.3-1.5 times. The simulation results showed that casting at a low pressure of 2.0 atm into a gypsum mold heated to a temperature of 200 °C filled a plate cavity with a thickness of 2 mm.

The results of the study of the influence of geometric parameters of the cellular structure on the mechanical properties of the structure:
1. During calculating the mechanical properties of aluminum samples with cells of different geometries, the hexagonal type of cells showed the highest strength characteristics compared to the round and square types of cells with a porosity of about 25%.
2. To assess the strength characteristics, tests were carried out on samples made of aluminum alloy (AISi9) with multi-dimensional cells. Samples with cells with a diameter of 5 mm have the maximum specific strength.

The cast cellular material will provide an extended service life, increased reliability, specific strength and energy efficiency of the part. In addition, the cost of production will be significantly reduced in comparison with foreign analogues.

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