Polymer composite material for the manufacture of molds in the production of evaporative patterns

Vladimir Sharshin, Denis Sukhorukov and Elena Sukhorukova
Vladimir State University named after Alexander and Nikolay Stoletovs, 87 Gorky Street, Vladimir, 600000, Russian Federation

Email: info@inlittech.ru

Abstract. The results of research on the development of a polymer composite material from a two-component polyurethane compound for the manufacture of foundry equipment for the production of gasified models and other products from expanded polystyrene by blowing with hot steam are presented. The requirements for the material of the molds in terms of heat capacity and thermal conductivity are indicated. Selected additives in the form of powders of copper, aluminum, iron and graphite. Samples of polymer composite materials were obtained. The research were carried out according to a specially developed technique based on the well-known method for determining thermophysical properties by eliminating variables. The result is a composition based on a polyurethane compound with 54.5 wt.% aluminum powder, meeting the specified requirements for both technological and thermophysical properties.

1. Introduction
One of the promising and most actively developing foundry technologies is lost foam casting [1-3]. This method has been successfully used for the manufacture of castings of any complexity category from all types of alloys into one-piece sand forms and therefore is one of the most economical [4-6]. Moreover, the maximum effect from the application of this method is achieved in the manufacture of castings with a complex branched surface, numerous deep undercuts and reverse slopes in the absence of a pronounced surface of the mold [7-9]. However, the use of this technology in a single and small-scale castings production is significantly limited due to the high complexity and, therefore, the high cost of manufacturing the equipment for lost foam patterns [10, 11].

Polymer compounds are widely used in the manufacture of technological foundry equipment for casting into single forms from sand and cold-hardening mixtures. The reason for this is the low cost of molds (in comparison with metal), high strength and hardness, good machinability of the material. Polymer foundry equipment has a resistance of up to 6-10 thousand shots, depending on the molding conditions. Polyurethane compounds have high fluidity and form filling ability. This allows to compete confidently with wood and metal in terms of price-quality-durability.

However, the quality of expanded polystyrene patterns obtained in polyurethane molds does not always meet the modern requirements [12]. This is due to the thermal conditions of the pattern formation, which depend on the thermo-physical properties of the material of equipment. Based on the analysis of literature data on the production technology of polystyrene foam patterns in molds from various materials [13-18], the requirements on the thermo-physical properties of the mold material were established. The heat capacity of the mold wall material should be no more than 1200 J/(kg · °C); thermal conductivity – not less than 0.21 W/(m · °C). Moreover, the heat capacity of known polyurethanes suitable for the manufacture of molds is more than 1380 J/(kg · K), the thermal conductivity is 0.19–0.03 W/(m · °C).

The aim of this work is to develop a cast polymer composite material with predetermined thermo-physical properties for the production of lost foam patterns or other products from expanded polystyrene.
The basis for obtaining lost foam patterns is the thermal treatment of polystyrene granules with hot water or hot steam. The low intensity of steam filtration through rapidly expanding polystyrene granules cannot provide continuous and long-term heat supply to all peripheral cavities of the forming pattern. Therefore, to achieve the required surface quality of the patterns, it is necessary to create conditions for the most efficient heat transfer from steam to the inner surface of the mold walls at the initial stage of purging and rapid heating of the surface layer of the working part of the pattern equipment. This can be achieved only with a small heat absorption of its inner layers. For this, the mold material must have a relatively high thermal diffusivity, thermal conductivity and low heat capacity. The specified conditions are fully met by metal molds, which are currently used to obtain lost foam patterns [19]. Polyurethanes obtained by casting from two-component compounds (the so-called cast polyurethanes), on the contrary, have low thermal conductivity (0.01-0.6 W/m · K) and a sufficiently high heat capacity (about 2000 J/kg · K). In other words, they do not conduct heat well and heat up for a very long time.

To achieve the required thermo-physical properties, polymer composite materials based on cast polyurethane were used. For this, the structure of the initial polyurethane was modified with reinforcing additives at the stage of compound preparation. Metal powders (aluminum, iron, copper) and graphite with particles of various fractions were used as reinforcement. Powders were selected based on information on their thermo-physical properties [20]. The amount and fractions of the powders was determined based on their ability to influence the thermo-physical properties of polyurethane. In the process of preparing polymer composite materials, their technological properties were controlled. The resulting liquid suspensions should have survivability (at least 10-20 minutes), fluidity and the ability to clearly reproduce the surface topography of the equipment.

This paper presents the results of studies of the basic thermo-physical characteristics of polyurethane and polymer composite materials based on it, intended for the manufacture of tooling elements for lost foam patterns.

2. Methods
The studies were carried out according to a specially developed technique. The essence of this technique consists in the controlled heating of the test sample with an average size of 70x70 mm and 25 mm thick, placed in a thermostat, according to the heat stroke scheme from a copper ingot preheated to 120 °C with simultaneous recording of the dynamics of temperature changes in the sample cross section according to the thermocouples. This ingot with known thermo-physical properties simulated in the experiment the steam supply process in the manufacture of lost foam patterns by the method of internal thermal shock. Thermocouple readings in the form of temperature field graphs were recorded on a personal computer and then were processed.

3. Results and Discussion
The duration of the experiments was determined by the time before the heating of the test sample to a depth of 15 mm from the plane of contact from the changes in the readings of the thermocouple located here. The size of 15 mm corresponds to the average wall thickness of metal molds used for the manufacture of foundry models. In the experiment, chromel-alumel thermocouples with an electrode diameter of 0.5 mm were used, connected to a PC through the KONTEL K1220-2.5 controller and a normalizing temperature converter NPT 1.2A, with a measurement range of 0-200 °C. Thermocouple readings in the form of temperature field graphs were recorded on a personal computer and then processed.

Figure 1 shows the dynamics of changes in the temperature of the ingot and the sample from ADV 13-2 polyurethane, as well as its temperature field at the time of completion of heating to a depth of 15 mm. Similar plots were obtained for all samples participating in the experiment. The construction of temperature fields was carried out using the KOMPAS-3D V12 software.

The type, quantity and thermo-physical properties of the additives are presented in Table 1. The number of additives, in percent by weight, was determined experimentally. It corresponds to the
maximum possible amount of reinforcement, at which pouring of the composition is possible, without significant (no more than 50%) fluidity loss.

**Table 1.** Characterization of reinforcing additives for the manufacture of polymer composites based on polyurethane

| Material Designation (brand) | copper | carbon | aluminum | iron |
|-----------------------------|--------|--------|----------|------|
| Sample No.                  | PMS-1  | GSM-1  | APS-2    | PAP-1|
| Size, mm                    | 2      | 3      | 4        | 5    |
| Amount of additive, % by weight | 71.1  | 27.4   | 33.4     | 54.5 |
| Specific heat, kJ/kg · °C   | 0.39   | 0.72   | 0.93     | 0.44 |
| Thermal conductivity, W/m·K | 401    | 500    | 210      | 92   |

Figure 1 shows the obtained results of studies in the form of temperature curves near the contact surface with the heater (a – 2 mm from the surface), inside the samples (b – 10 mm from the surface), at the periphery (c – 15 mm from the surface).

**Figure 1.** The nature of the temperature distribution in samples made on the basis of the ADV 13-2 polyurethane compound with the addition of: 1 – without additives; 2 – 71.1% of the mass of PMS-1; 3 – 27.4% of the mass of fuels and lubricants-1; 4 – 33.4% of the mass of APS-2; 5 – 54.5% of the mass of PAP-1; 6 – 77.4% of the mass of DSL 08; 7 – 43.8% of the mass of P-10; a – 2 mm from the surface; b – 10 mm from the surface; c – 15 mm from the surface.
According to the data obtained, the initial polyurethane is slowly heated from the surface and slowly transfers heat to the inside. Copper powder additives reduce the heating rate of the surface layer due to a more uniform temperature distribution throughout the sample and more heating of the inner layers. PAP-1 aluminum additives maximize the heating rate of both the surface layer and the entire sample over the cross section, especially at the initial stage (first 10-15 seconds). This is close to the time of manufacture of lost foam patterns in metal molds (10-20 seconds, depending on the wall thickness).

According to the data presented in Fig. 1 (c), the sample from the initial polyurethane heated longer than the others to a depth of 15 mm, specifically, 71.4 seconds. The shortest heating time is for the sample with the addition of 54.5 wt.% of aluminum powder PAP-1 – 14.1 seconds. The remaining samples heated faster than the original polymer, but much more slowly than that with aluminum powder.

As a result of the research, the thermo-physical properties of the pure polyurethane compound ADV-13-2, as well as polymer composite materials based on it with the addition of powder materials (aluminum, iron, graphite, copper) were determined.

Table 2 presents the obtained values of the main thermo-physical characteristics of the studied samples.

| Material | Designation (brand) | without additives | copper | carbon | aluminum | iron |
|----------|---------------------|-------------------|--------|--------|----------|------|
| Sample No. | ADV 13-2 | GSM-1 | APS-2 | PAP-1 | DSL-08 | R-10 | GSM-1 |
| Amount of additive, % by weight | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Heat storage capacity W/(m²·K) | 0 | 71.1 | 27.4 | 33.4 | 54.5 | 77.4 | 43.8 |
| Heat capacity, J/(kg·K) | 697.4 | 715.7 | 708.3 | 696.2 | 697.0 | 702.8 | 706.7 |
| Thermal conductivity, W/(m·K) | 2086.1 | 1218.6 | 1664.1 | 2088.3 | 1040.4 | 591.3 | 1196.9 |
| Thermal diffusivity, (m²/s)·10⁻⁸ | 0.18 | 0.14 | 0.21 | 0.15 | 0.27 | 0.24 | 0.21 |

From the data presented it follows that the aluminum powder PAP-1 and steel shot DSL 08 most significantly increase the thermal conductivity and thermal conductivity (heating rate) of polymer composite materials and at the same time significantly reduce the heat capacity, the least significant is the addition of aluminum clumped powder APS-2 and graphite GSM-1. Moreover, samples with aluminum powder showed the highest values of thermal conductivity and thermal diffusivity. Values of heat storage capacity after the introduction of additives changed slightly.

Thus, it is shown that it is possible in principle to affect the basic thermo-physical characteristics (heat capacity, thermal conductivity, thermal diffusivity) of polyurethane compounds by introducing additives in the form of particles of metals and nonmetals into its composition. As a result of the analysis of the obtained experimental data, it was established that the greatest influence on the complex of the thermo-physical properties of polymer composites was made by the addition of aluminum powder PAP-1. In addition, samples with PAP-1 aluminum powder showed higher values of technological properties: fluidity and mold filling ability.

The obtained values of heat capacity – 1040.4 J/(kg·K) and thermal conductivity – 0.27 W/(m·K) of the polymer composite material with 54.5% aluminum powder completely correspond to the above requirements for the material of the molds for the manufacture of products from foamed polystyrene.

As a result, this composition was successfully used in the manufacture of polymer molds for the production of lost foam patterns. Photos of the mold and the patterns obtained in it are shown in Fig. 2.
Figure 2. The mold and the lost foam pattern “Ball Valve ¾” obtained therein: a – mold for the production of gasified models made of expanded polystyrene, material: polyurethane compound ADV 13-2 with the addition of 54.5% PAP-1 aluminum powder; b – patterns of foamed polystyrene with a size of the initial granules of 0.1 mm, made by internal thermal shock at a vapor pressure of 0.26-0.29 MPa.

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