The influence of thermophysical conditions on the formation of wax models in moulds from polymer composite materials

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Abstract. Investment casting has always been referred to as mass casting. This circumstance is associated with the high cost of moulds. The paper deals with materials from polymer composite materials for the manufacture of moulds. Investigations of thermophysical properties of polymer composites under cyclic loads under heating-cooling conditions have been performed. The results obtained have been implemented in real industrial production and can be used for one-off production with a significant reduction in the cost of tooling and, as a consequence, castings.

1. Introduction

Lost wax and lost foam casting is used to make castings from all known casting alloys weighing from several grams to hundreds of kilograms, with a wall thickness of several tenths of a millimetre or more, with high precision and surface quality [1-4]. For this reason, the investment casting process is widely used all over the world, not only for the manufacture of mechanical engineering parts of increased complexity but also for the production of jewellery and art products. In addition, complex overall thin-walled structures with developed labyrinth cavities, which are not performed by other methods of machining or casting, are made by investment casting [5-7].

High precision and surface quality of castings are ensured by a higher quality of lost-wax models, which in mechanical engineering are made from pasty or liquid wax compositions by casting under high pressure (pressing) into metal or polymer moulds [8].

There are significant requirements for moulds for the production of investment models, the most important of which, in addition to surface quality, are:

• manufacturability of shaping elements, which determines the duration of manufacture and the cost of the mould;
• high intensity of heat removal from the solidifying model to the mould, determined by the thermophysical properties of the tooling material: the heat capacity of the mould wall material <1200 J/(kg°C); thermal conductivity ≥0.21 W/(m°C); thermal diffusivity ≥ 8.4 10^-8 m^2/s.
• ease of use when pressing in a model composition and extracting finished models;
• wear resistance, resistance to thermal cycling;
• the cost of equipment.

Metallic moulds made of steel, aluminium, or zinc alloys by traditional metalworking methods with the use of special technologies for the formation of internal cavities: electroforming, electroerosive processing methods, etc., meet the above requirements most fully [9]. However, the use of metal moulds is economically justified mainly for large-scale mass production of castings. In the conditions of the
prevailing production of castings in small batches today, the production of metal moulds becomes ineffective due to the low manufacturability of manufacturing the forming elements of the tooling, significant labour intensity, and cost of the mould.

Currently, due to the appearance of a significant number of new polymer materials, the model production of the foundry industry is "experiencing a rebirth". This is especially true of investment casting technology. The transition from metal moulds to polymer moulds in the production of wax models has made it possible to significantly reduce their cost while significantly increasing the accuracy and quality of the model surface imprint, as well as the productivity of modellers [10-12]. These advantages were especially noticeable in a single (3 - 5 removal of models from one mould per shift) production of castings with long-term cooling of the dies.

However, in the manufacture of wax models weighing more than 50 g in small batches, a significant drawback was revealed: with each repeated pressing of the mould with a liquid wax mass, alternating with cooling the forming elements to the working temperatures of the mould surface with compressed air or running water, the surface quality of the models decreases. After several successive fillings, looseness and porosity appear, and the sharpness and quality of the print decrease. Moreover, with an increase in the number of press fittings, the number of defects increases more and more until the quality of the models is completely lost.

Analysis of this phenomenon has revealed the following. It is known that the quality of cast products, both the surface and the body of the castings, substantially depends on the intensity of heat transfer from the melt to the mould [13]. In particular, the higher the heat transfer rate, the higher the surface quality of the castings. This property is especially noticeable, for example, when casting non-ferrous alloys under pressure into water-cooled moulds. As the intensity of heat transfer decreases, the clarity of the print is blurred, surface "granularity" appears, then porosity, etc. The intensity of heat transfer depends not only on the temperature difference at the interface between two media, but also on the thermophysical properties of the material of the form: its heat capacity and thermal conductivity. The highest heat transfer rate is observed when casting into metal moulds, since they have the best (for this process) thermophysical properties, for example, heat capacity: steel 460 J/(kg·K), aluminium - 930 J/(kg·K); thermal conductivity: steel 52 W/(m·°C), aluminium 230 W/(m·°C). The specified properties of polymeric materials differ significantly from metal ones. For example, the heat capacity of known polyurethanes suitable for the manufacture of moulds is more than 1380 J/(kg·K), the thermal conductivity is 0.019–0.03 W/(m·°C).

Therefore, the first wax models in polymer moulds are usually perfect. The intensity of heat transfer from the melt to the mould is high, since initially cold matrix bodies successfully absorb heat, and the surface of the matrix after each pressing is necessarily cooled with water or compressed air. In this case, the required temperature difference at the interface between the two media will remain unchanged.

However, with an increase in the number of press fittings, the bodies of the matrices gradually warm up, while their ability to absorb heat decreases. Due to the high heat capacity and low thermal conductivity of polymers, it is not possible to completely cool the bodies of the moulds with water or compressed air in the time intervals between pressings due to the excessive duration of the process and a significant decrease in labour productivity. Usually, it is possible to reduce to normal only the temperature of the matrix surface, which, after assembling the moulds in a closed space, rapidly rises because of heating from the remaining heat of the matrix body. As a result, the intensity of heat transfer with each subsequent pouring decreases, and the quality of the models deteriorates.

The aim of the work is to experimentally study the temperature regime of heating mould matrices and to develop, on this basis, an effective technology for the manufacture of forming elements of moulds from cast polymer composite materials for the production of wax lost wax models, which ensures a stable surface quality of models, as well as a significant increase in labour productivity.
2. Methods
To increase the intensity of heat transfer in the moulds during the production of wax models, it was decided to manufacture the mould matrices from cast polymer composite materials with fillers from metallic and non-metallic materials with different thermophysical properties.

For research, from the original polyurethane, as well as polyurethane with the addition of aluminium, iron, carbon, copper, samples of the matrix were made (figure 1) in the form of small tiles imitating the surface of the mould, with dimensions of 70x70, 25 mm thick, which were then placed in the experimental cell of special design (figure 2).

![Figure 1. Test sample.](image)

The sample thickness of 25 mm corresponds to the average thickness of the mould liner, measured in the direction of the axial heat sink: 15-30 mm. The length and width of the tiles - 70 mm were determined from the condition of maintaining the minimum distance to the heat-transfer surface from their ends of 30 - 35 mm, preventing the influence of the end heat transfer of the samples on the purity of the experiment.

For the production of prototypes, a master model was prepared in advance, that is, a prototype model, from which a print was then taken. A master model in the form of a bar with casting slopes was cut from a polyorganic plate 25 mm thick by mechanical processing. The resulting model was carefully cleaned, polished and treated with a silicone-based release agent. Then the model prepared in this way was placed in a shell made of thick cardboard. To exclude the leakage of liquid polymer, the shell was carefully fixed on the working plate and treated with degreasing and anti-adhesion compositions.

In this work, prototypes of the tooling were made from a two-component polyurethane compound ADV 13-2 with the addition of metallic or non-metallic materials.

To obtain a polyurethane compound, the calculated amount of component A of the polymer was measured; the catalyst and the corresponding amount of component B were introduced into it, and thoroughly mixed. The amount of catalyst was determined empirically in order to ensure the required polymerization time, based on the fact that to ensure uniform distribution of the viscous suspension over the surface of the model and create a high-quality print, a minimum technological exposure of 5 minutes is required.

In the experiments, the following materials were selected as fillers: copper electrolytic powder GOST 4960-2009, aluminium powder PAP-1 GOST 5494-95, lumpy aluminium powder APS-2 GOST 10096-92, radio-technical iron carbonyl R-10 GOST 13610-84, cast steel shot technical DSL 08 GOST 11964-89, special low-ash graphite GSM-1 GOST 17022-81. To obtain comparative data, all powders were
preliminarily dispersed into fractions. From the obtained sieve, powders with one fraction size were taken, which was 1.0 ± 0.2 mm.

Mixing of fillers (powders) was carried out as follows: after mixing component A and the catalyst, the necessary additives were introduced in the calculated amount, thoroughly mixed for 1-5 minutes, then component B of the polymer was added and mixed for 0.5-3 minutes until a homogeneous mass was obtained.

The obtained polymer composite material was poured into the shell onto the prepared master model. Withstood until completion of the polymerization process for 24 hours, in accordance with the recommendations of the manufacturers of polyurethane components.

The temperature of the sample simulating the wall of the LGM mould was measured with chromel-alumel thermocouples with a wire thickness of 0.3 mm and a ball diameter of 0.5 mm, located in its centre along the geometric axis of the sample in isothermal planes, i.e. in planes located perpendicular to the direction of the axial heat sink, at a distance of 2, 5, 10, 15 mm from the working surface as shown in figure 1.

The experimental cell (figure 2) was based on a body made of 25 mm thick asbestos-cement slabs fastened with metal studs and nuts. In the side part there are special holes for thermocouples. In the centre of the body there is a space for mounting a test sample and a mould working space for pouring liquid wax. The test sample, with installed thermocouples connected to a PC via an OWEN TPM 138 controller, was placed in the working space of the case and covered with an upper plate with a pre-made gating system for pouring liquid wax. The gating system consisted of a cylindrical riser with a diameter of 15 mm and a pouring funnel with an angle between the generatrix of the funnel and the base plate surface of 45 °C.

FREEMAN Flexible Blue liquid modelling wax was melted in a water bath and pressed into a mould prepared in this way at a temperature of 78 - 82 °C. In all experiments, the temperature of the wax was constant. The initial temperature of the tooling in all experiments was 16.5 - 17.0 °C.

After pouring, the wax casting was kept in the mould for 40 seconds to complete the solidification process. The mould was disassembled, the resulting model was removed, the tooling was completely cooled to the initial temperature, and the process was repeated. Moreover, the cooling of the tooling was carried out until the temperatures were completely equalized over the body of the mould in the range of the initial temperature values of 16.5 - 17.0 °C. For this, the cooling process of the control die of the mould was controlled using thermocouples installed on the thermal axis of the sample (figure 2).

![Figure 2. Schematic of the experimental cell.](image)
3. Results and Discussion

The results of studies of temperature changes over the cross section of a polymer composite sample, obtained in a series of five experiments of pressing a liquid wax mass after statistical processing, are presented in figures 3-4.

According to the data obtained, the original polyurethane heats up slowly from the surface and also slowly transfers heat to the inside. Additives of copper powder (curve 2) reduce the intensity of heating of the surface layer due to a more uniform temperature distribution throughout the sample and greater heating of the inner layers. The addition of carbon-based additives (curve 3) significantly increases the heating of the sample surface and insignificantly increases the heating of the inner layers.

The addition of aluminium and iron powders (curves 5 and 6) maximizes the heating rate of the entire sample over the section, especially at the initial stage (the first 10-15 s), which corresponds to the approximate time of formation and hardening of the surface layer of wax models in the mass production of castings (10-20 s, depending on wall thickness).

Since the surface quality of wax models is mainly determined by the intensity of heat removal during the initial period of casting formation, an increase in the heating rate of the sample in the first 20 seconds of model formation, which was noted in samples 5 and 6, will contribute to obtaining wax models with a high surface quality. Moreover, the highest intensity of sample heating was shown by PCM samples with aluminium powder PAP-1, GOST 5494-95. Studies of the thermophysical properties of this material showed: heat capacity – 1040.4 J/(kg°C), which is 2 times less than that of a cast polyurethane compound, thermal conductivity is much higher and amounts to 0.27 W/(m°C). Additionally, studies of the thermal diffusivity of these materials showed: the thermal diffusivity of PCM with PAP-1 powder is $14.5 \times 10^{-8}$ (m$^2$/s), which is more than twice the thermal diffusivity of the ADV 13-2 compound – $6.8 \times 10^{-8}$ (m$^2$/s).

On this basis, polymer composite materials based on the cast polyurethane compound ADV 13-2 with the addition of aluminium powder were selected for further research in the production of wax models in moulds for serial production of models.
Figure 4. The nature of the temperature distribution in the deep layer (10 mm from the surface) of the samples made on the basis of the polyurethane compound ADV 13-2 with the addition of:
1 - without additives;
2 - 71.1 wt.% of PMS-1;
3 - 27.4 wt.% of GSM-1;
4 - 33.4 wt.% of APS-2;
5 - 54.5 wt.% of PAP-1;
6 - 77.4 wt.% of DSL 08;
7 - 43.8 wt.% of P-10.

4. Conclusions
As a result of the production tests carried out in the conditions of the model area of LLC InLitTech, it was established: the use of a polymer composite material based on cast polyurethane ADV 13-2 with the addition of PAP-1 aluminium powder in the amount of 54.5 wt.% made it possible to stabilize the high quality of wax models weighing from 75 to 340 g with a labour productivity in model production of 16 - 32 removal of models from one mould per shift, which meets the requirements of small-scale production of castings.

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