Automated control of the production process of antifriction polymer materials

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Abstract. This paper presents a technique of controlling the process of oil filling of polymer and composite materials, which allows automated determination of volumetric heating of a polymer or composite sample for the purpose of drying. The differentiation of the obtained results, presented in graphical form, made it possible to quickly analyze the dynamics of temperature changes in the thickness of the material, the change of which determines the rates and time of impregnation to a certain depth of the body of the polymer or composite sample in figure 1. According to the developed methodology, studies of the impregnation of the oil filler of a mixture of M8-B motor oil and hexane were carried out. For each experiment, time dependences of the impregnation rate were obtained. Based on the work carried out, the optimal proportion of a mixture of hexane and engine oil and the most favourable temperature conditions were determined. At the end of the research, the assumption about the possibility of using this technique for the purpose of its industrial use in the technology of oil filling of antifriction products made of polymer and composite materials was confirmed.

1. Introduction
In order to increase the efficiency and reliability of the machines and mechanisms of the transport complex, the industry has developed a number of manufacturing technologies for oil-filled polymer materials used in friction units. Such technologies are very relevant, and they make it possible to increase the operational life of machines and mechanisms by increasing their wear resistance. In conditions of depleted lubrication (dry start), these types of materials exhibit self-lubricating properties and create a surface layer of lubricant on the mating parts. After analyzing the existing methods of oil filling, the existing disadvantages of these technological processes were identified, manifested in the absence of objective control of impregnation with certification of the obtained antifriction material. Also, the oil filling process doesn’t take into account the possibility of finding excess moisture in the processed material at the initial stage of processing. The analysis carried out within the framework of this study showed that the polymer isn't heated before filling with oil, although it is obvious that this would significantly reduce the operation time while reducing the percentage of moisture in it. The review showed that the studies of this problem aren't systematized and are fragmentary.

Thus, the aim of the study was to develop a technique for filling structural polymers and composites with antifriction materials. To achieve this goal, the tasks related to the development of methods and work of automated scientific research of the filling process of structural polymer and composite materials were identified, and on the basis of the results obtained, to develop recommendations for carrying out works with automated control of oil filling technology.
2. Temperature-dynamic method for determining the impregnation rate of a polymer sample

The first step in the research process was the selection of the preheating method. In order to perform this operation, the most promising and energy efficient one is high-frequency electrothermics.

During the development of the automated process, it was necessary to determine the method of monitoring the filled state of the polymer or composite material. For this purpose, a hypothesis was put forward about a dynamic temperature change in the volume of the material during the impregnation of the sample with the filler. The hypothesis states that when the filler is supplied the sample (at a certain height), the dynamics and the value of the temperature (decrease) will change due to the influence of the filler in this area. Based on this, theoretical and experimental studies have been conducted to prove this hypothesis.

To determine the filled state of a polymer and composite sample, a temperature-dynamic method for determining the impregnation rate of a polymer sample was developed, due to the pre-calculated location of sensors in the sample. It should be noted that the calculation method is original, author-developed and is not presented in this paper. However, the layout of the thermal sensors in the sample used is shown in figure 1 [1, 2].

![Figure 1. Layout of thermocouples in the sample. a - height, b - length, c - width](image)

According to the developed scheme for a test sample with dimensions of 4x50x50 mm, the results of calculations of the coordinates of the location of temperature sensors are presented. The depth diagram of the temperature sensors is shown in figure 2. NTC thermistors at 10 KOhm were used as temperature sensors [3, 4, 5].
Figure 2. Scheme and depth of location of temperature sensors, 1…5 – Temperature sensors

Full-scale tests were carried out using an experimental setup based on industrial equipment UZP 2500. The frequency of the generated signal was 27.12 MHz permitted for use in production. The power was kept constant due to the automated stabilization of the anode current readings (0.25–0.30 A) [6, 7].

The results of the experiment on heating and filling the polymer PA6 (polyamide) are presented in figure 3.

Analysis of the presented data shows that it is extremely difficult to determine the moment of temperature change due to the oil supply to the sensor. Determining the dynamics of temperature changes has become easy to analyze when taking the time derivative of the values obtained. For this purpose, the PowerGraph software was used, where, using mathematical processing, a sliding differentiation of the data on the cooling temperature of the sample immersed in an oil filler was carried out in the range of 100 points [8, 9, 10]. The result is shown in figure 4.

Figure 3. Sliding data differentiation by sample cooling temperature in the range of 100 points.

Figure 4. Cooling graph of a sample immersed in an oil filler.

Analysis of the obtained graphical data shows the reference point of the extremum (minimum) at approximately 27 seconds, which corresponds to the pattern previously determined by the authors, [1] the change in the polymer cooling temperature when an oil filler enters it.

Thus, the hypothesis put forward asserts that when the filler enters the sample (to a certain height), the dynamics and value (decrease) of temperature will change due to the action of the filler in this area, which is fully confirmed by the experimental studies carried out.

To develop recommendations for controlling the technological process of oil filling, it is necessary to conduct additional experimental studies to determine the rate and time of impregnation [11, 12, 13].

3. Determination of impregnation rate of a polymer sample and filling time
Based on the work carried out earlier [3], the temperature regimes of drying were determined. Among other things, the authors of the work made a decision to decrease the viscosity of the M8-B motor oil by adding hexane to it [14] in order to increase the effective impregnation of the sample, in a proportion
that will allow reaching the viscosity of the oil filler close to the viscosity of water. Also, options for the percentage of hexane in the oil filler have been compiled. Based on this, it became necessary to determine the rate and time of impregnation of the polymer sample.

For full-scale tests to determine the impregnation rate, a 4x50x50 mm sample of PA6 material was taken as a basis and experiments were performed according to the developed and explained above methodology [15].

3.1. Experimental results for a drying temperature of 120 °C without the addition of hexane

The results of the experiment are presented in figure 5 and in table 1.

![Figure 5. PowerGraph results at 120 °C drying temperature. The smooth curve is the sample cooling temperature at points 1, 2, 3, 4, 5 in the sequence from top to bottom; the wavy curve is the time derivative of temperature in the same sequence](image)

The data of the obtained results are summarized in tables 1, 2, 3.

Table 1. Experimental results for a drying temperature of 120 °C without the addition of hexane.

| Point | Initial temperature (°C) | Depth \( h \) (mm) | Depth \( \Delta h \) (mm) | Filling time \( t \) (s) | Filling time \( \Delta t \) (s) | Filling rate (mm/s) |
|-------|--------------------------|-------------------|--------------------------|-------------------------|------------------------|-------------------|
| 1     | 122                      | 0.4               | 0.8                      | 13                      | 12                     | 0.067             |
| 2     | 120                      | 1.2               | 0.8                      | 25                      | 16                     | 0.05              |
| 3     | 121.5                    | 2.0               | 0.4                      | 41                      | 13                     | 0.031             |
| 4     | 124                      | 2.4               | 0.8                      | 54                      | -                      | -                 |
| 5     | 121.5                    | 3.2               | -                        | -                       | -                      | -                 |

The average impregnation rate at 120 °C was 0.05 mm/s.
Based on the data obtained, a case of incomplete impregnation of the sample is visible, which can be justified by the insufficient viscosity of the oil filler.

3.2. *Experimental results for a drying temperature of 75 °C with a hexane content of 40 %*

The results of the experiment are presented in figure 6.

![Figure 6. PowerGraph results at 75 °C drying temperature. The smooth curve is the sample cooling temperature at points 1, 2, 3, 4, 5 in the sequence from top to bottom; the wavy curve is the time derivative of temperature in the same sequence.](image)

The impregnation rate, based on the technological system presented above, was calculated by the formula (1):

$$ V = \frac{\Delta h}{\Delta t} $$  

(1)

where $\Delta h$ is the depth difference between 1 and 2, 2 and 3, etc temperature sensors, mm; $\Delta t$ is the difference in the impregnation time between 1 and 2, 2 and 3, etc by thermal sensors, mm [16].

The data of the obtained results are summarized in table 2.

**Table 2.** Experimental results for a drying temperature of 75 °C with a hexane content of 40 %.

| Point | Initial temperature (°C) | Depth h (mm) | Depth $\Delta h$ (mm) | Filling time t (s) | Filling time $\Delta t$ (s) | Filling rate (mm/s) |
|-------|--------------------------|--------------|-----------------------|-------------------|-----------------------------|-------------------|
| 1     | 74.3                     | 0.4          | 0.8                   | 1.7               | 1.5                         | 0.53              |
| 2     | 77.45                    | 1.2          | 0.8                   | 3.2               | 5.8                         | 0.14              |
| 3     | 76.9                     | 2.0          | 0.4                   | 9                 | 4                           | 0.1               |
| 4     | 71.1                     | 2.4          | 0.8                   | 13                | 8                           | 0.1               |
| 5     | 70.9                     | 3.2          | -                     | 21                | -                           | -                 |

Thus, the average impregnation rate at 75 °C was obtained, which was 0.22 mm/s.
To determine the optimal ones in terms of energy efficiency, it was decided to lower the filling temperature, which was taken as a temperature of 50 °C.

3.3. Experimental results for a drying temperature of 50 °C with a hexane content of 60 %

The results of the experiment are presented in figure 7.

![Figure 7](image)

Figure 7. Experimental results for a drying temperature of 50 °C with a hexane content of 60%. The smooth curve is the sample cooling temperature at points 1, 2, 3, 4, 5 in the sequence from top to bottom; the wavy curve is the time derivative of temperature in the same sequence.

The data of the obtained results are summarized in table 3.

The average impregnation rate at 50 °C was 0.15 mm/s.

The experimental procedure provided for each measurement of the sample weight before and after drying and oil filling. For this purpose, analytical scales were used under normal conditions of the test laboratory.

In order to comply with safety measures, namely to protect the human respiratory system, respirators and medical gloves were used, since hexane is a harmful chemical.

**Table 3.** Experimental results for a drying temperature of 50 °C with a hexane content of 60 %.

| Point | Initial temperature (°C) | Depth h (mm) | Depth Δh (mm) | Filling time t (s) | Filling time Δt (s) | Filling rate (mm/s) |
|-------|--------------------------|--------------|---------------|-------------------|-------------------|-------------------|
| 1     | 52.7                     | 0.4          | 0.8           | 2                 | 3.2               | 0.25              |
| 2     | 50.6                     | 1.2          | 0.8           | 5.2               | 7.8               | 0.1026            |
| 3     | 51.2                     | 2.0          | 0.4           | 13                | 8.5               | 0.0471            |
| 4     | 49                       | 2.4          | 0.8           | 21.5              | 4.2               | 0.1905            |
| 5     | 50.6                     | 3.2          | -             | 25.7              | -                 | -                 |

After conducting all the experiments to determine the most favorable proportions of hexane and oil and the temperature conditions of impregnation, the final table 4 was compiled.

**Table 4.** The final results of the experiments.
| Hexane (%) | Filling temperature (°C) | Initial weight (g) | Weight after drying (g) | Weight after impregnation (g) | The difference between dry and with oil (g) | Average time, Δt (s) | Average filling rate (mm/s) |
|-----------|--------------------------|--------------------|------------------------|-------------------------------|------------------------------------------|----------------------|-----------------------------|
| 0         | 120                      | 11.4519            | 11.416                 | 11.4378                       | 0.022                                    | 13.7                 | 0.05                        |
| 40        | 75                       | 11.4484            | 11.427                 | 11.4659                       | 0.039                                    | 4.8                  | 0.22                        |
| 60        | 50                       | 12.2594            | 12.183                 | 12.2106                       | 0.028                                    | 5.9                  | 0.15                        |

The table 4 shows which modes and proportions of hexane and oil are most preferable, namely at a hexane content of 40% and a filling temperature of 75 °C, since the impregnation rate and the mass of the absorbed filler are much higher than the samples filled with other impregnation modes.

4. Conclusion
At the end of the work carried out, the hypothesis put forward about the method of controlling the filled state of a polymer or composite sample by a variable temperature in the body of the material was substantiated. The rate of impregnation of the sample for different concentrations of oil filler is determined. The results obtained are applicable to determine the time of impregnation of finished products to a given depth of penetration of the oil filler.

At the end of the experiments, recommendations were made on the modes of the technological process of filling polymer materials.

The proportions of antifriction fillers in the composition of 40% hexane to 60 % M8-B oil are recommended. The heating temperature of 75 °C should be taken as the most preferable, since at this temperature the highest impregnation rate of 0.22 mm/s is observed. Also, these modes contribute to the greatest absorption of the oil filler (0.039 g), which is 0.19% of the volume of the dry sample of 10000 mm³.

When working with hexane, it should be taken into account that it is dangerous for human life, namely for the respiratory system by prolonged inhalation, if swallowed it can cause harm to the lungs. Hexane vapors can cause drowsiness, dizziness, depression of the central nervous system and negatively affect the functioning of the peripheral nervous system by numbing the lower extremities. It is also harmful when exposed to the skin - it causes irritation. Therefore, when carrying out work and research activities, the workplace must be provided with a supply and exhaust ventilation system.

Thus, the technological process of filling structural polymers and composites with antifriction materials consists of the following operations:

- Drying of the polymer sample;
- Cooling to a temperature acceptable when using a certain proportion of hexane and engine oil;
- Supply of antifriction filler;
- Excerpt, in accordance with the recommendations proposed above.

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