Contact method of volume control of temperature of a polymer sample at high-frequency heating

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Abstract. This paper presents the results of research of the contact method of volumetric temperature control of a polymer sample. The scheme of thermocouples (TC) location in a polymer sample, finite-element model and general mathematical model for calculating the influence of the quantity of thermocouples on heating samples at high-frequency processing are constructed. Comparative analysis of the obtained results was conducted.

1. Purpose and objectives
The purpose of the study is to develop a contact method for measuring the temperature of a polymer sample over the entire volume during high-frequency processing.

To achieve this purpose, it is necessary to solve the following tasks:
- construction of a scheme of the location of thermocouples in the body of a polymer sample;
- construction of a finite-element mathematical model, for calculating the influence of the quantity of thermocouples on heating sample at high-frequency processing;
- construction of a general mathematical model for calculating the influence of the quantity of thermocouples on heating sample at high-frequency processing;
- conduct a comparative analysis of the results obtained.

2. Input data
Sample of the material PA6 TU 224-001-78534599-2006; dimensions: 50x50x4 mm; density: 1120 kg/m³; specific heat: 1601 J/kg•K; thermal conductivity: 0.23 W/(m•K). Thermocouple (TC) chromel-alumel; junction diameter: 0.25 mm; wire diameter: 0.1 mm; hole sizes: 0.25x25 mm [1-4].

The preliminary location of the thermocouples in the sample is specified in figure 1.
Figure 1. Scheme of thermocouples in the sample.

3. Finite-element mathematical calculation
The construction finite-element mathematical model, for calculating the influence of the quantity of thermocouples on heating sample at high-frequency processing was completed in the software package MSC Patran Sinda (figure 2).

The boundary conditions were: volumetric heating power capacity constant: 10 W, coefficient of convective thermal conductivity is constant $10 \text{ W/(K}\cdot\text{m}^2)$, ambient temperature $20 ^\circ\text{C}$ [5,6].

Figure 2. Finite-element mathematical model of the prototype.

The diagram is constructed (figure 3) of the temperature dependence on the number of holes for thermocouples in the polymer sample based on the results of calculations by MSC Patran Sinda, which are shown in table 1.
Table 1. Summary table of calculation results MSC Patran Sinda.

| quantity of thermocouples, pieces | temperature on the plane of symmetry, °C | surface temperature of the body, °C | temperature on the wall of the hole, °C |
|----------------------------------|-------------------------------------------|-----------------------------------|-----------------------------------------|
| 0                                | 220.746                                   | 202.701                           | -                                       |
| 1                                | 221.500                                   | 203.516                           | 220.251                                 |
| 2                                | 221.546                                   | 203.538                           | 220.263                                 |
| 3                                | 221.625                                   | 203.569                           | 220.282                                 |
| 4                                | 221.630                                   | 203.558                           | 220.271                                 |
| 5                                | 221.678                                   | 203.575                           | 220.293                                 |

Figure 3. Calculation results of MSC Patran Sinda.

From the graphic data obtained, it can be concluded that with high-frequency heating, the temperature of the polymer sample increases throughout the entire volume as the quantity of holes in the body increases.

A calculation of the error caused by the installation of thermocouples in a polymer sample.

\[ \Delta_1 = 100 - \frac{T_{without\, TC} \cdot 100}{T_{5\, TC}} = 100 - \frac{220.746 \cdot 100}{221.500} = 0.34 \% . \]

where are \( T_{without\, TC} \) - temperature in the body of the polymer sample without holes, °C; \( T_{5\, TC} \) - temperature in the body of a polymer sample with 5 holes, °C.

The results of constructing a finite-element mathematical model showed that the calculated error value does not exceed the acceptable value of 3%.

4. General mathematical calculation

Construction of a general mathematical model for calculating the influence of the quantity of thermocouples on the heating of the sample during high-frequency processing.

The process of volumetric heating of a polymer sample with dimensions of 50x50x4 mm, from internal heat sources, is attributed to the special case of thermal conductivity of a homogeneous plate.
Heat sources are evenly distributed throughout the entire volume $q_v = \text{const}$. Convective heat transfer coefficient, $\alpha = \text{const}$ and ambient temperature $T_{\text{air}} = \text{const}$. Due to uniform cooling, the temperatures of both surfaces of the plate are the same [3,4].

Under these conditions, the temperature of the plate will only change along the x-axis (figure 4), which is normal to the surface of the body. The temperatures on the axis of the plate and on its surface are denoted respectively by $T_0$ and $T_{\text{surface}}$; these temperatures are unknown. In addition, it is necessary to find the temperature distribution in the plate and the quantity of heat released to the environment [5].

![Figure 4. Calculation scheme of thermal conductivity of a homogeneous plate.](image)

\[ T(x) = T_{\text{air}} + \frac{q_v \cdot \delta}{\alpha} + \frac{q_v}{2 \cdot \lambda} (\delta^2 - x^2), \quad -\delta \leq x \leq \delta \]

(1)

where are $T_{\text{air}}$ - ambient temperature, 20 °C; $\alpha$ - coefficient of convective thermal conductivity is constant 10 W/(deg*m²); $\lambda$ - coefficient of thermal conductivity of the polymer (PA 6), 0.26 W/(deg m); $\delta$ - extreme position of the point in contact with the environment, 0.002 m; $q_v$ - volume capacity of internal heat sources, W/m³.[7-9]

Volumetric productivity of internal heat sources is calculated by the formula [10]

\[ q_v = \frac{Q}{V}, \]

(2)

where $Q$ is a thermal power from each internal heat source, 10 W; $V$ - body volume, m³.

The results of calculations of the volume capacity of internal heat sources are summarized in table 2.

| quantity of holes for thermocouples, pieces | $V$, m³ | $q_v$, W/m³ |
|--------------------------------------------|---------|-------------|
| 0                                          | 1.00000·10⁻³ | 1.000·10⁰  |
| 1                                          | 9.99877·10⁻⁶ | 1.001·10⁰  |
| 2                                          | 9.99754·10⁻⁶ | 1.002·10⁰  |
| 3                                          | 9.99631·10⁻⁶ | 1.004·10⁰  |
| 4                                          | 9.99508·10⁻⁶ | 1.005·10⁰  |
| 5                                          | 9.99385·10⁻⁶ | 1.006·10⁰  |

Surface temperature of the body ($x = \delta$) [10]
\[ T_{\text{surface}} = T_{\text{air}} + \frac{q_v \cdot \delta}{\alpha}. \]  

Temperature on the plane of symmetry (x = 0) [10]
\[ T_0 = T_{\text{surface}} + \frac{q_v \cdot \delta^2}{2 \cdot \lambda}. \]  

The results of temperature calculations on the surface of the body and on the plane of symmetry are summarized in table 3.

Let be given boundary conditions of the third kind, that is, the ambient temperature on the outside surface and the constant heat transfer coefficient on the outside surface.

The dependence of the temperature field, the formula (5) [11]
\[
T(r) = T_{\text{air}} + \frac{q_v \cdot \delta}{2\alpha} \left[ 1 - \left( \frac{\delta_f}{\delta} \right)^2 \right] + \frac{q_v \cdot \delta^2}{4\lambda} \left[ 1 + \left( \frac{\delta_f}{\delta} \right)^2 \cdot 2 \ln \frac{r}{\delta} - \left( \frac{r}{\delta} \right)^2 \right], \quad \delta_f \leq r \leq \delta
\]  

where \( \delta_f \) is the radius of the hole for the thermocouple, 0.000125 m.

Temperature difference between the surface of the body and the heat-giving surface of the hole wall, formula (6)
\[
T_{\text{hole}} - T_{\text{surface}} = \frac{q_v \cdot \delta^2}{4\lambda} \left[ \left( \frac{\delta}{\delta_f} \right)^2 - 2 \ln \frac{\delta}{\delta_f} - 1 \right],
\]

therefore
\[
T_{\text{hole}} = \frac{q_v \cdot \delta^2}{4\lambda} \left[ \left( \frac{\delta}{\delta_f} \right)^2 - 2 \ln \frac{\delta}{\delta_f} - 1 \right] + T_{\text{surface}}.
\]

The results of calculating the temperature on the wall of the hole are summarized in table 3.

**Table 3. Results of temperature calculations on the surface of the body, the plane of symmetry and on the walls of the hole.**

| quantity of holes for thermocouples, pieces | \( T_{\text{surface}}, ^\circ \text{C} \) | \( T_0, ^\circ \text{C} \) | \( T_{\text{wall}}, ^\circ \text{C} \) |
From the obtained dependencies, it can be seen that as the holes in the body increase, the temperature increases both on the surface of the sample and on the wall of the hole. This can be explained by a decrease in the sample volume, which leads to an increase in the volume capacity of internal heat sources at constant power.

Calculation of the error caused by the installation of thermocouples in a polymer sample

\[ \Delta \gamma = 100 - \frac{T_{\text{withoutTC}} \cdot 100}{T_{5\text{TC}}} = 100 - \frac{227.692 \cdot 100}{228.978} = 0.57\% . \]

where \( T_{\text{withoutTC}} \) - temperature in the body of the polymer sample without holes, °C; \( T_{5\text{TC}} \) - temperature in the body of a polymer sample with 5 holes, °C;

The results of constructing a finite-element mathematical model showed that the calculated error value does not exceed the acceptable value of 3%.

5. Comparative analysis
The applicability of this scheme was mathematically proved for the preliminary arrangement of thermocouples in the body of a polymer sample for controlling the temperature of volumetric heating during high-frequency processing. When calculating the error arising from the number of holes for thermocouples, performed using a finite element model in the software complex MSC Patran Sinda (0.34 %) and a General mathematical model using calculation formulas (0.57 %). The result of the research is the chosen method of constructing mathematical models by the result of finite-element analysis, as well as the correct method of measuring temperature of a polymer sample.

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