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OPTIMIZATION OF THERMOCOUPLE INSTALLATION FOR STUDY OF INTENSE
TRANSIENT THERMAL ACTIONS ON MATERIALS

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A method is proposed for determination of the optimum variant of thermocouple installation to reduce measurement error for the case of individual electrode welding.

In studying thermal processes in various devices and equipment the temperature and thermal fluxes in the most heavily loaded details often cannot be measured directly. For example, such a situation is typical of heat transport analysis on the surfaces of cutting and abrasive instruments, and in portions of casting machines in contact with the solidifying metal. The difficulties in experimental determination of such quantities usually involve rapid destruction of sensors by thermal or mechanical action or insufficient measurement accuracy [1]. In such situations it becomes desirable to perform indirect measurements and process them by converse problem methods [2].

One way to improve effectiveness of such studies is planning, by which we understand selection of the basic experimental factors [3]: the quantities to be measured directly, the number and location of primary transducers, special features of loading. For tempera-

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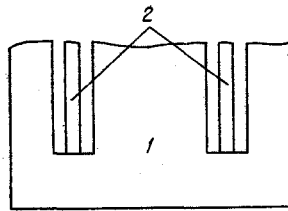


Fig. 1

Fig. 1. Thermocouple attachment by individual electrode welding: 1) loaded specimen; 2) electrodes.

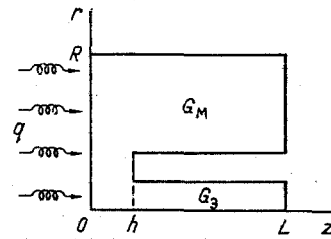


Fig. 2

Fig. 2. Solution region for thermal problem.

ture measurements at internal points, among such factors we have the geometric parameters of thermocouple electrodes and the orifices made for their insertion.

Analysis of the effect of thermosensor geometric parameters on the temperature field has been performed for the method of attachment by individual welding of electrodes to the specimen (Fig. 1). Such a method of temperature measurement eliminates the need of careful preparation of the thermocouple junction and significantly simplifies the thermosensor geometry, and thus aids quantitative analysis of measurement uncertainties, which is very important in the study of intense transient regimes, since in that case even slight disturbance of thermophysical homogeneity of the object can lead to marked distortions of the temperature field. However, this method of separating the thermoelectrodes, while possessing the advantages noted above, does have the feature that the electrodes, having differing thermophysical properties, distort the temperature field in different manners.

Many studies have been dedicated to clarification of the qualitative and quantitative principles of the perturbing effect of thermoelectrodes. We will note [4-7], characterized by a complete encompassing of the various situations which occur upon contact temperature measurements in solids. However, at small time intervals of the magnitude of seconds the expressions for uncertainty presented in those studies cannot be used, since in that case the assumptions upon which those expressions were derived are not satisfied. Consequently, one must turn to numerical computer modeling.

To determine the value of the distorting effect of the thermoelectrode on the body temperature field we will use a linear two-dimensional model of nonsteady state thermal conductivity in the presence of a sensor of cylindrical form:

$$C \frac{\partial T}{\partial \tau} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \lambda \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right), \quad 0 < \tau < \tau_m, \quad (1)$$

$$(r, z) \in G_M \cup G_e, \quad (2)$$

$$T|_{\tau=0} = 0,$$

$$-\lambda \frac{\partial T}{\partial z} \Big|_{z=0} = q(\tau), \quad (3)$$

$$\frac{\partial T}{\partial n} \Big|_{(r,z) \in \partial G} = 0, \quad (4)$$

where $q(\tau)$ is the thermal flux density entering the body from the external source; R, L are the dimensions of the spatial region; ∂G is the boundary of the calculation region excluding the surface $z = 0$. The functions $C = C(r, z)$ and $\lambda = \lambda(r, z)$ are piecewise-continuous volume heat capacity and thermal conductivity coefficients:

$$C(r, z) = \begin{cases} C_m(r, z) \in G_m, \\ C_e(r, z) \in G_e, \end{cases} \quad \lambda(r, z) = \begin{cases} \lambda_m(r, z) \in G_m, \\ \lambda_e(r, z) \in G_e. \end{cases}$$

where the subscripts m and e denote respectively the metal of the part being studied and the electrode (Fig. 2).

In such a case the degree of distortion of the temperature field can be characterized for each concrete function $q(\tau)$ by a quantity ε :

$$\varepsilon(\tau, d_o, d_e, R, h) = \frac{T(0, h, \tau)}{T(R, h, \tau)} - 1, \quad (5)$$

where d_o is the diameter of the orifice; d_e , electrode diameter; h , distance from the heating surface to the point where the electrode is welded.

The quantity ε indicates the difference between the temperatures at the point of electrode attachment and far therefrom at one and the same depth h , and is a function of time, as well as the geometric and thermophysical parameters of the model of Eqs. (1)-(4).

We must make several remarks relative to this model of Eqs. (1)-(4). First, we have assumed linearity of heat transport, i.e., temperature independence of the coefficients C_m , C_e , λ_m , λ_e . Thus, the data in [8] on thermophysical characteristics permit considering these coefficients constant in the temperature interval 273-473 K to an accuracy of 3% for such materials as some types of steel, chromel, alumel, copper, and constantin. Second, the thermal flux supplied to the body surface is considered one-dimensional and dependent solely on time, which is valid for cases where the value of R is significantly less than the length of the section of the part surface which is subjected to thermal loading. For example, the contact length of a roller with the ingot for castingsless rolling of metals and alloys is tens of times greater than the radius of the thermoelectrode perturbation region. At the same time the model considers the contribution to temperature field distortion by such significant factors as the ratio of the thermophysical parameters of the part and electrode, and the depth of the point at which the electrode is welded to the part.

A numerical calculation was performed for the model of Eqs. (1)-(4) for bodies of type 45 steel and a chromel-alumel thermocouple. The thermophysical properties of these materials were taken from [8]. The following parameter values were used in the solution: $R = 8 \cdot 10^{-3}$ m, $L = 1.8 \cdot 10^{-3}$ m, $h = 10^{-3}$ m, $\tau_m = 1$ sec, $q = \text{const} = 10^6$ W/m². The values of R and L were chosen such that over time intervals τ_m the thermal perturbations did not reach the boundary of the spatial region over which the thermal problem was solved. The temperature field on the quasiuniform space-time grid $n_r \times n_z \times n_\tau = 10 \times 25 \times 500$ was performed by the local one-dimensional method following the recommendations of [9]. A large number of time steps insured convergence of the solution. The algorithm was realized in the language PL/1, with the time for solution of the problem on an ES-1022 computer being 29 min.

Figure 3 shows results of calculating the parameters ε_c and ε_a for chromel and alumel electrodes, respectively. It is evident that for identical values of d_o and d_e the chromel thermoelectrode distorts the temperature field more than the alumel one, while with increase in d_e the quantitative difference between ε_c and ε_a increases. This can be explained by the higher thermal conductivity of the alumel, and thus, more intense heat removal along the electrode and lower temperature rise at the point of attachment, as compared to the chromel electrode. Qualitatively, the time behaviors of ε_c and ε_a are identical. In particular, the temperature at the attachment point of either the chromel or the alumel electrode is higher than the undistorted temperature at the same depth over the entire course of heating, which is explained by the low thermal conductivities of those materials as compared to type 45 steel. It can also be noted that with increase in electrode diameter the degree of distortion decreases, since in this case the heat loss through the electrodes increases and the temperature rise at the point where they are welded to the point becomes smaller.

Thus, at the points of electrode contact with the part the temperatures $T_c(\tau)$ and $T_a(\tau)$ ($T_c > T_a$) are known. Then the temperature $T^*(\tau)$ recorded by the secondary device will be the combination of two temperatures:

$$T^*(\tau) = f(T_c(\tau), T_a(\tau)), \quad (6)$$

since the part proves to be connected in the thermocouple circuit [10].

Knowing the temperatures $T_c(\tau)$ and $T_a(\tau)$ and using calibration characteristics, we can uniquely determine the value of $T^*(\tau)$. However, in practice we realize a situation where the temperature $T^*(\tau)$ is known. In the general case it is impossible to reestablish the values of $T_c(\tau)$ and $T_a(\tau)$ in view of the ambiguity of the reverse transform of Eq. (6). Only in a single case is it possible to determine T_c and T_a , namely for $T_c(\tau) \approx T_a(\tau)$, when Eq. (6) takes on the trivial form

$$T^*(\tau) = f(T_c(\tau), T_c(\tau)) = T_c(\tau) = T_a(\tau), \quad (7)$$

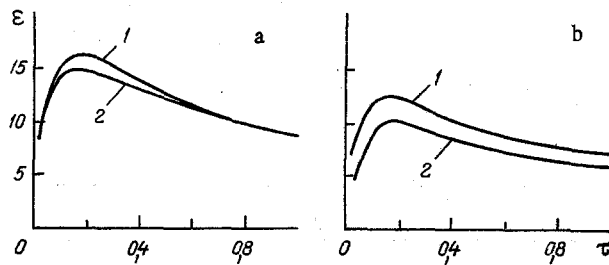


Fig. 3. Temperature field distortion vs time for $d_o = 1.2 \cdot 10^{-3}$ m, $d_e = 0.2 \cdot 10^{-3}$ m (a) and $d_e = 0.5 \cdot 10^{-3}$ m (b): 1) chromel electrode; 2) alumel electrode. ε , %; τ , sec.

TABLE 1. Ratio of Orifice Diameters for Chromel and Alumel Thermoelectrodes (10^{-3} m)

d_e	d_{oa}		
	$d_{oc}=1,2$	$d_{oc}=1$	$d_{oe}=0,8$
0,2	1,25	1,05	0,85
0,5	1,4	1,2	1,05
0,8	1,5	1,4	—

i.e., the temperature recorded by the external device will coincide with the temperatures at the points of thermoelectrode attachment.

Thus, our problem is to select dimensions of the thermoelectrodes and orifices which insure identical distortion of the temperature field by both electrodes. Our goal can be formulated more concretely: For each value of d_e , identical for both electrodes, it is necessary to select orifice diameters which insure a small difference between the functions $\varepsilon_c(\tau)$ and $\varepsilon_a(\tau)$.

This problem was solved by direct trial of d_e , d_{oc} , and d_{oa} values using the model of Eqs. (1)-(4). The ratio of the diameters of the electrode orifices producing practically identical temperature field distortion for several parameter values are presented in Table 1.

Naturally, selection of appropriate geometric sizes cannot reduce the error to zero, since the values of d_o and d_e are limited below and above by the technological possibilities of thermosensor installation. However, satisfaction of the condition $\varepsilon_c(\tau) \approx \varepsilon_a(\tau)$ in formulation of the converse problem of determining thermal conditions on the boundary excludes the body from the thermocouple circuit and makes it possible to use the thermal model of Eqs. (1)-(4) in calculations for one electrode alone, for example, the chromel one. A similar converse thermal conductivity problem in which the thermosensor was modeled by a cylindrical body was solved in [11, 12].

Although the calculations used a constant thermal flux density, the relationships between d_{oc} , d_{oa} , and d_e are valid for an arbitrary $q(\tau)$. In fact, in the general case the temperature at depth h can be calculated with the expression [2]

$$T(h, \tau) = \int_0^\tau q(\xi) \frac{\partial \theta(h, \tau - \xi)}{\partial \tau} d\xi, \quad (8)$$

where $\theta(h, \tau)$ is the temperature reaction at depth h per unit thermal flux. For $q = \text{const}$ we have the equality $\varepsilon_c = \varepsilon_a$, hence $\theta_c(h, \tau) = \theta_a(h, \tau)$ and calculation of the temperature with Eq. (8) gives an identical value for both the chromel and alumel electrodes, independent of the thermal flux density time distribution.

It should be noted that the data presented in Table 1 can be described to an accuracy of 5% by the following simple expression:

$$d_{oa} = d_{oc} + 0,7 \frac{d_e^2}{d_{oc}}, \quad (9)$$

which can be used in practice to calculate thermosensor parameters (for a Chromel-Alumel thermocouple) for installation in a part made of type 45 steel or material with similar properties.

Since $d_{oa} \geq d_{oc}$, the value of d_{oc} should be specified as small as possible, then used to select the value of d_{oa} . In the special case $d_e \approx 0$ (extremely thin electrodes) Eq. (9) yields $d_{oa} \approx d_{oc}$, which is intuitively obvious, since in this case there is practically no heat loss through the electrodes, and the measurement uncertainty is thus determined exclusively by the orifice diameters.

NOTATION

q , thermal flux density; T , temperature field; r, z , cylindrical coordinates; τ , current time; τ_m , observation time interval.

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