A METHOD OF DETERMINING THE SURFACE TEMPERATURE FIELDS OF INACCESSIBLE MACHINE COMPONENTS

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A description is given of a method for determining the temperature and the topology of the temperature field of parts that are inaccessible while the machine is operating. The method is based on the use of the sharp dependence of diffusion parameters of a material on temperature. The method has been tested on simple and complex multicomponent heterophase alloys.

The methods known for determining the temperatures of the surfaces of objects inaccessible during operation are change of hardness [1], cooling curve [2], use of alloy inserts [3], thermocouples, thermosensitive paint, and the optical pyrometer [4]. However, they possess a number of defects, which limit their region of usefulness. In particular, they do not permit one to determine (with the exception of the method of radioactive isotopes) a continuous field of temperature change or to record the "effective" value of temperature resulting from natural averaging of a set of values of instantaneous temperatures of a microvolume.

The present article describes a method that we have developed for determining the temperature field of parts inaccessible during operation over a wide temperature range (temperatures from 200° C upwards). The method uses the sharp temperature dependence of the quantities D_S and D_V, the surface or intercrystalline and bulk diffusion coefficients:

$$D_S = D_0 \exp(-Q_S/RT), \qquad D_V = D_0 \exp(-Q_V/RT),$$

where Q_S and Q_V are the activation energies of surface and bulk diffusion; R is the gas constant; and D_0 is a preexponential multiplier, practically independent of the temperature T.

It is evident that the quantities D_S, D_V, D_0, Q_S, Q_V uniquely determine T. Information concerning D_S and D_V may be obtained by measuring the path length x of surface or bulk diffusion during time τ ($D\tau \sim x^2$).

The fact that the activation energy Q_S for the surface diffusion process is considerably less than the activation energy for bulk diffusion, is the reason for the sharply pronounced inequality $D_S \gg D_V$, and so on. It is easy to see that the surface diffusion method is considerably more sensitive than the bulk diffusion method at low temperatures.

The path length x of surface diffusion may be determined both visually or (photographically) using stable materials as coatings, and by autoradiographic means using radioactive materials.

In practice the parameter $S = (s_T - s_0)/s_0$, where s_0 and s_T are the area of coating before and after, respectively, the influence of temperature on an object, is taken as a quantity which depends on the path length of surface diffusion of atoms and uniquely determines the temperature of the object.

To calculate the path length of bulk diffusion when working with radio-elements, we measure the ratio of the β-radiation to the γ-radiation of the radioactive isotopes ($K = J_\beta : J_\gamma$), which does not depend on the number n of atoms in the system an important point in developing the technology of the method, since fluctuations are possible in n and in the thickness of the protective coating δ from specimen to specimen and within a given specimen. It is not difficult to show that $K(\delta_1 n_1) : k(\delta_2 n_2) = 1$.

Then the determination of the temperature field of inaccessible parts is accomplished as follows. The surface whose temperature field it is desired to determine is covered by a coating of a radio-isotope ($2-3\,\mu$), and then a thicker ($50\,\mu$) non-radioactive, protective layer is put on top. The function of the latter is to maintain the system of radioactive atoms mechanically intact (the atoms must not leave the system during operation). Subsequently, a determination is made of the value K before (K_0) and after (K_T) the operation of the surface during time τ_0.

The ratios $S = (s_T - s_0)/s_0$ and $K_K = K_T/K_0$ permit us to determine the temperature of the object, with the aid of the previously constructed standard curves in S–T and K_K–T coordinates.

CONSTRUCTION OF THE STANDARD CURVE

This is done as follows:

1. Specimens are prepared of the same material as the surface being studied.

2. A coating is put on the surface of the specimen in the form of points or reference lines. The choice of the chemical element of the coating is made in each individual case to allow for the chemical conditions of the coating process and of annealing. The element may be both stable and radioactive.

3. A thick protective layer which will not oxidize during operation of the machine is applied above the radioactive coating.

4. a) Measurement (with the aid of a microscope) of the area of the points of coating applied to the specimen, or of the thickness of the reference lines when stable materials are used for the coating, or to obtain an autoradiograph of the coating, when a radio isotope is used.

b) Measurement of the β- and γ-radioactivity at a fixed point of the surface.

5. Annealing of the specimens under the same conditions that the test material will be exposed to during operation (for τ hours at different temperatures T).

6. a) Measurement of the areas s_T of the coatings—as in §4 after annealing.

b) Measurement of the radioactivity after annealing.

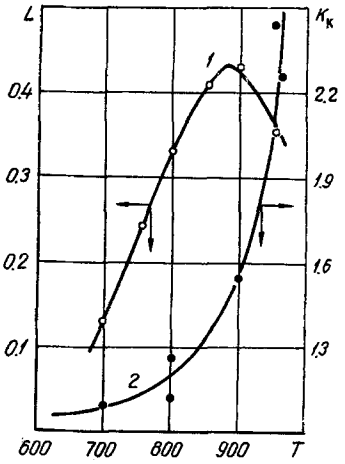
7. a) Determination of the quantity $S = (s_T - s_0)/s_0$.

b) Determination of $K_K = K_T = K_T/K_0$.

8. a) Construction of the curve S–T.

b) Construction of the curve K_K–T.

The points a) refer to the surface diffusion method, and the points b) to the bulk diffusion method.



Dependence of the value of the working parameter recorded in the diffusion method on the temperature of the object, T, °C. EI-283 alloy, quenched from T = = 1100° C (1—without annealing, 2—with homogenizing annealing for 12 hr).

Examples of construction of a standard curve for determination of temperature by the surface diffusion method. We checked the proposed method on an aluminum alloy AK-4, as well as on the alloys 65G, IKh18N9T, Kh12M, and EI283.

We shall examine in detail the technique for constructing a standard curve, for example, for 65G alloy. The proposed upper limit for the surface temperature of the object during operation does not exceed 500° C.

Specimens measuring 14 × 14 × 5 mm were prepared from 65G steel. Special attention was given to the preparation of the working surface of the specimen, which should be identical to the surface of the proposed object of investigation, as regards micro-geometry and structure. In the given case the specimens were subjected to grinding and polishing. Precipitation of the radioactive isotope Co 60 was carried out from a bath of the following composition (in gm per liter of water): $CuSO_4 \cdot 5H_2O$ 200–250 gm $\cdot l^{-1}$, H_2SO_4 20–30 gm$\cdot l^{-1}$, syrup of "molasses" 4–6 gm$\cdot l^{-1}$.

For a current density 1.5 A$\cdot$dm^{-2} and an electrolyte temperature 15–25° C, the rate of precipitation was 20$\mu \cdot$ hr^{-1}. The specific radioactivity of the solution was 2–5 mcurie $\cdot l^{-1}$. The coating had the form of "points" of diameter 600–90 μ. The layer thickness was 15–20 μ.

To obtain an autoradiograph, the surface of the specimen was placed in contact with the emulsion of a RT-1 X-ray plate. The exposure time was 25–35 hr. Annealing of the aluminum alloy of the specimens was carried out at atmospheric conditions in a muffle furnace at temperatures of 300, 400, and 500° C for 15 hr. The temperature in the furnace was controlled by a PP-thermocouple and regulated with the aid of a EPD-17 electronic potentiometer. After annealing an autoradiograph of the specimens was made.

The radiographs obtained were scanned and photographed on an MB-1 microscope with the aid of a MFN-1 microphotohead. The dimensions of the reflections (areas s_0 and s_T) were determined by weighing the positive print of the reflection. It is not difficult to establish that in this case the weight of the print P is proportional to S (when the photographic paper is uniform). The values found were plotted on a graph in terms of the S-T coordinates.

As an example of the use of stable materials for measurement of temperature of inaccessible objects, we shall examine the construction of a standard curve for specimens of the aluminum-base alloy AK-4. The suggested limit of temperature measurement on an actual object is 300–500° C.

The size of the AK-4 alloy specimens was 14 × 12 × × 5 mm. The working surface of the specimen was polished and oxidized. A copper coating was deposited on the surface of the specimen in the form of points 500–600 μ in diameter and 10–15 μ thick. The composition of the bath and the conditions for the coating were similar to those used for 65G steel without activation with Co60.

The specimens were annealed under atmospheric conditions at temperatures of 300, 400, and 500° C for 15 hr. The working surface of the specimens was photographed before and after annealing. Spreading of the coating as a result of surface diffusion at the annealing temperature was clearly seen on enlarged photographs (× 250) of the working surface of the specimen. As in the case when a radioactive coating was used, a determination of s_0 and s_T was carried out by weighing the positive print of the coating before and after annealing. The values of s_0 and s_T were obtained as the arithmetic mean, after weighing of a minimum of three photographic "points."

Construction of a standard curve by the bulk diffusion method. For the construction of a $K_K - T$ curve we chose a multicomponent hetero-phase chrome-nickel alloy with an iron base (20% Ni, 25% Cr, etc.,). The high heat stability and hot strength of this alloy are attained after high-temperature hardening, transferring it mainly to the γ-state.

We prepared specimens meaning 10 × 10 × 5 mm of this material. Some of the specimens were subjected to a homogenizing annealing (to ensure constancy of structure of the material throughout the working time of interest at 950° C for not less than 15 hr. Further increase of the time of high-temperature annealing did not lead to a noticeable development of phase transformations (950° C was the highest temperature which

we proposed to record on the surface of the object being examined).

On the radioactive coating containing Co60 we deposited a layer (thickness 50 μ) of nonradioactive chromium from a bath containing Cr_2O_3 (250 gm $\cdot$ l^{-1} of water), H_2SO_4 (2.5 gm $\cdot$ l^{-1}). The bath temperature was 50–55° C, the current density 50 a $\cdot$ dm^{-2}, and the duration of the process was 2.0 hr.

Annealing of a series of specimens for the construction of a K_K–T standard curve was carried out in vacuum, in air, or in an atmosphere of burnt vapor of MS-20 machine oil. The time of diffusion annealing as strictly suited to the given series of specimens allowed us to obtain a clear diffusion curve.

In order to record the γ-component of the spectrum, the β-radiation of the Co60 was filtered with aluminum foil 1 mm thick.

The result of one series of tests is shown in the figure, represented in the form of the K_K–T curve. Here $K_K = K_T : K_0$, $L = (s_0 - s_T) : s_0$, where K_T and K_0 are partial values obtained by subdivision of the ratios of β- to γ-radiation respectively after and before the test, and s_T and s_0 are values of the blackening of the photoemulsion in contact with the object, after and before the test.

It may be seen from the figure that a clearly defined dependence of temperature on the recorded diffusion parameter K_K is obtained, both in the case of the alloy existing in the working state (1), and in the case of preliminary homogenizing of the material (2). It is easy to see that the upper limit of temperatures measured with the aid of the diffusion method, is unbounded. By choice of a suitable radio-isotope and by use of the method of surface diffusion, the lower limit may be dropped to 150–200° C.

It is of interest to compare the results of temperatures measured with the aid of the diffusion method with data obtained by other means. According to calibration tests, the deviation of a measured temperature from the true value does not exceed $\pm 1\%$ for the lower part of the temperature range (400–500° C).

Thus, the proposed diffusion method for temperature-determination has the following advantages compared with other known methods: the possibility of determining the temperature of any surfaces of objects (including those inaccessible during operation); the possibility of measuring a continuous field of temperature variation in a given direction of the surface (volume) of the object (topology of the temperature field); the maintenance of the component intact; satisfactory accuracy and the possibility of measuring effective values of temperature, i.e., those on which corrosion, softening, disintegration, etc., of the material depend.

REFERENCES

1. A.B. Fridman and A.B. Podol'skii, GVF, no. 7, 1937.

2. I.I. Zverev, Tr. TsIAM, no. 139, Oborongiz, 1948.

3. A.I. Tolstov and N.I. Mironov, Sb. NAMI, no. 2, 1947.

4. G.R. Rikardo, High-Speed Internal Combustion Engine [in Russian], Mashgiz, 1960.

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