Anisotropic structured compositions for gradient heat flux measurement

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Abstract. The article presents new compositions used for gradient heat flux measurement, whose development prospects are associated with production of layered composite materials with a special set of properties. The of diffusion welding technology is proposed, providing acceptable sensitivity and durable bonding of composite layers.

Currently, gradient heat flux measurement is one of the best ways to determine heat flux value. Gradient heat flux sensors (GHFS) made of materials with anisotropy of thermal, electrical conductivity and thermoelectric coefficient have significant advantages.

L Gayling mentions such sensors for the first time [1]. The modern development of the GHFSs is mainly associated with the works of the group from Peter the Great St. Petersburg Polytechnic University, the results of which are summarized in monographs [2]. GHFSs successfully used in laboratory and industrial experiment. It is especially important that GHFSs have anomalously high time constant of $10^{-8}$...$10^{-9}$ s [2, 3], which is of $3...5$ orders of magnitude less than the world's best analogues [3].

However, the amount of natural anisotropic metals is small, and it is impossible to influence their effective kinetic coefficients. Therefore, the interest of researchers [6] to artificial anisotropic media is clear.

The first step was the creation of the GHFS based on the composition of stainless steel 12Cr18Ni9Ti + nickel, chromel + alumel and iron + constantan. These GHFSs are operational up to temperature of 1000 °C; the results of their calibration are presented in figure 1.

In temperature range of 250...400 °C, the characteristics of GHFSs made of chromel + alumel composition are monotonous, however, the volt-watt sensitivity of the sensors made of steel 12Cr18Ni9Ti + nickel composition is almost an order of magnitude higher, which allows this composition to be preferred.

As layers, it was possible to use not only monolithic, but also permeable materials: fibrous, mesh, with regular perforations, etc. Figure 2 shows the structure of composition of steel 12Cr18Ni9Ti (mesh) + nickel. During diffusion welding, intersection of the filaments of the grid are welded in the contact zones, and after cutting the structure becomes permeable for liquid or gas flows, and the resistance does not exceed tens of Pa/mm of thickness (and can be adjusted by selection of the grid, angle and plate thickness). Usage of such GHFS in research of injection systems, gas curtains, etc. gives clear and unparalleled benefits.
Technology for GHFS manufacturing is as follows. Metal plates are cut from both materials (nickel + steel, etc.). In diffusion welding, as a rule, surface roughness of $R_a = 2.5 \div 0.32 \mu m$ is required. In most cases, vacuum or inert gases are used to reduce the oxidation rate and create conditions for cleaning contact surfaces from oxides. During the welding process, a multilayer anisotropic bar is obtained. After cooling, it is cut into plates located at an angle of 20...45° to the working planes, and then connect the wires.

![Figure 1](image1.png)

**Figure 1.** Calibration curves for GHFSs compositions: 1 – steel 12Cr18Ni9Ti + nickel; 2 – chromel + alumel.

![Figure 2](image2.png)

**Figure 2.** Microstructure of GHFS made from steel 12Cr18Ni9Ti (mesh) + nickel composition (scale to the left in mm).

Connection quality at micro level was controlled by metallographic (figure 3), as well as with Camebax – Microbeam microanalyzer from Cameca (France). Observation was carried out in an optical microscope ($\times400$) and in secondary electrons in the scanning mode by an electronic probe ($\times100...20000$). The composition was determined by quantitative x-ray microanalysis using spectrometers with wave dispersion.

Usage of semiconductor + metal and semiconductor + semiconductor compositions is of special interest, since the values of the thermoelectric coefficient of semiconductors by an order of magnitude or more exceed the level of this characteristic for metals.
Figure 3. Microstructure of steel 12Cr18Ni9Ti + nickel composition made of layers of 0.1 mm thickness: (a) – before etching; (b) – after etching (the bright diffusion zone is outlined by a dashed line).

We managed to obtain silicon + aluminum composition by diffusion welding method (at temperature of 547 °C and holding for 1 hour) a diffusion compound with formation of diffusion zone of 5...15 µm wide. To increase the strength of single crystal of silicon + aluminum, welding should be carried out immediately after chemical treatment. Increase in roughness and (to a lesser extent) in microhardness of surface layer of single crystal reduces strength of diffusion bond.

Composition of alternating silicon layers with n- and p- conductivity is no less promising. We used aluminum foils with a thickness of 0.05 mm as spacers between the silicon layers and, using the technology described above, we obtained the n- silicon + p-silicon layered composite. Volt-watt sensitivity of such GHFSs is almost twice as high as that achieved by silicon + aluminum composition, and their heat resistance is limited by the softening temperature of silicon (827 °C).

Further research will be devoted to ensuring required mechanical strength and sufficient for practical application of GHFSs with a volt-watt sensitivity of compositions.

References
[1] Geiling L 1951 Zschr. F. Angew. Phys. 3 12
[2] Sapozhnikov S Z, Mitiakov V Yu and Mitiakov A V 2012 Principles of gradient heat flux measurement (Saint Petersburg: Polytechnic University Edition) 293 p
[3] Lartz D J, Cudney H H and Diller T E 1994 Proc. 10th Inter. Heat Transfer Conference (Brighton, UK) 2 pp 261–6