A shape-memory-metal based sensor for monitoring atmospheric-electrical processes

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Abstract. A sensor based on a paramagnetic substance (titanium nickelide) is developed. An element made of this material is capable of oscillating under constant mechanical loading with a cyclic temperature change relative to a certain critical point at which a phase transition of a substance from one modification to another takes place. Near this critical point, the system is essentially nonlinear and potentially capable of reacting to the effects of external factors that determine environmental conditions.

Introduction

The sensor is an element made of the equiatomic TiNi alloy subjected to preliminary cycling (about 1000 cycles) during martensitic transformation at a constant load of 50 MPa.

The alloy was obtained by the method developed at the Institute of Climatic and Ecological Systems, Siberian Branch, Russian Academy of Sciences, using special metallurgical vacuum equipment (Figure 1).

Figure 1. Schematic of the melting furnace chamber: (1) water-cooled melting chamber, (2) water-cooled inductor, (3) rotational melting crucible, (4) water-cooled crystallizer, (5) weighing buckets, (6) transport bucket, and (7) water-cooled six-position rotary drum.
The method of induction heating of a metal in a protective atmosphere was used. Automatic mixing of the melt provided a high uniformity of composition and accuracy of the ratio between the fractions of the atoms that were in the composition of components. The ingots were heated to 800–850 °C, treated with pressure to obtain a required diameter and a thickness, and then annealed in a vacuum furnace at 800 °C for 1 hour. Before and after annealing, the oxide surface layer was chemically removed. The onset temperature of the sensors obtained from the ingots subjected to final heat treatment and preliminary cycling was equal to ~ 22 °C for the low-temperature martensitic phase. The temperature characteristics of the sensor within the operating range used are shown in Figure 2.

![Figure 2](image-url)  
*Figure 2.* Electrical resistivity of the sensor $R = f(T)$ as a function of temperature within the working range. $M_s$ is the onset temperature of the phase transition.

The sensor operates in the continuous monitoring mode during thermal cycling under constant load in the form of self-oscillations according to the scheme described in [1]. The equipment with a built-in sensor is under heat- and humidity-stable conditions; the daily temperature deviation does not exceed 0.5 °C; humidity is kept constant. Self-oscillations accompanied by a change and restoration of the geometric shape of the sensor occur due to an external heat source (incandescent lamp) and the cold air of the working chamber. The oscillation phase related to a change in shape takes place during cooling under constant mechanical loading. In this case, after reaching the temperature of the phase transition the crystals of the new phase are formed in the sensor substance. These crystals grow under the applied load, which leads to a total change of the shape of the sensor. The shape recovery phase occurs during heating, when low-temperature crystals undergo a reverse phase transition. The described process is known in the literature as a shape memory observed in some metals and alloys.

In the sensor tests, the variable parameter was the strain rate during self-oscillating. The rate was determined by the flashes of the lamp that was switched on and off in the self-oscillating mode, providing a reverse change in the sensor temperature relative to the phase transition point. The amplitude of the sensor shape variations, observed in this case, was fixed, which was provided by the contactless sensors mounted at the edges. Thus, knowing the traveled distance and the time required for the change and restoration of the shape, the desired parameter, namely the strain rate of the sensor was obtained. The rate was measured in the monitoring mode with a 10-minute step. The measurement error was 0.2%. The value measured in the continuous mode was recorded by the control unit and sent to the computer for plotting of the strain rate as a function of time. The plots are constructed considering that the background value of the strain rate is conventionally taken to be equal to 1. Their typical form and the behavior of the variable in some cases are presented in Fig. 3. The irregular behavior of the variable $(a)$ changes to the quasiperiodic dependence $(b)$. There are certain types of dependencies such as pick-shaped $(a, \text{November 14, 2013})$ and II-shaped $(b, \text{July 4, 2016})$; a slow rise to the maximum and a rapid drop $(c)$; rapid rise and slow drop $(d)$. 
The analysis of the obtained data showed that the sensor can serve as a sensitive tool for monitoring meteorological processes [2]. In particular, a correlation was found in certain periods between the sensor readings and the behavior of stormglass that is well known for its selective sensitivity to storm weather conditions [3]. A sharp increase in the growth of crystals in the solution of stormglass was observed after several hours (3±4 h) after that the sensor detected a peak-shaped emission similar to that recorded on November 14, 2013 (Figure 3) and coinciding with a high-amplitude jump in the atmospheric pressure.

At the same time, after 3-5 days from the occurrence of such anomalies in the sensor readings, the pressure curves and a jump in the growth of crystals also show a change in the speed and direction of wind, which is characterized by a sharp change in the atmospheric circulation mode (Figure 4). The described situation, as a rule, occurs during the period of the near-decade minimum of atmospheric pressure with a frequency of up to three cases per month depending on the season.

Figure 3. Time dependences of the TiNi-element strain rate
Figure 4. Curves of the sensor oscillation speed (a), dynamics of the movement of stormglass crystals (b), atmospheric pressure (c), the change in wind direction (d).

The arrows show the fixation of the image.

The sensor also can be used to determine the leading factors forming the environmental conditions, including electric fields in the atmosphere. Synchronous variations indicating a common external factor affecting atmospheric processes were obtained comparing the simultaneous sensor readings and their values of a parameter characterizing the environmental conditions [4].

Figure 5 shows the curves of the sensor readings and the absolute humidity of the surface atmosphere for the same period of time. Low-amplitude humidity variations are known to be related to the variations in the concentration of drop quasicrystalline clusters formed due to electrical inter-drop interaction [5].
Figure 5. Comparison of the time dependences of the TiNi-element strain rate and the absolute surface humidity (data for February 19–24, 2011)

The coincidence of graphs is close to 100%, considering the fact that at certain moments the coincidence is related to the averaged sensor readings (sections marked with dashed lines), which is due to the mechanism of atmospheric humidity formation, including the inertia of this process.

Figure 6 shows a similar relationship between the sensor readings and the electric field intensity of the surface atmosphere. Here, the coincidence of graphs is also observed (in this case, a mirror coincidence), close to 100%.

Figure 6. Comparison of the time dependences of the TiNi-element strain rate and the surface electric field strength

The synchronous variations indicate that in doubled systems (metal - wet medium and metal - electric field) simultaneous processes take place in each of the systems. In both cases, there is an electric potential modulation, which is directly involved in the formation of variations in the humidity and the electric field intensity. However, the observed variations in the atmospheric electric field cannot influence on structural transformations in the paramagnetic substance of the sensor. Therefore, this fact indicates the synchronism of variations in the parameters due to the effect of a common external factor. Such an external factor, as the analysis of literature data shows, is most likely to be a factor of extraterrestrial origin, for example in [6]. This is also indicated by the nature of the substance from which the sensor is made (paramagnetic) and the conditions of its testing (underground facility with constant thermodynamic parameters). Considering these circumstances, this factor should have a significant penetrating ability and a high energy component to modulate the rate of martensitic reaction. These requirements are met by the factor considered in a number of articles, including [6]. It has a high penetrating ability and an energy component, the value of which exceeds any technogenic impact by several orders.

The presented data indicate that variations in permanently operating extraterrestrial high-energy corpuscular streams significantly contribute to the formation of environmental conditions, including electric fields in the atmosphere.
References
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