Heat losses and thermal imaging of ferroic components

S E Ilyashenko¹, A I Ivanova², O V Gasanov³, R M Grechishkin²,³, S A Tretiakov²,³, K B Yushkov³ and B B J Linde⁴
¹Tver State Technical University, 170026 Tver, Russia
²Tver State University, 170100 Tver, Russia
³National University of Science and Technology “MISIS”, 119049 Moscow, Russia
⁴Institute of Experimental Physics, University of Gdansk, 80-952 Gdansk, Poland

e-mail: SvIlyashenko@yandex.ru

Abstract. A study is made of spatial and temporal temperature variations in working devices based on ferroic functional materials. The measurement of the sample’s temperature is complemented with direct observation of its distribution over the sample surface. For the latter purpose a thermovision infrared videocamera technique was employed. Specific features of the temperature distribution and its evolution during heating and cooling of a number of piezoelectric, acoustooptic and shape memory components are revealed. Examples of hot spot observations indicative of structural defects in the samples under study are given thus suggesting the use of thermal vision for nondestructive testing. A proposal is made to combine the thermovision method with that of thermomagnetic analysis for the study of ferromagnetic shape memory alloys.

1. Introduction

The magnitude of the electrical and mechanical losses in components made of functional ferroic materials which are currently widely used in electronic circuits often determines the application of these materials [1-3]. Temperature and thermal characterization of ferroic materials, components and modules represents an important part in quantifying and minimizing temperature stresses for efficient thermal management. Diverse array of methods for local temperature measurements and thermography were developed to satisfy the requirements of materials science researchers and designers of electromechanical, optoelectronic, acoustic, acoustooptic, magnetooptic, magnetic and magnetoelectric devices, etc. Among the different thermal imaging technologies are imaging crystal thermography, fluorescent microthermography, scanning thermal microscopy, infrared radiation thermometry, thermoreflectance, acoustic thermography, photothermal deflection spectroscopy and many others [4].

Nowadays special interest is paid to the methods of infrared radiation thermometry. In addition to a number of great benefits inherent to these methods the researchers are inspired by rapid progress in the development of commercially available high-sensitive IR videocameras which are more and more employed in R&D activities.

In the present work we report on the experimental results of applying the IR thermal imaging technique for the examination of several types of ferroic-based components including ordinary piezoceramic actuators, piezoelectric macro fiber composites (NASA MFC), acoustooptic components on the base of piezoelectric single crystals, and ferromagnetic shape memory alloys [5].
2. Experimental

2.1. LZT piezoceramics

Thermal imaging and quantification of standard piezoceramic PbZr/TiO$_3$ (LZT) disk shaped samples excited at their frequency of resonance ~ 80 kHz was performed with the aid of FLIR ResearchIR camera (IR resolution 160×120 pixels, spatial resolution 2.72 mrad, thermal sensitivity <0.07 °C, spectral range 7.5…13 µm) with proper calibration procedure taking into account the coefficient of reflection of the materials under study. Figure 1 shows the thermal images of the surface of freely suspended LZT disk (diameter ~25 mm) together with the temperature line profiles starting from the moment of power switching on to the moment of establishing a steady-state regime. The presented data clearly show that the heating of the sample starts from its centre while the temperature distribution is much more uniform during unforced cooling under ambient conditions. This feature may have an influence on the choice of working conditions for components exploited in a pulsed mode.

Figure 1. Thermal images and temperature line profiles for a disk-shaped piezoceramic sample during heating (a, b) and cooling (c, d, e). Note the change of the $T(x)$ curve shape from conoidal (a) to a hat-like one (c – e)

2.2. Piezoelectric Macro Fiber Composite (MFC)

MFC’s belong to a relatively new class of smart structures utilizing the piezoelectric effect for sensing, actuation, energy harvesting and damping [5], so the information about their temperature behavior is important both from the academic and engineering point of view.

Figure 2 presents the images and temperature line profiles of an MFC flat sample with a size of 20 by 30 mm. It is seen that at the early stage of heating after activation the temperature distribution is rather asymmetrical (Figure 2, a, b). This asymmetry is much less pronounced during the cooling
process. The microstructural control of this sample by means of optical and scanning electron microscopy enabled to reveal a subsurface defect (delaminated flat spot ~5 mm in diameter) in this particular sample just corresponding to the region of thermal anomaly. This result demonstrates the usefulness of thermal imaging method for nondestructive testing of piezoelectric composites.

Figure 2. Temperature line profile of flexible MFC sample (size 20×30 mm) at $T_{\text{max}}$ 62.8 (a), 126.4 (b) and 87 °C (c). State (c) was achieved by cooling from (b)

2.3. Acoustooptic devices on the base of piezoelectric single crystal LiNbO$_3$ and α-TeO$_2$

Heat release in working acousto-optical (AO) device is inevitably accompanied by a change of its acousto-optical parameters. In the visible and medium-infrared the most called-for and effective materials for acoustooptic devices are paratellurite ($\alpha$-TeO$_2$) and lithium niobate (LiNbO$_3$) single crystals.

In the present work we focus on the specific features of the temperature distribution in large-size (36×25×22 mm) acousto-optic line utilized as a part of tunable acoustooptic filter (Figure 3). The filter was intended for astrophysical spectral studies described in detail elsewhere [6]. Large size of acousto-optic line necessary for high spectral resolution imposes strict requirements on the device thermostat control and temperature drift compensation of filter parameters exploited in terrestrial telescopes, all the more for spacecraft applications.

Figure 3. Acoustooptic tunable filter on the base of paratellurite single crystal with lithium niobate actuator. (a) schematic, (b) general view (cover removed), (c) thermal image. Cross marks correspond to measurement points Sp1...Sp5 allocated in the center and at the periphery of the image to obtain information on the temperature distribution over the output face.

The main results of the thermal testing are presented in figure 4, illustrating the time and frequency dependence of the temperature at reference points Sp1...Sp5 of the AO filter crystal. The data were registered at a speed of 25 frames/s with 10 MHz increments from 50 to 250 MHz (a, b…u) each 300 s and constant power. In addition, the temperature changes at the same points of observation...
Sp1…Sp5 are plotted for different input power values changed stepwise by 0.5 W increments starting from 0.5 W (region (a), 1.0 W (b), 1.5 W (c), … etc.

Figure 4. (a) Time and frequency dependence of the temperature at reference points Sp1...Sp5 of the AO filter crystal registered a 10 MHz increments from 50 to 250 MHz (a, b...u) each 300 s and constant power; (b) temperature changes at Sp1…Sp5 observation points for different power values changed stepwise by 0.5 W increments starting from 0.5 W (region (a), 1.0 W (b), 1.5 W (c), … etc. Generator frequency 140 MHz.

The performed tests show that relatively large temperature gradients of 4…5 K/cm are arising during the exploitation of the AO devices on the base of paratellurite. Evidently this fact is explained by the low heat conductivity of the latter. This unfavourable circumstance should be taken into account in the design of AO devices because temperature-induced distortion of the acoustic and light wave fronts results in additional distortion of the filter transmission function within the limits of designated spectral range.

2.4. Temperature effects in ferromagnetic shape memory alloys Ni-Mn-Ga

Ferromagnetic shape memory alloys on the base of Heusler alloys of the NiMn$_2$Ga family possess a unique set of magnetic, magnetocaloric, electric and mechanical properties, making them perspective candidates for a large number of various applications (see, e.g., [5]).

Among the characteristic features of these alloys is a martensite-type structural transformation from highly symmetric high-temperature cubic phase to a phase with lower symmetry. This transformation is accompanied by a number of anomalies of physical properties, in particular, thermal ones.

Figure 5. Temperature difference $\Delta T$ between the heating table and the Ni$_{2.16}$Mn$_{0.84}$Ga sample during heating and cooling

Figure 6. Superimposed time dependence of the Ni$_{2.16}$Mn$_{0.84}$Ga sample temperature and initial ac magnetic susceptibility
Figure 5 shows the variation of the temperature of a $\text{Ni}_{2.16}\text{Mn}_{0.84}\text{Ga}$ sample in the neighborhood of the phase transformation region measured with the aid of thermovision camera. Two characteristic peaks are clearly seen at the temperatures corresponding to those of martensite start and finish of this alloy. Moreover, due to remote character of thermal testings it became possible to combine this measurement with the differential thermal analysis (TMA) by the temperature dependence of the ac initial magnetic susceptibility $\chi$ (figure 6). The presented measurements were performed in the following way: starting from RT the sample was smoothly heated up to $37.5\,^\circ\text{C}$ and then allowed to cool to RT in a time of ~600 s. Both sample temperature $T$ and susceptibility $\chi$ were recorded as a function of time ($t$). Characteristic kinks are seen at the points A and B of the $T(t)$ curve (figure 6) indicative of magnetocaloric effect due to direct and reverse phase transitions at these temperatures. It is worthwhile to mention that this information is not available from the $\chi(t)$ data taken separately.

3. Conclusions

Based on the thermal vision infrared camera technique we demonstrated the spatial and temporal temperature variations in working components based on piezoceramic, piezoelectric macro fiber composite, acoustooptic single crystals and ferromagnetic shape memory alloys. Specific features of the temperature distribution and its evolution with time after switching on the exciting voltage (heating) followed by cooling are shown. Hot spot detection indicative of defects in the structure of materials are observed thus suggesting the use of thermal vision for nondestructive testing. A proposal is made to combine the direct thermal observations of the surface of ferromagnetic shape memory alloys with their simultaneous thermomagnetic analysis by the temperature dependence of initial ac magnetic susceptibility. This combination adds a new dimension in the characterization of structural phase transformations.

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