Michał KOPEĆ
LODZ UNIVERSITY OF TECHNOLOGY, INSTITUTE OF ELECTRONICS
211/215 Wolczanska St., 90-924 Lodz

Recognizing the authenticity of the postal envelopes sealing using IR thermography and thickness measurement

Abstract

This paper presents two methods to recognize authenticity of the postal envelopes sealing. These methods are: infrared thermography and thickness measurement. Additionally, microscope inspection is presented. Based on the results, quantitative assessment was developed. The proposed methods make it possible to recognize authenticity of the postal envelopes sealing.

Keywords: envelope, sealing, infrared camera, caliper, microscope.

1. Introduction

Postal envelope sealing ensures protection of its content. There are several types of postal envelope protection [1]. Security envelopes are used for shipping of important documents and for evidence in a legal proceeding. Security envelopes heave special tamper-resistant features e.g. patterned tint printed on the inside. This solution makes difficult to read the contents without opening envelope. TRIFIX system is another protection method; it's characterized by:

- holes which allow to use clips,
- strong glue or double-sided adhesive strip. These are associated with permanent and temporary closure, respectively. The adhesive elements in double-sided strip are usually polypropylene (*PP*) and polyester (*PET*) films or thin synthetic fibers,
- finger-lift – also called tear-off cover.

The next protection methods are types of sealing, what influence on protection of correspondence [2]. Wet sealing is a traditional way, designed for personal correspondence and automatic packaging. Another method is a self-adhesive sealing. The self-adhesive sealing is very often applied in administrative correspondence. The last method is a multiple sealing. The multiple sealing enables to reuse of envelope, it is applied in shipment by internal post.

The originality of envelope closure can be changed in many ways. These transformations depend on fragment removal, adding new element to existing element or optimal storage conditions. In Europe, currently applied solutions to recognize authenticity of the envelope sealing are open plus method or detector method [3]. In USA is also performed string and button method. In this article infrared method and thickness measurement were proposed.

2. Materials and methods

The aim of these studies is recognize authenticity of the postal envelopes sealing. The experiments are performed for C5 size (162 × 229 mm) postal envelopes (typically used for personal correspondence). The first envelope is closed with double-sided adhesive strip. The second envelope is closed with double-sided adhesive strip, next the envelope is opened, next glue stick layer is applied, after which the envelope is closed again. The used envelopes are made of paper with double-sided adhesive strip. Taking into account appearance, the envelopes are made of plain paper without printed inside. The density of paper ρ is equal 75 g/m^2.

Two methods are proposed for recognize authenticity of the postal envelopes sealing. These methods are: thickness measurement (Fig. 1) and infrared thermography (Fig. 2).

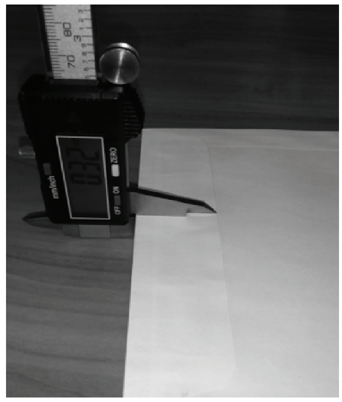


Fig. 1. The measurement test rig with digital caliper

The Cedip Titanium® 560M infrared camera with a cooled InSb FPA detector matrix (640 × 512 pixels resolution) providing a NETD value of 20 mK [4] is used to measurements. Sealing flap is in the front of the infrared camera during measurement.

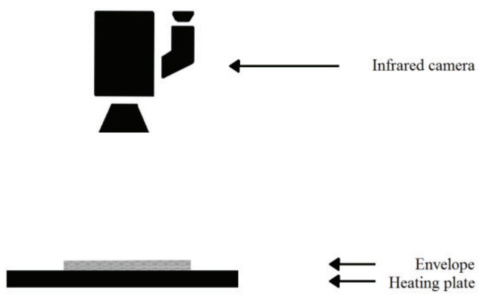


Fig. 2. The measurement test rig with infrared camera

A active thermography is chosen for the studies. This method depends on observing the thermal response to excitation energy or its loss [5]. The exemplary time curves which show the shape of the thermal responses are shown in Fig. 3a and Fig. 3b, respectively.

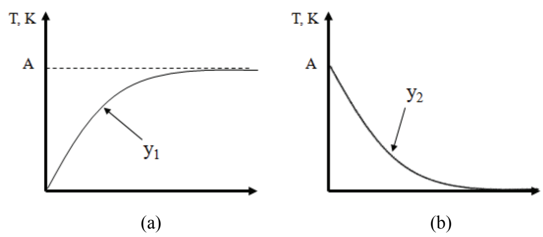


Fig. 3. The exemplary thermal responses

The temperature curve y_1 is the response of the system resulting from appear of the excitation energy (1) (Fig. 3a) and the temperature curve y_2 is the response of the system resulting from loss of the excitation energy (2) (Fig. 3b).

$$y_1 = A \cdot \left(1 - e^{-\frac{t}{\tau}}\right) \quad (1)$$

$$y_2 = A \cdot e^{\frac{t}{\tau}} \quad (2)$$

where: A – maximum temperature value, K; t – time, s; τ – time constant, s.

The time constant τ in the time domain is a parameter which relates to energy accumulated in material (Fig. 3a) or the response to excitation energy (Fig. 3b) [6]. The time constant for the response of the system resulting from appear of the excitation energy (Fig. 3a) is approximately equal $\frac{A}{1-\frac{1}{e}}$ which is 0.632 of initial value. In turn, the time constant for the response of the system resulting from loss of the excitation energy (Fig. 3b) is approximately equal $\frac{A}{e}$ value which is 0.368 of initial value.

The recorded sequence of 7200 thermograms is analyzed in the time domain using the time constants values. The T3Ster Master [7] is used to determine value of time constants.

An area of observation (Fig. 4) which is marked as dashed rectangle is chosen to purpose of the article. The area of observation is used to make the thermographic investigations (Fig. 5) and microscope inspection (Fig. 6).

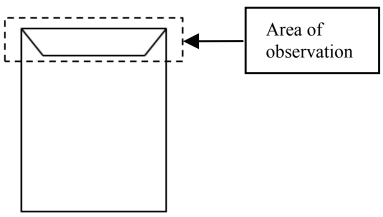
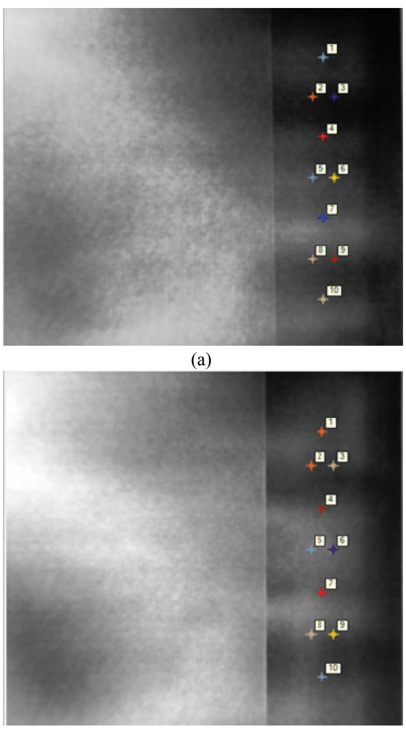


Fig. 4. Schematic of postal envelope

3. Results

The first measurement method is infrared thermography. The exemplary thermograms of the postal envelopes are shown in Fig. 5. For 10 chosen points are obtained data from thermograms acquisition.



(a)

(b)

Fig. 5. Exemplary thermograms (5500 frame from acquisitions) of postal envelopes – (a) – originally sealed envelope, (b) – resealed envelope

The thermal responses for point 1 are shown in Fig. 6.

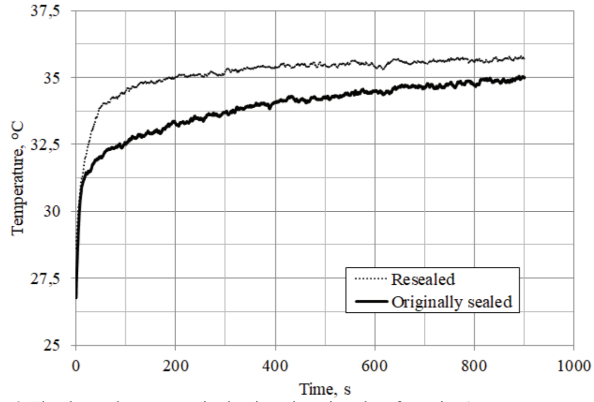


Fig. 6. The thermal responses in the time domain - data for point 1

The thermal responses are further analyzed with T3Ster Master software. The obtained values of time constants τ are presented in Tab. 1.

Tab. 1. The time constants values

Point number	Originally sealed envelope		Resealed envelope	
	τ_1, s	τ_2, s	τ_3, s	τ_4, s
1	5.88	295.12	21.88	295.12
2	6.31	309.03	16.98	281.85
3	6.46	309.03	18.20	288.19
4	5.62	309.03	17.38	295.12
5	5.25	331.13	16.22	288.48
6	5.75	316.23	17.38	275.47
7	5.37	316.23	15.85	316.23
8	6.46	295.12	14.79	316.26
9	7.08	295.12	16.22	309.01
10	7.24	288.40	16.60	316.22

The second method is thickness δ measurement using digital caliper. For each envelope, n = 10 measurements were made. The obtained results are shown in Tab. 2.

Tab. 2. The thickness measurements using caliper

n	Originally sealed envelope	Resealed envelope
	δ, mm	δ, mm
1	0.32	0.36
2	0.31	0.36
3	0.31	0.33
4	0.30	0.34
5	0.30	0.34
6	0.29	0.34
7	0.31	0.33
8	0.32	0.36
9	0.31	0.33
10	0.30	0.35

Additionally, microscope inspection is presented. In Fig. 6a and Fig. 6b are visible adhesive strip and layer of the glue, respectively. Several hundred times magnification give the opportunity to see all details of the structure, what isn't possible with naked eye.

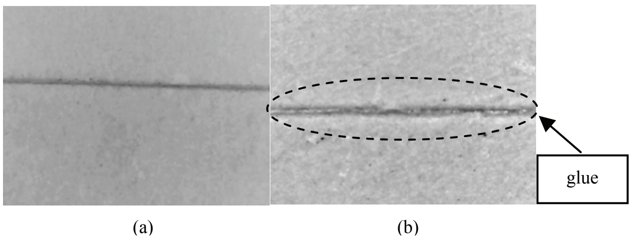


Fig. 6. Images obtained during microscope inspection; (a) – originally sealed envelope, (b) – resealed envelope

4. Analysis

Analysis of the obtained results is divided into several steps. In the first step is considered a steady heat conduction. One place on the envelopes is analyzed – at the sealing flap height. In Fig. 7 and Fig. 8 are shown heat conduction processes at sealing flap place. For originally sealed envelope (Fig. 7) three layers of paper and one layer of adhesive are considered.

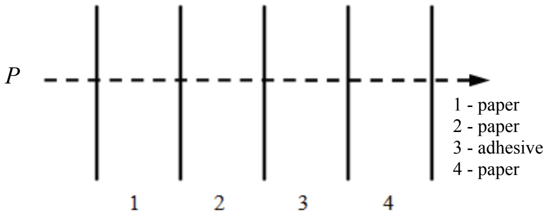


Fig. 7. Heat transfer through multilayer flat wall on the example of originally sealed envelope – at the sealing flap height

Three layers of paper, one layer of glue stick with air molecules and one layer of adhesive are considered for resealed envelope (Fig. 8). The density of paper ρ is an important parameter which should be taken into account. The density of used envelope ρ is equal 75 g/m^2. This value is low, so paper is flabby and susceptible to damage.

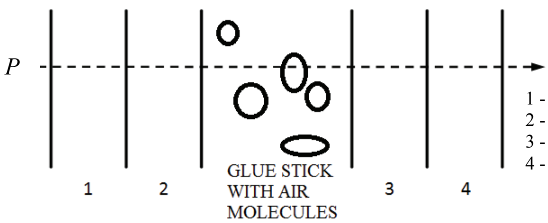


Fig. 8. Heat transfer through multilayer flat wall on the example of resealed envelope – at the sealing flap height

So, the process of opening a sealed envelope lead to damage of paper structure. The paper becomes more fluffy in the place of damage. The next sealing of the envelope will not be so permanent. The paper will be wrinkled after using glue stick. Therefore, air molecules may be present in some places. The heat conduction process make it more difficult in these places. The reason is low value of air thermal conductivity $\lambda = 0.0259\ \frac{\mathrm{W}}{\mathrm{m \cdot K}}$. The thermal conductivity values of the materials in tested objects are shown in Tab. 3 [8].

Tab. 3. The thermal conductivity values

	$\lambda, \frac{\mathrm{W}}{\mathrm{m \cdot K}}$
paper	0.038
glue stick	0.12
air	0.0259

The thermal conductivity value for glue stick $\lambda = 0.12\ \frac{\mathrm{W}}{\mathrm{m \cdot K}}$ is higher than for air and paper. According to (4), the high value of the thermal conductivity improves heat conduction – thermal resistance decreases. Consequently, the time constant which represent thermal behaviour of the envelope should have lower value. However, the thickness of glue layer is low, by what glue has little impact on the time constant value.

In Tab. 1 are shown the time constant values calculated using T3Ster Master software. For each point, two time constants were obtained. The first one (τ_1, τ_3) is representing the thermal behaviour of the envelope and the second one (τ_2, τ_4), an order of magnitude longer, is representing the convective cooling of the envelope. The latter will not be taken into account in the further analysis.

From a mathematical point of view time constant τ is a result of multiplication of thermal resistance R_{th} and thermal capacity C_{th} [9]. The time constant is expressed by (3).

$$\tau = R_{th} \cdot C_{th} \tag{3}$$

The thermal resistance R_{th} is a parameter describing material's ability to conduct a heat. Amount of transferred heat is dependent on material parameters λ, δ and cross sectional area S (4).

$$R_{th} = \frac{\delta}{\lambda \cdot S} \tag{4}$$

The thermal capacity C_{th} depends on material volume V, density ρ and specific heat c_p (5). The material volume is expressed by (6).

$$C_{th} = V \cdot \rho \cdot c_p \tag{5}$$

$$V = S \cdot \delta \tag{6}$$

The next step of analysis is indirect measurement. For each envelope, $n = 10$ measurements are made (Tab. 2). A digital caliper is used for this purpose. The envelopes are measured after closing, along sealing flap. The envelope thicknesses δ_i are averaged δ_{AVG} (7). The results are shown in Tab. 3.

$$\delta_{AVG} = \frac{\sum_i^n \delta_i}{n} \tag{7}$$

Moreover, the measurement uncertainty is estimated. The uncertainties of type A and B are determined [10]. For direct measurements A type uncertainty (8) comes down mainly to calculating a standard deviation s_{δ}.

$$u_A(\delta) = \sqrt{s_{\delta}^2} = \sqrt{\frac{1}{n(n-1)} \cdot \sum_{i=1}^{n} \left(\delta_i - \bar{\delta}\right)^2} \tag{8}$$

Type B uncertainty is expressed by (9). A caliper accuracy defines the calibration uncertainty $\Delta\delta$. The calibration uncertainty $\Delta\delta$ specified by the producer is equal 0.02 mm. The type B standard uncertainty is equal 0.012.

$$u_B(\delta) = \frac{\Delta\delta}{\sqrt{3}} \tag{9}$$

The combined uncertainty $u(\delta)$ is expressed by (10).

$$u(\delta) = \sqrt{s_{\delta}^2 + \frac{(\Delta\delta)^2}{3}} \tag{10}$$

The expanded uncertainty $U(\delta)$ with the confidence level $k = 2.26$ is as follows (11).

$$U(\delta) = k \cdot u(\delta) \tag{11}$$

Tab. 3. Summary results of thickness uncertainty

	Originally sealed	Resealed
δ_{AVG} , mm	0.307	0.344
$u_A(\delta)$, mm	0.031	0.036
$u_B(\delta)$, mm	0.012	0.012
$u(\delta)$, mm	0.042	0.047
$U(\delta)$, mm	0.096	0.106
δ, mm	(0.307±0.096)	(0.344±0.106)

The same procedure is repeated to estimate the expanded uncertainty $U(\tau)$ of the thermal time constants τ_1 and τ_3 (Tab. 2). The uncertainty $u_A(\tau)$ is determined using (8). Type B uncertainty is calculated from (12).

$$u_B(\tau) = \frac{\tau \cdot error_{RMS}}{100\sqrt{3}} \quad (12)$$

where $error_{RMS}$ is equal 0.1818% [11].

The combined uncertainty $u(\tau)$ and expanded uncertainty $U(\tau)$ are associated with equations (10) and (11), respectively. The obtained results are shown in Tab. 4.

Tab. 4. Summary results of thermal time constants uncertainty

	Originally sealed	Resealed
τ_{AVG} , s	6.14	17.15
$u_A(\tau)$, s	0.26	0.44
$u_B(\tau)$, s	0.06	0.18
$u(\tau)$, s	0.33	0.62
$U(\tau)$, s	0.74	1.40
τ, s	(6.14 ±0.74)	(17.15 ±1.40)

Based on the data from Tab. 3 one can concluded that the expanded uncertainty $U(\delta)$ is high in comparison to averaged thickness of envelope δ_{AVG} and is equal to 31% of δ_{AVG} value. In turn, the expanded uncertainty $U(\tau)$ (Tab. 4) is much smaller in comparison to averaged time constant value τ_{AVG}. This fact confirms that using infrared camera and thermal impedance method makes it possible to recognizing the authenticity of the postal envelope sealing.

5. Conclusions

In this article, the authenticity of postal envelope sealing was considered. Two methods were used for this purpose: infrared thermography and thickness measurement. It was established that it is possible to determinate if the envelope was reopen. Hence:

- observation of time response to excitation energy using infrared camera is an interesting solution from a scientific point of view. It was confirmed that the time constant value for resealed envelope was higher than the time constant value for originally sealed envelope. The reason was the presence of air molecules between paper layers.
- the resealed enveloped had higher thickness. The reason was low paper density, which results in susceptibility to damage. The paper in the damage place became more fluffy, what translated into increased thickness (Tab. 3).
- microscope inspection gave the opportunity to see all details of the structure, what wasn't possible with naked eye. The glue layer was visible after several times magnification (Fig. 6b).

6. References

[1] Western States Envelopes & Label: Seals and closures. [28.03.2017]. Available: http://www.wsel.com/envelopes/envelopes-101/seals-and-closures

[2] Sealing methods. [24.03.2017]. Available: http://www.blake-envelopes.com/pages/sealing-methods/34

[3] Tompla: International manufacturer of envelope. [1.05.2017]. Available: http://www.tompla.pl/fabryka_produkcja_kopert.htm

[4] FLIR, Flir Titanium Infrared Camera for research & development

[5] Maldague X. P. V.: Introduction to NDT by Active Infrared Thermography. Materials Evaluation, vol. 60, no. 9, pp. 1060-1073, 2002.

[6] Székely V., Rencz M.: Thermal dynamics and the time constant domain, IEEE Transactions on Components and Packaging Technologies. vol. 23, pp. 587-594, 2000.

[7] Thermal Transient Evaluation Tool User's Guide, T3Ster-Master Version 2.2, Mentor Graphics MicRed Division 2000-2012.

[8] Institute of Cracow University of Technology: Thermal conductivity coefficients. [4.03.2017]. Available: http://www.fizyka.pk.edu.pl/tabele/wsPrzewC.htm

[9] Kopeć M., Więcek B.: Thermographic detection of abraded pipeline walls in the industrial installations. Quantitative Infrared Thermography Conference 2016. DOI: 10.21611/qirt2016.062.

[10] Minkina W., Dudzik S.: Infrared thermography - errors and uncertainties. Measurement Automation Monitoring, vol. 55, no. 11, pp. 868-873, 2009.

[11] Kopeć M., Chatzipanagiotou P., De Mey G., Więcek B.: Detection of inner defects in industrial pipelines using transient IR thermography. Measurement Automation Monitoring, 2017.

Received: 10.11.2016 *Paper reviewed* *Accepted: 02.02.2017*

Michał KOPEĆ, MSc

Michał Kopeć graduated from the Faculty of Electrical, Electronic, Computer and Control Engineering (2014), in Electronics and Telecommunications. Currently he is a PhD student at the Electronic Circuits and Thermography Department of Lodz University of Technology. He is author or co-author of 8 papers. His areas of research are non-destructive testing using thermography, heat transfer problems and widely defined electronics.

e-mail: michal.kopec@dokt.p.lodz.pl