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Efficiency of two non-destructive testing methods to detect defects in polymeric materials

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Properties

ABSTRACT

Purpose: The aim of this paper was to compare application possibilities of non-destructive ultrasonic and thermographic testing methods to detect defects in polymeric materials. In experimental part, subsurface defects were made in specimens of polymeric materials such as PE, PMMA, laminate then experimentally detected and directly displayed in ultrasonic and thermographic images.
Design/methodology/approach: In this paper the development of a real-time non-invasive technique using pulsed infrared (IR) thermography to measure the temperature of polymer materials is described. In this study 16 specimens were pre-heated during specific time using infrared lamp. After that the specimen's surface temperature was scanned during cooling down process by a thermovision camera, then defects were detected by means of a thermographic images analysis. The second method applied was ultrasonic testing using the pulse-echo technique as a type of non-destructive testing commonly used to find flaws in materials and to measure the objects thickness. Frequencies of 2 to 10 MHz are common but for special purposes other frequencies are used.
Findings: The experimental results have demonstrated that application of ultrasonic and thermographic testing are effective methods to visualize and reveal defects in the polymeric materials.
Research limitations/implications: It is not possible to detect defects after a long pre-heating time of researched material because it results in uniform temperature on the whole surface of specimen. The most problems about identification of defects in tested materials by ultrasounds concern laminates.
Originality/value: This paper is a unique because it compares two non-destructive testing methods usually used separately to detect defects in polymeric materials.
Keywords: Non-Destructive Testing; Thermography; Ultrasounds; Polymeric materials

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1. Introduction

There are many different non-destructive testing techniques which can be applied to polymer materials, but so far, ultrasounds has occupied one of the leading places [1-4]. Nowadays, also utilization of thermography in various technical disciplines becomes increasingly common. This non-destructive testing technique has its applications in ecology, medicine (cancer testing), rescue, civil engineering, in observing thermal process and in material testing, and also to monitor manufacturing and transforming process when casting. The purpose of non-destructive testing is to determine defects of various type and size and their properties. It is not possible with one technique, thus various techniques are used to describe various defects [5-7].

Taking the way of thermal process activation thermography into account is classified into two categories: passive thermography, where object's outside temperature distribution and changes are observed without observer interference and active thermography which consists in observing the researched object's thermal answer to external thermal impulse stimulation being a function of time and in recording this answer by means of a thermograph. There are several types of thermography depending on a method of thermal activation: pulsed thermography, lock-in thermography with modulated heating, pulsed phase thermography.

The term thermography and thermovision include testing methods based on recording infrared part of radiation spectrum emitted by a body which then is converted by a special camera into a colour map of temperature [8, 9]. The thermovision system allows to measure temperature remotely and in many places at once. Therefore, the suitability of infrared thermography (IRT) to non-destructive testing depends on the ability to detect temperature variation or thermal contrast induced by a defect. Indeed, the defect visibility depends on several factors which involve the defect geometry (mainly defect diameter and position in testing material), the relative thermal characteristics (e.g. thermal conductivity, thermal diffusivity) between the defect and the host material, the way thermal stimulation is performed and the sensitivity of the used infrared imaging system. The presence of a defect at a certain depth interferes with the heat flow causing local surface temperature variations [10-16].

Ultrasounds and ultrasonic testing is the most popular non-destructive materials testing method [17-18].

Mostly, when we are searching defects and discontinuities we use pulse-echo methods. Pulse-Echo method uses a single head which is the impulse generator and the receiver at this same time. The impulse generated by the head passes through material and is reflected from the opposite material surface or from discontinuities, creates echo and returns to the head. Figure 1 illustrates the idea of the ultrasound pulse-echo testing method. This figure shows a longitudinal ultrasonic wave impulse generated by a single head [19].

When the ultrasonic head is in position 1 – we can see the image of the pulse reflected from the bottom of the object on the detector's screen. In the position 2 we can see the image of the pulse reflected from the bottom of the object, but also from the defect [20-26].

Parameters of the echo furnish information about occurrence and dimensions of defect. On the basis of ultrasound velocity in materials we can determinate distance between the ultrasonic head and defect. The height of the pulse (echo) from the defect allows for approximation of the defect's size.

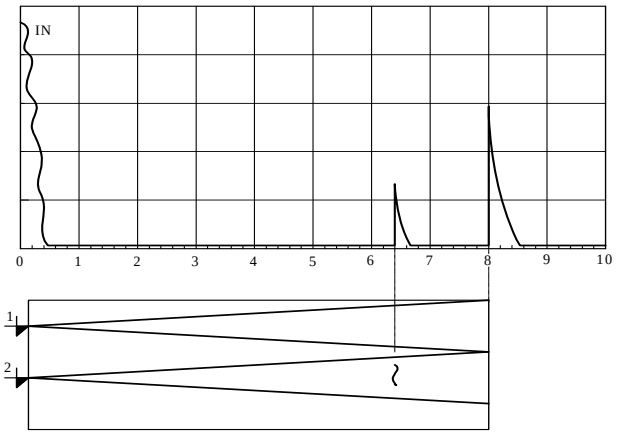


Fig. 1. Idea of the ultrasound pulse-echo testing method. The top image shows the flaw detector's screen. IN – trigger pulse. The bottom image shows the ultrasound wave passing through the material [19].

The size of the pulse reflected from the defect is influenced by many different factors, such as:

- type and shape of discontinuity,
- area of discontinuity,
- discontinuity orientation,
- distance between ultrasonic head and defect,
- elastic properties of tested material,
- homogeneity and anisotropy of this material.

The smallest size of the defect possible to be detected by ultrasound flaw detector depends on wavelength and head frequency. If the defect is smaller than half wave size then wave passes through the defect without any effect and we cannot see the image of defects on the detector's screen [27-30].

The first aim of this work was to present the ultrasonic and thermographic testing techniques used to detect defects in polymeric materials. The second aim was to compare research results of both methods.

2. Experimental

The aim of this research is to determine the possibility of the use of non-destructive ultrasonic and thermographic testing to detect defects in polymeric materials.

2.1. Materials for research

Non-Destructive Testing research was carried out on twelve polymeric specimens. Three different materials and four different shapes were used to compare holes of the same geometry made in each specimen. Materials used in the study are presented in Table 1. The photograph of three specimens is shown in Figure 2.

Table 1.
List of materials used in research

Material	Manufacturer
High density polyethylene	Plate manufacturing company "Szagru" Sp. z oo – Pszczyna (Poland)
Polymethacrylate(methylate)	Plate manufacturing chemical company "Dwory" S.A. – Oświęcim (Poland)
Phenyl-cotton laminate	Plate manufacturing company "IZO-ERG" S.A. – Gliwice (Poland)

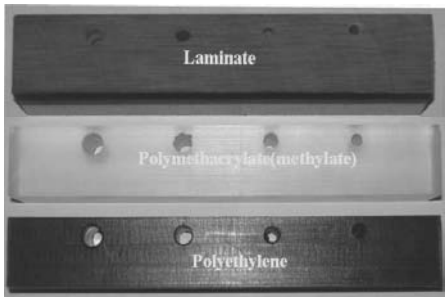


Fig. 2. Photograph of three testing specimens

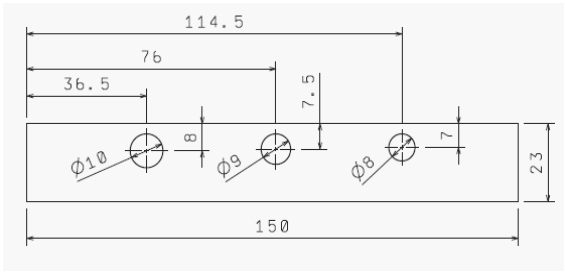
The specimens in the form of a rectangular prism having dimensions of 23,5x35x150 mm and holes of different diameters placed in a distance of about 3mm from the searched surface were tested. A fourth specimen from each material had only holes 5mm in diameter, situated in a sample so that their distance from the test surface was different. Before thermographic testing all specimens surfaces were uniformly painted with black matt coating to assure good heat emission. The defects geometry and spacing in specimens is shown in Fig. 3.

2.2. Methodology

The specimens were tested using two non-destructive testing methods, namely ultrasonic and active thermography. The methods used in the described research belong to pulsed infrared thermography and pulse-echo ultrasonic method.

In purpose to carry out thermographic testing a special stand was prepared (Fig.4). This stand includes: infrared radiator (IR) (Victory Lightning) [31], insulating shield in the form of frame with specimen mounted and a thermovision camera (Inframetrics type 760B USA). Specimens were activated by short pre-heating time. The investigation is about observing the temperature distribution of the surface with subsurface defects after short thermal impulse. Specimens were searched during cooling-down process. Specimen's surface temperature during cooling down process was observed in areas above defects and in areas without defects. The specimens were located at a constant distance of 80mm from radiation source. Together with the end of the pre-heating process, the surface temperature recording procedure began.

a)



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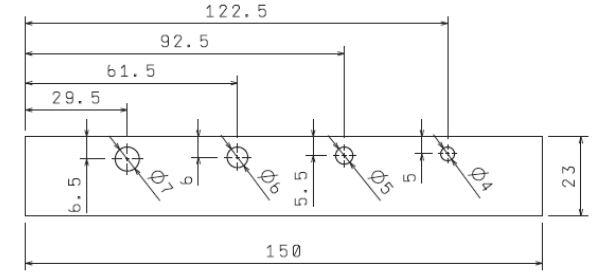

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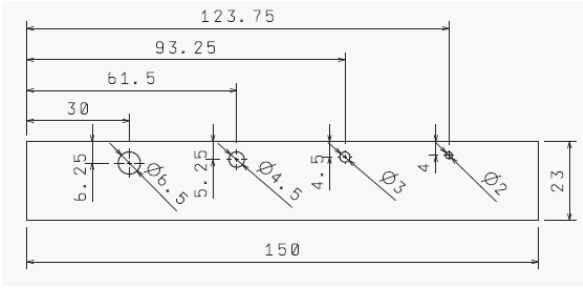

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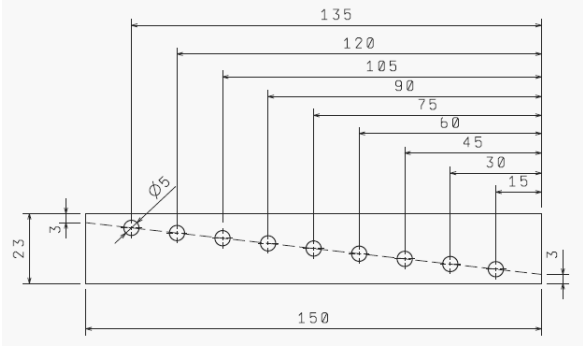

Fig. 3. Specimens and defects geometry: a) specimen with holes Φ10mm, Φ9mm and Φ8mm, b) specimen with holes Φ4 – Φ7mm, c) specimen with holes Φ2mm, Φ3mm, Φ4.5mm and Φ6.5mm, d) specimen with holes placed at different distances to surface

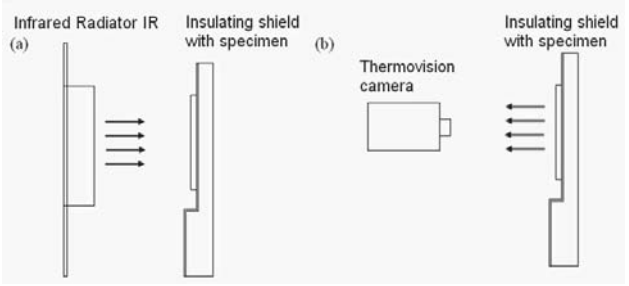

Fig. 4. Scheme of thermovision research stand: a) specimen pre-heating process, b) observing specimen's surface by a thermovision camera

Procedure of ultrasonic testing.

In our testing we used a digital ultrasonic flaw detector UMT - 17 supplied by ULTRAMET company (Poland), being in communication with a computer via a standard PC including USB connection. This test stand is presented in the Figure 5.

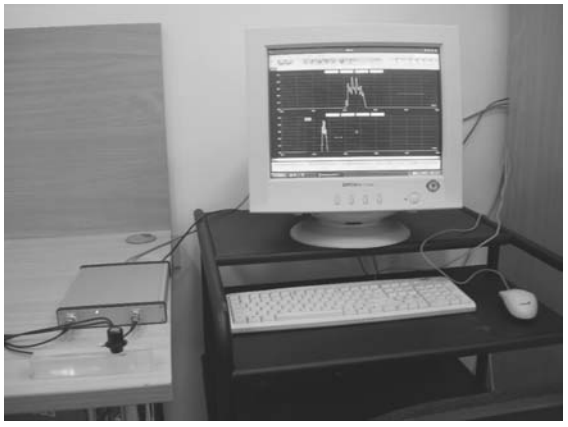

Fig. 5. Ultrasonic testing stand

In our testing we used 2LDL13 head supplied by UNIPAN (Poland) with the following parameters:

- oscillation frequency of transmitter: 2 MHz,
- type of excited waves: longitudinal,
- head diameter: 13mm,
- head type: double-transducer.

This head was used because of the relatively low internal response distortion in comparison with other heads and its universality - head emitting ultrasonic waves with 2 MHz frequency allows to study both steels and polymeric materials. This feature makes it possible to carry out comparative studies with polymeric samples and reference sample made of steel.

3. Result and their analysis

Thermal imaging technique enables to observe continuously surface temperature changes. It is not possible to present all thermographic images and temperature measurement results so only selected examples will be shown. Similarly, in the case of ultrasonic testing we present only few chosen images obtained from the flaw detector.

3.1. Polyethylene

Polyethylene HDPE has the lowest density of the tested materials (0.94 - 0.97 g/cm^3). After the flaw detector is calibrated a picture of the pulse from the bottom of the image of the sample is obtained. On the basis of the sample's dimension ultrasonic velocity of wave penetration across the material was calculated. The result was 2450 m/s.

The shape of the pulse image from the flaw detector was very similar toall holes (defects) of different sizes, placed at 3mm distance from the surface of the test piece (Fig. 6).

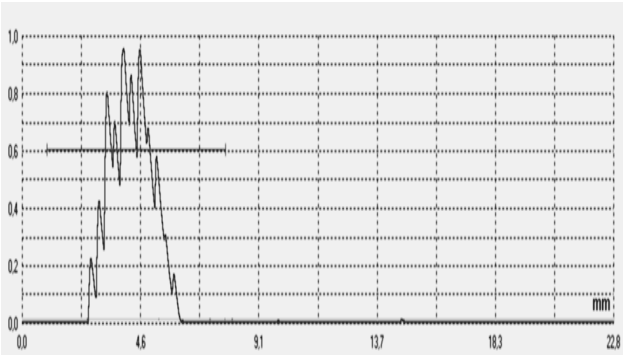

Fig. 6. Pulse image obtained from the 10mm diameter defect 3.25mm under the surface. Ultrasonic head was at the central position above the defect. (Amplification - 72.40 dB; Undercutting - 49, 46 %)

Changing the defect size (diameter) from bigger to smaller caused also a decrease of the amplitude of the signal received from defect. However, with defects smaller than 4mm it was not possible to obtain a single pulse image from the defect but two pulse images - one from the defect and second from bottom of sample (Fig. 7).

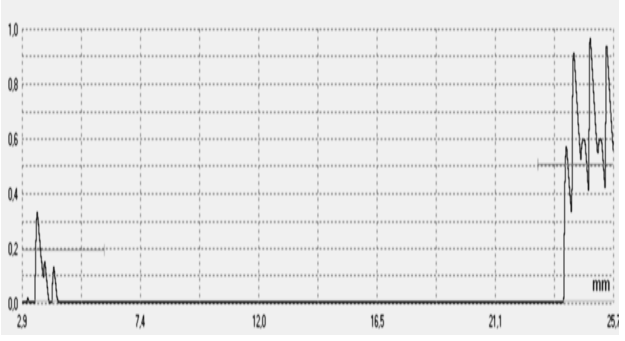

Fig. 7. Pulse images obtained from the 2mm diameter defect at 3.44 mm depth. Ultrasonic head was at the central position above the defect. (Amplification - 72.40 dB; Undercutting -72, 17 %)

For defects with a diameter of 5mm, located at different distances from the surface of the test piece the following results were obtained. The hole located at 2.5 mm distance from the surface gave the pulse image with the smallest amplitude. Up to the 10,8mm depth, the greater was the distance between defect and the surface, the bigger was the amplitude.

The temperature profile on the thermographic image shows that one can detect subsurface defects (Fig. 8). Because of lower air thermal conductivity than solid material conductivity existence the defect is manifested by higher temperature in the defected region. Comparing thermograms taken at different time it was observed that about 1 minute after the end of the pre-heating process (in case of polymeric materials) temperature profiles revealed the internal defects. In order to get a clear picture of searched defects the pre-heating time cannot be too long. Long-time pre-heating led to even temperature distribution over entire searched surface. This effect was observed independently on type of a heat source (quartz or ceramic radiator) and on the position of the radiator. After many trials it was stated that an appropriate warm-up time in case of polymeric materials should be about 2 seconds and to compare steel samples it should be about 10 seconds. It is probable due to higher steel thermal conductivity. Short heat pulses are very quickly distributed and consumed to sample warming.

It is also important that only for PE specimen (Fig.10) it was possible to detect all defects, while in the remaining samples it was not possible to defect 4mm in diameter. In case of PE specimens we also noted greater differences in temperature during observation of the defected areas than in other materials.

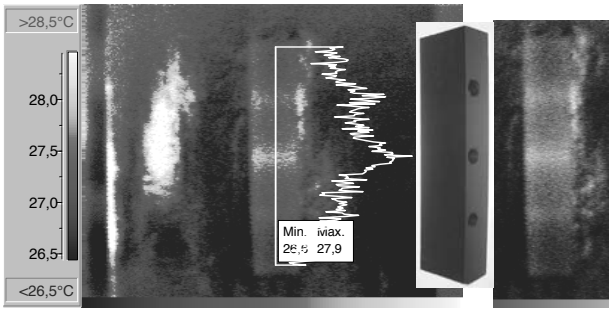

Fig. 8. The thermal image of polyethylene specimen registered ninety seconds after the end of pre-heating process

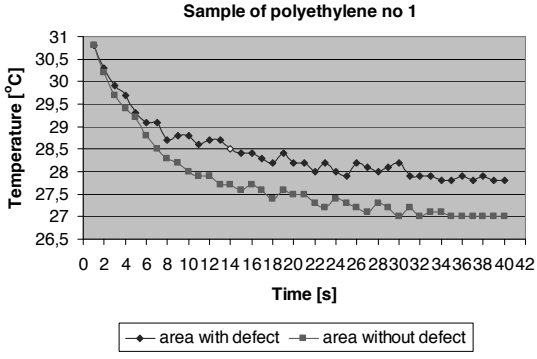

Fig. 9. The dependence of temperature on cooling time for areas with and without defect

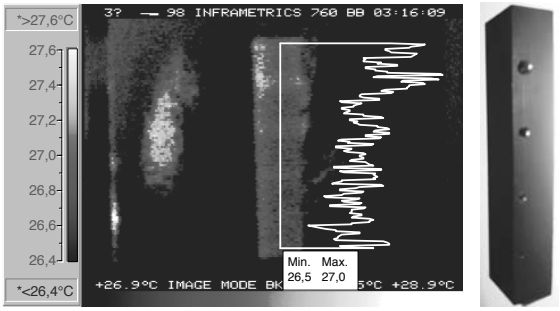

Fig. 10. The thermal image of polyethylene specimen registered sixty seconds after the end of pre-heating process

Figure 9 shows temperature changes against time. It can be noticed that the area without defect is cooled down more slowly in relation to the area with defect. On the basis of such graphs for shape comparison, it is possible to detect defects placement.

With the decrease of defects size, irrespective of the tested material, detection ability of defects also decreases, what is undoubtedly a limitation of this method of research (Fig. 10).

3.2. Polymethacrylate (methylate)

Density of the polymethacrylate (methylate) PMMA is 1.17 – 1.20 g/cm^3. Amplitude of signal in PMMA was 0.91, and it was greater than the amplitude of the signal obtained in polyethylene sample, which was 0.90, while reinforcement was 59.20 dB. Taking the sample's dimension into account, velocity of ultrasonic wave propagation across the material was calculated. The result was 2720 m/s.

To compare test results obtained for different materials, it was necessary to increase amplification. After an increase in the value of the undercutting to -72, 00 %, images of the polymethacrylate (methylate) did not differ much from images obtained during the study of polyethylene (Fig. 11).

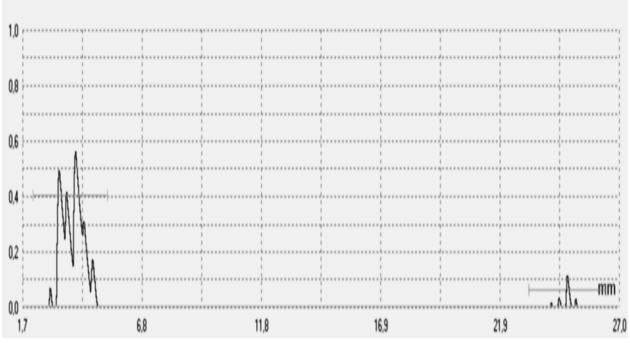

Fig. 11. Pulse image from the 10mm diameter defect at a depth of 3, 24 mm. Ultrasonic head was placed at the central position above the defect. (Amplification - 72.40 dB; Undercutting -72, 00 %)

In the Figure 12 the second pulse image is visible (on the right side of the picture) reflected from the bottom of the sample. This

pulse image we received even when the head was placed in central position over a defect (hole). Damping of the ultrasonic wave in the PMMA was smaller than in polyethylene so distinct images of pulse reflected from the bottom were observed for defect-holes with 6.5mm diameter or less.

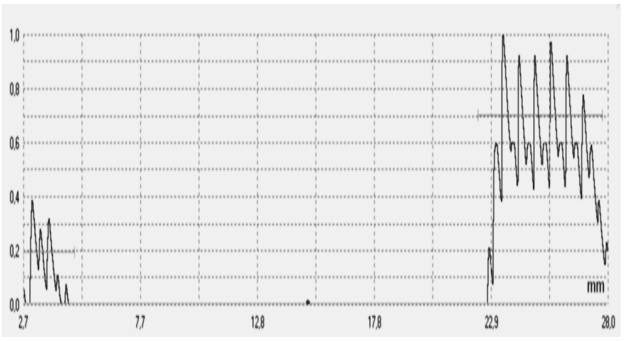

Fig. 12. Pulse image from the 2mm diameter defect at 2, 99 mm deep. Ultrasonic head was placed at the central position above the defect. (Amplification - 72.40 dB; Undercutting -72, 00 %)

For defects with a diameter of 5mm, located at different distances from the surface of the test piece the following results were obtained. As a result of lower damping of the ultrasonic waves in PMMA than in the PE, each time, images of pulse reflected from defects and bottom of the sample were visible.

In thermographic research, in case of polymeric materials temperature differences resulting from defects began to appear after about one minute from the end of pre-heating process (Fig. 13). A relation between temperature and time elapsing after pre-heating interruption achieved in defect area are characterized by a higher temperature in connection to the rest of the specimen. Also, the cooling process in the area with defect runs much longer (Fig. 14).

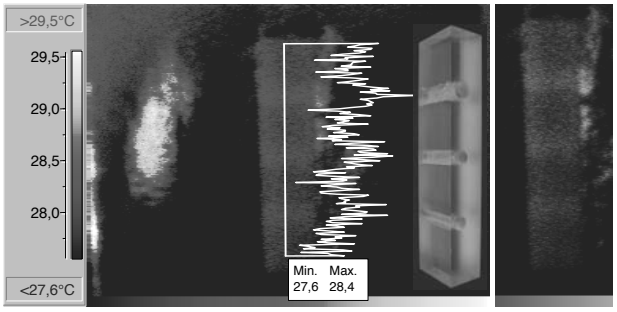

Fig. 13. The thermal image of polymethacrylate (methylate) specimen recorded one hundred fifty seconds from the end of pre-heating process

Collected thermograms show that both geometry and distribution of defects affect the obtained results. In specimen of polymethacrylate (methylate), thermography failed to detect defects with diameter smaller than 4mm (Fig. 15).

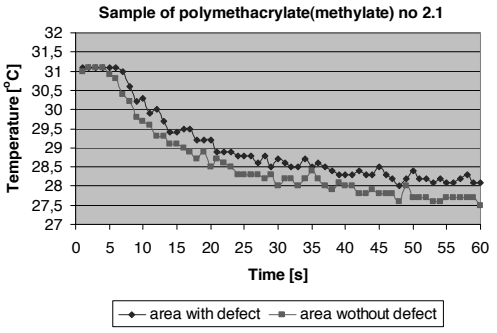

Fig. 14. The dependence of temperature on cooling time for the areas with and without defect

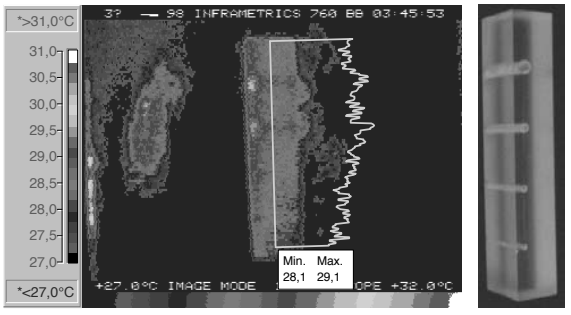

Fig. 15. The thermal image of polymethacrylate (methylate) recorded sixty seconds from the end of pre-heating process

3.3. Laminate

Density of the cotton-phenolic laminate is 1.30 ÷ 1.40 g/cm^3. Taking the sample's dimension into account, velocity of ultrasonic wave propagation across the material was calculated. The result was 2670 m/s.

Damping of the ultrasonic wave in the laminate was the greatest among all tested materials. Pulse reflected from the bottom of the laminate sample was strongly damped. On the ultrasonic flaw detector screen one can see more small images of pulses reflected not only from bottom of sample (Fig. 16).

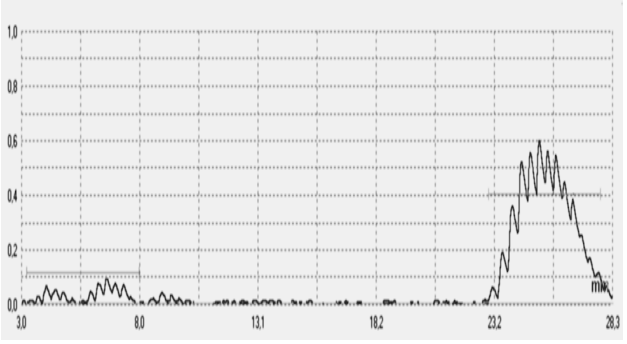

Fig. 16. Image of pulse reflected from the bottom of the laminate sample. (Amplification - 72.40 dB; Undercutting - 10, 12 %)

In case of ultrasonic testing of laminates we did not obtain simultaneous images of the defect and the bottom of the sample. When we have just strongly reinforced trigger pulse, then we had simultaneous picture of pulse reflected from the defect and bottom of the sample (Fig. 17).

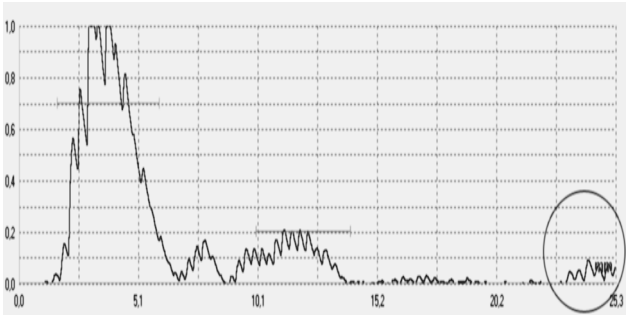

Fig. 17. Image of pulse reflected from the 4mm diameter defect being 2, 58 mm deep and reflected from the bottom of the laminate sample (in the circle). (Amplification - 72.40 dB; Undercutting - 10, 12 %)

In these pictures one can see a very large quantity of small pulses (interferences) coming from successive layers of laminate. This situation makes it difficult to identify defects unambiguously.

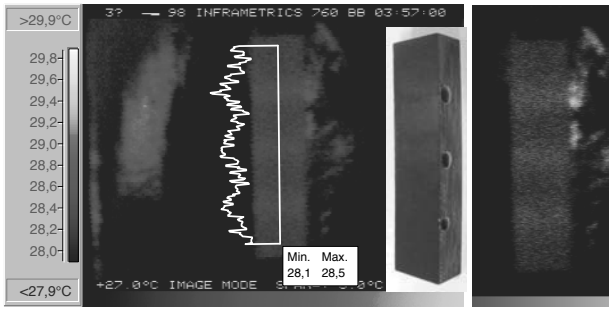

Fig. 18. The thermal image of laminate surface recorded one hundred and fifty seconds from the end of pre-heating process

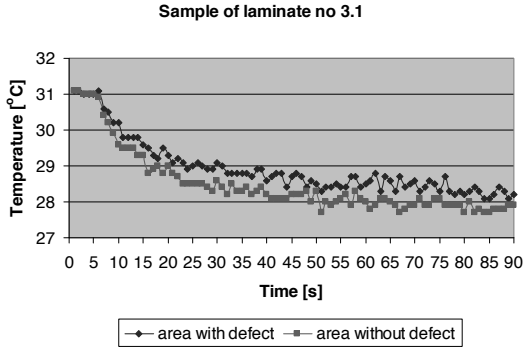

Fig. 19. The dependence of temperature on cooling time for the areas with and without defect

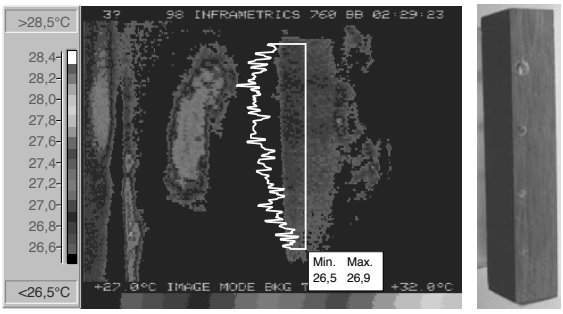

Fig. 20. The thermal image of laminate recorded sixty seconds from the end of pre-heating process

Thermographic tests showed that in the laminate sample it was possible to detect major defects (8-10mm) (Fig. 18) while the smaller defects were difficult to observe. Almost uniform temperature distribution on the sample surface was obtained with few defect indications after samples pre-heating with a short heat impulse (Fig. 20). Curves shown in (Fig. 19) indicate, as before, those areas above large defects (8-10mm) which posses higher temperature than areas without defects. In the area above holes cooling-down process was slowed down.

4. Conclusions

The obtained results allow to draw the following conclusions:

1. Radiation heating and thermographic images analysis is an effective method for revealing defects in the polymeric materials. It is possible to see the defects on thermographic image, but the determination of their geometry and position is restricted and not very precise.
2. Non-destructive ultrasonic testing can be used to detect defects in polymeric materials.
3. In case of thermographic methods it is not possible to detect defects after long time of pre-heating of the studied material. In case of ultrasonic methods it is difficult to locate many defects placed in small distance.
4. Ultrasonic research showed that very many small imperfections accumulated in laminates during manufacturing process can make it difficult to detect bigger defects.
5. Both testing methods require specific skills and long labour-consuming attempts (test, probations) to achieve good results in defects detection in polymeric materials.

Acknowledgements

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