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Methodology of Non-Destructive Testing of Selected Adhesively Bonded Metal Sheets Using Active Thermography

Abstract: The article presents the methodology of non-destructive tests of adhesively bonded metal sheets using active thermography, illustrated with an example of selected imperfections related to the application of adhesive. The experimentation involved the design and the making of specimens reflecting actual car body joints with simulated imperfections such as the complete lack of or the insufficient amount of adhesive between two sheets. The research also involved the selection of a measurement technique, the development of a testing procedure and the manner of interpreting thermographic test results in the form of recorded sequences of images. The thermographic tests were performed in a two-sided arrangement, where a specimen was situated between a heat source and a thermographic camera. Such an arrangement enabled the uniform heating of the specimen surface and, as a result, the obtainment of legible images used for determining the maximum temperature contrast. The test results made it possible to assess the size and approximate shape of the layer of adhesive between two sheets of analysed lap joints. This article constitutes the continuation of previously initiated works dedicated to the development of active thermography related to non-destructive tests of permanent joints.

Keywords: non-destructive testing, adhesive bonding, active thermography

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Introduction

Due to their advantages, including joints of excellent strength, the lack of negative effect on anticorrosive properties of joined elements, and the ability to damp vibration, adhesive joints of steel sheets are becoming increasingly popular in, among others, the automotive industry when making car bodies. In addition, such joints do not generate any or almost any additional stresses in structures as is the case with traditional joining methods. As a result, in some technically permissible applications (car body production), it is possible to observe the tendency of implementing adhesive joints, while at the same time decreasing the number of traditional joints.

Adhesive joints used in the automotive industry are basically divided into two categories, i.e. structural joints (of car body steel elements) and elastic joints (of two different materials,

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e.g. windowpanes and a car body). Adhesive structural joints are primarily made using one or two-component epoxy adhesives characterised by a high post-cure coefficient of elasticity. A desirable thickness of an adhesive layer in such applications is restricted within a range of 0.1 to 0.5 mm, whereas in practice, for technological reasons, the thickness of such layers can locally be much greater. In turn, elastic joints are made primarily using polyurethane adhesive of low elasticity coefficients, where layers of adhesive can reach thicknesses of approximately 5 mm. Among other things, elastic joints are used when connecting elements made of various materials whose significantly different thermal expansion is compensated by the layer of adhesive [1, 2].

In spite of numerous and unquestionable advantages of adhesive joints, there are numerous cases when such joints reveal imperfections, which as regards production practice, can be divided into unrelated and related to adhesive application. The first group of imperfections, presented schematically in Figure 1, can concern the adhesive itself or the preparation of surfaces of elements to be joined.

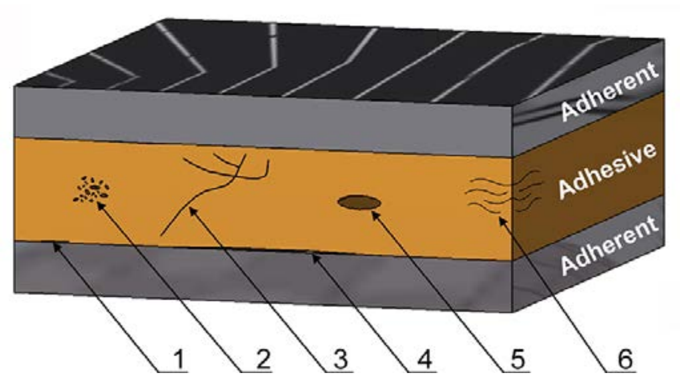

Fig. 1. Imperfections in adhesive lap joints; 1 – "kissing" bond, 2 – porosity, 3 – crack, 4 – delamination, 5 – cavity, 6 – poor cure

However, in industrial practice, high-volume production is accompanied by the generation of imperfections related to adhesive application, such as local lacks of adhesive continuity, varying volumes of applied adhesive (non-uniform filling), or applications of adhesive in undesirable areas. Because of numerous cases of the above named imperfections, the automotive industry has expressed its demand for an effective, non-contact, automated and non-destructive method of assessing adhesively bonded sheets. Very good effectiveness and measurement accuracy related to assessing the local lack of adhesive between two sheets (illustrated with an example of 0.8 mm thick adhesively bonded car body sheets) have been obtained using ultrasonic techniques [4]. However, due to efficiency and the necessity of non-contact testing, alternative methods continue to be sought.

Presently, the Department of Welding at the Silesian University of Technology, among other things, is working on the development of active thermography in relation to non-destructive tests of permanent joints. In previous research works, this method was successfully applied for analysing overlap brazed joints [5,6] and laser welded joints without full penetration [7]. This article suggests using a similar testing methodology in relation to adhesively bonded sheets, illustrated with an example of selected imperfections connected with the application of adhesive. The research involved analysing the effectiveness of active thermography as regards the assessment of the size and shape of an adhesive layer between two sheets of an overlap joint (an important aspect in terms of quality control concerning adhesive joints in the automotive industry).

Active Thermography as a Non--Destructive Testing Method

As a non-destructive testing method, active thermography consists in the initiation, for measurement purposes, of an unsteady flow of heat through a specimen, and the recording as well as the subsequent analysis of a time-changing field (distribution) of temperature over a selected area of the specimen. The momentary distribution of temperature obtained for the analysed area of the specimen provides information about the presence of imperfections located under the surface of a given material.

Selected Measurement Techniques

Active thermographic tests utilise several internal and external methods for exciting unsteady flows of heat. The most common is the external thermal excitation preformed in order to heat one of the surfaces of a specimen, which, as a result, causes heat to flow across the thickness of the specimen and consequently makes it possible to obtain temperature distribution on an area subjected to analysis. The external heat excitation is performed using one or two-sided measurement systems (stations) (often designed to test a specific specimen) [8]. In the two-sided system, a specimen is located between a thermographic camera and a heat source (Fig. 2a). In turn, in the one-sided system, a thermographic camera and a heat source are located on the same side of a specimen, where the camera is usually positioned at a certain angle in relation to a surface subjected to analysis (Fig. 2b).

Depending on what type of "response" is needed for further analysis, in both cases it is possible to use pulsed or lock-in thermography [8]. Exemplary heat excitation sources used for external heating include photoflash lamps, halogen lamps, lasers, IR radiators, hot water or hot air with an intensive and directed injection.

Selected Methods for Analysing Test Results

Various measurement techniques entail the use of various methods for interpreting results of thermographic tests. Such methods are based on the determination of temperature contrast or on the determination of thermal diffusivity (or apparent thermal diffusivity). A temperature contrast, $\Delta T(t)$, is defined as a difference between temperatures present at two points, one of which comes from an area not containing imperfections, with the second one coming from an area containing an imperfection. The thermographic test practice shows that the value of temperature contrast close to zero (of any temperature unit) within the entire range of temperature changes recorded in time indicates the lack of an imperfection (or damage) in a material being tested. In turn, a characteristic increase in the value of temperature contrast (e.g. by approximately 1 of the previously adopted temperature unit) implies the existence of an imperfection. Such a manner of result interpretation can be used regardless of whether a given test was performed in a one or two-sided system. Another method of interpretation, providing results in quantitative forms, is a procedure based on the determination of thermal diffusivity using the thermal impulse method (Parker's method [9]) analogous to the thermographic method used in the two-sided system. In this procedure, a short thermal impulse strikes one of the specimen surfaces, causing an unsteady heat flow across the specimen thickness and resulting in a temporary increase in temperature on the rear surface of the specimen (i.e. the surface opposite to the

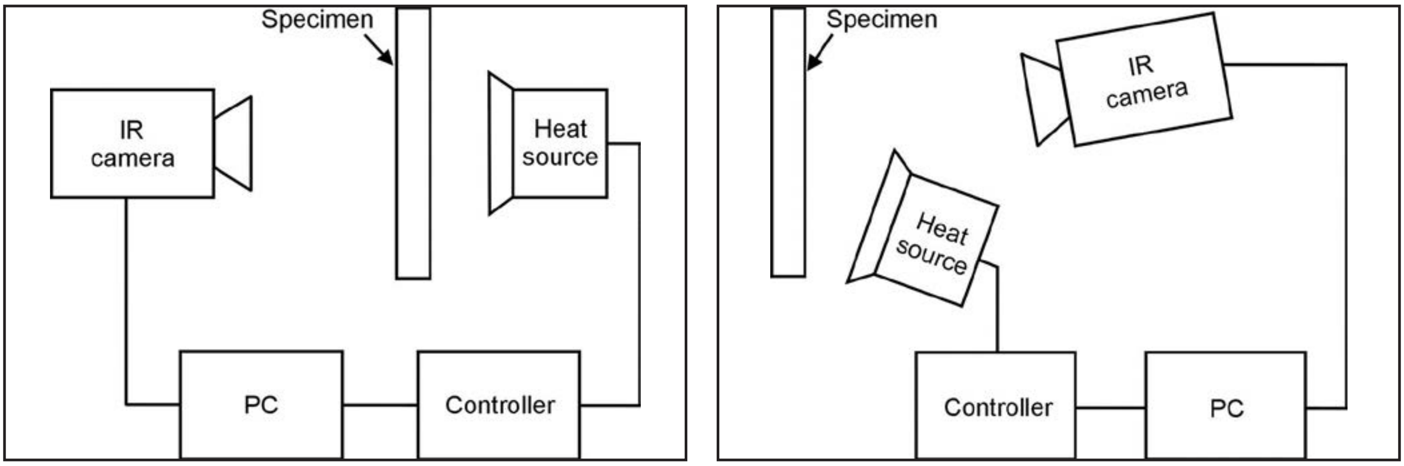

Fig. 2. Schemes for active thermography experimental setups: a) double-sided, b) single-sided

surface being heated). Diagrams of temperature changes in time are recorded from the beginning of a heating process. In spite of the fact that thermal diffusivity is, by definition, a quantity characterising a uniform material, it can be used for analysing results obtained in thermographic tests (also in relation to laminar materials) as a conventional measure used for the quantitative expression of results in cases when thermographic experiments are performed in accordance with the procedure used for the determination of thermal diffusivity.

Testing Methodology

In order to perform an active thermography--based experiment to test adhesively bonded overlap joints, it was necessary to develop a testing methodology taking into consideration the selection of a measurement technique, to determine parameters related to the excitation of heat flow through the material being tested, and to work out a manner of preparing specimens to be used in the tests. A measurement active thermographic technique used in the tests was pulsed thermography in the two-sided system, where a specimen was located between a thermographic camera and a heat source (in accordance with a scheme presented in Figure 2a). The use of such a measurement system aimed to obtain the uniform heating of the specimen surface, which was to ensure the obtainment of thermographic images most precisely reflecting the shape of simulated imperfections in welded joints. The fact that the purpose of the research work was only to provide an active thermography-based testing methodology aimed to assess sizes and approximate shapes of imperfections in adhesively bonded overlap joints entailed the simplified analysis of results based on the determination of the maximum temperature contrast over a predefined measurement length along a straight line representing the position of the adhesive layer axis.

The active thermographic tests were performed at the Welding Department of the Silesian University of Technology using an individually designed test rig combined with a Flir A655sc thermographic camera. The test results were analysed using the ResearcherIR software programme. The test rig was composed of three primary functional systems, i.e. a specimen fixing system, a heating system, and a system for recording images. Heating was performed using a flat ceramic IR radiator located 20 mm away from the specimen surface. A heating time was determined experimentally by performing trials for several variants (1.0; 2.0 and 3.0 s), in order to obtain various values of the maximum temperature contrast.

Specimens and Materials

The experiment involved making four specimens in the form of adhesively bonded overlap joints. Each specimen was made of two square steel sheets (100 mm×100 mm) of various thicknesses (0.7 mm and 1.2 mm) bonded by structural epoxy adhesive. The use of sheets of various thicknesses aimed to reflect actual joints of two car body elements, i.e. panelling (sheet thickness of 0.7 mm) and structure (sheet thickness of 1.2 mm). Figure 3 presents a model of an exemplary specimen with marked areas for adhesive application (A and B).

The specimens used in the tests were designed in such a manner that one of them was proper, i.e. contained a similar (or identical)

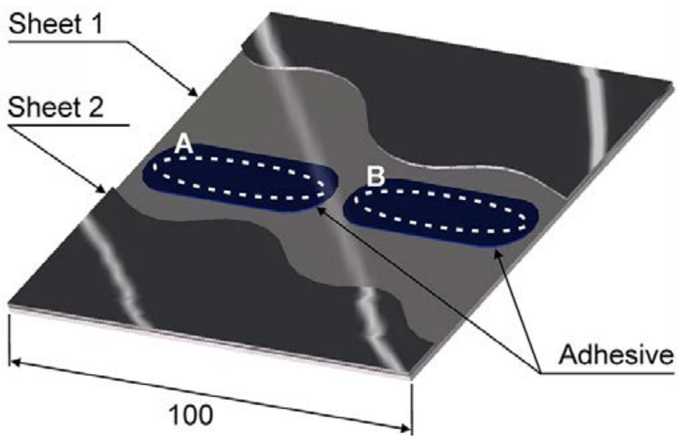

Fig. 3. Model of adhesively bonded sheet metal overlap joint with section of upper sheet 2, with specified fields (A and B) for applying adhesive

and uniformly spread amount of adhesive in both fields A and B (specimen 1), whereas the remaining specimens contained simulated imperfections (related to adhesive application) in the forms of the total lack of adhesive in field B (specimen 2), a slight amount of adhesive in field B (specimen 3) and an excessive amount of adhesive in field B (specimen 4). In turn, field A of each specimen was applied with a layer of adhesive, the width of which constituted a variable depending on the local volume of applied adhesive and could slightly differ between individual specimens. Because of the fact that in production practice the quality control of structural adhesive joints of car body elements is usually performed before a given element enters a heating chamber (for the cure of adhesive), the specimens were not subjected to the process of cure. Although the applied epoxy adhesive was characterised by a partial ability to absorb fat (usually present on the surface of car body sheets at the as-delivered state or after pressing); before the application of adhesive, each sheet was degreased in order to eliminate the accidental effect of sheet purifying agent on the joint quality at the adhesive-sheet "boundary" (thus influencing the efficiency of heat transfer between the sheet and the adhesive as regards thermographic tests). In accordance with the manufacturer's recommendation, before application the adhesive was heated up to approximately 50°C in a heating chamber in order for the adhesive to obtain appropriate fluidity enabling dosing and ensuring the proper wetting of surfaces to be joined. Immediately after the application of adhesive on one of the sheets, the other sheet was placed and pressed against the first sheet so that an overlap joint (reflecting the actual joint of car body elements) could be obtained. The thickness of the adhesive layer between the two sheets was restricted within a range of 0.4 to 0.6 mm. Because of the previously mentioned fact that the adhesive was not subjected to cure, in order to prevent the shifting of the sheets, each specimen was additionally heated at four points located at the corners of the sheets. In order to unify the coefficient of emissivity over the entire surface of the specimen, the specimens were coated with a thin film of black mat paint.

Test Results and Discussion

The active thermographic tests resulted in the obtainment of sequences of images subjected to further analysis. First, in the thermographic images a control straight line (80 mm in length) in the adhesive joint axis was marked. On this control line, at characteristic areas three measurement points were defined, i.e. the first (T_A) located in field A, the second (T_B) located in field B, and the third one (T_0) located between fields A and B (i.e. in the area deliberately free from adhesive). Afterwards, for the defined measurement points mentioned above, the values of the maximum temperature contrast $\Delta T_{AB}(t)$ were determined; the temperature contrast constituted the difference between the two values of temperature $[|T_A(t) - T_B(t)|]$ coming from the diagrams of temperature changes in time, created starting from the moment when the unsteady flow of heat through the specimen was initiated (the initial temperature of the specimen was the same as room temperature, i.e. approximately 22°C). On the basis of contrast $\Delta T_{AB}(t)$ it was possible to determine the presence (and assess the size) of the varying amount of adhesive applied between fields A and B and to ascertain whether that amount was restricted within the range of adopted tolerance values. However, because of the fact that in the experiment planned as described above, it could not be excluded that the same amount of adhesive, yet still significantly different from the required one, might be present in both fields A and B, it was necessary to introduce an additional parameter, e.g. the difference between T_A and T_0 (or between T_B and T_0), constituting a quantity of reference. For the thermographic images corresponding to a relatively high temperature difference between one selected field (of the highest temperature T_A or T_B) and the remaining area of the specimen, it was possible to record diagrams presenting a momentary temperature profile along the adhesive joint axis which could be used (due to its shape) for assessing the quality of the adhesive joint. Figures 4-7 present the most representative thermographic images obtained as a result of using a heating variant for the highest temperature contrast (i.e. for a heating time of 3.0 s).

In accordance with the methodological assumption, the presented thermographic images represent the approximate shape of an area filled with adhesive between two sheets. The thermographic image of the surface of specimen 1 (Fig. 4) reveals two separate areas located along the joints axis and characterised by significantly higher temperature (if compared with the temperature of the remaining part of the specimen). The sizes of the above named areas differ only slightly, which indicates the varying width of the area filled with adhesive caused by unintended fluctuations in the amount of adhesive applied between fields A and B. Because of the fact that specimen 1 was intended to be the reference specimen in the experiment (i.e. the standard specimen with a properly made adhesive joint), the obtained result in the form of the thermographic image with the corresponding momentary temperature profile can be used as the "standard" for assessing the remaining overlap joints. The remaining fields characterised by higher temperature result from the effective pure heat transfer in areas filled with adhesive whose presence provides local "material continuity" between two sheets. The thermographic

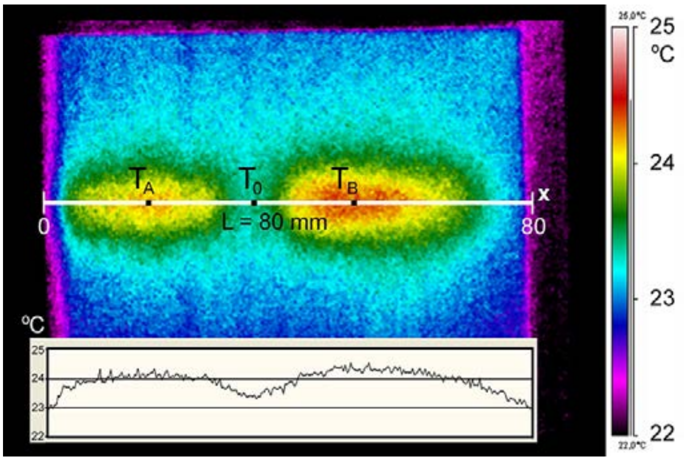

Fig. 4. Thermographic image of the surface of specimen 1 with the momentary temperature profile along the straight line representing the location of the adhesive layer axis

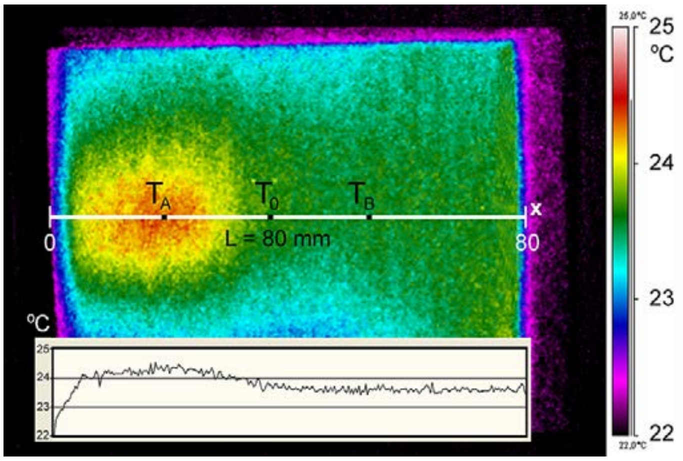

Fig. 5. Thermographic image of the surface of specimen 2 with the momentary temperature profile along the straight line representing the location of the adhesive layer axis

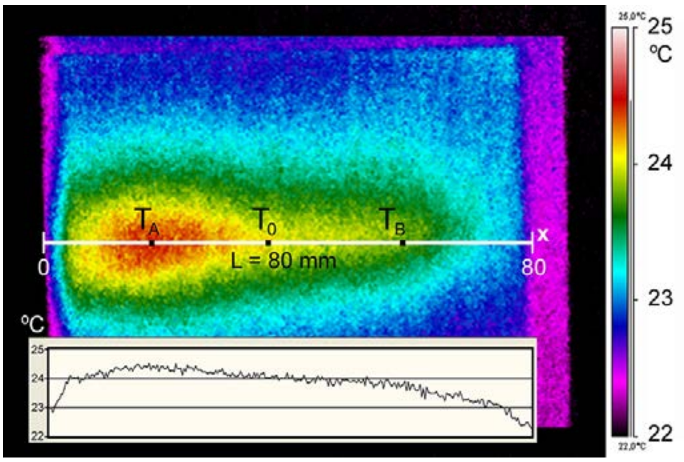

Fig. 6. Thermographic image of the surface of specimen 3 with the momentary temperature profile along the straight line representing the location of the adhesive layer axis

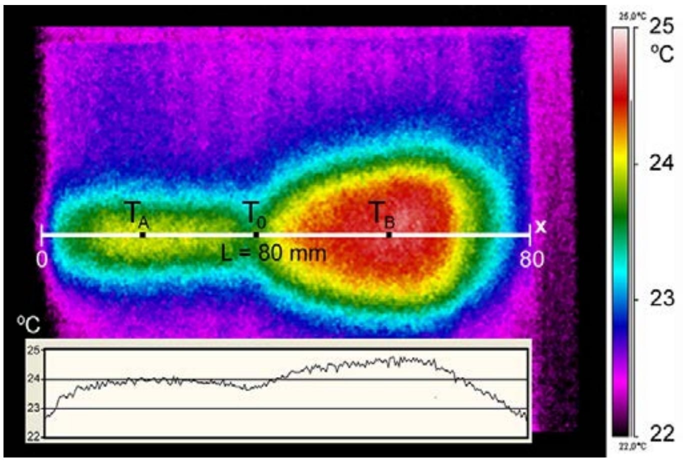

Fig.7. Thermographic image of the surface of specimen 4 with the momentary temperature profile along the straight line representing the location of the adhesive layer axis

image of the surface of specimen 2 (Fig. 5) reveals an area of significantly higher temperature (on the left), identifying the specimen where field B is totally void of adhesive. It is also possible to notice a large area (at the height of field B) characterised by a temperature similar to the temperature present at the right edge of the specimen (Fig. 5). This significantly higher temperature can be ascribed to the entire lack of adhesive in field B, leading to the decreasing distance between the overlap bonded sheets until their coming into contact with each other (due to the force of electrodes applied in the corners of the sheets during spot welding), which is clearly visible on the left side of the image (Fig. 5). In spite of this, it was possible to obtain the significantly high (sufficient for the correct assessment) value of temperature contrast between measurement points T_A and T_B. In turn, the thermographic image of the surface of specimen 3 (Fig. 6) reveals one continuous area characterised by higher temperature and becoming narrower from the left to the right side, indicating the presence of the proper amount of adhesive in field A and implying the undesirable presence of adhesive in the area between fields A and B. In turn, the right side of the image reveals the presence of a small (narrow) area characterised by a slightly elevated temperature, indicating the overly small amount of adhesive in field B in comparison with the standard specimen. Figure 7 presents the thermographic image of the surface of specimen 4 characterised by the greatest area of significantly higher temperature resulting from the greatest area of effective heat transfer due to the excessive amount of adhesive applied in field B. The above named exemplary images obtained in measurement conditions confirm the effectiveness of the proposed method for assessing the size and approximate shape of areas filled with adhesive in the overlap joints of the sheets. Table 1 presents individual temperature values, the resultant temperature contrast and difference T_A-T_0 for the presented thermographic images.

Table 1. Selected results of the analysis of thermographic images

Specimen no.	T_0 [°C]	T_A [°C]	T_B [°C]	$\Delta T_{AB(t)}$ [°C]	$T_A - T_0$ [°C]
1	23.4	24.2	24.4	0.2	0.8
2	23.8	24.3	23.6	0.7	0.5
3	24.1	24.4	23.8	0.6	0.3
4	23.8	24.1	24.6	0.5	0.3

Table 1 reveals that specimen 1, i.e. containing a properly made joint, is characterised, if compared with the remaining specimens, by a significantly lower value of contrast $\Delta T_{AB}(t)$ and, at the same time, by the highest value of difference T_A-T_0. Therefore, on the basis of the analysis of these quantities, it is possible to quantitatively assess the quality of adhesive joints by determining related dependences associating a temperature contrast with any freely adopted parameter characterising an adhesive layer (related to a size taken into consideration or the arrangement in relation to the control points). Although in the tested adhesive joints the epoxy adhesive was uncured, and consequently (due to its low coefficient of elasticity) was characterised by low thermal conductivity, it was possible to obtain sufficient values of temperature contrast (for the correct interpretation of the results), confirming the properly adjusted measurement conditions of the experiment.

Summary

The presented experiment performed using the proposed testing methodology enabled the obtainment of test results demonstrating the effectiveness of active thermography when assessing the quality of adhesively bonded lap joints containing typical imperfections occurring in production practice. The use of the two-sided measurement system enabled the obtainment of required thermal excitation conditions, making it possible to obtain legible thermographic images as well as to assess the size and approximate shape of the layer of adhesive between two sheets.

Individual imperfections were already visible when observing the distribution of temperature on specimen surfaces. The further analysis, based on the procedure of determining the maximum temperature contrast enabled the presentation of results in the numerical form.

In spite of the fact that the idea of applying active thermography for assessing the quality of permanent joints is not new, it is necessary to continue this research in order to extend the efficiency area of this modern and continuously developed testing method. Because of the growing area of application of widely described laser techniques [10], among other things, for joining critical large-sized elements in the aviation industry and related need for an effective NDT method, the author intends to continue research works on the development of active thermography also involving tests and analyses of laser welded joints.

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