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NON-DESTRUCTIVE TESTING OF ADHESIVE BONDED STRUCTURES

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Abstract

Adhesive bonded joints are one of the most popular type of joints in the production process of modern cars [1, 2, 3]. That came from their uncommonly good features i.e. durability, visual and economical properties [1, 2]. However, during the production process some defects can occur. There are many Non-Destructive Testing (NDT) methods which allow detection of different defects of adhesive joints and increase the quality of the production process as well as the produced part. In the first part of the article, a review of the most valuable NDT methods was presented, especially from the point of view of application to automated testing of automotive parts. In the second part, two contactless NDT methods (EMAT ultrasonic technology and active thermography) were applied to prepared bonded joints. Results of preliminary laboratory tests were compared. The aim of the research was to point out the most suitable method for industrial application.

Keywords: NDT methods, adhesive bonded joints, active thermography, EMAT

BADANIA NIENISZCZĄCE POŁĄCZEŃ KLEJONYCH

Streszczenie

Połączenia klejone posiadają liczne zalety wpływające na podniesienie trwałości karoserii i obniżenie kosztów produkcji [1, 2, 3]. Obok zalet istnieją również wady, które mogą przyczynić się do pojawienia defektów złącza zarówno na etapie procesu produkcji jak również w trakcie eksploatacji [2, 3]. Ocena własności złącza klejonego na etapie procesu produkcji oraz w trakcie eksploatacji jest przedmiotem badań prowadzonych przez różne jednostki naukowo badawcze [4, 5]. Z punktu widzenia wytwórców samochodów istnieje potrzeba skutecznej detekcji wad technologicznych połączeń klejonych. Aktualnie w większości przypadków wykrywanie wad technologicznych realizowane jest poprzez stosowanie inwazyjnych i nieniszczących metod badawczych. Metody inwazyjne są dobre i umożliwiają skuteczną ocenę stanu połączenia. Ich główną wadą są wysokie koszty m.in. wynikające z konieczności całkowitego zniszczenia podzespołu. Z tego powodu, by ograniczyć potrzebę częstego ich stosowania, połączenia klejone dodatkowo bada się metodami nieniszczącymi (NDT). Istnieje szereg nieniszczących metod badawczych dedykowanych do detekcji różnych wad materiałowych i nieciągłości strukturalnych [7]. W artykule scharakteryzowano wybrane metody NDT mające swój udział w badaniach złączy klejonych w jednostkach badawczych i zakładach przemysłowych. Skupiono się m.in. na metodach radiograficznych [6, 7], akustycznych [2, 5], ultradźwiękowych [16, 17], metodzie szerografii laserowej [9, 10, 11] oraz metodach termografii aktywnej [7, 12, 14]. Ze względu na wymienione w treści artykułu zalety oraz dostępność sprzętu pomiarowego postanowiono wykonać badania i porównać rezultaty stosowania termografii aktywnej oraz ultradźwiękowej technologii EMAT.

Słowa kluczowe: metody NDT, złącze klejone, termografia aktywna, EMAT

1. INTRODUCTION

Application of adhesives in the automotive industry increasingly growing due to their inherent advantages. Adhesives are especially effective for bonding dissimilar materials that often cannot be joined using rivets or welds. Using adhesives, it is possible to obtain inexpensive and durable joints of body-car sheets and other metal components.

In some modern cars, use of adhesive bonds is even greater than welds. Some of the more popular locations which could be glued are presented in Fig. 1.

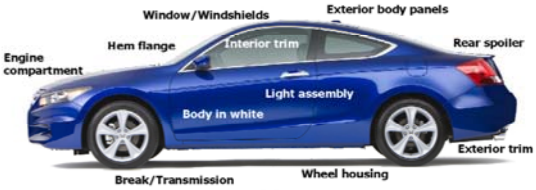

Fig. 1. Applications of adhesives and sealants in automobile manufacturing (based on [1])

Structural adhesives also help reduce noise, vibration, and harshness, and can improve crash performance [1]. Adhesive bonding can sometimes be useful for high volume production requiring large bonded areas and can be less expensive and faster than conventional fastening methods [2]. The advantages of adhesive bonded joints can be leveraged in the design stage to facilitate the usage of alternate materials in favour of weight savings. Adhesive bonding offers greater synergies when compared to traditional joining processes of welding and their variations Fig. 2 [3]. Using structural adhesives can also eliminate some of welds, since they provide a more continuously bonded surface area than spot welds or rivets [1]. With their satisfactory primary functional use, adhesives have also satisfied secondary applications like gap filling and sealing which protects car body parts against corrosion. The multi-functional applications of adhesives can be utilized during the design phase to develop multipurpose joints [3].

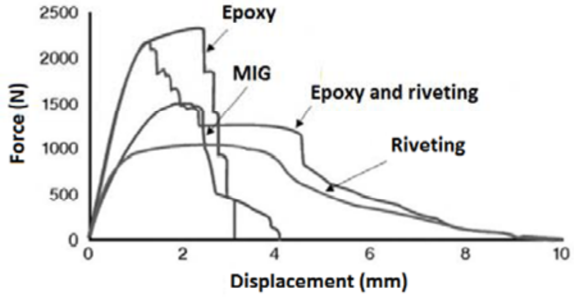

Fig. 2. Comparison of shear strength of an elements joined by different techniques [3]

The increasing use of adhesively bonded structures and adhesive joining technologies in all fields of vehicle manufacturing as an alternative to the traditional methods of fastening materials involves an increasing demand on quality control. It follows from the susceptibility of the joining process to different instabilities which can give different defects like delamination, poor cures, cracks, porosity, voids, “kissing” bonds and discontinuity or lack of adhesion (Fig. 3). The most critical defect is disbonding caused by incorrect adhesive application, or movement of parts after application [4].

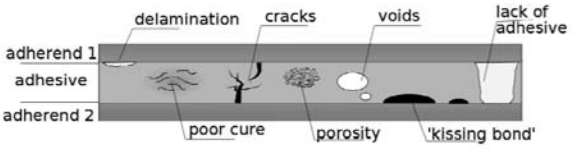

Fig. 3. Defects occur in a bonded structures

Any defects can influence the quality of mechanical and functional properties of the adhesively bonded joint, which is why it is necessary to control quality of the joints in order to eliminate problems in the adhesive application process. There are some destructive and non-destructive methods allowing investigation of defects of bonded joints. Destructive methods are very common in bonded joint structures assessments, but are very costly due to the necessity of complete specimen destruction. For this reason, a variety of NDT methods are used to reduce applicability of destructive ones. A survey of the most used NDT methods is presented below.

2. SURVEY OF NDE METHODS OF ADHESIVE BONDED STRUCTURES

Non-destructive evaluation (NDE) of adhesive joints can be performed using radiographic, vibroacoustic, thermographic and ultrasound methods. Some of them can be used for automated inspections of the adhesive joints. This survey takes this into consideration due to the aim of future work being connected to the development of industrial quality control methods of adhesive joints of automotive structures.

2.1. Radiographic Testing (RT)

The radiography scanning method, which is widely known in medical applications, is a very useful tool for evaluating structural discrepancies in industrial applications.

Radiography uses X-rays which are electromagnetic waves with an energy that is 100–100,000 times greater than that of visible light. Like visible light, X-rays can be scattered and absorbed by materials, however, since X-rays have a much higher energy, these rays tend to pass through materials that block visible light. The amount of X-rays that pass through a material is dependent on the elemental structural properties. Radiographic inspections are very useful in determining structural changes in material density, thickness, or composition [5] and also verify the integrity of the adhesive layer in bonded joints [6]. In Fig. 4, the marked areas show a contrast enhanced enlarged area of the border. The darker grey values indicate increasing adhesive layer thickness, where many voids can be seen [6, 7].

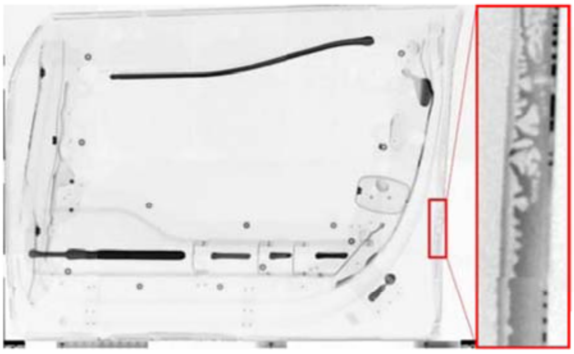

Fig. 4. Car doors neutron radiograph with zoomed part of bonded path [6]

The radiation imaging method of NDE provides an advantage over many other NDE methods in that it is inherently pictorial and its interpretation is to some extent intuitive. Analyzing and interpreting the images requires skill and experience, but a casual user of radiation imaging services could easily recognize the item being imaged and could often recognize discontinuities without expert interpretation [7].

This method is generally very accurate and efficient, however, has several disadvantages which limit its use to certain situations, especially for industrial application for an in-line monitoring process. One of the limitations is undoubtedly the cost of these studies, which include not only the equipment, but also a large number of security measures to be taken to reduce the impact of dangerous radiation on the environment surrounding the investigated place. Radiographic inspections also require two-way access to the investigation area, which in many cases may prove problematic or even impossible [5, 6, 7].

2.2. Vibroacoustic NDE methods

These methods use measurements of vibration and acoustics, as well as ultrasonic signals generated in the structures after its external excitation. A flawless structure gives a characteristic response in a selected frequency range. After, the defect occurrence response is different, thus detection of the defect is based on analyzing differences between the responses. Some of these methods are based on modal analysis techniques like Mechanical Impendence Analysis (MIA) or resonance analysis. This class of methods are rarely implemented in industrial applications.

2.2.1. The Mechanical Impendence Analysis (MIA) method

The MIA test method uses a single-tipped, dual-element probe. A drive element generates audible sound waves and a receiving element detects the effects of test-piece bond variations on probe loading. During setup, the drive frequency is swept through the range of 2 kHz to 10 kHz to establish the optimum test frequency. Testing is then performed at a fixed frequency. A schema of the testing method is presented in Fig.5. The sensor loading is affected by the stiffness of the sample, which changes from very high to low, respectively from bonded to disbonded regions. The defect stiffness is dependent on the size and thickness of the disbond. Generally, the measurements difference between well-bonded and disbonded structures is higher for stiffer structures. Detection values vary with frequency, thus the proper test frequency is critical to obtain good results [8]. This method does not require couplant and has a small contact area; it can therefore be used on irregular or curved surfaces. It works well on disbonds, and internal defects of investigated structures. It is also applicable for mechanical scanning systems [8].

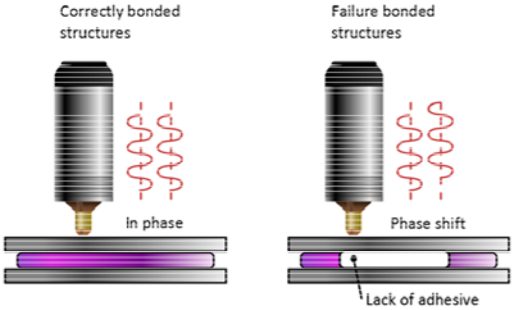

Fig. 5. Difference in the received signal – information about defect appearance [5]

2.2.2. Resonance method

The resonance method uses special narrow-bandwidth ultrasonic contact probes. This method is based on the change in impedance of the sharply resonant high-Q ultrasonic transducer when acoustically coupled to a material. The measured electrical impedance of the transducer is affected by the acoustic impedance of the test sample. The ultrasonic contact probe is driven at its resonance frequency and placed on the sample along with couplant. To detect disbonds, electrical impedance changes in the sensor are analyzed [2]. This method can detect many types of disbonds [8]. In an adhesive-bonded joint (Fig.6), changes in the effective thickness caused by disbonding significantly affect the phase and amplitude of the signal at the resonance frequency of the transducer. In a multilayered joint, the signal phase is related to the depth of the disbonded layer [2].

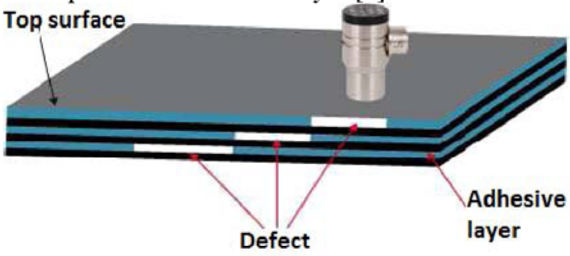

Fig. 6. Flaw detection in multilayered sample test [8]

This test requires a liquid couplant and a variety of probes which can limit or complicate its application [2].

2.3. Laser Shearography

Shearography is an optical method based on speckle interferometry used for non-contact measurement of out-of-plane deformations of a material surface. The method has been developed to particularly overcome the sensitivity to external vibrations that is common in standard interferometry techniques [9].

This method's main purpose is to detect small deformations of the surface which indicate subsurface defects. It uses a laser head to light the investigated region and a camera to detect differences in the reflected laser beam coming from the object (Fig.7). The returning laser beam is doubly imaged, with one of the coherent images slightly shifted or 'sheared' relative to the other image. Then, a second similar recording is made with the object being put under a slight strain. The two laser speckle patterns are superimposed resulting in a fringe pattern. The fringes do not show the contours of the displacement, but instead show the derivative of the displacement (gradient of deformation). Digital image processing of the data is further done to enhance the defect presentation (e.g. filtering and fringe unwrapping) [9]. The essential feature of this configuration is that the camera is focused on the test surface, but views this surface through reflections in each of the indicated mirrors. Because one mirror is tilted slightly, one of the image replicates is shifted laterally by a small amount [5].

Because of the optical technique, the specimen should not have a shiny surface (although a standard coating is acceptable). The inspection time is largely determined by the limitations of the field of view [9]. The detectable defect size decreases with increasing defect depth (defect diameter must exceed its depth). Shearography can be used with a limitation for defect sizing, but the technique is not suited for defect depth estimation [9]. There are several publications where various bonding structures were tested [10, 11].

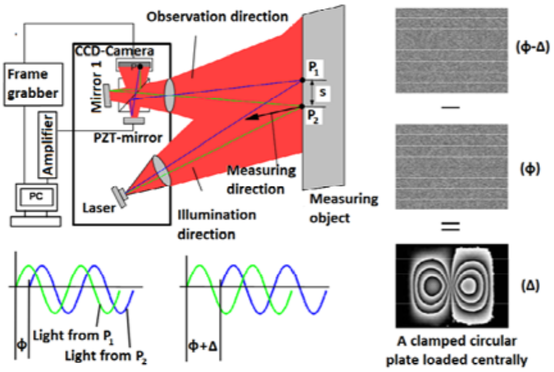

Fig. 7. Laser Shearography [9]

2.4. Active Thermography

Infrared thermography and particularly active approaches such as the NDT technique have been known for many years, however an official NDT method has only been considered recently. It is usually called IR NDT. When compared with other classical NDT techniques, active thermography is safe, nonintrusive and noncontact, allowing the detection of relatively shallow subsurface defects under large surfaces at once, and in a fast manner [7, 12]. IR NDT is largely used in the aerospace industry to test the integrity of the fuselage of planes, in the automotive industry and everywhere where testing materials, tubes, welds, uniformity, quality etc. is needed. Active techniques can also be applied to evaluation of adhesive joints [13, 14, 15]. Active thermography testing applies an external stimulus to heat up or cool down the investigated object while simultaneously an infrared camera is used to observe how the heat propagates in materials. Invisible defects within the inspected material strongly affect the diffusion of heat. Thus, defective areas may look cooler or hotter in respect to non-defective areas of the sample. This difference of temperature caused by non-defects or non-uniform material is visible through infrared cameras. Depending on the external stimulus, different approaches of active thermography have been developed, such as pulse thermography (PT), step heating (SH), lock-in thermography (LT), and vibro-thermography (VT).

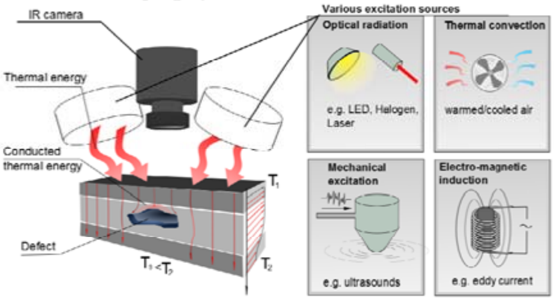

Fig. 8. Idea of active thermography

2.4.1. Pulsed thermography (PT)

In pulsed thermography (PT), the specimen surface is submitted to a heat pulse using a high power source such as photographic flashes or halogens. A heat pulse can be thought of as the combination of several periodic waves at different frequencies and amplitudes. After the front of the thermal wave comes into contact with the specimen's surface, a thermal front travels from the surface through the specimen [14].

As time elapses, the surface temperature will decrease uniformly for a piece without internal flaws. On the contrary, subsurface discontinuities (e.g. porosity, delaminations, disbonds, fiber breakage, inclusions, etc.), can be thought of as resistances to heat flow that produce abnormal temperature patterns at the surface, which can be detected with an IR camera.

Pulsed thermography is fast (from a few seconds for high conductivity materials to a few minutes for low conductivity materials) [14]. There are also numerous thermogram processing techniques available although many of them are complex [14].

2.4.2. Lock-in thermography (LT)

In Lock-in thermography (LT), also known as modulated thermography, the investigated structure is thermally stimulated using heating lamps (halogens), and can sometimes be called optical lock-in thermography (OLT), elastic waves generators, or ultrasound lock-in thermography (ULT). As it is a stimulation source, eddy currents induced by electromagnetic induction could be used. During the thermal stimulation of the object, a periodic wave propagates by radiation through the air until it touches the investigated object surface where heat is produced and propagates through the structure. Periodic heating input leads to a similar transient variation of the surface temperature of the object. Sinusoidal waves are typically used in LT, although other periodic waveforms are possible. Using sinusoids as input has the advantage that the frequency and shape of the response are preserved and only the amplitude value and phase delay could change.

Modulated thermography is used for the detection of defects and characterization of solid and composite structures used in aerospace, automotive, electronics and other industries [13, 14, 15].

Active thermography methods have some advantages as well as disadvantages. Most of them are presented in the Table 1.

Table 1. Advantages and disadvantages of the active thermography methods

Advantages	Disadvantages
It can be used in many cases where only one side of the bonded joint is available; Test is fast for elements with extensive joint surface; Evaluation time is comparable with other methods of non-destructive testing; Safety requirements are not as stringent as e.g. for radiographic examination.	To obtain a signal suitable for analysis, it is necessary to regulate the uniformity of the heating cycle with sufficient accuracy; Variability of surface emissivity can cause blurred contrast; The effects of convective cooling may produce false results.

2.4. Ultrasonic testing (UT)

Ultrasonic testing is one of the most widely used NDT methods today in inspections of adhesively bonded structures [16, 17]. Ultrasonic waves have frequencies above 20 000 Hz and their propagation in solids is the fundamental phenomenon underlying ultrasonic NDT. It is possible to use the features of an ultrasonic wave (velocity, attenuation) to characterize a material's composition, structure, elastic properties, density, and geometry.

The basic technique of ultrasonic inspection is simple: a transducer transforms a voltage pulse into an ultrasonic pulse (wave). One places the transducer onto a specimen and transmits the pulse into the test object. The pulse travels through the object, responding to its geometry and mechanical properties. The signal is then either transmitted to another transducer (pitch–catch method) or reflected back to the original transducer (pulse–echo method).

Unfortunately, in the majority of cases the transducer must be in contact with the object, through a water- or gel-coupling layer. In many cases, UT is also inefficient mainly for large surface structures. Also, ultrasonic waves typically cannot reveal planar flaws (cracks) whose length lies parallel to the direction of wave travel. A classic UT defectoscope equipped with a single transmitter and detector has some limitations. Inspections using this equipment can be time consuming and thus expensive to operate [5]. However, there are some solutions developed to reduce those disadvantages. The ultrasonic phased array (UT-PA) method is a special UT method that uses a special scan head (Fig.9) equipped with multiple ultrasonic elements driven independently [9].

Fig. 9. An example of UT-PA testing head [9]

Other interesting methods using different phenomena of excitation of ultrasonic waves in the inspected structure are based on contactless laser and EMAT technologies [5]. The last one could be especially useful in inspections of bonded metal parts which are commonly used in the automotive industry.

2.4.1. Electromagnetic Acoustic Transducers technology (EMAT)

EMAT technology is an alternative method of ultrasonic testing that differs from the classical methods of UT, a way of exciting the elastic waves in the tested structure. EMAT technology is suitable for testing metallic parts and uses a special head made of coil driven by high-frequency impulse current and magnet (or electromagnet) which is the source of the static magnetic field. When the sensor is close to a metallic sample, an eddy current density is induced in it; the interaction of this current density with the bias magnetic flux density generates a Lorentz force (Fig.10). This disturbance is transferred to the lattice of the material, producing an elastic wave. In a reciprocal process, the interaction of elastic waves in the presence of a magnetic field induces currents in the receiving EMAT coil circuit. For ferromagnetic conductors, magnetostriction produces additional stresses that enhance the signals to much higher levels than could be obtained by the Lorentz force alone [5, 18].

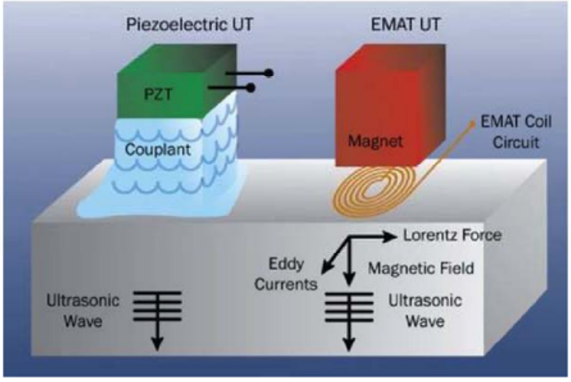

Fig. 10. Comparision of EMAT and clasic UT technologies [19]

Application of a different combination of RF coils and magnets in the EMAT head makes it possible to generate and detect bulk longitudinal and shear waves, Lamb and Shear Horizontal waves in plate-like structures as well as torsional, flextural and longitudinal modes in pipes and wires.

The most important advantages and disadvantages of the EMAT technology are presented in Table 2.

Table 2. Advantages and disadvantages of EMAT technology

Advantages	Disadvantages
No contact No couplant needed Multiple mode excitation High temperature inspection High speed inspection Reproducibility	Low signal-to-noise ratio Special electronics required Material-dependent Working only on good conductors or highly magnetostrictive metals

3. EXPERIMENTAL COMPARISON OF EMAT AND ACTIVE THERMOGRAPHY TO DETECTION OF ADHESIVE JOINT DEFECTS

In order to evaluate which NDT method could be the most suitable for application for detection of adhesive joint defects, laboratory research were carried out. During the research, two NDT methods were applied: EMAT ultrasonic technology and active thermography methods.

The test was performed on a specially prepared specimen made of two 1mm thick automotive steel plates with dimensions of 250x250mm. The steel sheets were joined by 5 paths of adhesive as presented in figure (Fig. 11). Some adhesive paths were intentionally broken to simulate a defect that mimicked a lack of adhesive. The research focused on detection of a 18mm gap in the adhesive path as indicated in Fig. 11.

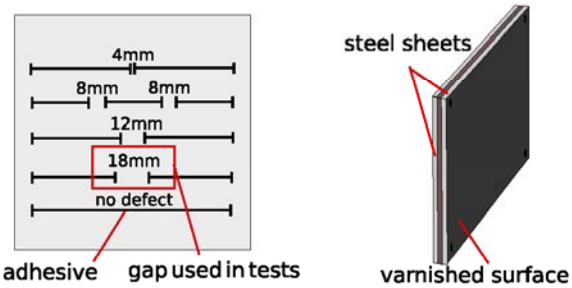

Fig. 11. Layout of adhesive paths applied to tested specimen

One side of the prepared sample was painted black in order to obtain a high emissivity value of the surface required for active thermography tests.

3.1. Laboratory stand and testing procedure

Experimental research was performed in laboratory conditions using two different test benches for EMAT and Active thermography testing.

3.1.1. EMAT test bench

The ultrasound tests were carried out using a 3D scanner and commercial EMAT instrument Temate® PowerBox®-H with a standard sensor consisting of a permanent magnet and spiral coil. The 3D scanner allowed us to sweep the surface of the investigated specimen line by line with an experimentally set resolution of 2.5mm. During each sensor pass, a response signal was recorded. The set of recorded signals was finally processed in order to obtain a scanning map showing different attenuation of ultrasonic signal over the investigated area.

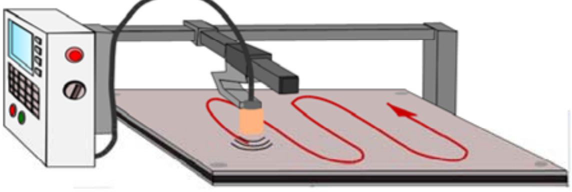

Fig. 12. Idea of EMAT test stand used in mentioned experiments.

3.1.2. Active thermography test bench

Active thermography research was performed using a test stand consisting test chamber with specimen holder and two halogen lamps with powers of 1kW each. The lamps were connected to the power regulator. Infrared images were acquired using an uncooled infrared camera VarioCam connected to the PC with installed acquisition and control software. The camera has a resolution of 640x480px, a temperature resolution of about 0.1@30°C, and is able to acquire images with frame rate of 50 fps. PC was also used to control power regulator in order to generate appropriate thermal excitation. Hardware and software allowed tests using pulsed and harmonic modulated signal with approximately 90 levels of power change. A simple diagram and the internal structure of the power regulator can be seen in Fig. 13. Raw images acquired during thermographic tests were processed to characterize the simulated defects of adhesive joints. An exemplary raw image acquired during the active thermography test is presented in Fig. 14.

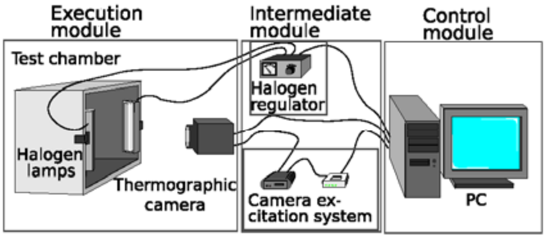

Fig. 13. Test bench used to active thermography tests

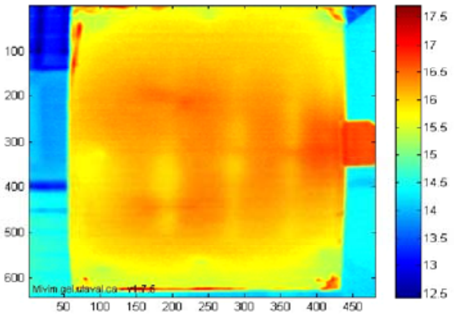

Fig. 14. Example of raw thermal image of investigated specimen with visible adhesive paths

3.1. Research results

The aim of the research was to detect a simulated defect of the adhesive joint and answer the question of which method better characterizes the defect. Data obtained during the EMAT and Active thermography tests after processing allowed us to generate color maps which were the basis for further visual evaluation and comparison of the NDT methods. Color maps are presented in Fig. 15 in the following order:

- map of the adhesive path after ultrasonic scanning using the EMAT head movable along the surface of the sample in the region of interest (250x50mm). Finally, 20 parallel rows of scanning every 2.5 mm and 250 mm long was performed. The recorded data were processed using a signal processing algorithm based on an operation such as signals synchronization, rectification, envelope analysis, and peak amplitude estimation.
- map of the adhesive path after application of lock-in active thermography tests with use of modulated sine waveform and with 34% of maximum available power. A three periods of sine wave was recorded for excitation frequencies of 0.016 Hz (period time 3 min. 11 sec.) and 0.01 Hz (period time 5 min.). Infrared images were obtained with 1Hz frequency. Infrared images obtained during the LT test were filtrated using a median filter (3x3 window) and transformed to a frequency domain using a FFT operation. Spectra obtained for each pixel were presented in the form of phase images.
- map of the adhesive path after application of pulse active thermography tests with use of full power of excitation source and heating time 500ms. The 30 seconds of data were recorded with a frequency of 10 Hz. In the case of the PT data, at least a few different image processing methods were used in some situation combining them to obtain a final image with the best visibility of the simulated defect. For those experiments, a combination of such operations such as Particle Components Thermography (PCT), Differential Absolute Contrast (DAC), Thermograph Signal Reconstruction (TSR), and the Fixing Contrast Algorithm (FCA) were used.

The presented maps indicate the defective region.

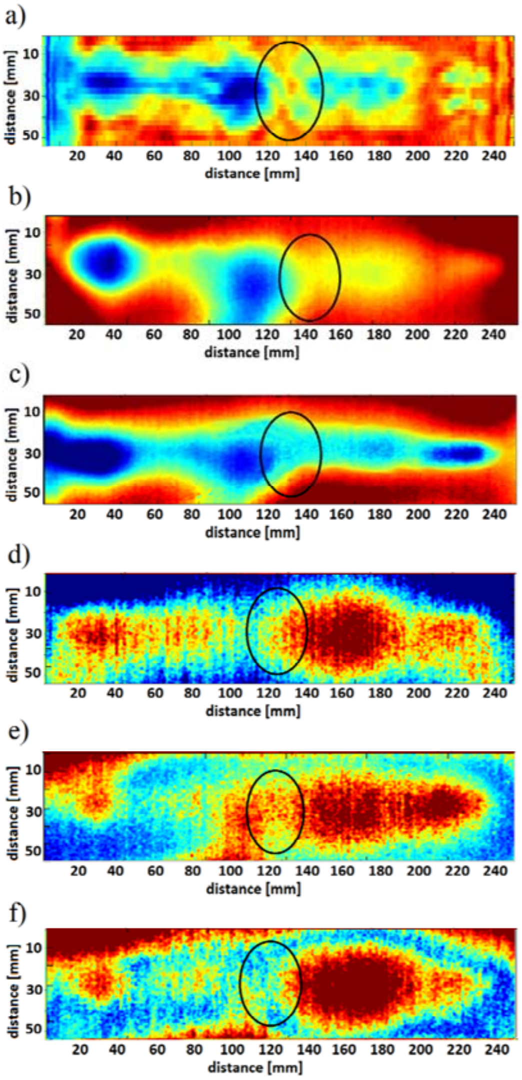

Fig. 15. Color-map obtained after data processing obtained respectively for: a) EMAT test, b) LT 0.016 Hz test, c) LT 0.01 Hz test, d) PT 500ms test and PCT algorithm (3rd EOF with 2.6% of data variation), e) PT 500ms test and DAC + FCA(5th order), f) PT 500ms test and TSR + FCA(5th order)

Obtained color maps both for EMAT and active thermography tests make it possible to detect and characterize the simulated defect. The defect should have a length of 18 mm, however due to adhesive flow after plate assembly, the distance was shortened. The image obtained after the ultrasonic test using EMAT technology is more detailed in comparison to images generated during active thermography investigations. The defect and details of localization of the adhesive path is very visible.

Images obtained using active thermography methods, in contrast to the EMAT color map, have blurred edges between areas with and without adhesive. Both tested NDT methods require calibration and tune up of test parameters. In the case of the presented research, such operations were done, however there is still a possibility to improve the sharpness of the observed object in infrared images by application of a more sensitive infrared camera as well as to improve image processing algorithms. In the case of EMAT, there is also potential to manipulate test parameters by selecting different sensors and increasing scanning resolution. The considered NDT methods could be compared also from the test speed point of view. In this situation, the best solution is pulse thermography (PT), because the test takes a few seconds and the first results can be observed directly after the test during the cooling process of the tested structure. In the case of PT, a crucial issue is the power source localization which has influence on heating uniformity. This limitation does not exist in the case of Lock-in thermography, but the test is more time consuming especially in the case of specimens made of metals due to their high conductivity. Highly conductive materials require lower excitation frequency [20]. In comparison to active thermography testing, use of the EMAT technology took the most time but achieved the best detection of the defect. It is possible to shorten the duration of the test; however, it will affect the quality of the scan image and thus the defect's visibility.

4. CONCLUSIONS

This survey of NDE methods indicates huge potential in testing of adhesively bonded structures, however, one should remember that not every method is equally successful for a specific problem.

Due to the operating phenomena, some of the methods can be used outside the production line (off-line) in a laboratory environment, but at least two methods considered during the survey can be successfully applied for testing parts on-line during manufacturing process. In the author's opinion, such methods are active thermography and ultrasonic scanning using EMAT technology. Results of the preliminary research confirm suitability of EMAT and Active thermography to inspection of adhesively bonded structures. Tests performed in laboratory conditions successfully allowed detection of simulated defects of an adhesive joint in a prepared sample. The fastest but less accurate defect evaluation in its characterization gave pulse thermography with use of a standard bolometric camera. The most precise, but very time consuming method is ultrasonic scanning using EMAT technology. From the author's point of view the best solution would be integration of both methods into a hybrid and automated system where active thermography could quickly and roughly evaluate general conditions of the tested structure and after detection of suspected flaws, the EMAT technology could be applied to investigate in detail the indicated area, giving precise characterization of the potentially defective region. Such approaches requires additional research on many aspects of the testing, which will be the subject of the author's future study.

LITERATURE

1. Ann R. Automotive Structural Adhesives Drive Material Changes. Design News 9/2/2014, http://www.designnews.com/document.asp?doc_id=274494&dfpPParams=ind_183,industry_auto,aid_274494&dfpLayout=article
2. Vedula S. Infrared Thermography and Ultrasonic Inspection of Adhesive Bonded Structures, Overview and Validity. Clemson University, August 2010.
3. Adams RD. Adhesive Bonding: Science, Technology and Applications. Elsevier, 8 mar 2005
4. Allin JM. Disbond detection in adhesive joints using low-frequency ultrasound. A thesis submitted to the University of London for the degree of Doctor of Philosophy. University of London, May 2002.
5. Shull P. J. (ed.) Nondestructive Evaluation. Theory, Techniques and Applications. Marcel Dekker, Inc. 2001.
6. Vontobel P, Lehmann E, Frei G. Neutrons for the study of adhesive connections. Paul Scherrer Institute, Villigen, Switzerland 2004-11.
7. Onoszko K. Metody stosowane w badaniach nieniszczących. Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska, 2012;4:11-14.
8. BondMaster Application Guide, http://www.olympus-ims.com/pl/.downloads/download/?file=285213057&fl=en_US
9. Heida JH, Platenkamp DJ. Evaluation of in-service non-destructive inspection methods for composite aerospace structures; November 2011
10. Liu B, Guo XM, Qi GJ, Zhang DS. Quality evaluation of rubber-to-metal bonded structures based on shearography. Science China Physics, Mechanics & Astronomy 2015;58(7).
11. Andersson J, van den Bos B. NDI on Bonded Sandwich Structures with Foam Cores and Stiff Skins – Shearography the Answer?. Application Report No. 02. 01 of Attemeyer AG. http://www.ndt.net/article/wcndt00/papers/idn389/idn389.htm
12. Automotive Circle International 2012, Active Thermography – NDT Method for Structural Adhesive and Mechanical Joints

13. Bai W, Wong BS. Evaluation of defects in composite plates under convective environments using lock-in thermography. Meas. Sci. Technol. 2001;12:142–150.
14. Ibarra-Castanedo C, Genest M, Piau JM, Guibert S, Bendada A, Maldague X. Active infrared thermography techniques for the nondestructive testing of materials Chapter XIV of the book: "Ultrasonic and Advanced Methods for Nondestructive Testing and Material Characterization", ed. Chen CH, 2007:325-348.
15. Meola C, Carlomagno GM, Squillace A, Giorleo G. The use of infrared thermography for nondestructive evaluation of joints. Infrared Physics & Technology 46, pp. 93–99, 2004.
16. Rams B. Zastosowanie klejenia w połączeniach zgrzewanych metodą FSW. Przegląd Spawalnictwa, 2009;3:33-38.
17. Stachurski M. Nowoczesne metody ultradźwiękowego badania materiałów oraz nowoczesne przetworniki ultradźwiękowe. Biuletyn Instytutu Spawalnictwa, 2007;4:45-51.
18. Power Box H. Operation manual. Innerspec Technologies, Inc. 2014.
19. Lopez B. In-Service Inspections Using EMAT and MRUT. July/August 2015 issue of Inspectioneering Journal.
20. Kurpiński M, Fidali M. Application of active thermography methods to defect detection of bounded joints. 13th Quantitive InfraRed Thermography, Lipiec 4-8, Gdańsk 2016.

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