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Application of active thermography methods to defect detection of bounded joints

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Abstract

Joining by use of adhesive bonds is one of the most widely used way to connect and/or seal steel/plastic panels used in the automotive industry. Due to the technological process faults different kinds of defects could appear in the bounded joint. There are many destructive and non-destructive methods allowing investigation of defect of bonded joint. In this article the active thermography methods like PT (Pulsed thermography) and LT (Lock-in thermography) were used to detect of discontinuities in sealing joints between two steel plates. Results of the research shown that defect of bounded joints could be recognised however it is necessary to ensure proper test conditions.

1. Introduction

Bonded joints are very popular methods of making connections between different parts at the automotive industry. The adhesives perform many different functions in the vehicle construction creating stable and durable joint which also perfectly seals any gap and dump a vibrations.

In the adhesive joint could appear different kind of defects presented in Fig. 1. From the car manufacturers point of view it is necessary to provide effective detection of technological flaws of adhesive bounded joints like breaks in adhesive path, wrong substrates preparation and process parameters (temperature and pressure). Currently, the Statistical Process Control (SPC) is one of the most famous tool used to achieve high quality of the products. SPC uses results of destructive (DT) and non-destructive (NDT) testing methods. The destructive methods are very common in bonded joint structures assessment but are very costly due to necessity of completely specimen destruction. For this reason, there are many various type of NDT methods in use to reduce applicability of destructive ones. To detect defects of bounded joints a vibroacoustic, radiographic, thermographic and ultrasound methods could be applied [2]. The ultrasound testing (UT) methods seems to be the most popular. However, the main nature of the UT techniques disallows them to be used to test large area parts in reasonable time. As an alternative an active thermography methods [1, 3] could be used. Active thermography is rarely applied in testing the bonded structures in automotive industrial conditions. The aim of the authors is to develop an industrial method of quality control of adhesive bonded joints by use active thermography methods. To reach this target it is necessary to investigate usefulness of existing active thermography methods to testing of bounded joints and find optimal test conditions as well as proper way of infrared image processing. The article presents a part of research, which involve a PT and LT tests parameters optimization.

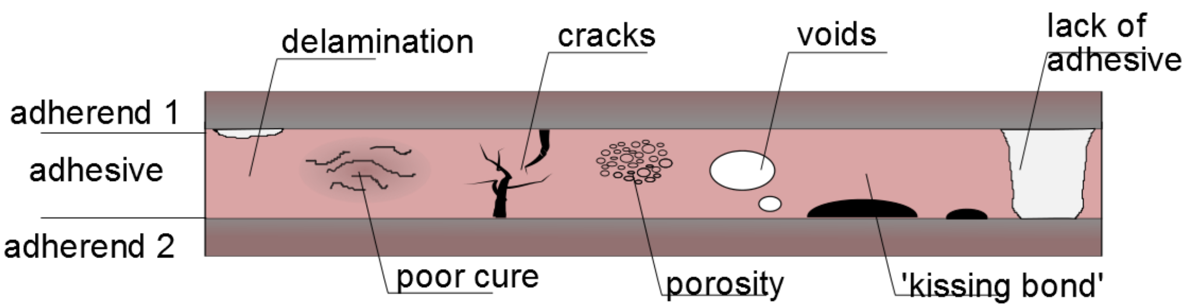

Fig. 1. *Possible adhesive-bonded structures defects*

2. Test stand and investigated specimens

In order to find an optimal PT and LT parameters like thermal excitation power, pulse duration and frequency of harmonic excitation a test stand (Fig. 2) was prepared. A test stand consist test chamber with specimen holder and halogen lamps with power 1kW each. The lamps were connected to the power regulator which was designed to cooperate with peripheries with maximum 10 A current use. Infrared images were acquired using uncooled infrared camera Infratec VarioCam connected to the PC with installed acquisition and control software. Camera has resolution of 640x480px, temperature resolution about 0.1@30°C and is able to acquire images with frame rate of 50 fps. PC also was used to control power regulator in order to generate appropriate thermal excitation. Hardware and software allow preparing both: pulsed and harmonic modulated signal with approximately 90 levels of power change. That level amount came from prepared software and calibration procedure. Simple diagram and internal structure of power regulator could be seen in Fig. 3. The device is designed to be shock-proof, compact, simple and cheap. Programmable AtMega8 CPU allows extending device functionality.

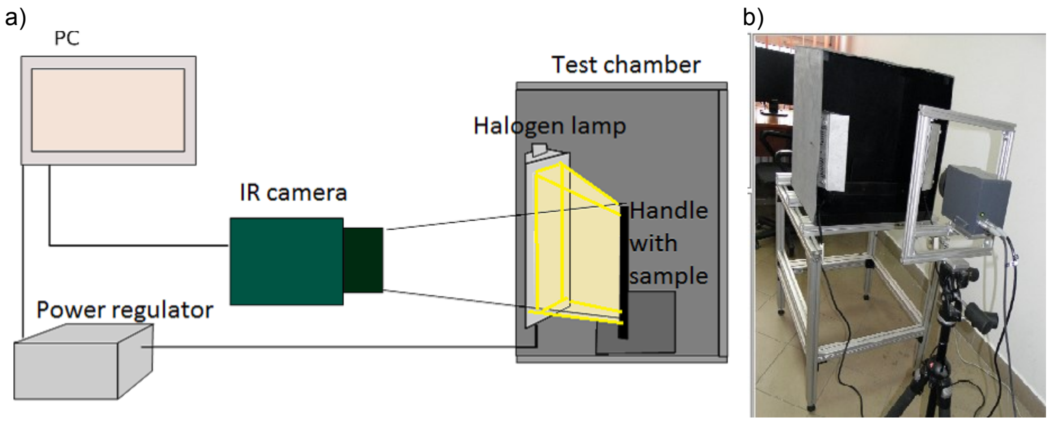

***Fig. 2.** Experimental setup (a) its real view (b)*

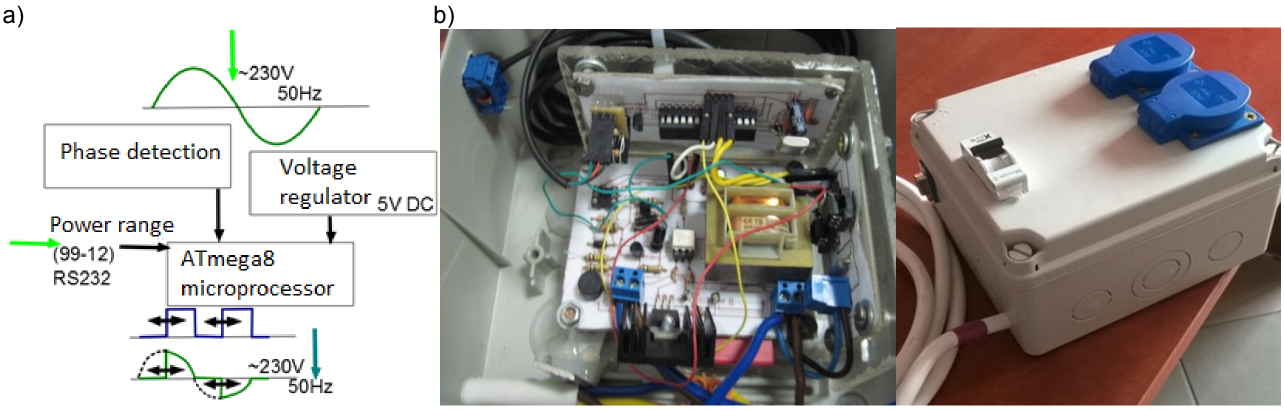

Fig. 3. Diagram explained power regulator functionality (a) and its internal structure (b)

The three samples were tested during the research. Each of the sample consisted two steel sheets 150x100x1,1 mm with adhesive path localised between them. In the one sample the adhesive path has gap 50 mm long. Lack of adhesive simulated as a technological defect caused by improper adhesive application (Fig 4). Two other specimens were covered properly with path of adhesive but one of them was combined without pressure what induce other further joint integration failures. The surfaces of steel sheets have been black painted which was planned at design level. Heavily reflectivity of the steel surface is a real problem in optical based measurement methods. Authors own research allow to select a paint which estimate emissivity was about 0.92. Selected paint was also used on test chamber to decrease environment radiation reflection.

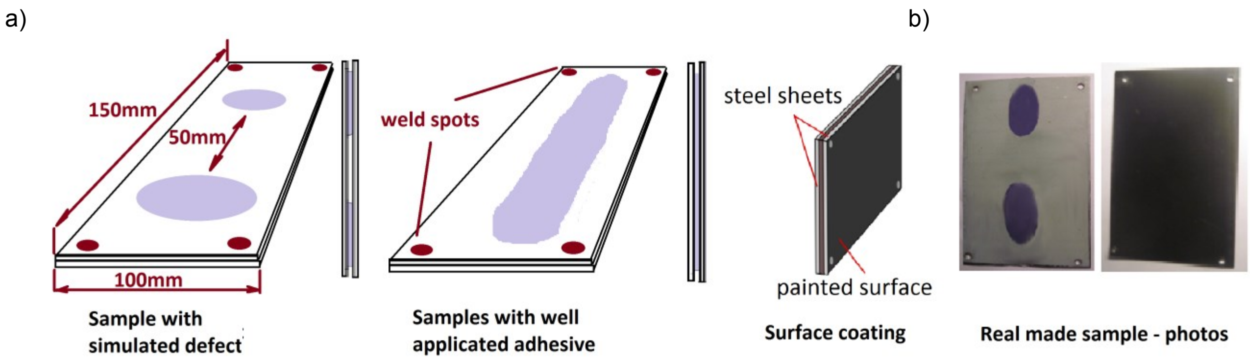

***Fig. 4.** Experimental samples concept(a) and photos from one of made sample-before and after bounding (b)*

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3. Results of application of pulsed thermography

Prepared specimens were tested using pulsed thermography techniques. Firstly the series of tests were performed in order to determinate optimal excitation parameters. Preliminary tests have showed that pulse duration and power of lamps equal respectively to 500ms and 2 kW gave quite good results. It was shortest excitation time possible to generate with use of currently configured test stand. In figure 5-7 shown plots of temperature curves measured in bounded and no bounded areas of all tested specimens. Measurements were performed at excitation energy 2kW*500ms=1kJ. Preliminary PT tests allowed us to find also optimal location of halogen lamps and camera frame rate (5 Hz).

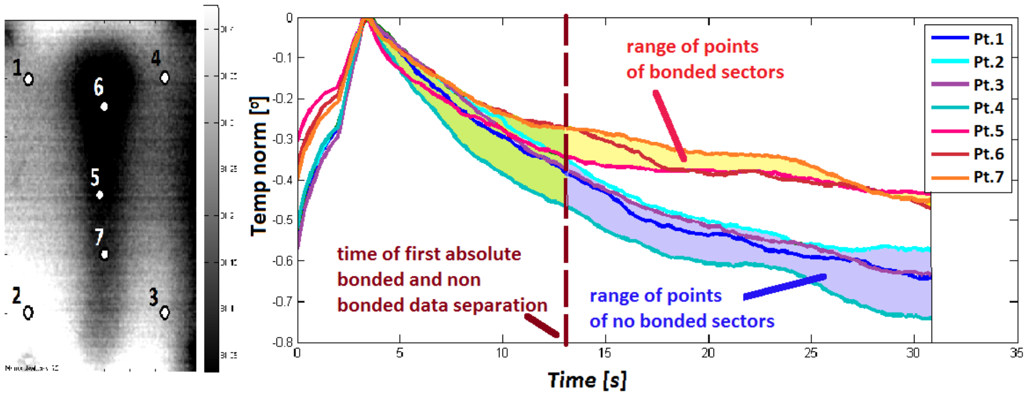

Fig. 5. *The temperature curve acquired in 7 points localized on bonded and no bonded sectors. Vertical dash line shows moment when courses of the sectors start to isolate each-other. Test made for 500ms excitation time pulse for well-prepared sample*

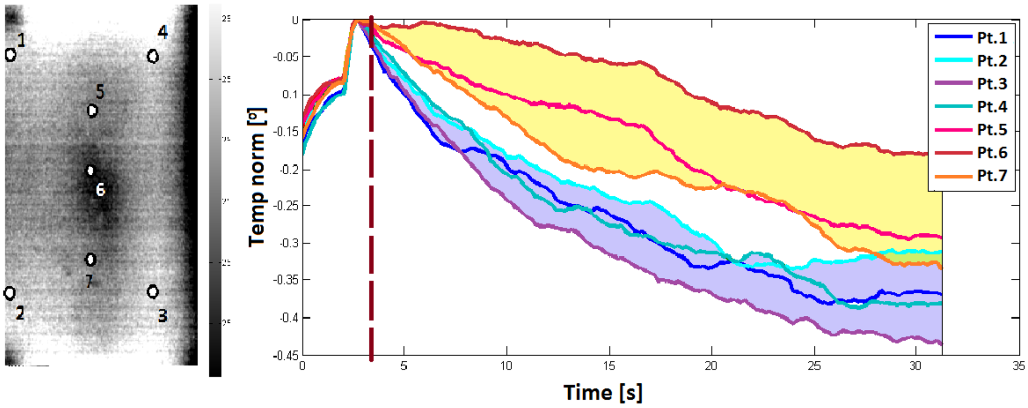

Fig. 6. *The temperature curve acquired in 7 points localized on bonded and no bonded sectors. Vertical dash line shows moment when courses of the sectors start to isolate each-other. Test made for 500ms excitation time for sample with integration fault. Vertical line and areas type description like on Fig. 5*

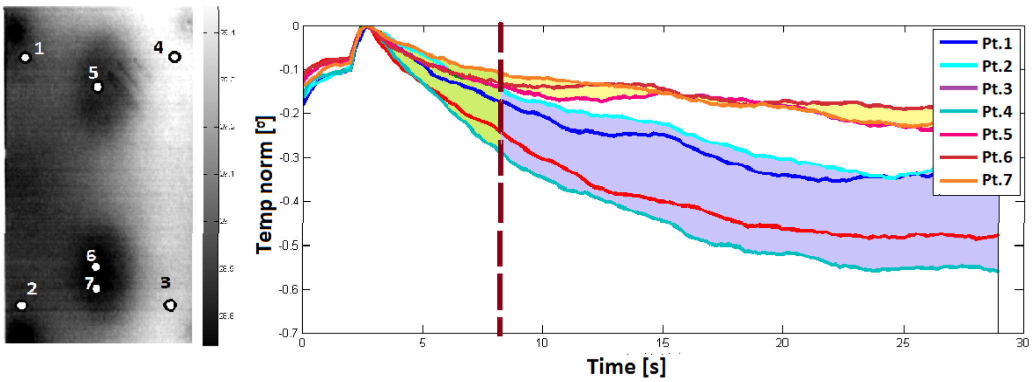

Fig. 7. *The temperature curve acquired in 7 points localized on bonded and no bonded sectors. Vertical dash line shows moment when courses of the sectors start to isolate each-other. Test made for 500ms excitation time for sample with application fault. Vertical line and areas type description like on Fig. 5*

Further changes provided to halogens location and acquisition software calibration made possible to obtain much more condensate thermal energy pulse. That also permits to use shorter excitation time and improve thermal contrast. Specimens were tested using excitation time from 100 to 1000ms with 100ms interval. Obtained data plots for 4 different excitation duration times could be seen below (Fig. 8.). Results of tests performed after improvements of thermal excitation system shows that temperature curves in no bonded and bonded sectors for the same points like in Fig 5-7, are able to separate even after 300 ms of thermal heating and after about 8.1-15.4 second for presented range (Fig. 10). Simple software allows comparing contrast of bonded and no bonded areas between all frames of any thermographic data set. An algorithm allows indicating time when the highest difference between mean temperature values in points localised in bounded and no bounded areas occurred. The time of maximum differences is shown as green vertical line on each plot presented in Fig. 8. The brown vertical line presented in Fig. 8 shows the moment of time when temperature difference between sound and defect area begins grow (Fig. 9). Parameters with absolute difference between mean temperature values in considered areas are presented on chart in Fig.10. As could be noticed the temperature difference increased with time however defect visibility decreases.

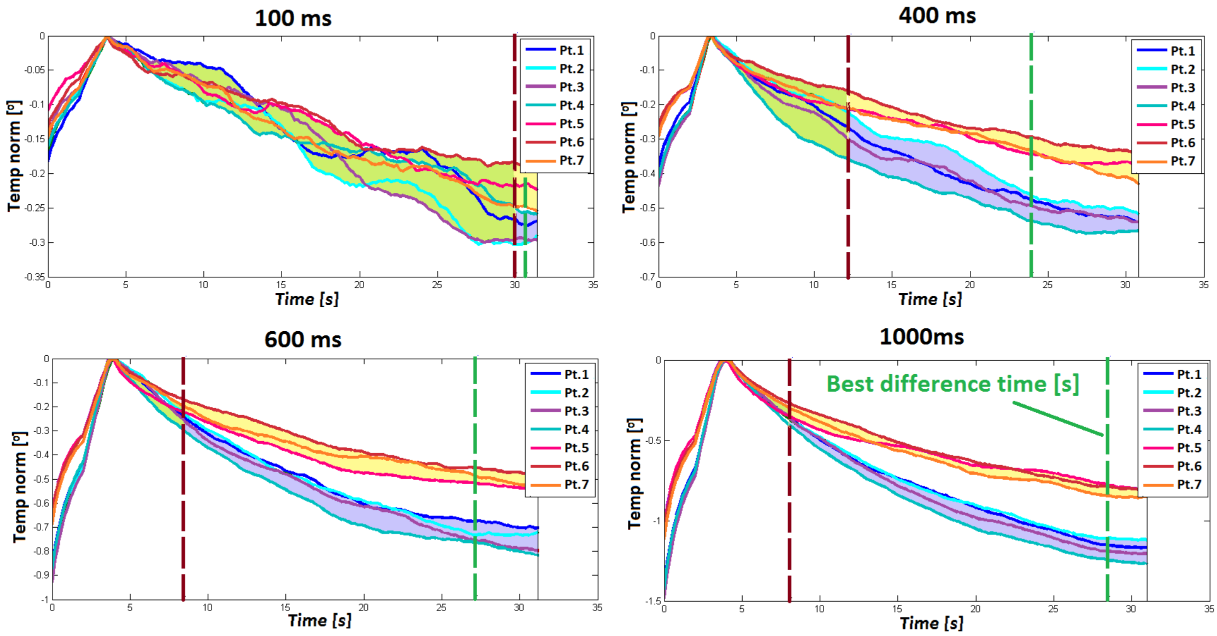

Fig. 8. *The results of four chosen plots of PT method with different excitation time experiments provided on specimen without any simulated defect. Points 1-4 and 5-7 are representing no bonded and bonded sectors respectively (Localization of points could be seen in Fig.5)*

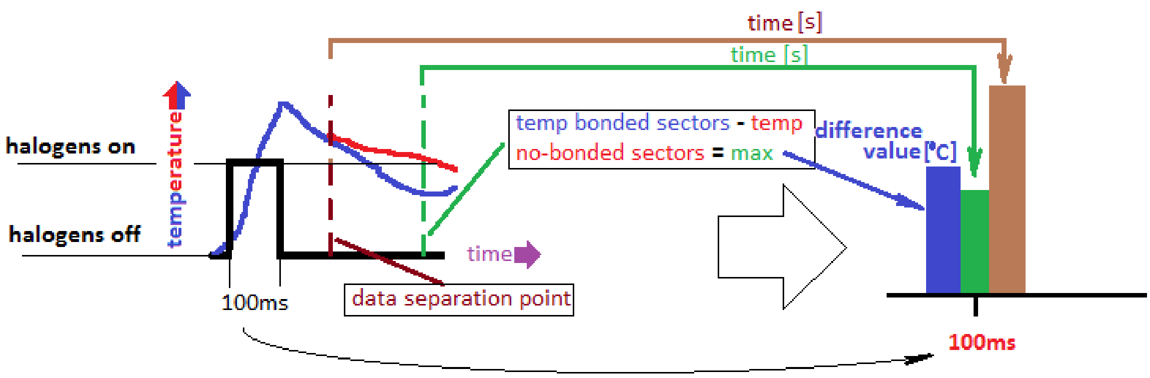

Fig. 9. *Explanation of parameters extraction from the data plots (Fig. 8.) into column chart representation (Fig. 10)*

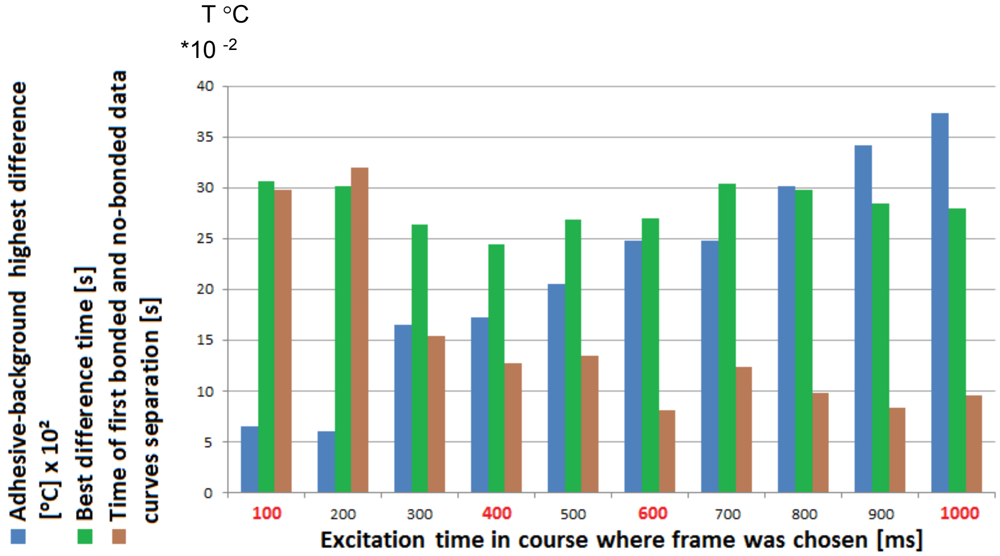

Fig. 10. *Prepared software results of sample without simulated defects (points location like in Fig. 5). Parameters extracted from plots in Fig.8. are indicated by red coloured values. The vertical axis represents values of all extracted parameters (Fig.9.)*

Most important criteria should be connected with clearance of visibility of edges between bonded and no bounded area. Proposed solution based on developed algorithm was presented in Fig. 11. Firstly, one, short profile across bonded and no bonded should be defined (example: Fig 11., left side picture). Temperature profile allows us to assess temperature gradient. Secondly, to minimalize errors provided by preheated sectors (they could appear after multiple experimental sessions realized one-by-one in row) simple operation should be obtained. First frame isolated and subtracted from remaining frames could extremely increase the sectors contrast. Next step is using the selected profile to estimate data dispersion by the E factor equation (Fig. 11., 4th step). This factor should be obtained for every frame from acquired thermographs sequence. Frame with the highest factor value should show the sharpest frame in the data set.

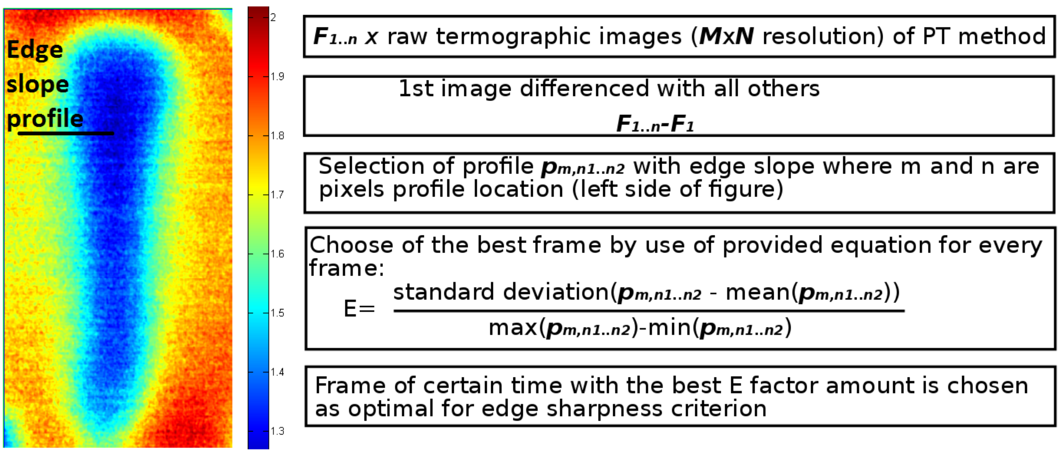

Fig. 11. *Proposed assessment procedure for detect the sharpest boundary from target course*

For further assessment, the thermal profile marked on the left–sided picture at the Fig. 11 was tested by the algorithm in function of heating time from 100 to 1000 ms with 100 ms interval. The best thermographic images were chosen for each excitation time. Earlier specified slope profile (Fig, 11., left side) were extracted, normalized and plotted as a time function in Fig. 12. It should be noticed that profiles become smoother with rising energy provided to the joint. It is hard to choose the sharpest one, so to help make a best-suited decision, appearing time and E factor parameters extracted (Fig. 13.) and presented in Fig. 14. Anyway, the first mentioned criteria should be the most decisive among other factors like time, economical aspects or critical temperature of use for applied adhesive provided by the manufacturer.

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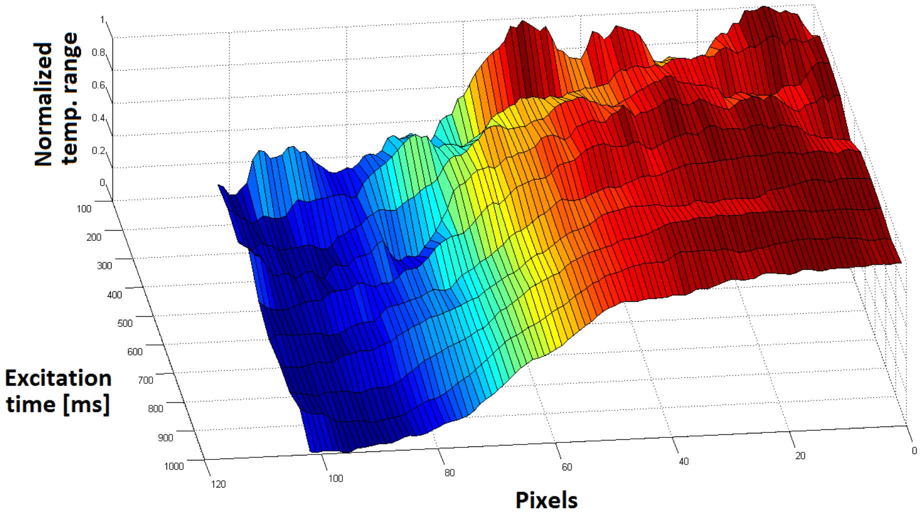

Fig. 12. *Edge slope profile (Fig. 11., left side picture) for the best E factor value in different excitation time*

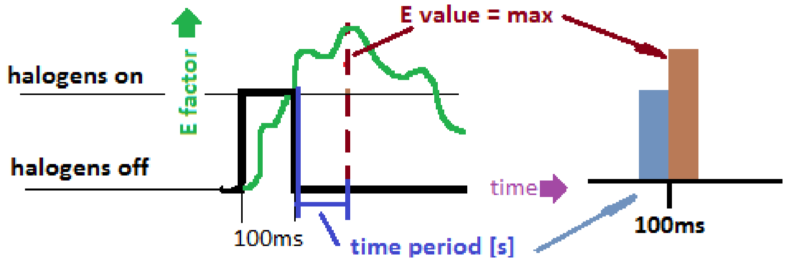

Fig. 13. Idea of data extraction from the E factor plots into representation presented in Fig. 14

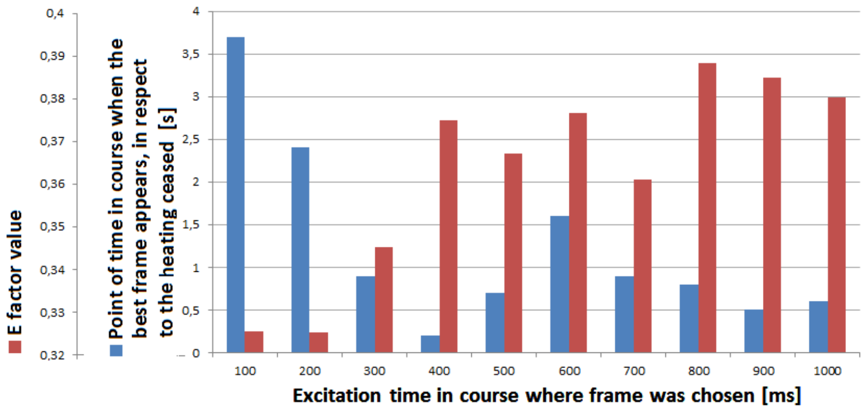

Fig. 14. The best values of E factor and corresponding time periods

4. Results of application of pulsed thermography

During the LT tests an optimal frequency of harmonic excitation and power of lamps were looking for. Frequency of harmonic excitation signal has been changed iteratively from 0,1 Hz to 0,008 Hz. From acquired sequence of IR images the phase images were obtained by use of FFT algorithm. It is important to remember that data transformation (not only FFT algorithm is available) has to be present in the pre-processing sequence to obtain appropriate data appearance for further processing operations. A quality measure allowing evaluation of excitation frequency was phase difference $\Delta\Phi$ in sound and defect area. Each specimen needs definition original temperature profile for further appropriate verification. It was important to cut two fundamental areas (bounded and no-bounded) but it is also worth to have in mind that line should lay on sectors where adhesive thickness variation is expected. Such adhesive layer irregularity could be seen at Fig 15-b. That helps to decide to provide the profile along a vertical direction beside of Fig 15-c case.

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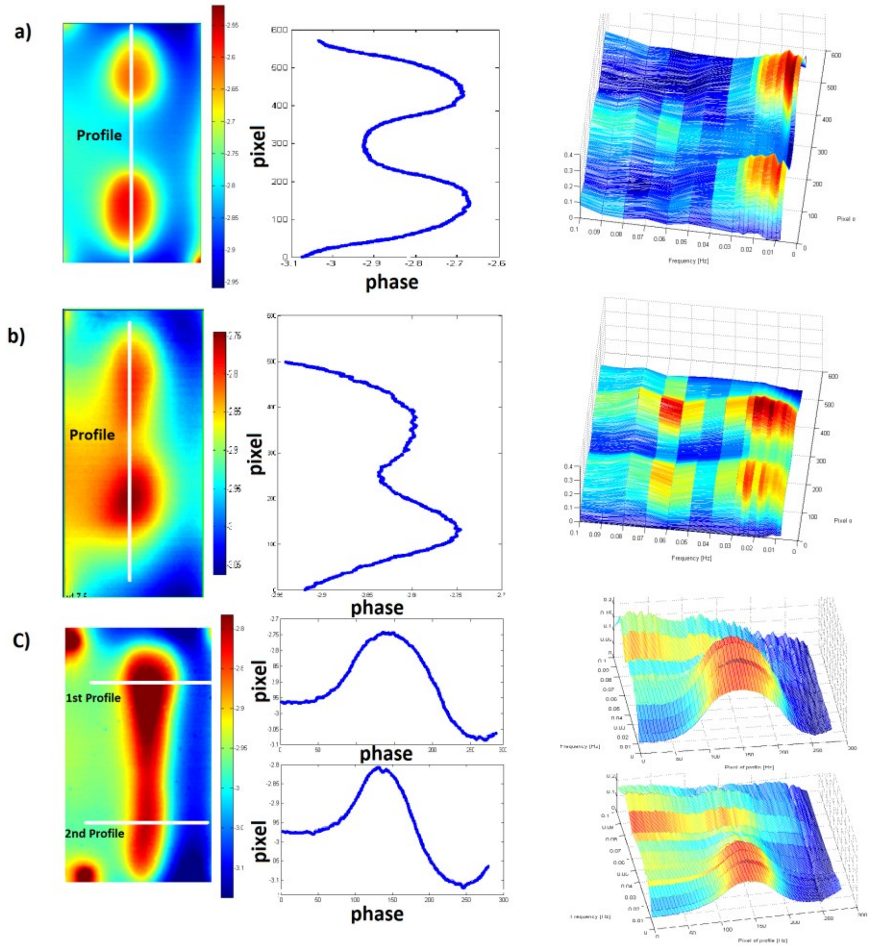

Fig. 15. *Phase images of investigated specimens obtained during LT experiments . From left: the best sample phase images with profiles indication, example plot of the profile, profile change in the function of excitation frequency*

During investigations of data presented before, it was clearly noticeable that lower frequencies provide better results. Unfortunately, time of experiment rises exponentially, so optimal phase graphs have to be isolated in acceptable test period. To set optimal acquisition and modulation frequency parameters one of the sample's profile (Fig 15. a) was divided into bonded and no bonded sectors (Fig. 16). Contrast of this zones pixels value was provided for each excitation source frequency (from 0.1 Hz to 0.008Hz) and showed in Fig. 17. As could be noticed in the figure, difference between bonded and no-bonded sectors starts to rise instantly with excitation frequency fall from 0.06Hz and slowdown near 0.014 Hz.

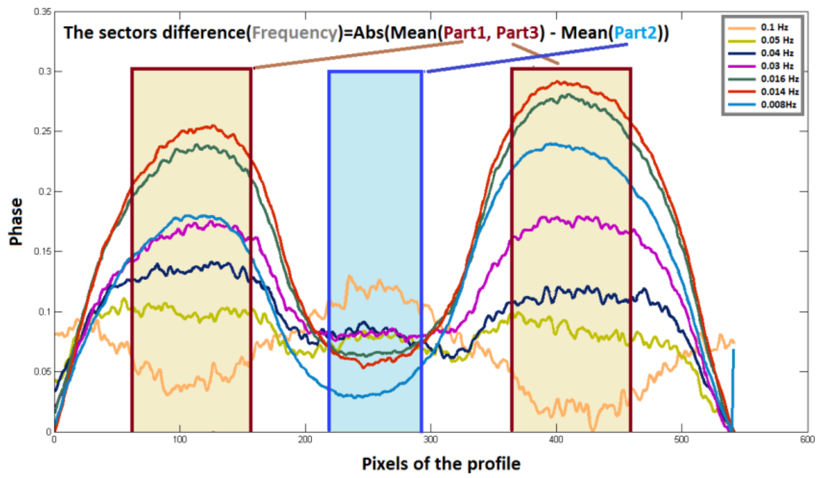

Fig. 16. *Profile shape from Fig 15.a for chosen frequencies with indicated sections of the profile and equation for contrast assessment. Part 1, 2 are the bonded sections and Part 3 is no-bonded section*

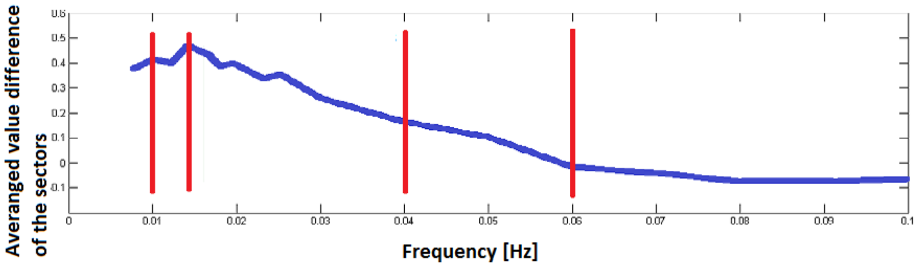

Fig. 17. *Plot of the contrast between bonded and no-bonded section of Fig. 16 centrally presented profile computed in the function of frequency. Red vertical lines indicates chosen frequencies, for which the phase images of all three samples has been prepared and shown on Fig. 18.*

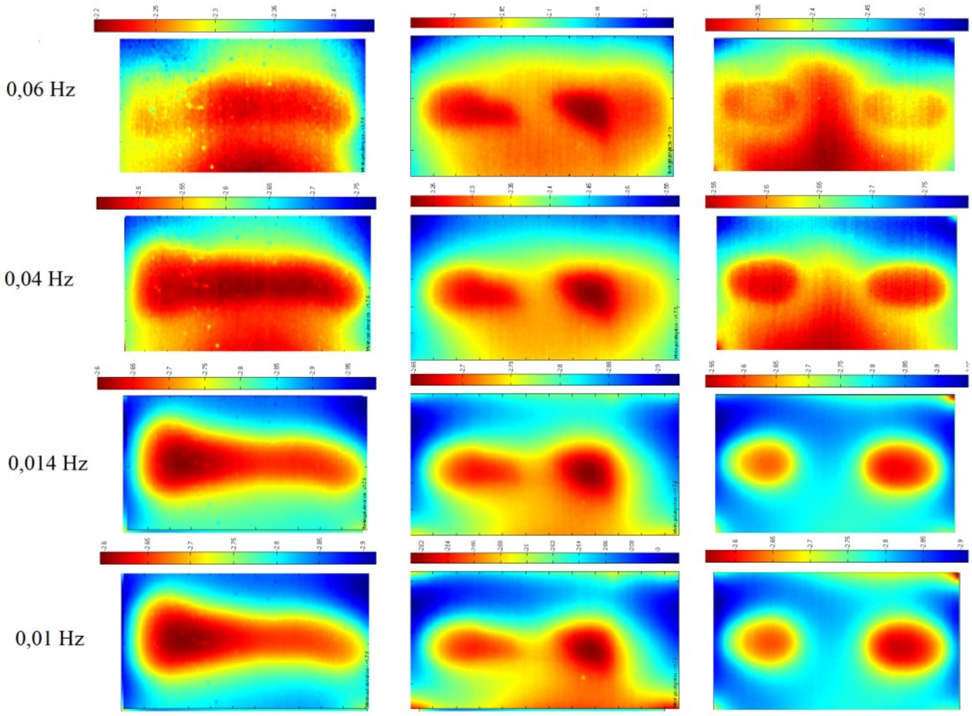

Fig. 18. *Three samples phase graphs of 4 different chosen excitation source frequencies*

It is clear visible that phase graphs as FFT thermographs transformation result are much more common because of its natural feature to skip influence of environmental conditions and non-uniform surface heating. It is worth-mention that signal's constant component removal could improve bonded sectors visibility in amplitude graph from many noising factors as it is presented in the figure 19.

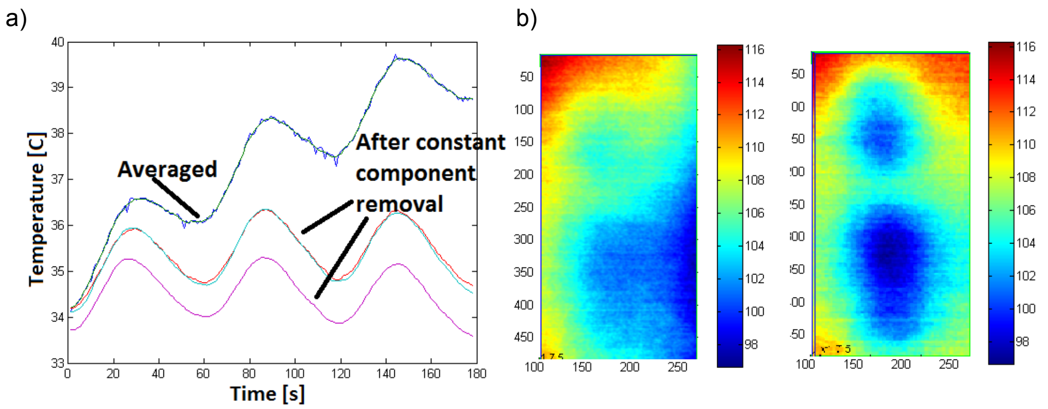

Fig. 19. *Two processing methods results showed by time courses(a) amplitude-graph before and after processing operations (b)*

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5. Comparison of results obtained by use of pulsed and lock-in techniques

Finally the determined optimal parameters were used to test the samples. For LT method 0,014 Hz excitation frequency was chosen and for PT method an 600 ms pulse length duration was also used. After application a basic data pre-processing methods all samples are presented in Fig. 20. As one can see both methods are able to detect defects in adhesive bounded joint of two steel plates. However the better results obtained using LT method. In case of PT images a strong noise exists.

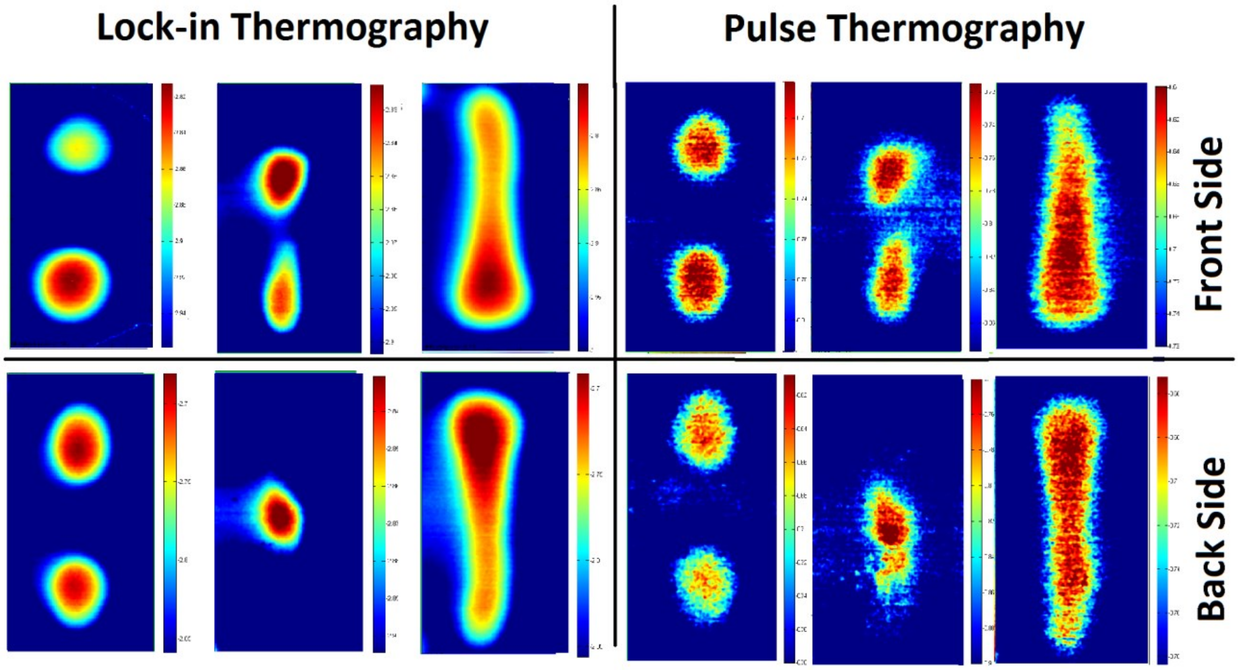

Fig. 20. Comparison of application of *LT and PT to adhesive bounded automotive steel plates with and without defect*

6. Conclusions

The performed tests show that the best active thermography method to detect discontinuities in adhesive path is LT. It gives phase images with very good thermal contrast however in case of steel plates the optimal frequency of the harmonic excitation is very low what makes testing process a time consuming. In case the PT the test results could be better if heat source will have higher power and after application additional image processing methods. It should be mentioned that during PT and LT tests intentionally not used any further image processing method. The aim of the study was to obtain the best images only under properly chosen parameters of the test. Development of the image processing methods for the obtained images will be aim of the future research of the authors.

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