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Evaluation of selected thermal properties of components of bonded joint for purposes of active thermography

Abstract

Adhesively bonded joints are widely used in the automotive industry. Different kinds of defects could appear in the bounded joint during its creation. The defects could be detected by use of many destructive and non-destructive methods including active thermography. Application of active thermography requires setting of test parameters. It could be done based on analytical or numerical models which requires material properties of bonded components. In the article presented results of measurements of thermal diffusivity and specific heat of automotive steel and adhesive for purposes of further modelling and estimation of active thermography test parameters.

Keywords: diffusivity, specific heat, active thermography.

1. Introduction

The increasing use of adhesively bonded structures and adhesive joining technology in all fields of automotive industry [1] as an alternative to the traditional methods of fastening materials involves an increasing demand on quality control. It follows from susceptibility of joining process to different instabilities which can give different defects like delamination, poor cure, cracks, porosity, voids, "kissing" bonds and discontinuity or lack of adhesive [2]. Any defects influencing the quality of mechanical and functional properties of adhesively bonded joint that's why it's necessary to control its quality to eliminate problems in adhesive application process. 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 alternative some active thermography methods [3, 4] could be used. Active thermography is rarely applied in testing the bonded structures in automotive industrial conditions. Authors preliminary research [4] shows that both pulse and lock-in thermography can be successfully applied to revel some defects in adhesively bounded metal-metal joints. Effective implementation of active methods in industrial conditions requires development of technique of fast estimation of active test conditions as well as proper way of infrared image processing. One of very helpful way of assessment of test condition could be application of thermal model of adhesively boned joint. Such models should be feed by some very important thermal parameters like diffusivity and specific heat of each layer of bonded joint. In this article results of assessment of thermal diffusivity and specific heat of automotive steel and adhesive are presented.

2. Modeling of heat transfer of bonded joints during thermal stimulation

Active thermography testing applies external stimulus to heating up or cooling down the investigated object and 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 in images generated by the 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), vibro-thermography (VT). Due to simplicity, the most popular are PT and LT with use of optical stimulation devices like heating lamps (halogens or flashes).

During the optical thermal stimulation of the object, thermal wave propagates by radiation through the air until it touches the investigated object surface where heat is produced and propagates through the structure.

Adhesively bonded joints belong to multilayer structure and in case of classical automotive bounded joint can be represented by three layers model: steel – adhesive – steel. However, if we take into consideration that source of heat stimulation will be at the same side as infrared camera observing stimulated surface we can simplify consideration to two-layer model of structure steel – adhesive.

In case of such structure the interface between layers affects heat, propagation process and reflects some portion of the transferred heat. Thermal behaviour at the interface between two materials depends on their effusivities, and is characterised by thermal reflection coefficient R [5]:

$$R = \frac{e_1 - e_2}{e_1 + e_2}, \tag{1}$$

where:

$e = \sqrt{\lambda \rho c_p}$ – thermal effusivity.
λ – thermal conductivity, W/m·K,
ρ – density, kg/m^3,
c_p – specific heat, J/kg·K

In case of properly manufactured adhesively bonded joint interface between layers should be uniform. However, if adhesive discontinuity occurs the thermal coefficient will locally change causing differences in response on thermal stimulation.

Assuming waveform of stimulating signal (pulse, step, sine) and one dimension case of heat transfer equation (2) it is possible to build a mathematical model which allow to estimate optimal parameters of excitation waveform (frequency, duration, power ect.) [5]:

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t}, \tag{2}$$

where:

$\alpha = \frac{\lambda}{\rho c_p}$ – thermal diffusivity, m^2/s,

To use the model, it is necessary to evaluate fundamental thermal parameters of materials of bonded joint layers following from eq. 1 and 2.

3. Evaluation of thermal diffusivity and specific heat

Thermal diffusivity α is a specific property of every material. It describes how a heat propagates in an unsettled condition and how the material reacts on temperature changes. Moreover, thermal diffusivity is necessary to predict material behavior during cooling process and simulate space-temporal changes of the temperature.
There are many possible methods and normalized procedures to obtain this parameter [6-8]. For the testing of thermal properties of various materials transient state methods and methods based on

stable thermal state are used. The methods of stable state allow to achieve a good accuracy but measurement process is usually time-consuming. Measurement method applied in this work for determination of thermal diffusivity and specific heat belongs to transient state methods. The principle of the method is based on Parkers's method [10] and is called a flash method.

In the flash method, the thermally insulated homogeneous sample of uniform thickness L (original Parker's model) is first stabilized at a certain $T_0=T(x,\ t=0)$ temperature. Next, the front face of the sample is irradiated by an instantaneous, high-energy laser pulse. Simultaneously, the increase in temperature with time $\Delta T(L,t) = T(L,t) - T_0$ on the sample's rear surface is measured. The solution of Fourier's equation which describes 1D transient heat transfer through the sample (expressed by Eq. (2)) for measurement conditions, can be written as (3), [10]:

$$\chi = \frac{\Delta T(L,t)}{\Delta T_m(L,t_m)} = 1 + 2\sum_{n=1}^{\infty}(-1)^n \exp\left(-\frac{n^2\pi^2\alpha\, t}{L^2}\right) \tag{3}$$

where ΔT_m represents the maximum rise of the temperature on the rear sample surface. It can be proved that for χ=1/2 from relation (3) can be obtained expression for calculation of thermal diffusivity:

$$\alpha = 1.37\, L^2/(\pi^2 t_{1/2}) = 0.1388\,(L^2/t_{1/2}) \tag{4}$$

where $t_{1/2}$ denotes the time of reaching half of the maximum rise in temperature of rear sample surface, s.

As it can be seen, it is not necessary to know the amount of energy absorbed in the front surface to determine thermal diffusivity. However, this quantity must be known if measurement of specific heat is required. The amount of laser pulse energy absorbed by the tested sample is influenced by various parameters and it is not possible to measure directly this quantity. Because of it, during the measurement of the specific heat capacity of the sample under consideration, a second sample of known thermal features (thermal diffusivity and heat capacity) is simultaneously tested in the same measurement conditions. Next, a correction factor is calculated and specific heat capacity for the tested sample can be determined. The calculation is realized by internal software of measuring device.

3.1. Considered materials

Car body consists parts make of different kind of steels sheets of different thickness. For the research two types of an automotive steel and one type adhesive were taken into consideration. It was the CR210 and CR4 [9] steels which are non-aging mild steels, mostly applied as car chassis part in the auto-mobile industry.

At the market, many different structural adhesives are relevant to join car body steel sheets. For the research purposes, TEROSON RB 5194 GB was taken into consideration. It is a thermosetting, solvent-free, one-component, rubber-based adhesive. The adhesive can be use as sealant or/and as a binder, along edge of a car body joint.

3.2. Investigated specimens

Before the measurements, it was necessary to properly prepare the tested samples. Accordingly to requirements of measuring device (par. 3.3), the specimen must be a circle shaped pad with 0.5 inch of diameter. Fabricated 2 samples of CR4 and one of CR210 steel with thicknesses respectively 1.75mm, 1.74 mm and 1.21mm. The samples were marked: S1 and S2 for CR2 steel and S3 for CR210.

After the measurements of steel samples on selected surface of each sample a layer of the TEROSON RB 5194 adhesive was applied. Procedure of adhesive application illustrated in (Fig. 1). The steel samples with adhesive layer assigned following ids: SA1, SA2, SA3. Thickness of the samples were respectively: 3.42 mm, 3.27 mm, 3.01 mm.

A single sample of adhesive-only was also prepared. To do this the paper mold was used. Sample of adhesive has thickens 2 mm and was marked by id A1. Examples of fabricated samples were presented in Fig. 2.

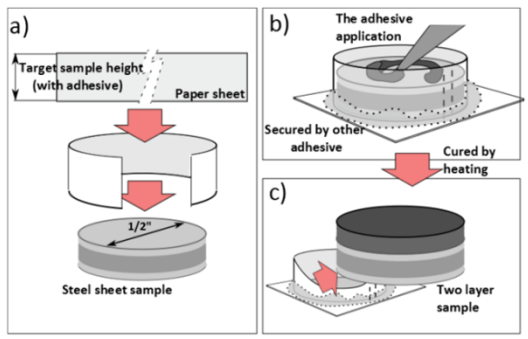

Fig. 1. Two layered sample preparation procedure: a) paper mold preparation, b) adhesive application, c) specimen removal

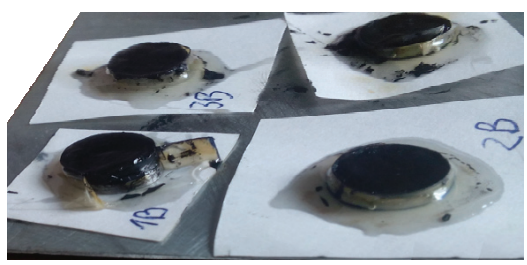

Fig. 2. Final steps of two layer sample manufacturing procedure

3.3. Laboratory equipment and measurement procedure

Measurements of thermal diffusivity as well as specific heat were performed in the Laboratory of Thermal Technology of the Institute of Thermal Technology at Silesian University of Technology. For measurements, the device LFA 457 Microflash (Laser Flash Apparatus) was used. The instrument has a vertical set up with a laser system arranged on the bottom, the sample is in the centre and the detector on top. The detector of InSb type is cooled by means of liquid nitrogen. The instrument has the capability to measure thermal diffusivities within the range of 0.01 mm^2/s to 1000 mm^2/s. For the most materials, an accuracy better than 3% can be achieved. Generally, the device allows to measure thermal diffusivity within temperature range from minus 125°C to +1100°C. For temperature below room temperature (RT) a special second exchangeable furnace should be used. The device consists of several components. The main part of the instrument is presented in Fig. 3.

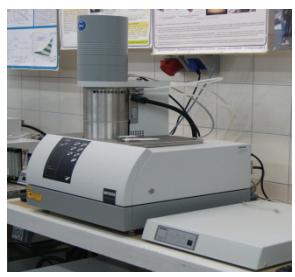

Fig. 3. The measuring device LFA 457 in the laboratory (LTT) of the Institute of Thermal Technology

4. Results of the research

Results of measurements of diffusivity and specific heat are presented below. In the figures are shown all measured values and in the tables presented general statistics for measurements for the different temperatures.

Due to high scatter of diffusivity values obtained for samples AS1, AS2 and AS3 where the substrate for the adhesive were steel samples, the results only for sample AS3 are presented.

Based on measures values of diffusivity and specific heat and accuracy of the measurement instrument a combined uncertainty was calculated. Combined uncertainties for diffusivity and specific heat measurements were respectively $u_{c\alpha S}$=0.34, $u_{c\alpha A}$=0.01 and u_{ccpS}=17, u_{ccpA}=92 .

Discussion of the obtained results is presented in the conclusions.

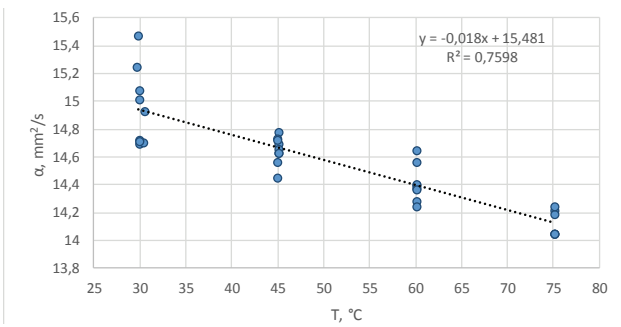

Fig. 4. Plot of measured values of diffusivity for steel sample S1

Tab. 1. Mean values of diffusivity and standard deviations for steel sample S1

T, °C	Mean α, mm^2/s	Std. dev. σ_α, mm^2/s
30	14.9	0.26
45	14.6	0.09
60	14.4	0.13
75	14.1	0.08

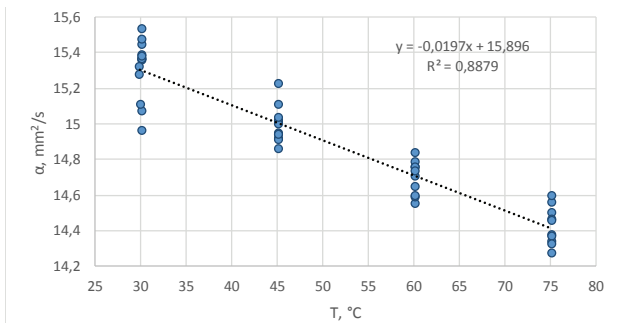

Fig. 5. Plot of measured values of diffusivity for steel sample S2

Tab. 2. Mean values of diffusivity and standard deviations for steel sample S2

T, °C	Mean α, mm^2/s	Std. dev. σ_α, mm^2/s
30	15.3	0.16
45	15.0	0.09
60	14.7	0.09
75	14.4	0.10

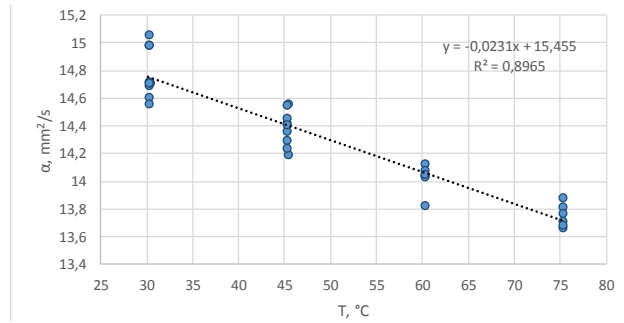

Fig. 6. Plot of measured values of diffusivity for steel sample S3

Tab. 3. Mean values of diffusivity and standard deviations for steel sample S3

T, °C	Mean α, mm^2/s	Std. dev. σ_α, mm^2/s
30	14. 8	0.17
45	14.4	0.12
60	14.0	0.10
75	13.8	0.08

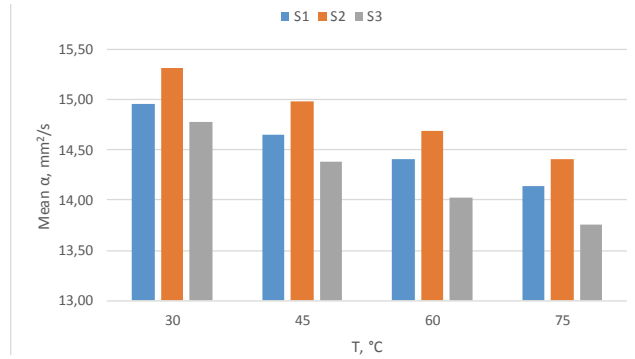

Fig. 7. Comparison of mean diffusivities for investigated steel samples

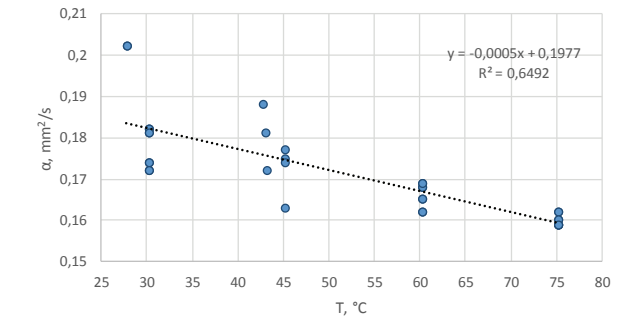

Fig. 8. Plot of measured values of diffusivity for adhesive sample A1

Tab. 4. Mean values of diffusivity and standard deviations for adhesive sample A1

T, °C	Mean α, mm^2/s	Std. dev. σ_α, mm^2/s
30	0.18	0.004
45	0.17	0.005
60	0.16	0.003
75	0.16	0.001

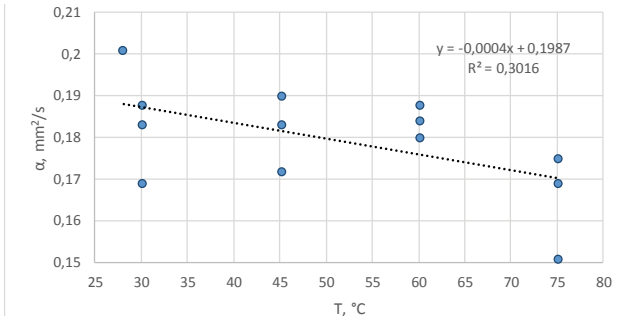

Fig. 9. Plot of measured values of diffusivity for adhesive sample AS3

Tab. 5. Mean values of diffusivity and standard deviations for adhesive sample AS3

T, °C	Mean α, mm^2/s	Std. dev. σ_α, mm^2/s
30	0.18	0.008
45	0.18	0.007
60	0.18	0.003
75	0.17	0.010

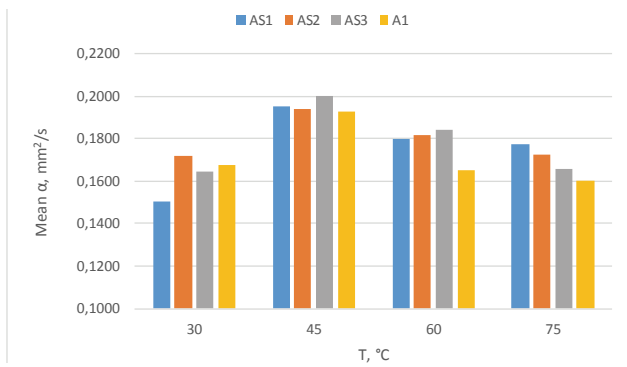

Fig. 10. Comparison of mean diffusivities for investigated adhesive samples

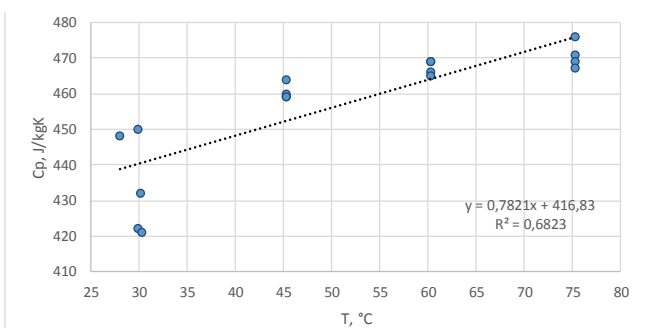

Fig. 11. Plot of measured values of specific heat for steel sample S2

Tab. 6. Mean values of specific heat and standard deviations for steel sample S2

T, °C	Mean c_p, J/(kg K)	Std. dev. σ_{cp}, J/(kg K)
30	431	11.6
45	460	2.1
60	467	1.8
75	471	3.3

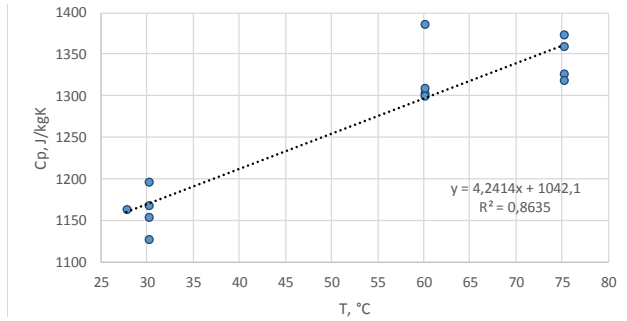

Fig. 12. Plot of measured values of specific heat for adhesive sample A1

Tab. 7. Mean values of specific heat and standard deviations for adhesive sample A1

T, °C	Mean c_p, J/(kg K)	Std. dev. σ_{cp}, J/(kg K)
30	1161	25.2
60	1324	35.7
75	1344	22.4

5. Conclusions

Article presents results of diffusivity and specific heat measurements performed for steel and adhesive applied in automotive industry. Knowledge of these parameters are necessary to estimate conditions of active thermography test of adhesively bonded joints.

Mean values of diffusivity and specific heat measured for the steel samples are correct in reference to values found in the literature. In case of investigated adhesive there are any information about its thermal properties. The research was performed for different temperatures thus we obtain full description of the thermal properties of considered materials. As one can have expected diffusivity decreased linear with temperature grow. In case of specific heat, the trend is reversed. Analysis of measurement values and general statistics shown in the tables allows to indicate, that diffusivity and specific heat at low temperatures have grater variation which is confirmed by standard deviation values. Probably, it results from some problems with measurement temperature stabilization during the measurements because this temperature was very close to RT temperature. The good method is to consider a trend occurring for greater temperature values.

Form active thermography point of view proper assessment of diffusivities for lower temperatures (25–40)°C are important because in most cases NDE test are performed in this temperature ranges. It can be performed using extrapolation of obtained trend.

In case of steel samples, one can observe differences in results of diffusivity measurements. The samples have different thickness however it is not the reason of variation in measurements results because diffusivity does not depend on material thickness. Differences in diffusivities between samples S1 and S2 follows from number of performed measurements and imperfections in the samples preparation. For sample S2 performed more measurements. Noticeable differences in diffusivity values for samples S2 and S3 probably follows from various material properties.

A greater scatter of measurement for temperature 30°C observed also for specific heat values. It follows from the same measurement method.

In case of results obtained for adhesive samples only measurements performed for pure adhesive sample A1 can be useful for the further research. In comparison to different adhesive properties presented in the literature an order of measured diffusivity and specific heat values seems to be correct. Measurements of diffusivity performed for samples AS1, AS2 and AS3 where the substrate for the adhesive were steel samples have

significant scatter of values for temperatures 30°C and 45°C what makes it impossible to compare the results and build the trends as a temperature function.

Despite of existing scatter of diffusivity and specific heat values especially for low temperature obtained results of research are very useful for author's needs. Further research will be focused on building of analytical model of heat transfer in multilayer bounded joint. Model will allow to assess heat stimulation conditions of active thermography test.

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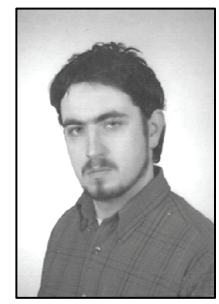

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