ACTIVE THERMOGRAPHY for QUALITY ASSURANCE of joints in automobile manufacturing

C. Srajbr, G. Tanasie, K. Dilger, S. Böhm

ABSTRACT

Today's automotive engineering increasingly demands state-of-the-art quality control. In order to assure their quality, components have to be inspected – ideally by means of non-destructive tests. However, many test cases do not offer reliable and automated non-destructive testing methods. Active thermography offers solutions to assure joint quality. This relatively new non-destructive evaluation method for materials and components is robust, contactless and two-dimensional. This paper provides an overview on the physical properties of the different investigated thermographic technologies: ultrasound, inductive and optical excitation of heat flows. By demonstrating the various test cases, by testing structural and elastic adhesives, mechanical clinch joints and laser-welded joints, the possibilities of respective excitation methods were discussed and examples of the results were demonstrated. Furthermore, the aspects of quality rating and automated testing were reflected.

IIW-Thesaurus keywords: Adhesive bonding; Automobile engineering; Defects; Heat flow; Laser welding; Nondestructive testing; Quality assurance; Resistance spot welding; Thermography.

1 Motivation

One principle task of today's automotive engineering is to reduce vehicle weight, no matter whether it is driven by ecological and economic specifications. On the other hand, customers and authorities demand increasingly more safety and comfort requiring additional components in automobiles. Such contrary requirements make it absolutely imperative to reduce car body weight. This can be achieved by engineering differential lightweight structures which are accurately designed for the required static and dynamic forces.

One of the major tasks when engineering lightweight structures is to reliably join the employed components. Even though modern joining techniques are continuously improving, it is essential to develop suitable inspection methods to evaluate the quality of joints. There are a multitude of well-established test methods using component-like specimens which are severed (e.g. tensile-shear-tests) and tests performed directly on the components (e.g. micrographs, chisel tests). But component-like tests cannot provide reliable information on the component quality in all cases and tests directly performed on components can only provide random information. Such tests often require enormous effort and produce large quantities of test scrap. In comparison, non-destructive testing (NDT) methods deliver direct information on the tested joints. For most joints types, a number of different NDT methods (e.g. visual inspection, ultrasonic testing, x-ray, …) are available. For the majority of the test cases, however, only few market-ready techniques are available, which combine reliability, automation potential, acceptable testing durations, allow to use a wide range of materials, 100 % in-line monitoring and thus considerably reduced reject. [1] Due to the high potential for time- and cost-effective testing of many automotive joining applications, the authors of this paper are convinced that active thermography provides an excellent alternative for the detection and evaluation of imperfections in automotive joints.

2 Methods of active thermography

Thermography can be classified in passive and active techniques. Passive thermography includes the direct evaluation of surface temperatures. Examples are the detection of heat loss in buildings or in electrical circuits of switch cabinets, and the energy performance assessment of production processes in foundries. For welding processes, for example, passive thermography imaging process heat is a feasible evaluation method. But it is not a general technique suitable for any kind of joint. Active thermography is based on forced excitation of the conductive heat flow in a component. In contrast to flawless specimens, flawed joints show variations in the heat

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flow; this can be detected by transient surface temperature contrasts. Differences in heat images (recorded with infrared cameras) of flawed and flawless specimens are used for the evaluation.

A number of different techniques are available to generate heat flows. They can be separated into internal and external excitations. External heat excitation warms up the tested body surface and this energy diffuses in the body. Examples are optical pulses/waves induced by a lamp or a laser, and warm/cold air flows. Internal heating concepts use effects that directly warm the inside of the tested material and partially warm the flawed areas or interfaces of the tested materials. Feasible internal heating methods are eddy currents or dynamic mechanical loads (i.e. ultrasound excitation). Figure 1 shows the excitation methods which will be discussed here, mechanical loads by powered ultrasound, inductive heating and optical warming by flash lights and halogen lamps.

Optical techniques can be used for transmission or reflection. The transmission mode requires an experimental set-up where the test specimen is positioned between infrared camera and optical wave source. In the reflection mode, as shown in Figure 1, camera and optical excitation source are on the same side of the test specimen. The physical principle is a transformation of optical waves into thermal waves on the material surface, and diffusion by heat conduction and a partial reflection or deceleration at imperfections and interfaces of flawed specimens. Compared to defect-free specimens this causes thermal irregularities on the specimen's rear. In the reflection mode thermal waves have to travel twice the distance, because they are also reflected from the specimen's rear and the thermal image is taken on the specimen's front. Optical thermographic arrangements can provide large-surfaced, uniform and non-contact warming, but they strongly depend on the optical properties of the specimen surface. That way, energy input can be problematic when highly reflective materials are tested.

Ultrasound excitation has two effects. On the one hand, it warms through a hysteresis effect caused by the dissipation of dynamic mechanical loads, and, on the other hand, heat is generated by friction of the interfaces (such as at the crack edges or delaminated boundary layers). Interface friction allows to detect defect directly, because, under frictional loads, test specimens with imperfections create detectable hot spots in thermal images. This makes this method so-called defect selective. Drawbacks are the needed contact of the sonotrode, resonances which can cause discontinuous warming and possible high testing loudness due to lower harmonics.

The inductive excitation process is as follows: by inducing eddy currents, thermal waves are generated, heating partial areas of the test specimen. The heat is generated through the dissipation of energy from losses of eddy currents and also losses of magnetic hysteresis – provided the specimen is ferromagnetic. The penetration depth of eddy currents in the heated area can be controlled by the operating frequency, it determines the skin-effect along with the electrical and magnetic properties of the material. Benefits of this technique are the high energy input and the contactless testing mode. However, it is more difficult to heat non-magnetic and impossible to heat non-electroconductive materials, and it is also difficult to generate a continuous, large homogeneous heated zone. A two-dimensional heat flow excitation without amplitude shifts is difficultly feasible, but absolutely mandatory to reduce measuring artefacts generated by fluctuating excitation and it is the basis for automated data evaluation. [2]

In addition, to select the proper excitation technique, an appropriate method to evaluate thermal waves has to be chosen. In the simplest case, thermography methods are based on an evaluation of transient temperature gradients in recorded thermal images. The underlying principle of this so-called pulse thermography is the differential in thermal wave traveling times, caused by heat flows retarded or increased through thermal conduction irregularities of defects in test specimens. This method offers quick evaluation even on moving test specimens. However, test results strongly depend on the bodies' surface characteristics and are also susceptible to external interferences. Lock-in-thermography, which modulates the

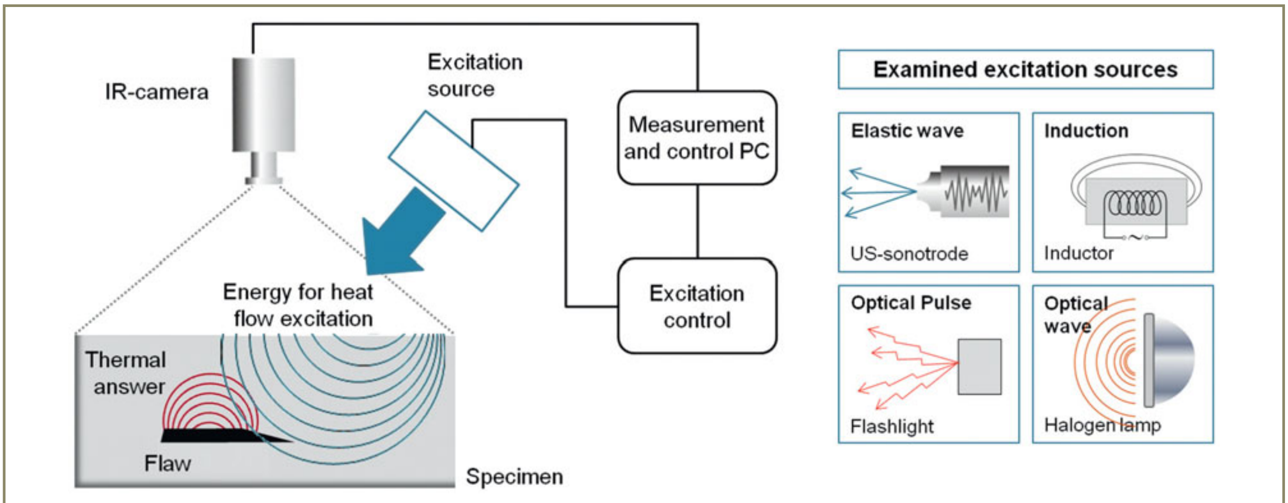

Figure 1 – Schematic diagrams of thermographic experimental set-up and examined excitations

excitation source by a locking frequency, is an improvement. In comparison to flawless regions of the test specimens, defects will cause a different angular phase shift between excited and detected thermal waves. Recorded thermal images are transformed by the Fourier-method and the phase images can be interpreted by the phase shifts between flawed and unflawed areas. In addition to being more insensitive to external interferences, the lock-in method allows to determine the flaw depth. However, this test method requires motionless arrangements of camera and test specimens and state-of-the-art testing and control equipment. [3]

When comparing benefits and drawbacks of the different methods for heat flow excitation and data evaluation, it becomes apparent that the method optimal for joints must be carefully selected in order to reliably detect the relevant imperfections and thus best possible application in the respective production process.

3 Adhesive joints

Due to the benefits when joining of hybrid structures, due to the increased stiffness through two-dimensional load transmission and also due to the high dynamic strength and vibration damping, structural bonding has become increasingly popular in modern automotive lightweight design. But for the production of safety-relevant components and for joining process chains creating added value, the successful use adhesive bonding technology depends on successful quality assurance systems. [4] Active thermography offers good evaluation possibilities for bonded joints, mostly because relatively wide joints can be tested in one measuring step.

During the various adhesive bonding processes, a multitude of imperfections can occur. Flaws, such as trapped air in the bonded joint, porosities, insufficiently large adhesive beads and inhomogeneous adhesive layers can be caused by faulty adhesive application. Other flaws are caused by stresses due to faulty component handling or internal strains, resulting in delaminations, cracks or so-called "kissing" bonds. "Kissing" bonds are zero-volume defects with non-adherent but coherent interfaces, resulting from contaminated surfaces (oil, grease, etc.). Hardening failures or impurities of the adhesive can also occur. [4]

In order to examine whether these imperfections can be detected by a thermographic NDT-system, it is required to separate adhesive joints used in automotive engineering into two main categories. The first category is structural bonding in car body assembly. The second category is elastic bonding for wind-shields and rear windows, and/or sealing applications. This paper will further discuss particular applications of each category and show the necessity to optimize different thermography systems. Structural bonding is usually done using one- and two-component epoxies and two-component polyurethanes. Specifications require thin adhesive layers (generally, $t_{a,\,min} = 0.1$ mm to $t_{a,\,max} = 0.5$ mm adhesive thickness) with high Young's Modulus. These adhesives are mostly used for bonding metal sheets. Flaws in structurally bonded joints are often safety- and lifecycle-relevant, and they reduce joint stiffness and strength. Elastic bonding in contrast is usually done using one-component polyurethanes with thick adherent layers (about $t_a = 5$ mm). Adhesives properties feature a lower Young's modulus. Elastic bonding is mainly used to join strongly different materials, such metal sheets with glass. Since the major function of elastic bonding is sealing and strength and stiffness are usually secondary, flaws in these joints are not safety-, stiffness- and strength-relevant but should not impair sealant properties. [5]

When evaluating bonded joints by means of active thermography, each of the aforementioned heat excitation sources could theoretically be considered. Optical excitation, however, is not optimal because of its low energy input in reflective surfaces (such as metal and glass), and will therefore not be further discussed. Due to its sensitivity for frictional interfaces and defect-selective properties, ultrasound excitation of thermal waves appears to be the optimal technique for detecting the most critical imperfections in bonded joints: delaminations and "kissing" bonds. Tests were performed on peel joint specimens, manufactured with two stainless steel sheets (thickness $t_a = 0.8$ mm) and a thin adhesive layer (thickness $t_a = 0.3$ mm). Structural adhesives (2C-Epoxy) and elastic

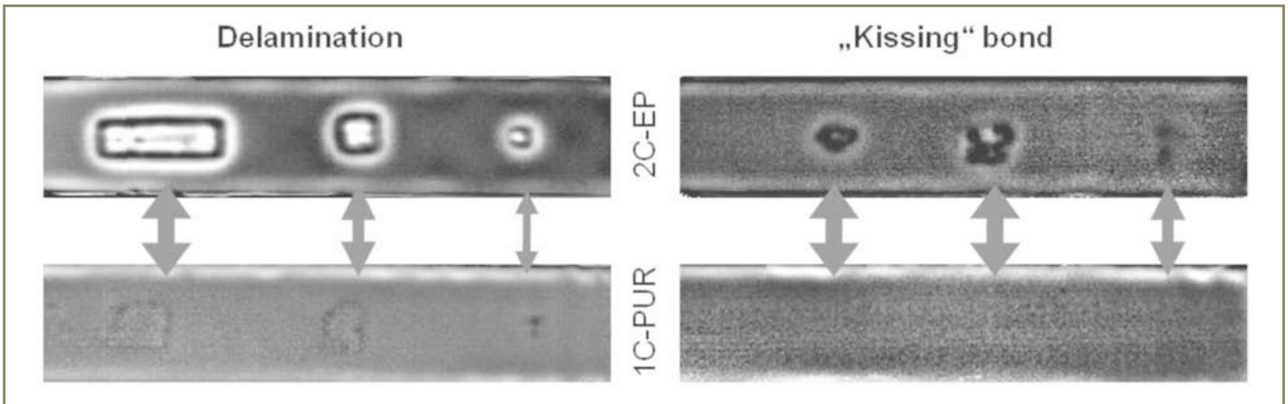

Figure 2 – Phase shift images of ultrasound excited lock-in-thermography for structural (top) and elastic (bottom) adhesive bonding, with delamination defects and "kissing" bonds" (arrows) [4]

adhesives (1C-Polyurethane) were applied. Some specimens were furnished with "kissing" bonds" by contaminating three points of the surface with lube oil, applied as in thin layers of d = 10 mm diameter, comparable to fingerprints on stainless steel sheets. Delaminations were simulated by thin PTFE-films in three different sizes. Figure 2 shows the results for these test samples excited by ultrasound lock-in thermography (ULT), displayed as phase shift images, separated in delamination flaws (left) and "kissing" bonds (right) of different sizes (regard arrows) for structural bonding (top) and elastic bonding (bottom).

Both simulated types of imperfections in structural adhesives were very easy to detect by means of ULT. But detecting delaminated layers in the 1C-polyurethane specimen (bottom row) was much more difficult than in the 2C-epoxy (top row) and the detection of kissing bonds in elastic bonding (right bottom) was nearly impossible, even if thin adhesive layers and thin steel sheets were used. This effect increases with the thickness of the adhesive layers as a result of the high energy dissipation and the poor heat flow properties of elastic bonds. It can be concluded that ULT seems to be the optimal technique to detect critical flaws in structurally bonded joints by friction based effects, but is not feasible for elastically bonded joints. [6]

In order to find the optimal excitation method for elastic joints, it is useful to take a closer look at field applications of elastic bonds. A typical example would be joining glass to the metal frame of a retractable automotive sunroof, for which the feasibility of thermographic testing was investigated. The bond line of this component had a width of w_{bl} = 15 mm, a thickness of t_a = 5 mm. It joins a t_g = 5 mm-thick glass roof to a steel sheet. Since ultrasound and optical excitation sources do not apply for this sample, inductive excitation must be used. This excitation source generates high temperatures in the metal sheet, resulting in a powerful heat flow through adhesive layer and glass. In order to validate the results, specimens with equal structures were manufactured and tested with induction excited thermography. Figure 3 shows the outcome of these tests with the flawless and defective specimen (necking, delamination and "kissing" bond"), compared to the respective specimens displayed as sketch.

Where poor thermographic characteristics are concerned, i.e. high material thickness combined with poor thermal conductivity, the interpretation of recorded images of the glass surface and the visualization of the imaginary part after Fourier-transformation, cannot be performed as well as for structural bonding. Boundaries between flawless and flawed regions can only be detected to a lesser extent. Nonetheless, imperfections, characterized by a discontinuous adhesive layer with therefore compromised thermal conductivity (i.e. delaminations and neckings), can easily be detected due to the massively changing intensity compared to flawless regions. The image on the left of Figure 3 (two differently shaped neckings) shows, contrary to the flawless specimen (centre) a massively changed intensity on the necked bond seam, as much as at the image on the right at the displayed delaminated regions. Due to its lower sensitivity for tangent interfaces, the detection of "kissing" bonds is hardly possible with this induction excited lock-in thermography – contrary to ultrasound excitation techniques. Compared with flawless regions, these imperfections exhibit only marginal variations in the thermal conductivity properties. A detection of such marginal variations by means of inductive excitation is only possible, if the tested components consist of thinner semi-finished products and adhesive layers.

The presented results prove the high potential of active thermography for detecting imperfections in bonded joints. Indeed, there is no universal excitation method, but through specification of the requirements, an excitation method can be found for both structural and elastic bondings. If the detection of adhesion loss and tangent interfaces ("kissing" bonds) is a requirement on top of the application of structural adhesive, and if the inspection of a testing solution allows contact to an ultrasound sonotrode, then ultrasound is the optimal excitation method. If the component is not as susceptible to these types of defects, or if "kissing" bonds can be eliminated by process monitoring alternatively, contactless inductive excitation should be chosen. This method also allows to test bonded components exhibiting poor thermographic properties, such as thick bond lines or semi-finished products and elastic adhesives (also in uncured conditions).

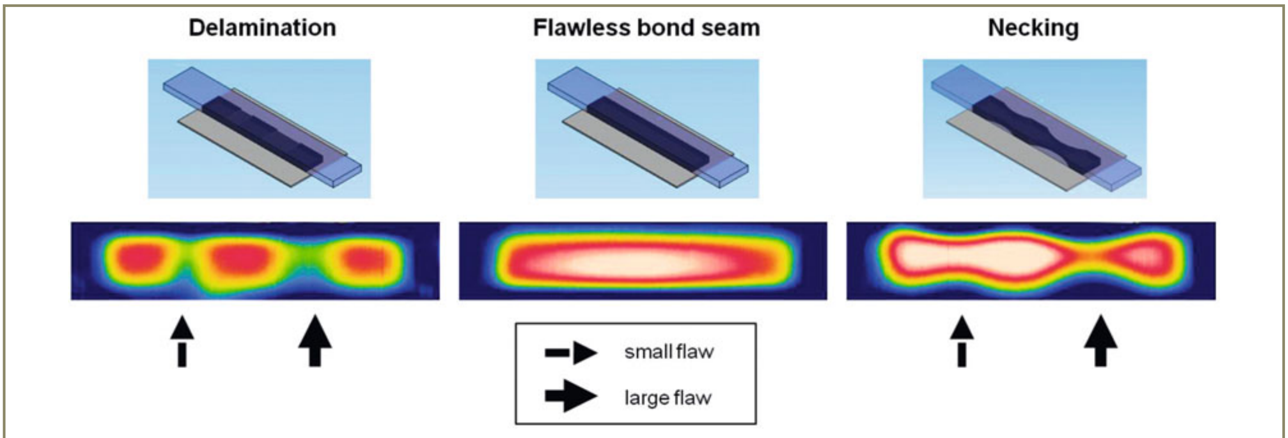

Figure 3 – Results of induction excited lock-in thermography of elastic bonds, displayed by images of the imaginary part with the respective specimen displayed as sketch

4 Mechanical joints

Analogue to the increasing use of adhesive joints, mechanical joints are also on the rise, because of hybrid structures making inroads in automotive engineering. These joints are often used to fix components until adhesives are cured to final strength, but they are also applied for sole joining. Mechanical joining techniques in automotive applications primarily use self-cutting screws and blind rivets for one-sided accessibility. Where accessibility from both sides is required, clinching joints are used for easily formable metals, semi-tubular self-piercing rivets for high-strength metals and self-piercing solid rivets for metals with low formability. [7]

Various studies have been conducted on the feasibility of thermographic evaluation methods for mechanical joints in aerospace applications. Most of them conclude that thermography is well-suited for mechanical joints (for example [8]). To show the suitability of thermographic quality inspection for mechanical joints in automobile production, this paper takes clinch joints as the example. Clinch joining is a metal forming process where the joining is performed by material yielding, which generates an undercut in between the joined metal sheets. Quality inspection of clinch joints is usually performed online through intelligent, process-integrated sensor technology, such as force or displacement measurements. However, joint strength determining parameters, such as undercut, neck thickness, etc., cannot be determined without destructing the joint. [9] Therefore, non-destructive thermographic testing represents an interesting alternative to destructive tests.

Within the framework of a public funded research, project studies have been carried out on clinch joints without a cutting element with separated and unseparated dies – the type of clinch joint commonly used in automotive manufacturing.[10] In order to determine characteristic defect images with thermal imaging, fundamental tests have been conducted on single overlap joints (equal and hybrid materials), adjusted to frequently occurring joining failures and were verified by micrograph cross-section visualization. The non-destructive tests were performed using the four most common thermal imaging stimulation methods – pulse and lock-in optical excitation (flash and laser) and lock-in ultrasound and induction excitation.

For the conclusion, characteristic failure images were verified on series components provided by auto-motive industry and the feasibility of non-destructive quality inspection was examined using various thermal imaging processes.

All laboratory tests performed showed that the proposed thermal imaging processes ensure the detection of the most important quality-relevant imperfections, with the exception of bottom thickness, by a change of heat flow in the clinching joints. For an absolute determination of the bottom thickness, only excitation by pulse-phase thermal imaging with flash turned out to be useful. For the generation of every imperfection image, it is required not to be impacted by factors such as material, joining system and surface properties. These factors can be compensated by selecting particular excitation parameters and data evaluation methods. Due to a variety of reciprocally influencing factors, an absolute determination of imperfection magnitudes is not generally possible. For instance, differences in thermographic images can also be affected by a variety of other factors, such as strain inside the part, edge distance, etc. The validation of single spot test results was conducted using defective close-to-production parts. Figure 4 shows examples of these validation measurements.

The top row of Figure 4 shows micrographs of specimen, assigned to the results of the NDT in the bottom row, performed with induction excited thermography, and displayed as phase shift images. The left micrograph and phase shift image show a flawless specimen. Imperfections on the other specimens from left to right show an eccentricity between clinching tools (punch and die), a die failure

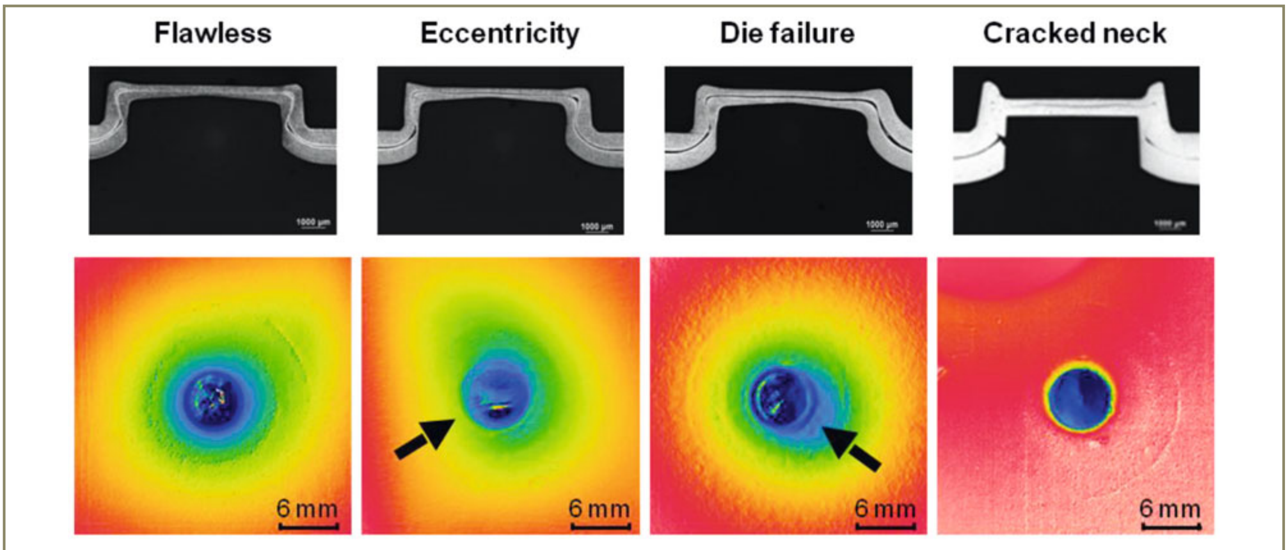

Figure 4 – Comparison of micrographs (top row) and the respective phase shift images (bottom row), recorded with induction excited thermography for flawless and diverse flawed clinch points

and a cracked neck of the clinching element. All of these imperfections can be successfully distinguished by interpreting the phase shift image compared to the defect-free specimens.

Furthermore, these parts served to create scenarios for the implementation of a NDT-unit in series production. These tests proved that, due to the contactless, flexible and practical application and short testing periods, induction excited lock-in thermal imaging is an excellent NDT-system for clinching elements.

The studies proved that thermographic testing systems for the evaluation of mechanical joints, such as clinch joints, are feasible. But, often, mechanical joints are not so quality-relevant that they generally require NDT. Due to the very high costs, online testing at the clinch caliper and by this a NDT directly integrated into the joining process, is neither economical nor productive, even though cheaper cameras (like bolometric IR-Cameras) for the analysis of process signals are available. Even a 100 % in-line test within the clinching process cycle would require high investment costs. A thermal imaging test system is whereas suitable for (random) offline tests, especially due to its excellent automation potentials, and can completely replace random destructive offline tests. Because it is applicable for other joining processes, it could be also economical interesting to use a thermal imaging system for the quality assurance of several joining processes in the production of a component.

5 Welded joints

Welding as a substance-to-substance bonding process is applied in many fields of engine and civil engineering, where mono-material semi-finished products (usually metals) are joined. In automobile body lightweight construction, standard joining methods, such as gas-shielded arc welding play a subsidiary role. These welding techniques are process-reliable, and offer, in addition to classic visual testing, a number of established NDT methods. That is why hardly any active thermography is used to test these welds.

However, thermographic methods are attractive to test components with dimensions that do not allow x-ray or ultrasonic testing, or to test processes integrated at series production. In automotive body-in-white construction, resistance spot welding and laser beam welding are commonly used joining techniques. In close cooperation with users and research institutes, suppliers of active thermographic have developed first industrial-scale systems for these joints. They are based on pulse-thermography, excited by optical (flash) or convection (hot air) methods. [11]

This paper demonstrates the potential of active thermography for the evaluation of welded joints by means of examinations conducted on laser beam welded (LBW) joints. Laser beam welding is often required for joint designs using thin metal sheets and providing only single-sided accessibility. In addition, laser beam welding offers benefits, such as high process velocity and low heat-affected distortion. It is particularly simple and cost-effective for square butt-welded single lapped joints. To ensure high component stability and good corrosion resistance, a completely shaped cross-section of the weld is essential. A reliable quality assurance method is recommended to monitor these requirements.

Samples with weld defects have been manufactured to examine the potential of the thermographic process. Besides easy to detect defects, such as pores, cavitations, undercuts, etc., very difficult to detect defects were created in the connecting cross-section, where the welded joint has only a fraction of the actual stiffness. Special attention was paid to this so-called “false friend” defect. According to state-of-the-art, this defect cannot, or only with great difficulty, be detected visually or with non-destructive testing. By varying the gap on the overlap joint (weld gap) between the metal sheets, weld joints could be created, which appear flawless from the outside, but only have a small contact cross-section. Another method of producing this defect is to mill off defined material layers from the weld. Gap changes were achieved which border at the weld joint and lead to “false friends.”

All excitation methods discussed were used in the tests, and showed sensitivity to detect the produced defects. Particularly noteworthy was the application of optically excited reflection mode pulse thermography. Reasons for this are simple handling and the unidirectional and extensive non-destructive testing. The restriction of having only relatively low energy input efficiency can be neglected due to the low total sheet thickness (max. 3 mm) and the effective heat transfer in thoroughly welded areas. In addition, the reflection of the excited energy is reduced due to the massive oxidation along the welded joint.

Figure 5 shows optically excited pulse thermography images of a perfectly welded sample of 2 steel sheets (ZSTE 340 zinc coated, sheet thickness: $t_s = 1.25$ mm), and diverse flawed weld seams with porosities, incomplete penetration of weld seam (image of rear side) and a “false friend” sample. The captured transient infrared sequences were filtered using direct Fourier-transformation ($f_{dft} = 0.4$ Hz) to time and frequency domains. The weld seam is clearly distinguishable to the not joined areas of the sheets, and also to the flawed areas of the seam, by a higher intensity. It can be seen that all defects can be perfectly detected using this process [12]

This proves the suitability of active thermography for the quality inspection of laser welded joints. The represented results are also representative for determining the diameter of weld nugget at resistance spot welded joints, which allows drawing conclusions on the joint strength. Further developments use lock-in techniques and inductive excitation methods for the testing of resistance spot welds, which allow obtaining in-depth information from the

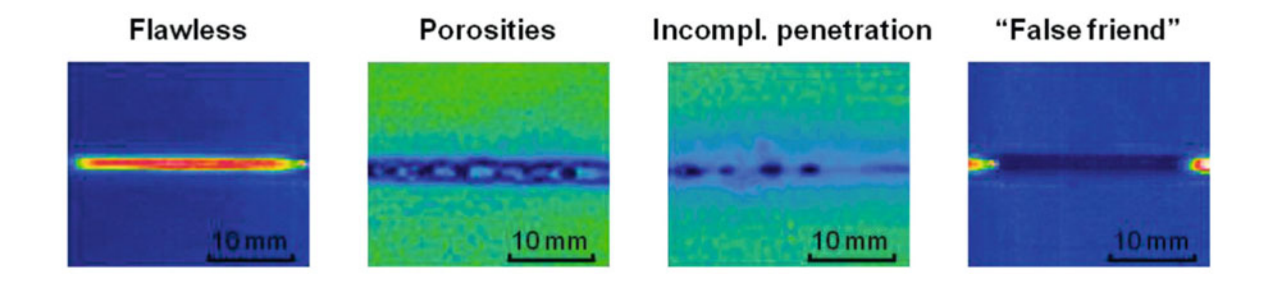

Figure 5 – DFT-Phase shift images of optically excited pulse thermography (OPT) on laser beam welded square butt joints, flawless and diverse flawed weld seams

recorded thermal signals. This is essential information for the evaluation of joints with more than two metal sheets and sheets with strongly differing sheet thicknesses. In addition, results are less affected by reflective behaviour of component surface.

6 Implementation of testing systems

An essential requirement for active thermography NDT-systems is that they can be integrated and implemented in existing automotive production processes. Following, this aspect will be discussed.

The detection of imperfections in components by means of active thermography is based on the comparison of measurement results of flawed specimen with the flawless reference components. But besides flaws of the tested component, thermal irregularities can also result from changes in semi-finished parts and irregularities in the heat flow excitation. Further disturbances in the images are due to reflections, caused by external influences. A very basic quality rating method would reject each part having thermal irregularities compared to the reference. This approach might be feasible for highly quality-sensitive parts. Often imperfections cannot be avoided in the production process. However, cost-intensive part reject must be minimized in order to produce efficiently. That is why the system's susceptibility to external influences must be evaluated, in addition to examining the detectability of relevant flaws in joints, and prior to the development of an automated NDT-system.

Furthermore, the evaluation of impacts of joint defects on the assembly quality is an essential step in the NDT process. If common defects can be classified and information on defect type, location and size can be achieved, a quality rating of the component is possible. Some defects might have no or only insignificant impact on the product quality. More research is necessary to evaluate the strength of bonds with imperfections. Therefore, generating critical values of defects resulting in intolerable joint quality is absolutely mandatory. Mechanical properties of joints are influenced by the type, size and location of possible defects. These have to be evaluated based on empirical data, experiments, FE-analyses know-how and guidelines of the manufacturers. [13]

Figure 6 shows a quality rating flow, which allows quality evaluation of a generic component based on the defect characteristics detected by active thermography. After recording the resulting thermographic testing image, containing thermal irregularities compared to the reference image, a decision must be made whether this is a defect or a thermal structure, and the defect characteristics (type/size, location) have to be determined. For quality rating of the component and/or joint, impacts of defect must be evaluated based on data determined by FE-analysis, experience or heuristic methods.

In order to select the optimal test procedure, the point of time when to perform the test must be selected in accordance with the production sequence and adapted to excitation source and evaluation method. Tests with adhesives in uncured condition, for example, would make ultrasound excitation impractical. Testing on fully assembled components could cause mechanical stress and thus damage the assembly. Tests on clinched components could be hindered by surface conditions of the joining materials (polished or oil removed metal sheets provides much lower emissivities than oxidised, oiled or galvanised sheets), which can prevent optical heat flow excitation.

It is also important to determine the minimum required measurement accuracy, because it is the basis for choosing the infrared camera specifications. Parallel to the

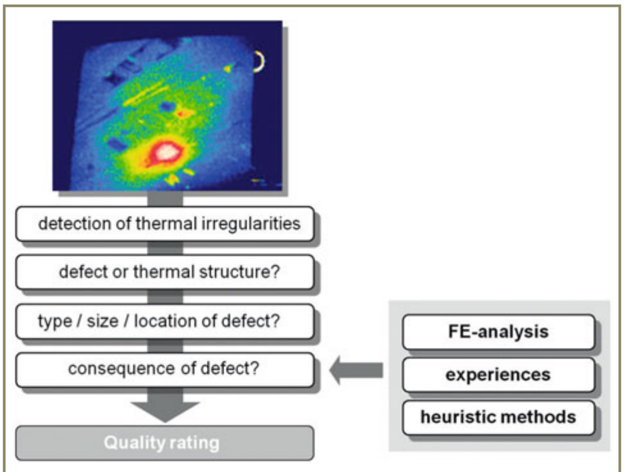

Figure 6 – Basic approach to quality evaluation

thermal resolution, the physical resolution ultimately determines the price of an IR-camera. Depending on the required detection magnitude, the resolution defines the size limit of imperfections (detectable imperfections must have the size of multiple pixels), the test scope, and, combined with excitation and evaluation parameters, the test duration. 100 % inline testing may be impractical and compromised by these factors, which could result in a decision for a random analysis of components or joints.

7 Conclusion

Non-destructive evaluation of joints by means of active thermography improves the quality of modern lightweight structures. It is applicable for all investigated adhesively bonded, mechanical and welded joints and, therefore, allows detecting any type of quality-relevant defect. However, a smart choice of the excitation method suitable to the specific test case is necessary to effectively detect relevant defects because it is impossible to find an excitation source optimal for every test case.

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About the authors

Dipl.-Ing. Christian SRAJBR (c.srajbr@tu-bs.de), Dipl.-Ing. Gheorghe TANASIE (gtanasie@lear.com), Prof. Dr.-Ing. Klaus DILGER (k.dilger@tu-bs.de) and Prof. Dr.-Ing. Stefan BÖHM (s.boehm@uni-kassel.de) are all with Institute of Joining and Welding (ifs), University of Braunschweig, Braunschweig (Germany).