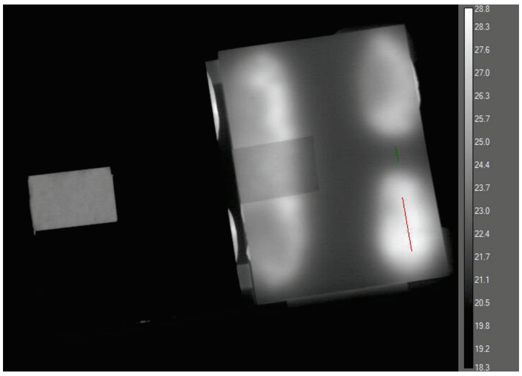
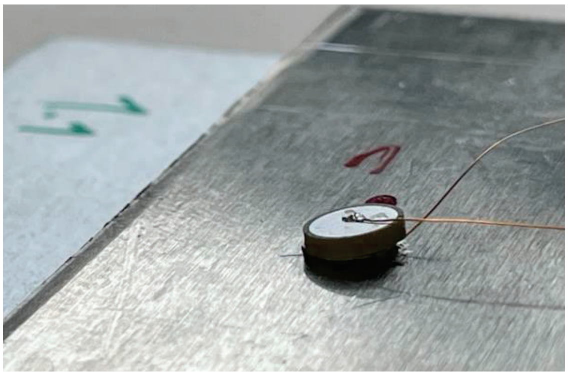
Quality assurance and quality control of adhesive bond joints in battery packs (QABB)





Public report

Project within FFI Circularity
Author Oscar Andersson, Christer Johansson
Date 2025-01-14

FFI Fordonsstrategisk Forskning och Innovation

Content

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: www.ffisweden.se

1. Summary

The QABB project aimed to identify reliable and efficient Quality Assurance (QA) and Quality Control (QC) processes for adhesive joints in battery packs, driven by the increasing use of adhesive bonding in automotive manufacturing, particularly in battery packs. The degradation mechanism of adhesive bond joints in battery packs is still not fully known, and there are no established QA or QC methods used in industry.

The project was performed through literature reviews, experimental trials, and discussions with industry experts. The research focused on defining project scope and requirements, mapping and evaluating QA/QC methods, and identifying potential for a large-scale follow-up project. Key requirements for adhesive joints were identified, and test materials and specimens were developed.

The project evaluated several QA/QC methods, including Ultrasonic Testing (UT), Electromechanical Impedance Spectroscopy (EMIS), and Active and Passive Thermography. Other methods, such as radiography, CT scanning, terahertz measurement, and equipment process monitoring were excluded from the pre-study scope.

The results showed potential for UT and EMIS methods, while thermography was less promising for aluminium surfaces. The project concluded with recommendations for further research and development, including data analysis, automation, and exploration of other applications.

Further research should focus on data analysis and automation of UT and EMIS methods, as well as investigation of other potential applications in the automotive industry and other sectors that utilize adhesive joints. The project also highlighted the need for continued collaboration between industry and research institutions to develop standardized QA/QC methods for adhesive joints in battery packs and other critical applications.

2. Sammanfattning på svenska

QABB-projektet syftade till att identifiera tillförlitliga och effektiva processer för kvalitetssäkring (QA) och kvalitetskontroll (QC) för limfogar i batteripaket, drivna av den ökande användningen av limbindning i biltillverkning. Nedbrytningsmekanismen för limfogar i batteripaket är fortfarande inte helt känd, och det finns inga etablerade QA- eller QC-metoder som används i branschen.

Projektet genomfördes genom litteraturgenomgångar, experimentella försök och diskussioner med branschexperter. Forskningen fokuserade på att definiera projektets omfattning och krav, kartlägga och utvärdera QA/QC-metoder och identifiera potential för

ett storskaligt uppföljningsprojekt. Nyckelkrav för limfogar identifierades och testmaterial och prover utvecklades.

Projektet utvärderade flera QA/QC-metoder, inklusive ultraljudstestning (UT), elektromekanisk impedansspektroskopi (EMIS) och aktiv och passiv termografi. Andra metoder, såsom röntgen, CT-skanning, terahertzmätning och övervakning av utrustningsprocesser uteslöts från förstudiens omfattning.

Resultaten visade potential för UT- och EMIS-metoder, medan termografi var mindre lovande för aluminiumytor. Projektet avslutades med rekommendationer för ytterligare forskning och utveckling, inklusive dataanalys, automatisering och utforskning av andra applikationer. De viktigaste resultaten och leveranserna från projektet listas nedan.

- Krav på QA-metoder för limning har identifierats.
- Potentiella metoder för QA har kartlagts genom en litteraturöversikt.
- De mest potentiella metoderna för QA för adhesiv bindning har utvärderats experimentellt.
- UT visade lovande förmåga att upptäcka brist på vidhäftning och brist på bindning i proverna.
- EMI-mätresultat visar också lovande resultat. Brist på vidhäftning och avsaknad av lim kan potentiellt upptäckas av EMI, men mer data och dataanalys behövs för att fullt ut förstå dess potential och noggrannhet.
- Termografi är inte lämplig för applikationer där aluminium används som inspekterad yta. Det kan dock vara mer lämpligt för andra material som PP eller andra termoplaster.

Framtida forskning bör fokusera på dataanalys och automatisering av UT- och EMIS-metoder, samt undersökning av andra potentiella tillämpningar inom fordonsindustrin och andra sektorer som använder limfogar. Projektet lyfte också fram behovet av fortsatt samarbete mellan industri och forskningsinstitutioner för att utveckla standardiserade QA/QC-metoder för limfogar i batteripaket och andra kritiska applikationer.

3. Background

Battery packs are expected to serve a vehicle until they have 80% of their initial energy capacity, meaning a lifetime of approximately 8-10 years, 4000 charges or 120 000 km of mileage. During that lifetime, the adhesive bonds will be exposed to elevated temperatures, numerous heat cycles and varying humidity due to the proximity to the battery cells.

These products are increasingly joined with adhesive bonding instead of legacy methods such as welding or mechanical fasteners. This is driven by a need for lightweight and mixed materials, without compromising product properties such as crashworthiness, stiffness, compactness, or tightness. This trend is particularly pronounced in the design of battery packs, where adhesive bond joints are used between battery cells, between battery modules and the tray, between the modules and the cooling plate and between the battery modules

The degradation mechanism of adhesive bond joints in battery packs is still not fully known, and there are no established quality assurance (QA) or quality control (QC) methods used in industry. This is a relatively new field of research which has so far not been sufficiently explored.

In the shorter timeframe in serial production, multiple methods have been investigated for QA for adhesive bond joints, such as ultrasonic testing, acoustic microscopy, electromechanical impedance spectroscopy, piezoelectric sensors, thermography, and shearography. Some of these methods have also been implemented in industrial manufacturing. However, all the methods have associated disadvantages such as low accuracy, material incompatibility, cumbersome or time-consuming procedures or high cost.

Another promising technology is fiber Bragg grating (FBG) sensors, which can monitor the swelling strain in adhesive joints continuously while they are embedded in the joint. This can in turn give an indication of the quality of the adhesive bond joint.

Moreover, there are still few studies focusing on the long-term properties and degradation of adhesive bond joints and no results were found for time periods or conditions corresponding to the entire expected lifetime of a battery pack. Most studies on long-term properties have focused purely on the mechanical fatigue life, while there is less focus on heat cycling or hygrothermal cycling.

In the shorter timeframe in serial production, multiple methods have been investigated for QA for adhesive bond joints, such as ultrasonic testing [1], acoustic microscopy [2], electromechanical impedance spectroscopy [3], piezoelectric sensors [4], thermography [5], and shearography [6]. Some of these methods have also been implemented in industrial manufacturing. However, all the methods have associated disadvantages such as low accuracy, material incompatibility, cumbersome or time-consuming procedures or high cost.

A parallel development, is the industrial introduction of computed topography (CT) scanning equipment, sometimes referred to as 3D X-ray. While CT is still relatively expensive for large-scale industrial applications there are efforts to examine adhesive bond joint quality that show some promise [7]. Another promising technology is fiber Bragg grating (FBG) sensors, which can monitor the swelling strain in adhesive joints continuously while they are embedded in the joint. This can in turn give an indication of the quality of the adhesive bond joint [8].

Moreover, there are still few studies focusing on the long-term properties and degradation of adhesive bond joints and no results were found for time periods or conditions corresponding to the entire expected lifetime of a battery pack. Most studies on long-term properties have focused purely on the mechanical fatigue life [9], while there is less focus on heat cycling [10] or hygrothermal cycling [11].

4. Purpose, research questions and method

The purpose of the QABB project was to

i) Define the scope of the project based on relevant challenges and goals, including definition of requirements on joints and requirements on QA and QC methods.
ii) Map QA and QC methods and evaluation and compare promising methods theoretically and on a laboratory scale.
iii) Identify potential for a large-scale project as a follow-up to QABB.

The following research questions have guided the research work:

- What are the key requirements for adhesive joints in the target applications, and which existing or potential QA and QC methods are most relevant to these requirements?
- How do different QA and QC methods perform against the defined evaluation criteria when applied to representative adhesive joint samples, and what are their respective strengths and weaknesses?

The project was performed through a number of different methods such as literature reviews, experimental trials and discussions with industry experts from the automotive industry. These experts were both from product development and manufacturing areas in industry. In Figure 1, the over-arching workflow of the project is illustrated.

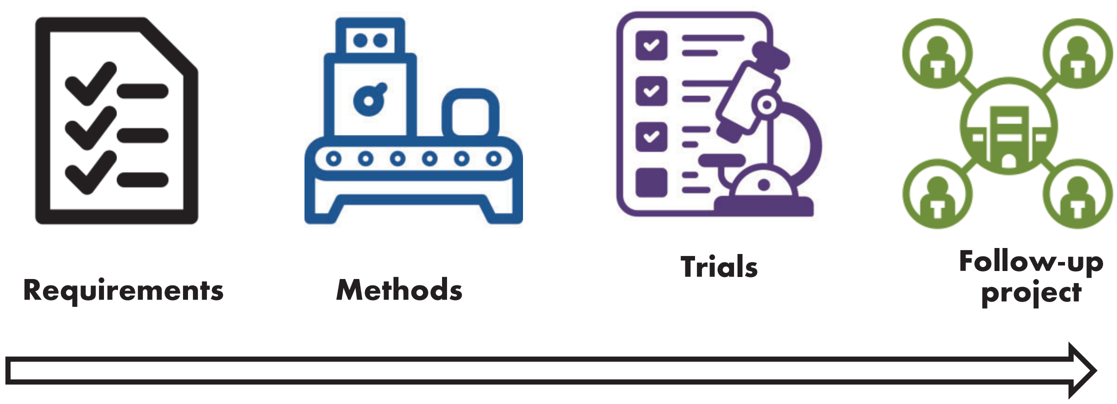


Figure 1 Over-arching workflow of the methodology of the project

5. Objective

This project's objective is to identify potentially reliable and efficient QA and QC processes for adhesive joints. The objectives are structured across three distinct work packages (WPs), each contributing to the overall goal. The objectives of the project can be summarised in the following points connected to the different work packages and milestones presented in the project application.

Work package 1 Requirements and Methods Definition

Milestone 1 (M1): Define the relevant requirements for adhesive joints and identify potential QA and QC methods.
Milestone 2 (M2): Compile a list of relevant QA and QC methods for further investigation.
Milestone 3 (M3): Develop a test plan to evaluate the identified QA and QC methods.

Work package 2 Evaluation and Selection

Milestone 4 (M4): Evaluate and rank the identified QA and QC methods based on the defined test plan, culminating in the selection of the most suitable methods for a demonstrator project.

Work package 3 Consortium Formation and Application

Milestone 5 (M5): Identify and form a consortium for a subsequent full-scale demonstrator project.

These objectives, defined by the listed milestones, collectively aim to establish a robust framework for QA and QC in adhesive joining processes, paving the way for a full-scale demonstrator project that will showcase the effectiveness of the selected methods.

During the course of the project, the ambitions were slightly changed, though the initial objectives were kept. Due to the lowered urgency of offline QA methods in manufacturing at Volvo Cars and to higher reliability on process monitoring from the equipment it is still not decided on the focus areas of a demonstrator project. However, the QABB pre-study has identified several possible areas which can be further explored in a demonstrator project depending on the interest from industry.

6. Results and deliverables

The complete results from the project are collected in a series of presentations. The final present final report includes a summary and examples of most relevant results. The results are presented below according to the objectives stated above.

Requirements

During extensive discussions with industry experts and review of industry standards and general international standards a list of relevant requirements on adhesive bond joints was collected as seen in Table 1. It should however, be noted that not all requirements are relevant for all joints. As an example, thermal conductivity is only relevant to some jointsk for example when joining the cooling plate of the battery pack. The list of requirements formed the basis for the evaluation of the QA methods. However, it was agreed by the project group that the most critical requirements is that of adhesion between the adhesive and the substrate. Thus, the experimental trials focused primarily on the ability to detect adhesion errors and faults.

Table 1 List of functional requirements associated with adhesive bond joints in battery packs.

Functional requirement
Adhesion
Adhesive area spread out
Thermal conductivity
Adhesive volume
Adhesive mixing
Tightness

Test materials and test specimens

Following the work on defining the requirements, relevant applications for adhesive bonding were identified. These were based on current pre-development projects from Volvo Cars. However, these applications were converted to general test specimens according to the materials and thicknesses in Table 2 and dimensions in Figure 2

Dimensions of test specimen. A typical test specimen is shown in Figure 3. The aluminium coupons were laser treated according to industry standards at RISE in Mölndal. The thermoplastic polymer, polypropene, was reinforced with 30% glass fibre (PP30GF).

Table 2 Test matrix with associated materials, adhesives and debonding mechanisms

#	Sheet 1	Sheet 1, thickness [mm]	Adhesive	BLT	Sheet 2	Sheet 2, thickness [mm]	Debonding	Repetitions
1.X	AL 6082-T6	3	2K PUR TIM	0.5	AL 6082-T6	3	Teflon tape	2
2.x	AL 6082-T6	3	2K PUR TIM	0.5	AL 6082-T6	3	Air gap	2
3.X	AL 6082-T6	1	2K PUR TIM	0.5	AL 6082-T6	3	Teflon tape	2
4.X	AL 6082-T6	1	2K PUR TIM	0.5	AL 6082-T6	3	Air gap	2
5.X	AL 6082-T6	3	2K PUR Structural adhesive	2.5	PP30GF	3	Teflon tape	2
6.X	AL 6082-T6	3	2K PUR Structural adhesive	2.5	PP30GF	3	Air gap	2
7.X	AL 6082-T6	1	2K PUR Structural adhesive	2.5	PP30GF	3	Teflon tape	2
8.X	AL 6082-T6	1	2K PUR Structural adhesive	2.5	PP30GF	3	Air gap	2

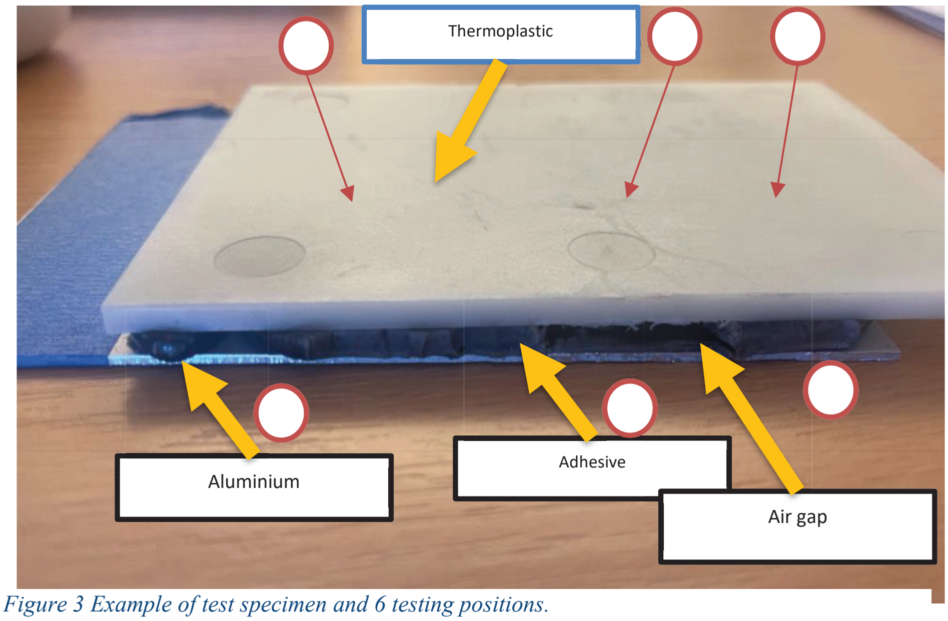


Figure 3 Example of test specimen and 6 testing positions.

6.1 Ultrasonic Testing (UT)

Ultrasonic testing (UT) was performed with industrial UT equipment as shown below. The equipment was a Olympus Epoch 650 and coupling gel was used between the probe and the substrate. All testing was done at a constant ultrasonic wave frequency of 5.0 MHz. For the interpretation and visualization of the test results, velocity settings of 6171 m/s and 3240 m/s were used when measuring from the aluminium side and the thermoplastic side, respectively. These velocities were collected from the equipment manual.

Figure 5 Ultrasonic Testing equipment and coupling gel.

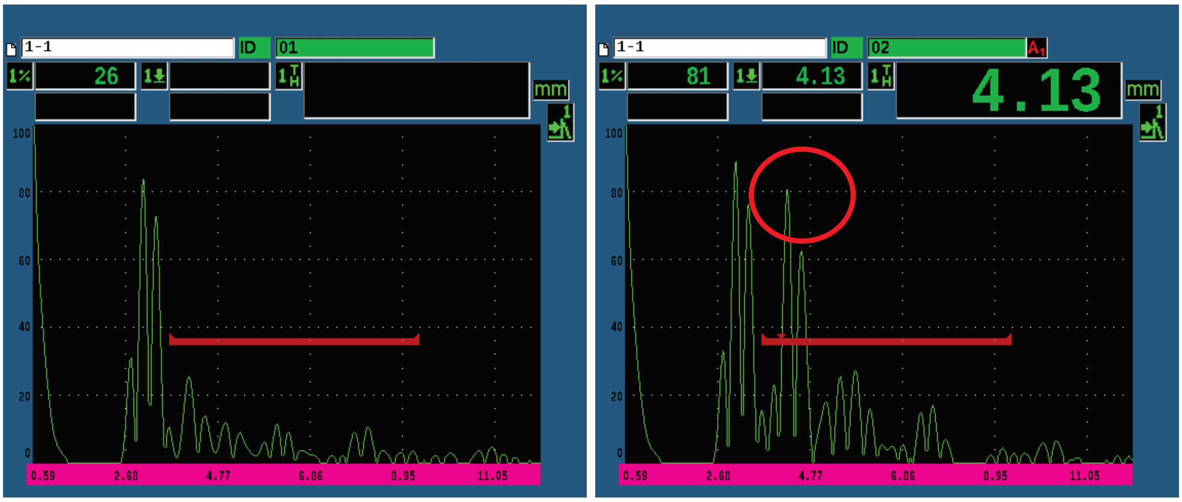


Figure 4 Examples of UT test results

UT A-scans were performed on 8 samples with various scanning positions and scanning directions. The A-scans indicate that lack of adhesive or local debonding can be detected with UT. In the figure above right, the echo due to the air gap is clearly indicated by the red circle. The figure above left shows the corresponding measurements from the location where no defect was included. In most of the cases the defects were clearly demonstrated, as shown above. However, in some cases it needed more analysis and in some cases it was not as obvious.

6.2 Electromechanical impedance spectroscopy (EMIS) testing

A piezoelectric crystal (5 mm in diameter and 1 mm in thickness) of the material PZT (Lead zirconate titanate) purchased from TDK was used in the impedance measurements. Insulated Cu-wires (diameter of 0.1 mm) was soldered to the crystal on each side of the sensor (no degradation of the piezoelectric behaviour was noticed). The PZT sensor together with the Cu-wires connected to a PCB-board can be seen in Figure 6.

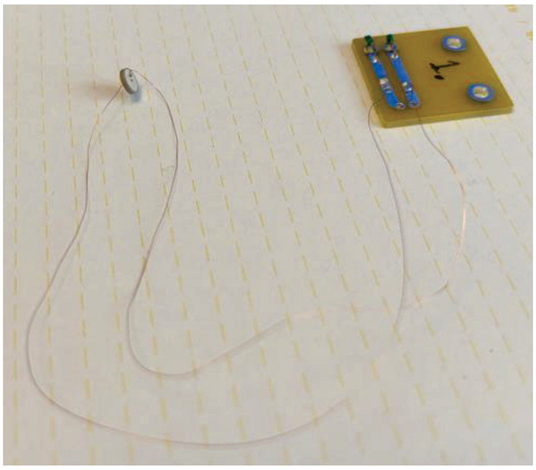


Figure 6 PZT-sensor with soldered Cu-wires to PCB-board.

The PZT-sensor was mounted both by gluing to the sample substrate or using ultrasound gel. From the initial analysis by comparing the result when the sensor was glued or mounted using ultrasound gel to the sample substrate, we decided to use the ultrasound gel to mechanically couple the sensor to the different sample substrates (i.e. the result showed small differences in EMI spectra between glue and ultrasound gel). In the real application the piezoelectric sensor shall be glued to the substrate frame. The test coupon samples are described above.

For the impedance measurements we used a compact impedance analyser form Digilent (Analog Discovery 2 and 3) equipped with an impedance PCB-board, see Figure 7.

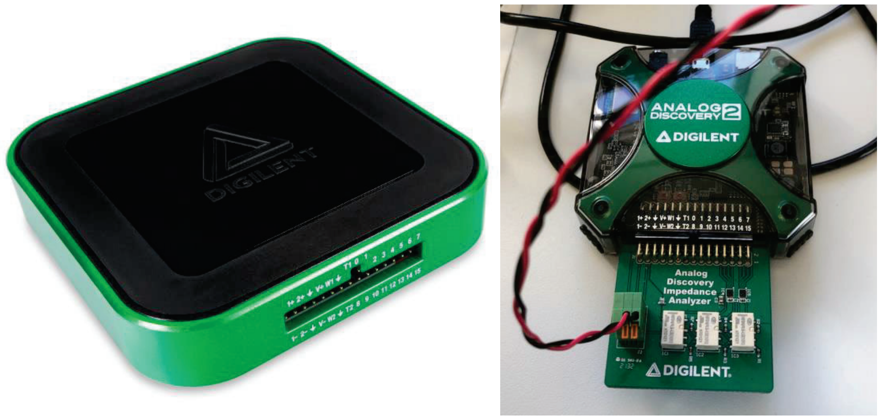


Figure 7 (right) Analog Discovery 3 (mostly used and in the final measurements) and (left) Analog Discovery 2 (used in the beginning of the project) equipped with the PCB-impedance board. The dimensions of the reading unit are 10.0 cm × 10.0 cm × 2.0 cm.

The Analog Discovery system was controlled with a laptop (via USB-C) and using the software (Waveform from Digilent). A typical measurement run can be seen in Figure 8, showing the amplitude of the impedance (top) and the phase of the impedance (below) versus the frequency of applied sensor voltage.

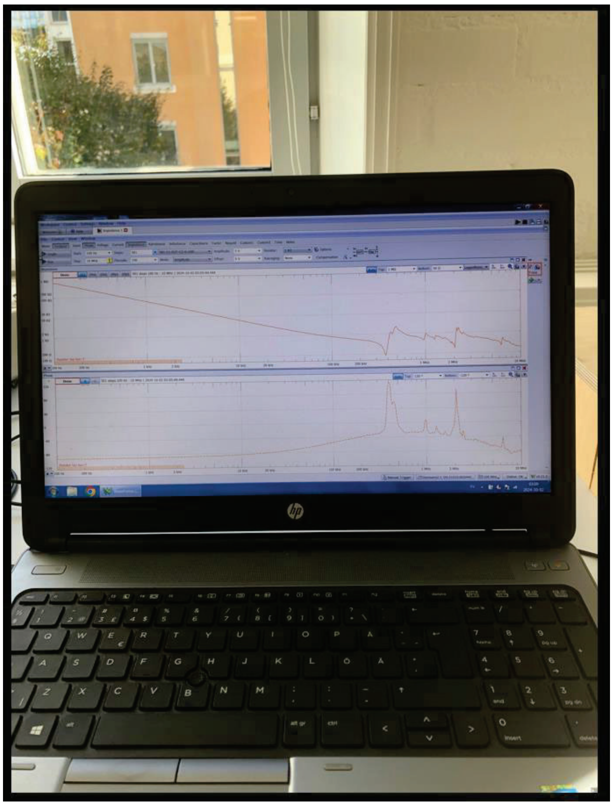


Figure 8 A laptop controls and collect the data from the PZT sensor through the Waveform software.

Impedance measurements were carried out between 10 kHz and 20 MHz. We have analysed the impedance data at and near the intrinsic piezoelectric resonance frequencies at frequencies in the range of 100 kHz up to 6 MHz. The measurements at frequencies well below the resonance frequency (10 kHz and above) were carried out in order to study the pure capacitive response (to check the electric properties of the sensor). Impedance measurement of a "free" PZT-sensor in air (i.e. not mounted to a rigid surface) for frequencies between 10 kHz and 10 MHz can be seen in Figure 9.

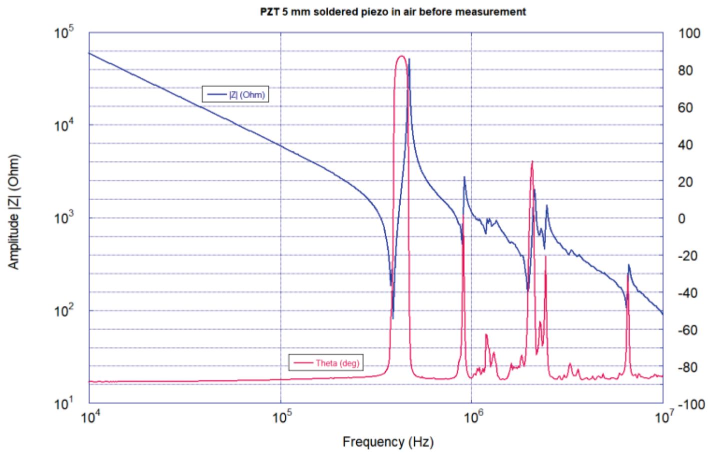


Figure 9 Amplitude (blue) and phase (red) of the impedance (blue) versus frequency of PZT-sensor in air (not mounted to a rigid surface).

As can be seen in Figure 9, in the beginning of the impedance frequency sweep (below about 100 kHz) the PZT sensor behaves as an ordinary capacitance with a linear dependency of the impedance with frequency (in a log-log plot). The major intrinsic piezoelectric resonances of the PZT sensor can be seen as features (peaks) in both amplitude and phase of the impedance at about 425 kHz, 898 kHz, 2 MHz and at 6.5 MHz. There are also some minor features in both amplitude and phase of the sensor that is due to the intrinsic resonance properties. As pointed out in the introduction it is at these resonances that the sensor displacement is largest and thus vibrates the backplane/substrate where the sensor is mounted also delivers maximum vibration energy to the backplane/substrate. As we will see in the result chapter the shape and position in frequency of the resonances, will change dependent on which substrate material the PZT sensor is placed on and the different mechanical properties of the substrate/backplane.

After running through the entire test matrix the following conclusions can be drawn from the EMIS trials.

- From the result we can deduce that all samples show differences in the impedance spectra (amplitude and phase) when changing the measuring sensor positions (for positions 1 – 3 and weaker differences between position 4 - 6) that have different mechanical properties due to the debonding (simulated by air gap and teflon tape) or not. The changes in the impedance is definitely due to the changes in sensor positions (different mechanical properties) and not to any signal variations due to an unstable sensor mounting (since several senor response measurements was carried out at the same senor positions with no significant changes in impedance response).
- Why the sensor response changes are less for sensor positions 4 – 6 is not fully understood (perhaps the glue has been smeared out giving almost the same mechanical properties).
- The difference in sensor response could be found, 1. for both debonding types (air gap and teflon tape), 2. of the different backplane thicknesses (1 mm and 3) and also for the different glue materials being used in the study.

- When comparing the results for sensing positions that should have the same mechanical properties, we can see a very good resemblance in both impedance and phase (for samples 1 – 6), but there are some results (samples 7 – 8) where this correlation was not so obvious. This have to be studied further to better understand the obtained EMI spectra.
- The differences in the impedance spectra (both amplitude and phase) show almost as "scattered data" that is not due to electric noise but instead is probably due to that the vibrations of the backplane/substrate (due to the sensor vibrations) interfere mechanically with the sensor that gives a change in impedance. The piezoelectric sensor itself is inverse, meaning not only that a voltage applied to the sensor gives a dimension change but also that a mechanical stress/strain to the sensor will give a piezoelectric voltage (or electric charges) that will add and change the impedance measurement in a "scattered" way as shown from the result.
- In order to use this method as a stable and reliable NDT method for measuring the mechanical adhesive properties, more measurements and analysis have to be carried. But these initial results are promising since we get changes in impedance that can be correlated with the attachment of the piezoelectric sensor to the backplane/substrate and that the result depends on the mechanical properties of the backplane/substrate.
- From the result from this study some suggestions of future work may be; 1. Investigate the sensor response when increasing the voltage amplitude of the applied voltage to the sensor. A larger voltage amplitude will give a larger sensor displacement (vibrations to the backplane) and the impedance response will be more easily detected, 2. In the real application the sensors must be rigidly glued to the backplane/frame and this must be further investigated.

6.3 Active thermography testing

The principle of active thermography centers around inducing a transient thermal state (i.e. heating and cooling) in an object using an external energy source and then analyzing the resulting temperature changes over time to reveal information about the object's internal structure and the presence of defects. An external energy source, as a heat lamp, is used to stimulate the object being inspected. The applied energy penetrates the object and propagates through its volume. The way heat flows is governed by the material's thermal properties (e.g., thermal conductivity, diffusivity, specific heat) and its internal structure. An infrared (IR) camera then captures the temperature evolution of the object's surface as it heats up and/or cools down. For the application of adhesive bonding, the hypothesis is that areas where there is a lack of adhesion the heat will transfer less efficiently compared to areas where there is complete adhesion.

The limited tests on two samples in the QABB pre-study were performed with an external supplier. Unfortunately, the tests showed little promise when using active thermography on aluminium surfaces due to the high reflectivity and low emissivity of aluminium, in particular aluminium sheets as used in this project. On the aluminium surfaces, no debonding or lack of adhesion could be detected using active thermography. However, on the thermoplastic side, the air gaps and lack of adhesive could be clearly illustrated in the results. More studies are needed to fully understand the potential and accuracy of active thermography even for QA of thermoplastic materials.

6.4 Passive thermography testing

Passive thermography works on the same principle of active thermography with one important difference. In passive thermography, the heat is not generated from an external heat source but from the analysed component itself. In the case of 2C adhesive bonding, the heat is generated from the curing process of the adhesive. The trials for passive thermography were done at RISE in Mölndal using a FLIR X6540sc IR thermal camera.

Two applications were tested; firstly an open adhesive bead to clearly illustrate the thermal reaction and secondly an overlap joint with the materials in the test matrix.

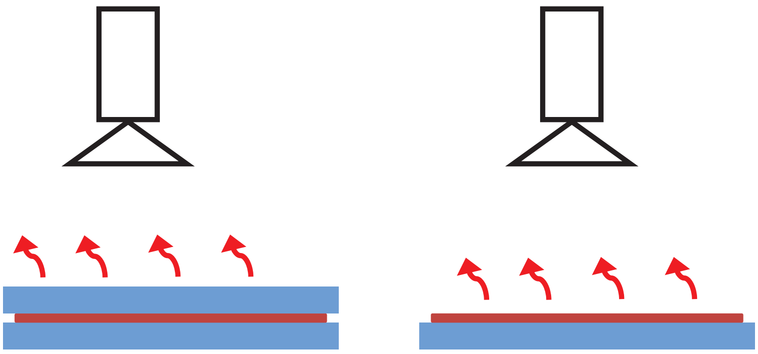


Figure 10 Principle of passive thermography testing with open adhesive (right) and an overlap joint (left)

The open adhesive bead was done with two different adhesives: 2C PUR adhesive (as used for the test coupons) and a 2C METHYL METHACRYLATE (MMA) based adhesive. The MMA adhesive was selected due to its known high reactivity and heat generation. The open trials showed that the heat reaction from the PUR adhesive was minor (only a few degrees C). However, the heat reaction from the MMA adhesive was significantly higher, as expected. The temperature development of the adhesive bond is shown in Figure 11. As seen the temperature reaches as high as 70C after approximately 15 minutes.

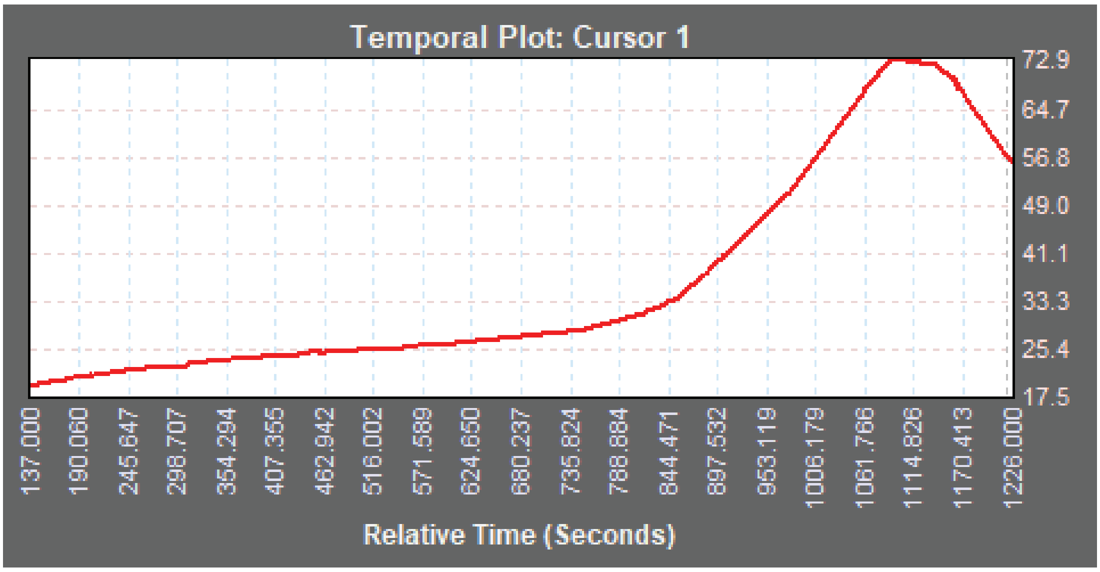


Figure 11 Temperature reaction of MMA based adhesive.

Due to the results of the open bead tests, it was decided to only proceed with overlap trials for the MMA adhesive. The figure below, illustrates the results from the passive thermograph trials of the overlap joint with the MMA adhesive. As in the active case, it is seen that the high reflectivity of the aluminium renders no useful results from the thermography camera. However, when analysing the thermoplastic (PP) surface, the adhesive curing can be clearly seen and gaps between the adhesive beads can be visually determined.

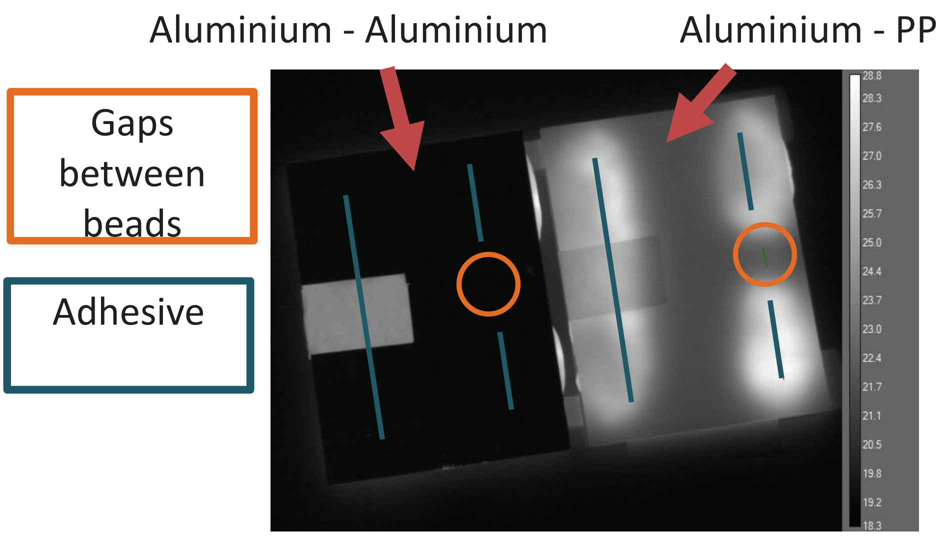


Figure 12 Thermography plot for the overlap joint and MMA adhesive.

The following conclusions can be drawn from the thermography trials.

- Aluminium, due to its high emissivity, is likely not suitable for thermography applications as a QA method for adhesive bonding.
- Temperature increase in the PUR adhesive is too low to effectively use it as a heat generator for passive thermography.
- Temperature increase in the MMA adhesive is significantly higher in shorter time and could be used as a heat generator for active thermography. More trials and investigations are needed to fully understand its potential and suitable process parameters.

6.5 Excluded test methods

While found in the literature review, the following test methods were excluded from the pre-study scope: radiography and CT scanning, terahertz measurement and equipment process monitoring. However, it should be noted that all of these methods may have potential in future projects or in other applications, which should be examined separately.

6.6 Outlook and project continuation

The results from the project have illustrated possible continuations and extensions of the present work. This could form the basis for a larger scale project. Potential extensions are summarised in the points below.

- Further evaluation of the most promising QA methods, such as UT and EMI.
- Data analysis of results to add intelligent and automatic evaluation of collected data. This could include AI or machine learning models to enhance understanding and prediction of result data.
- Extend scope to other applications such as body-in-white, cab or aerospace applications. This could also include other materials for analysis.
- Robotization of QA methods for automatic inspection of products, both in serial production and in after-market applications.

Potential sectors and partners, relevant for such an extension project has been identified for further research and development.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	The literature study led to increased knowledge of QA and QC methods. Moreover, the experimental trials increased knowledge for potential methods to be further developed for industrial introduction.

Be passed on to other advanced technological development projects	X	A follow-up project based on the findings of the pre-study is planned. Also, the findings of the project has been transferred to the FFI Circularity project 2CAP.
Be passed on to product development projects	X	The project participants have used the findings of the project to influence decisions on strategies for serial production QA methods.
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

No publications from the project have been planned so far.

8. Conclusions and future research

The main finding from the pre-study are listed below,

- Requirements on QA methods for adhesive bonding have been identified.
- Potential methods for QA have been mapped through a literature review.
- The most promising methods for QA for adhesive bonding have been experimentally assessed at RISE and at external partners.
- Ultrasonic testing (UT) show promising capabilities to detect lack of adhesion and lack of bonding in the specimens in the present project.
- Results from electromechanical impendence (EMI) measurements also show promising results. Lack of adhesion and lack of debonding can potentially be detected by EMI, but more data and data analysis is needed to fully understand its potential and accuracy.
- Thermography (both passive and active) is not suitable for applications where aluminium is used as the inspected surface. However, thermography could be more suitable for other materials such as PP or other thermoplastics.
- A list of future research topics has been collected and includes areas such as, data analysis and AI, automation and an extension of industrial applications.

9. Participating parties and contact persons

Oscar Andersson (project leader) Ola Albinsson Christer Johansson	Kerstin Wasmuth Thomas Karlsson Benny Brunnberg

References

[1] C. J. Brotherhood, B. W. Drinkwater, and S. Dixon, "The detectability of kissing bonds in adhesive joints using ultrasonic techniques," *Ultrasonics*, vol. 41, no. 7, pp. 521–529, Sep. 2003, doi: 10.1016/S0041-624X(03)00156-2.

[2] B. Yilmaz, D. Smagulova, and E. Jasiuniene, "Model-assisted reliability assessment for adhesive bonding quality evaluation with ultrasonic NDT," *NDT & E International*, vol. 126, p. 102596, Mar. 2022, doi: 10.1016/j.ndteint.2021.102596.

[3] W. Roth and V. Giurgiutiu, "Structural health monitoring of an adhesive disbond through electromechanical impedance spectroscopy," *Int J Adhes Adhes*, vol. 73, pp. 109–117, Mar. 2017, doi: 10.1016/j.ijadhadh.2016.11.008.

[4] V. Giurgiutiu, "Tuned Lamb Wave Excitation and Detection with Piezoelectric Wafer Active Sensors for Structural Health Monitoring," *J Intell Mater Syst Struct*, vol. 16, no. 4, pp. 291–305, Apr. 2005, doi: 10.1177/1045389X05050106.

[5] J. A. Schroeder, T. Ahmed, B. Chaudhry, and S. Shepard, "Non-destructive testing of structural composites and adhesively bonded composite joints: pulsed thermography," *Compos Part A Appl Sci Manuf*, vol. 33, no. 11, pp. 1511–1517, Nov. 2002, doi: 10.1016/S1359-835X(02)00139-2.

[6] M. Y. Y. Hung, "Review and comparison of shearography and pulsed thermography for adhesive bond evaluation," *Optical Engineering*, vol. 46, no. 5, p. 051007, May 2007, doi: 10.1117/1.2741277.

[7] S. Zheng, J. Vanderstelt, J. R. McDermid, and J. R. Kish, "Non-destructive investigation of aluminum alloy hemmed joints using neutron radiography and X-ray computed tomography," *NDT & E International*, vol. 91, pp. 32–35, Oct. 2017, doi: 10.1016/j.ndteint.2017.06.004.

[8] S. Minakuchi, Y. Okabe, and N. Takeda, "Real-time Detection of Debonding between Honeycomb Core and Facesheet using a Small-diameter FBG Sensor Embedded in Adhesive Layer," *Journal of Sandwich Structures & Materials*, vol. 9, no. 1, pp. 9–33, Jan. 2007, doi: 10.1177/1099636207064457.

[9] A. L. Loureiro, L. F. M. da Silva, C. Sato, and M. A. V. Figueiredo, "Comparison of the Mechanical Behaviour Between Stiff and Flexible Adhesive Joints for the

Automotive Industry," *J Adhes*, vol. 86, no. 7, pp. 765–787, Jul. 2010, doi: 10.1080/00218464.2010.482440.

[10] G. Viana, M. Costa, M. D. Banea, and L. F. M. da Silva, "Behaviour of environmentally degraded epoxy adhesives as a function of temperature," *J Adhes*, vol. 93, no. 1–2, pp. 95–112, Jan. 2017, doi: 10.1080/00218464.2016.1179118.

[11] A. Ameli, M. Papini, and J. K. Spelt, "Hygrothermal degradation of two rubber-toughened epoxy adhesives: Application of open-faced fracture tests," *Int J Adhes Adhes*, vol. 31, no. 1, pp. 9–19, Jan. 2011, doi: 10.1016/j.ijadhadh.2010.10.001.