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ORIGINAL PAPER

Two-stage leak detection in vacuum bags for the production of fibre-reinforced composite components

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Abstract
The increasing application of fibre-reinforced composite components in aviation results in new problems in production when compared to the conventional production of components from aluminium alloys. For instance, the existence of leakages in the vacuum bag can substantially impact the component quality. A significant increase of both time and cost, and even the rejection of the entire component are caused. Commercially available methods are suitable for identifying leakages in vacuum bags; however, their application is predominantly associated with high outlay in labour and time, and, thus, high costs. Market analysis and comparison of different available leakage detection technologies conducted in the course of the advanced detection of leakages project with our collaborative partner Airbus Operations GmbH Stade has shown that the combination of run-time based leakage detection and infrared thermography is the most promising concept for quick, reliable, and automated identification of leakages in vacuum bags for large components. In combination, both technologies are able to compensate for their respective detection limits, and significantly reduce the time required. In addition to the analysis and assessment of different technologies for leakage detection, the investigations presented also include the development of run-time based leakage detection using sensors integrated into the vacuum bag. Furthermore, the linking, further development, and automation of leakage detection using infrared thermography are described.

Keywords Leakage detection · Vacuum bagging · Infrared thermography · Composite · Autoclave

1 Introduction

Since 2014, there has been close collaboration between airbus and dlr stade, with the aim of developing and improving leakage detection in vacuum bags for prepreg components. In addition to the development of infrared thermography for leakage detection, the project also successfully investigated its application for leakage identification inside autoclaves.

The projects showed that there are many different approaches to detecting leakages in vacuum bags. Although all methods can essentially identify leakages within a vacuum bag, each method has different detection limits. In addition, some methods are associated with a high outlay in time and costs, or cannot be automated. The aim of the advanced detection of leakages (ADeLe) project was to compare the leakage detection technologies available on the market, and to highlight their differences.

This publication focuses on the analysis and comparison of the individual technologies, and the development of a concept for a future competitive leakage detection system for large components. To this end, the current state-of-the-art will be explained and the ADeLe project presented, along with its results. On this foundation, the final concept of two-stage leakage detection in vacuum bags will be explained for the production of fibre-reinforced composite components.

2 State-of-the-art

2.1 Vacuum bag for prepreg components

Vacuum bags are required to cure prepreg components inside an autoclave under elevated temperature and pressure. Its purpose is the application of evenly distributed pressure onto

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the component during the curing cycle. To guarantee this, the vacuum bag must form a closed system with respect to the autoclave atmosphere, by hermetically sealing the component between tooling and vacuum film.

Figure 1 shows a schematic setup of a vacuum bag which consists of different auxiliary materials. For leakage detection, vacuum film and sealing tape are particularly relevant, as is the breather cloth as air-conducting layer.

Figure 2 shows the vacuum bag of an aircraft component. It can be seen that the component is stringer-reinforced and that the vacuum bag is accordingly more complex. To avoid excessive tension of the film, it is folded in the relevant areas to provide sufficient material.

If the vacuum bag is not airtight or if the vacuum film tears during the autoclave cycle, serious impairment of the component quality can occur. It is, thus, imperative that the vacuum bag is examined for leakages subsequent to construction.

2.2 Leakage detection

Current leakage detection on aviation components starts with the application of a sensitive ultrasonic microphone to detect small and large leakages along the sealant tape during the evacuation of the component. This process step is shown in Fig. 3 on the left-hand side.

After evacuation, a dial pressure gauge (as shown in the right-hand side of Fig. 3) is used to check the entire system and assess its leak tightness. For this check, the component is disconnected from the vacuum and the increase in pressure within the vacuum bag is monitored over a specified period. Permitted values vary between 5 and 15 mbar/min. If the value is higher, the leakage must be located. In older aircraft programmes, this is done using the sensitive microphone that has already been used to check the sealant tape. Newer aircraft programmes additionally use the helium leak test and a test dye to locate leakages. The helium leak test and the test dye are presented in greater detail in Sects. 3.1.5 and 3.1.6 [2].

Once defects are found, they are repaired using adhesive tape or sealant tape. Should defects be unidentifiable, or too large for reworking, the vacuum film must be replaced.

This process is very time-consuming and extremely dependent on the experience of the workers. Therefore, the need for faster and more robust processes for leakage detection in vacuum bags is present in the production of fibre-reinforced composite components.

According to Airbus Stade, the costs for a standard vacuum test are approximately €30–80 per component, but this value is highly dependent on component size. Depending on the production rate, this results in €25–45 k per component per year for the leakage tests alone. Additional expenditure of approximately €5.5 k per year and component type arises for searching possible leakages or replacing the vacuum bag. In combination with the costs of repairs and scrapping of components due to unidentified leakages, this results in leakage-associated costs of approx. €50.5–70.5 k per year and component type.

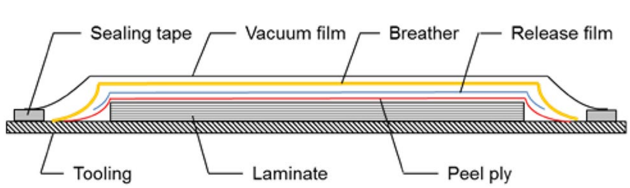


Fig. 1 Schematic setup of a vacuum bag (based on [1])

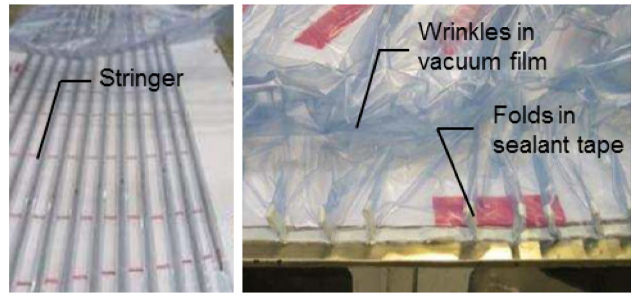


Fig. 2 Vacuum bag of a stringer-reinforced prepreg component

3 Project ADeLe (advanced detection of leakages)

The ADeLe project was established in 2016 by Airbus and DLR Stade, with the aim of improving leakage detection prior to the autoclaving process, thereby making it more robust while reducing process time. The project initially included a market analysis of the technologies available for leakage detection. These were collected and then compared with each other and the current state-of-the-art using a text matrix.

Fig. 3 State of leakage detection technology on vacuum bags in the aircraft industry

3.1 Technologies for leakage detection

The market analysis identified a total of eight leakage detection technologies:

- pressure increase test;
- ultrasound microphone;
- infrared thermography;
- leakage detection film;
- microphone array;
- piezoelectric sensors;
- dyes;
- gas detectors.

The pressure increase test and the ultrasound microphone represent the current state-of-the-art and are used by Airbus in production. The other technologies will be presented briefly in the following.

3.1.1 Infrared thermography

The leakage detection system using infrared thermography and patented by DLR is based on the Joule–Thomson effect [3]. The effect describes how the air flowing into a leakage falls to a lower pressure and—in doing so—expands and cools down [4]. This cooling can be identified as a cold spot in the image acquired by the thermal camera and explicitly identifies the position of the leakage, as shown in Fig. 4.

This technique is simple to use and is contact free, thus having no effect on the component or the vacuum bag. In addition, leakages have a characteristic temperature profile, which facilitates automated recognition and analysis of the thermal image [5].

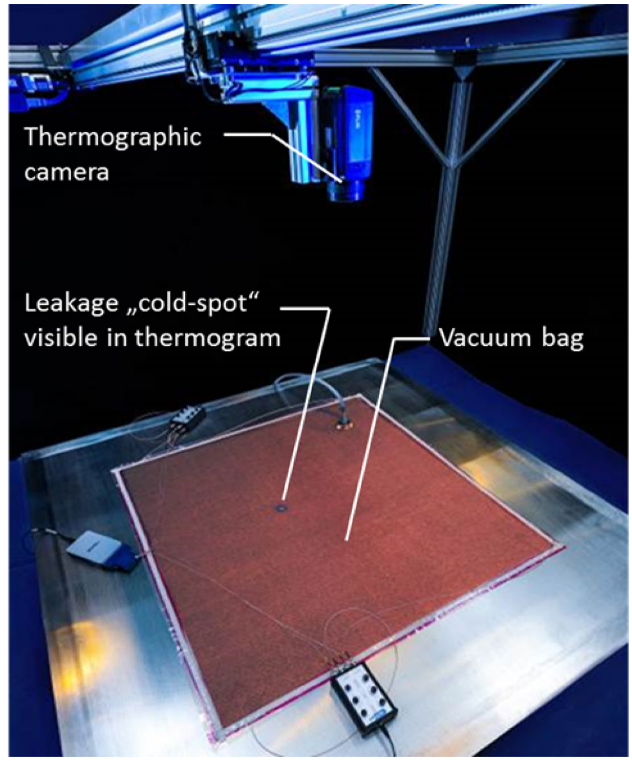


Fig. 4 Leakage detection using infrared thermography. The thermal image acquired by the camera is projected onto the device under test

3.1.2 Leakage detection film

A leakage detection film is a film that holds a gas-permeable membrane, which contains oxygen-sensitive material. As soon as a leakage occurs and the material comes into contact with oxygen, its appearance changes and the leakage can be detected visually [6].

Regarding this technology, only one patent exists at the moment, and the film is not commercially available. Therefore, it was not able to be tested within the project. However, it must be noted that this film would represent an additional auxiliary material within the vacuum bag. On one hand, this increases cost and time outlay in construction of the vacuum bag, and on the other hand, an increased volume of waste if it is not possible to integrate this material into a vacuum film.

3.1.3 Microphone array

Leakage detection using manually placed ultrasonic microphones is already state-of-the-art. In the field of compressed-air leakages, these are initially investigated using microphone arrays and beam forming, a procedure to identify the position of sources of wave fields, and to locate them over large distances [7].

Some preliminary trials are being carried out using ultrasonic microphones to use this technology for vacuum leakages. Here, it is apparent that the distance between the microphone and the vacuum bag should not exceed 30 cm. The greatest disadvantage, however, is that not every leakage appears to emit sufficient sound in the ultrasonic range. Apparently, some leakages have a predominantly laminar flow, such that hardly any high-frequency sound is generated. On the other hand, sounds in the ultrasonic range that are detected by the microphones may also be produced at obstacles to the flow or structural transitions without there being leakages (for example, between individual mats in the breather layer or close to the vacuum connection), thus misdirecting the microphone operator.

Due to these results, this technology was not considered any further in the trials.

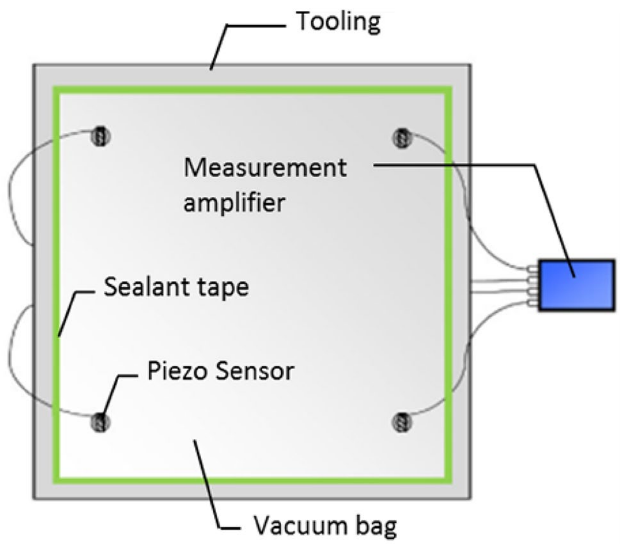


Fig. 5 Vacuum bag with integrated piezoelectric sensors

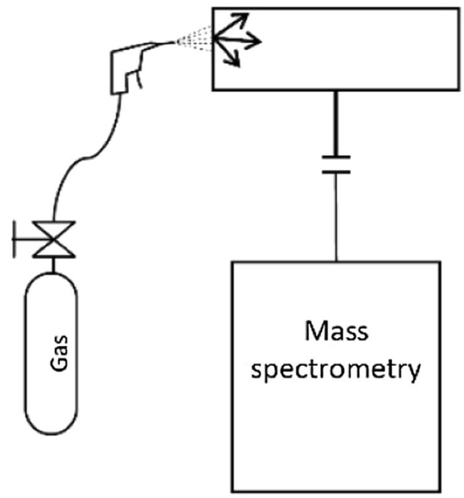


Fig. 6 Leakage detection using the spray test (based on [9])

3.1.4 Piezoelectric sensors

For this method, specifically adapted piezoelectric sensors based on iNDTact's standard iMPactXS tactile sensors were used. As shown in Fig. 5, four sensors were used in the tests, placed in the four corners of the vacuum bag. The sensors were covered with the breather cloth and integrated into the structure in a vacuum-tight manner.

The local pressure change within the vacuum bag produced in the case of a leakage is recorded by the sensors and analysed using software. To correctly locate the leakage, the input signals (in mV) are compared and the probable position of the leakage is calculated using a multilateration process. The output is an x–y coordinate [8].

3.1.5 Dye

Leakage detection based on ink or dye is performed using EpoDye. It is a fluorescent colouring agent, which is primarily used to detect cracks and pores in metals and ceramics.

For use in leakage detection, the EpoDye, dissolved in isopropanol, is applied directly onto the vacuum film. If there is a leakage in the vacuum bag, the dye penetrates the leakage and spreads through the breather cloth. The applied colouring agent is then removed from the film and any leakages can be detected visually.

3.1.6 Gas detectors

Helium is the primary gas used in leakage detection with gas detectors. Gas is sprayed manually or automatically on the surface of the tested structure, as shown in Fig. 6. If the gas penetrates into the vacuum bag through a leakage, it is identified by a gas detector connected in front of the vacuum pump. It is, thus, possible to narrow down the area affected by a leakage [9].

Leakage detection using helium is state-of-the-art in newer aircraft programmes. During production use, some disadvantages of this method have become apparent. On one hand, the test is very time-consuming, as only small areas can be tested. On the other hand, the test can only identify the area and not the exact position, quantity, or type of leakage. Furthermore, it has been observed that vacuum films can become permeable to helium atoms over time. In this case, a leakage would be indicated as a false-positive. Due to these results, no further trials were carried out within the project.

3.2 Trials

3.2.1 Test assemblies

To compare the different technologies, different test assemblies were used to model various boundary conditions. To ensure a comparison of all the methods, first tests were performed on a small scale. A table-top tool 1500 mm × 1500 mm in size was used. As shown in Fig. 7, an optical metering cell including a thermal camera attached to a linear drive was used.

The most promising detection technologies were subsequently tested on a larger scale. An A350 fuselage shell tool with double-curved geometry was used for this purpose. Vacuum bags 4300 mm × 1500 mm and 2000 mm × 2000 mm in size were constructed. At this size, longer signal propagation times occur, leading to a higher accuracy for leakage detection using sensor measurements.

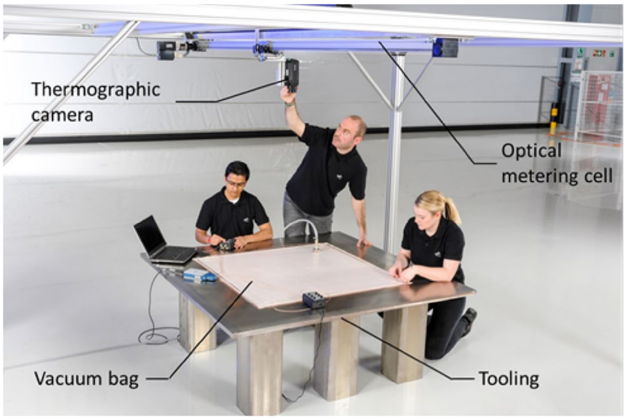


Fig. 7 Table-top tool with optical metering cell

In a further series of tests, stiffening elements and film folds were integrated into the vacuum bags to check the effects of these interfering factors on the various detection methods.

Leakages were artificially introduced into the vacuum bag using hypodermic needles of different diameters or box cutters, depending on the desired leakage type. To ensure isolated existence of artificial leakages, the vacuum bag was checked for leakages using the pressure rise method prior to each trial and an initial vacuum of ≤ 50 mbar was applied.

3.2.2 Leakage types

Different types of leakages in vacuum bags had to be addressed within the trials. To this end, a list containing the various leakage types was generated in cooperation with Airbus. The list is shown in Fig. 8.

The considered leakage types are the primary leakages that occur within the vacuum film and the sealant tape. Other leakages can occur in the mould or at the vacuum ports. These cases were not considered in the scope of the project.

For the frequency of the occurrence of these different leakage types, it can be indicated that leakages in sealant tape are more common than the once in the vacuum film. Almost every other part has a leakage in the sealant tape after the first vacuum bagging. These leakages are almost always detected prior to curing by the used detection method and easily repaired. More critical are the leakages in the vacuum film. These leakages are harder to detect and occur approximately every tenth part depending on part and vacuum bag complexity, resulting in the costs indicated in Sect. 2.2.

3.2.3 Assessment criteria

Considering the various test assemblies and leakage types, a test matrix was generated in which all the available detection

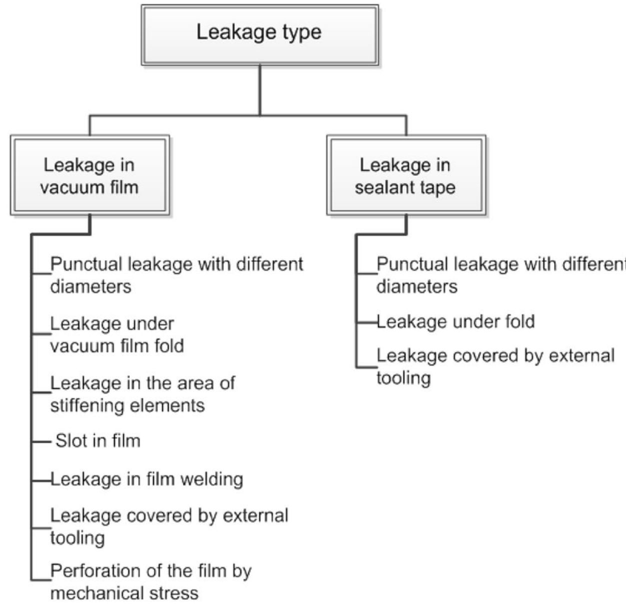


Fig. 8 Classification of the different leakage types

technologies could be compared with one another. The following assessment criteria were used:

- automated or manual;
- duration;
- handling;
- can be integrated in the autoclave;
- minimum size of detectable leakage;
- maximum component size;
- cost.

A weighting factor was assigned to each assessment point to produce a final overall assessment for each method.

3.3 Results

3.3.1 Preliminary trials

As described in Sect. 3.2.1, trials were initially performed on a small scale. Here, it could already be seen that not all technologies were equally suitable for reliable leakage detection and localization.

The pressure increase test, which is currently being used in production, is only suitable for determining the existence of a leakage, but does not enable the localization of the leakage. With increasing component size, the detectability of a leakage becomes less explicit, since time and the positioning of the metering device play a crucial part.

The trials for the ultrasonic microphone confirmed the results from the preliminary trials described in Sect. 3.1.3. It must be noted that larger leakages are already perceived by human hearing, and the handset is intended for smaller leakages. The scanning of the film surface is exceptionally laborious, as the distance should not exceed 30 cm. On the other hand, better results were achieved on the vacuum sealing tape, as only linear areas had to be inspected. As described in Sect. 3.1.3, an additional drawback is that not every leakage seems to emit sounds, and sometimes, sounds occur in the vacuum bag, even if there are no leakages.

Leakage detection using ink or dye especially shows problems in case of film folds and around stringers. Reliable application and removal of the dye is associated with a greater expenditure of time. The detection of leakages is also made more difficult by folds. As expected, it became evident that leakage detection is absolutely dependent on the presence of a white breather cloth. CFRP stringers that are already cured are generally not covered with breather cloth, such that leakages in these areas are almost impossible to identify due to the poor visibility of the relatively thin, yellow dye on the black CFRP stringers.

In preliminary trials, infrared thermography and piezoelectric sensors appeared to be the most suitable with regard to the assessment criteria and were examined on a larger scale. The results are shown individually below.

3.3.2 Infrared thermography

Leakage detection using IR thermography has emerged as a very reliable method. Especially leakages in the vacuum film on top of breather cloth are easily identified by thermography. As expected, the leakage location stands out very clearly as a cold spot. Perforations in the film ≥ 0.1 mm can be identified in this way.

A drop in temperature can be detected in the immediate vicinity of the leakage, as shown in Fig. 9. This is of particular significance if the position of the leakage itself cannot be imaged directly by the camera lens, as may occur when there are folds in the vacuum film. The temperature drop in the wider surroundings of the leakage still allows it to be roughly located.

Leakages on the upper sides of folds, i.e., in places where the air-mass flow has to travel some distance before reaching the breather cloth, are particularly hard to identify. The temperature difference of the air presumably reduces along the route of the flow, such that the breather layer experiences little to no cooling. Leakages at stiffening elements that are not covered with a breather layer are also hard to identify. The reason for this is likely the high thermal capacity of the material or its high coefficient of thermal conductivity.

One advantage is that leakage detection by thermography has already been carried out successfully in the autoclave. For this purpose, a thermography system inside a water-cooled pressure vessel has been integrated in the research autoclave in Stade [10].

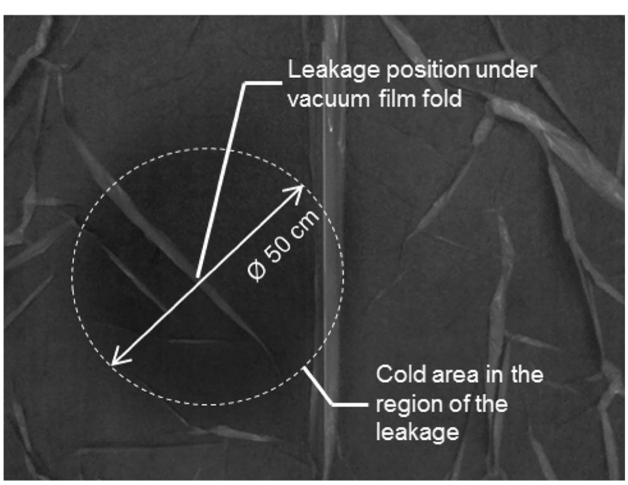
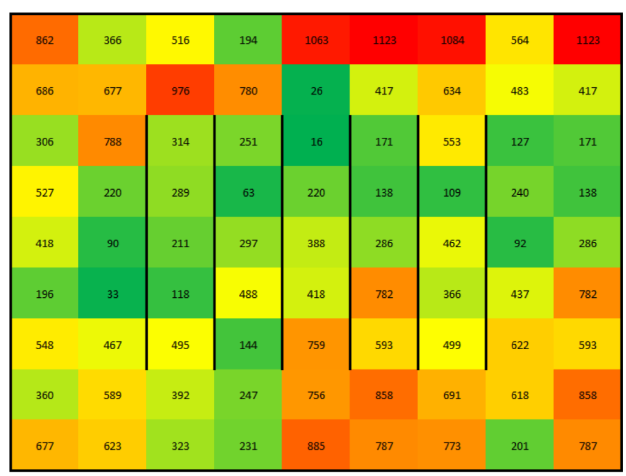


Fig. 9 Thermal image of a leakage under a film fold. A drop in temperature in the area around the leakage can be identified

3.3.3 Piezoelectric sensors

Piezoelectric sensors are the only method that was able to detect all the types of leakages unless several leakages occurred in a single vacuum bag. Further development of the analysis software is required for this.

As expected, improved accuracy of the identified leakage location occurred during the large-scale trials, since the signal propagation times also increased. The data recorded in this test are shown in Fig. 10. It must be noted that stiffening elements were incorporated into the vacuum bag during this test which are represented as black lines in the figure.



862	366	516	194	1063	1123	1084	564	1123
686	677	976	780	26	417	634	483	417
306	788	314	251	16	171	553	127	171
527	220	289	63	220	138	109	240	138
418	90	211	297	388	286	462	92	286
196	33	118	488	418	782	366	437	782
548	467	495	144	759	593	499	622	593
360	589	392	247	756	858	691	618	858
677	623	323	231	885	787	773	201	787

Fig. 10 Leakage detection using piezoelectric sensors. The deviation between the real and the determined position is given in millimeters. Deviation is indicated as acceptable by green colouration; yellow indicates marginal deviation; red indicates an unacceptable result

The size of each examined field, in the centre of which the test leakage was introduced, is 200 mm × 200 mm. Within the diagram, the respective deviation between the real and the determined leakage position is given for each field and indicated by colour. The average deviation between actual and calculated leakage positions is 471 mm.

It is easy to see that the reliability of the calculation procedure is not equal at all points, but its distribution is not chaotic either. It is evident that the values obtained close to the edges are more unreliable. A positive aspect is that a negative influence of the procedure by the stiffening elements is not observed.

The trials show that the technology is essentially suitable for narrowing down the location of a leakage, but an accurate determination of the position is not yet possible.

3.3.4 Evaluation

The conducted trials and the results of the test matrix show that the best results are achieved using infrared thermography and piezoelectric sensors of all the tested methods for leakage detection. Figure 11 shows the results of the trials in the test matrix in a radar chart. Infrared thermography is very accurate and can determine the exact position of the leakage. Piezoelectric sensors, on the other hand, can quickly narrow down the area of a leakage, but cannot determine its exact position. However, the performed trials also show that further development is required to improve the software and the sensors, such that they can detect several leakages in one vacuum bag in a reproducible manner. All other tested procedures require more time and/or higher manual effort, as, for example, the dye and ultrasound microphone procedures.

An additional advantage of leakage detection using thermography is its option to be used during the autoclave cycle. The same applies for piezoelectric sensors, if they are integrated into the tools. The technologies have been successfully transferred to larger, more complex components for fuselage geometries.

4 The concept of two-stage leakage detection

The findings obtained in the ADeLe project showed that all of the technologies available on the market may be suitable for identifying leakages in vacuum bags, but they have detection limits or are associated with high time and cost outlays. Overall, leakage detection using thermography and piezoelectric sensors performs the best in the test matrix. However, both technologies also have their respective disadvantages when it comes to speed (thermography) or accuracy (piezoelectric sensors). This has resulted in the idea of linking both procedures to obtain a two-stage, robust-leakage detection system.

Combining the technology of sensor-supported leakage detection with infrared thermography represents a highly promising concept when it comes to detecting leakages in the vacuum bags of large components quickly, reliably, and in an automated manner. In combination, both technologies are able to compensate for their respective detection limits and significantly reduce the time required.

Figure 12 depicts the current technique and the new process as flowcharts. This direct comparison shows that the pressure rise test is retained as decision basis for whether the component can be passed on to the next process stage. If this is not the case, the detection procedures are used.

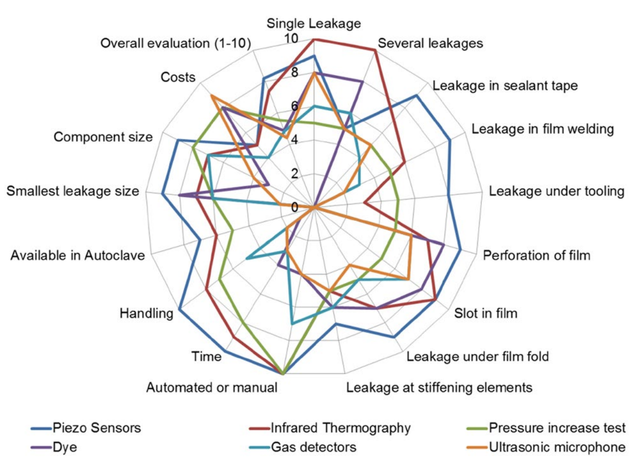


Fig. 11 Analysis of the trial results in a radar chart. On a scale from 0 to 10, 0 stands for particularly bad and 10 for very good

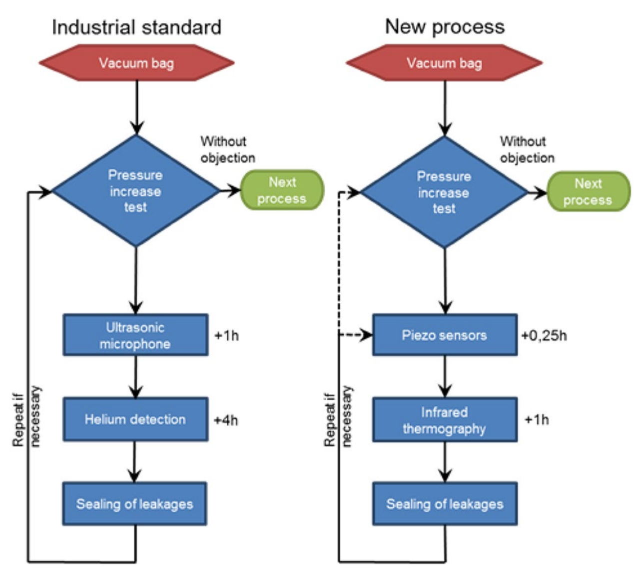


Fig. 12 Comparison of flowcharts for the current technique and the new process

Using current leakage detection technology, this may mean an additional time requirement of up to 5 h.

In the new process, piezoelectric sensors are initially used to check the vacuum bag, to narrow down the areas affected by a leakage. After this limitation, thermography is used. The coordinates determined by the software are passed on to the thermographic camera, which is located on an arch or robot. The areas determined by the sensors are automatically checked, one after the other. This process has the potential to reduce the additional time outlay by 3.75–1.25 h.

5 Summary and outlook

The investigations have shown that leakage detection using piezoelectric sensors and infrared thermography offers the most acceptable results. The other methods turned out to be inaccurate or associated with too much effort.

Potential leakage areas can be quickly identified using piezoelectric sensors. The thermographic camera can automatically check these areas and identify the exact position of the leakage. This two-stage leakage detection allows for compensation of the technologies' respective detection limits and reduction of the process time for detection by up to 75%.

Based on the trials, leakage detection by piezoelectric sensors will be further investigated and developed in the next step. Hereby, the focus will be on the identification of several leakages within a single vacuum bag. Furthermore, the other component geometries, such as wing shells, will be inspected. The optimal number of sensors required for reliable detection of leakages must be identified in further trials. So far, all tests have been carried out using four sensors, but, for larger components, the use of additional sensors may be required. Communication between the two systems for two-stage leakage detection must also be developed further. The aim is to set up a leakage test facility at DLR in Stade, to demonstrate the functionality and interaction of the two systems.

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