Zeitschrift Kunststofftechnik
Journal of Plastics Technology

www.kunststofftech.com · www.plasticseng.com

Scientific Alliance of the University Professors of Plastics Technology

archivierte, peer-rezensierte Internetzeitschrift
archival, peer-reviewed online Journal of the Scientific Alliance of Polymer Technology

eingereicht/handed in: 24.08.2021
angenommen/accepted: 05.10.2021

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Influence of leaky vacuum bags on the quality of composite parts made from prepreg material

Leakage in vacuum bags for fibre composite production is a frequently occurring defect, especially in the manufacture of components using the open mould process. The previous limit values for assessing the leak tightness of a vacuum set up are mostly historical and based on empirical values. In this paper, the effects of leaks that have been introduced in a defined manner into a vacuum bag are investigated. The physical processes that occur during curing within the leaking vacuum structure are analysed optically as well as by means of ultrasonic testing and thickness measurement and a better understanding of the effects on laminate quality is generated. It is found that there is a difference between leakages in the vacuum bag only and leakages that affect both the vacuum and release film.

Einfluss von undichten Vakuumaufbauten auf die Qualität von Faserverbundteilen aus Prepreg Material

Leckagen in Vakuumaufbauten zur Faserverbundherstellung sind ein häufig auftretender Fehler gerade bei der Herstellung von Bauteilen im Open Mould Verfahren. Die bisherigen Grenzwerte zur Beurteilung der Dichtigkeit eines Vakuumaufbaus sind meist historisch gewachsen und beruhen auf Erfahrungs-werten. In diesem Paper werden die Auswirkungen von Leckagen, die definiert in einen Vakuumaufbau eingebracht wurden untersucht. Die physikalischen Vorgänge, die während der Aushärtung innerhalb der undichten Vakuumstruktur auftreten, werden sowohl optisch als auch mittels Ultraschallprüfung und Dickenmessung analysiert und ein besseres Verständnis für die Auswirkungen auf die Laminatqualität geschaffen. Es stellt sich heraus, dass es einen generellen Unterschied zwischen Leckagen in der Vakuumfolie und der Trennfolie gibt.

Influence of leaky vacuum bags on the quality of composite parts made from prepreg material

A. Haschenburger, J. Stüve

1 INTRODUCTION

Vacuum bagging is an essential process step during the production of fibre reinforced composites in the open mould process [1]. A laminate made out of prepreg material is hermetically sealed against the environment to apply the pressure during the curing process as evenly as possible [2]. By evacuation of the vacuum bag and pressurisation of the ambient, a pressure difference is generated that is a determining factor for the quality of the produced laminate. It hinders the formation of voids or porosities in the composite part by ensuring the evacuation of entrapped air or volatiles [3, 4].

If a leakage is present in the vacuum bag, the pressure difference is not created homogeneously and air can flow into the vacuum bag [2]. In the aerospace industry, there are precise specifications as to how much a vacuum assembly may be affected by leakage. However, these specifications are mostly based on empirical values and not on technical analyses [2]. Within this paper a number of different trials is performed to investigate if the impact of a leakage on the part quality in terms of porosity and voids can be physically explained and characterized. The tested leakages can be divided in leakages that only appear in the vacuum bag and leakages in the vacuum bag and release film with direct contact to the laminate.

The focus of the tests is to assess the amount of porosity and void increase in relation to the leakage position and size. It is not a question of assessing the extent of these defects. The effect (porosities) of the defect (leakage) is examined, the evaluation of the effect, i.e. the porosities, is out of scope. No investigations are carried out into the altered mechanical characteristics caused by the defects in the laminate. The investigations focus on drawing conclusions about which defects cause leakage of a certain size and position in certain areas of the laminate. The research question can be summarized as:

What are the reasons why a leak of a certain size and position causes a defect at a certain position in the laminate?

The methodology of this paper is to design and assess a test series with artificially introduced leakages to different vacuum bags. A surrogate model based on spring analogy will then be applied to evaluate and explain the results.

2 STATE OF THE ART

The open mould process is state of the art for manufacturing of aerospace components. After the layup of a prepreg material on the mould is finished, a vacuum bag is created to apply the pressure during the autoclave curing cycle as even as possible onto the component [1]. A typical set up of a vacuum bag and its constituents is shown in Figure 1.

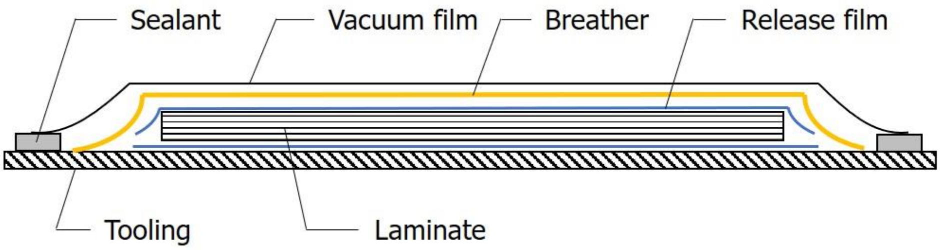

Figure 1: Schematic setup of a vacuum bag based on [1]

While the release and vacuum film are both barriers to prevent resin to leak out of the component or air to leak into the bag, the breather a coarse polyester fleece that is used to promote airflow across the entire surface of the laminate during evacuation. [5] This function is highly temperature and pressure dependent. The change in air flow of different breather materials at 7 bar and increasing temperature is shown in Figure 2. From this it can be seen that all breathers exhibit process-dependent permeability.

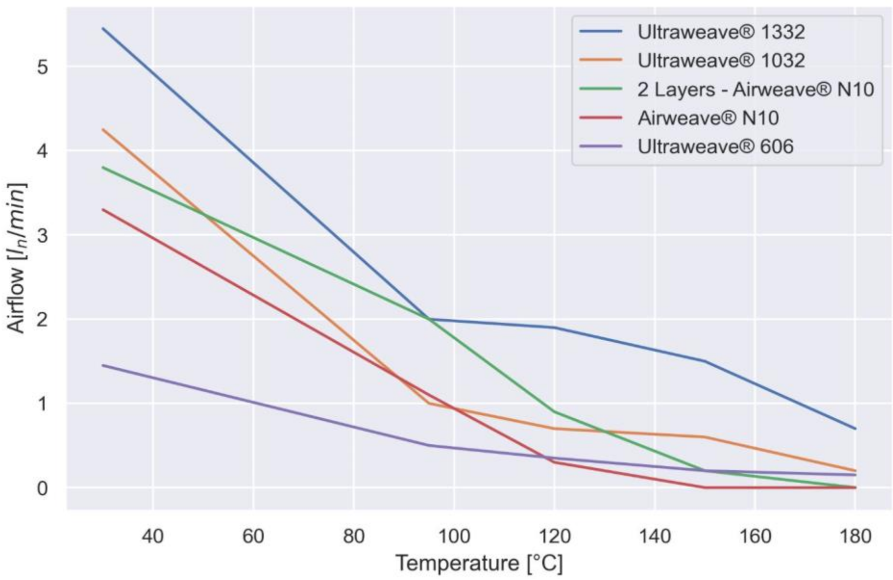

Figure 2: Airflow of Airtech breathers at 7 bar and increasing temperature cf. [5]

A high degree of evacuation of the vacuum bag is desired to achieve high forces onto the laminate to gain the desired high fibre volume content and to hinder porosity or void formation [2]. These consolidation processes are better understood by reference to a mechanical analogy. Under a load the porous medium, like the breather and the laminate, is compressed like a spring. If the voids are filed with a fluid it is compressed or, in case of incompressibility, escapes across the boundaries of the sample [6]. Porosity is defined as the volume fraction of small (voids) in a material, where a void in a composite is the space not occupied by resin or fibres [3]. The reason for void formation is complex and has been studied in a few researches especially for out of autoclave materials [3, 4]. Fernlund et al. [3] described void sources that increase the risk of porosity, like entrapped air, leaks and volatiles and void sinks that counteract this risk, like high evacuation level, elevated resin pressure and bubble mobility. Even though leakages are listed as a cause of porosity, the effect during curing is little studied.

In addition to porosity and reduced fibre volume, the penetration of air into the vacuum structure can have other undesirable consequences. It cannot be ruled out that chemical side reactions can take place during curing. One example is the degradation by oxygen radicals that is observed in epoxy resins from about 100°C. The oxygen radicals preferentially attack the carbon atom directly adjacent to the nitrogen. A radial chain reaction takes place in several stages and requires an initiation reaction that causes chain branching. After several rearrangements, the bond between the carbon and the nitrogen atom is split and a carbonyl group is formed, see Figure 3 [7-10].

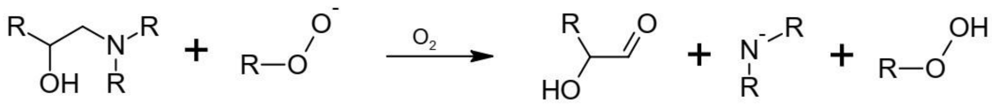

Figure 3: Schematic representation of the degradation of an epoxy resin network by oxygen radicals according to [7, 8]

To ensure that no leakage is present in the vacuum bag, leakage detection is performed before the autoclave cycle. The state of the art is the pressure increase test where the vacuum bag to be tested is connected to a vacuum pump and a pressure gauge to be evacuated completely. The vacuum lines are disconnected from the vacuum bag after the desired vacuum level is reached and the pressure increase for a specified time is monitored. Leakages lead to a pressure increase inside the vacuum bag while no pressure increase indicate its airtightness [2]. Typical aerospace manufacturer instructions specify that a pressure increase in the vacuum bag must not exceed 66 mbar within two minutes so that the component and the vacuum bag can be released for the autoclave process [11]. New detection methods include among others volumetric flow rate measurement and infrared thermography [2, 12].

3 METHODOLOGY

In the context of this paper and the performed tests, the consequences of leakages in the vacuum bag on the laminate quality are investigated. For this purpose, a series of autoclave trials has been performed. The investigations have been carried out on flat components where various leakages have been introduced into the vacuum bag before the autoclave process.

3.1 Laminate and vacuum bag composition

The material that has been used for the experiments was Hexcel M21/45%/120 [13], a Glass Fibre (GF)-reinforced prepreg system. A GF-reinforced material has been chosen to make it easier to detect the resulting porosities in the component due to its transparent properties. Porosities in Carbon Fibre Reinforced Plastics (CFRP) components can only be detected with the help of additional tests such as ultrasound or X-rays, whereas in the case of GF components, visual inspection can detect the defects.

The maximum component size in the tests was approx. 500 x 500 mm², in order to be able to handle the final components, to realise several tests at once and to carry out further quality checks. The laminates each consisted of 1, 10 or 20 equally orientated layers of M21/45%/120 material which corresponds to a final component thickness of approx. 0.1, 1 or 2 mm respectively. The single layer test has been chosen to determine if there is a preferred direction of leakage propagation in the satin fabric of the prepreg material. The prepreg material consists of a 4HS satin weave reinforcement structure and the 45% depicts the resin content of the material by weight [13].

The vacuum bagging has been carried out according to Figure 1 and consisted of the materials listed in Table 1.

Material	Manufacturer	Product
Prepreg	Hexcel	M21/45%/120 [13]
Release film	Airtech International Inc.	Wrightlon WL5200 [14]
Breather	Airtech International Inc.	Ultraweave 1332 [15]
Vacuum film	Airtech International Inc.	Ipplon DP1000 [16]
Sealant tape	Airtech International Inc.	GS-213-3 [17]
Adhesive tape	Nitto Inc.	PS-1 [18]

Table 1: Vacuum bagging materials

3.2 Leakage insertion

The leaks have been inserted into the vacuum bag in three different ways and can be divided into leakages in the vacuum film and leakages in the vacuum and release film. While the first case is the most common, the case where the vacuum and the release film is damaged is the most critical and can happen if very sharp objects, e.g. scissors, drop onto the finished bag. Furthermore, the direct connection of the leak to the laminate can simulate the case of a leakage in the mould, e.g. at weld seams or at integrated sensors.

3.2.1 Leakage in vacuum bag and release film

To simulate leaks in vacuum bag and release film single-use hypodermic needles have been inserted. This procedure can be seen in Figure 4 and has been used in different leakage studies like [2, 12]. The size of the needles varies between 0.3 mm and 1.2 mm outer diameter. To ensure a constant leak size, the needles have been left in the vacuum setup throughout the curing process. The needles have been wrapped and secured with extra sealing tape to prevent the needles from slipping out or moving during the autoclave process due to air movement, see Figure 4 right-hand side. All plastic components of the needle had to be removed before curing to prevent melting and clogging of the needles.

It should be noted that the size of the leaks, especially if they are pierced with a metal needle is subject to certain temperature fluctuations due to the thermal expansion of the materials. However, due to the small size of the leaks, these variations are negligible as they are lower than the variations due to the piercing process itself. Former investigations showed that this variation is up to 7% of the volumetric flow rate due to a side flow that may enter the vacuum bag at the outer sides of the inserted needle [2].

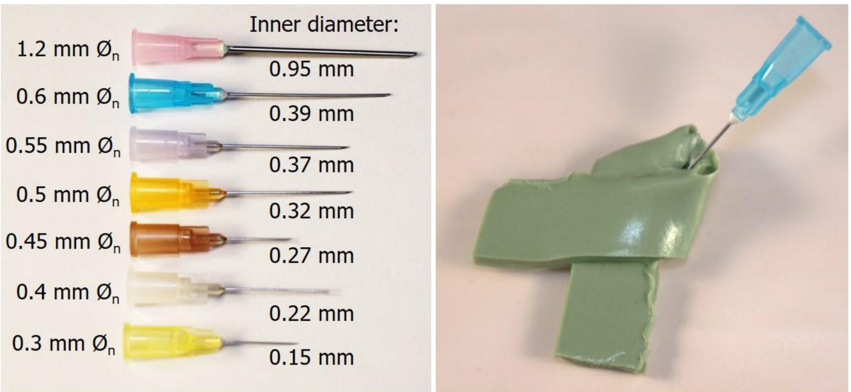

Figure 4: Hypodermic injection needles used for leakage creation and the created leakage in a vacuum bag

3.2.2 Leakage in vacuum film only

To replicate leakages only in the vacuum bag, two different methods have been used. The first approach to the artificial creation of leaks is the insertion by drilling into metallic plates. Figure 5 shows one of the aluminium plates used in which holes of different sizes have been drilled. The theoretical hole size varies between 0.1 mm and 0.35 mm. Examination under the microscope showed that the real hole size is much larger due to manufacturing tolerances.

The real leakage sizes varied between 0.34 mm and 0.73 mm and have been determined individually by microscope measurement and by evaluating the resulting flow rate before the tests. On the right-hand side of Figure 3 it is shown, how the plates have been integrated into the vacuum bag. The vacuum bag has been cut and replaced by the plate in the area where the leakage was intended. It was placed airtight on the vacuum bag and fixed with adhesive tape. Only the leakage size used for the test had been cut out of the adhesive tape and thus represented the artificial leakage.

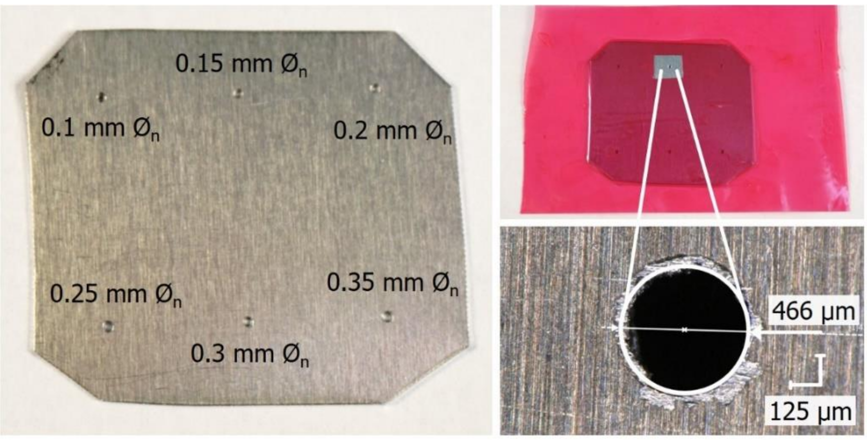

Figure 5: Aluminium plates with different theoretical size holes to simulate leakages

It is possible that the stiffness of the plate may have an influence on the compaction of the breather and laminate in the direct area, therefore holes have been also made in an alternative way and the influence of the metal plate and the limitations of the results have been examined.

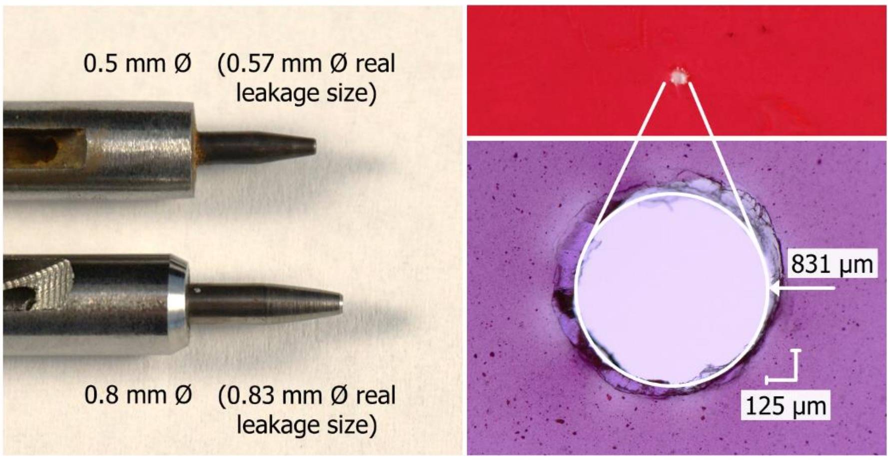

Figure 6: Punching tools and resulting artificial leakage in vacuum bag

The third method of simulating leaks has been to punch the holes in the vacuum bag in predefined areas with a punching device. Figure 6 shows the tools and the resulting hole in the vacuum bag. To prevent the film from being torn out in the area of the hole, a strip of adhesive tape has been applied in the area of the leakage. This strengthened the film locally and also simplified the insertion of the hole. The theoretical hole size has been 0.5 mm and 0.8 mm and the real leakage size 0.57 mm and 0.83 mm respectively.

3.3 Autoclave set up

All together three autoclave trials have been performed to evaluate the influence of leakages on the laminate quality. Within these tests, the autoclave cycle, described in Chapter 3.4 was kept the same, only different configurations of leakages, plate sizes and superstructures have been tested. The three autoclave cycles have been necessary because of the limited tool size. Table 2 provides an overview of the tests.

Autoclave cycle	Laminate size	Plys	Leakage type	Leakage size
1st	$500 \times 500\ mm^2$	20	none	none
	$500 \times 500\ mm^2$	20	needle	Ø $0.15\ mm$
	$500 \times 500\ mm^2$	20	needle	Ø $0.39\ mm$
	$500 \times 500\ mm^2$	20	needle	Ø $0.95\ mm$
	$300 \times 150\ mm^2$	20	no vacuum	
2nd	$500 \times 500\ mm^2$	1	needle	Ø $0.39\ mm$
	$500 \times 500\ mm^2$	20	plate	Ø $0.33\ mm$
	$500 \times 500\ mm^2$	20	needle	Ø $0.39\ mm$
	$250 \times 250\ mm^2$	20	needle	Ø $0.22\ mm$
	$250 \times 250\ mm^2$	20	needle	Ø $0.27\ mm$
	$120 \times 120\ mm^2$	20	plate	Ø $0.47\ mm$
	$120 \times 120\ mm^2$	20	plate	Ø $0.42\ mm$
3rd	$500 \times 500\ mm^2$	20	needle	Ø $0.32\ mm$
	$500 \times 500\ mm^2$	20	needle	Ø $0.37\ mm$
	$500 \times 500\ mm^2$	20	punch	Ø $0.57\ mm$
	$500 \times 500\ mm^2$	20	punch	Ø $0.83\ mm$
	$120 \times 120\ mm^2$	20	needle	Ø $0.39\ mm$
	$120 \times 120\ mm^2$	10	needle	Ø $0.39\ mm$

Table 2: Overview of the configurations of the performed trials

Figure 7 shows the autoclave set-ups and the introduced leakages for each trial. Before the autoclave cycle, both the volumetric flow rate measurement and a pressure increase test have been performed to evaluate the airtightness of the vacuum bags.

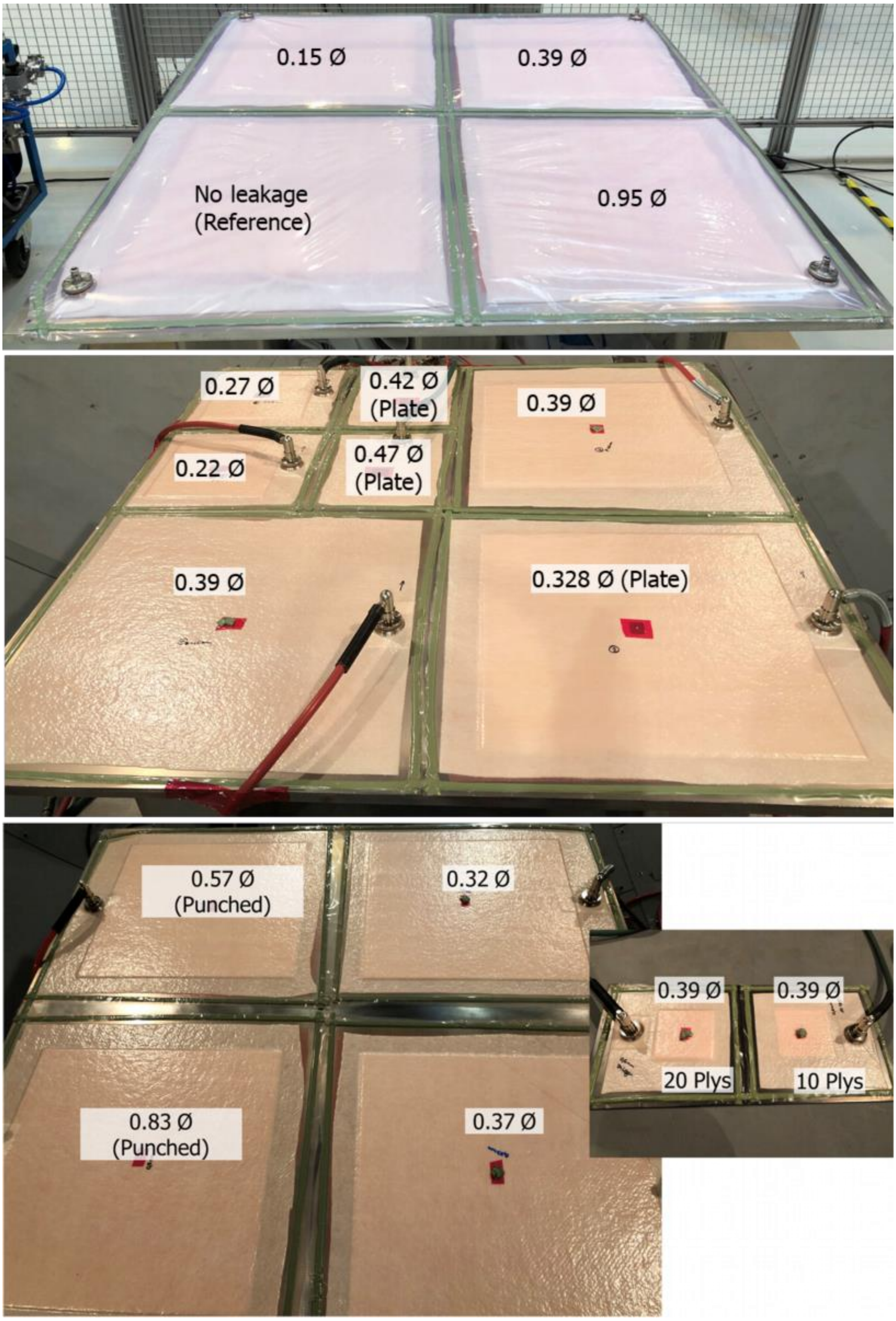

Figure 7: Setup of the three autoclave trials and the introduced leakages

3.4 Curing

The autoclave cycle used for curing has been the cycle specified for Hexcel M21 materials in the data sheet [13]. The autoclave cycle includes a 180-minute hold at the temperature of 150°C and the final cure at 180°C held for 120 minutes. The pressure in the autoclave is 7 bar relative (where 0 bar relative is equivalent to approximately 101325 Pa ≈ 1 bar absolute) over the complete curing cycle. After the pressure is applied the vacuum is reduced to -0.2 bar in the cycle specified by Hexcel. In the tests carried out, the vacuum has been kept at -1 bar for the entire cycle in order to be able to better investigate the effects of the artificially introduced leaks. In addition, flow meters have been integrated into four of the vacuum ports on the autoclave side in order to monitor the flow values during the autoclave cycle.

3.5 Testing methods

After the specimens have been cured in the autoclave, they have been examined and evaluated in various ways. One of the most important tests is the visual inspection of the laminates for porosity. In order to check whether a visual inspection of the glass laminates is sufficient to detect all porosities, additional ultrasonic tests in the form of a c-scan have been carried out on two plates. The tests have been carried out according to the Airbus test specifications AITM 6-4010 [19] and AITM 6-4012 [20]. The evaluation of the results has been carried out according to the airbus standard AITM 6-0011 [21]. These tests have been supplemented by micrographs and thickness measurement. To investigate the influence of leakage on the laminate thickness, thickness measurements have been carried out on some of the test panels. Figure 8 shows the measuring clamp used and the test plate with the measuring points drawn in. The leakage (if any) is located at the origin of the coordinate system used.

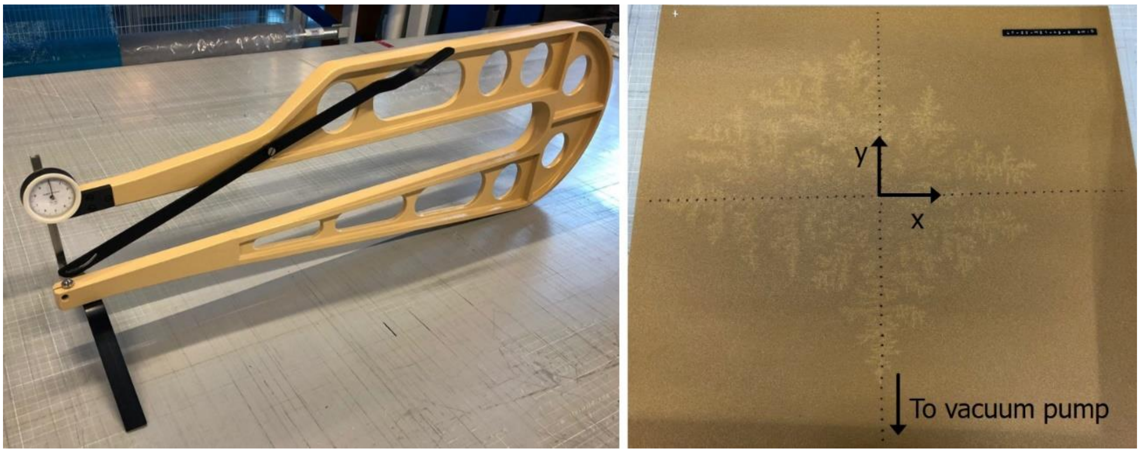

Figure 8: Thickness gauge and test grid on a test plate with the leakage at the origin

3.6 Spring model

In order to understand the cause and background of the test results, the findings are compared with a surrogate model, based on the spring analogy. As described in Chapter 2 springs are often used to better understand the processes. In Figure 9 the four different test configurations are shown with the help of the replacement model. Springs have been used to represent the compression of the breather material and the laminate (grey).

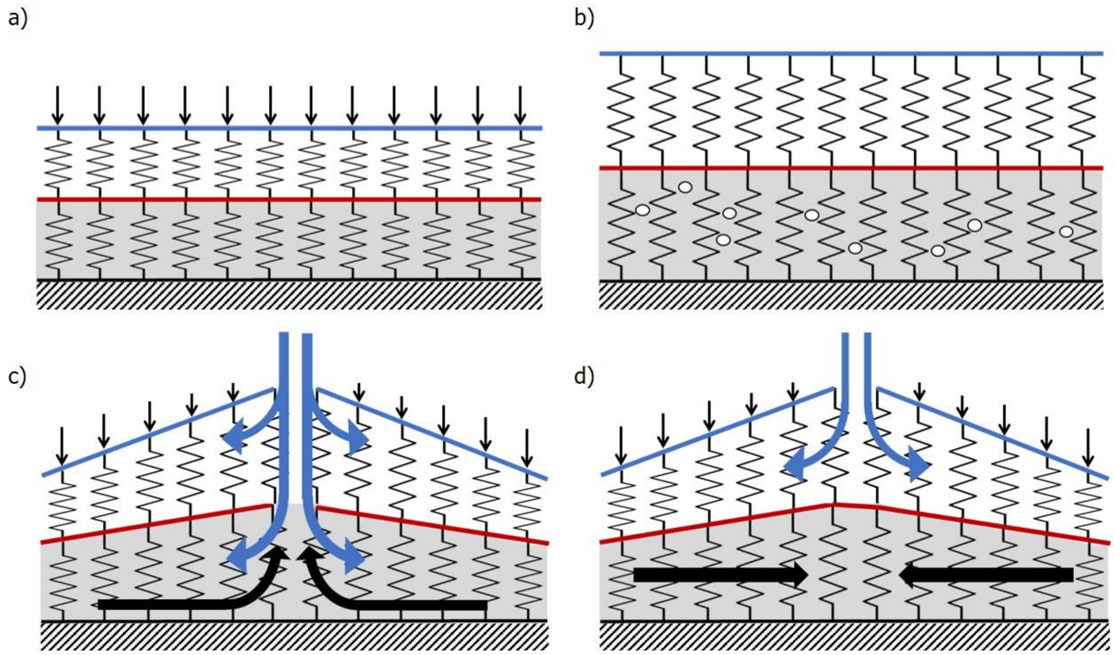

Figure 9: Schematic representation of the pressure inside the vacuum bag during curing. a) Reference without a leakage and full vacuum, b) Reference without vacuum and compaction, c) Vacuum bag with leakage in vacuum film and release film, d) Vacuum bag with leakage in vacuum film

Figure 9a shows the reference case where there is no leakage in the vacuum setup. The black arrows symbolize the ambient pressure in the autoclave acting on the vacuum bag and compressing both the breather and the laminate. Air trapped in the assembly during the manufacturing process has been evacuated and the part can cure without porosity or voids.

If no pressure difference can be built up between the laminate and the environment, e.g. because a pressure equalization takes place due to a large tear in the film, no compression of the laminate takes place. Figure 9b shows that entrapped air could not be removed from in-between the layers and that the laminate cures without any applied forces.

The leakage artificially introduced into the vacuum assembly by a needle has locally damaged not only the vacuum bag but also the release film, like shown in Figure 9c. In this case, the ambient air can enter the vacuum setup. It spreads both in the breather and in the laminate. The blue arrows symbolize the air flow. The effective pressure on the laminate and the breather decreases locally and there is a resetting of the materials in this area. The resin flow, represented by black arrows, goes in the direction of leakage, as the pressure on the laminate is lowest here.

Figure 9d shows the substitute model with a leak only in the vacuum film. This has been realised in the tests by punching the vacuum bag. The ambient air can penetrate the vacuum bag and spreads out in the breather material. The effective pressure on the laminate drops in the vicinity of the leakage, so the breather and laminate relax in this area and increase in thickness. The resin beneath the release film flows into the area with the lowest effective pressure on the vacuum setup, which is in the area of the leakage.

4 RESULTS

In the following, the results of the tests are presented and analysed. In addition to the expected porosities and defects in the final component, further effects are observed in the laminate, which will also be discussed in the following subsections. These include the leakage test, colour changes, porosity, thickness changes and resin flow.

4.1 Leakage test

Before the autoclave cycle, both the volumetric flow rate measurement and a pressure increase test is performed. The corresponding values can be taken from Table 3.

It can be seen that the vacuum bag with no leakage has almost no volumetric flow rate and the pressure increase can be neglected. The limit relevant for aerospace manufacturing of 66mbar in two minutes is exceeded for leakage sizes bigger than 0.15 mm. Only the vacuum bag without a leakage and the vacuum bag with the 0.15 mm leakage meet the criterion with a pressure increase of 10 mbar and 40 mbar respectively. The other vacuum bags have a higher pressure increase and would therefore not be approved for the autoclave process in the series production process. The measured volumetric flow rate of the 0.5 mm and 0.95 mm leakage is the upper limit of the applied flow meter. The true flow rate at these leak size should be higher. In previous trials a volumetric flow rate of ~ 1.8 l_n/min and ~ 5 l_n/min was determined for the needle sizes used.

Leak size	Volumetric flow rate $[l_n/min]$	Vacuum value at start $[bar\ relative]$	Vacuum value after 2 min $[bar\ relative]$
None	0.010	−1.01	−1.00
Ø $0.15\ mm$	0.086	−1.00	−0.96
Ø $0.22\ mm$	0.196	−1.01	−0.87
Ø $0.27\ mm$	0.251	−0.99	−0.87
Ø $0.32\ mm$	0.444	−1.00	−0.73
Ø $0.33\ mm$ (Plate)	0.597	−0.99	−0.77
Ø $0.37\ mm$	0.545	−0.97	−0.77
Ø $0.39\ mm$	0.545	−0.97	−0.75
Ø $0.39\ mm$	0.770	−1.00	−0.73
Ø $0.39\ mm$ (1 Ply)	0.773	−0.99	−0.74
Ø $0.39\ mm$ (10 Plys)	NA	−0.93	−0.67
Ø $0.39\ mm$ (20 Plys)	NA	−0.93	−0.71
Ø $0.42\ mm$ (Plate)	0.836	−0.94	−0.37
Ø $0.47\ mm$ (Plate)	0.755	−0.96	−0.56
Ø $0.57\ mm$ (Punched)	1.080*	−0,94	−0.77
Ø $0.83\ mm$ (Punched)	3.700	−0,94	−0.03
Ø $0.95\ mm$	1.080*	−0.91	−0.03

*Table 3: Volumetric flow rate measurement and pressure increase test for the performed trials. The * marks measurements where the upper measurement limit of the used sensor is exceeded.*

4.2 Colour gradation of laminates and vacuum bags

During the debagging of the experiments of the first trial, discolouration of the vacuum bags can be detected. The left side of Figure 10 shows the vacuum set-ups of the first test directly after the autoclave. It can be seen that the vacuum bag without leakage has the lightest colour. The greater the leakage, the darker the colour of the corresponding vacuum bag. The same can also be seen in the respective breather materials. These have darkened accordingly depending on the size of the leak, shown in Figure 10 on the top right-hand side.

In addition to the breather, the laminate also shows increasing discolouration with increasing leakage size, see Figure 10 on the bottom of the right-hand side. An explanation for this seems to be a side reaction of volatile, short-chain constituents of the EP resin with the residual oxygen, causing the discolouration, like described in Chapter 2. Since this is a chemical reaction, it may also be progressing under the film and in the laminate. This also fits with the increasing hole size: more air ingress leads to more side reaction. Even if the autoclave is filled with nitrogen during the process for safety reasons, a certain amount of residual oxygen will remain inside the pressure vessel. This seems to be sufficient to cause a side reaction with the epoxy resin.

Figure 10: Colour gradation of vacuum bags, breather and laminate right after autoclave cycle

4.3 Porosity and voids

The simulated leakages and tests carried out can be divided into two categories, those in which the leakage extends through the release film into the laminate and those in which the release film remains intact and the leakage only occurs in the vacuum film. Since the results of the two leakage types are very different in terms of porosities, the following evaluations are divided into the two categories leakages in vacuum and release film, and leakages in vacuum film.

4.3.1 Leakages in vacuum and release film

When a leakage is inserted with a hypodermic needle, the release film on the laminate is always damaged as well. This means that the incoming air can penetrate not only the breather but also the laminate. A first indicator for this is a resin accumulation in the breather in the immediate vicinity of the leakage. The resin has the opportunity to flow through the damaged release film into the breather; at the same time, the air has the opportunity to flow through the leak into the laminate.

Figure 11 shows the results of the first series of tests. It can be seen that there is a clear formation of porosity around the leakage at the needle size of 0.39 mm and 0.95 mm. The flaws form in a branch shape starting from the leakage into the laminate. It appears that the spread of the 0.95 mm needle is somewhat greater than that of the 0.39 mm needle. With the 0.15 mm needle, only a slight shadow can be seen in the area of the puncture.

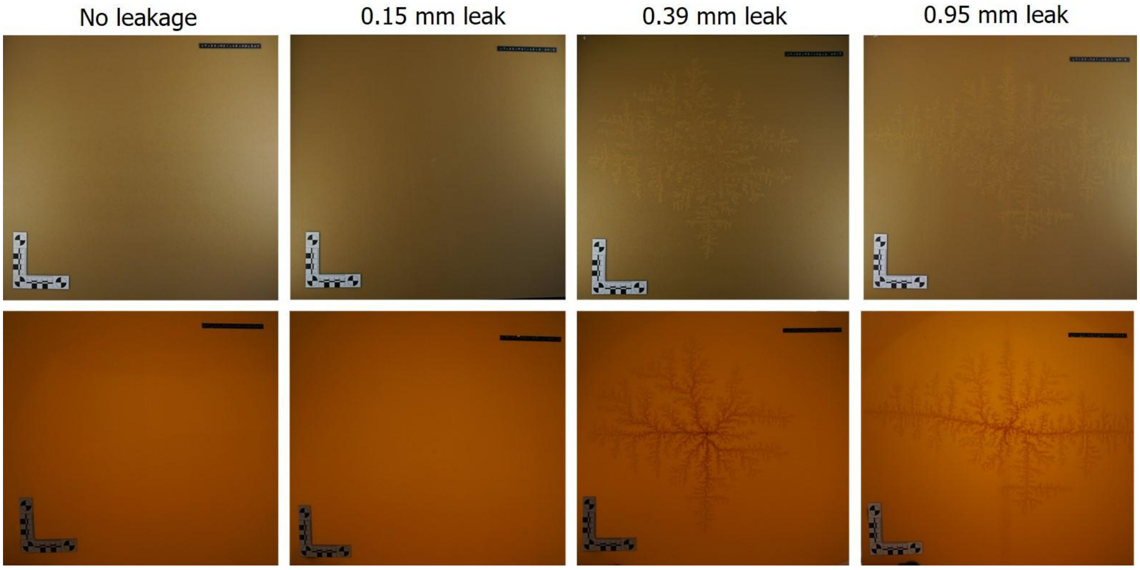

Figure 11: Leakage size and resulting laminate quality of the first trial (upper row with incident light and lower row with back light)

The non-uniform pattern in the x and y directions can be explained by the fact that no attention was paid to the warp and weft direction of the individual layers of the 4HS fabric during the production of the laminates for the first test series. It can be assumed that the air can spread more easily in the weft direction due to the lower undulations of the fibres.

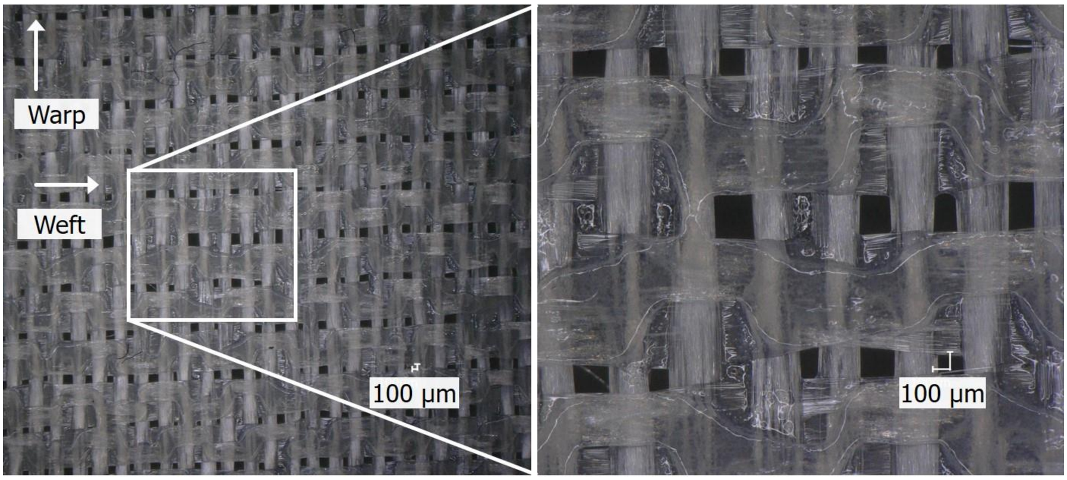

Figure 12: Microscope image of the uncured prepreg material with 30x and 100x magnification

The micrographs in Figure 12 show that in the uncured prepreg material, the resin has predominantly settled on the undulated weft threads. This additionally blocks the air flow. In the following tests, care was taken to align the plies evenly in order to confirm the phenomenon.

In order to find out from which needle or leakage size porosities arise, the range between 0.15 mm and 0.39 mm is further resolved. In the tests with 0.22 mm and 0.27 mm needles, no defects were found in the laminate. Only from a size of 0.32 mm do the typical branch-like flaws appear. In the case of the 0.32 mm needle size, porosities form within a 40 mm radius around the injection point, see Figure 13.

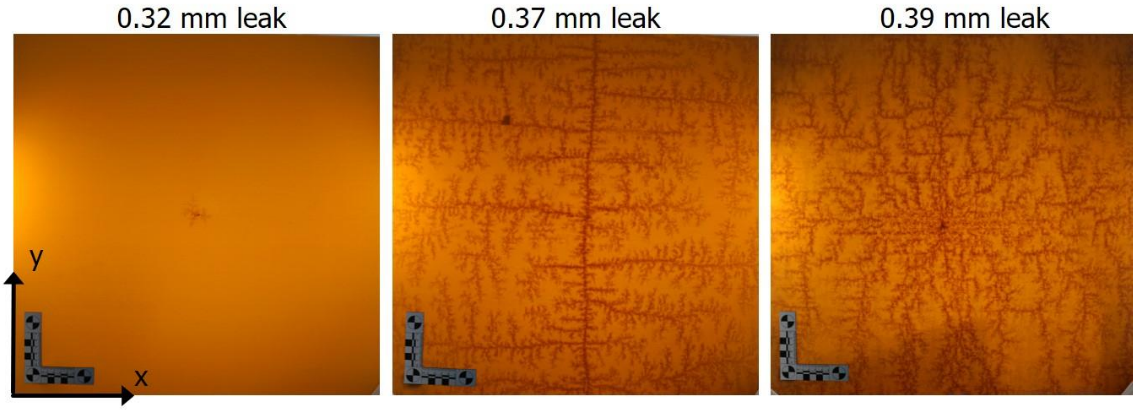

Figure 13: Leakage size and resulting laminate quality for 0.32 mm, 0.37 mm and 0.39 mm needle size

The results for the 0.37 mm and 0.39 mm leaks show significantly more porosity than the results from the first trial. The reason for this is the extent of the damage to the release film in the different tests. While in the first test the release film was only slightly damaged, in the second test the damage was much more severe, as confirmed by microscopic examination of the release film after curing. Figure 14 shows that the film in the first test shows one tear, while the release film in the second test shows several punctures and holes. This can be explained by a possible movement of the hypodermic needle during curing in the autoclave. The strong air flow can set the needle in motion and damage the release film in several areas. More damage to the release film therefore means more air entering the laminate.

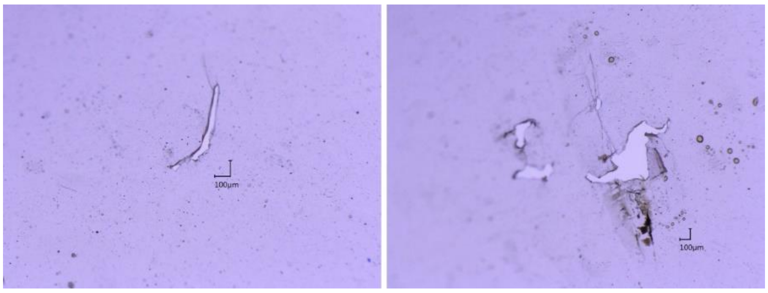

Figure 14: Damage of release film for the 0.39 mm leakage in the first (left side) and second trial (right side)

The plates with the 0.15 mm and 0.95 mm leakage are selected for ultrasonic testing. The 0.15 mm leakage plate shows only a little shadow so the ultrasonic test can validate if a real defect can be detected. The 0.95 mm specimen shows large porosity areas so that a comparison between visual inspection and ultrasonic testing can be made.

Figure 15 shows the ultrasound results. It can be seen that the visual and ultrasonic tests provide consistent results. In the case of the 0.15 mm leakage, a slight shadow was detected in the final laminate in the area of the injection point. However, the evaluation of the ultrasonic test could not detect any porosities here. The porosities of the 0.95 mm plate also show up in the ultrasonic image exactly as they can be seen in the visual inspection. The evaluation according to the Airbus criteria (AITM 6-0011 [21]) shows the framed red area 1 as a defect with an extension of 554 x 349.7 mm² and a resulting area of 193733.8 mm².

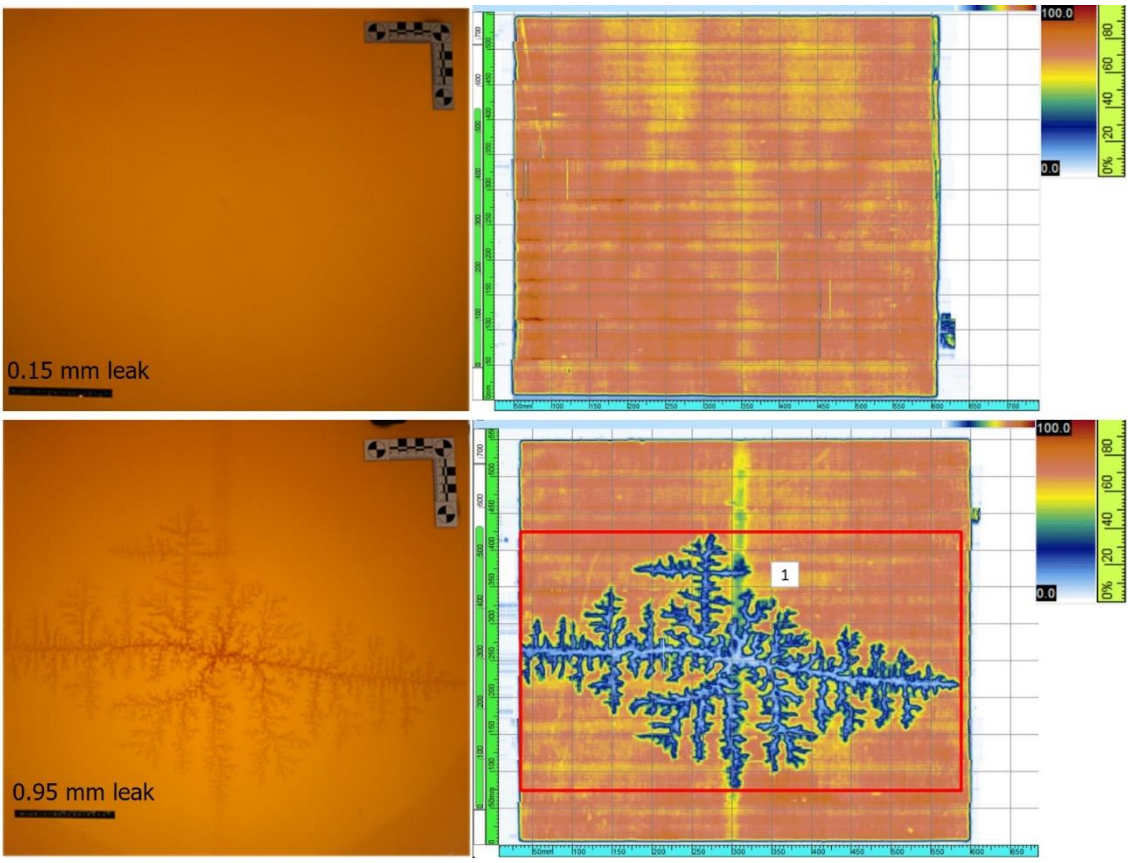

Figure 15: Original laminate and c-scan results for the 0,3 mm and 1,2 mm needle leakage

Additional micrographs are taken from the plates with leakage sizes of 0.22 mm and 0.37 mm and from the reference plate without vacuum in order to check the depth of the leakage. Figure 16 shows a comparison of the micrographs of the three laminates.

It can be seen that the laminate with the 0.22 mm leakage has no defects. The laminate with the 0.32 mm leakage shows some porosities and voids. A determination of the percentage of voids over the cross-section results in approximately 10%. The porosities are found across the entire thickness of the laminate and are mostly located in the voids of the fabric, next to the intersections. As expected, the laminate cured without vacuum shows the highest percentage of porosity with about 30% across the cross section. Here, too, the defects are distributed over the entire thickness of the laminate. In addition, it can be seen that the laminate has a significantly higher thickness than the other two laminates due to the high proportion of porosities and the lack of compression during curing.

Figure 16: Micrographs of the laminates with a 0.22 mm and 0.37 mm leakages, and without vacuum

The tests show a high agreement with the spring model created in Chapter 3.6. In case of the continuous leak through the vacuum and release film, described by Figure 9c, the resin may leak out and spread in the breather material, as was observed in the trials. It can also be seen, that the air is flowing not only into the breather but also into the laminate, forming the porosity branches seen in Figure 13 and 15. In case of the no vacuum test panel the laminate thickness is very high and volatiles released during curing remain in the laminate and form additional voids, like seen in Figure 9b and 16.

4.3.2 Leakages in vacuum film

For the leakage insertion with the metal plate, no defects were found in the laminate but it showed that the plate and the underlying breather in this area were strongly marked in the laminate. This can be explained by the higher stiffness of the plate compared to a flexible vacuum bag. The metal plate, even though it is very thin, imprints the underlying breather more into the laminate compared to the flexible vacuum bag. Since it cannot be ruled out that the locally altered stiffness of the film due to the metal plate has an influence on the effects of the leakage, the punching method is used in the other trials.

Two sizes are tested with the punching tool: 0.57 mm and 0.83 mm. Figure 17 shows the laminate with a 0.83 mm leakage. No defects are visible in both of the laminates. A subsequent ultrasonic examination also revealed no porosities in the component (see Figure 17).

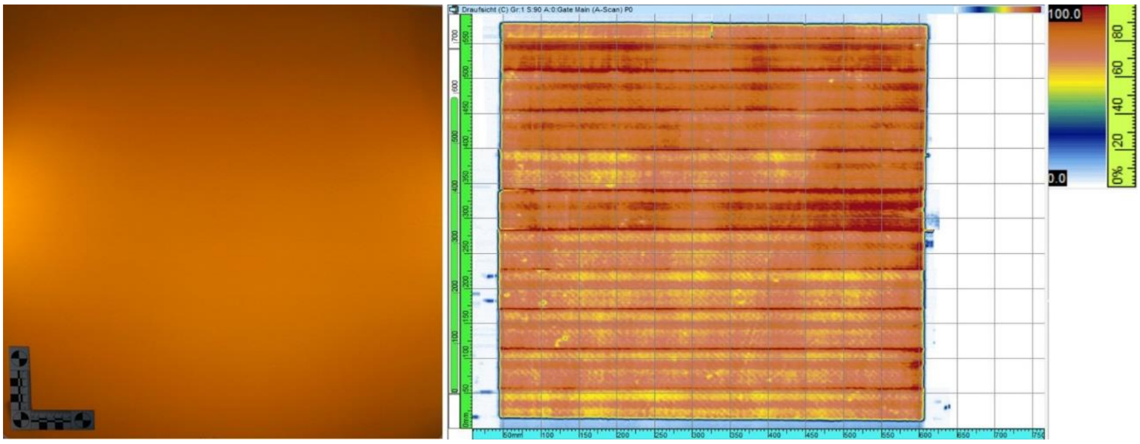

Figure 17: Original laminate and c-scan results for the 0.83 mm punched leakage

Both tests show that a release film hermetically seals the laminate and that the air flowing in through the leakage cannot enter the component. The air flows through the breather and is evacuated by the vacuum pump. These results are also supported by the spring analogy described in Chapter 3.6. Figure 9d shows the case where the leakage is only in the vacuum film. Here, no air may enter the laminate and no porosities were found in the tests, like seen in Figure 17.

Even though no porosities were found in the laminates, a higher flow of resin to the suction unit was detected in the tests in which only the vacuum bag showed a leak. In some cases, the resin flow was so high that accumulations formed in the area of the vacuum connection. In all tests, the vacuum connections were positioned at the same distance from the leakage. The higher resin flow towards the pump was not observed in the tests with the hypodermic needles. Here, only the resin flow into the breather in the area of the leakage was noticeable.

4.4 Laminate thickness

As can be seen in the micrographs in Figure 16, there are large differences in thickness between a laminate cured under pressure and vacuum and one cured without pressure. Figure 18 and 19 show the results of the thickness measurement in x and y direction. It can be seen that the thickness of the reference plate without leakage has an almost constant thickness of 2.2 mm. The reference plate, which was cured without vacuum, shows a significantly higher thickness of 3.6 mm and is thus much thicker than all other test plates. The test plates with the highest porosities, such as the plates with the 0.6 mm and 1.2 mm needles, show a higher thickness of 2.3-2.4 mm in the area of the leak and the propagation zone of the porosities.

The test component with the metal plate shows only a small change in thickness directly in the area of the leakage. The variation in thickness of the plates with the punched leaks is particularly interesting. Here it can be seen that an increased thickness occurs in the direct area of the leakage, even without porosities in the laminate. In the y-direction, the laminate thickness visibly decreases to 2.1 mm towards the vacuum pump and increases to 2.25-2.3 mm in the area of the leakage, before it returns to a normal level of 2.2 mm opposite the vacuum pump.

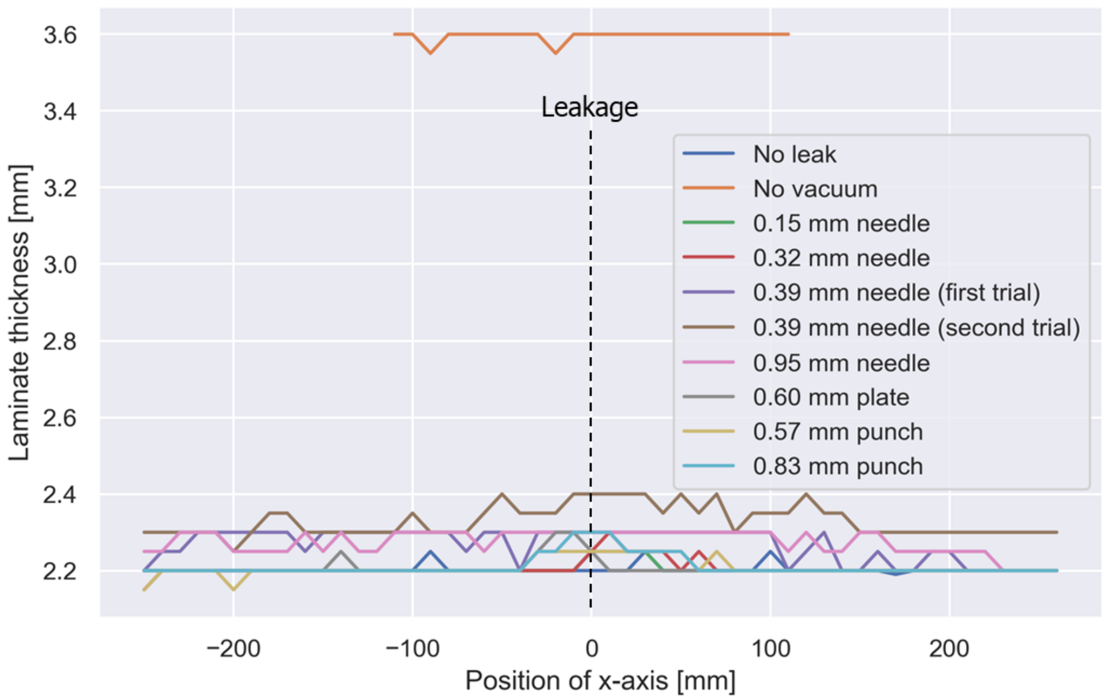

Figure 18: Laminate thickness of test plates in x-direction

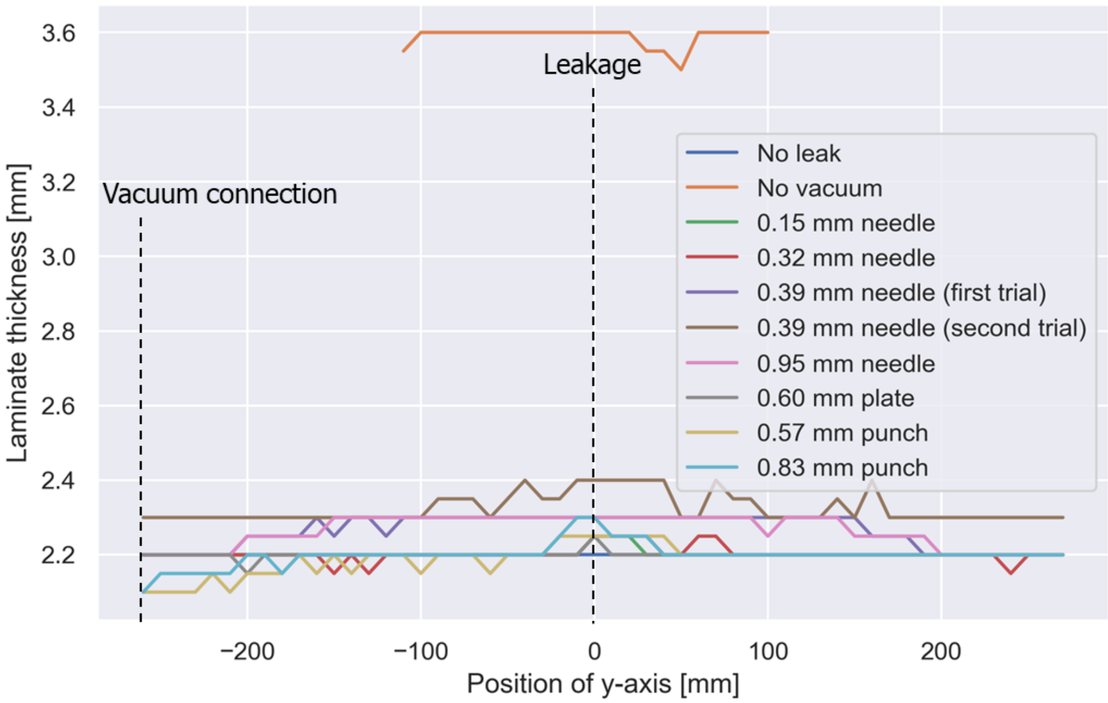

Figure 19: Laminate thickness of test plates in y-direction

5 DISCUSSION

The research discussed above by Fernlund et al. [5] and Boey et al. [6] illustrate the reasons for void formation in laminates. They mention that leakages are a source for porosities in laminates but do not explain to which degree. The investigations performed in this paper complement this research and focus on the explanations why and to which extend leakage cause voids and porosities in the final composite part.

The results for the continuous leakages in vacuum and release film show that the air enters not only the breather but also the laminate. Since air chooses the path of least resistance, the first consideration would be that it flows primarily through the breather to the vacuum pump, since this should offer particularly good flow properties and low air resistance. The test results show, however, that the air also spreads in the laminate during the curing process if there is a possibility to do so. This indicates that during curing, heat and pressure cause compression of the breather, which adversely affects permeability, like shown in Figure 2. The air then escapes into the interstices of the laminate and spreads out in a circular pattern starting from the leakage. At some point in the process, the permeability of the laminate appears to be greater than or at least equal to that of the breather, allowing the air to spread through the laminate and create porosities.

In the tests carried out with leakages only in the vacuum film, the resin flows toward the leakage, as this is the area with the lowest effective pressure. This corresponds with the findings of the thickness measurement. The decrease in laminate thickness towards the vacuum connection can be explained by the strong air flow in the breather. This causes not only the air to be evacuated but also the resin to flow towards and into the vacuum connection, thus reducing the laminate thickness in this area. No porosities were found in the laminate in this leakage case. This may be related to good evacuation of the trapped air before the autoclave cycle. If this air is not fully evacuated, potential air pockets would accumulate together with the resin flow towards the leakage and the area with the lowest effective pressure. Evacuation of trapped air becomes more difficult with increasing component size and complexity, and the likelihood of porosity accumulating in areas of lower pressure increases.

Considering the results mentioned above, the research question is answered. The possibility to demonstrate the physical processes that occur inside a leaky vacuum bag by a surrogate model based on spring analogy, also used by Dave et al. [4] is shown. In further investigations, it seems to be reasonable to examine lager parts and leakages to validate if the findings especially for the vacuum bag leakage hold true and the specifications for airtightness could be adjusted. The aim of the study was not to investigate the resulting mechanical properties of the laminates, which might also be of high interest when evaluating the influence of leakage introduced quality issues. Furthermore, in subsequent studies, it is of great interest to determine the statistical signifi-cance of the obtained results. Therefore, multiple runs of each individual scenario should be tested in order to determine statistical parameters.

6 CONCLUSION

The tests carried out in this work have shown the effects that undetected leaks can have on component quality. A distinction must be made between two types of leakages: those in which there is a direct connection between the atmosphere and the laminate, and those which are located only in the vacuum film with a laminate that is still sealed off by a release film.

While the first case is much more critical because the air flows directly into the laminate and creates porosities, it is very unlikely for this to happen in production. However, it can be transferred to leakages in tools, e.g. at welding seams, where a solution could be to use additional release film between tool and component.

If the leakage is only in the vacuum bag, no defects could be detected in the laminate even with leakage sizes of up to 0.83 mm. This leakage type proved to be hardly critical and only led to slight local changes in thickness, even if the pressure increase was well above the aircraft manufacturers regulations.

The results indicate, that this type of defect only leads to defects in the laminate in combination with increasing component size and complexity as well as insufficient evacuation before the process.

The results of this paper offer major advantages for composite manufacturing industry, as they indicate that the current specifications could allow a greater margin, especially for leakages that do not have a direct connection to the laminate. Furthermore, it is shown, that the effects of leakages can be physically explained and characterized with the spring analogy.

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DOI 10.3139/O999.01042021
Zeitschrift Kunststofftechnik / Journal of Plastics Technology 17 (2021) 4; page 204–229

ISSN 1864 – 2217

Keywords:
Vacuum bagging, composite, autoclave, leakage

Stichworte:
Vakuumaufbau, Verbundwerkstoffe, Autoklav, Leckage

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Verlag / Publisher

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