CHARACTERIZATION OF THE MULTI-AXIAL MATERIAL BEHAVIOR OF POLYMER FOAMS DURING THE RTM PROCESS

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Abstract
Integration of high performance sandwich structures into carbon fiber reinforced plastic (CFRP) body parts has become target of current developments in the automotive industry. The test stand introduced in this study allows for investigation and analysis of the deformation behavior of various foam core materials under process related conditions. Tests were carried out at room temperature and elevated temperature using test fluids with a viscosity of 20 mPa·s, which is in accordance to resin systems used in the resin transfer molding process (RTM). During the test, cavity pressure, fluid temperature and specimen deformation were recorded. Deformation measurement was done using a 2D digital image correlation system. Tests at 23°C and 80°C on polymer foam specimens showed the expected temperature dependent material behavior. Moreover the test results are in good correlation to the mechanical behavior of the polymer foams observed in the RTM process.

1. Introduction

Sustainable lightweight design is a key technology to meet upcoming CO_2 emission standards in the automotive industry. Besides metal, the use of carbon fiber reinforced plastics (CFRP) in car body increases due to its outstanding specific mechanical properties. Against this background, the high-pressure compression resin transfer molding process (HP-C-RTM) has a high potential for large-scale production of such components. To further improve the lightweight design quality, integration of high performance sandwich structures into highly integral body parts has become target of current developments. The challenge is to introduce an economic and robust production process for CFRP sandwich structures using light and cost-effective core materials. For this purpose, the development of a virtual process chain considering all relevant influences is indispensable. In case of CFRP sandwich structures produced in the HP-C-RTM process, this involves core deformation and failure during resin injection as well as during the compression step. These information are needed for preselection of potential core materials as well as for process optimization and process simulation.
Several authors [1, 2, 3] describe the defects that may occur during manufacturing of RTM sandwich structures using polymer foams such as incomplete fill, core shifting, core deformation and core collapse. Their studies highlight the need for process related characterization as high modulus under elevated temperatures does not accompany with high robustness in the RTM process. Deleglise et al. [4] performed experimental and simulative tests on polyurethane foams and other foam materials regarding the influence of foam deformation on the inlet pressure during the RTM process. With a

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similar target, Binetruy [5] developed an analytical model to couple the fluid flow and material deformation during isothermal mold filling. They concluded that the deformation of the foam depends on its characteristics as well as on the initial foam compression, the flow rate and the fluid viscosity.
The multi-axial behavior of polymer foams has been studied by many authors in order to develop constitutive equations [6-8]. Therefore, specimens were sealed with protective layers in order to prevent intrusion of fluid. Also, the viscosity and the temperature of the fluid were not considered in these studies.

Against this background, a method is presented that allows the investigation of the multi-axial deformation behavior of foam core materials in dependence on time, temperature, pressure and viscosity of fluid, respectively. The deformation of the test specimen is analyzed using a 2D digital image correlation system to prevent interference of results. Furthermore, with this technique material anisotropy can be considered.

2. Experimental

2.1 Materials

To achieve a maximum lightweight design quality whilst providing adequate mechanical performance, rigid polymer foams with a maximum density of 300 g/l are examined in this study. Additonaly, to meet the requirements of large-scale productions, the observed materials offer final-shape manufacturing of complex geometries without trimming or joining.

Polymethacrylimid particle foam (PMI-PF) is used as a reference material. It is in use for small-scale RTM production in the automotive industry. PMI-PF is manufactured by filling PMI granulate and bonding agent into a heated mold. It is characterized by its high compression stiffness even at elevated temperatures and a homogeneous global density. The PMI-PF specimens examined in this study have a density of 200 g/l.

Polyurethane rigid foam (PURF) is considered in this study because of the excellent cost-per-kg ratio of the unprocessed raw materials. The used polyurethane is a commercial system with focus on high temperature resistance and a high compressive modulus. For comparison with the reference material, PURF specimens have a global density of 200 g/l. Additonally, specimens with a global density of 300 g/l are examined to show the influence of density on the process behavior of the material.

2.2 Specimen Preparation and Setup for Hydrostatic Test

Specimen Preparation
PMI-PF specimens were cut out from plates with a thickness of 50 mm. This precedure is appropriate for PMI-PF as it does not have a closed surface after molding which could affect the materials process behavior.
The PURF specimens were manufactured in a cubic mold to create an entirely closed surface as it is representative for PURF.

All test specimens have the dimensions 50x50x50 mm³. Conditioning was done as recommended by the foam supplier to avoid influence of humidity on the test results. After conditioning, the weight and the size of each test specimen were determined to calculate the global density. In a next step, a spray pattern was applied on one surface of each specimen that is neither the top nor the bottom surface regarding foaming direction. The spray pattern allows for the measurement of the deformation area by area. Besides, deformation in foaming direction (y-direction) and in plane direction (x-direction) can be analyzed separately. No further surface treatment such as sealing or sandblasting was performed on the specimens.

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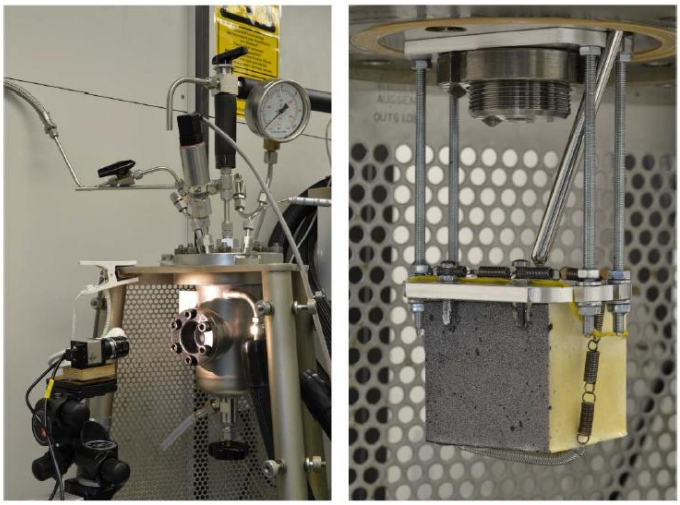
Hydrostatic Test Setup
The test stand consists of a heatable autoclave (Büchi Glas Uster BEP 280), a dosing system (Brabender FD DKMP-3), a gas controller (Büchi pressflow gas controller bpc 6002) and a nitrogen gas cylinder with a pressure of 200 bar. The autoclave (Fig. 1a) has an inner diameter of 82 mm and a filling volume of 1000 ml. For recording of the deformation, the autoclave offers a window made of borosilicate glass 3.3 with a diameter of 40 mm and a thickness of 15 mm.
The test specimens were fastened inside the autoclave with an adjustable apparatus and soft springs to ensure proper positioning and to prevent movement of the sprayed surface relative to the camera. (Fig 1b).
Images for deformation analysis were captured using a digital camera (IDS uEYE UI2240SE) with a lens (COSMICAR/PENTAX TV LENS) 16mm, aperture 1:1,4.



a) b)

Figure 1. test stand (a) and fastened test specimen (b)

The used test fluid was a transparent silicone oil (PDMS, Ebelsil Silikone. The oil used for tests at 23°C had a viscosity of 20 mPa·s. To guarantee plausible comparison, the silicone oil for high temperature tests had a viscosity of 20 mPa·s at the test temperature of 80°C.

Before each test, a specimen was placed inside the autoclave and the fluid was injected using the dosing system. With the help of a riser pipe, trapt air was removed from the autoclave. In a next step, pressure was increased using the pressflow gas controller until a maximum pressure of 45 bar was reached. During the tests, fluid temperature, pressure inside the autoclave and deformation of the specimen were recorded. The specimens' starting temperature was 23°C. Also for tests at 80°C the specimens were not preheated in order to emulate the thermal loads occurring during the RTM process.
Analysis of the captured images was done using the software Vic2D. For a compromise between precision and computing speed, analysis was done in an averaging field of 15 mm x 15 mm with 100 facets. For the PMI-PF specimen the analysis points were reduced to 250 while for PURF a reduction was set to 500 points.

Each test series consisted of 5 tests and the average deformation was calculated to guarantee statistical results. For interpretation of the results, relative standard deviation was calculated as well as the first derivative. Relative standard deviation is used to determine reliability of the results as well as an indicator for failure of the specimen. Calculations of the first derivative are the basis to differentiate between linear and nonlinear deformation behavior.

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2.3 Specimen Preparation and Setup for RTM Test

Specimen Preparation
The foam specimens used in RTM tests had an identical global density as the foam specimens used for hydrostatic tests. The foam geometry is inspired by a tophat profile with a thickness of 20 mm, an average width of 170 mm and a length of 1120 mm. Conditioning was done similar to the hydrostatic test specimens.

RTM Test Setup
RTM tests were performed using a steel RTM mold adapted to a hydraulic press to prevent opening of the mold cavity during the process. Resin was injected using a high-pressure RTM machine. To realize a hydrostatic pressure without any influence of resin flow during injection, a flow aid textile with a thickness of 2,7 mm was used for positioning of the specimen instead of a fibre textile. The mold was heated to an average temperature of 90°C. The used resin system was preheated to process temperature showing a viscosity of 20 mPa·s.
Pressure inside the cavity was recorded at two diffent positions to confirm a hydrostatic pressure state.

Before tests, the flow aid textile was placed inside the mold, followed by the foam specimen. Another flow aid textile was placed on top of the foam specimen to prevent movement of the specimen during injection. After closing, the mold was evacuated to reduce influence of trapt air on the pressure measurements. In a next step, resin was injected with a constant mass flow of 80 g/s until a total mass of 2000 g resin was injected. Pressure was recorded from closure to opening of the mold. All tests were performed 3 times to ensure statistical reliability of the results.

3. Results and Discussion

3.1 Hydrostatic Test Results at 23°C

In this study, the analysis focuses on the deformation in y-direction as the deformation in x-direction shows similar characertistics. However, a difference in maxmimum value of deformation is noticed. While PMI-PF 200 specimens tend to higher stiffnesses in x-direction, PURF specimens show a contrary behavior. This anisotropic material behavior is presented in Fig. 2.

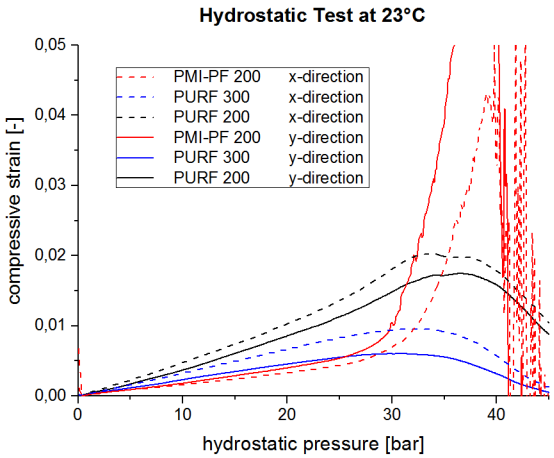

Figure 2. Average deformation in x- and y-direction at 23°C

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Fig. 3 shows the deformation in y-direction of PMI-PF 200 as well as the relative standard deviation. For small deformations, the compression behavior of PMI-PF 200 is linear. At ~25 bar cavity pressure and a deformation of 0.5 %, the compression increases nonlinearly with a significant increase of standard deviation. Further compression leads to the loss of a clear optical signal, which is indicated by the wavering signal. This is due to an abrupt large deformation of the specimen. Hence, reliability of the measurement at higher pressure values can not be assured regarding PMI-PF 200 at 23°C. However, the increase of standard deviation followed by the loss of a clear optical signal is an indicator for structural failure of the material.

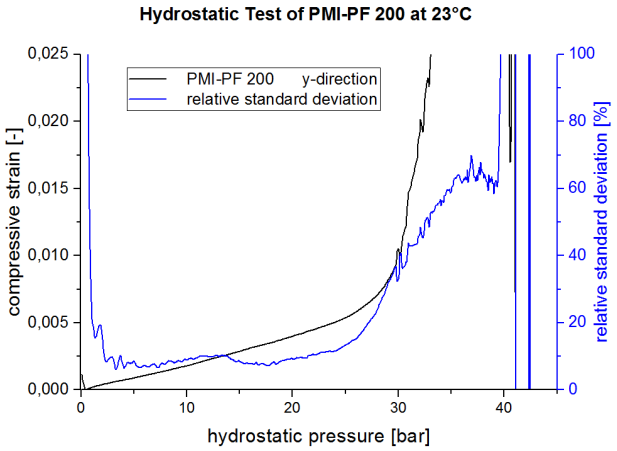

Figure 3. Deformation and standard deviation of PM-PF 200 at 23°C

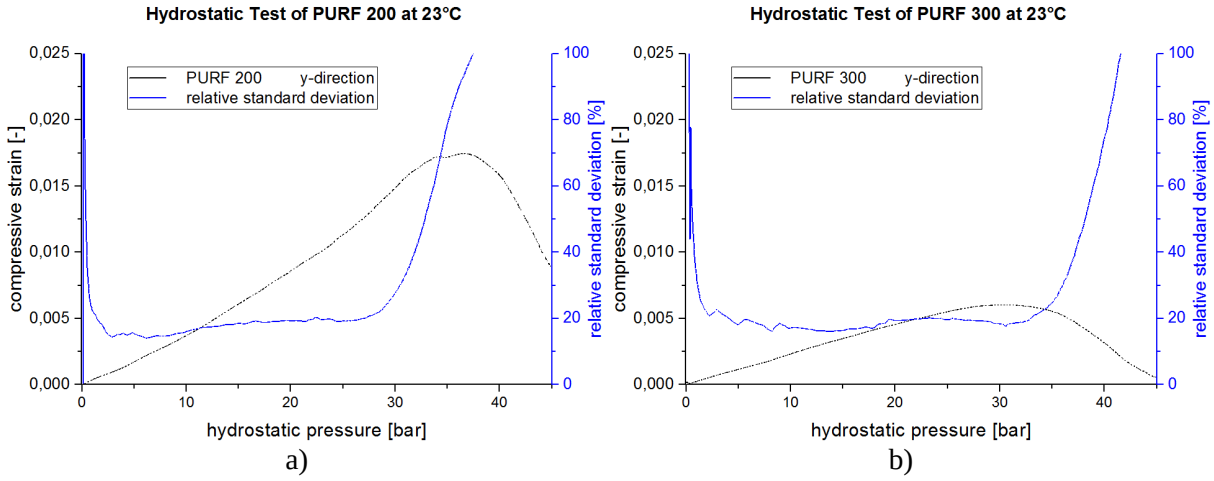

Figure 4. Deformation and standard deviation at 23°C of PURF 200 (a) and PURF 300 (b)

Fig. 4a shows the deformation behavior of PURF 200 at 23°C. Calculation of the first derivative indicate no explicit linear deformation. The relative standard deviation is slightly increasing with increasing pressure until ~28 bar but can be assumed as constant compared to the sharp increase starting at ~28 bar. At this point, deformation becomes strongly nonlinear – appearing as a turning point of the derivative curve. Similar to PMI-PF 200, the increase of relative standard deviation indicates structural failure against the background of the use as an engineering material.
For PURF 300, calculation of the first derivative shows a linear deformation behavior until a cavity pressure of ~20 bar and a deformation of 0,5 % is reached. Further pressure increase entails nonlinear

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deformation with a negative slope. Up to a pressure of ~33 bar the relative standard deviation can be described as constant. At higher pressures, further compression leads to a significant increase of relative standard deviation and a reduction of deformation. As for the other materials, this point is indicated as onset of structural failure.

3.2 Hydrostatic Test Results at 80°C

Fig. 5 shows a comparison of the average deformation in y-direction for tests at 23°C (a) and 80°C (b). For all tested materials, deformation maximum value increases at high temperature. This phenomenon can be traced back to the temperature dependency of polymers. The increase of temperature leads to a reduction of mechanical performance.

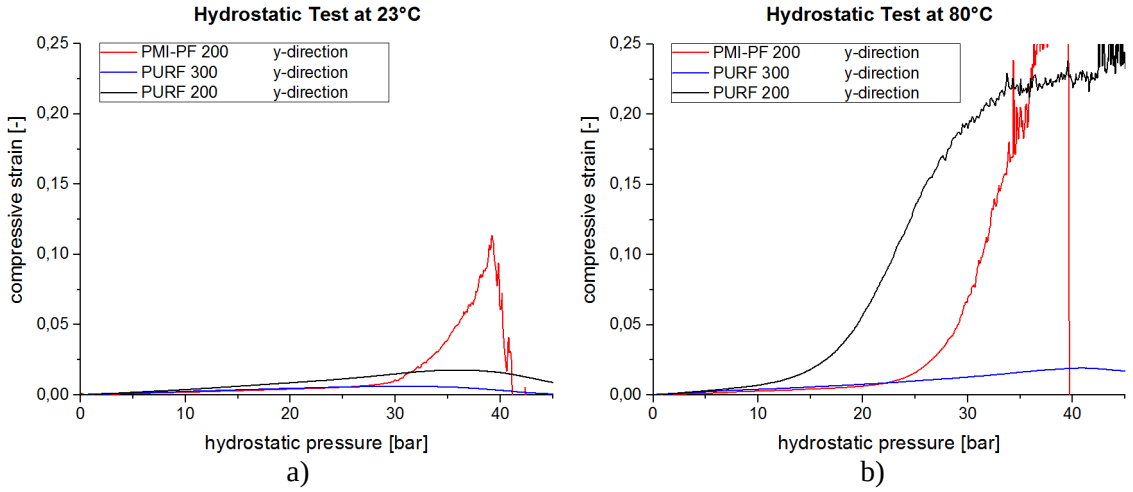

Figure 5. Global deformation of specimens at room temperature (a) and high temperature (b)

Resin intrusion after both test series (23°C and 80°C) was examined by determing the weight of the specimen. PMI-PF 200 specimen showed a slight increase of weight. For both, tests at 23°C and 80°C, the increase measured is less than 5 %. The reason is remained silicone oil in gaps between foam particels on the specimens' surface. No resin was found inside the specimen.
Weight measurements of PURF 200 reveal a significant increase of weight after the tests. At 23°C, the weight has raised by 400 %, while specimen tested at 80°C showed an increased weight by 320 %.
A weight increase of 300 % is noticed for PURF 300 after tests at 23°C. The weight increase after tests at 80°C is 280 %.
As the starting point of resin intrusion into PURF specimens is not clearly identified in these experiments, deformation behavior might partly be superimposed by resin intrusion. Against this background, calculation of material constants under hydrostatic pressure is not expedient for PURF under these conditions.

For further investigations it is recommended to perform additional tests using a membrane to prevent resin intrusion into PURF in order to distinguish between foam deformation and resin intrusion. Chosing a membrane with a stiffness that is several magnitudes lower than the stiffness of the specimen reduces its influence on the results. Moreover, the comparison between the deformation curve of specimen with membrane and specimen without membrane allows determination of resin intrusion onset.

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3.2 RTM Test Results

For validation of the hydrostatic test results, RTM tests were performed. Fig. 6 shows the increase of pressure inside the cavitiy during a simplified HP-C-RTM compression step. For PMI-PF 200 specimens, a steep linear pressure increase is recorded upto a pressure of ~35 bar. At this point, pressure proceeds nonlinear to ~42 bar, where a plateau is reached. Further resin injection is followed by only slight increase of pressure. Similar to hydrostatic tests, this behavior indicates a structural failure. The reason for the higher value of the plateau as compared to the hydrostatic tests can be found in the higher deformation rate in RTM tests. Additionally, microscopic analysis of test specimens show no resin intrusion during RTM tests, which is in accordance to the findings of hydrostatic tests.
Both, PURF 200 and PURF 300, show a linear increase of cavity pressure with a lower ascent as compared to PMI-PF 200. This is due to the lower stiffness of PURF, but can also indicate an overlayed resin intrusion. Unlike PMI-PF 200, the process behavior of PURF specimen does not lead to a plateau in pressure. Microscopy of specimen that were loaded with varying pressure show resin intrusion even at low pressure values. Considering all results it is concluded that in mold pressure development is influenced by deformation as well as by resin intrusion resistance of the foam specimen.

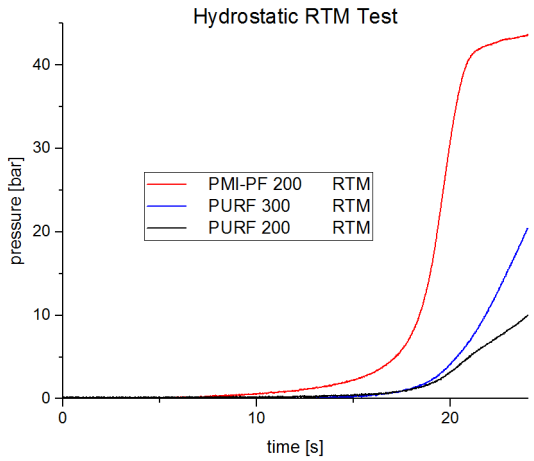

Figure 6. Pressure curve of simplified HP-C-RTM compression step

4. Summary and Conclusions

The presented method allows for the deformation measurement of CFRP sandwich foam core materials while hydrostatic pressure is applied. The use of a heated fluid with a defined viscosity enables the replication of load conditions applied during HP-C-RTM process. The deformation of PMI-PF and PURF with varying densities were examined in this study. By calculating the first derivative of the static deformation curve, distinction between linear and nonlinear material behavior was enabled. By separate analysis of deformation in x- and y-direction, it could be proven that material anisotropy can be taken into account. The influence of temperature on the deformation behavior was investigated by additional tests at 80°C. Here, all specimen showed a visible increase of compressive strain compared to 23°C while deformation characteristics remained the same. Failure of PMI-PF 200 is indicated by an abrupt large compression, whereas this material showed only marginal fluid intrusion during the tests. The deformation behavior of PURF is superimposed by fluid intrusion, which was confirmed by weight measuremts before and after testing. The material behavior examined during hydrostatic test could be validated by RTM tests. Here, PMI-PF 200 showed an abrupt deformation increase as it was noticed in the hydrostatic tests. Analysis of PURF specimens from RTM tests confirm the phenomenon of combined deformation and resin intrusion.

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However, the onset of fluid intrusion into PURF can not clearly be indicated using the presented test method. Further tests with a modified specimen preparation for determining failure onset regarding resin intrusion need to be performed.

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