EXPERIMENTAL INVESTIGATION OF THE RADIUS FORMING BEHAVIOR OF FIBER REINFORCED THERMOPLASTICS

A. Schug[1], R. Hinterhölzl[2] and K. Drechsler[1]

[1]Fraunhofer Institute for Chemical Technology ICT, Augsburg Branch Functional Lightweight Design FIL, Am Technologiezentrum 2, 86159 Augsburg, Germany
Email: alexander.schug@ict.fraunhofer.de, Web Page: http://www.ict.fraunhofer.de/FIL
[2]Institute for Carbon Composites, Technische Universität München, Boltzmannstr. 15, 85748 Garching, Germany

Keywords: thermoforming, thermoplastic, radius, ATL, PEEK

Abstract
The following work focuses on the experimental analysis of the forming behavior of fiber reinforced thermoplastic layups with a special focus on the radii. Possible factors influencing the result and quality of the forming shall be investigated. Considered parameters were the thickness of the layups, the fiber orientation, the size of the radius and the preload of the layup. The layups were produced with a Fiberforge RELAY2000® ATL machine and consolidated in a heated hydraulic press as a subsequent step. The consolidated layups were then thermoformed using two matched dies. During the forming, the material was cooled down until it reached a solid state and could be removed from the mold. These test specimens were then analyzed regarding their draping pattern, occurring defects and forming quality using microsections and the optical analysis system ATOS by GOM. The investigations showed that especially the thickness of the layup and the size of the radius had an influence on the part quality. But also the fiber orientation affected the formation of imperfections. The preload of the layup was of less importance for the forming behavior.

1. Introduction

In recent years, the importance of carbon fiber reinforced thermoplastics (CFRTP) has increased [1], especially for the automotive sector. Reasons are that they possess numerous advantages such as short cycle times, weldability [2,3] and recyclability. A promising production technology is the automated tape laying (ATL) of unidirectional (UD) tapes. Using this technology, the fiber orientation of the plies can be varied easily and can therefore be adapted to the respective load case, also short cycle times can be realized. To produce a 3D part out of the flat layups, a subsequent thermoforming step is necessary. During this forming, defects can arise, which are caused by the adaption of the material to the mold geometry and resulting forming mechanisms. Especially the corners and radius sections are prone to defects resulting from the high local forming degree [4]. Typical defects occurring in these areas are wrinkles, dry spots, delaminations or thinning of the material. Studies have been conducted regarding the forming forces [5] and temperatures [6,7].

Excerpt from ISBN 978-3-00-053387-7

2. Experimentation

2.1. Material

The material used for this investigation was a carbon fiber reinforced PEEK UD-tape of the Royal Ten Cate Corporate, Netherlands. The tape had a fiber volume fraction of 59% and a nominal thickness of 0.14 mm. Using the automated tape laying (ATL) machine Fiberforge REALY2000® the tapes were stacked and afterwards consolidated between two flat steel plates, which were heated by a hydraulic heating press. The test specimens consisted of the following layups: $[0]_{14}$, $[0/90]_{7}$, $[0]_{29}$ and a symmetrical 0/90-layup with 29 plies, which resulted in thicknesses of 2 mm and 4 mm, respectively. The consolidation temperature was 360 °C and the pressure amounted to 20 bar. The size of the consolidated plates was 750 mm x 500 mm. These were then cut into 6 samples with sizes of 310 mm x 130 mm each.

2.2. Experimental setup

The experimental setup consisted of two matched aluminum molds and a removable support frame. The geometry of the molds was a 90°-angle with changeable radius inserts. The molds were installed in a 137t hydraulic heating press. The press was used to heat the tools up to the desired temperature, apply the forming pressure and track the data during the forming. In addition to this equipment, an infrared-oven was used to heat the specimens prior to the forming step. This oven consisted of two heating fields that heat the specimens from above and below in order to achieve an even temperature distribution. The support frame was used to transfer the specimen between the infrared-oven and the heating press.
Within the support frame the specimens were tensioned on two sides by a variable number of constant-force springs. The number of springs could be varied between one and five on each side to adjust the pretension of the specimen. Each spring produced a force of 15.4 N. In that way the pretension of the specimen could be varied between 15.4 N and 77 N. On the one side the springs were fixed to the support frame and on the other side to a clamp, which was holding the specimen. The clamps were wrapped with aluminum foil to prevent the material from heating in these areas.
The lower mold was mounted to a base plate that enabled the installation in the heating press. On this base plate there were also four pillars holding the support frame in the correct position during the forming (Figure 1). The upper mold was installed in the heating press using a base plate, too. The tools were directly heated by the heating platens of the press. During the experiments the temperature of the molds was controlled by thermocouples that were connected with the controller of the press.

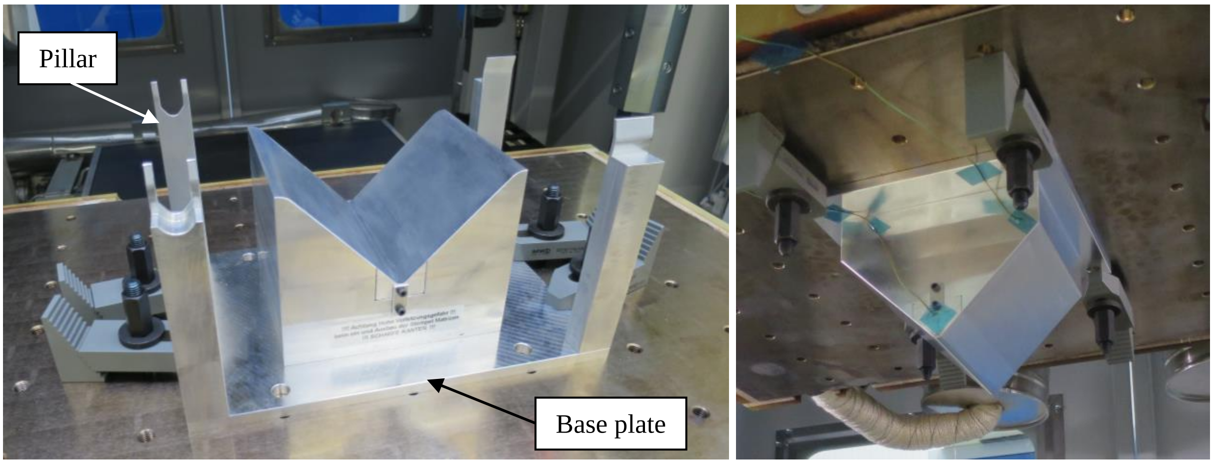


Figure 1. Lower mold (left), upper mold (right)

Excerpt from ISBN 978-3-00-053387-7

3. Methodology

3.1. Tests

For conducting the forming experiments, the specimens were tensioned in the support frame using the two clamps. The frame was then placed in the infrared oven between the two heating fields and heated to the desired forming temperature, which is recommended to be between 370 °C and 400 °C. To have enough time for the transfer, the temperature was set to 390 °C. During the heating the temperature was measured by two pyrometers that pointed at the top and bottom surface and were controlled by an integrated PID controller. As soon as the desired temperature was reached, the support frame was manually transferred to the press and placed between the molds, which were held at a temperature of 200 °C. The transfer time was kept as low as possible to reduce the cooling of the specimen. Then the press was closed until the desired thickness of 2 mm or 4 mm was reached and a pressure of 18 bar was applied. The molds were kept close for 2 minutes to ensure that the material was completely solidified before it was demolded.
The varied parameters within this study are shown in the following table (Table 1). For conducting the experiments, a full factorial parameter variation was chosen. The only exception was that for the specimens with thickness of 4 mm no tests with an inner radius of 5 mm were conducted.

Table 1. Varied parameters

Parameter	**Unit**	**#1**	**#2**	**#3**
Thickness	[mm]	2	4	-
Layup	[-]	UD	[0/90]	-
Pretension	[N]	15.4	46.2	77.0
Inner radius	[mm]	3	5	-

The following identifier was used for the specimens: *Thickness-layup-number of springs-inner radius-repetition*, e.g. *2-UD-3-3-1* for a specimen with a thickness of 2 mm, UD-layup, pretension of three springs, inner radius of three millimeters and the first repetition.

3.2. Measurements

To investigate the quality of the forming experiments, different measurements were conducted. The main quality criteria in this study were the thickness and thickness distribution of the parts after forming. Besides that, the parts were also examined regarding effects like fiber wrinkles or deflections and delaminations. First, to see, if there were differences regarding the thickness within the radius section and the flat sides, all specimens were measured using a thickness dial gauge. For that purpose, 15 measuring points were defined on the surface of the parts; six on each side and three in the radius (Figure 2). There were no measuring points near the edges in order to reduce the influences of edge-effects.

Excerpt from ISBN 978-3-00-053387-7

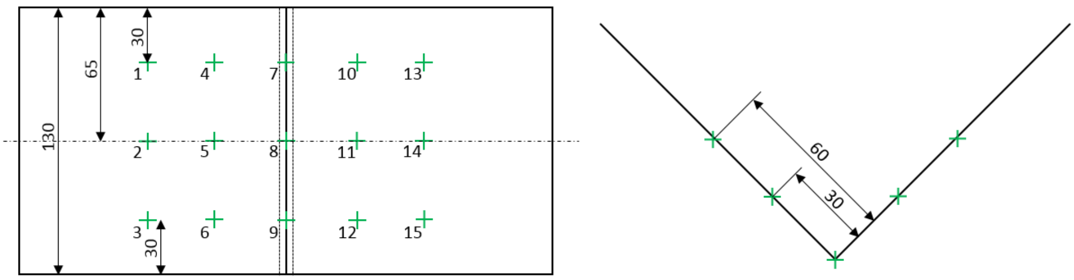
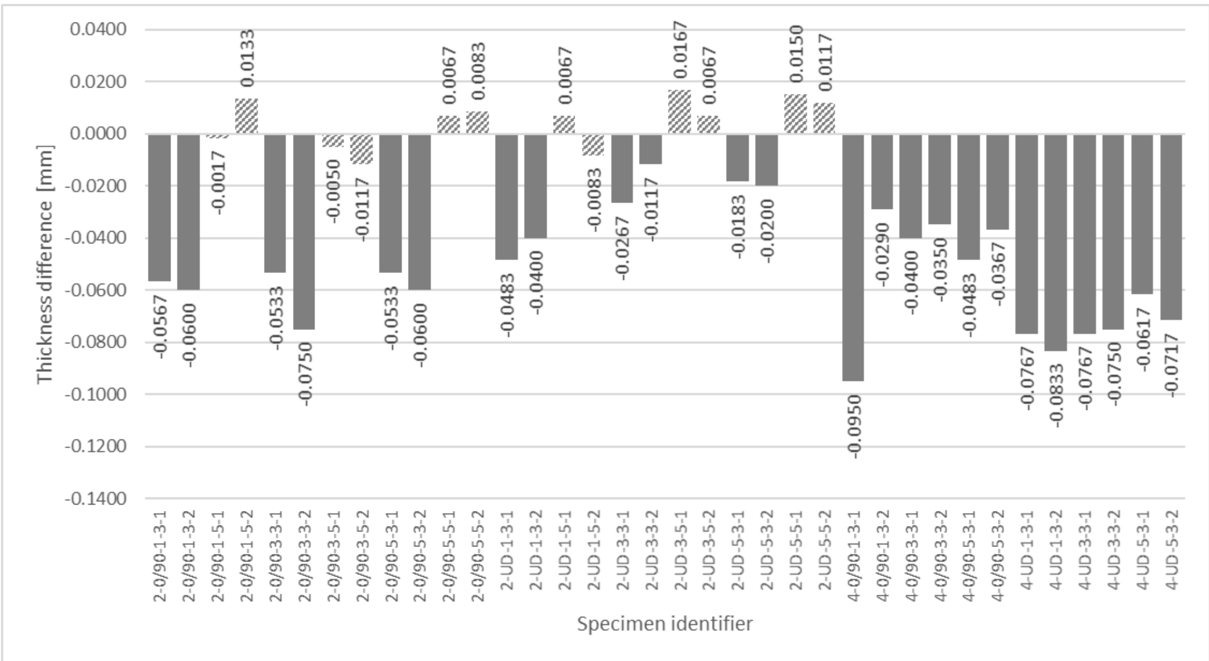


Figure 2. Position of the measuring points

The thickness distribution served as an indicator of quality with special focus on possible thinning of the radius section caused by the pretension of the specimen or inter-laminar shear within the material. In addition, a selection of formed parts was scanned and analyzed with the ATOS Core 300 3D-scanner of GOM. This should help to receive an overview of the thickness distribution and the uniformity of the surface. For that the parts were measured using the 3D-scanner and subsequently the data was analyzed in the ATOS software. To evaluate also the inner quality of the parts, microsections of the formed specimens were made. The focus of this investigation was on the presence of defects like delaminations, voids or fiber waviness. Especially should be compared, whether there were differences in der radius area and the flat areas regarding the laminate quality that could have developed during the forming process.

4. Results

For the evaluation of the thickness measurements, the results of the 12 measuring points on the flat areas and the 3 measuring points in der radius section were averaged. Then the difference between the mean values was calculated with a negative result meaning a thinner radius section. The diagram below (Figure 3) shows the results of the thickness measurements.



Excerpt from ISBN 978-3-00-053387-7

Figure 3. Thickness difference between flat area and radius section

It can be seen that every part formed with the 3 mm inner radius (grey columns) is thinner in the radius section, independent of other parameters. In contrast, the thickness differences of the parts with the 5 mm inner radius (hatched columns) are clearly smaller. At some parts the radius section is even thicker than the flat areas. So it can be noted that the size of radius clearly has an influence on the thickness distribution. Therefore, the radius should be chosen as big as possible to improve the laminate quality.
Besides the influence of the radius size, the results show that dependent of the laminate thickness and layup the radius forming behavior changes. For the laminates with a thickness of 2 mm the 0/90-layup shows more thinning than the UD-layup, for the 4 mm laminates it is the other way round. A reason for that could be the open cavity. As there is no barrier on the side of the molds, the matrix is not detained of flowing and this effect seems to be lager for the 4 mm UD-layups especially at the radius section. This can also be seen by the increased width of the specimen after forming. For the 2 mm laminates this effect is clearly smaller (Figure 4).

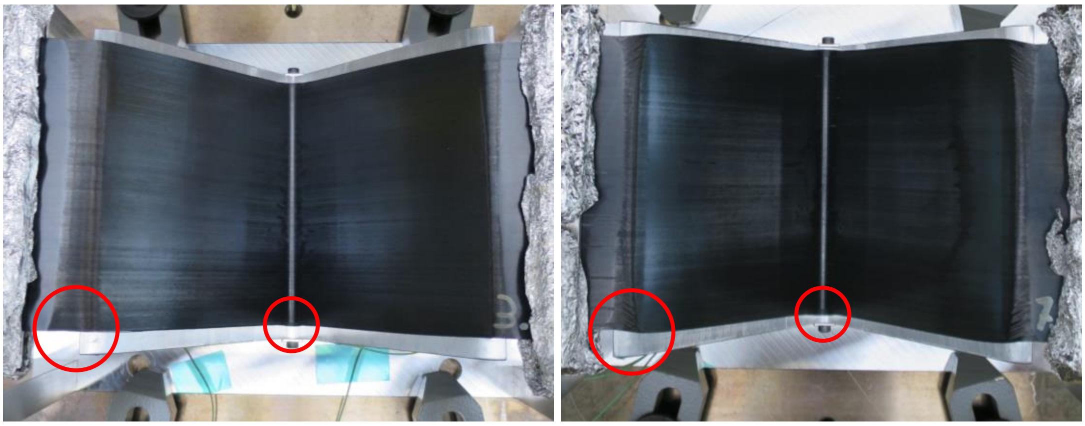


Figure 4. Flowing of the matrix perpendicular to the fiber direction. UD 2 mm (left, 2-UD-5-3-1), UD 4 mm (right, 4-UD-3-3-1)

Looking at the 2 mm specimens in Figure 3, also an influence of the pretension on the thinning in the radius can be seen. It seems that a lower pretension causes more thinning than a higher pretension. For the 4 mm specimens this correlation is not that distinctive.

Figure 5 shows the thickness distribution of 5 parts made with the ATOS system of GOM. Here also the thinner radius sections can be seen.

Excerpt from ISBN 978-3-00-053387-7

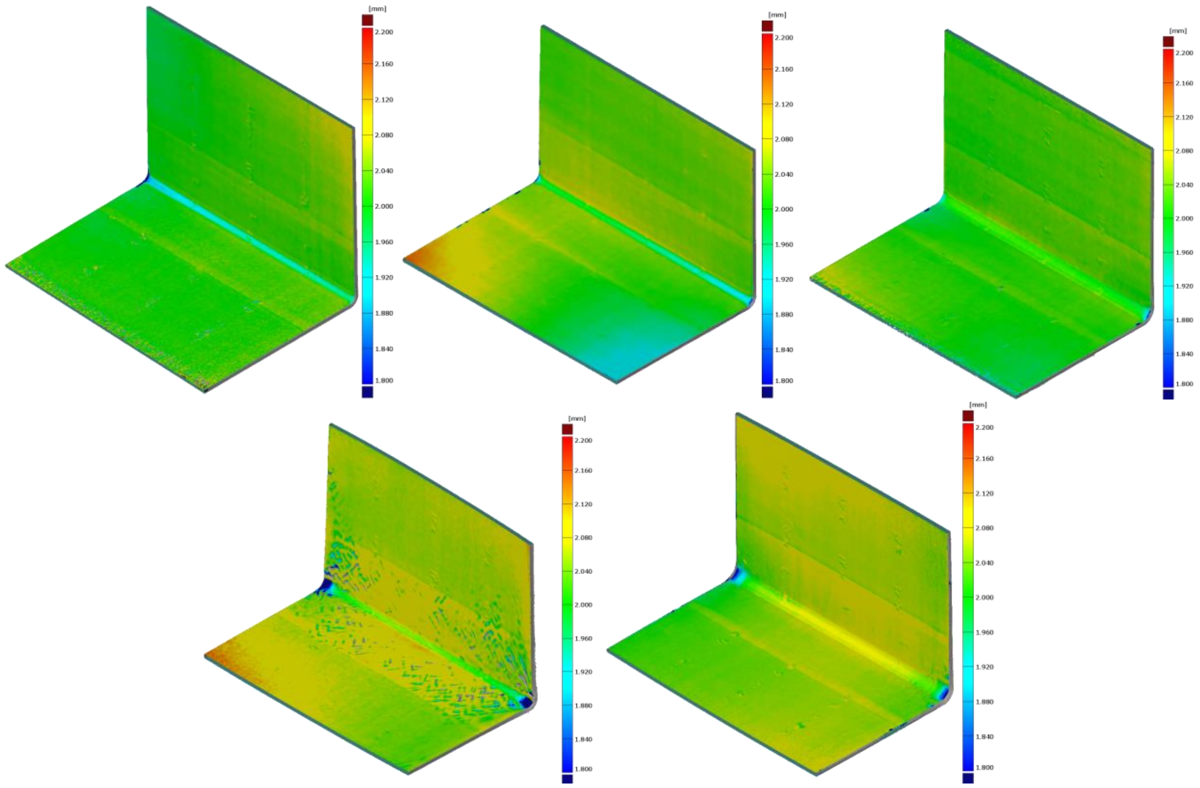


Figure 5. Thickness measurements with the ATOS system. From the top left: 2-0/90-1-3-2, 2-0/90-3-3-2, 2-0/90-5-5-1, 2-UD-3-3-2, 2-UD-5-5-1

The local thinning of the laminate in the radius area leads to a locally increased fiber volume fraction in combination with a worse surface quality as there is no contact with the lower mold (Figure 6). The influence on the mechanical performance has to be investigated in a subsequent study.

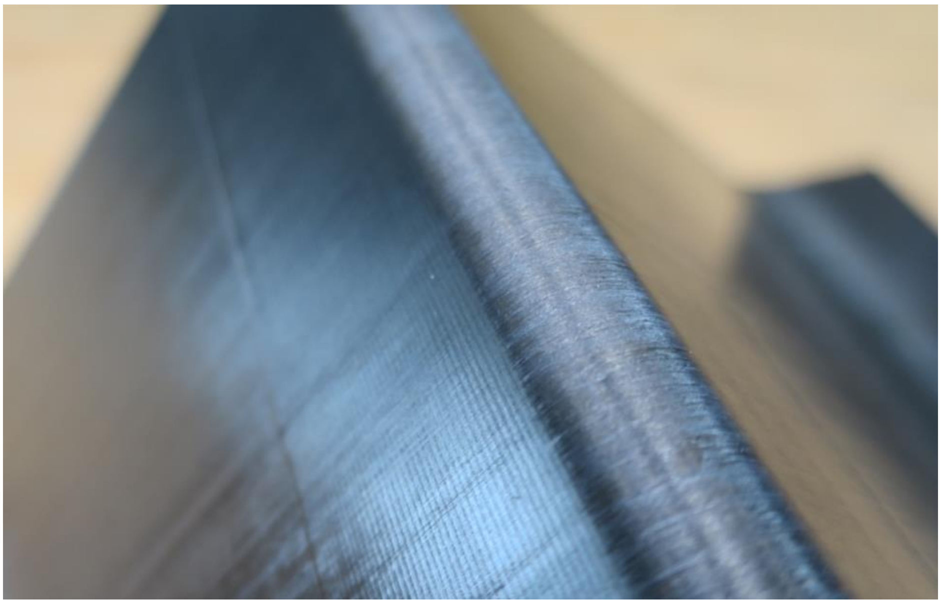


Figure 6. Surface quality on the outside of the radius (4-0/90-5-3-2)

Excerpt from ISBN 978-3-00-053387-7

Besides the thinning of the radius sections, also other effects can be noticed on the formed parts. Close to the inner radius a fiber waviness of the first ply can be seen (Figure 7, left), which is present on every part. In addition to that, most of the UD-specimens show a severe wrinkle formation, which influences the surface quality (Figure 7, right). This phenomenon is less present for the specimens with higher pre-tension and not existing for the 0/90-layup.

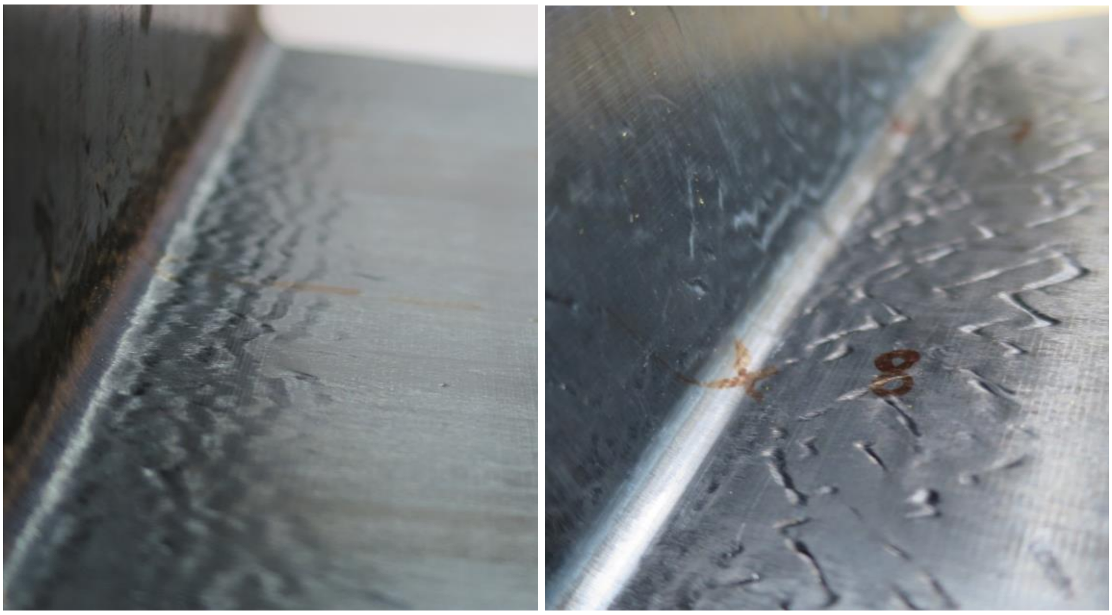


Figure 7. In-plane waviness (left, 4-UD-5-3-2), wrinkles (right, 2-UD-1-3-2)

To get a better impression of the inner laminate quality a microsection of the radius section was made (Figure 8).

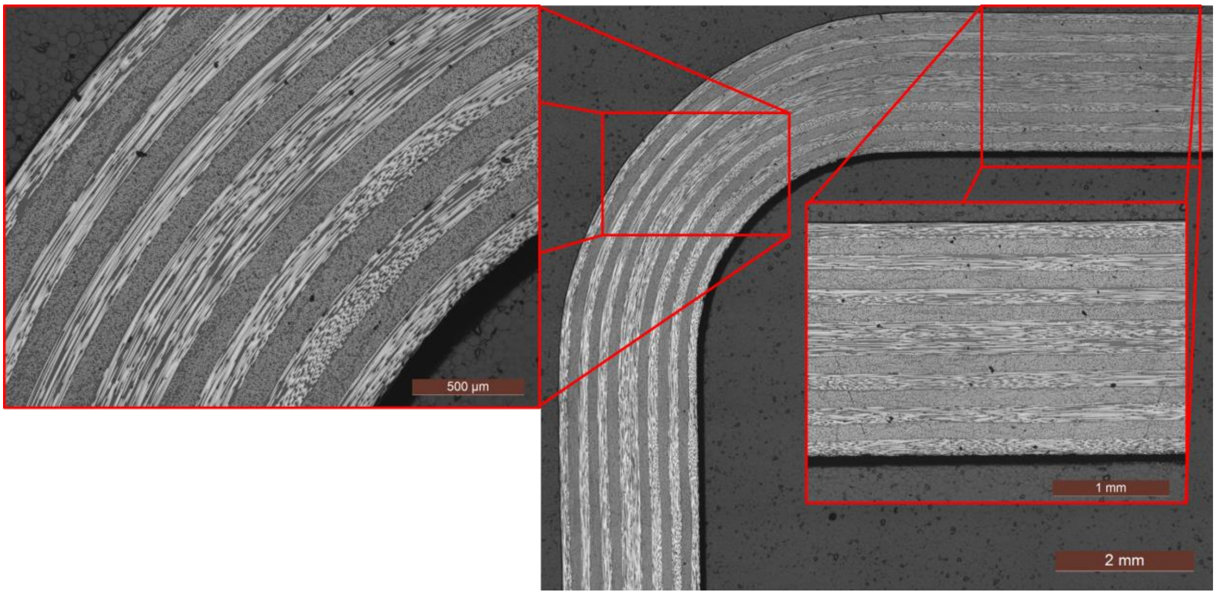


Figure 8. Microsection of 2-0/90-3-3-2 at measuring point 8

Excerpt from ISBN 978-3-00-053387-7

There can be seen that the fibers of the outer three 0°-plies are almost parallel to the picture plane, which is an indicator for stretched fibers. In contrast the fibers of the inner three 0°-plies seem to come out of the picture plane indicating in-plane waviness. Apart from this, the microsection reveals a good laminate quality containing very little pores and no delaminations.

5. Conclusion

In this work, the radius forming behavior of carbon fiber reinforced PEEK was investigated and four parameters were evaluated regarding their influences on the laminate quality, especially on the thickness distribution. The considered parameters were the size of the radius, the thickness of the specimen, the fiber orientation and the pretension in the support frame. The results showed that the size of the radius and the thickness of the laminate had the greatest influence on the thinning of the material in the radius area. The layup and the pretension of the specimens were of less importance. The experiments also revealed that fiber waviness of the 0°-plies can occur on the inner radius. Besides that, a good laminate quality could be achieved within the radius section and the flat areas.

Acknowledgments

The authors would like to thank the German Federal Ministry for Economic Affairs and Energy (BMWi) for the funding of the project GeKo-Therm. Thanks also to the Airbus Helicopters Deutschland GmbH for providing the material that has been used in this work.

References

[1] U.K. Vaidya and K.K. Chawla. Processing of fibre reinforced thermoplastic composites. *International Materials Reviews*, 53(4):185–218, 2013.

[2] T.J. Ahmed, D. Stavrov, H. Bersee, A. Beukers. Induction welding of thermoplastic composites—an overview. *Composites Part A: Applied Science and Manufacturing*, 37(10):1638–1651, 2006.

[3] A.R. Offringa. Thermoplastic composites—rapid processing applications. *Composites Part A: Applied Science and Manufacturing*, 27(4):329–336, 1996.

[4] P. Hubert and A. Poursartip. Aspects of the Compaction of Composite Angle Laminates: An Experimental Investigation. *Journal of Composite Materials*, 35(1):2–26, 2001.

[5] U. Berthold. Beitrag zur Thermoformung gewebeverstärkter Thermoplaste mittels elastischer Stempel. Dissertation, TU Chemnitz, 2001.

[6] R. McCool, A. Murphy, R. Wilson, Z. Jiang, M. Price, J. Butterfield et al. Thermoforming carbon fibre-reinforced thermoplastic composites. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 226(2):91–102, 2012.

[7] H. Lessard, G. Lebrun, A. Benkaddour, X.-T. Pham. Influence of process parameters on the thermostamping of a [0/90]12 carbon/polyether ether ketone laminate. *Composites Part A: Applied Science and Manufacturing*, 70:59–68, 2015.

Excerpt from ISBN 978-3-00-053387-7