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Mechanisms and sources of spring-in and spring-back of fiber reinforced thermoplastics

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ABSTRACT

Fiber reinforced thermoplastics (frt) have a complex spring-in and spring-back behavior due to residual stresses depending on several process parameters and mechanisms such as interply-slip, anisotropic thermal expansion and crystallization. The shape distortions can lead to problems during assembly. Thus, it is important to understand the influence of different parameters and mechanisms on spring-in or spring-back in order to optimize the forming process. In this work, photomicrographs of formed frts will be analyzed to show the mechanisms that lead to named distortions. To analyze the influence of interply-slip to the resulting bending angle frts made of one layer will also be formed.

Index Terms **–** spring-back, fiber reinforced thermoplastics, interply-slip, crystallinity

1. INTRODUCTION

Fiber reinforced thermoplastics (frt) have a complex spring-in (-) and spring-back (+) behavior (Fig°1) due to residual stresses after the manufacturing process. It depends on several parameters such as velocity, pressure and temperature, as well as part geometry. These shape distortions can lead to problems during assembly. Because of this, it is important to understand the influence of different parameters on spring-in (spring-back) in order to optimize the forming process. In the past, several authors analyzed the resulting bending angles of formed frts. Experimental results of [1] and [2] showed negative angular deviations. They described this spring-in phenomenon (-) because of anisotropic coefficients of thermal expansion (CTE) that lead to anisotropic contraction during cooling. [3] shows experimental test results either with spring-in or spring-back angles, positive angular deviations, depending on the forming temperatures.

The author assume that low forming temperatures and high cooling rates lead to spring-back due to suppressing of interply-slip. Interply-slip (Fig°1) is the most important mechanism while forming of multilayered sheets [4]. The several layers have to slide over each other to compare the difference between the inner and outer bending radius to avoid wrinkling [5, 6, 7]. [8] also presents a phenomenological approach of interlaminar shear behavior and its influence to spring-back but his experimental results do not show spring-back angles.

In prior studies the spring-in behavior of a formed V-shape has been analyzed by [9] under variation of different process parameters. The experimental tests show significant angular deviations, positive and negative as well. Theoretical relations between the forming mechanisms, the cooling rate and resulting spring-in or spring-back angle, have been described. In this work photomicrographs (Fig°3) of formed V-shapes of multilayered frts will be analyzed to verify the visible mechanisms (interply-slip, matrix-migration) that lead to spring-back or spring-in. The results will be compared to the assumptions that have been described before. To eliminate the influence of interply-slip in a first step and anisotropic coefficients of thermal

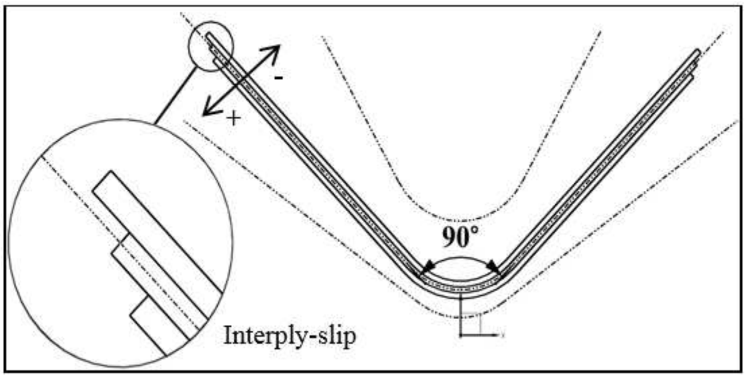

Fig. 1: Spring-in and interply-slip of a multilayered sheet

expansions in a second step, sheets made of one layer and sheets made of polyamide 6 without any reinforcement will be formed.
The unreinforced specimens shall also show the relationship between inhomogeneous cooling and contraction due to different crystallinity.
In chapter 2, different forming mechanisms and sources of spring-back or spring-in will be described that should be verified in this work on the basis of forming tests and photomicrographs. Furthermore, the chapter will give a short overview about prior studies of other authors and a comparison of their results considering used process parameters. Afterwards the experimental test results and photomicrographs of this work will be discussed.

2. FORMING MECHANISMS AND SOURCES OF SPRING-BACK

Fiber reinforced thermoplastics have to be heated over the melting temperature of the polymer matrix before the forming process. If the matrix is melted, the fibers are able to move. Important forming mechanisms need the flexibility of the fibers. In case of woven fabric reinforcement, intraply-shear enables the forming of a 3D shape. When bending multilayered sheets to form a 2D shape, for example an open profile, interply-slip (Fig°1) is the primary deformation mode [4]. As mentioned before, [3, 9] assume that the suppression of interply-slip leads to spring-back. The process temperature and heat transfer as well as the normal pressure and (relative) velocity influence it [5, 10]. Several authors explain that the plies are separated by a matrix film that affects the interply-slip [10, 11, 12]. The melted matrix built up a lubricant film and thus the friction between the plies is hydrodynamic. [5, 13] refer to the Stribeck curve (Fig°2) that describes the amount of friction forces plotted against the Hersey number (1).

$$H = \frac{\eta \times U}{N} \quad (1)$$

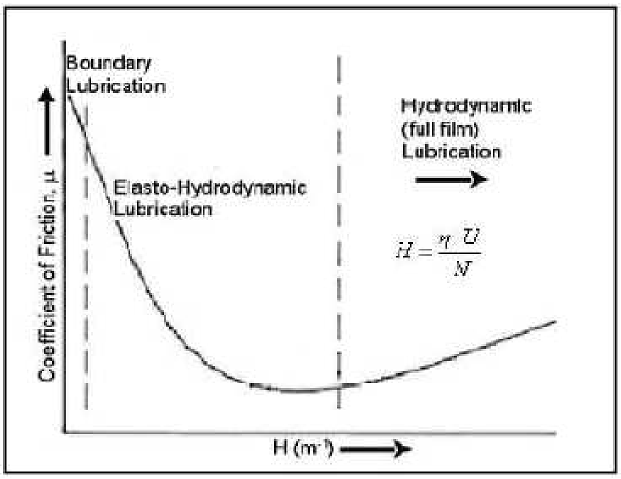

Fig. 2: Stribeck curve [15]

The Hersey number (H) considers the influence of viscosity (η), sliding velocity (U) and normal pressure (N) on liquid film thickness or the amount of melted polymer between several layers, respectively. According to the Hersey number, friction forces are proportional to matrix viscosity and sliding velocity and inversely proportional to normal pressure. Matrix viscosity in turn is also dependent on sliding velocity and actual matrix temperature. [9]
There is a critical temperature for interply-slip. The sheet temperature can fall below this critical value due to low forming velocity [14]. Thus, [3] explains that low forming velocities lead to spring-back. [9] confirms

this phenomenon but nut for the whole tested range of bending radii. Furthermore, the fabrics of each layer can get caught [8].

Besides the suppression of interply-slip due to low matrix viscosity and high friction forces as a result of high cooling rates within the forming process leading to spring-back, the main reason for spring-in is supposed to be anisotropic thermal contraction. Salomi et al. [1] and Lee et al. [15] assume that the in-plane CTE is dominated by the fiber reinforcement and the through-thickness CTE is dominated by the matrix system. In case of frts with glass fibers and polyamide matrix the in-plane CTE has to be much higher than the through-thickness CTE and equation 2 would always result in spring-in (cp. [9]). This equation is proposed by [1, 2] to predict the residual bending angle after forming depending on thermal contraction during cooling from forming temperature to room temperature.

$$\Delta\theta = \frac{(\theta - 180)(\alpha l - \alpha t)\Delta T}{(1 + \alpha t\ \Delta T)} \qquad (2)$$

[1] showed differences between theoretical results according to equation 2 and experimental results. The author formed a U-profile with different radii at the two corners. Eq. 2 does not consider the radius, thus the theoretical spring-in angle is the same, but experimental results showed a difference between the spring-in angles of both corners. The author explains that process induced defects at the corner, like inhomogeneous fiber distribution and thickness as well as fiber wrinkling, effect the CTE and thus the spring-in angle. This effect is more relevant for smaller radius, confirmed by higher spring-in angles. [16] also describes that anisotropic CTEs and the geometry of the corner of a formed part influence its spring-in angle.
In addition to the anisotropic CTEs, the anisotropic cooling of the sheet also leads to stresses within the material that causes distortions.
Another important factor is that volume contraction not only depends on thermal contraction but also on crystallization [17]. [18] explains that this effect can be significantly higher than the effect of thermal expansion due to temperature changes.
The crystallization factor of the polymer matrix depends on the cooling rate. Due to inhomogeneous cooling of the test specimen, there are areas with more or less crystallinity and with these different relative densities. [19] describes this behavior for processing of unreinforced polymers. Lower cooling rates lead to more crystallization and thus more contraction. If the polymer gets into contact to the cold tools, the crystallization can be suppressed completely. The other parts of the material cool down slowly and thus have more crystallinity. This effect leads to compression stresses at the surfaces and tensile stresses inside of the part. Furthermore, high cooling rates can lead to an undercooled state. The crystallization will be shift to lower temperatures.
The last reason for spring-back that will be investigated in this work is the bending stiffness of the fibers. [14] explains that there are bending stresses of the fabric due to their stiffness and if the matrix doesn't solidify completely till the end of the forming process, the stresses can lead to distortions of the sheet.

2.1 Influence of process parameter onto the forming mechanisms

[9] assume that suppressing of interply-slip before the end of the forming process due to decreasing sheet temperature leads to spring-back. Thus, low velocity and low tool and sheet temperature would result in spring-back. [3] shows an increasing spring-back of a formed sap profile with decreasing velocity.
Furthermore, increasing normal pressure leads to increasing friction forces between individual plies and interply-slip would be suppressed. Another reason is that the fabric layers can get

caught [14]. Forming pressure and the geometry can influence the fiber distribution at the corners of the formed part. Thus, the fibers can move to the inner radius and the matrix can move to the outer radius. This effect is called matrix migration. There are local variations in CTEs and crystallinity leading to different stress distributions.
[9] showed that low velocities would not always result in spring-back depending on the size of the bending radius (Fig°4). Another assumption is that increasing bending radii lead to increasing cooling rates while the punch moves down due to increasing contact area. This effect would result in suppressing of interply-slip leading to spring-back. [1] shows higher bending angles for higher radius for the forming of a U-channel. According to figure 4 the effect just applies to high forming velocities. [8] makes the same assumption but results did not confirm. Thus, the author supposes that the melted sheet sags due to its own weight and has no or less contact to the punch until the tools are closed. Thus, different bending radii have no influence onto the cooling behavior. [14] shows experimental tests for the forming of a V-shape that result in decreasing bending angles with increasing radius. Compared to the results of figure 4 the pressure is lower, velocity is nearly the same and dwell time is higher.

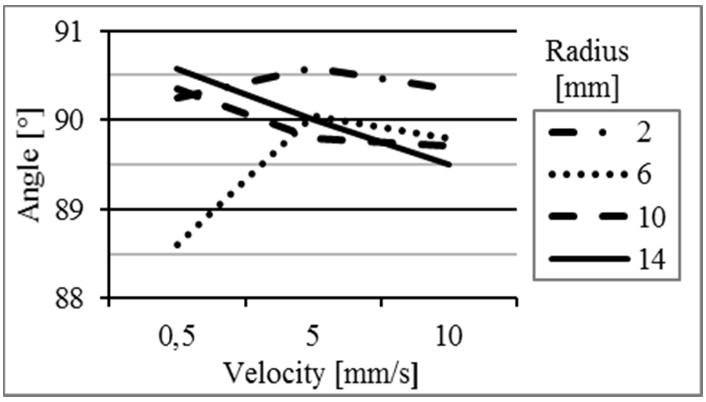

Fig. 4: Bending angle depending on radius and velocity [1]

According to [14] increasing dwell time leads to lower distortion of the part and bending angles become nearly 90°. Test specimens with lower dwell time showed significantly spring-back or spring-in angles influenced by the architecture of the reinforcement. If the dwell time is too low, the test specimen has to cool down outside the tool and the matrix did not solidify completely. Thus, there is a relaxation of the fibres for example.
The photomicrographs in the next chapters should show the mechanisms that lead to spring-back and the elimination of interply-slip and anisotropic coefficients of thermal expansion should help to understand the complex spring-back behavior.

3. FORMING OF A V-SHAPE (TEST-SETUP)

Spring-in characteristics have been tested with a simple die-bending test that bends a small sheet to an angle of 90 degrees. The investigated material is a glass fiber reinforced polyamide 6 with three layers of twill fabric. The test procedure has been described in [9]. In this work, the sheet is just heated to 300°C because of the lower melting temperature of polyamide 6 instead of polyamide 66. After the transfer step the sheet temperature decreases to 260 °C. The tests were conducted under variation of different process parameters that are listed in table 1. Based on the results of previous studies [9] process parameter values have been chosen that should result in a wide variety of resulting bending angles from spring-in to spring-back to analyze which forming mechanisms lead to which kind of distortion.
Besides the measurement of the angles, the relative displacement between several plies of the multilayered sheets are identified. Therefor the distance between the inner and outer ply has been measured at the photomicrographs on both sides of the specimen. The total displacement and thus the amount of interply-slip is the sum of both values. In theory, the ideal value, if the plies can slide over each other without any friction forces, would be the difference between the

outer (U_a) and inner circumference (U_i) at the bending radius. Equation 3 shows that this value is independent from the bending radius(r_i; r_a) and just depends on the thickness of the sheet (t).

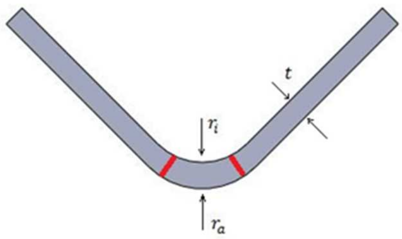

Fig. 3: Bending radii

$$\Delta s = U_a - U_i = \frac{1}{2}\pi * (r_i - r_i + t) = \frac{1}{2}\pi * t = 2{,}356\text{mm} \quad (3)$$

Within this work, the influence of interply-slip onto the spring-in behavior should be analyzed. Thus, on the one hand multilayered sheets will be formed to measure the interply-slip as described before. On the other hand, sheets made of one layer will be formed to eliminate the effect of interply-slip. To reach the same cooling rate for one layer as for multilayered sheets several layers will be stacked with thin films of aluminum (Fig°4). The multilayered sheets have been fitted with aluminum to realize the same tool-ply friction conditions.
First experimental results have shown that there is no difference between the resulting bending angles of formed multilayered sheets with or without thin films of aluminum. This suggests that the foil has low influence onto the part stiffness and its deformation.
In a next step, the influence of anisotropic material properties and especially the anisotropic coefficient of thermal expansion should be eliminated to analyze the influence of anisotropic cooling of the sheet and draw conclusions from the crystallization of the polymer. Therefor 15 foils of polyamide 6 have been stacked between two thin films of aluminum and formed to a V-shape under variation of different process parameters (red marked values in table 1). The specimens made of polyamide 6 could only be tested with the low velocity of 0,1mm. The test procedure has been force controlled, that means the punch moves down until a specified force value has been reached. However, the testing machine was not able to control the force value due to low stiffness of the polymer without reinforcement.

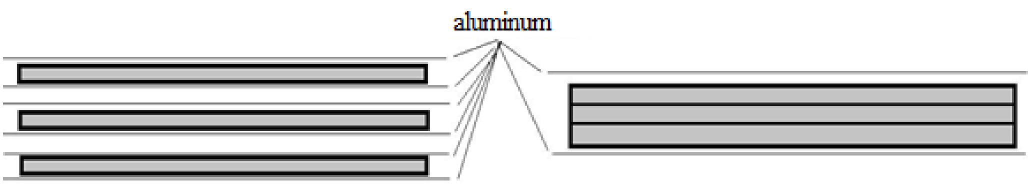

Figure 4: Stacked frt with aluminum (left: one layer; right: multilayered)

Table 1: Process parameter values

Parameter	fix	variable	variable
Bending radius	6mm	2mm	14mm
Normal pressure	10bar	30bar	50bar
Velocity	1mm/s	0,1mm/s	2mm/s
Dwell time	15s	1s	-

3.1 Photomicrographs

After the forming process and the measurement of the bending angle the test specimens were cutted according to Figure 5 and 6. It shows the direction of grinding in the middle of the test specimen.

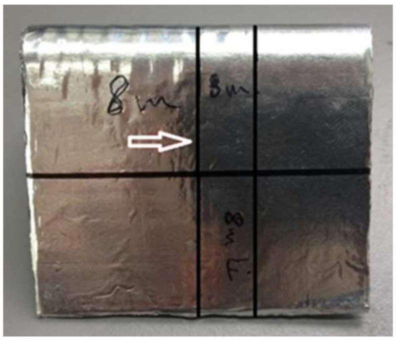

Fig. 5: Grinding direction

Fig. 6: Cutted test specimen

4. RESULTS AND DISCUSSIONS

4.1 Multilayered sheets

The process parameters, which are used in this work, lead to following results for the bending angles. Figure 7 to 10 show the results for the multilayered sheets.
Increasing velocity leads to increasing bending angles of the part (Fig°7). Previous studies show the same behavior for bending radii of 2 mm and 6 mm and velocities up to 5 mm/s (Fig°4). According to chapter 2, the heat flow between the punch and the sheet decreases with decreasing bending radii or the melted sheet sags and has not contact to the punch. Thus, the polymer matrix does not cool down since the tools are closed. The measurement of the interply-slip shows, that increasing velocity leads to decreasing interply-slip (Fig°8). The individual plies may have not enough time to slide over each other completely. Furthermore, the friction forces between the plies increase with increasing velocity due to increasing friction forces and viscosity of the matrix in case of hydrodynamic lubrication (Fig°2). The test specimens with a radius of 6 mm and velocity of 1 mm/s show matrix migration at the outer radius and the fabric layers move to the inside radius (Fig°9). The concentration of the polymer matrix could lead to stresses at the outside radius due to the crystallization of the polyamide leading to shrinkage. In addition to the lower value of interply-slip this phenomenon may lead to increasing bending angles. Figure 11 also shows matrix migration for a radius of 2 mm and a velocity of 1 mm/s. In this case, the matrix concentrates at the inside radius and the shrinkage would result in decreasing angles which is confirmed by the measured angle values (Fig°7).
At low velocities, the bending angle is lower for the higher radius. At higher velocities, the bending angle increases with increasing radius. The second phenomenon also occurs for other pressure and dwell time values (Fig° 10 and Fig° 12).

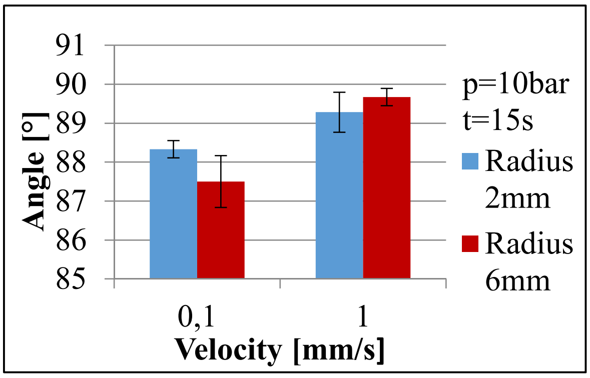

Fig. 7: Bending angle depending on velocity and radius (multilayered sheet)

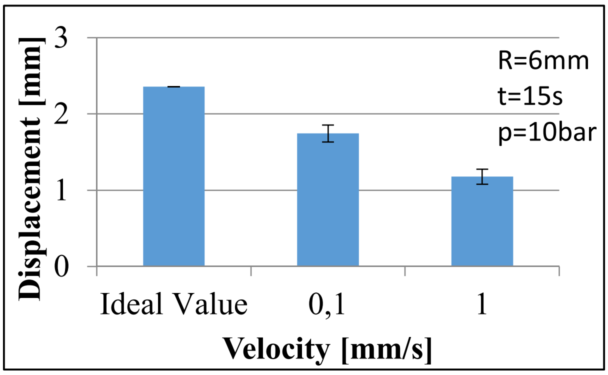

Fig. 8: Interply-slip depending on velocity (multilayered sheet)

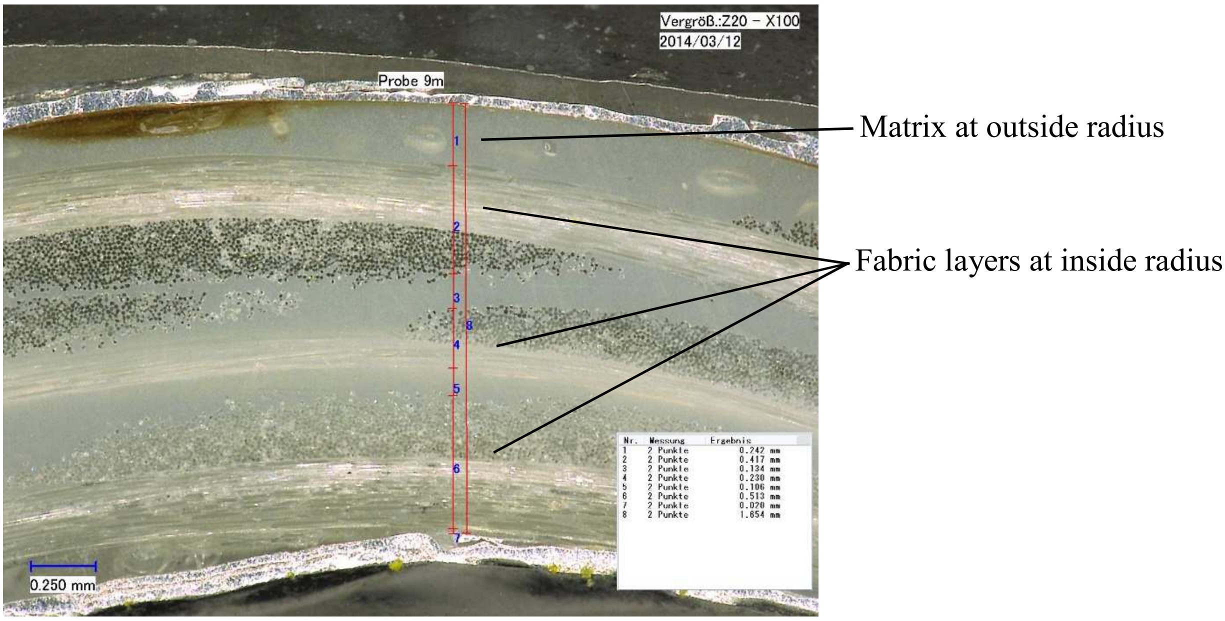

Fig. 9: Matrix migration at outside radius (R6)

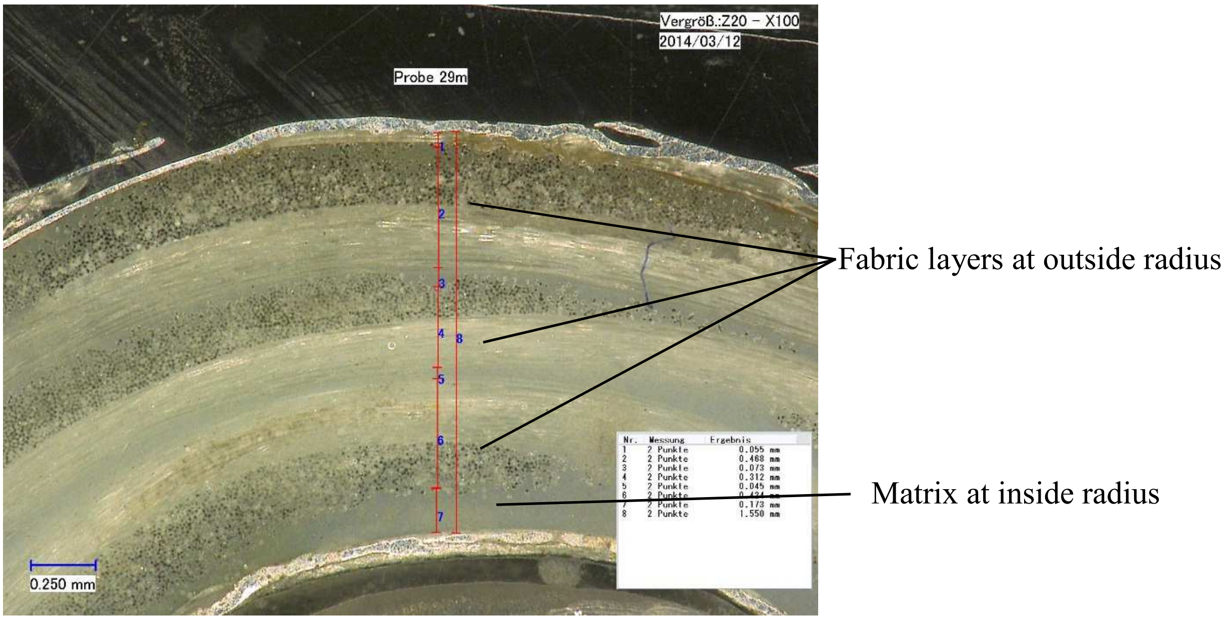

Fig. 10: Matrix migration at inside radius (R2)

Figure 11 shows, that increasing dwelltime leads to increasing bending angles. At low dwelltime the different bending radii have greater influence onto the bending angle than for higher dwelltime values. [14] explains that matrix temperature is high at low dwelltime and the polymer did not solidify completely. Thus, stresses due to the forming process can release. The angle of a radius of 2mm is 2° lower than the angle of a radius of 6mm. Therfore, the forming process with lower bending radius must lead to more stresses that lead to spring-in if they can release.

Figure 13 shows the values of interply-slip for a dwelltime of 15 seconds. The interply-slip increases with increasing radius but increasing radii lead to increasing bending angles. For this, the theoretical relations are not valid for these parameter combinations. Therefore, there has to be more mechanisms that lead to spring-back than just the suppressing of interply-slip due to low forming temperatures. The different angles may cause by elastic stresses of the fibres that increase with increasing bending radii.

Another reason could be the shrinkage of the matrix due to its crystallinity. The test specimens with a low dwell time have more residual heat after deforming than specimens with a higher dwell time. Thus, they have to cool down in air and therefore a lower cooling rate, which leads to more crystallinity and contraction. The spring-in at lower dwell time indicates for stresses at the inside radius. Photomicrographs do not show matrix migration. Thus, the stresses have to be the result of anisotropic cooling caused by different sizes of contact areas depending on bending radius.

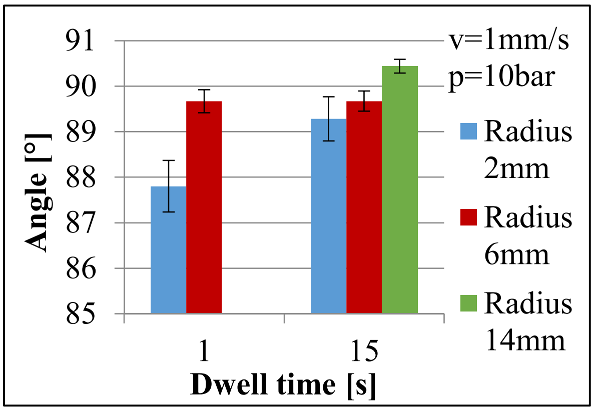

Fig. 11: Bending angle depending on dwelltime and radius (multilayered sheets)

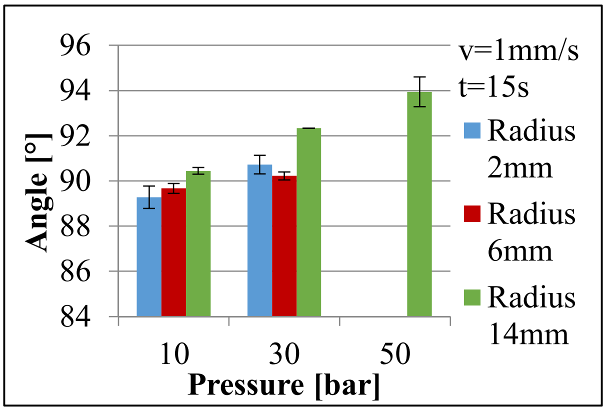

Fig. 12: Bending angles depending on pressure and radius (multilayered sheets)

Figure 12 shows the resulting bending angles for different pressure values. Increasing pressure values lead to increasing bending angles. Higher values of normal pressure result in decreasing interply-slip (Fig° 13). This effect leads to spring-back effect. According to Figure 2 friction forces between the plies decrease with increasing pressure in case of hydrodynamic lubrication. The pressure does not built-up until the tools are closed. Thus, higher pressure values may suppress creeping effects that cause lower displacements between the individual plies. Another effect is, that the fabrics of each layer can get caught which would be intensified with increasing pressure.

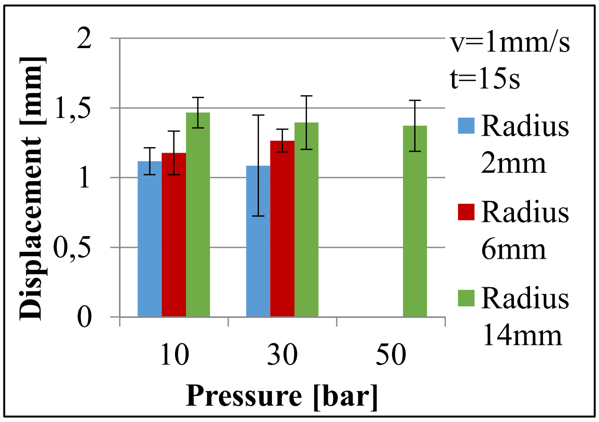

Fig. 13: Interply-slip depending on pressure and radius (multilayered sheets)

4.2 One-layer sheets

Figure 15 illustrates the resulting bending angles of the test specimens with one layer. The plies at the outside radius show spring-back angles and the plies at the inside radius show spring-in. The central ply has least distortion. Further test specimens with other radii, pressure and dwell time show the same phenomenon. Figure 14 shows the cooling behavior of the individual plies. The inside and outside radii have higher cooling rates due to the contact to the tools. The red marked areas have no contact to the tools and therefore lower cooling rates. Thus, the polymer matrix at the outside radius of the inside ply and at the inside radius of the outside ply has more crystallinity and shrinkage. This phenomenon results in spring-back of the inside ply and spring-in of the outside ply. Furthermore, increasing velocity results in increasing bending angles although there is no interply-slip (Fig°15). There has to be another reason for spring-back for sheets made of one layer. Increasing velocities seem to influence the cooling rate, which leads to increasing bending angles.

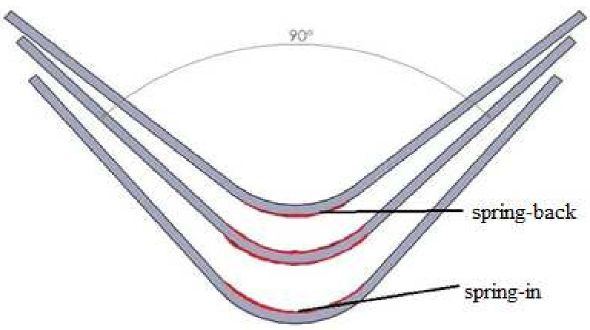

Fig. 14: Spring-in/ spring-back of one layer

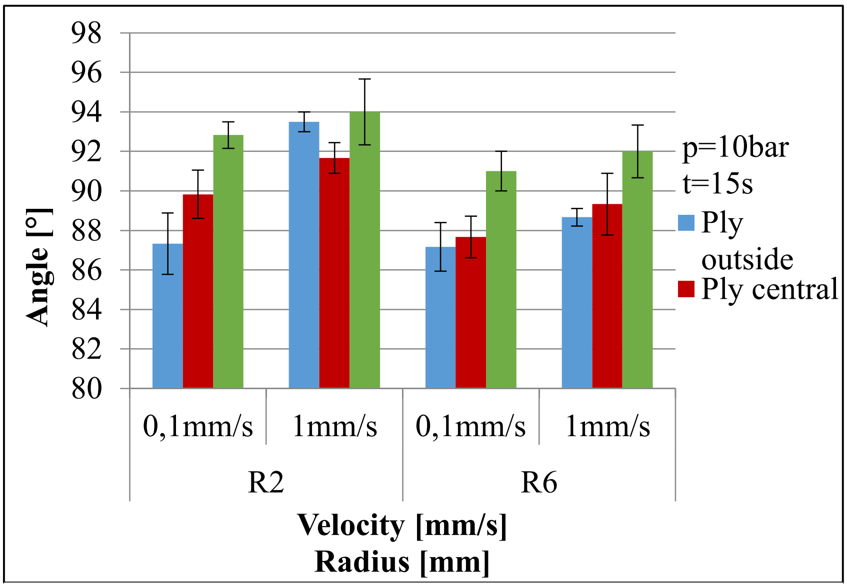

Fig. 14: Bending angles depending on velocity and radius (one layer)

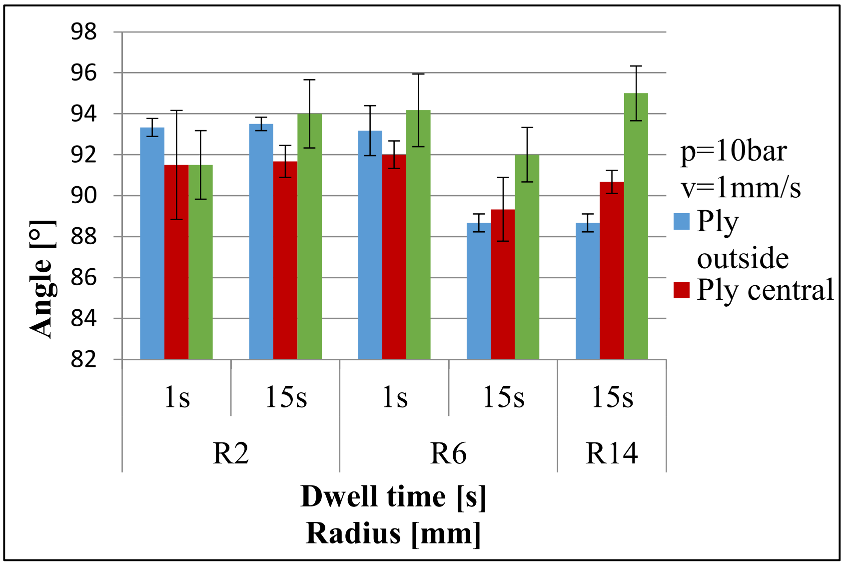

Fig. 16: Bending angle depending on dwell time and radius (one layer)

The influence of the dwell time onto the bending angle varies for different radii (Fig°16). Increasing the dwell time leads to increasing spring-back for the inside ply for a radius of 2 mm. The other plies are hardly influenced. For a radius of 6 mm the increase of the dwell time results in decreasing angles of the plies. According to the assumptions of chapter 2, increasing the dwell time should lead to lower distortions and resulting bending angles of nearly 90°. This assumption does not apply to the lower radius.

Figure 17 shows the results for different pressure values. Higher pressure values lead to increasing bending angles for a radius of 6 mm and 14 mm but not for a radius of 2 mm. Thus, the normal pressure has great influence onto spring-back although there is no interply-slip. Therefore, it has to effect more mechanisms, the elastic stresses of the fabrics or the cooling rates for example.

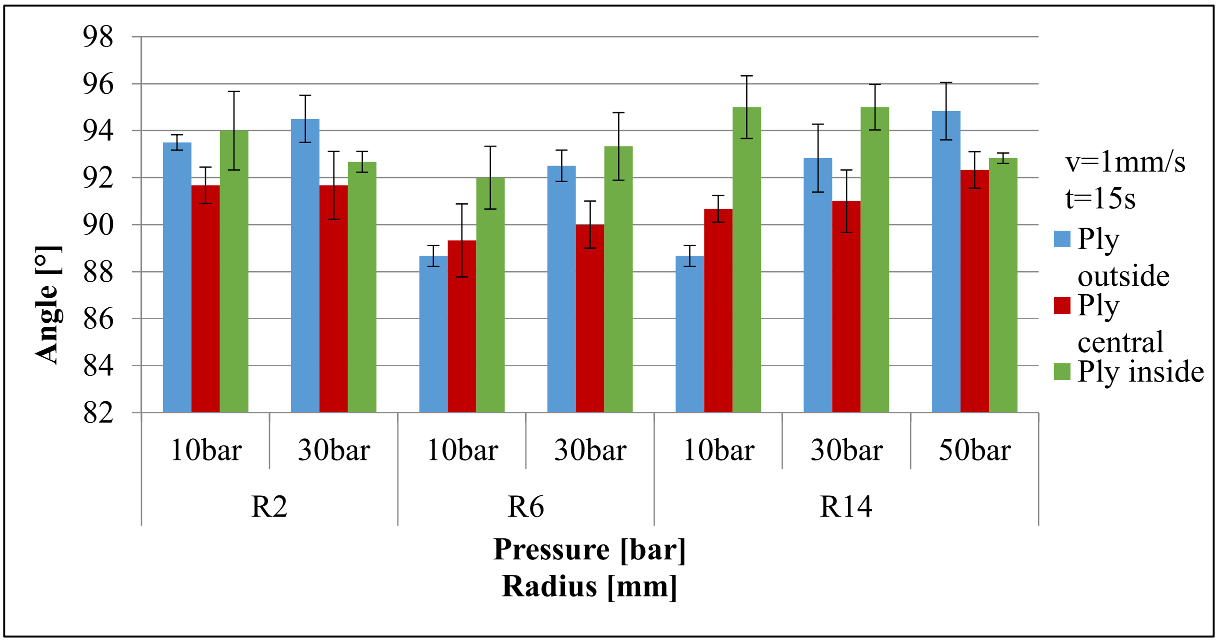

Fig. 17: Bending angle depending on pressure and radius (one layer)

4.3 Polymer sheets

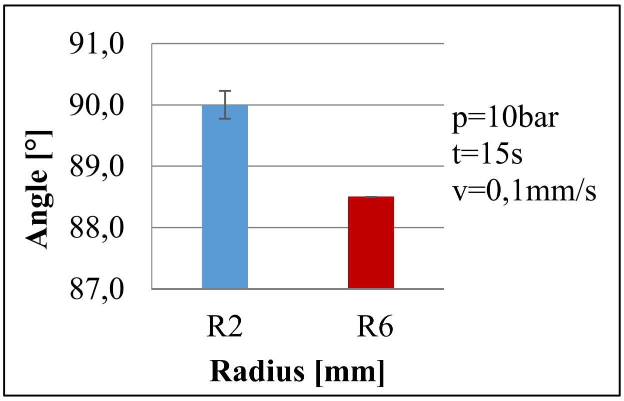

Fig. 18: Bending angle depending on radius (polymer sheet)

Figure 18 shows the results of the formed polyamide specimens without reinforcement. The increase of the radius leads to spring-in. Because of the isotropic CTE the shrinkage has to be caused by anisotropic cooling of the sheet. The radius of 6 mm leads to a higher contact area between the punch and the sheet. Thus, the sheet temperature can decrease in the contact area when the punch moves down until the tools are closed. According to the assumptions of chapter 2 this would result in lower crystallinity at the inside radius and thus more shrinkage at the outside radius. Therefore, there should be a spring-back effect. [8] explained, that the melted sheet sags during the forming process. The cooling rate of the sheet in contact to the punch at the beginning of the process might be smaller than assumed and the polymer matrix did not solidify until the tools are closed. This would result in decreasing cooling rates at the inside radius when the sheet is in contact to the whole tools. Therefore there is more crystallinity at the inside radius leading to the spring-in effect.

The variation of the pressure and velocity does not show any effect onto the bending angles.

5. CONCLUSION

This work show, that test specimens with spring-back angles also show interply-slip. For this, the theoretical relations that spring-back is caused by the suppression of interply-slip due to high cooling rates does not apply. Furthermore, the forming process of the sheets made of one layer partly result in spring-back angles. One reason could be the elastic stresses of the fibers. The increasing spring-back angles with increasing pressure values for the sheets made of one layer indicate for this.
Another assumption is that spring-in is caused by anisotropic coefficients of thermal expansions. The sheets made of polymer without reinforcement showed spring-in for a bending radius of 6mm. Thus, also sheets with isotropic CTEs can warp. The contraction of polymer not only depend on thermal contraction but also on crystallization. Thus, the effect of crystallization seems to be significantly higher than the effect of thermal expansion due to temperature changes.
As explained, different process parameter effect different mechanisms. Therefore, the spring-back behavior of frts is complex.

6. OUTLOOK

Test procedure
The test procedure and especially the transfer step will be improved to reach a better reproducibility of the forming temperature. This temperature is highly influenced by the time needed for transferring the heated sheet between the heating unit and the forming tools. The transfer time in this work varies between 8 and 10 seconds. This could lead to a variation of forming temperature of about 10°C and should be reduced for the next studies.
Sensitivity of thickness
The measurement of the thickness have shown that there is a variation of about 0.1 mm. Thus, a sensitivity analysis will be performed in further studies to analyze its influence onto the spring-back angles. The contents of fibers and polymer matrix influence the thermal expansion coefficients and this can lead to different thermal stresses during the cooling of the formed parts.
Therefore, sheets with a thickness of 0.4, 0.5 and 0.6 mm will be compared with different tests. At first, their fiber volume fraction will be measured to recognize whether the variation of thickness is due different contents of fibers and polyamide or due to more or less consolidation during the manufacturing process of the sheets. Another reason for less thickness could be that the fabrics of several layers gear into each other. Thus, the measurement of voids content should be done in addition to the measurement of fiber volume fraction because the voids content indicates for the quantity of consolidation.
If the variation in thickness is due to different fiber volume fractions, the sheets with a thickness of 0.4, 0.5 and 0.6 mm will be formed with specified parameters in a second step to analyze the influence onto the spring-in angle and the forming mechanisms that lead to the distortion.
Crystallization
Analysis of degree of crystallization to show the influence of different cooling behavior onto the shrinkage of the sheet. Areas of more crystallization have a higher amount of molecular chains, which lead to higher hardness. Thus, a measurement of hardness will be done at different areas of the formed sheets.

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