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BENDING OF UNIDIRECTIONAL REINFORCED THERMOPLASTICS

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ABSTRACT

Due to their high specific stiffness and strength, composite materials are suitable for lightweight design. The material composition can be tailored to meet specific requirements, but also increases the complexity of processing techniques. The overall forming behaviour results from the interaction of the specific forming behaviour of the composite components in their structural set-up. This complicates the prediction of results in comparison to metal forming processes. Because of the required heating and cooling in forming processes for thermoplastic composites, distortions due to thermal shrinkage arise. These result in a spring-in of bend components. For sequential heating processes as for bending processes, springback is observed as well, suggesting that additional residual stresses need to be accounted for. Therefore, an investigation of the influence of forming temperature and forming velocity in a rotary draw bending process for a thermoplastic tape is carried out, to develop a suitable forming process for thin bent parts.

Index Terms – Bending, Thermoplastic Tape, Fibre Reinforcement, Forming Temperature, Forming Velocity, Springback

1. INTRODUCTION

To enable forming mechanisms in fibre-reinforced thermoplastics, a heating step is required. The matrix material is plastified and the reinforcement fibres elastically deform and may move through the matrix to fit the forming tools surface. In a cooling step, the matrix solidifies, preserving the fibre condition. Due to the temperature change, anisotropic thermal behaviour and different heat transfer conditions during processing residual stresses arise, causing distortions [1, 2, 3, 4]. Those distortions result in spring-in of bent parts. [1] and [2] give predictive calculations of spring-in considering thermal residual stresses.
For thermoplastic tapes being draw bent, not spring-in but springback is observed, which suggests that other residual stresses need to be accounted for. In this paper, a bending processes of thermoplastic tapes is analysed to develop a forming model that can be used for analytical springback calculation. A rotary draw bending process for thermoplastic tapes is set-up and the influence of different forming velocity and forming temperatures on the resulting radii is shown. Also, two different bending strategies and their influence on fibre alignment in bent parts is discussed.

2. SPRINGBACK MOMENT DUE TO MECHANICAL RESIDUAL STRESSES

For ambient temperature the assumption is made, that reinforcement fibres and thermoplastic matrix build a solid coupling. If the fibre distribution is evenly in through-thickness direction, the ideal bending moment M_i may be calculated using beam theory

$$M_i = \frac{E_c \cdot I_c}{R_m} \quad (1)$$

$$I_c = \frac{w \cdot t^3}{12} \quad (2)$$

with the representative modulus of the composite E_c, the moment of inertia I_c of the composite, the radius R_m being the middle radius of the bent specimen, the tape width w and the tape thickness t.
For high bending factors as for thin tapes being bent by relatively large radii, the local maximum bending stress does not exceed the yield strength of the composite components and bending occurs elastically. Therefore, the springback moment

$$M_s = M_i. \quad (3)$$

This leads to a full springback with release of the bending load.

These assumptions cannot be kept with increase in temperature. The coupling weakens due to the softening of the matrix. With increase in temperature, fewer shear is transmitted, leading to inter-fibre slip and fibre movement.

3. EXPERIMENTAL SET-UP

3.1 Set-up and procedure

For this investigation, a rotary draw bending process was chosen. Due to the tension force used to induce the bending moment, fibre buckling is prevented. Because of the instability of the tape when heated above the matrix melting temperature, a full-supported forming zone is also favoured compared to a free form bending process.
The experimental set-up for the bending process was carried out as shown in figure 2 on a hydraulic bending machine at the chair of forming technology.

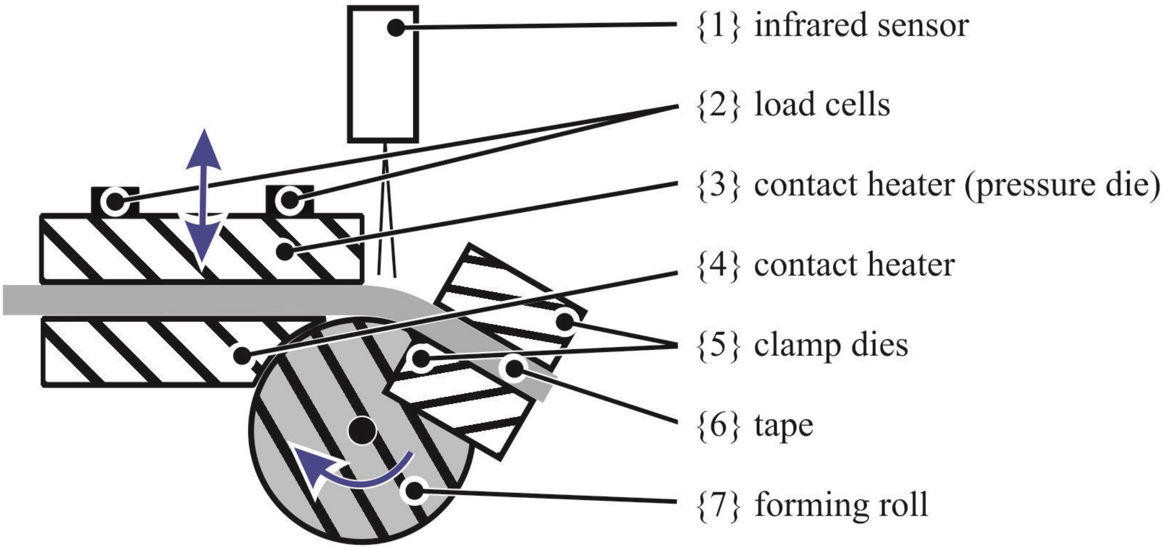

Figure 2: Rotary draw bending of unidirectional thermoplastic tapes

The tape specimens {6} according to table 1 are fixed between the clamping dies {5} and bent around the forming roll {7}.

Table 1: Specimen properties

Property	Value	Unit
Matrix Material:	Polypropylene	
Melting Temperature:	173	°C
Fibre Material	Glass	
Fibre Volume Content	44	%
Tape Thickness	0.26	mm
Tape Width	20	mm
Tape Length 1	300	mm
Tape Length 2	150	mm

In the experiments, two dimensions for specimen -with a length of 150 mm and 300 mm, respectively- are chosen. This accounts for two different forming tasks. For the short specimens a 90°-bent is achieved with the specimen being completely heated. For long specimens 90°-bents leave part of the specimen unheated.
The outer contact heater {3}, which is also used as pressure die, is attached to two load cells {2} measuring the counter force of the induced bending moment. The die can be moved normal to the specimen surface to simplify the insertion of the specimens and to adjust the contact pressure. To assure a homogeneous heating to a defined forming temperature, contact heaters {3} and {4} are used. Copper was chosen as construction material to endure forming temperatures from ambient temperature to about 200°C and offer a homogeneous temperature distribution due to its high heat conductivity compared to steel. Close to the forming area (15 mm from end of pressure die) an infrared sensor {1} measures the post-bending temperature to obtain a qualitative result describing the cooling rate. After bending, the clamping dies are detached and the specimen removed.
It is remarked, that the specimens where cut out of a coil. Therefore, they were not straight but pre-bent. In the experiments all specimens were inserted towards the pre-bent.

3.2 Measurement and analysis of process parameter

The temperature of the contact heaters, and therefore the initial forming temperature is controlled and measured by thermocouple elements. To ensure a full heating of the specimen the minimum heating time was determined. A thermocouple element was attached between two tapes and this specimen was inserted in the contact heaters. The time to reach forming temperature between the two tapes was recorded and set to be the minimum heating time for a single layer process.
In rotary draw bending processes according to [5], the normal force F_n at the pressure die is calculated using the ideal bending moment in

$$F_n = M_i \cdot \frac{3}{l_{pd}}, \quad (4)$$

with l_{pd} being the length of the pressure die. The factor 3 derives from the assumption of a distributed load over the pressure die to calculate the lever arm for the normal force. For solid state of the matrix, the calculated counter force F_c using (6) equals 0.55 N for the given tape.

4. RESULTS OF FORMING EXPERIMENTS

The specimens are evaluated in respect to geometrical changes (e.g. springback, dimensions), the counter force and post-bending temperature for the variations in process parameters.

The geometrical change of the specimens bent with forming temperatures T_f (Temperature steps: ambient temperature (a. t.), 150°C, 160°C, 170°, 180°C) can be seen in figure 3.

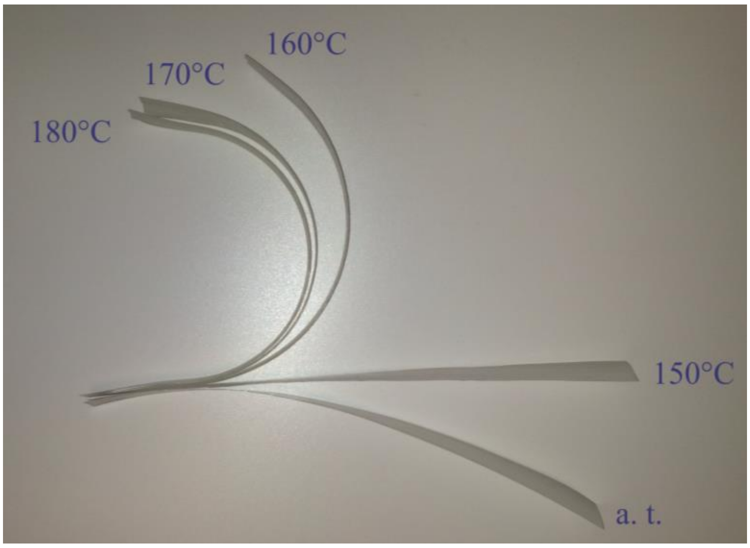

Figure 3: Geometrical shape of specimen for different forming temperatures

The specimens bent under ambient temperature show no measured geometrical differences to their initial state. Whereas, the pre-bent radius of specimens bent at 150°C is straightened. With forming temperatures above 160°C, the springback reduces significantly with increase in temperature as shown in figure 4. Also, the variance of the resulting radii decreases. For the specimens of the experimental series demonstrated in figure 4, it is not measurable for a forming temperature of 182.5°C.

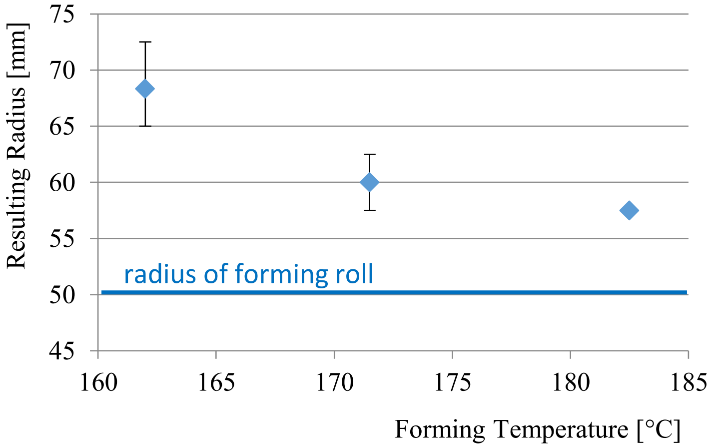

Figure 4: Resulting radii in respect to forming temperature for a constant bending velocity (v_1=19°/s)

With change in velocity, the resulting radii change as illustrated in figure 5. The differences between the varied velocities are only small.

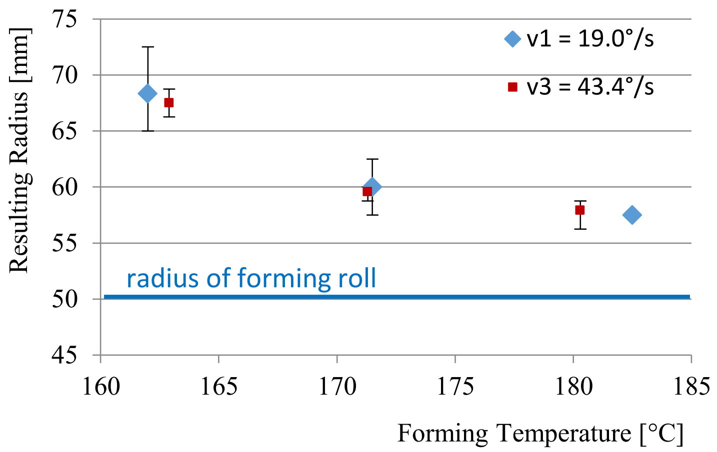

Figure 5: Change in resulting radii for different forming temperatures and two bending velocities

Also, the influence of the specimen type is evaluated. The results obtained in a fractional factorial experiment series are visualized in figure 6.

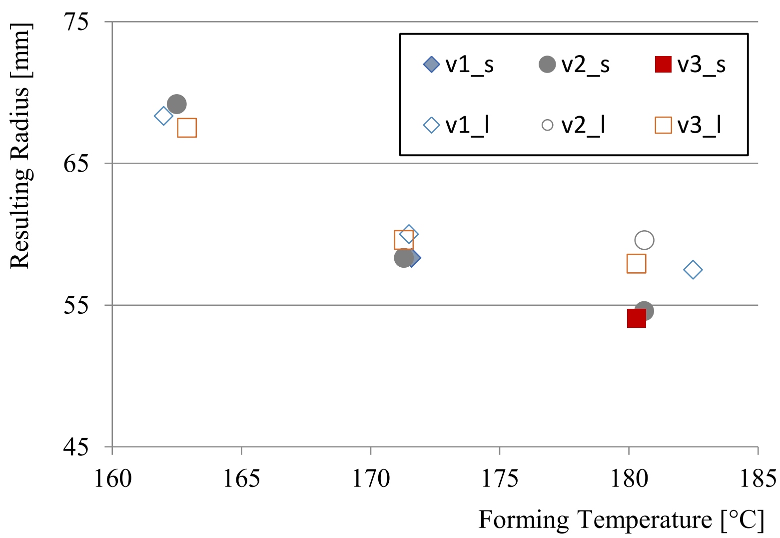

Figure 6: Resulting bending radii for different forming temperatures, forming velocities (v_1=19°/s, v_2=26°/s, v_3=43°/s) and specimen dimensions (s=short, l=long)

The short, fully-heated specimens show a reduced springback compared to the long, partly-heated specimens for high forming temperatures. The differences in springback due to the bending velocity appear to be low, as well.

Further, the counter forces during the bending process were measured. The obtained results for the difference of the counter force at the end of bending and after loosening the clamping dies are printed in figure 7. With increase in temperature, the counter force reduces. For high temperatures, the counter force appears to converge.

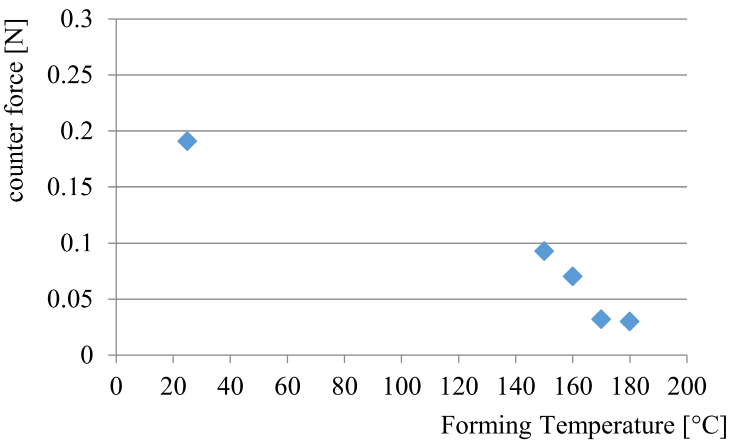

Figure 7: Counter forces on pressure die for different forming temperatures (forming velocity v_3=43°/s)

In comparison to the calculated counter force for specimens being bent at ambient temperature (0,55 N) the measured forces are lower.

5. DISSCUSSION

The results show, that for the examined tapes an increase of temperature leads to a decrease in springback. With increase in temperature, according to [6] the resistance of the matrix reduces. Therfore, the transmitted forces on the fibres are expected to reduce, which is supported by the counter force measurements exhibiting a decrease in force for higher temperatures.

For temperatures below the melting temperature, however, the resulting change in shape of the specimens is low. A thermal activated or accelerated reduction of internal stresses may have straitened the tape at a forming temperature of 150°C. In [7] it is shown, that polypropylene does not have a melting point but a melting zone. For 160°C the melting process already starts. For 173°C the matrix is completely molten. Due to a semi-molten state of the matrix the differences in formability of the tape and a higher variance of measured radii is expected for temperatures in between.

The smaller resulting radii for fully heated specimen than for partly heated specimen suggest that residual forces decrease, or are not built up as high as with a restriction of the forming zone by solid matrix. The forming mechanism for the specimen types are modelled in figure 7.

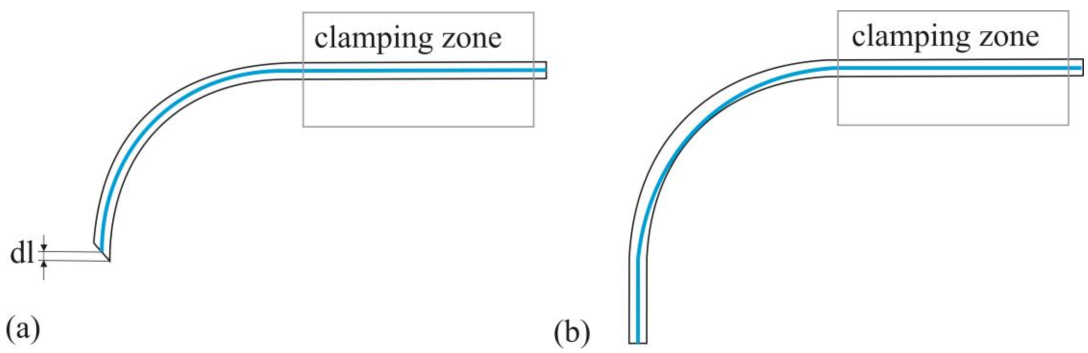

Figure 7: Model of through thickness fibre alignment in bent, thermoplastic tapes with free (a) and fixed (b) ending

The models show inter-fibre slip for (a) and matrix migration/fibre movement towards the inner arc in (b). In fact, both forming mechanism are expected for each specimen type in a specific ratio. These models can be used to set up a calculation model to obtain the ideal bending moment for heated tapes.
The formula for calculating the counter force using the bending moment needs to be revised, though. The assumption of a distributed load on the pressure die may become invalid, because of the low stiffness of the tape.
Due to the differences in tape thickness and width over the full length of the specimens, differences in counter force arise.
For the set-up of bending processes for thin tapes, this investigation suggest, that forming temperatures should be well above the melting temperature of the matrix to reduce residual stresses.

6. CONCLUSION AND FORECAST

A rotary draw bending process was set-up to gain an understanding of the influence of forming parameters as initial forming temperature, forming velocity and heating strategy.
In further investigations, it is necessary to examine the resulting fibre alignment to derive a calculation model. Micro sections show good contrast between fibres and the matrix, but due to the small tape thickness and the need to fix the specimen for polishing, the specimens need to be cut. The alignment of the section and the mapping is challenging. Therefore, micro section might not be appropriate for those investigations and the applicability of computer tomograms or other raying techniques should be determined, instead.
To cope with the high variance of the results the experimental series needs to be extended. In addition, an experiment is set-up to investigate the friction force for the different forming temperatures at the contact heaters and account for them in the calculation.

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