Determination of the Mechanical Properties of Oriented Short Fibre Reinforced Thermoplastics under Different Stress States

F. Becker*, A. Kraatz, M. Moneke
*fbecker@dki.tu-darmstadt.de

Deutsches Kunststoff-Institut (DKI), Darmstadt, Germany

Abstract:

This paper presents several methods to examine fibre reinforced specimens at the three principle stress states and at different fibre orientations. The specimens for the different stress states were machined out of the same injection moulded high oriented test bar. The specimen preparation allows load directions in and perpendicular to the fibre orientation. From these experiments the influence of the fibre orientation on the material properties can be determined.

Keywords:

tension, compression, shear, material data, fibre, reinforced

1 Introduction

As mechanically loaded construction parts are increasingly made from polymers, reinforced polymers are getting more and more important. Different fillers like fibres, glass beads or mineral fillers are incorporated in polymers to improve the mechanical properties of injection moulded parts. The specific flow profile of the melt during the injection moulding process leads to a heterogeneous orientation of the incorporated fibres. Hence the injection moulded parts have a complex fibre orientation with a complex mechanical behaviour.

To describe the mechanical behaviour of parts made from polymers it is necessary to describe the mechanical behaviour with a material model [1] [2]. To apply these models to the finite element analysis (FEA), parameters specific for each material are needed. These parameters can be obtained from different mechanical tests e.g. experiments at uniaxial stress states. The principle stress states, resulting from the main forces, are uniaxial tension, compression and shear. For reinforced polymers the orientation of the sample has to be considered. These tests should be performed for an uniaxial orientated specimen in order to yield an orthotropic symmetry in the specimen.

With injection moulding simulation programs the fibre orientation of construction parts can be calculated and transferred into a finite element program (FEM). Each single element of the finite element mesh is described by orthotropic material properties depending on the calculated fibre orientation in the element.

In this study a method is introduced to determine the mechanical properties of a fibre reinforced injection moulded polymer for different fibre orientations and different stress states. The specimens are made from the same injection moulded geometry. The aim of the new method is to determine all relevant parameters to create material cards for reinforced polymers. The material cards can be used for the FEM simulation.

2 Experimental setup

Specimen geometry

At the DKI three specimens for tests with three different uniaxial stress states were developed (Fig. 1). For comparing the results these specimens were cut out from the same injection moulded geometry. This can be a plate or a broad tension bar. The fibre orientation can be chosen in or perpendicular to the testing orientation.

Fig. 1 shows the geometries for the three different stress states. In Fig. 2 the real specimens with the fixtures for compression and shear tests are shown. The geometry for tension follows the geometry for classical tension bar (Fig. 1-a). The parallel part has a width of 12 mm to get a more accurate lateral strain for the calculation of the Poisson’s ratio.

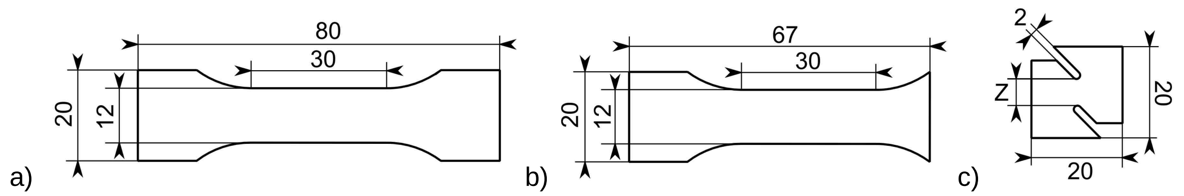

Fig. 1: Specimen geometry for three stress states: tension (a), compression (b), shear (c)

For the compression tests the tensile bar was cut at the lower end (Fig. 1-b). To prevent buckling a fixture was used (Fig. 2-b) which was mounted at the testing machine. The upper end of the specimen was clamped in the machine like in tensile tests. Because of this fixture the maximum reachable strain was limited to $\varepsilon = 0.15$. The open area in the fixture allows the tracking of the specimen by an optical system.

To perform shear tests, a fixture (Fig. 2-c) was developed to apply the square specimen (Fig. 1-c) to the testing machine. The specimen was bonded to the fixture and both clamped in the testing machine. In relation to former specimen geometries [3] this specimen can be rotated to get different fibre orientations. The length of the shear zone Z between the two notches can be adapted depending on the material.

The thickness of the specimens is variable and depends on the available base material. Good results were achieved by using a thickness between 2 and 4 mm. All tests can be done on a standard uniaxial testing machine without modifications.

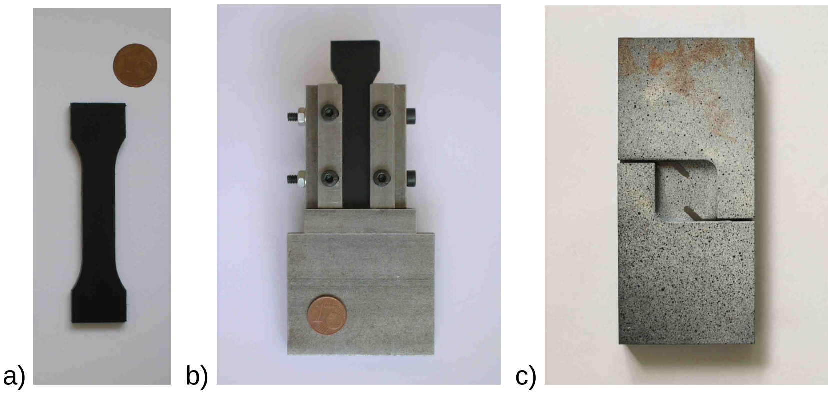

Fig. 2: Real specimen and clamps for three stress states: tension (a), compression (b), shear (c)

Sample preparation

To test fibre reinforced materials and determine the influence of the orientation highly orientated specimens are needed. Fig. 3 shows the geometry of a tensile bar including the inlet which was developed at the DKI [4]. The convergent inlet results in a specific melt flow. From there the fibres in the parallel part are highly orientated in the flow direction.

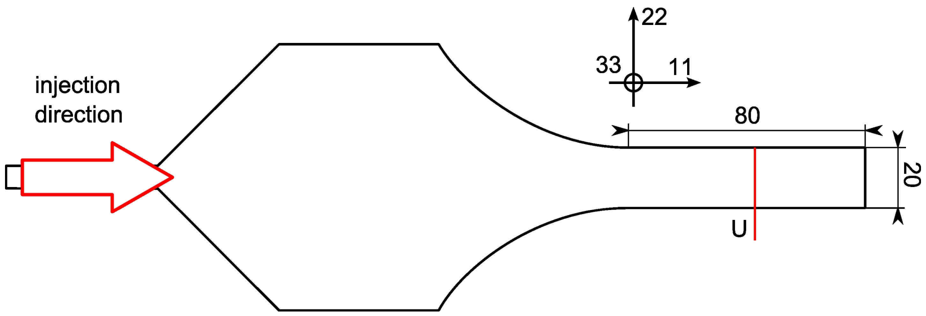

Fig. 3: Geometry of the injection moulded test bar with high fibre orientation [4]

The quality of the orientation is shown in Fig. 4. This orientation was measured at PBT with a fibre concentration of 10%. The diagram shows the values of the orientation tensor along the thickness of the tensile bar at position U. The values are averaged along the width of the specimen. The diagram shows that the orientation tensor has a high value around 0.8 in the flow direction a11 and a very small deviation along the thickness.

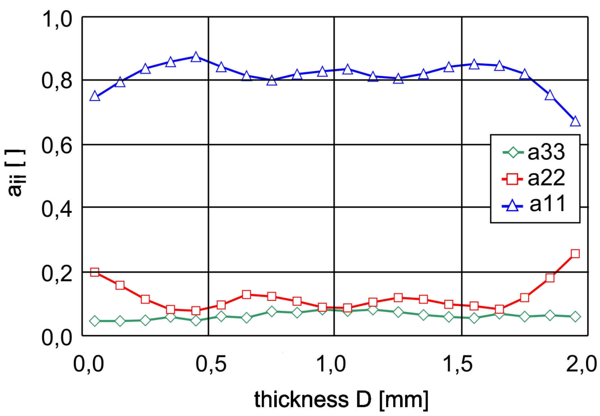

Fig. 4: Orientation scheme of the test bar (Fig. 3) at position U [4]

Fig. 5 shows the preparation position of the specimens in the high oriented test bar. The specimens were machined out by CNC milling. For the tension and compression tests at an orientation of 90° the specimens were machined out of small pieces with an orientation of 90°. For this four pieces were welded together to the test bar length.

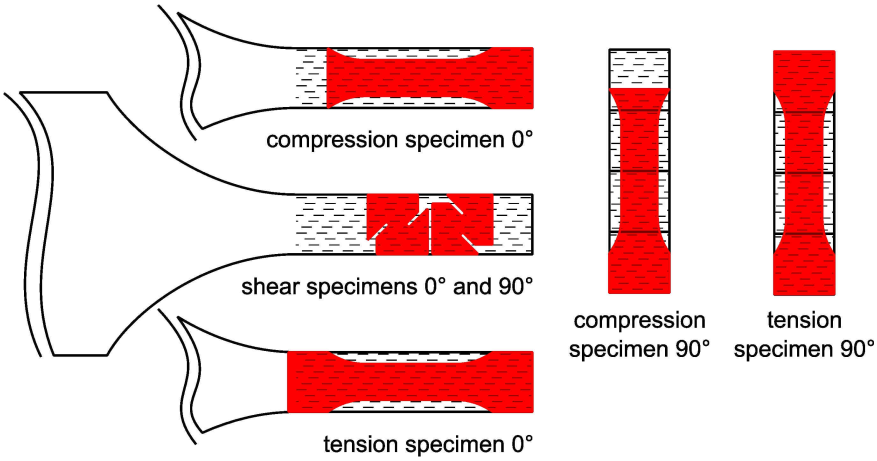

Fig. 5: Fibre orientation in the specimens

Machine setup and data measurement

All tests were performed on an uniaxial testing machine (Zwick Z020). The specimens were clamped with a pneumatic system with compensation of the axial clamping forces. The force was measured by a load cell applied at the lower clamp. The displacement was measured by a capacitive displacement transducer applied between the clamps. The test speed for all tests was 1 mm/min.

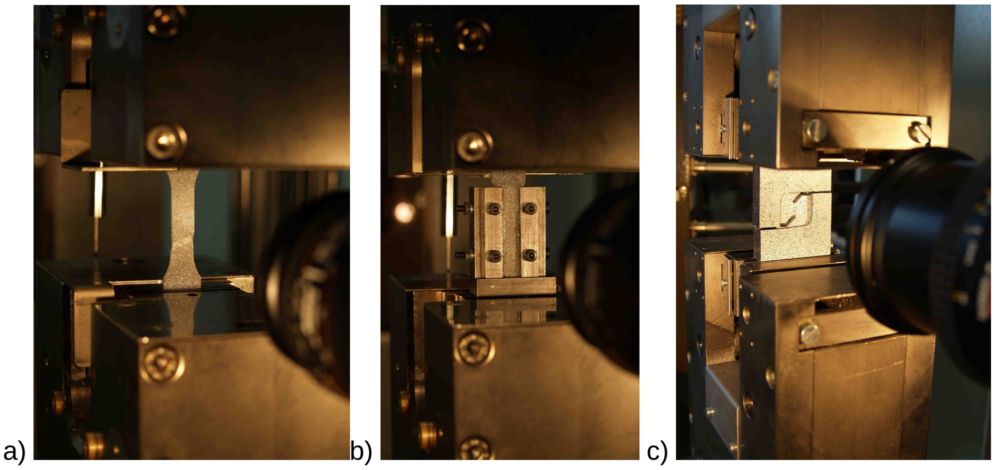

Fig. 6: Machine setup at for the different stress states: tension (a), compression (b), shear (c)

The strain for all stress states was measured by an optical system using the grey scale correlation. The system comprises a black-and-white CCD-camera with a resolution of 1280 x 1024 px and a colour depth of 8 bit. The scale of the pictures is 8 µm/px. A maximum of 250 pictures of the speckled specimen for each test was taken with a frequency of around 1 s. For the strain determination the 2D correlation software Vic2D of Limess GmbH was used.

3 Experimental results

In this paper all tests are performed with a fibre reinforced polycarbonate of Bayer AG. The fibre content was 10%. The specimens were tested until failure occured.

To explain the results from shear experiments, a closer analysis of the shape of the shear deformation and also the mechanism of the deformation of the sample is necessary. For this purpose the pictures from the experiment were analysed under different aspects: Two of these pictures are shown in Fig. 7 at two different strain states before and after the failure.

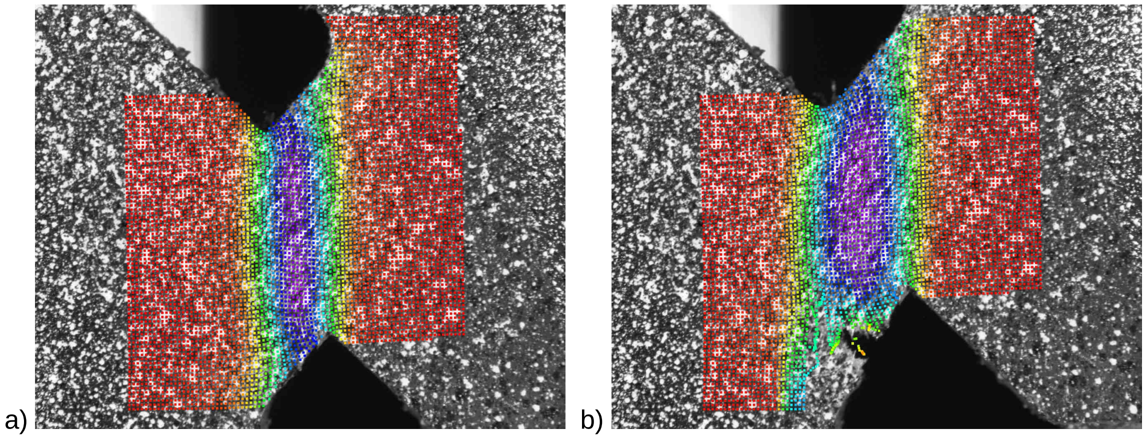

Fig. 7: Pictures of the shear field plotted with shear strain distribution in the correlation area at different strain levels before (a) and after (b) the failure

Fig. 8 shows the different types of locations and orientations used in the following analysis: The shear direction is along the virtual line between the two notches (in all analyses the y-direction). The shear field specifies the area around the shear line in x- and y-direction. The shear area is the area between the two notches in the third z-direction. The fibre orientation can be parallel (0°) or perpendicular (90°) to the shear direction. Further on there are the directions for the extraction of several values along (y-direction) and across (x-direction) the shear direction.

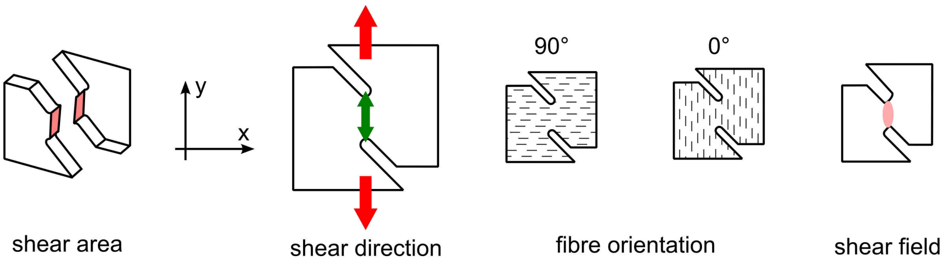

Fig. 8: Definitions of the different positions and directions at the shear specimen

The in-depth analysis of the pictures is important for the later determination of the stress-strain diagram and the material properties. The two important aspects of a shear test are the shape of the shear area [5] [6] and the generation of a defined shear stress state.

The first aspect can be checked by analysing the whole shear field of the specimen. Fig. 9 shows the 3D-shape of the shear field calculated from Fig. 7-a. This displacement of the traverse was *v = 2.2 mm* and the maximum shear $\varepsilon_{xy} = 0.6$. At this position there was no failure of the specimen yet. One can notice that the shape of the shear field has a very small width and a constant height at the maximum between the two notches.

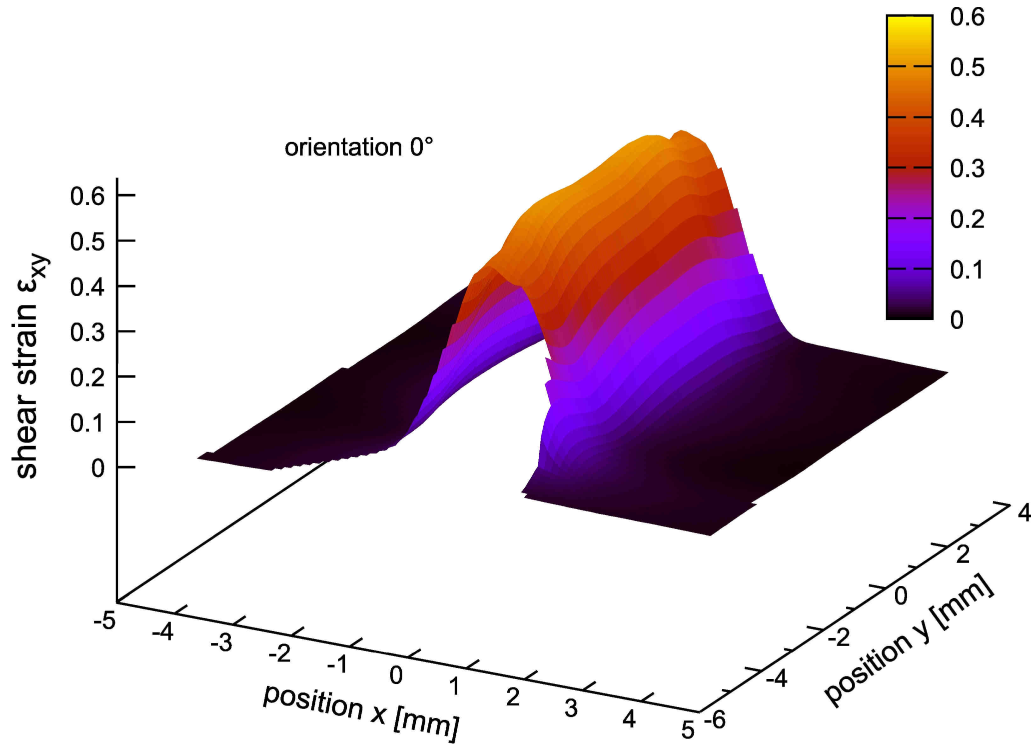

Fig. 9: 3D-shape of the shear field

A detailed description of the shape of the shear field is shown in two sectional views along the x- and y-direction in Fig. 10. The centrel point of the sample *(x = 0, y = 0)* is the centre of the shear field between the two notches. The width of the notch base, *2 mm*, is marked by two vertical green lines (Fig. 10-a). The pink horizontal line indicates the strain at yield stress ($\varepsilon_{xy} = 0.049$) for an orientation of 0°.

The yield stress was determined from the stress-strain curve (Fig. 14). Below this point the material is still in the elastic state and above this point the material yields. Fig. 10-b shows the distribution of the shear strain along the y-direction at *x=0*. Only at the notches there are decreasing of the values.

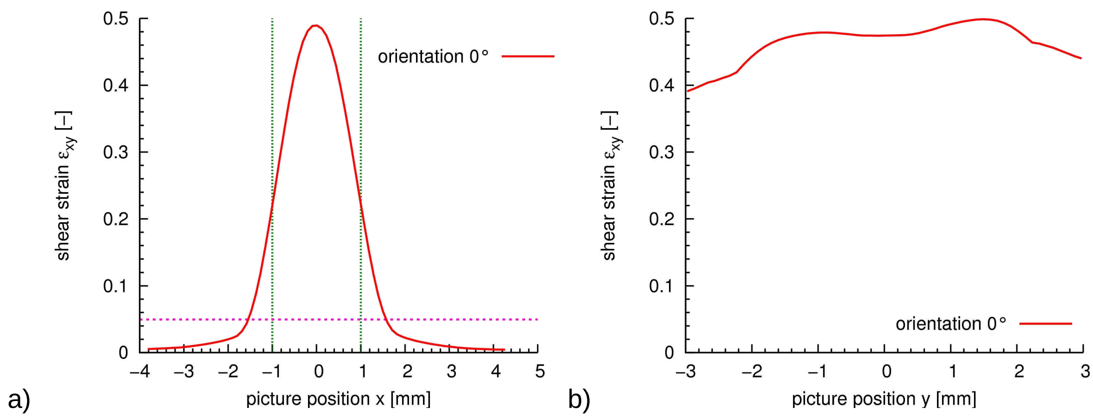

Fig. 10: Quality of the shear zone in shear direction –
along shear direction (a) and across the shear direction (b)

The propagation of the shear field can be extracted from time resolved plots of the sectional views (Fig. 10) of the shear field, see Fig. 11. This shows the shapes along the x- and y-direction at different displacements of the traverse. One can notice that the borders left and right of the peak (Fig. 10), defined by the strain at yield stress, of the yielding area tend toward a limit value.

Out of these analyses of the shape of the shear field, the following procedure is chosen for determining the stress-strain curve. Because of the softening of the material (Fig. 14) at increasing shear strain the measured force were related to the area of the highest shear strain. In this area the deformation values correlated by the Vic2D software was averaged. Therefore the yield areas left and right to the centre points are not considered.

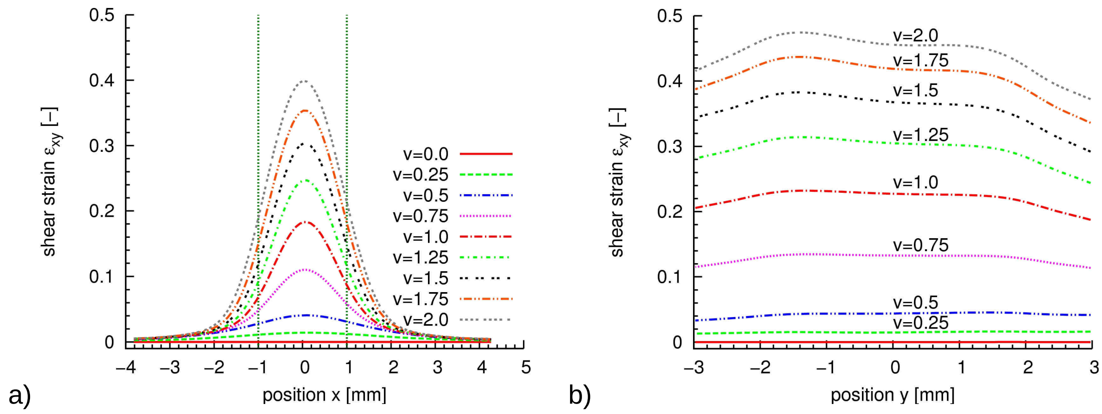

Fig. 11: Propagation of the shear zone at different displacements v of the traverse – along shear direction (a) and across the shear direction (b)

The second quality aspect is the actual stress state. To explain this, we need to differentiate between simple and pure shear (Fig. 12). Both result from the same direction of the force. In the case of simple shear there is a superposed tension strain because of the disabled displacement of the upper edge. This tends to the elongation of the sample in x-direction. This elongation results in a tension strain in one direction. At pure shear, there is only a shear deformation and no elongation and, therefore, no strain of the edges.

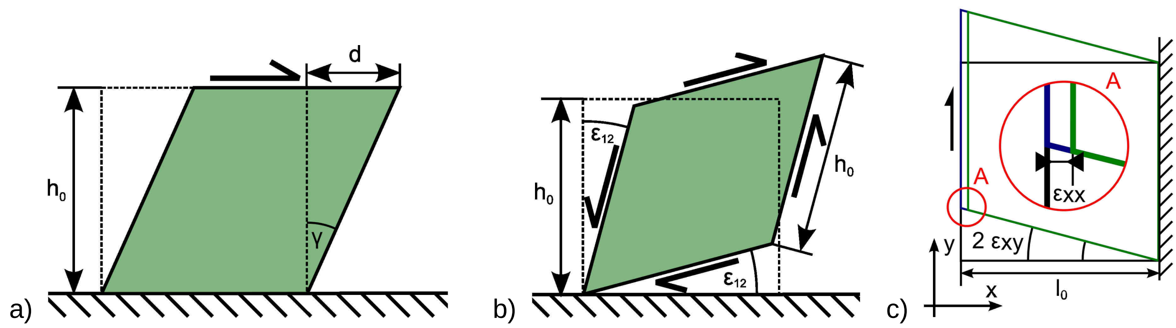

Fig. 12: Simple (a) and pure (b) shear and relation between both (c)

For the further processing of the data it is important to determine the shear type of the tests. An indicator of the shear cases is the elongation or the tension strain described before. The relation between the superposed tension strain and the shear strain as shown in Fig. 12–c is

$$\frac{\Delta l}{l} = \varepsilon_{xx} = -\cos(2\varepsilon_{xy})\,. \tag{1}$$

Fig. 13 shows the calculated and the measured tensile strain for the two orientations 0° and 90°. For an orientation of 0° the calculated and measured strains have the same progression. This is because there is only a simple shear state in the specimen. In the other direction there is a difference between the two curves. This is due to the obstruction of the lateral strain ε_{xy} by the fibre orientation. The same effect can be seen at the lateral strain within tensile tests.

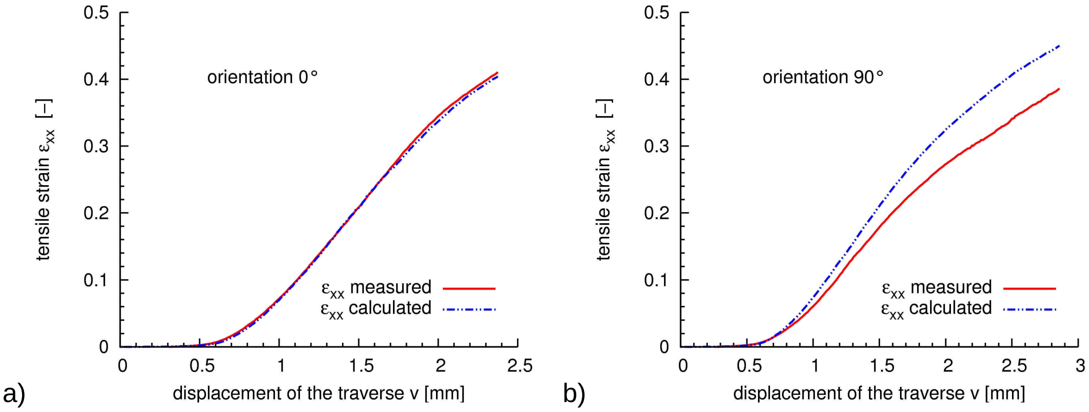

Fig. 13: Relation between simple and pure shear and calculated relation from shear tests – fibre orientation 0°(a) and 90°(b)

Fig. 14 shows the resulting stress-strain curves for the shear tests at different fibre orientations. The two curves are the mean of five iterations drawn with two times the standard deviation as error bars. In the elastic region of the curves there are no differences between the two fibre orientations. The differences starts after reaching the yield stress. The specimens with an orientation of 90° show a higher yield stress than the specimen with an orientation of 0°.

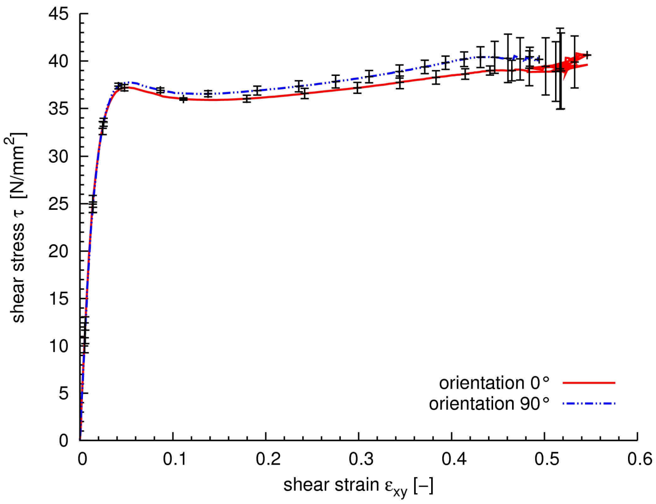

Fig. 14: Shear stress – differences between an orientation of 0°and 90°

Referring to the results shown in Fig. 13 and Fig. 14 a fibre orientation of 90°with a fibre concentr ation of 10% yields an approximate by 10% higher strength of the material at yielding. For the behaviour of the material in the elastic area there is no evidence for an influence of the fibre orientation

4 Conclusion and Outlook

This work presents several significant tests to get information about the mechanical material properties of reinforced thermoplastics under the three principle stress states: tension, compression and shear. For reinforced polymers the mechanical properties are related to the fibre orientation. Therefore the use of highly uniaxial oriented specimens is essential. An injection moulded tension bar is developed to realize high oriented specimens. Out of the parallel part, specimens for tension, compression and shear tests in and perpendicular to the fibre direction can be machined out.

The results of the shear test with a 10% glass fibre reinforced polycarbonate show the significant influence of the fibre reinforcement. The effect should be increasing by increased fibre concentration. Also the lateral strain at shear stress shows a dependency on the fibre orientation. This influences the shear stress state and the interpretation of the experiment because it is necessary to differentiate between simple and pure shear.

Further the methods can also be used to test materials at high strain rates. Also correlations with micro mechanical models are possible to confirm the accuracy of the models. Another possibility is to perform test with bonded specimens to get material data of the bond.

5 Acknowledgement

Financial support from the Federal Ministry of Economics and Technology [Bundesministerium für Wirtschaft und Technologie (BMWi)] through the Federation of Industrial Cooperative Research Associations “Otto von Guericke” [Arbeitsgemeinschaft industrieller Forschungsvereinigungen “Otto von Guericke” e.V. (AiF)] (AiF-No. 14795 N) is gratefully acknowledged.

6 References

[1] KOLUPAEV, V. A.; MONEKE, M.; BECKER, F.: *Mehraxiales Kriechen von Thermoplast-Formteilen*. Fortschrittsberichte VDI 703, VDI Verlag GmbH, Düsseldorf, 2005

[2] JUNGINGER, M.: *Characterisierung und Modellierung unverstärkter thermoplastischer Kunststoffe zur numerischen Simulation von Crashvorgängen*. Universität der Bundeswehr, München, Diss., 2002

[3] IOSIPESCU, N.: *New accurate procedure for single shear testing of metals*. Journal of Materials, **3**, pp. 537-566 (1967)

[4] AMBERG, J.: *Ermittlung temperaturabhängiger anisotroper Stoffwerte für die Spritzgießsimulation.* AiF-Projekt 13220, Köln, 2004

[5] *Standard Test methods of Shear Properties of Composite Materials by the V-notched Beam Method*. ASTM Designation: D 5379/D 5379M – 39 (1993)

[6] MELIN, N.: *A Modified Iosipescu Shear Test For Orthotropic Materials*. Kungliga Tekniska Högskolan, Stockholm, M. Sc. Thesis, 2003