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Out-of-Plane Biaxial Tests of Thermoplastics

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Abstract: *To determine the biaxial deformation and failure behavior of elastomers and thermoplastics a novel testing device along with data acquisition and data reduction software tool was developed and the first results are described in this study. Thin disc shaped specimens are pressurized and in the bulge an out-of-plane biaxial displacement state is realized. Due to the compact form, full-field optical measurements are also possible and were used for determining the biaxial strain components in these experiments. In addition to the monotonic pressure control, cyclic tests with various loading shape can also be performed. The comparison between two polypropylene grades revealed differences both regarding the biaxial yield stress and the volume strain in the post-yield regime.*

Key words: *bulge tests, thermoplastics, measurement of biaxial strain, calculation of true stress.*

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1. Introduction

A number of engineering polymers are exposed to complex loads which results in a biaxial stress/strain state in specific components (e.g., large thermoplastic panels, carbon and glass fibre fabrics and reinforced composites and elastomers and elastomer composites). Hence, the determination of relevant deformation and fracture properties under monotonic and cyclic biaxial loading conditions is of prime practical importance.

Due to the large degree of deformation, the characterization and modeling of the biaxial deformation of engineering polymers is a challenging task. For elastomers, the out-of plane biaxial test (stretching of balloons in bulge tests) is widely used to determine parameters for various hyperelastic material models which are applied in finite element models to describe the large deformations for elastomers [1-3].

The nominal stress can analytically be calculated and the biaxial strain measured by optical methods during these experiments. This method can effectively be used to determine material models for elastomers under stress/load controlled conditions. The following restrictions were observed and considered in the previous model [4-5]:

- due to the pressure change, the test is essentially load controlled and the strain rate is not constant in the material during the pressurization.
- due to the practical pressure limit of these test systems, the stiffness range of the specimens applied is mostly restricted to the low stiffness range (i.e., elastomers or other soft materials).
- the application of cyclic loads is also complicated and is possible over a very low frequency range (up to about 0.01 Hz).

To overcome above limitations an in-plane biaxial test system was developed and implemented [6]. However, the determination of relevant stress values is difficult in-plane test [7] and in one driven axis the deformation is limited up to about 50 %.

In spite of the fact that biaxial stress state is one of the most relevant for many thermoplastic components and complex micromechanics simulations require material data in the biaxial loading regime, hardly any data are available for thermoplastics [8]. Hence, based on previous experience of the characterization of the biaxial deformation behavior of elastomers, a novel testing device for characterizing both elastomers and thermoplastics in biaxial stress state was developed and implemented. The test system is able to perfume test under the following conditions:

- Monotonic internal pressure control
- Cyclic pressure control (up to about 0.5 Hz, depends on the strain level)
- Local strain control based on the image of the DIC system both using monotonic and cyclic signals

A screen shot of the cyclic module is shown in Fig. 1.

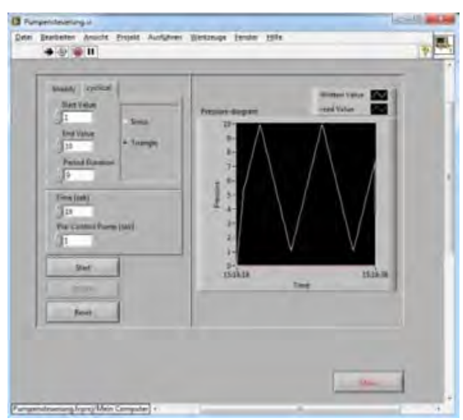

Fig. 1. *Screen soft of the LabView control software tool.*

In addition to the higher stiffness, there are significant differences between elastomer and thermoplastic tests. While elastomers reveal large scale reversible hyperplastic deformations over a very wide strain range (up to several 100 % of strains) and the volume constant is a plausible assumption (Poisson's ratio is appr. 0.5 or very close to this value), thermoplastics reveal an elastic plastic behavior. Based on a number of uniaxial tensile tests and several planar tensile tests, the biaxial yield strain is assumed in the range from 3 to 10 %. The Poisson's ratio is not equal to 0.5 neither in the elastic nor in the plastic deformation range. This indicates different amount of volume change.

Cyclic loading may be used for determining adequate parameters of Mullins models for finite element simulations in short time tests (N < 20 cycles) and for long-term fatigue tests (up to 10^6 cycles) under biaxial conditions for elastomers. To accelerate these tests however, a suitable artificial strain concentration must be introduced into the test specimen. The FE simulations regarding this task are ongoing.

The objective of this paper is the description of the biaxial test system along with the proper test methodology used for selected thermoplastic under pressure controlled monotonic loading.

2. Experimental

2.1. Development of Test Device

A novel test device applying pressurized air up to 10 bar was developed and implemented in the laboratory. To ensure material relevant loading, a low pressure set-up for elastomers (up to 2 bar) and a high pressure set-up (10 bar) for thermoplastics was implemented. Both set-ups consist of the pressure vessel along with various fixtures, programmable pressure valve along with control and data acquisition electronics and software (CompactRIO, LabView, National Instruments, San Antonio, TX, USA). The biaxial strain is measured by a digital image correlation based optical test system (Aramis, GOM, Braunschweig, D). The measurement system is shown in Fig.2. The digital image correlation method was used to determine displacements and to calculate strains. For more information regarding the DIC technique please refers to [9-10].

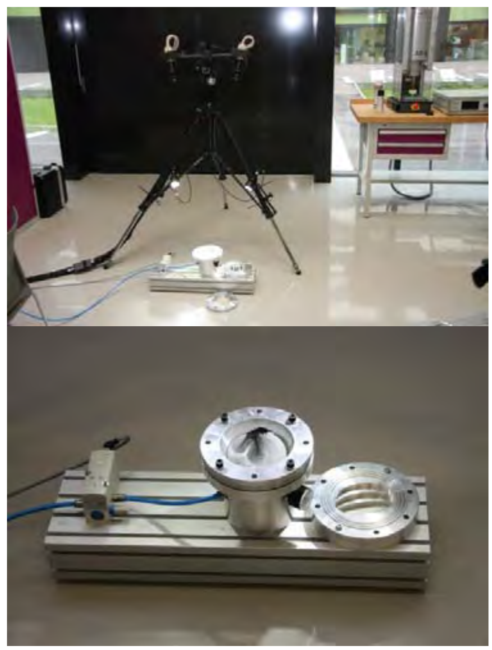

Fig. 2. *Biaxial test set-up (digital image correlation system and pressurization device with specimen.*

In addition to the equi-biaxial deformations for homogenous specimens, non-equi-biaxial tests for anisotropic specimens can also be performed.

2.2. Test Conditions and Data Reduction

There different polypropylene grades (homopolymer, PP(H); beta modified homopolymer, β-PP(H) and a copolymer, PP(RC)) and a polyethylene (PE-HD) were used in these tests.

The pressure rate dp/dt was constant and varied from 0.05 up to 1.25 bar/s. The membrane stress was determined by

$$\sigma = \frac{\Delta p \cdot r_B \cdot \lambda^2}{2 \cdot t_0} \qquad (1)$$

Where p is the pressure, r_B is the radius of the sphere, λ is the stretch and t_0 is the nominal thickness.
The schematic representation of the experimental set-up is shown in Fig. 3. While the pressure and the radius of the sphere can easily be determined (see Fig. 4), considerations are required for the thickness.

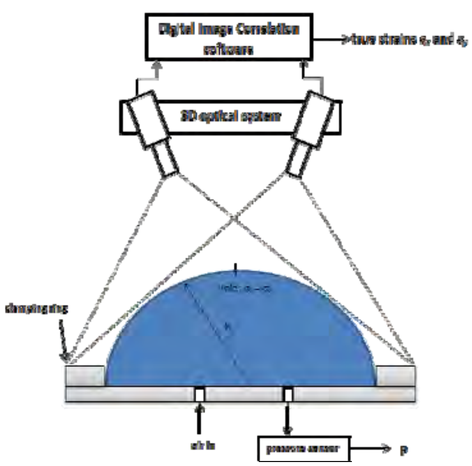

Fig. 3. *Schematic representation of the biaxial measurement.*

The following options are available:

- Constant thickness, $t=t_0$; nominal stress-strain curve
- Constant volume assumption, $t=t_\varepsilon$
- Specific volume strain $t=t(\varepsilon,\varepsilon_v)$; ε_v is determined in uniaxial experiments.
- Measured thickness (not available yet).

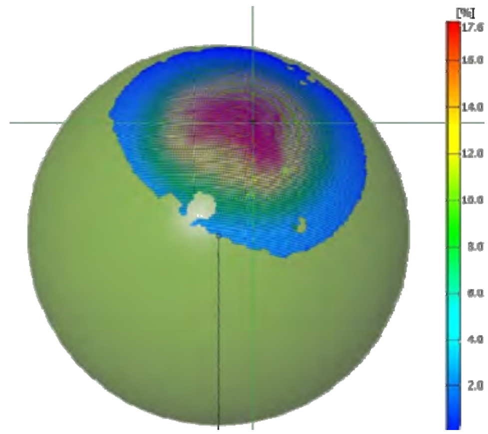

Fig. 4. *Measurement of the actual dimeter of the sphere.*

The biaxial strain components were determined by Aramis and an example is shown in Fig. 5. A vertical (right image) and a horizontal section (bottom image) was defined in the image and strain values were determined along these sections.

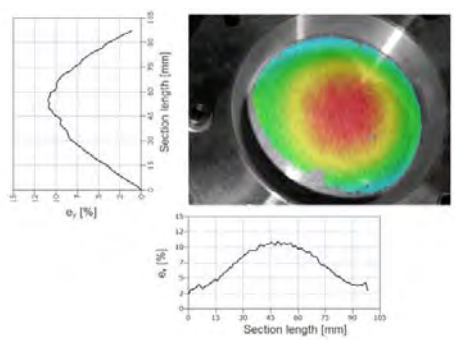

Fig. 5. *Full-field strain measurement with sections for ε_x and ε_y for β-PP(H).*

The spatial distribution of the strain was determined and as it was expected a nearly perfect biaxial strain state was observed during the tests. Furthermore, the temporal strain distribution was determined by using stage values in the maximum point of above diagrams and one selected example is shown Fig. 6.

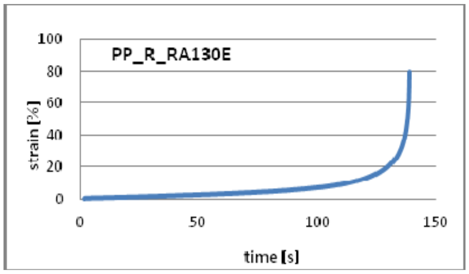

Fig. 6. *Change of the maximal strain during the experiment.*

3. Results

3.1 Method development

To determine adequate material model parameters for elastic-plastic material laws which considers the inherent pressure dependence of the yield and post-yield behaviour, in addition to the conventional uniaxial tests, monotonic pressurization tests which results in an equi-biaxial state are performed and biaxial stress-strain curves are determined. Nominal ($t=t_0$) and true test strain curves (both with $t=t(\varepsilon)$ and $t=t(\varepsilon,\varepsilon_v)$) were determined at various loading rates and an example is shown in Fig. 7. In addition to determine adequate Poisson's ratio values for calculating volume strain values the same DIC method was used in uniaxial tensile tests as for the biaxial test. Examples of these curves are shown in Fig. 8.

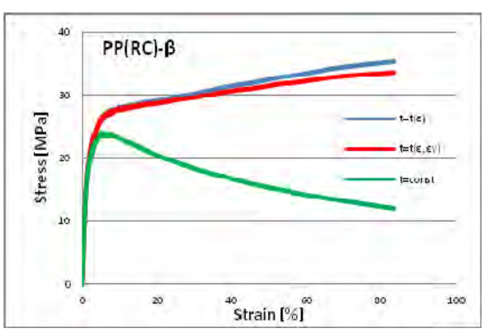

Fig. 7. *Comparison of the various biaxial stress-strain curves for PP(RC).*

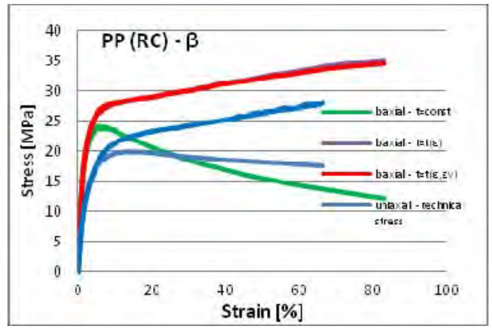

Fig. 8. *Comparison of the various stress-strain curves for PP(RC).*

3.2 Material characterization

The comparison of the deformation behavior of two different PPs (β-PP(H).and PP(RC)) revealed significant differences. The first visual comparison of the strain gradients in the sections revel differences between the two PP materials. Steeper strain localization was observed for PP(RC) (compare Fig. 5 and 9).

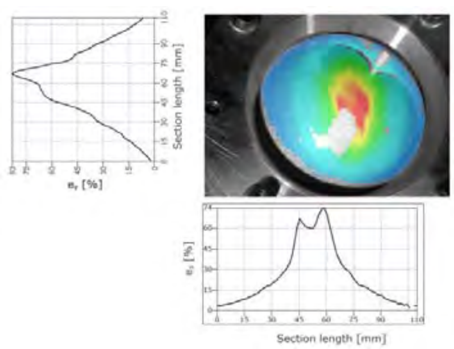

Fig. 9. *Full-field strain measurement with sections for ε_x and ε_y for PP(RC).*

Furthermore, the yield stress is higher for *β-PP(H)* as it is show in Fig. 10. Moreover, while only a minor difference between the true stress-strain curves was observed for PP(RC) (see Fig. 8) a significantly higher difference was observed for *β-PP(H)* and it is shown in Fig. 11. This difference was associated with higher volume strain during the plastic (residual) deformation.

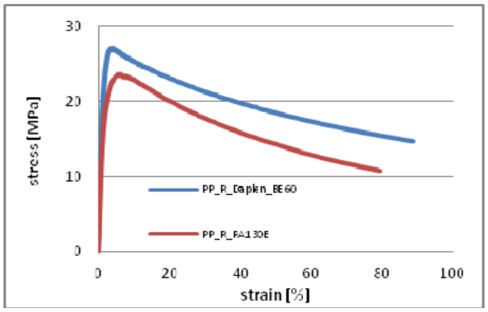

Fig. 10. *Comparison of the nominal biaxial stress-strain curves for β-PP(H)and PP(RC).*

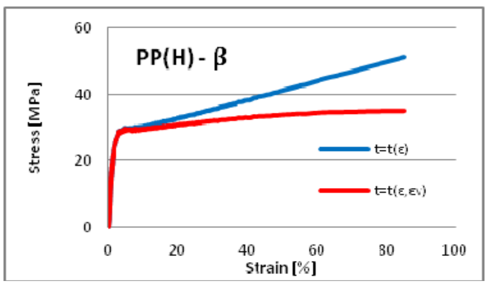

Fig. 11. *Comparison of the true biaxial stress-strain curves for β-PP(H) with the assumptions of t=t(ε) and t=t(ε,ε_v).*

These biaxial stress-strain curves are implemented in material models which consider pressure dependence of the deformation behavior and used for FE simulations.

4. Summary and outlook

A pressurized out-of-plane biaxial test set-up was developed and used for characterizing the large strain biaxial deformation behaviour of different polypropylene materials. Nominal and true stress–strain curves were generated using various assumptions and compared. As expected biaxial stress strain curves are shifted to higher stress values at specific strain values and hence reveal also higher yield stress. Differences between the two PP s were also observed, higher yield stress followed by significantly higher volume strain in the post yield regime for *β-PP(H). T*he next step is the in-situ measurement of the specimen thickness during biaxial loading to calculate more accurate true stress-strain data. These data will be implemented in material models which accounts for pressure (stress state) dependence in the yield and post-yield regime.

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References

1. Jones, D.F. and Treloar, L.R.G.: J. *Phys. D: Appl. Phys.*, Vol. 8, 1975.
2. Reuge, N. et al.: *Polymer Engineering and Science*, Vol. 41, No.3, 2001, pp. 522-531.
3. Murphy, N., Hanley, J., Jerrams, S. and McCartin, J., *Determining multiaxial fatigue in elastomers using bubble inflation*, 4th Europian conference for constitutive models for rubbers, Stockholm, Sweden, 2005.
4. Feichter, C., Major, Z., Lang, R.W, 2006, *Deformation Analysis of Notched Rubber Specimens*, Strain 42, pp. 299-304.
5. Feichter, C., Major, Z. and Lang, R.W., *Method for measuring biaxial deformation on rubber and polypropylene specimens*, Experimental Analysis of Nano and Engineering Materials and Structures, 2007. pp. 273-274.
6. Vezér, Sz. And Major, Z., *Development of an in-plane biaxial*

test setup for monotonic and cyclic tests, 25th Danubia-Adria Symposium on Advances in Experimental Mechanics, Budweis, CZ.
7. Quaak, G., *M.Sc Thesis*, Eindhoven University of Technology, May, 2008.
8. Galliot, C. and Luchsinger, R.H., Uniaxial and biaxial mechanical properties of ETFE foils (EMPA), *Polymer Testing 2011; 30(4):356-365.*
9. Jerabek, M., Major, Z. and Lang, R.W., *Strain determination of polymeric materials using digital image correlation*, Polymer Testing 29 (2010) 407–416.
10. Sutton, M.A., Orteu, J-J. and Schreier, W., *Image correlation for Shape, Motion and Deformation measurements- Basic Concepts, Theory and Application*, Springer, 2009.