Optical measurement of deformation of paper under tensile load

Paul-Philipp Post, Christian Berger, Klaus Villforth, Heinz-Joachim Schaffrath, Samuel Schabel

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SUMMARY: A test method for simultaneous contactless measurement of lateral contraction and change in thickness of paper in tensile testing is presented. All the investigated paper samples showed transverse shrinkage as well as an increase in thickness during loading. Consequently, in-plane Poisson's ratios for different tested papers were positive, whereas Poisson's ratios in thickness direction had negative values. In general, the transverse shrinkage proved to be detectable while the resolution and accuracy of the thickness determination in some cases still requires optimization.

ADDRESSES OF THE AUTHORS: Paul-Philipp Post (post@papier.tu-darmstadt.de), Christian Berger (berger@papier.tu-darmstadt.de), Klaus Villforth (villforth@papier.tu-darmstadt.de), Heinz-Joachim Schaffrath (schaffrath@papier.tu-darmstadt.de), Samuel Schabel (schabel@papier.tu-darmstadt.de): Technische Universität Darmstadt, Chair of Paper Technology and Mechanical Process Engineering (PMV), Alexanderstr. 8, D-64293 Darmstadt, Germany.

Corresponding author: Paul-Philipp Post

If paper is subjected to uniaxial load it extends in the direction of loading but also shows lateral contraction and a change in thickness. These deformations transverse to the direction of stretching are of special interest for a realistic description of the material behavior. They can be quantified by Poisson's ratio: $\nu = -\frac{\Delta d/d}{\Delta l/l}$, where ν is the resulting Poisson's ratio, d the initial thickness and l the initial length. Most materials have positive values of Poisson's ratio, i.e. they contract perpendicular to the direction of stretching. However, there are cases when a material expands when stretched. The phenomenon is called auxetic material behavior (Evans et al. 1991). An example of a simple microstructure that shows auxetic behavior is shown in *Fig 1*. Auxetic material behavior can be shown by natural (single crystals of arsenic and cadmium, iron pyrites, certain forms of skin and load-bearing bones) as well as artificial (honeycomb and foam structures, microporous polymers, fibre-reinforced composites etc.) materials (Alderson and Alderson 2007).

Also paper can be considered to be an auxetic material as it has repeatedly been reported that the thickness of paper can increase when it is subjected to in-plane strain (Göttsching and Baumgarten 1973; Öhrn 1965; Stenberg and Fellers 2002). *Fig 2* gives an illustration of the probable reason for this phenomenon: a stretching of curved fibers.

Handsheets and industrial papers both showed elastic thickness increase during testing. A permanent plastic

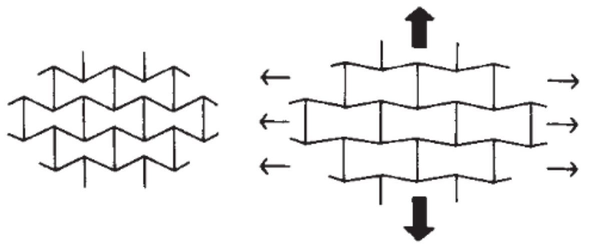

Fig 1. Two-dimensional re-entrant honeycomb, showing transverse expansion on stretching (Evans et al. 1991).

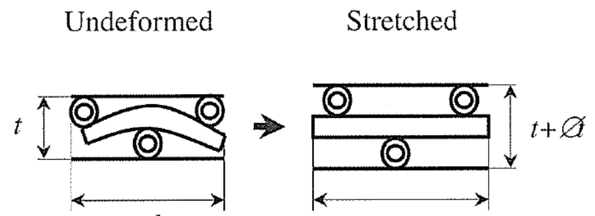

Fig 2."Possible mechanism for the increase in thickness of paper under in-plane loading. Stretching of fibers results in the separation of the transverse fibers causing a thickness increase of the paper." (Stenberg and Fellers 2002).

increase in thickness was only reported for anisotropic papers (Göttsching and Baumgarten 1973; Öhrn 1965; Stenberg and Fellers 2002). However, previous work did not use optical measuring techniques. Instead, the thickness was measured between two movable anvils that were resting on the surface of the paper (Göttsching and Baumgarten 1973), or with different mechanical devices in a single point (Öhrn 1965). Stenberg and Fellers 2002 used displacement transducers to measure the nip between two spheres. Two moving arms allowed unrestricted in-plane movement over the test piece. They recorded the local thickness continuously during tensile testing. However, the probability of errors is relatively high with all contact type measuring methods because of surface influences and complex measuring procedures.

It is also possible to measure ultrasonic wave velocities which typically relate directly to the elastic constants of paper. Baum and Bornhoeft 1979 related the in-plane ultrasonic velocities to the in-plane Poisson's ratios of paper and compared the results with values measured using a biaxial tester. They found a good agreement between the measured and calculated ratios. Mann et al. 1980 used similar measuring techniques and investigated the out-of-plane Poisson's ratios of heavy milk carton. They found very high ratios greater than one, "meaning that a stress applied in the x direction results in a greater strain in the z direction than in the x direction." They also noted that the out-of-plane Poisson ratios were „measured least accurately of all the elastic constants" and that there was no model to explain the results.

Summing up it must be pointed out that there is no simple and reliable method to measure the out-of-plane Poisson ratios of paper. Therefore, the objective of this research is to evaluate whether optical measurement of the change in dimensions of paper under tensile load is feasible and promising.

Material and Methods

Tensile tests were made with a tensile testing machine Zwick Z010. The xy-plane as well as the xz-plane could be photographed concurrently due to a first surface mirror placed at an angle of 45 ° next to the test specimen, *Fig 3*.

Simultaneously with tensile testing pictures of the test specimen were taken with a Nikon D300 camera.

The resolution was 12.3 megapixel which corresponded to 12.104 µm per pixel.

The test strips were 15 mm wide and the free clamping length was 100 mm. Strain rate was 5 mm/min. To ensure correct alignment and prevent the test samples from buckling a relatively large preload of 15 N had to be applied. All the tests were carried out at standard climate.

A Matlab programme was used for starting the measurement and capturing the images. Matlab was also used for image analysis. In-plane analysis covered an area of 750 mm², out-of-plane properties were examined at a length of 50 mm.

Images were stored in raw file format and converted without losses to Digital Negative (DNG). The further image processing steps are schematically shown in *Fig 4*. A high-quality linear filter was used for demosaicing (Malvar et al. 2004). Greyscale images were normalized and converted to binary images. Morphological opening and closing algorithms eliminated irregularities in the paper structure and noise in the background image, *Fig 5*.

In order to separate the data of the mirror image (xz-plane) and the xy-plane, connected objects were detected and analysed. Images were subdevided in 30 zones of approx. 1.67 mm. The accuracy was increased to a sub-pixel resolution of ~1 µm by averaging (integrating) pixels along the edges of each zone.

In each section the specimen width was calculated by dividing the measured area by the length of the section. If only one object could be detected or if the variations from one section to the next were too high the corresponding section was excluded from the calculations.

Table 1 gives an overview of the tested paper samples. A Rapid Köthen sheet former was used for making the isotropic handsheets 1 – 4. The anisotropic handsheets were made with an M/K automated sheet former.

Fibre curl K_{fIII} of sample 3 was increased in a laboratory kneader from 18 % (sample 2) to 24 %.

To adjust the moisture content of sample 4 the sheets were moisturized with a plant sprayer and kept in plastic bags for at least 24 hours for homogenization.

Table 1. Tested paper grades.

Nr	Material	Freeness SR	Grammage g/m²	TSI MD/CD
1	Kraft pulp	14	260	1
2	Kraft pulp	25	260	1
3	Kraft pulp 24 % fibre curl	25	260	1
4	Kraft pulp 20 % moisture content	25	200	1
5	Kraft pulp anisotropic	30	260	1.8
6	Multi ply board		510	2.3
7	Sack paper		160	0.8

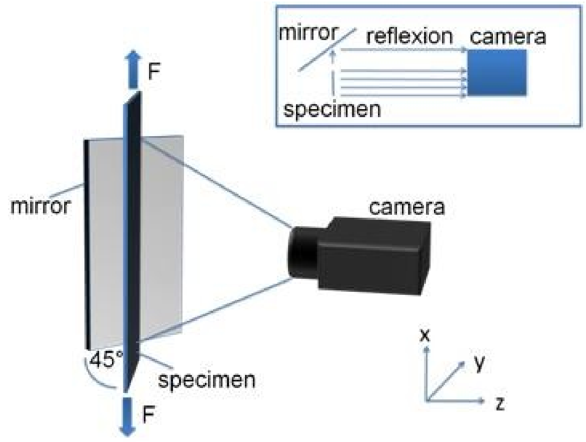

Fig 3. Measuring setup. Front and side view of a test specimen under tensile load can be photographed simultaneously (Berger 2012).

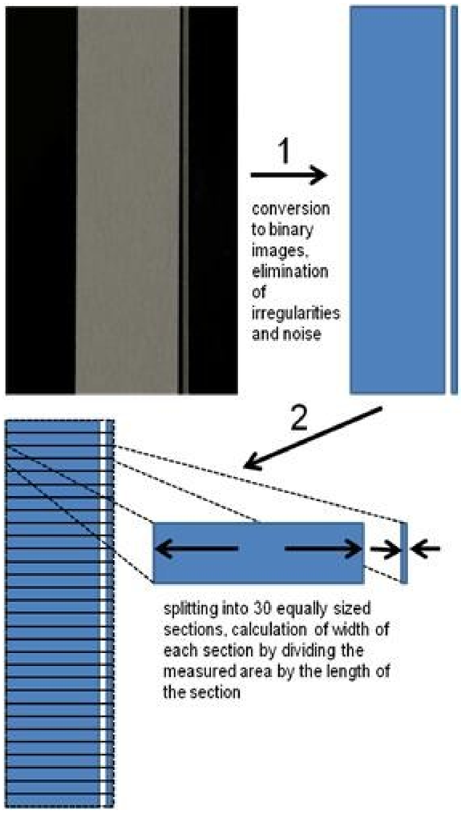

Fig 4. Schematic illustration of image processing steps

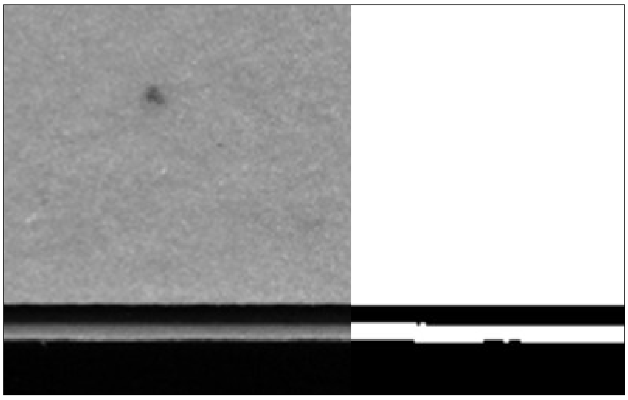

Fig 5. Section of a greyscale image (left) and processed binary image (right)

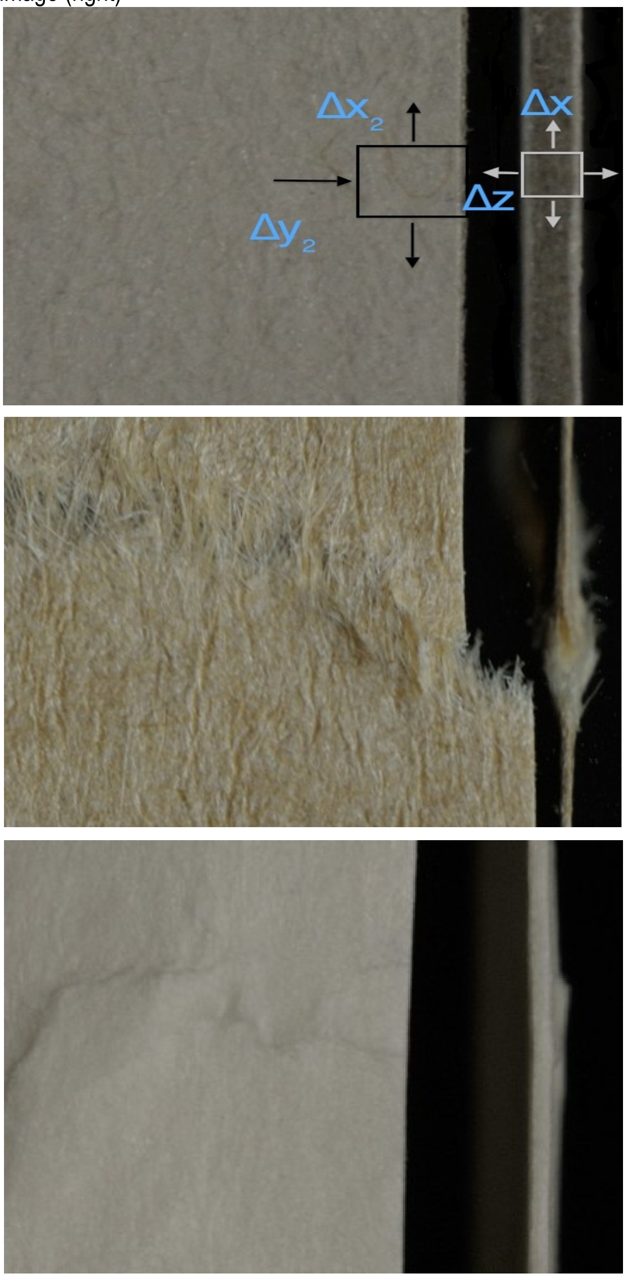

Fig 6. Specimen details: a) ideal image without shadows or misalignment, b) crack, c) improper image showing buckling.

Results and Discussion

Correct alignment of the specimens proved to be very important for successful image analysis. *Fig 6 a)* shows a section of a correctly aligned specimen with indication of the displacements in normal directions. *Fig 6 b)* gives an example of a captured crack. Buckling in the vicinity of breaking strain clearly deteriorates the analysis.

Consequently it was not possible to determine the Poisson's ratio exactly at break. Dependent on the fracture behavior the last few pictures had to be discarded. As the Poisson's ratios showed slightly non-linear behavior it follows that there is a small distorting effect on the results of the analysis.

Fig 6c) shows another buckling case creating shadow left to the mirror image. Therefore, it was necessary to carefully adjust the threshold level and to check the measured web deformations separately if reasonable. *Fig 6c)* also shows that ruptures at the surface can significantly increase the apparent thickness. As a result checking of the calculated web deformations for plausibility was necessary.

Fig 7 shows measured dimensional changes in width and thickness against in-plane strain for paper samples 2, 6 and 7. All investigated paper samples (including the not shown) showed transverse shrinkage as well as an increase in thickness. Both width change and increase in thickness were slightly nonlinear, resulting in non-constant Poisson's ratios. While the transverse shrinkage was detectable, the resolution and accuracy of the thickness determination was not always satisfactory. In some cases (moist specimens, specimens that tended to crack at the surface) the results were fluctuating heavily so that no meaningful interpretation appeared admissible.

Table 2 gives the Poisson's ratios close before rupture that were derived from the test data. The results are generally consistent with previous research results that also showed a thickness increase of various paper grades on stretching.

Anisotropic papers showed a greater cross-shrinkage when loaded in MD than in CD. This does not agree with the results of Baum et al. 1981 who found Poisson's ratios to be generally higher in CD than in MD. Further research is therefore needed to determine whether the look at only one edge of the paper is sufficient to determine the Poisson's ratio in z-direction. Baum et al. (1981) also claim that $(\nu_{12}\nu_{21})^{1/2}$ is close to 0.3 for a wide range of paper materials and moisture content. Not all results shown in *Table 2* agree with that. Stenberg and Fellers 2002 reported the out-of-plane Poisson's ratios to be lower in MD than in CD. The first two graphs in *Fig 7* give a slight indication that this is also the case for the investigated cardboard sample. No significant influence of an increased fibre curl on the results could be found. However, increased moisture content led to a significant increase in cross shrinkage.

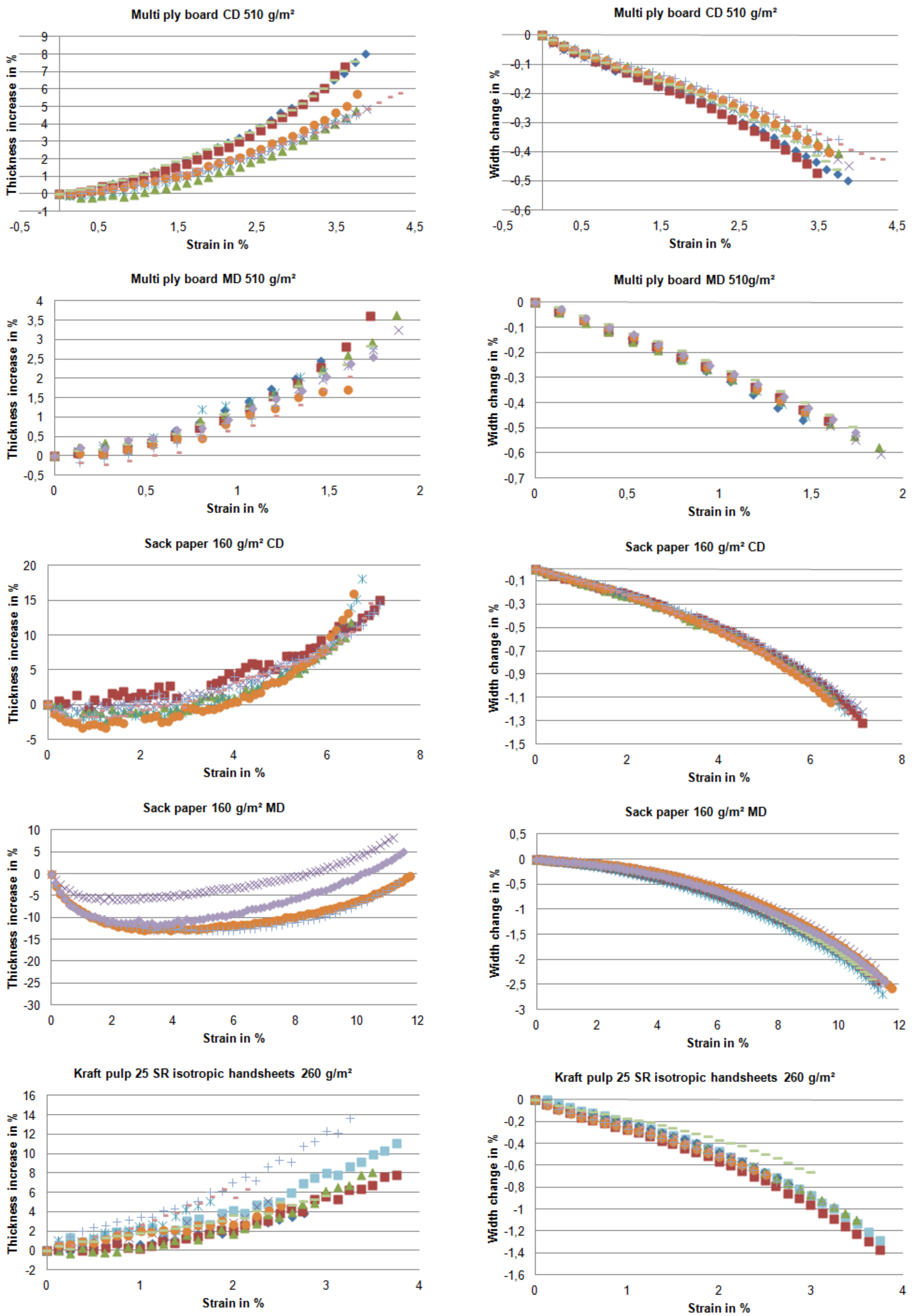

Fig. 7. Changes in thickness and width during loading.

Table 2. Poisson's ratios close before rupture

Nr.	Material	In-plane Poisson's ratio	Out-of-plane Poisson's ratio
1	Kraft pulp handsheets 14 SR	$\nu_{12} = \nu_{21}$: 0.18 ± 0.04	$\nu_{13} = \nu_{23}$: -2.34 ± 0.91
2	Kraft pulp handsheets 25 SR	$\nu_{12} = \nu_{21}$: 0.29 ± 0.04	$\nu_{13} = \nu_{23}$: -2.45 ± 0.70
3	Kraft pulp handsheets 25 SR, 20 % fibre curl	$\nu_{12} = \nu_{21}$: 0.28 ± 0.05	$\nu_{13} = \nu_{23}$: -1.57 ± 0.74
4	Kraft pulp handsheets 25 SR, 20 % moist. cont.	$\nu_{12} = \nu_{21}$: 0.78 ± 0.14	n/a
5 a	Kraft pulp handsheets 30 SR, anisotropic, MD	ν_{12} : 0.49 ± 0.03	n/a
5 b	Kraft pulp handsheets 30 SR, anisotropic, CD	ν_{21}: 0.24 ± 0.02	n/a
6 a	Multi ply board MD	ν_{12}: 0.30 ± 0.01	ν_{13} : -1.57 ± 0.25
6 b	Multi ply board CD	ν_{21}: 0.11 ± 0.01	ν_{23}: -1.52 ± 0.38
7 a	Sack paper MD	ν_{12}: 0.21 ± 0.01	n/a
7 b	Sack paper CD	ν_{21}: 0.18 ± 0.02	n/a

Future investigations shall include tracking the trajectory of individual points at the surface of the test samples, detection of local variations in the stretching properties and connection of this data with sheet properties like flock structure and formation. Also the plastic behaviour of the observed thickness increase and the influence of the strain rate on the results will be investigated.

Conclusions

The introduced measurement method uses the means of image analysis to detect the web deformation in tensile testing. All investigated paper samples showed transverse shrinkage as well as an increase in thickness when stretched.

These experimental results encourage the assumption that the standard numerical models for predicting the mechanical behavior of common materials like metals etc. are not sufficient to describe the 3-dimensional deformation behavior of paper.

However, more detailed studies are needed concerning general validity of the results and transferability to fields of application (e.g. simulation of deep drawing or other converting processes). The results of the thickness measurement are subject to a certain doubt, since only the cut edge can be considered. In addition, ruptures and bulges at the surface of the test specimen can distort the results. Therefore in some cases no reasonable statement on the thickness change could be made.

Acknowledgements

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