MECHANICAL TESTING FOR GENERATING INPUT TO NUMERICAL SIMULATION OF IMPACT RESPONSE OF INJECTION-MOULDED COMPONENTS

E. Andreassen[1*], H. Daiyan[1], F. Grytten[1], O.V. Lyngstad[2], R.H. Gaarder[1] and E.L. Hinrichsen[1]

[1] *SINTEF Materials and Chemistry, Oslo, Norway – erik.andreassen@sintef.no; hamid.daiyan@sintef.no; frode.grytten@sintef.no; rune.h.gaarder@sintef.no; einar.l.hinrichsen@sintef.no*
[2] *Plastal AS, Raufoss, Norway – ole.vidar.lyngstad@plastal.com*

Abstract – Numerical simulation of the impact response of injection-moulded components has gained importance in several industry sectors, in particular in the automotive industry. Recent studies have demonstrated progress in modelling special features of ductile polymers' mechanical response. However, several experimental challenges remain. Some of these will be addressed in this presentation, based on an ongoing study with polypropylene materials. Tests for high-speed uniaxial tension, uniaxial compression and shear are summarised. Work in progress is presented for tensile loading/unloading response, and for effects of injection moulding conditions on mechanical response.

Introduction

Numerical simulation of impact loading of polymer materials is of great industrial interest, as these materials are increasingly being used in critical applications and constructions. The response to impact loads is of particular interest for automotive applications related to passenger and pedestrian safety, in which the materials may undergo large multiaxial deformations at high strain rates. Hence, the automotive industry is a driving force in this field. Also electronic casings and various 'everyday' products must be designed to resist impact loads. The performance of sub-sea structures at oil and gas fields is a more specialised application, but of great importance for installations in the North Sea.

Recent work [1-4] has demonstrated progress in modelling special features of polymer materials, such as plastic dilatation in tension and sensitivity of yield stress to hydrostatic stress.

Our aim is to improve the prediction of the mechanical response of automotive components for pedestrian protection, as illustrated in Fig. 1. Our work focuses on ductile thermoplastics, typically polypropylene compounds containing elastomers and talc. Models for these materials have shortcomings when it comes to predicting multiaxial loading, unloading response (rebound), and failure. The unloading response, in particular, is important when designing parts for a pedestrian protection system.

Ductile polymeric materials show a complex behavior in impact loading involving large strains. The complexity applies to the micromechanical mechanisms as well as the macroscopic response. Therefore, more complex constitutive models are needed, requiring material input functions which are difficult to determine experimentally. Data from experiments with well-defined stress states are needed as input for numerical simulation. Furthermore, true stress–strain data must be calculated from the experiments. These data must be available up to high strains (hardening curves), and for high strain rates. The strain rates will depend on the geometry of the component. However, it could be mentioned that in *Euro NCAP* tests for pedestrian protection the loading rate is 40 km/h (11 m/s). This loading rate can e.g. be attained with inexpensive falling weight impact test machines, and with more specialised high-speed servohydraulic test machines.

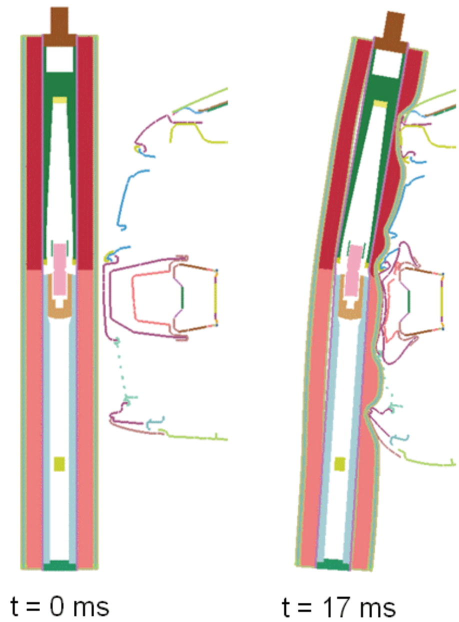

Figure 1. Simulated deformations in impact between pedestrian (leg) and car front. Note the energy absorber behind the bumper. Impact speed: 40 km/h

An earlier paper from our group [4] dealt with the validity of linear-elastic viscoplastic constitutive equations. A Mises type model and a modified model were studied. The modified model included a yield stress dependent on hydrostatic stress, and plastic dilatation (volumetric strains during plastic deformation). Model parameters were obtained by tensile testing over five decades of strain rate, as well as quasi-static compression. The models were then checked by simulating two test cases at a range of loading rates: Three-point bending of beams and central loading of circular plates. One conclusion from this study was that, in addition to the shortcomings of the models, several experimental challenges remain, in order to generate reliable input to the models. Some of these challenges will be addressed in this paper.

To summarise, our focus is on ductile thermoplastic polymers at moderately high strain rates. We seek to improve the prediction of unloading response and failure, but we also acknowledge that there is still room for improvement regarding the prediction of quite simple load cases.

A summary of test methods and challenges

As mentioned in the Introduction, true stress-strain data for well-defined stress states is needed for the material models. Furthermore, data up to large strains (hardening curves) are needed at high strain rates. Some remarks on the status and challenges are given below. The stress states should be chosen to describe the yield surface adequately. In addition to the most common stress states mentioned below, data for e.g. biaxial tension can be important for some polymers [1]. In principle, there are two primitive deformations that a material can be subjected to, and different stress states set up different combinations of these two. The two primitive deformations are hydrostatic compression (change of volume, but not shape) and shear (change of shape, but not volume) Uniaxial tension (and compression) is a combination of bulk compression and shear. That is why both crazing and shear yielding can occur when testing a material in uniaxial tension, and which mechanism that will dominate depends on the conditions, e.g. the strain rate.

Uniaxial tension

High-speed servohydraulic testing machines are now available in many labs. Commercial machines have cross-head speeds up to 25 m/s, and special fixtures and force measuring solutions. However, testing and data analysis is not trivial. Ductile polymers (large strains) with low yield stress are challenging. At high loading rates, dynamic effects lead to oscillations in the recorded force. Furthermore, strains can not be measured with conventional extensometers. Contact-less optical techniques, such as digital image correlation (DIC), can be used to obtain the true stress-strain response. Some of the challenges when trying to obtain true stress-strain for uniaxial tension are:

- Strain localisation (necking)
- Plastic dilatation (volumetric strains during plastic deformation)
- Transversal anisotropy (different strains in the two transversal directions)

A recent ISO standard [5] describes how tensile data at high strain rates can be determined by extrapolation of data at lower rates, thus avoiding some of the problems and errors associated with testing at high rates. The standard quotes a study that indicated that the extrapolation procedure gave properties with satisfactory accuracy for at least 2 decades of strain rate above the maxium rate in the measurements. To have a more uniform strain distribution for large strains, the standard also proposes a tensile specimen with a machined narrowing (circular waist) at the center of the specimen length. With this specimen, the strain localisation occurs at the center of the specimen where the axial and transversal strains are measured.

Special specimen geometries are often used in high-speed tensile testing, in particular dogbones with a short narrow section. With a shorter narrow section, higher strain rates are obtained for a given cross-head speed. If, for instance, the narrow section is only 10 mm long, the strain rate is about 100 s^{-1} for a cross-head speed of 1 m/s. At such low speeds the force oscillations mentioned above are normally not problematic.

Uniaxial compression

In uniaxial compression testing, the specimen geometry (slenderness) is traditionally a trade off in order to avoid buckling, while having a reasonably uniform stress field (avoid 'barreling'). Standards such as ISO 604 typically recommend a long specimen for compression modulus measurements, and a short specimen for compression strength measurements. Height/width ratios from 1 [6] to 2.5 [3,7] are typically used in the literature, when focusing on the response at large strains, and the compressive strength. Special test geometries (as alternatives to straight cylinders or parallelepipeds) have been proposed, claiming to perform well for a wide strain range [8]. Plane-strain compression tests can also be an alternative [9-10].

In order to obtain reliable data up to large strains, a non-uniform stress distribution is perhaps the main problem. The end surfaces of the specimen can be lubricated to reduce the degree of barreling. Alternatively, the friction can be increased so that the end surfaces are not deformed, and the data can be corrected for non-uniformity. Full-field strain measurements (see separate section below) is an important tool in this case.

Most compression tests in the polymer literature are quasi-static with strain rates below 1 s^{-1}. High-speed servohydraulic machines can be used for compression testing, e.g. using a reverse-cage compression rig [11]. With such equipment, strain rates of several hundred s^{-1} can be obtained. With split-Hopkinson pressure bars even higher strain rates are obtained, typically above 10^3 s^{-1} [12].

Shear

There are several fixtures available for shear testing, some recommended by standards and some developed and used only by certain research groups. The literature on shear testing of unreinforced polymers is scarce, but there are some studies with variants of the Iosipescu fixture [13-14], the Arcan fixture [3] and some other fixtures/specimens [10,15-16]. An Arcan-type fixture was recently used to obtain input to impact simulations of polypropylene [3], although the test was quasi-static as all the shear tests cited above. This Arcan fixture had a purpose-built extensometer, thereby avoiding the use of strain gauges, and also allowing for larger strains to be measured. In general, full-field strain measurements (see separate section below) are useful for shear tests. Finally, note that some Arcan fixtures can also be used to generate biaxial tension and other stress states.

Shear data of polymers are often considered to be unreliable for modelling purposes, since different fixtures/tests tend to give different results. In particular for large strains, the stress field is no longer uniform pure or simple shear, and many polymers do not or can not experience a shear fracture [14,17-18]. It can be mentioned that in a study with a simple shear test fixture, a polyethylene was tested to a strain of 10 without extensive crazing [15].

Full-field strain measurements

Equipment for full-field strain measurements, such as digital image correlation (DIC), has been available for some years. Commercial systems have been expensive. However, new developments in digital imaging technology, increases in data processing power, and a reduction in camera prices, have led to advances and price reductions in optical techniques for measuring strain fields. For the tests mentioned above such techniques are important tools in order to obtain true stress-strain data [19-20].

Inverse modelling

For tests such as uniaxial compression and shear it is difficult to achive a well-defined stress state, at least for large strains. Numerical simulation can be integrated with the experimental work, to improve the stress-strain data and the material models by inverse modelling schemes, i.e. optimising model parameters and models to achive the best correlation between simulated and experimental results for a set of tests. Inverse modelling can also be applied to cases with multiaxial stress states [2], and it can be utilised to extract data corresponding to constant strain rates. Finally, inverse modelling can provide input for improving the geometries of specimens and fixtures.

Some results from an ongoing study

Some results for injection-moulded test specimens of polypropylene (PP) are given below. The PP is a mineral and elastomer modified grade from Borealis. According to the datasheet, the density is 940 kg/m^3 and the melt flow rate (230°C/2.16kg) is 17 g/10min. Standard dogbone specimens (type 1A of ISO 527-2) are used in tensile tests, and 80 x 10 x 4 mm^3 sections cut from these specimens are used in bending tests.

Unloading from uniaxial tension (damage)

As mentioned in the Introduction, the unloading response of these polymers is poorly predicted with present models. A simple model for the unloading [1,21] is to introduce an effective modulus for the unloading response

$$E_{eff} = E(1 - d)$$

where d is a damage parameter which increases with increasing plastic strain. Data for simulations can be obtained by testing at a range of strain rates and unloading strains. Unloading (rebound) response at high strain rates can e.g. be measured with falling weight impact instruments [4]. Some results obtained with uniaxial tensile testing are shown below. Fig. 2 shows some typical loading/unloading curves. The modulus and the effective moduli increase with increasing strain rate (Fig. 3). However, in the limited interval investigated so far, the damage factor can be considered to be independent of strain rate (Figs. 4-5).

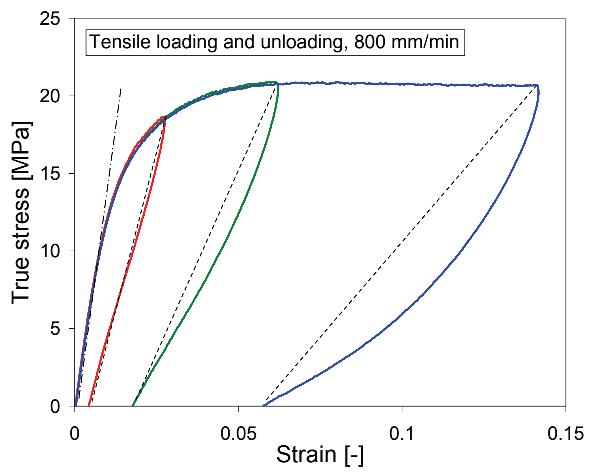

Figure 2. Tensile loading to different strains, followed by unloading at the same rate. Dash-dotted line: Tensile modulus. Dashed lines: Effective moduli E_{eff} (different fits than those shown can certainly be imagined).

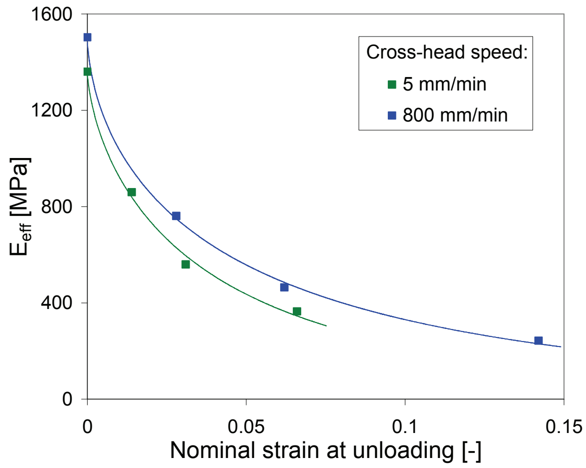

Figure 3. Effective modulus vs. nominal strain at unloading for tensile testing with two different cross-head speeds. The lines are guides for the eyes.

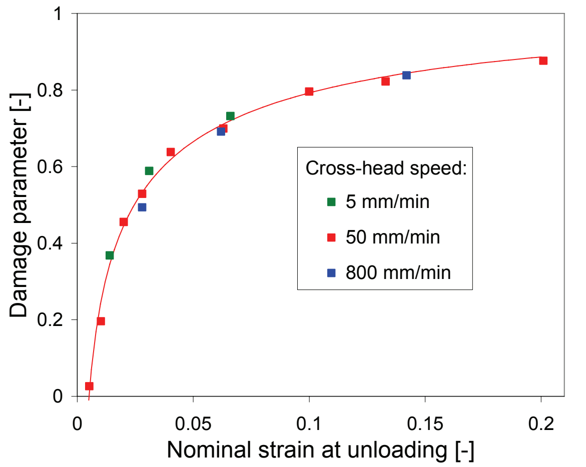

Figure 4. Damage factor vs. nominal strain at unloading. for different cross-head speeds. The line is a guide for the eyes.

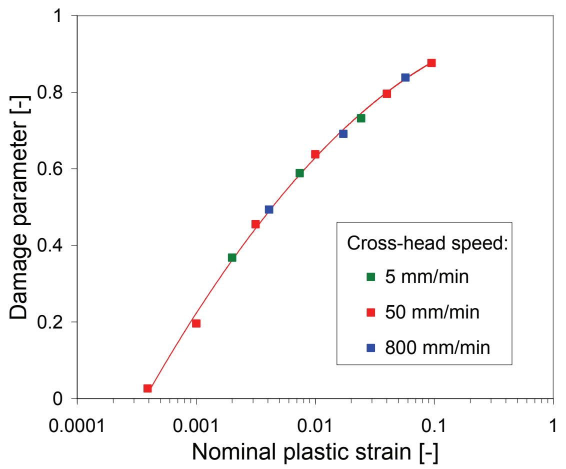

Figure 5. Damage factor vs. plastic strain for different cross-head speeds. The plastic strain is the actual value from the measumrents, not the one calculated using the effective modulus. The line is a guide for the eyes.

Effects of processing conditions

The anisotropy and inhomogeneity of injection-moulded parts is a challenge when trying to simulate their mechanical response at large strains. The ultimate goal is to simulate the mechanical response using local mechanical parameters from a simulation of the moulding process, but this has so far only been demonstrated for simple geometries and/or small strains. Even for simple test specimens there are several questions: How much do the mechanical properties vary with processing conditions, specimen thickness and gating? How do differences in morphology, anisotropy etc interfere with the stress distributions? How much does the skin layer affect the test results? How about residual stresses from the moulding process?

We have started a study in this area. Some results for specimens moulded with two different injection speeds are shown below. The lowest speed is that specified for producing such test specimens in the ISO standard [22] (0.2 m/s is the melt front speed though the narrow portion of the dogbone). The highest speed is nominally five times higher than this. With a specimen thickness of 4 mm the effect of injection speed is usually not large, but we observe some differences. High-speed tensile data (Fig. 6) shows that the high injection speed gives somewhat higher yield and post-yield stresses, and a lower strain at break. As expected the difference between the two specimens is larger when testing in bending (Fig. 7), because the near-surface layers (oriented by the flow during injection) contribute more to the mechanical response than the core of the specimen. A new mould insert (Fig. 8) will be used in further studies. With this insert, 80 x 80 mm^2 plates with two different thicknesses can be moulded, each with two different gatings (film gate and gating from two corners). Hence, with specimens machined from these plates, effects of processing conditions, weld lines, anisotropy and cavity thickness can be studied.

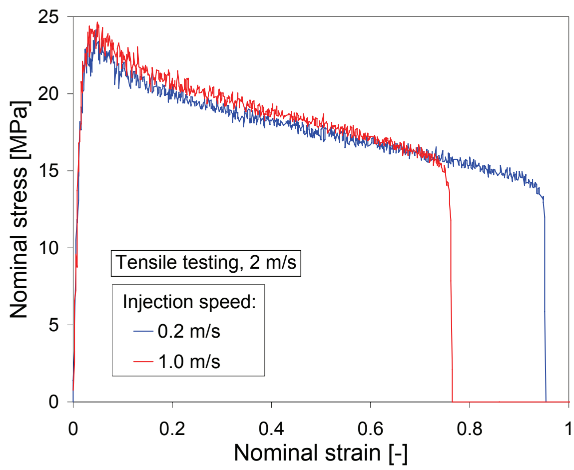

Figure 6. High-speed tensile testing of specimens moulded with two different injection speeds.

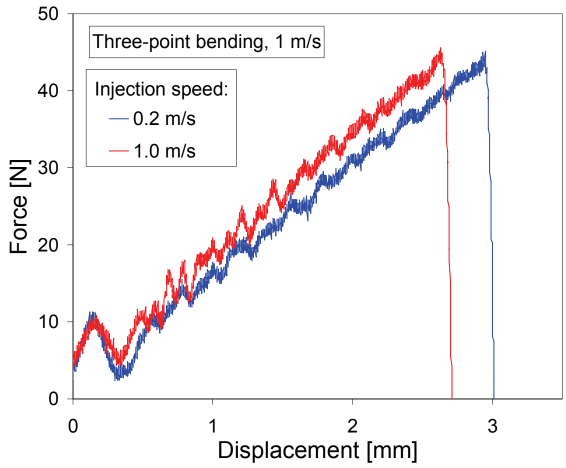

Figure 7. Three-point bending of specimens moulded with two different injection speeds. Specimens tested flatwise in an instrumented falling weight impact tester.

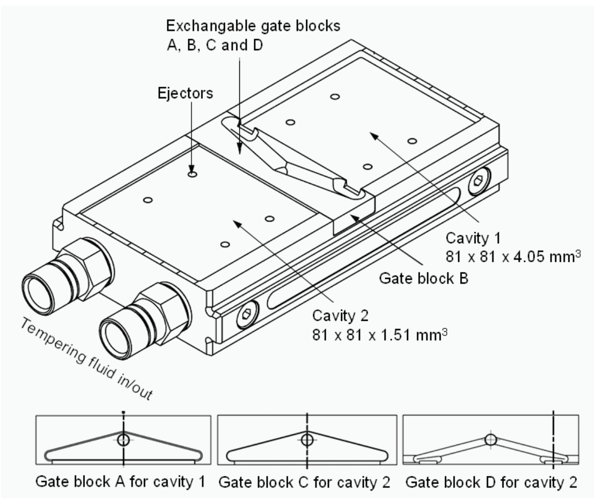

Figure 8. Mould insert for studying effects of processing conditions, anisotropy, weld lines and cavity thickness. For each cavity there is a combined pressure/temperature sensor in the other mould half.

Striker concepts for reduced force oscillations

As mentioned in the Introduction, force oscillations is a problem for high-speed tests, either with high-speed tensile testers or instrumented falling weight impact testers. The oscillations are reduced when moving the force sensor closer to the specimen, thereby shortening the 'load train' and reducing the number of interfaces at which elastic stress waves are partly reflected. The material and the design of the 'load train' including the force sensor also play a role, and the system is usually designed to have a natural frequency far above that of the test specimen.

In order to improve the force signal, we have made some modifications to our high-speed tensile tester (*Schenk/Instron VHS*). Some work on modifying the striker for three-point bending (and Charpy impact) in our instrumented falling weight impact tester (*Rosand/Imatek Type 4*) is in progress. Placing the force sensor close to the contact point between the specimen and the striker head perhaps gives the most substantial improvement [23]. We have also looked at alternative materials in the striker rod – initially with the load sensor in the original position (Fig. 9). The idea was to see if a rod with higher damping could dampen reflected stress waves. Titanium alloys have been used in striker rods [23]. We see an improvement with rods in titanium and composite (pultruded carbon fibre reinforced vinylester), compared to the original steel rod, especially for the initial response (~ 0.5 ms) of brittle specimens. Also, there seems to be less superimposed waves with the composite rod compared to the titanium rod (Fig. 10), making it easier to interpret or filter the force signal. It should be mentioned that with a thin layer of grease on the specimen the oscillations in Fig. 10 can be significantly reduced.

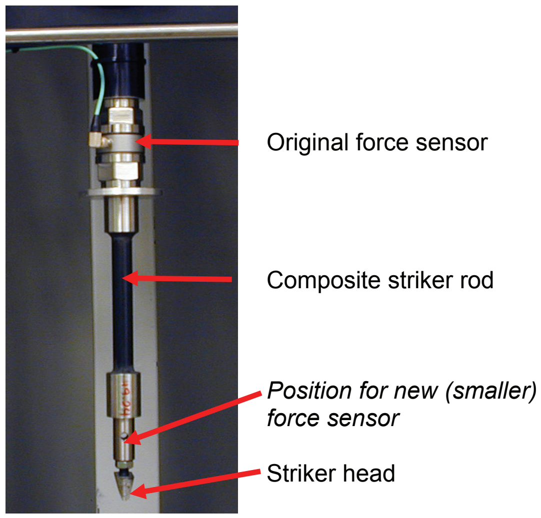

Figure 9. Assembly for testing a composite striker rod.

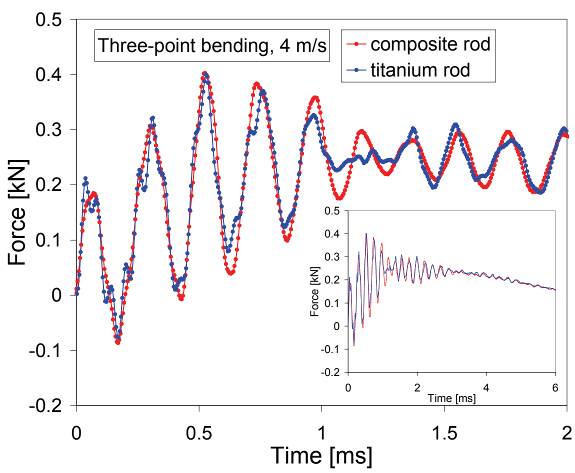

Figure 10. PP specimen subjected to three-point bending edgewise (impact against 4 mm thick side).

Acknowledgements

We would like to thank Pierre Deruddre and Rolf Kalland at SINTEF for assistance with the mechanical testing. The project is funded by an industrial consortium and the Norwegian Research Council via the BIA programme.

References

1. S. Kolling; A. Haufe; M. Feucht; P.A. Du Bois in Proceedings from LS-DYNA User Meeting, Bamberg, Germany, 2005.
2. J.C. Viana; A.M. Cunha; N. Billon *Polym. Eng. Sci*. 2007, *47*, 337.
3. G. Dean; L. Crocker *Plast. Rubber Comp*. 2007, 36, 1.
4. T. Glomsaker; E. Andreassen; M. Polanco-Loria; O.V. Lyngstad; R.H. Gaarder; E.L. Hinrichsen in Proceedings from PPS07ea, Göteborg, Sweden, 2007.
5. International standard ISO 18872:2007.
6. B.A.G. Schrauwen; R.P.M. Janssen; L.E. Govaert; H.E.H Meijer *Macromolecules* 2004, *37*, 6069.
7. International standard ISO 604:2002.
8. E.M. Odom; D.F. Adams *J. Test. Eval.* 1994, *22*, 104.
9. P.B. Bowden; J.A. Jukes *J. Mater. Sci.* 1972, *7*, 52.
10. R. Quinson; J. Perez; M. Rink; A. Pavan *J. Mater. Sci.* 1997, *32*, 1371.
11. B.L. Boyce; T.B. Crenshaw, *Sandia Report SAND2005-5678*, Sandia National Laboratories, USA, 2005.
12. C. R. Siviour; S.M. Walley; W.G. Proud; J.E. Field *Polymer* 2005, *46*, 12546.
13. K. Liu; M.R. Piggott *Composites* 1995, *26*, 829.
14. C. Xiang; H.-J. Sue *J. Appl. Polym. Sci.* 2001, *82*, 3201.
15. C. G'Sell; S. Boni; S. Shrivastava *J. Mater. Sci*. 1983, *18*, 903.
16. G. Hedner; R. Selden; P. Lagercrantz *Polym. Eng. Sci.* 1994, *34*, 513.
17. K.Liu; M.R. Piggott *Polym. Eng. Sci.* 1998, *38*, 60.
18. K.Liu; M.R. Piggott *Polym. Eng. Sci.* 1998, *38*, 69.
19. S. Glaser; A. Wüst; D. Jansen *Kunststoffe*, 2006/9, 168.
20. E.M. Parsons; M.C. Boyce; D.M. Parks; M. Weinberg *Polymer* 2005, *46*, 2257.
21. P.A. DuBois; S. Kolling; M. Koesters; T. Frank *Int. J. Impact Eng.* 2006, *32*, 725.
22. International standard ISO 1873-2:2007.
23. I. Horsfall; C.H. Watson; C.G. Chilese in *Fracture of Polymers, Composites and Adhesives II*, B.R.K. Blackman; A. Pavan; J.G. Williams, Eds., Elsevier, 2003; 221-229.