An Easy Procedure for Anisotropic Non-Linear Behavior of Short-Fiber-Reinforced Plastics

Sascha Pazour, Wolfgang Korte, Marcus Stojek

PART Engineering GmbH, Germany

For fiber reinforced parts the consideration of anisotropic material behavior is required to receive reliable results. In the scope of this fact a procedure is described how to consider these effects in terms of process-structure interaction and how to achieve possible benefits such as weight reduction and shorter development cycles shown for examples of the industry .

The developed procedures show how to consider the anisotropic mechanical behavior of injection molded short-fiber-reinforced plastics parts in FE analysis. It is shown how the existing information, which is provided by injection molding simulation software, can be processed and transferred into mechanical simulation models. The procedure is outlined with practical applications.

Keywords: Composites, Fiber-Reinforced, Injection molding, Process-Structure-Interaction, Anisotropic, Hill´s Potential

1. Introduction

It is evident that due to the anisotropic behavior of short-fiber-reinforced parts the structural analyst is interested in considering these effects. Such a consideration may result in a more accurate prediction of the mechanical behavior of the investigated component or part.

In the following article, a strategy will be described to predict the elastic-plastic anisotropic behavior of injection-molded short-fiber-reinforced plastics based on the theory of Hill.

2. General

The injection molding process causes a local anisotropic material behavior within the part due to fiber orientations in the short-fiber-reinforced plastic. These orientations vary not only at different locations in the part but also across the wall thickness. The laminar flow of the melt in combination with the velocity profile in the flow channel lead to characteristic fiber orientations across the wall thickness with fibers mainly aligned parallel to the flow direction in the outer so-called shear layers and fibers mainly aligned transverse to the flow direction in the mid layer.

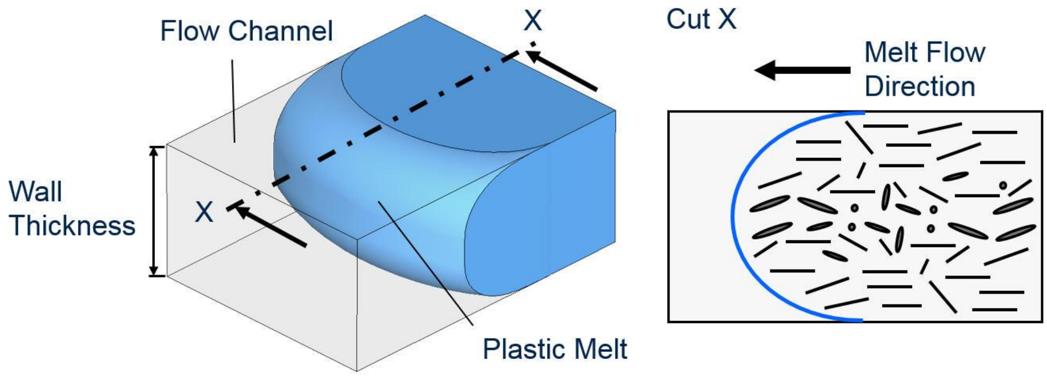

Figure 1. Fiber Orientation Across the Wall Thickness of an Injection Molded Part

2.1 Micromechanics of Short-Fiber-Reinforced Plastics

In the past a lot of researches dealt with micromechanical modeling of fiber-reinforced plastics. In this paper we consider the theory of Tandon and Weng. Tandon and Weng developed an analytical transversal isotropic approach. They derived closed analytical equations from Eshelby's theory of ellipsoidal inclusions. Their model can be extended also for the orthotropic case but remains purely elastic. The model provide the elastic response of the composite in different directions by assuming that the composite behaves as a continuum. The individual behavior of the different phases of the material - fiber and matrix - cannot be distinguished anymore.

However for a lot of cases in practical applications these assumptions do not restrict the usability of this model in order to make reasonable statements with regard to the part stiffness and design limit.

2.2 Consideration of Fiber Orientation Distributions

In real injection molded short-fiber-reinforced parts there are fiber orientation distributions instead of ideally aligned fibers and because of the fact that in a finite element model the element size is never small enough to include only one fiber the material model has to have properties referring to that distribution. It is evident that for nearly ideal aligned fibers different mechanical properties result than for nearly un-oriented fibers. This has to be considered in the definition of the anisotropic material properties.

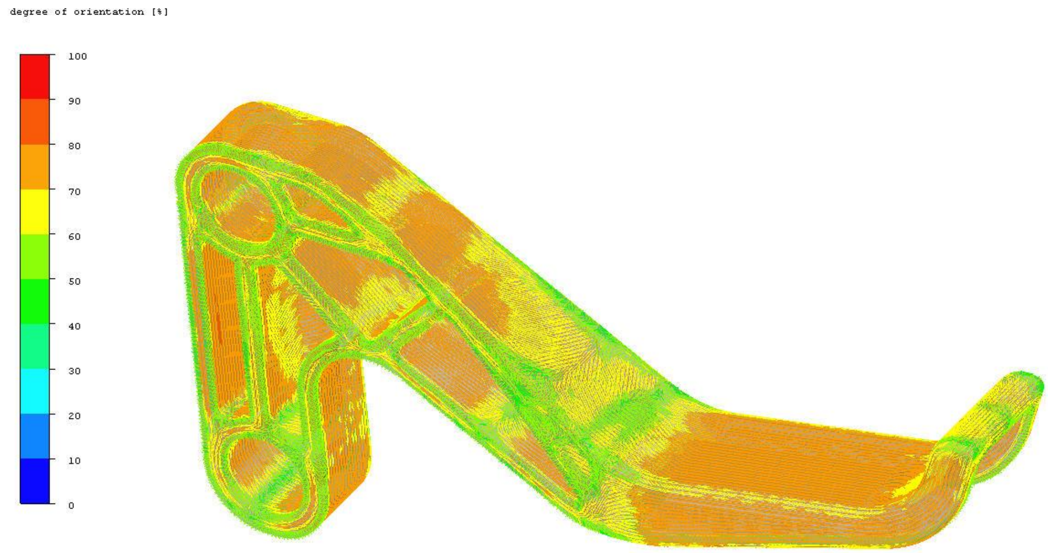

Figure 2. Fiber Orientation and Degree of Orientation in an Injection Molded Plastic Example Part

For this a so-called orientation averaging can be applied (Advani and Tucker). The mechanical properties determined for the idealized unidirectional volume element are weighted with their local degree of orientation. For a narrow distribution the degree of orientation is close to unity and for a very broad distribution close to zero (quasi-isotropic). The information about the local degrees of orientation can be extracted from the orientation tensor which is provided for every element as standard output by most injection molding solvers.

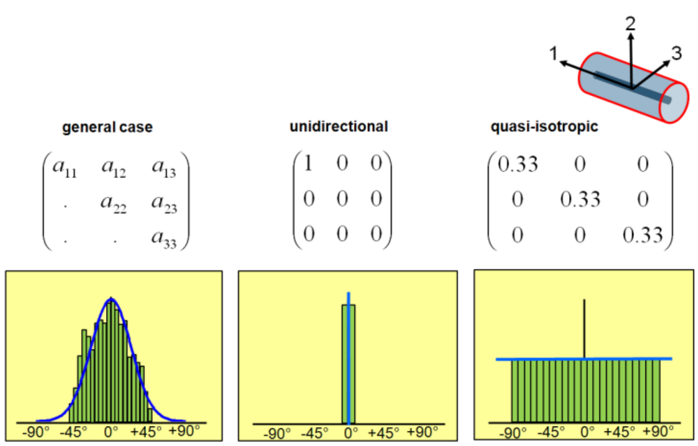

Figure 3. Orientation Tensor Example

3. Fundamentals

The analysis and interpretation of results obtained by means of an anisotropic analysis is generally carried out otherwise than it is done in an isotropic analysis. In particular, the evaluation of all stress and strain invariants such as principal stresses and strains or the von Mises stress is not meaningful in an anisotropic analysis. Because all components of the stress and strain tensor here refer to local element coordinate systems that are generated by the software CONVERSE. Accordingly, only the components of the stress or strain tensor should be evaluated. Since by definition in CONVERSE, the 11-direction is always aligned with the main fiber orientation direction, the individual tensor components e.g. $\sigma_{11,}$ $\sigma_{22,}$ σ_{33} therefore also always relate to the fiber orientation directions within each element. For example, for fiber orientations transferred from surface or midplane injection molding models, the stress component σ_{11} of the composite is the stress in fiber direction. The stress component σ_{22} is the stress component of the composite transverse to the fiber direction in the plane of melt flow. The stress component σ_{33} is the stress component of the composite transverse to the fiber direction transverse to the plane of melt flow (i.e. pointing in direction of the wall thickness). In a surface or midplane injection molding simulation fiber orientations in the out-of-flow plane do not exist by definition. The melt flow plane is assumed parallel to the local part surface respectively cavity wall.

In the case of fiber orientations transferred from 3D injection molding models, the stress components σ_{22} and σ_{33} cannot further distinguished with regard to their alignment to the cavity wall. Here, the fibers can be oriented in all spatial directions (melt flow respectively fiber orientation in wall thickness direction is possible).

3.1 Stiffness Assessment

The stiffness of a part calculated with the linear-elastic anisotropic material model applied in CONVERSE has to be considered as base stiffness. At which base stiffness is being understood as the stiffness of the part in the approximately linear-elastic range. If the load on the part is such that the stress in the supporting cross-sections of the structure does not exceed the nearly linear-elastic range the calculated base stiffness should reflect the real stiffness of the part within the general model accuracy. This should be valid even if local stress concentrations (e.g. in notched areas) exceed the linear elastic limit significantly and would undergo plastic deformations in reality as far as this yielding does not affect the global deformation of the part.

Also for dynamic oscillating loads and in modal analyses the calculated base stiffness should match the real behavior within the overall model accuracy. On the one hand all mechanical solvers linearize at the operating point the response of the structure anyway for dynamic analyses in the frequency domain. And on the other hand the oscillation amplitudes are comparatively small, so that the assumption of a linear material response is justified anyway as far as the structure is not subjected to an initial load, so that the operating point is shifted into the nonlinear range of the stress-strain characteristic. The limitation of the linear-elastic material model that is applied in CONVERSE is for most practical cases acceptable. Since, fiber-reinforced plastics behave as opposed to unreinforced grades over a relatively large range approximately linear. Furthermore plastics parts undergoing long term loads or dynamic loads should anyway not stressed to the nonlinear range. Stresses should be kept well below the fracture or yield point and should remain in the nearly linear-elastic range. Hence, the tabulated ultimate failure values of the material, in the context of a conservative part design, have to be reduced accordingly and can then be compared with the calculated linear stresses and strains.

3.2 Strength Assessment

If a strength assessment has to be done based on an anisotropic analysis the calculated stresses respectively strains have to be compared with appropriate failure indicators. The assessment of failure has to be done by distinguishing the local fiber orientations. Accordingly, different failure indicators parallel and transverse to the fiber orientation have to be determined. As an estimate for the strength of the composite parallel to the fiber direction (σ_{11}) the strength of the composite (σ_B or σ_S) from material Databases such as CAMPUS Plastics may be used. As an estimate for the strength of the composite transverse to the fiber direction (σ_{22}) the strength of the matrix material of a corresponding unreinforced grade may be used. These values are of course only rough estimates. More reliable failure limits can be obtained by using injection molded test plaques with a film gate in order to achieve aligned fibers along the side of the plaque. From these plaques specimen can be taken for tensile tests parallel and transverse to the fiber orientation.

4. Elasto-Plastic Behavior of Short-Fiber-Reinforced Plastics

Even though in most cases linear elastic material behavior is enough for several analysis tasks in some cases an elastic-plastic formulation is required. Fortunately with a new approach this material behavior can be given by a built in material model in structural simulation software. Therefore a material formulation in a user subroutine (UMAT) is not necessary anymore.

4.1 The Hill´s Potential

The *POTENTIAL command is able to define stress ratios for anisotropic yield and creep behavior. It can be used in conjunction with the *CREEP or *PLASTIC option. Also rate dependency can be considered. Here only the Plastic option is used and explained.

Anisotropic yield behavior is created through the use of yield stress ratios R_{ij} In the case of anisotropic yield the yield ratios are defined with respect to a reference yield stress σ^0.

The Hill's potential function is an extension of the von Mises function. In a rectangular Cartesian system it can be expressed as:

$$f(\boldsymbol{\sigma}) = \sqrt{F(\sigma_{22}-\sigma_{33})^2 + G(\sigma_{33}-\sigma_{11})^2 + H(\sigma_{11}-\sigma_{22})^2 + 2L{\sigma_{23}}^2 + 2M{\sigma_{31}}^2 + 2N{\sigma_{12}}^2},$$

The components F, G, H, L, M, N are defined as:

$$
\begin{aligned}
F &= \frac{(\sigma^0)^2}{2}\left(\frac{1}{\bar\sigma_{22}^2}+\frac{1}{\bar\sigma_{33}^2}-\frac{1}{\bar\sigma_{11}^2}\right)=\frac{1}{2}\left(\frac{1}{R_{22}^2}+\frac{1}{R_{33}^2}-\frac{1}{R_{11}^2}\right),\\
G &= \frac{(\sigma^0)^2}{2}\left(\frac{1}{\bar\sigma_{33}^2}+\frac{1}{\bar\sigma_{11}^2}-\frac{1}{\bar\sigma_{22}^2}\right)=\frac{1}{2}\left(\frac{1}{R_{33}^2}+\frac{1}{R_{11}^2}-\frac{1}{R_{22}^2}\right),\\
H &= \frac{(\sigma^0)^2}{2}\left(\frac{1}{\bar\sigma_{11}^2}+\frac{1}{\bar\sigma_{22}^2}-\frac{1}{\bar\sigma_{33}^2}\right)=\frac{1}{2}\left(\frac{1}{R_{11}^2}+\frac{1}{R_{22}^2}-\frac{1}{R_{33}^2}\right),\\
L &= \frac{3}{2}\left(\frac{\tau^0}{\bar\sigma_{23}}\right)^2=\frac{3}{2R_{23}^2},\\
M &= \frac{3}{2}\left(\frac{\tau^0}{\bar\sigma_{13}}\right)^2=\frac{3}{2R_{13}^2},\\
N &= \frac{3}{2}\left(\frac{\tau^0}{\bar\sigma_{12}}\right)^2=\frac{3}{2R_{12}^2},
\end{aligned}
$$

where each σ_{ij} is the degree of orientation dependent yield stress value. σ^0 is the user-defined reference yield stress.

The R_{ij} values are the anisotropic yield stress ratios and the τ^0 can be evaluated with σ^0/0,577. Therefore the six yield stress ratios are defined as follows.

$$
\frac{\bar\sigma_{11}}{\sigma^0},\quad \frac{\bar\sigma_{22}}{\sigma^0},\quad \frac{\bar\sigma_{33}}{\sigma^0},\quad \frac{\bar\sigma_{12}}{\tau^0},\quad \frac{\bar\sigma_{13}}{\tau^0},\quad \frac{\bar\sigma_{23}}{\tau^0}.
$$

These values have to be defined for each degree of orientation in the material card.

Obviously the *POTENTIAL command is not able to consider different behavior between tensile and pressure loads.

In the following picture the broad distribution of the nonlinear behavior of short-fiber-reinforced materials is shown. 1 is the highest and 0 the lowest stiffness and strength possible.

With considering this effects such materials can be simulated a lot closer to reality then by using isotropic material behavior (only one curve).

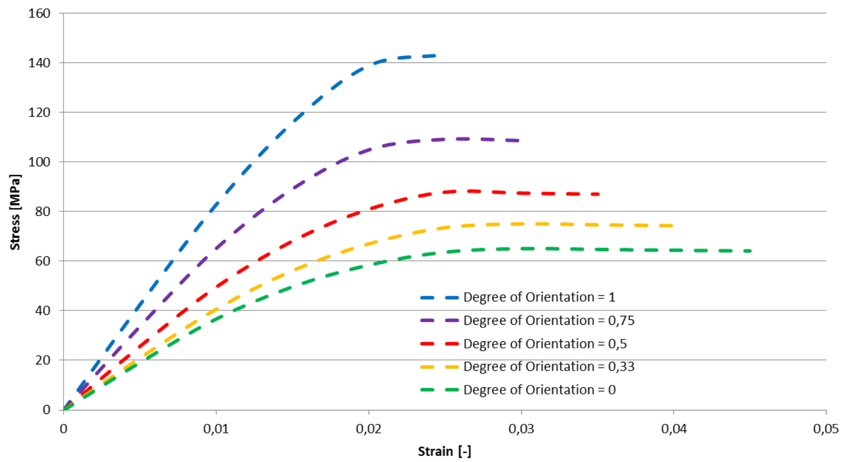

Figure 4. Plastic Behavior for Different Fiber Distribution

5. Workflow

To assign fiber orientation, the fiber distribution and non-linear anisotropic material behavior to a FE-model the use of a software tool seems to be the best choice.

There are several software tools available. Some are direct interfaces from the injection molding solver and therefore only support this specific solver and others are third-party products like the one used for this example (CONVERSE). The workflow can be seen as a general workflow for this type of simulation, no matter what software is used.

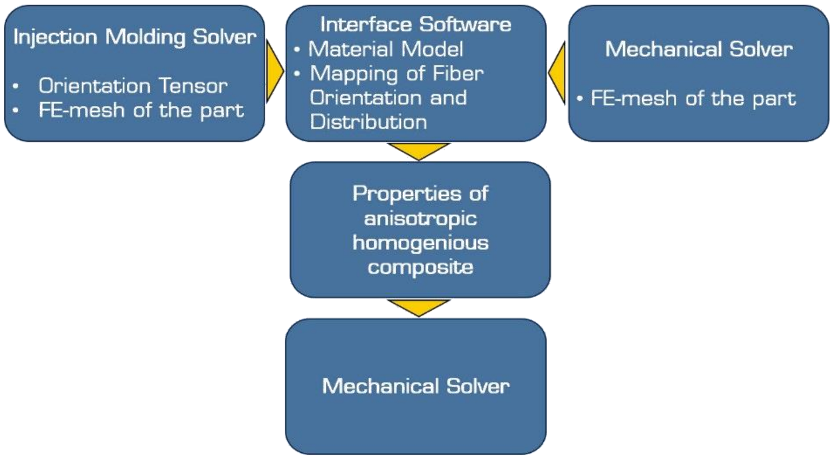

Figure 5. Workflow

The only material data required to create such a material is a stress-strain curve of your composite material (e.g. from Campus Database).

6. Example Results

Unfortunately the created values for different degrees of orientation cannot be validated on Test results since it is not possible to produce test specimen with only one certain fiber direction and distribution. Nevertheless it is possible to simulate test specimen with all kinds of orientation and distribution in it and the physical max. and min. values can be checked by comparing the result non-linear behavior of the degree of orientation 1 and 0 with the behavior of a two phase representative volume element. The RVE shows the behavior of a 100% orientation of fibers in and perpendicular to the fiber direction.

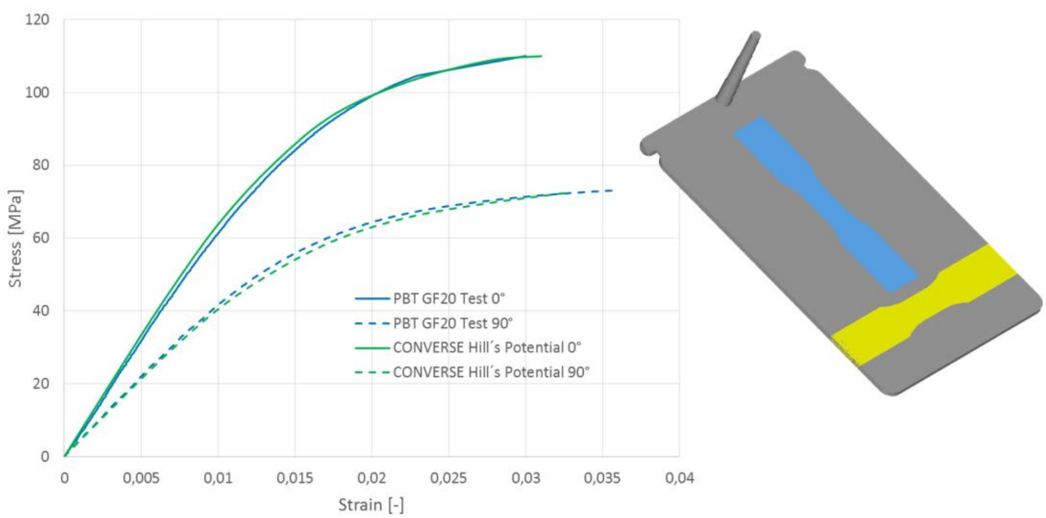

Figure 6. Tensile Test Example (Material PBT GF20)

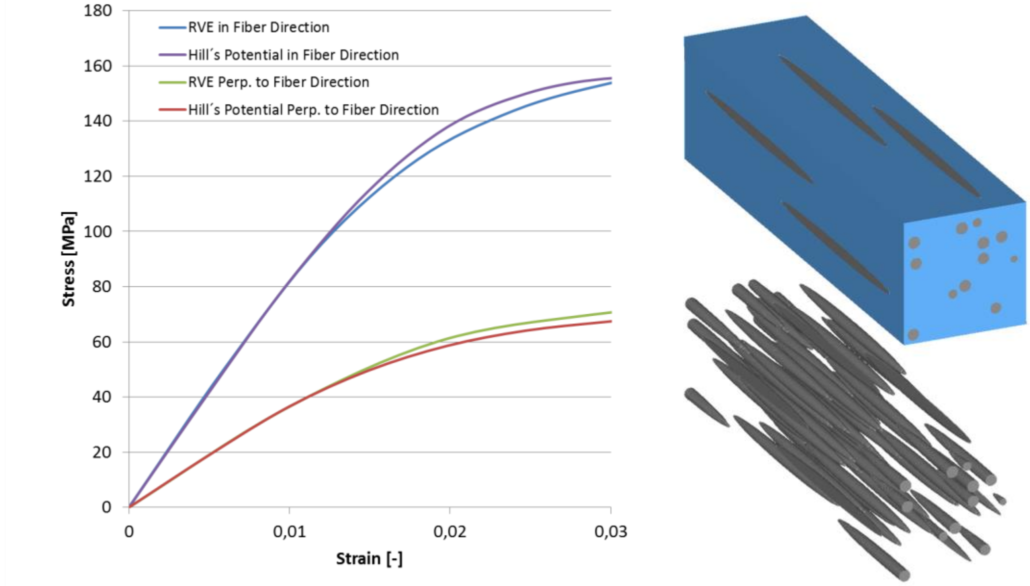

Figure 7. Representative Volume Element (Material PBT GF20)

7. Abaqus Syntax commands

Orientation information has to be given by local orientation systems at each element by using a `*DISTRIBUTION` card and assigned through an orientation card `*ORIENTATION, DEFINITION=COORDINATES`
The fiber distribution is given by orientation tensor values as field variables, where there are only the values in and across the main fiber direction required because of the fact that the sum of all three is always 1 `*INITIAL CONDITIONS, TYPE=FIELD, VARIABLE=1`.
The material properties have to be provided different in the linear-elastic case and the elasto-plastic case. In the linear elastic case the material properties are defined by using the `*ELASTIC,TYPE=ENGINEERING CONSTANTS,DEPENDENCIES=number` command.
The elastic-plastic anisotropic material behavior is possible through the `*POTENTIAL` command.

All these formulations are supported by the Software CONVERSE.

8. Summary and Prospect

With the outlined procedure it is possible to obtain reliable results for structural simulation of short-fiber-reinforced plastic components.

The anisotropic nonlinearity can be considered with existing Abaqus Syntax commands without any user subroutine. That makes the simulation a lot faster and robust.

The simulation speed is even the same as for isotropic material definition.

With existing methods the opportunity is given to simulate nonlinear anisotropic temperature dependent material behavior with a minimum of effort.

Even strain rate dependency, creep and damage behavior can be added on top.

But this would have been leaded too far for this documentation.

9. References

1. Abaqus Analysis User's Manual, Version 6.12-2, Dassault Systémes Simulia Corp., Providence, RI.
2. Korte, W., Stojek, M., "Entwicklung einer Software zur orientierungsgradabhängigen Kalibrierung eines anisotrop elasto-plastischen Standard-Materialmodells zur FEM-Simulation von kurzfaserverstärkten Kunststoffbauteilen" unpublished report ZIM Koop research and development project No. KF3056701RR2, Bergisch Gladbach, Germany, 2015.
3. Stommel, M., "Entwicklung und Umsetzung einer hybriden Simulationsmethodik zur effizienten Berechnung und Auslegung von kurzfaserverstärkten Kunststoffbauteilen" unpublished report ZIM Koop research and development project No. KF2214510RR2, Saarbrücken, Germany, 2015.
4. CAMPUS website, www.campusplastics.com
5. PART Engineering GmbH website, www.part-engineering.de
6. M. Stommel, M. Stojek, W. Korte, „FEM zur Berechnung von Kunststoff- und Elastomerbauteilen", Carl Hanser Verlag, 2011
7. CONVERSE Documentation, CONVERSE 3.6 Manual, Feb. 2015
8. Tandon, G.P. and Weng, G.J, "The Effect of Aspect Ratio of Inclusions on the Elastic Properties of Unidirectionally Aligned Composites", Polymer Composites, Vol. 5, Nr. 4, John Wiley & Sons, 1984
9. Eshelby, J.D. "The Determination of the Elastic Field of an Ellipsoidal Inclusion and Related Problems", Proceedings of the Royal Society of London 241, No. 1226, 376-396, Birmingham, 1957
10. Advani, S.G. and Tucker, C.L. "The use of tensors to describe and predict fiber orientation in short fiber composites", J. of Rheology Vol. 31 (1987) No. 8, p. 751-784

10. Acknowledgment

Part of the investigations in this paper are sponsored by Federal Ministry of Economics and Technology due to a resolution of German Federal Parliament in the scope of the funding program „ZIM - Zentrales Innovationsprogramm Mittelstand "

Teile der Untersuchungen in dieser Veröffentlichung sind gefördert durch das Bundesministerium für Wirtschaft und Technologie aufgrund eines Beschlusses des Deutschen Bundestages im Rahmen des Förderprogramms „ZIM - Zentrales Innovationsprogramm Mittelstand"