Strength Assessment of a Plastic Component considering local Fiber Orientation and Weld Lines

Sascha Pazour, Wolfgang Korte

PART Engineering GmbH, Bergisch Gladbach

Abstract

The aim of the study was to provide static strength assessments for a short fiber reinforced plastic part considering anisotropic material properties and strength drop caused by weld lines. The sequential coupling of process and structure simulation opens up additional potential for the development process. It is shown how significantly this additional information influences the quality of the assessment.

In focus are methods used to assess the strength distribution in the plastic part as well as the comparison between the results of the measurement and final structural-mechanical simulation. More over various failure assessment approaches, ranging from simple estimating procedures, like reduction factors, to the full consideration of fiber orientations, are presented to compare their performance.

Introduction

The molding process is the cause for the formation of a specific microstructure within the molded part, which in turn is the root cause for the mechanical properties of the part. Especially for plastics this microstructure can be molecular orientations or in the case of SFR plastics fiber orientations, leading to an anisotropic material behavior. In this sense it can be said that the material is composed during the molding process.

The injection molding process causes a local anisotropic material behavior within the molded part due to the alignment of the fibers dependent on the local flow conditions in the part (Fig. 1). The fiber orientation varies 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 a characteristic fiber orientation across the wall thickness. The fibers are 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.

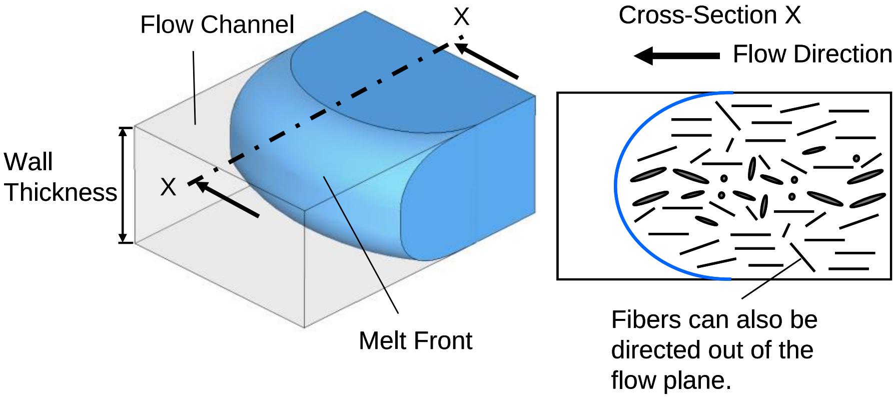


Fig.1: Injection Molded Fiber Orientation

It is evident that the structural analyst is interested in considering these effects. Such a consideration may result in a more precise prediction of the mechanical behavior of the investigated component.

The use of injection molded SFR parts take place in many different industries. In particular, in the automotive industry SFR plastics are increasingly being used as the preferred engineering plastic. This is due to the excellent mechanical and thermal properties of these materials compared to non-reinforced grades. The use of these materials enables the manufacturer of automotive components to a significant weight reduction compared to metallic materials and lower manufacturing costs as well due to the fact that a plastic part is typically a finished part without any further processing necessary.

In this paper, a strategy is described to predict stiffness and strength of injection-molded short-fiber-reinforced (SFR) plastic components.

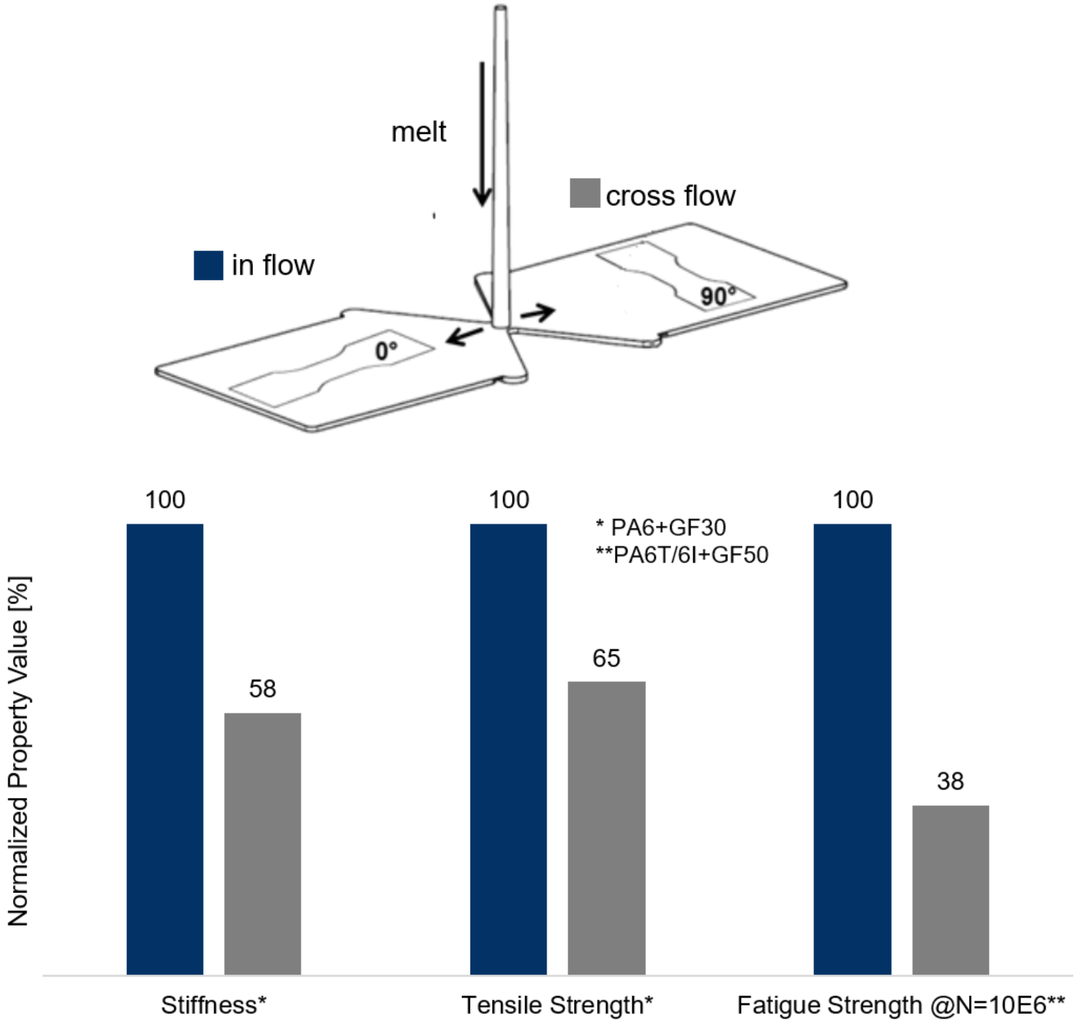


Fig.2: Direction Dependent Material Properties

Material Modeling of Short-Fiber-Reinforced Plastics

In general, the specific material behavior of SFR plastics requires an anisotropic elasto-plastic material description, at least if an evaluation of the ultimate component strength is considered. In this case the deformation of the material exceeds the linear respectively linear-viscoelastic range and irreversible plastic deformation occurs. Such an anisotropic elasto-plastic material description is available; in most FEM solvers the so-called Hill potential [1] is implemented.

The R values are called yield ratios. The yield ratios are the ratios of the yield stress in a certain direction to a reference yield stress. In this sense the R-values can be seen as scaling factors that scale the yield stress from a reference curve valid for a particular direction to the yield stress in a different direction.

$$\sigma_{eq,Hill} = \sqrt{F\left(\sigma_{22}-\sigma_{33}\right)^2 + G\left(\sigma_{33}-\sigma_{11}\right)^2 + H\left(\sigma_{11}-\sigma_{22}\right)^2 + 2L\sigma_{23}^2 + 2M\sigma_{13}^2 + 2N\sigma_{12}^2}$$

$$F = \frac{1}{2}\left(\frac{1}{R_{22}^2} + \frac{1}{R_{33}^2} - \frac{1}{R_{11}^2}\right)$$

$$G = \frac{1}{2}\left(\frac{1}{R_{33}^2} + \frac{1}{R_{11}^2} - \frac{1}{R_{22}^2}\right)$$

$$H = \frac{1}{2}\left(\frac{1}{R_{11}^2} + \frac{1}{R_{22}^2} - \frac{1}{R_{33}^2}\right)$$

$$L = \frac{3}{2R_{23}^2}$$

$$M = \frac{3}{2R_{13}^2}$$

$$N = \frac{3}{2R_{12}^2}$$

with: $$\mathrm{R}_{11} = \frac{\sigma_{11}^y}{\sigma_0^y};\quad \mathrm{R}_{22} = \frac{\sigma_{22}^y}{\sigma_0^y};\quad \mathrm{R}_{33} = \frac{\sigma_{33}^y}{\sigma_0^y};\quad \mathrm{R}_{12} = \frac{\sigma_{12}^y}{t_0^y};\quad \mathrm{R}_{13} = \frac{\sigma_{13}^y}{t_0^y};\quad \mathrm{R}_{23} = \frac{\sigma_{23}^y}{t_0^y}$$

In injection molded SFR parts there is a fiber orientation distribution instead of ideally aligned fibers. This means there exist principal anisotropy axes and planes but additionally each of them is superimposed with a fiber orientation distribution function (ODF) giving the information how many fibers are aligned exactly in these anisotropy axes and how many in certain discrete angles to them. Which in return influences the mechanical behavior of the material significantly (Fig. 2).

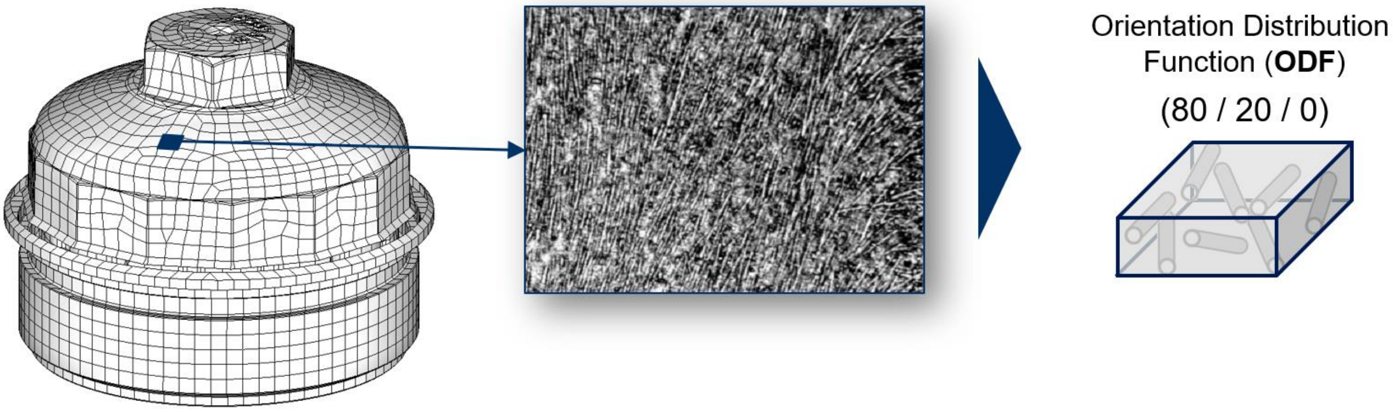


Fig.3: Orientation Distribution Function (ODF)

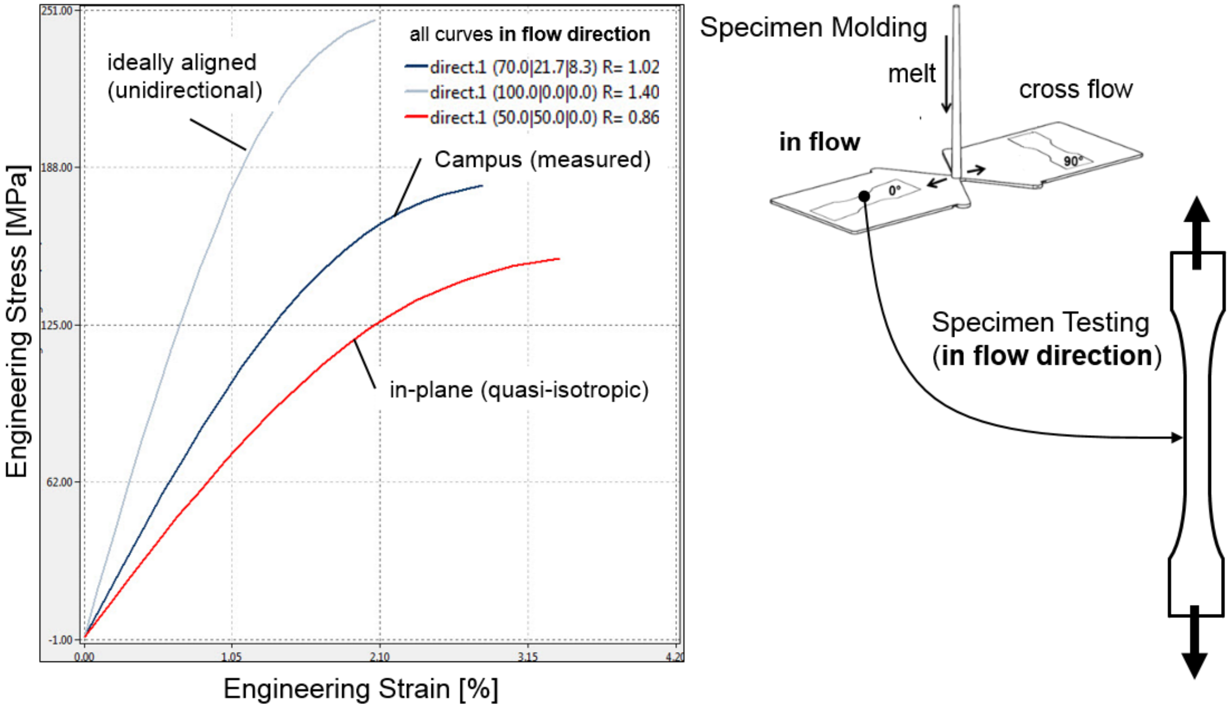


Fig.4: Influence of local ODF on stress/strain-curve

If one aims to simulate the mechanical behavior of SFR parts this has to be taken into account. For this a so-called orientation averaging can be applied (Advani and Tucker [2]). The unidirectional mechanical properties, here initially the elastic stiffnesses are meant, are weighted with their local degree of orientation. E.g. 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 degree of orientation can be extracted from the orientation tensor which is provided as standard output by most injection molding solvers. Additionally, the plastic part of the material description has to be defined dependent on the ODF. Therefore, the classic unidirectional Hill formulation is modified in such a way that the yield ratios are not anymore constant rather than defined as a function of the local ODF.

In addition to the consideration of the local ODF the anisotropic material properties themselves have to be determined. It is possible to compute the required parameters and not to determine them experimentally. This can be conducted by utilizing a micro-mechanical model. Such a model applies a so-called homogenization scheme, it is capable to determine the anisotropic material properties of a unidirectional ideally aligned unidirectional representative volume element (RVE) only based on the constituents of the composite. That are the properties of the matrix, the fiber, the aspect ratio (fiber length vs. diameter ratio) and the volumetric fiber fraction (Mori and Tanaka [3]). After that is done the ODF is taken into account by applying the orientation averaging scheme on the determined unidirectional material properties. By applying this strategy, a minimum of experiments is required in order to calibrate the material model. Typically, two tests, in-flow and cross-flow, are sufficient. If even these tests are not accessible a reasonable estimation can be made by using only an in-flow test specimen.

Analysis of SFR Plastic Components in LS-DYNA® with Material Type 108 or 157

In order to conduct the described procedure automatically and efficiently the software “Converse” [5] is available, that incorporates all described algorithms, including a micro-mechanical model. It is stressed here that the micro-mechanical model applied is only used in order to provide all required anisotropic elastic and elastic-plastic material properties. The whole process works in pre-processing. For the analysis of the actual component at hand only solver built-in material models are used.

In the past the only possibility to consider non-linear anisotropic material behavior for such materials was given by so called user subroutines. These user materials led to an increase of CPU time and convergence problems. To avoid the usage of such subroutines the anisotropic elastic-plastic behavior has to be considered by using built in material models and assign different plastic behavior to each element depending on the fiber orientation and the orientation distribution.

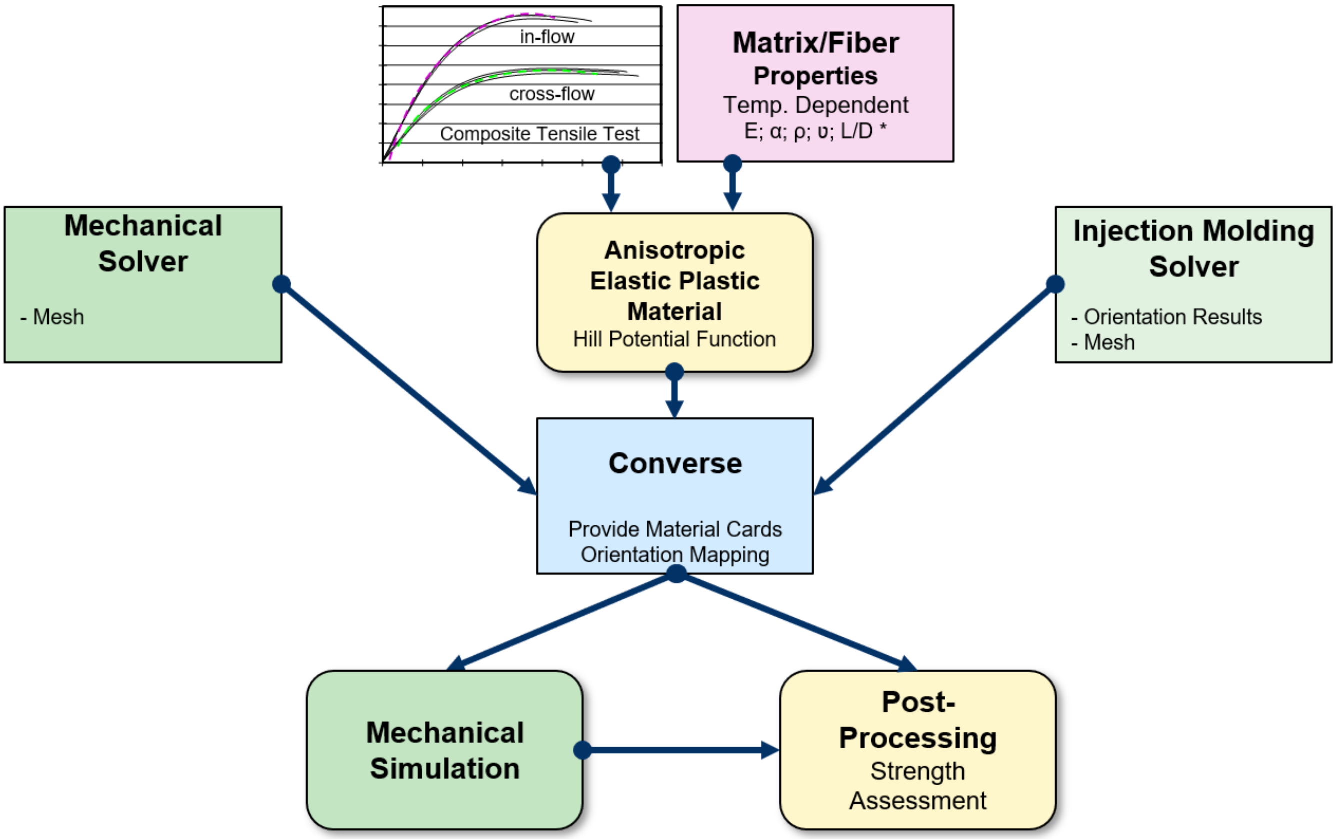


Fig.5: Workflow

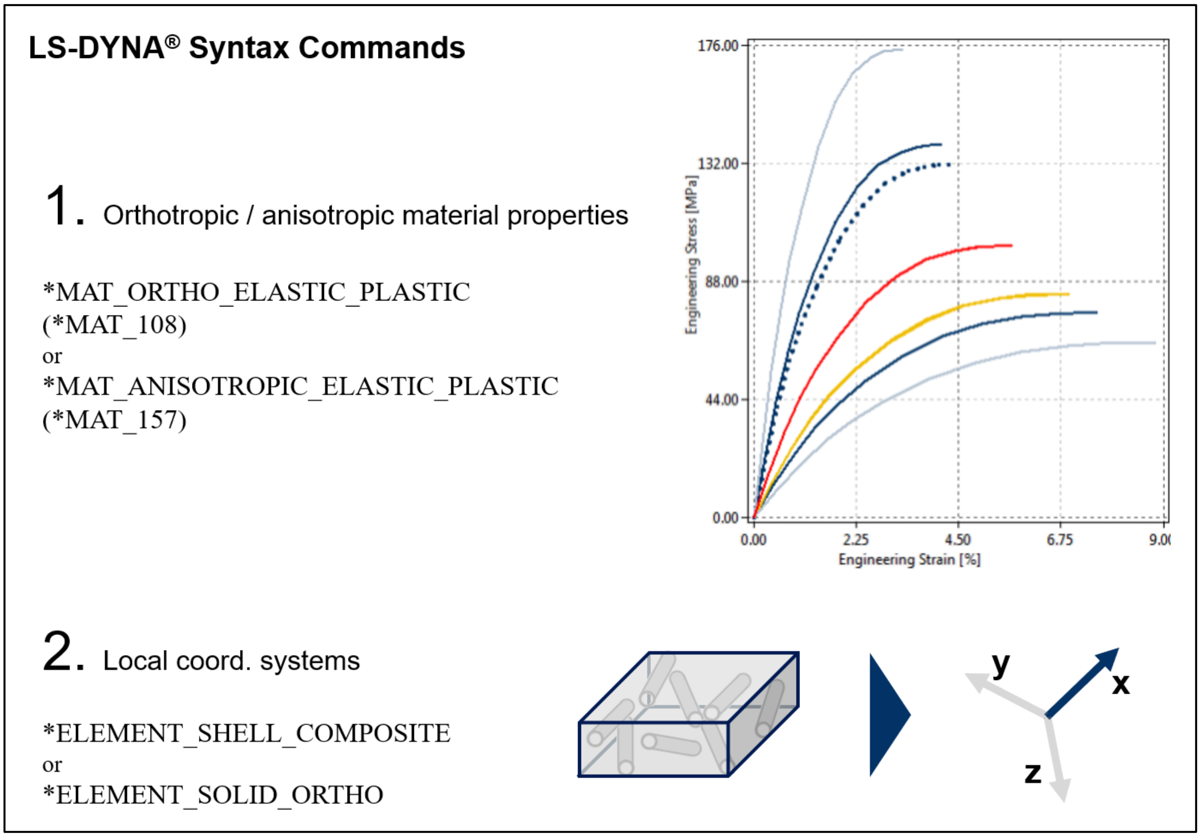
This is possible by using the material type 108 *MAT_ORTHO_ELASTIC_PLASTIC for shell elements and with the material type 157 for solid elements, which is a combination of the anisotropic elastic material model (MAT_002) and the anisotropic plastic material model (MAT_103_P) [6]. The stiffness has to be defined in a 6 × 6 anisotropic constitutive matrix where an orthotropic system can be used and due to partly symmetry only 9 values are needed. Theses 9 material properties describe the anisotropic linear-elastic material behavior. For the plastic part of the material model, described by MAT_103_P additionally the 6 anisotropic parameters for the

Hill yield criterion and a load curve id that refers to the materials reference stress/strain-curve have to be provided. So far these 15 parameters describe the anisotropic unidirectional behavior of the material.

The required incorporation of the ODF is done by defining 45 different sets of those 15 parameters for particular local ODFs. The elements in the component to be analyzed then are classified in those 45 classes respectively according to their belonging local ODF. The provision of the ODF for each element as well as their classification is done by "Converse". Which provides as well all 45 required sets of material parameters.

By using this approach for a strength assessment, it is assumed implicitly that the Hill yield surface describes not only the yield but the failure location as well. So far this approach has been applied for real components under loading which lead to local plastic straining in notch roots. A subsequent failure occurred mainly due to tension stresses up to a maximum of the ultimate breaking stress of the stress/strain-curve.

Since the orthotropic material properties also need local orientation for each element / layer the orientation information coming from the injection molding solver needs to be assigned to the LS-DYNA® mesh. This can be done by using the commands *ELEMENT_SHELL_COMPOSITE or *ELEMENT_SOLID_ORTHO to define local varying principal directions.



LS-DYNA® Syntax Commands

1. Orthotropic / anisotropic material properties

*MAT_ORTHO_ELASTIC_PLASTIC
(*MAT_108)
or
*MAT_ANISOTROPIC_ELASTIC_PLASTIC
(*MAT_157)

2. Local coord. systems

*ELEMENT_SHELL_COMPOSITE
or
*ELEMENT_SOLID_ORTHO

Fig.6: LS-DYNA® Syntax Commands

Influence of Weld Lines

In case of a SFR plastic the most significant reduction of the material behavior is already given by the fiber orientation in that weld line region. When the two melt fronts meet the resulting orientation is different from other regions of the part.

The ultimate failure of a weld line depends on rheological process parameters such as pressure and temperature as well as the angle.

The higher the angle, the less critical a weld line is and might be called a flow line, since the melt is still flowing in that area and heals the effects of the former weld line.

The most critical weld line is created at the end of the injection molding process and affects the whole cross section.

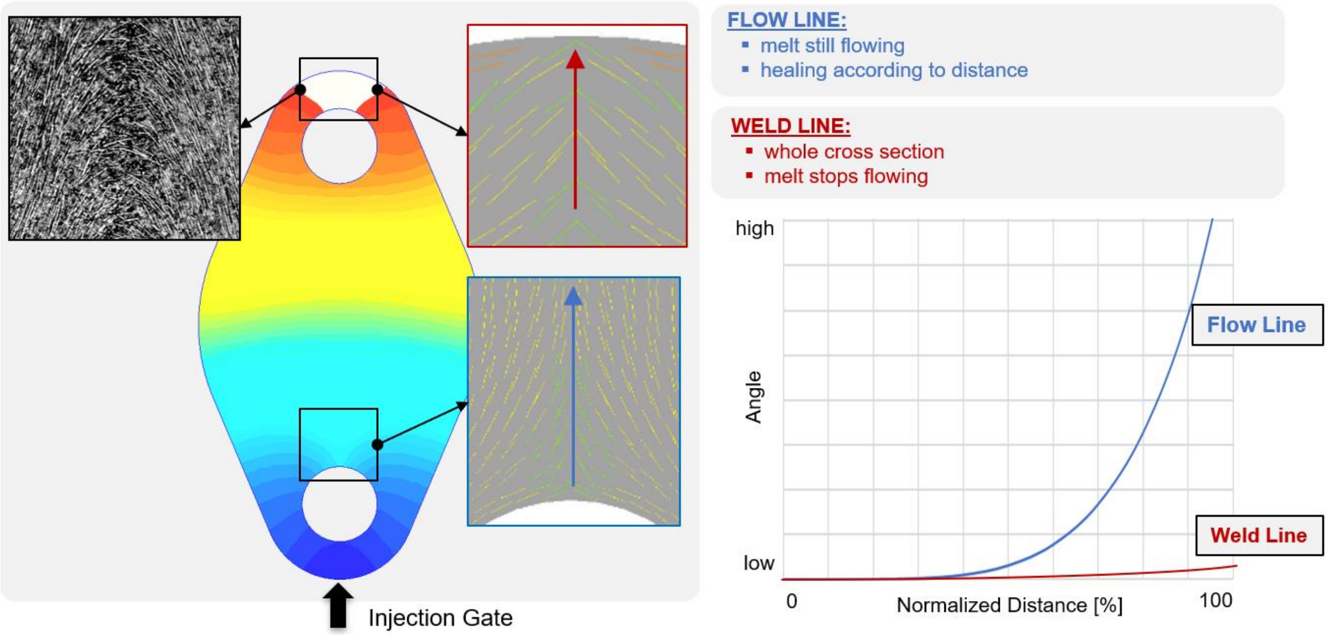


Fig.7: Weld- and Flow Lines

Conclusion

The consideration of anisotropic material behavior is indispensable in order to achieve realistic simulation results for SFR components due to more accurate simulation of part stiffness and strength assessment compared to isotropic approaches and consideration of the influence of gate positions onto the mechanical behavior (position of weld lines). This leads to huge trade-offs with regard to accuracy and reliability of FEA results.

References

[1] Hill, R.: A theory of the yielding and plastic flow of anisotropic metals. Proc. Roy. Soc. London, 193 (1948), p. 281–297

[2] 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

[3] Mori, T.; Tanaka, K.: Average Stress in Matrix and Average Elastic Energy of Materials with Misfitting Inclusions, Acta Metallurgica 21 (1973), p. 571-574, Tokyo

[4] N.N.: CONVERSE, http://www.partengineering.com/software/converse/, PART Engineering GmbH, Bergisch Gladbach, 24.02.2020

[5] Livermore Software Technology Corporation, *MAT_ANISOTROPIC_ELASTIC_PLASTIC, LS-DYNA® Keyword User´s Manual Volume 2, p. 823-828