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A VISUALIZATION METHODOLOGY FOR EVALUATING PARTS MADE OF SHORT FIBER REINFORCED THERMOPLASTICS REGARDING THEIR LIGHTWEIGHT POTENTIAL

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ABSTRACT

Injection molded, short fiber reinforced thermoplastics are a promising lightweight material. However, the component design is getting complex with this type of material due to the process induced fiber orientation. To achieve substantial progress in lightweight design, the resulting anisotropic material properties have to be taken advantage of effectively. The most important correcting variables influencing the fiber orientation are the part's geometry and the gate design (position and type of gates).

The goal of the present paper is introducing a new evaluation method, supporting the product developer at detecting the most appropriate geometry and gate layout. The basic idea behind the new approach is examining the deviations between the load path and the fiber orientation pattern. With the help of new quality criteria it can be rated to which extent load path and fiber orientation are in harmony. The methodology is implemented as a software tool, delivering a mean quality criterion per part as well as a contour plot enabling also the analysis of the local distribution of the focused quality criterion. The potential of the new approach is demonstrated within a brief case study.

Keywords: visualization, decision making, simulation, lightweight design, short fiber reinforced thermoplastics

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1 INTRODUCTION

Short fiber reinforced thermoplastics (SFRT) are a promising lightweight material, since they are characterized by a beneficial stiffness to weight ratio and can be processed cost efficiently at large quantities with the help of the injection molding technique. However, lightweight design cannot be achieved, just by substituting conventional materials like metals with SFRT. On the one hand, new 'design for manufacturing' criteria arise from changing the manufacturing process. On the other hand, the fiber dependent anisotropic behavior has to be taken advantage of effectively.

Besides using lightweight materials, another key aspect to achieve substantial progress in lightweight design is the adequate exploitation of the early design steps, since they offer maximum freedom of design. This means that already in the stage of the initial geometry definition, an ideally load adapted design has to be created. In the context of fiber reinforced structures, it is important that the fiber orientation fits the load path as good as possible. This can be analyzed indirectly by performing an anisotropic structural finite element simulation, which accounts for the process induced fiber orientation. Therefore, a coupling of process and structural simulation – often referred to as 'integrative simulation' (Michaeli and Baranowksi 2011) – is necessary. However, these simulation approaches can be considered as very time consuming. Consequently, in early design steps the anisotropic behavior is commonly neglected and mainly isotropic analyses are carried through.

As a result of the explanations above the following research question arises: How can the product developer be supported adequately at creating SFRT-parts, which are characterized by a load adapted fiber distribution? In order to achieve maximum lightweight quality, the assistance should be suitable for early design steps.

The basic idea of the methodology being introduced is comparing the load path resulting from the applied forces with the part's fiber orientation pattern and quantifying respectively visualizing the deviations. The method is implemented as an easy to use software tool, allowing a quick evaluation of the parts lightweight quality. In early design steps, the product developer often has to choose the most beneficial design among several solutions. With the help of the new evaluation technique also the suitability of the fiber orientation can be taken into account.

The paper starts with a description of the fundamentals of component design of parts made of SFRT and theoretical backgrounds of predicting load paths as well as the fiber orientation. Subsequently, a methodology quantifying the potential of a part being made of continuous fiber composites is depicted (Durst 2008). Durst's work can be considered as starting point of the approach introduced in the present paper. The focus of the paper lies on the explanation of the new evaluation technique, which is applied within a case study. The paper concludes with a summary.

2 DESIGN PROCESS OF PARTS MADE OF SHORT FIBER REINFORCED THERMOPLASTICS

2.1 Definition of initial geometric solutions

In order to create a load-adapted geometry within the early phases, methods like topology optimization (Bendsoe and Sigmund 2002) can be deployed to determine a first design proposal. Although these techniques assume isotropic material properties, they are commonly used for predicting the initial geometry of parts made of composite materials. Since only a few basic manufacturing constraints (e.g. the draw direction) can be defined for the optimization task, the derived geometry has to be transformed – primarily manually – into a feasible design. In this context, generic DFM criteria for injection molded parts (Malloy 2010) like guidelines for draft angles and suitable wall thicknesses have to be considered. The addition of reinforcement particles like short fibers affects the manufacturing constraints only weakly. However, the fibers strongly influence the mechanical properties of the part (Akay and Barkley 1991). Bionic studies of wood show that reinforcement fibers should be aligned parallel to the maximum stresses (Mattheck and Kubler 1995).

The fiber orientation state within the part is a result of the flow condition during the manufacturing process. The process parameters have a minor influence on the flow pattern. It is mainly influenced by the parts geometry and the type, respectively the position of the gates (Mlekusch 1997). The geometry is typically created by the design engineer. The gate design is primarily governed by manufacturing

related aspects. Since there are lots of different influencing aspects (Osswald et. al. 2008) there is certain leeway in terms of positioning the gates yet.
Besides fulfilling the basic demands stated in the requirement list, the geometry defined by the product developer also has to lead to a beneficial fiber orientation pattern. Furthermore, proposals for a promising position of the gates should be made. Since the gates strongly influence the orientation pattern, its type and position has to be considered during the early stages of the geometry creation. This enhanced scope of duties of the product developer goes hand in hand with the conclusion of Puri et. al. (2001). He stated that the design process of composite structures has to be performed in accordance with the manufacturing process in order to create proper fiber filled products.

2.2 Pre-selection of design solutions

Since creating the geometry is characterized mainly by manual work, commonly several different design proposals are generated. Consequently, a pre-selection narrowing the solution space is necessary. One of the most important aspects to be considered within this pre-selection is the structural mechanical performance of the part. This aspect will be the focus of the present paper. The mechanical behavior can be evaluated by performing an integrative finite element simulation. In this context, the process induced fiber orientation causing the anisotropic material behavior is determined by an injection molding simulation, which is linked with a succeeding structural simulation (Michaeli and Baranowksi 2011). This analysis method indirectly enables predicting, if the fiber orientation fits the load path as desired. However, these coupled simulation approaches are not suitable for early design steps. Common coupling interfaces lead to extensive FE-models, which complicate the model setup within the preprocessing (Gruber and Wartzack 2013). Furthermore, these simulations are characterized by an extensive computation time.
Especially in early design steps, for reasons of simplification an isotropic material behavior is commonly assumed. Therefore, the material properties (e. g. young moduli and strength parameters) are decreased using a reduction factor of 0.6 to 0.8. This simplified procedure often leads to over designed structures and therefore should be avoided to improve the lightweight quality (Gruber and Wartzack 2012).

3 THEORETICAL BACKGROUND

3.1 Orientation state of parts made of short fiber reinforced thermoplastics

In the following, the process induced fiber orientation as well as its prediction will be described more detailed. In general, the orientation distribution can be divided into three different layers (see figure 1): one core layer and two skin layers (Patcharaphun 2006). The skin layers are characterized by a strong orientation parallel to the flow direction. The core layer is characterized mainly by an orientation condition perpendicular to the flow direction. The skin layers are characterized by a stronger degree of orientation and therefore primarily affect the part’s anisotropic behavior.

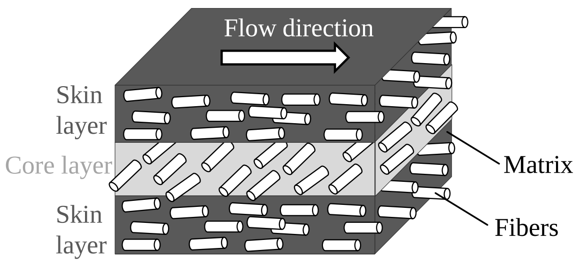

Figure 1. Three layer model of the cross section of a part made of SFRT

The orientation condition of the actual part can be determined with the use of injection molding simulation. In this context, the orientation state is described as an orientation probability for a group of fibers. The basic equation necessary for the prediction of the orientation pattern is the model of Folgar and Tucker (1982). This model describes the motion of the fibers in a fluid as well as their mutual interactions. The result of the model of Folgar and Tucker is a description of the orientation condition in form of an orientation probability function at each spatial point. However, the calculation of the probability function is connected with remarkable computational effort. A much more efficient way of representing the orientation condition within simulation is the use of a set of even order fiber orientation tensors (Advani and Tucker 1987). The general orientation state is described by the symmetric 2nd order tensor a_{ij}. By performing a principal axis transformation, the principal orientation axis (eigenvectors) and the corresponding degree of orientation (eigenvalues) are defined. As shown in figure 2, the orientation state is commonly visualized as ellipsoid with its principal axis coinciding with the eigenvectors of a_{ij}. A more detailed review describing the fundamentals of the numeric prediction of the orientation pattern can be withdrawn Chung and Kwon (2002).

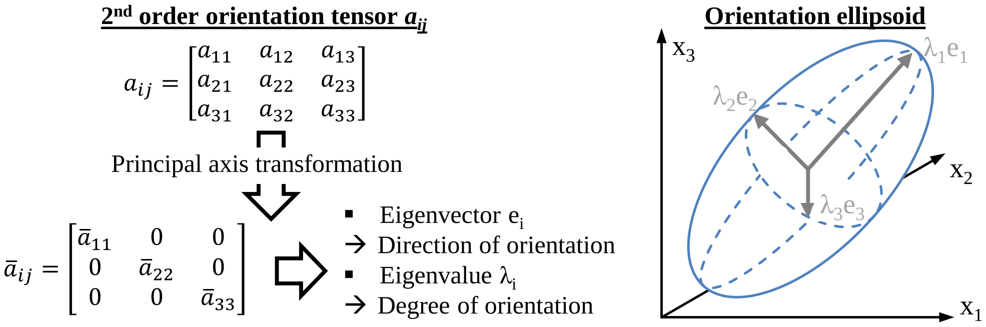

Figure 2. Fiber orientation condition described by the 2nd order orientation tensor a_{ij}

3.2 Prediction of the load path

The load path is an illustration of the stress condition in a part widely used in numerous educational books. Although it's a common expression, this term is not defined uniformly in the literature. A common method describing the load path is the interpretation of principal stress trajectories derived from the stress tensor σ_{ij}. The calculation of the stress trajectories resembles the determination of the principal fiber orientation. In the three dimensional space, the three orthogonal eigenvectors of the stress tensor define the orientation of the principal normal stresses σ_i. The three eigenvalues define the intensity of the corresponding stresses. With respect to the coordinate system defined by the eigenvectors, the shear stresses disappear. By definition, the mayor principal stress is defined as σ_1 and the minor principal stress is defined as σ_3. According to Ledermann (2003) reinforcement fibers should be aligned parallel to the major principal stress trajectories in order to achieve maximum stiffness. By doing so, it can be guaranteed that – as desired – the fibers are not subjected to any shear stresses.

3.3 Evaluation method of Durst

A methodology using principal stress trajectories to evaluate a component's suitability for the use of *continuous* fiber reinforced composites is presented by Durst (2008). Since components made of composites are usually thin walled parts, all of his considerations refer to plain stress theory. So the finite element models being used within his automated evaluation tool are discretized by shell elements. Consequently, when talking about principal stresses, only two stress vectors (σ_1 and σ_2) are present.

Durst introduced three factors as basis for his evaluation technique. At first, he defined a so called principal stress factor describing the state of stress. More precisely, this factor shows whether a plain tensile stress state, an ideal biaxial stress state or a mixed form is present. The principal stress factor is defined as the ratio of major stress σ_1 and minor stress σ_2. The second factor rates the angular deviation of σ_1 and a predefined direction of the preferred laminate orientation. An intermediate angle close to 0° can be considered as optimum. Since in practice components are usually subjected to several different load cases, a weighting factor is introduced. With the help of these three factors one elemental evaluation criterion is derived. In conclusion, the arithmetic mean value of all elemental evaluation criteria is formed. The result is a part criterion rating the component's suitability for the use of continuous fiber composite materials. To improve the analyses comfort, each part's part criterion of the investigated assembly can be visualized as contour plot with the help of a software tool.

4 EVALUATION METHODOLOGY

In the following, a new methodology for visualizing the lightweight potential of parts made of SFRT will be presented. Durst's basic idea of analyzing stress trajectories can be considered as starting point. Since the method of Durst doesn't support the direct comparison of several design solutions, additional tasks have to be fulfilled. The actual orientation pattern of the focused part has to be quantified adequately. Moreover, new evaluation techniques enabling the comparison of the stress and the orientation condition have to be developed. The orientation description of the focused *short* fibers – being represented by an orientation probability – can be regarded as additional challenge.

4.1 Prediction of stress and orientation condition

The prediction of the stress and the orientation condition will be performed using finite element simulation. As components made of SFRT are usually thin walled parts, a finite shell mesh will be deployed. The stress tensors are derived within a linear elastic structural simulation. In order to reduce the modeling effort, an isotropic material model is assumed. Since the actual anisotropic behavior weakly affects the general pattern of the stress trajectories, this can be seen as justifiable simplification. The fiber orientation is calculated within an injection molding simulation. To simplify the comparison of load path and fiber orientation, the identic triangle shell mesh is used for both types of simulations.

The examination of the stress condition is carried out on the basis of the stress tensors determined for each shell element. The stress tensors are provided with respect to an orthogonal elemental coordinate system at the lower and the upper surface of the laminar part. As displayed in figure 3a, the local x-axis coincides with the connecting line of the first two nodes of the element. By performing a principal axis transformation the stress trajectories σ_1 and σ_2 are derived. The stress state is defined by the intermediate angle α between σ_1 and the local x-axis and the length of σ_1 and σ_2 (see figure 3b). The stress condition at the mid plane ($z_{local} = 0$) can be derived by averaging the components of the pairs of stress tensors given at the lower and the upper surface.

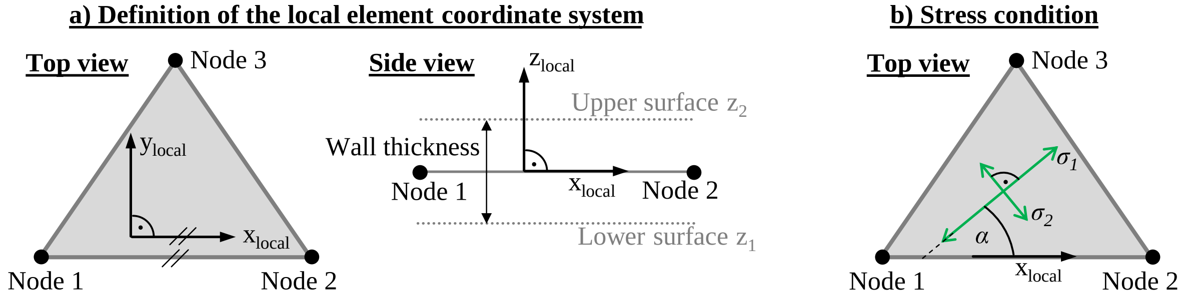

Figure 3. Local element coordinate system and stress trajectories in tria shell element

The fiber orientation condition is provided by the injection molding software for each shell element in form of a 2nd order orientation tensor a_{ij} introduced in section 3.1. The tensor can be either exported as average tensor describing the mean orientation condition of the element, or can be given for distinct layers of the shell elements. In contrast to the stress tensor, a_{ij} describes a *three* dimensional orientation condition with its components given with respect to a *global* coordinate system. For the purpose of evaluating the orientation pattern with the stress condition two measures are mandatory. The orientation ellipsoids have to be projected on the shell plane, since the share orthogonal to the shell cannot be used for the comparison with a plane stress state. Additionally, the components of a_{ij} have to be transformed into the local element coordinate system. By doing so, the direction of the maximum principal orientation vector Θ_1 can be expressed by an angle β with respect to the local x-axis. Since α and β refer to the same coordinate system, the intermediate angle between Θ_1 and σ_1 can be determined easily.

In figure 4, the average orientation as well as the layerwise orientation in form of a projected ellipsoid – resulting in an orientation ellipse – is displayed. So both stress and orientation condition can be characterized by an angle and the length of the principal vectors.

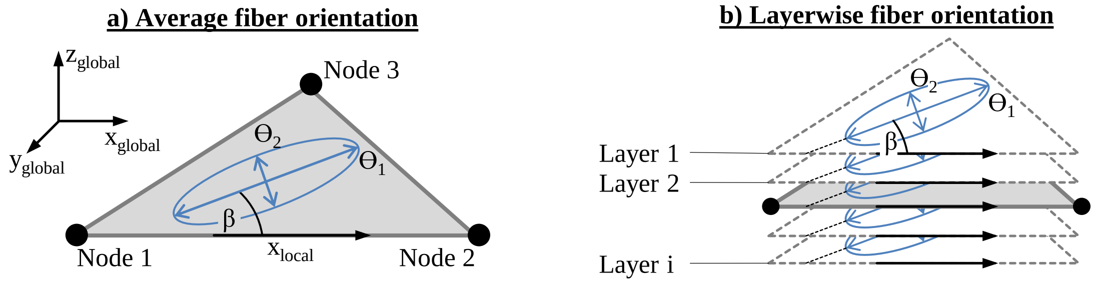

Figure 4. Fiber orientation in tria shell element

4.2 Evaluation criteria

The goal of the new evaluation technique is quantifying to which extent the fiber orientation harmonizes with the load path. In other words, the orientation quality with respect to the load condition has to be rated. Therefore, appropriate quality criteria have to be introduced. Since the comparison of several design proposals is focused, the quality criteria shall be defined as scaled values (from 0 to 1) rather than absolute values.

Angle criterion c_α

The most obvious evaluation method is determining the intermediate angle γ between the maximum principal axes σ_1 and Θ_1 for each finite element. Consequently, γ is defined by the following equation:

$$\gamma = |\alpha - \beta| \qquad (1)$$

The intermediate angle will be scaled from 0 to 1 leading to the angle criterion c_α. An intermediate angle close to 0° (c_α = 0) can be considered as optimum. In case γ is close to 90° (c_α = 1) a critical orientation condition is given.

However, the angle criterion in itself is not sufficient to rate the orientation quality. Imagine at a certain area of the part c_α tends to 1 ($\gamma \approx 90°$) while at the same time the stresses are very low. In this case, the fiber orientation shouldn't be considered as critical although γ is very large. To consider the influence of the load level an additional weighting factor called load level factor w_{ll} is introduced. w_{ll} represents the load level with values scaled between 0 and 1, with the maximum values of σ_1 being represented by w_{ll} = 1. As described by the logic table of figure 5, in the event of low stress levels or minor intermediate angles the status of the part can be considered as uncritical. Only the combination of high stresses *and* high intermediate angles leads to a critical condition. So consequently the geometric mean – also used for the evaluation of costs within standard VDI 2225 – is a suitable way to combine w_{ll} and c_α. The resulting weighted angle criterion will be abbreviated with c_{α_w}.

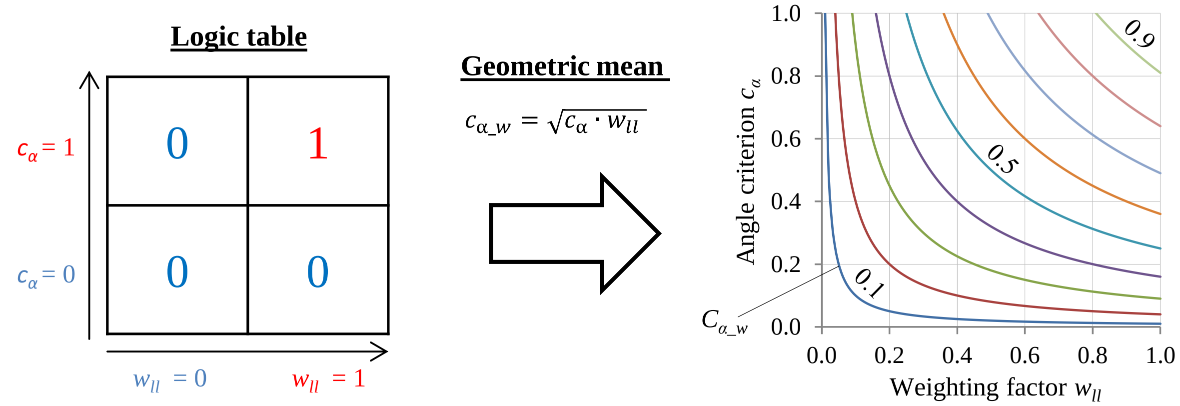

Figure 5. Weighting of the angle criterion c_α with the load level factor w_{ll}

Ellipse based orientation quality criterion c_Q

A disadvantage of the angle criterion c_α is the fact, that it does not take into account the magnitude of the eigenvalues of the stress and the orientation condition. This can lead to problems in case of biaxial stress states ($\sigma_1 \approx \sigma_2$) respectively, in almost isotropic orientation conditions ($\Theta_1 \approx \Theta_2$). This issue is displayed in figure 6. In the event of an almost isotropic fiber orientation distribution the intermediate angle can jump back and forth between 0° and 90° if major and minor orientation switch its position. So, almost identic stress and orientation conditions can lead to entirely different values of c_α.

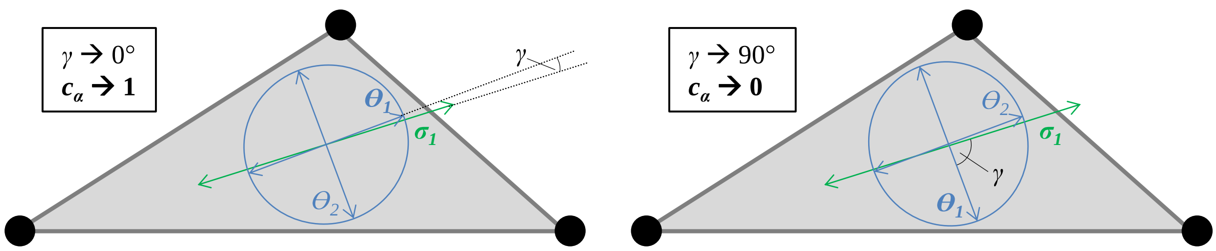

Figure 6. Angle criterion c_α in case of almost isotropic fiber orientation

Due to these limitations, a further quality criterion will be introduced. There as well the principal *stresses* will be interpreted as ellipses with σ_1 and σ_2 defining the semi-major and the semi-minor axis. This so called orientation quality criterion c_Q is defined by the overlap rate of the areas of the stress ellipse and the orientation ellipse (see figure 7). To calculate the coordinates of the intersection points being necessary for the determination of the cut surface, the ellipses are approximated as polygons with 30 line segments.

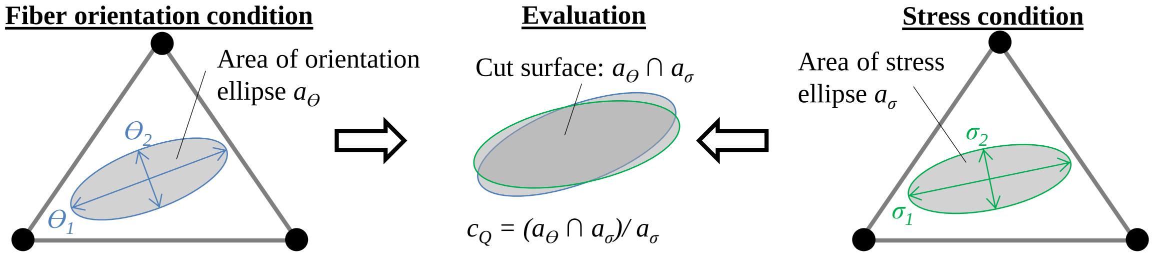

Figure 7. Determination of the overlap rate of stress and orientation ellipses

As a result of the definition of the orientation tensor a_{ij}, the ellipsoids describing the orientation condition (see figure 2) are normalized, meaning that the sum of the three semi-axis equals one. The two dimensional orientation ellipses resulting from the projection on the shell plane are still normalized. However, due to the projection, the orientation degree orthogonal to the shell plane is lost. So consequently, the sum of the two semi-axis of the orientation ellipses normally equals a value less than one. To enable a comparison between the orientation ellipses and the stress ellipses, the semi-axes of the stress ellipses have to be normalized as well. In case of the standard normalization, the maximum values of σ_1 are represented by a semi-axis of the stress ellipse with the length of one. If local stress peaks are present, this standard normalization method produces small stress ellipses on average. Since the area of the stress ellipse is the reference surface when forming c_Q, this standard normalization can lead to high c_Q values in general. In this situation, it's advisable to assign the maximum semi-axis of the stress ellipse (semi-axis equals one) for instance to the upper 20% of the maximum σ_1 values.

4.3 Visualization tool

The objective of the new evaluation approach is supporting the product developer at the decision making process in early phases when several design proposals are opposed. To reach this goal, it is necessary to implement the evaluation methodology as software application. To guarantee an optimum assistance of the product developer, the following requirements have to be fulfilled by the new evaluation tool:

- Delivering quick results while considering the anisotropic behavior
- Visualizing the results intuitively
- Quantifying the lightweight quality clearly

The input data for the evaluation are the results of an injection molding simulation and a linear elastic structural finite element simulation. The complex coupling procedure referred to as integrative simulation (see chapter 2.2) can be avoided with the help of the introduced approach. The new methodology can be rather considered as enhanced post processing solution. The additional calculation time necessary for the evaluation can be considered as negligible. Since the fiber orientation condition is considered within the comparison, the lightweight potential can be analyzed based on the part's anisotropic behavior.

As stated by Gumpinger et. al. (2011), intuitive visualization techniques supporting the product developer at the decision making process are a key factor especially in the context of lightweight design. The new analysis tool enables visualizing weak spots of the part and the general suitability of the fiber orientation distribution as contour plot. To objectify the comparison of several design proposals, the lightweight quality of the focused part is also quantified by the mean value and a histogram of the chosen quality criterion.

The evaluation procedure and the handling of the evaluation tool are described in the following at the example of a clutch pedal (see figure 8). Initially, a design proposal has to be created as CAD geometry. After converting the geometry into a mid-surface model, the meshing can be performed. The resulting mesh represents the geometry within the following structural and injection molding simulations. Theses simulations deliver the stress tensor as well as the fiber orientation tensor for each element in form of a text file. These tensor data as well as the geometry are the input for the fiber orientation evaluation tool. This tool enables visualizing the orientation pattern as well as the load path (standard visualization section). The focus of the new tool lies on the advanced evaluation capabilities. Both evaluation criteria introduced in section 4.2 can be used for the examination of the part. In case of the orientation quality criterion c_Q, the normalization of the stress ellipses can be controlled additionally, as described in section 4.2.

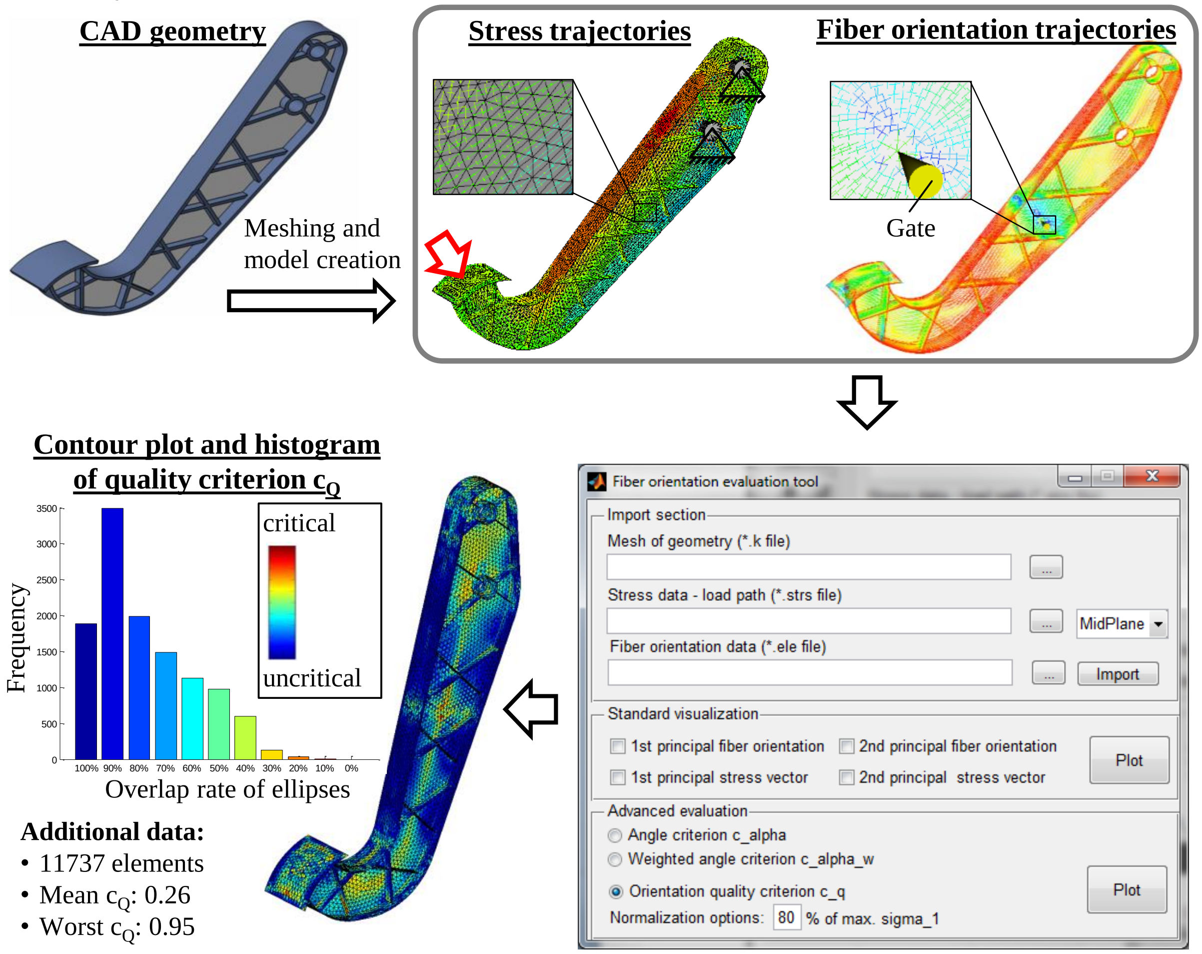

Figure 8. Workflow of the evaluation procedure

With the help of the evaluation tool, different geometric solutions or designs with different gate locations respectively different types of gates can easily be compared by opposing their contour plots or by directly forming a rank order with the help of each design's mean quality criterion. It is advisable that the analysis of the mean quality criterion (including its histogram) and the contour plots go hand in hand. By doing so, the global orientation condition as well as local effects are examined likewise.

5 CASE STUDY

The case study is executed with the help of two flat tensile bars. The evaluation is performed based on the stress tensors being present at the mid plane (z_{local} = 0) and the average fiber orientation state (see figure 4a). Intentionally, a simple example is chosen, so that the plausibility of the results can be recognized easily. The tensile bars being analyzed have the same geometry, only the gate settings will differ. By comparing specimens of identic geometry it can be guaranteed that exclusively the suitability of the fiber orientation pattern is evaluated. It should be noted, that the new evaluation method can also be applied for analyzing different geometric design solutions.

The rectangular bar has a fix support at one edge and is loaded with a force parallel to the tensile bar at the opposite edge (see figure 9). The first tensile bar (TB1) has its injection point at the center, leading to an undesirable chaotic ordination condition. The second tensile bar (TB2) is injected with the help of a fan gate which enables a favorable homogenous fiber orientation parallel to the tensile load path.

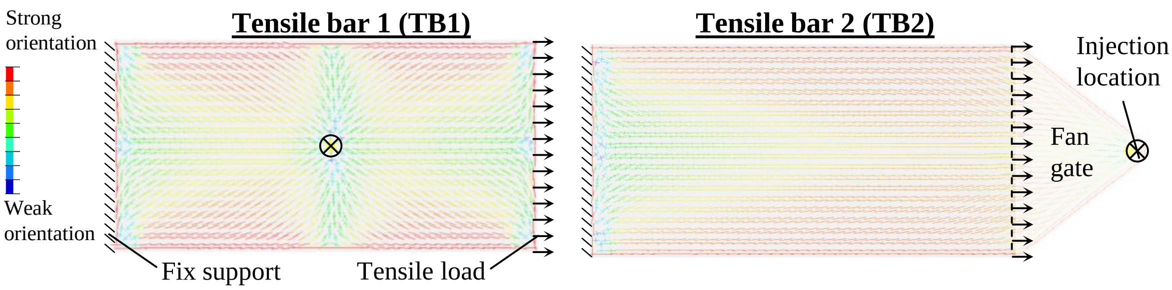

Figure 9. Test setup and orientation pattern of test objects

The goal is determining the design with the stiffest behavior. To quantify the reference stiffness, an integrative simulation is carried out. This simulation shows that the use of the fan gate leads to an increased stiffness of 16 %. Both tensile bars are evaluated using the evaluation criteria described in section 4.3. The contour plots of the quality criteria c_{α_w} and c_Q as well as the deviations of each global mean criterion of TB1 and TB2 are displayed in figure 10. The improved accordance between load path and fiber orientation pattern resulting from using the fan gate can be verified with all three criteria. Due to the homogenous stress condition the difference between c_α and c_{α_w} is insignificant. It can be noted, that the new evaluation criteria are much more sensitive towards changes of the fiber orientation than the integrative simulation. For the purpose of an evaluation tool this can be seen as benefit, because even weak differences in the orientation pattern can be detected.

The applied forces lead to an almost plain uniaxial stress pattern parallel to the long edged of the test specimens. Consequently, the desired fiber orientation pattern also circulates parallel to the long edge. Accordingly, the quality of the orientation pattern can be gathered directly from the contour plot of the fiber orientation shown in figure 9. The weak area around the injection location of TB1 can be detected in the contour plots of c_{α_w} and c_Q. The whole cross section at the center of TB1 is displayed as very critical in the plot of c_{α_w} since in this area the fibers are oriented almost perpendicular to the load path. However, the degree of orientation is relatively weak and tends to an isotropic orientation. So, this area should not be considered as very critical and therefore the plot of c_Q is more reliable. Also the analysis of TB2 shows that c_Q is the preferable quality criterion. The boundary area close to the gate is characterized by a non-optimum orientation direction as well as non-optimum degree of orientation. This semi critical area is predicted more clearly using the orientation quality criterion c_Q.

In general, c_Q delivers a smoother distribution of the quality criterion, due to the effects described in figure 6. This can clearly be observed at the elements directly next to the gate of TB1. Furthermore, the local distribution of c_Q reflects the orientation pattern shown in figure 9 more closely and hence can be considered more meaningful.

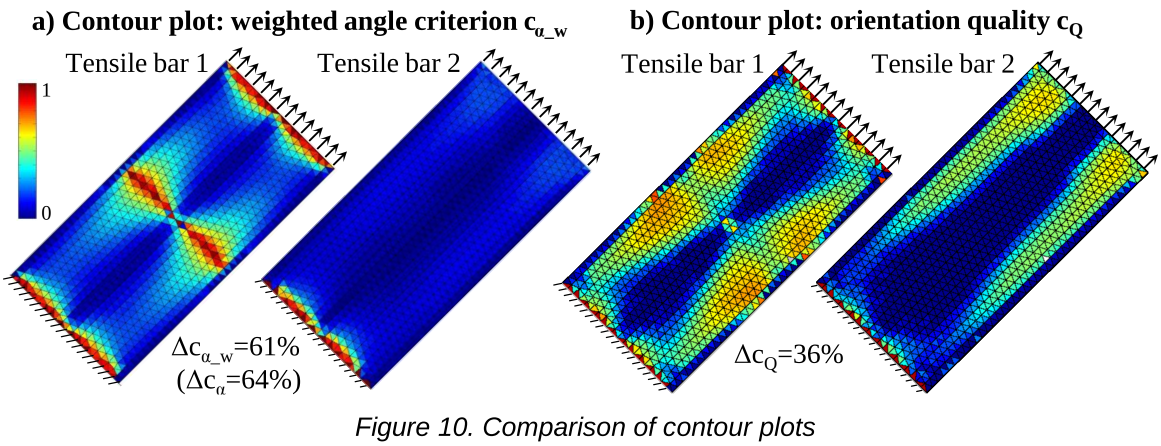

Figure 10. Comparison of contour plots

In exceptional cases, the discretization of the ellipses can lead to corrupt intersection coordinates of the stress and the orientation ellipse, if σ_2 tends to zero (sharp ellipse). Consequently, corrupt values of c_Q would result. This can be avoided by increasing the number of sub segments being used to approximate the ellipses (see section 4.2). However, a finer approximation goes hand in hand with an increased computation time. It's more advisable to evaluate the c_{α_w} simultaneously and check areas subjected to uniaxial stresses for plausibility. The calculation of the criterion c_{α_w} can be considered as strongly stable. So c_{α_w} can be regarded as helpful addition to orientation quality criterion. Due to manufacturing related aspects, Θ_2 won't tend to zero and therefore sharp orientation ellipses won't be present.

6 SUMMARY

In the present paper, a methodology was introduced which enables evaluating if the fiber orientation pattern is in harmony with the load path of a given design proposal. Therefore, two evaluation criteria – an angle criterion and an orientation quality criterion – were introduced. The first one is defined by the intermediate angle between the major principal fiber orientation Θ_1 and the major principal stresses σ_1. The latter one results from the overlapping ratio of the entire fiber orientation and stress condition which are both expressed as ellipses.

Since the orientation pattern within parts made of short fiber reinforced thermoplastics is mainly controlled by the parts geometry and the location respectively the type of gates, it is important to examine these aspects early in the development process. To assist the product developer at narrowing the solution space, the described evaluation method was implemented as a software tool, enabling an analysis based on contour plots of the presented quality criteria. The global suitability of the part's orientation pattern can also be quantified with the help of the mean value and a histogram of the focused quality criterion. The new evaluation technique supports the product developer at choosing design proposal being characterized by the most favorable orientation pattern and consequently having high quality mechanical properties with respect to the given load case. The ellipse based quality criterion c_Q allows a more reliable examination of the orientation pattern, since the eigenvalues of the stress and the orientation condition are taken into account as well.

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