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Material modelling of short fiber reinforced thermoplastic for the FEA of a clinching test

B. -A. Behrens[1], R. Rolfes[2], M. Vucetic[1], J. Reinoso[2], M. Vogler[3], N. Grbic[1]*

[1] Institute of Forming Technology and Machines, Leibniz Universität Hannover, Germany
[2] Institute for Statics and Dynamics, Leibniz Universität Hannover, Germany
[3] Matthias Vogler, Consulting Engineer, vogler.consulting@email.de
* Corresponding author. Tel.: +49 (0) 511 762 3861; fax: +49 (0) 511 762 3007 *E-mail address*: grbic@ifum.uni-hannover.de

Abstract

In modern car body construction, multi-material and hybrid design is used, whereby short fibre reinforced plastics combined with light metals represent an interesting class of work-piece materials. In order to realize modern hybrid construction, suitable joining techniques are therefore required. Clinching represents a cost-effective and easy to implement joining method. In this paper the material modelling of the short fibre reinforced thermoplastic sheets considering the fibre orientation tensor for the FEA of the clinching process is presented.

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Keywords: Clinching; short fiber reinforced plastics; aluminum; material characterization; material modeling

1. Introduction and Motivation

Realization of effective and optimized structural concepts in the aerospace and automotive industries has received a great deal of attention in the last years. Particularly, recent requirements for weight reduction in the automotive industry have motivated considerable progress in lightweight construction technologies of car bodies. This is the case for the combined use of aluminium and thermoplastics, where significant weight reductions that might lead to notable fuel consumption savings can be achieved. Therefore, multi-material and hybrid methods are used in modern car body construction, whereby short fiber reinforced plastics in addition to light and high strength metals represent an interesting class of work-piece materials. In order to realize such modern hybrid constructions, appropriate joining techniques are demanded. Joining procedures can be carried out by means of conventional methods such as welding, soldering, riveting or clinching. Contrarily to welding and soldering processes, one of the most appealing aspects of the clinching process relies on the fact that no special surface treatment is needed. Clinching is a mechanical fastening technique that allows sheet metal and other materials to be joined together by a cold-forming process without the need for additive elements such as the bolts, rivets, or adhesives (Fig. 1) [1, 2]. Hence, clinching represents an interesting method for joining dissimilar materials as is the case for metals and short fibre reinforced plastics.

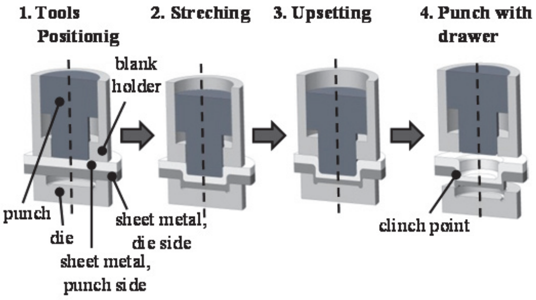

Fig. 1. Schematic representation of the clinching process

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An essential challenge when clinching metals and fibre reinforced plastics is the consideration of the different deformation behaviour with respect to the respective strength and stiffness. Furthermore, the anisotropic material behaviour of both materials, the short fibre reinforced plastic and the aluminium sheet, has to be regarded. In this context, from the experimental point of view, preliminary tests were performed at the Institute of Forming Technology and Machines (IFUM, Hannover) in order to investigate the reliability of such joints. Thereby an AlMg3 sheet and semi-finished plates with different glass fibre reinforcements of Polyamide PA6 (PA6GF0, PA6GF15, PA6GF30), each of the sheets of thickness $s_0 = 1$ mm, were joined by a clinching technique. Note that the last number of the denomination of this thermoplastic material refers to the corresponding percentage in volume of fiber content. These tests proved the feasibility to form an interlocking button (clinch point) between AlMg3 and PA6GF30 by means of a clinching process at room temperature (Fig. 2). However, under these thermal conditions, specimens including PA6GF0 and PA6GF15 materials showed a poorer performance of the clinch point when they joint to AlMg3 [3]. This issue is motivated by low fiber content of these materials.

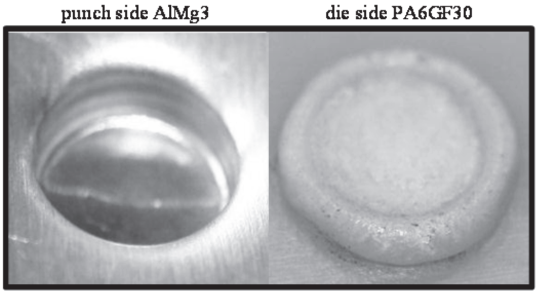


Fig. 2. Interlocking connection (clinch point) between AlMg3 and PA6GF30

Additionally, from the numerical perspective, the development of computational techniques that allow the accurate characterization of such joining procedures to be accomplished is needed. In this regard, an-invariant based elasto-plastic material model is applied for this purpose.

In light of the previous arguments, this paper concerns the applicability of the aforementioned invariant-based elasto-plastic model for the short fiber reinforced thermoplastic materials that are subsequently used in the hybrid clinching procedure of this work. Particularly, this model incorporates the anistropic character the thermoplastic constituent by means of the use of a tensorial-based description, which is addressed through the use of CT scans. We demonstrate the ability of this material formulation by recourse the simulations of several simple loading tests, observing a good agreement between the numerical and the experimental results.

2. Theoretical principles

The semi-finished plates made of short-fiber-reinforced thermoplastic are produced by an injection molding process between two flat tools. During the injection molding process a molten matrix material (PA6) spreads by two flow processes. Due to the elongational flow (Fig. 3) the fibers become oriented radially to the flow direction. This flow type occurs particularly in the middle of the sheet thickness.

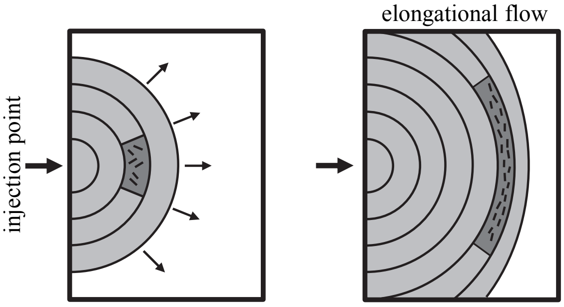


Fig. 3. Elongational flow during the injection molding processes [4]

The boundary area of a molten matrix material, which is in contact to the tool surface during the injection molding process, is affected by shear flow (Fig. 4). Due to the shear flow, the fibers become oriented in the injection molding direction [4].

On the basis of the presented production process for manufacturing the semi-finished plates made of short-fiber-reinforced thermoplastic, a multi layered structure following a sandwich design through the sheet thickness is formed. The fibers of the outer layers are oriented along the zero-degree direction (that coincides with that corresponding to the injection molding), whereas the fibers in the middle layer are oriented along the 90-degree direction with respect to the injection molding.

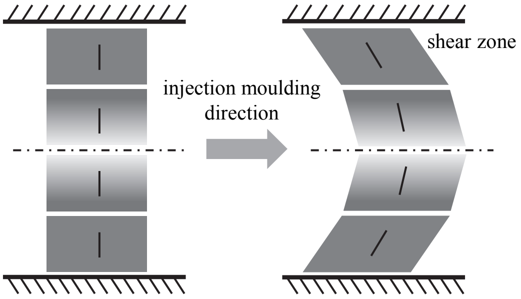


Fig. 4. Shear flow during the injection molding processes [4]

The fiber orientation through the sheet thickness can be described by the fiber orientation tensor [5, 6]. This tensor for PA6GF30 is determined experimentally by Computer Tomography (CT) scans, as is presented below.

3. Material characterization by CT scans

The accurate information of the fiber orientation and fiber orientation distribution in the material is required for an accurate analysis and interpretation of the mechanical properties. Therefore the experimental tests for the determination of the fiber orientation distribution in the semi-finished plates with high fibre content PA6GF30 and PA6GF60 (s_0 = 1 mm) were carried out using high-resolution micro-computer tomography (μ-CT, with a spatial resolution of about 7 μm) at BAM (Federal Institute for Materials Research and Testing). Thus, virtual cut images can be created in all three dimensions, resulting in 3D-illustrations of the fiber orientation distributions. Exemplary CT results for PA6GF30 are shown in Fig. 5.

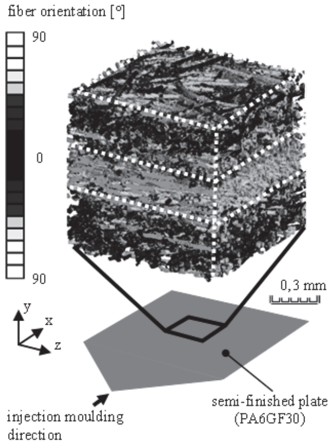


Fig. 5. Fiber orientation in 3D-volume

Here, a typically layered structure regarded by short-fiber-reinforced thermoplastic sheets can be observed. In order to achieve a fiber orientation through the sheet thickness, the second order orientation tensors are measured.

$$a_{ij} = \begin{pmatrix} a_{xx} & 0 \\ 0 & a_{yy} \end{pmatrix}$$

All orientation tensors are graphically presented over the sheet thickness in a diagram (Fig. 6).

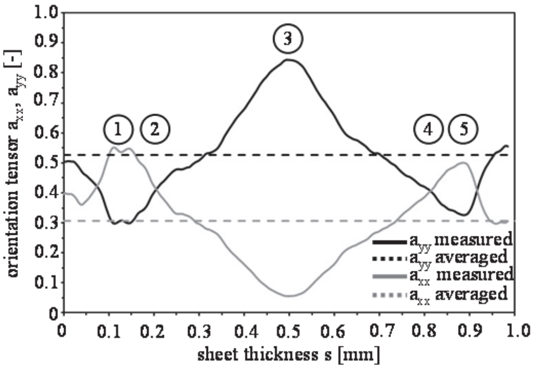


Fig. 6. Orientation tensor with averaging

The Fig. 7 shows characteristic slices from the cross section represented in Fig. 6. Thus a typically fiber orientation is regarded.

For the homogenization of the fiber distribution through the sheet thickness, the orientation tensors are averaged over the whole cross section. In this manner, the following orientation tensor is determined.

$$a_{ij} = \begin{pmatrix} 0.52 & 0 \\ 0 & 0.31 \end{pmatrix}$$

Alternatively, more precise approaches for modelling the fibre distribution can be obtained by means of an averaging method that relies on the uniformity of the fibre alignment. Thus, the specimen domain is split into several sections and the corresponding averaging procedure is accomplished in each of those subdomains.

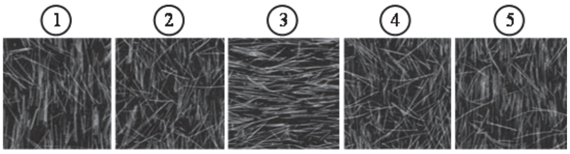


Fig. 7. Cut images with fiber orientation

In this case, the cross section is split in three sections, where the averaging process aforementioned regarding the fiber orientation tensor is accomplished for each of them (Fig. 8).

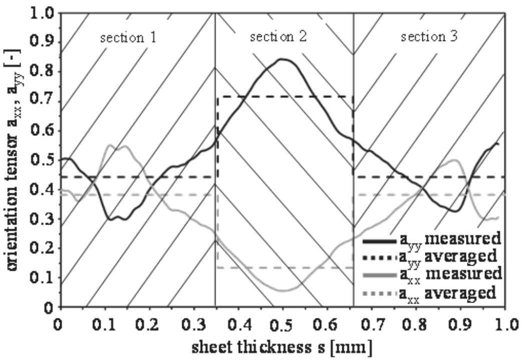


Fig. 8. Orientation tensor with sectional averaging

By this method, the corresponding orientation tensor for each of the three material layers that compose the material is accordingly determined. Consequently, as a consequence of the sandwich structure of the short fiber reinforced thermoplastics, two of those three tensors are the coincident:

For Section 1 and 3: $a_{ij} = \begin{pmatrix} 0.38 & 0 \\ 0 & 0.44 \end{pmatrix}$

For Section 2: $a_{ij} = \begin{pmatrix} 0.13 & 0 \\ 0 & 0.72 \end{pmatrix}$

These tensors are needed for accurate parameterisation and modelling of short fiber reinforced thermoplastic sheets used for the corresponding FEA.

4. Material model

This section deals with the basic description of the numerical model developed for the treatment of short fibre reinforced thermoplastics. The typical layered structure of such materials, as a result of the injection molding process, can be regarded by means of a transversely-orthotropic material model. Thus, the main directions of the fibre orientation tensor are used to perform a weighting process of the structural tensor that characterizes the material response [3, 4]. Alternatively, it is also note that a substitute approach for modelling this thermoplastic material can be accomplish by employing the isotropic material model SAMP-1 (*MAT_187) implemented in the FE software LS-DYNA [10], whose theoretical formulation is beyond of the scope of this paper.

4.1. Formulation of the invariant-based material model

The material model proposed consists of an elasto-plastic model, assuming the additive decomposition of the strain tensor ($\boldsymbol{\varepsilon}$) into the elastic ($\boldsymbol{\varepsilon}^{e}$) and the plastic parts ($\boldsymbol{\varepsilon}^{p}$):

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{e} + \boldsymbol{\varepsilon}^{p} \tag{1}$$

The anisotropic behaviour of short fibre reinforced thermoplastics is caused by the internal arrangement and orientation of the fibre embedded in the polymeric matrix. From a mathematical standpoint, the fibre orientations are commonly expressed through the structural second order tensors $\mathbf{A}$, that are defined as the dyadic product of the vectors of the preferred directions $\mathbf{a}$,

$$\mathbf{A} = \mathbf{a} \otimes \mathbf{a} \;\rightarrow\; A_{ij} = a_i a_j. \tag{2}$$

Due to the elastic symmetries, the material response is characterized by five independent constants. The structural tensor defined in (1) is used as an additional tensor argument in order to formulate the elastic free energy density, the yield function and the plastic potential [7, 8]. The elastic free energy density for the transversely orthotropic model, which includes the tensorial arguments $\boldsymbol{\varepsilon}$ and $\mathbf{A}$, yields:

$$\begin{gathered}\Psi(\boldsymbol{\varepsilon}, \mathbf{A}) = \tfrac{1}{2}\lambda(\mathrm{tr}\boldsymbol{\varepsilon})^2 + \mu_T \mathrm{tr}(\boldsymbol{\varepsilon})^2 + \\ \alpha(\mathbf{a}\boldsymbol{\varepsilon}\mathbf{a})\mathrm{tr}(\boldsymbol{\varepsilon}) + 2(\mu_L - \mu_T)(\mathbf{a}\boldsymbol{\varepsilon}^2\mathbf{a}) + \\ \tfrac{1}{2}\beta(\mathbf{a}\boldsymbol{\varepsilon}\mathbf{a})^2.\end{gathered} \tag{3}$$

With the five elastic constantsλ, μ_T, μ_L, α, β as invariant coefficients. According to [3], the stress $(\boldsymbol{\sigma})$ and the elasticity tensor ($\mathbb{C}_{\mathbf{e}}$) can be obtained by computing the first and the second derivatives of the free energy density with respect to the strain tensor, respectively:

$$\boldsymbol{\sigma} = \partial_{\boldsymbol{\varepsilon}}\Psi(\boldsymbol{\varepsilon}, \mathbf{A}); \quad \mathbb{C}_{\mathbf{e}} = \partial^2_{\boldsymbol{\varepsilon}}\Psi(\boldsymbol{\varepsilon}, \mathbf{A}) \tag{5}$$

The construction of the yield function (f) requires the structural tensor and the stress tensor along with the equivalent plastic strain (ε^{eq}) defined in [3]:

$$f = f(\boldsymbol{\sigma}, \varepsilon^{eq}, \mathbf{A}) \leq 0 \tag{6}$$

In accordance with the invariant theory, the functional basis formed by the argument tensors $\boldsymbol{\sigma}$ and $\mathbf{A}$ can be used without loss of generality. Henceforth, the set of transversely isotropic invariants using the decomposition of the stress tensor into plastic inducing stress ($\boldsymbol{\sigma}^{pind}$) and reaction stresses ($\boldsymbol{\sigma}^{reac}$) [3], reads:

$$\begin{gathered}f(\boldsymbol{\sigma}, \varepsilon^{eq}, \mathbf{A}) = \alpha_1 I_1 + \alpha_2 I_2 + \alpha_3 I_3 + \\ \alpha_{32} I_3^2 + \alpha_4 I_4 + \alpha_{42} I_4^2 - 1 \leq 0,\end{gathered} \tag{7}$$

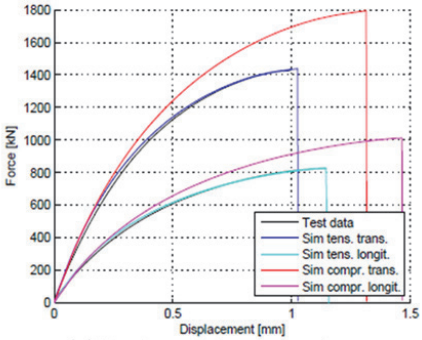
where the constants α_i in (7) are characterized by a set of a uxiaxial/biaxial tensile and compressive and shear tests. Indeed, the invariants in (7) can be expressed in terms of the aforementioned decomposition of the stress tensor as follows:

$$\begin{aligned} \mathrm{I}_1 &= \tfrac{1}{2}\mathrm{tr}\left(\boldsymbol{\sigma}^{\mathrm{pind}}\right)^2 - \mathbf{a}\left(\boldsymbol{\sigma}^{\mathrm{pind}}\right)^2\mathbf{a}, \\ \mathrm{I}_2 &= \mathbf{a}\left(\boldsymbol{\sigma}^{\mathrm{pind}}\right)^2\mathbf{a}, \\ \mathrm{I}_3 &= \mathrm{tr}(\boldsymbol{\sigma}) - \mathbf{a}\boldsymbol{\sigma}\mathbf{a} \\ \mathrm{I}_4 &= \frac{3}{2}\mathbf{a}\boldsymbol{\sigma}^{\mathrm{dev}}\mathbf{a} \end{aligned} \tag{8}$$

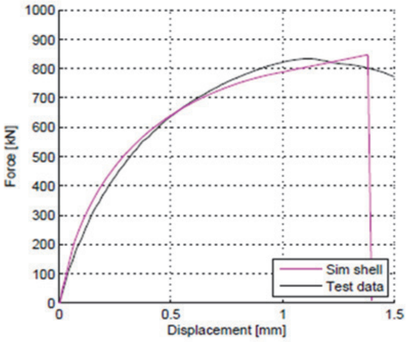
Further details corresponding to the present material model are omitted here for the sake of conciseness. The reader is addressed to consult [7, 8] and the references therein.

4.2. Material model: verification

This section covers the verification process of the material model here proposed through simple standard tests. This set of experiments allows the assessment of the accuracy and reliability of the material model for short fiber reinforced applications to be carried out. Simulations results using the model proposed for PA6GF60 are shown in Fig. 9. Different yielding behaviours under uniaxial tensile/compression along the longitudinal, the transverse directions (Fig. 9a) and under shear loadings (Fig. 9b) were taken into consideration. It is worth mentioning that in these plots, the anisotropic character of the thermoplastic material becomes evident, since significantly different responses under transverse and longitudinal tensile/compressive conditions (with respect to the predominant fiber orientation) are observed. In both illustrations, a satisfactory correlation between the numerical and the experimental data can be observed, addressing the capability of the model to accommodate the mechanical response of the short fibre reinforced material mentioned above.



(a) Tension and compression



(b) Shear

Fig. 9. Experimental-numerical correlation for PA6GF60: different yielding behaviour in longitudinal and transverse uniaxial tension/compression and under shear loading

5. Summary and Outlook

In this paper, we have addressed the characteristics clinching process between the metallic AlMg3 and the thermoplastics PA6GF- materials, especially regarding the fiber content of the latest constituent. In particular, experiments have evidenced that in the clinching process of AlMg3 and PA6GF30 at room temperature an interlocking button (clinch point) has been realized successfully, whereas lower fiber content compositions (PA6GF0 and PA6GF15) exhibited poorer clinching characteristics due to appearance of localized cracks at the joining surface.

Concerning the numerical developments, with the aim of performing reliable FEA simulations of the clinching process, accurate material models of both connection partners, i.e. AlMg3 and PA6GF30 are required. The material model developed by Barlat for modeling anisotropic material behavior in forming processes, which is implemented in FE-software LS-DYNA, is used for modeling AlMg3. Regarding the PA6GF30, the incorporation of its anisotropic character into the FE simulations is accomplished via the development of the tensorial-based transversely-orthotropic material model. This formulation accommodates this anisotropy by using a structural-tensor representation. In particular, two main approaches for performing the homogenization of the structural tensors are discussed: (1) an averaged fiber distribution over the whole sheet thickness, and (2) a domain-based procedure that takes into consideration the corresponding fiber orientation of each of the layer that compose the specimen. Based on the experimental measures obtained through CT scan, it is observed that the latest methodology provides a closer representation, though it requires the further development of the material model in order to account for multilayer structures. An alternative would regard the inclusion of several finite elements over the sheet thickness, however this alternative would increase the computational solution demands especially in case of an explicit FE formulation is employed (as is the case with LS-DYNA). The applicability of the material model for a correct characterization of short thermoplastics is demonstrated through the experimental-numerical correlations of several experimental tests, namely: uniaxial tensile and compressive tests along with an in-plane shear test. This fact underscores the high versatility of the invariant-based model employed. In this sense, subsequent investigations will incorporate such model into the complete modeling of the clinching process among dissimilar materials (metallic and thermoplastics). Additionally, further work will be devoted to optimizing FEA of clinching process, with special emphasis on computing demands and stability of FE-solution with regard to the use of different contact algorithms and potential damage techniques, among other issues.

Acknowledgements

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