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EXPERIMENTAL AND NUMERICAL INVESTIGATIONS FOR THE CHARACTERISATION OF FLOW BEHAVIOUR OF HYBRID STRUCTURES PRODUCED BY NON-KINEMATICAL CONSTRAINT MANUFACTURING PROCESSES

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Abstract

With regard to the challenges in the automotive production sector, caused by political regulations of CO_2 emissions, lightweight concepts are focussed by industrial development. Fibre reinforced plastics (FRP) represent an alternative material compared to monolithic steel. On the one hand FRP materials offer advantages like less density with high specific strength, on the other hand new production concepts and processes are needed. A possible approach is the combination of different forming processes for the production of new hybrid components. Polymer based and conventional sheet metal material characteristics differ strongly. Therefore an extensive material characterisation is needed as well as appropriate mathematical methods concerning the material modelling. This publication deals with the material characterisation of glass mat reinforced thermoplastic composite (GMT) and the finite element based design of a manufacturing process of hybrid components with metallic inlays.

Key words: Glass mat reinforced thermoplastic composite, Hybrid material, Sheet metal, FEA

1. INTRODUCTION

Regarding the political driven reduction of CO_2 emissions, the use of fiber reinforced plastics (FRP) is a promising approach for component manufacturing in automotive and aerospace sector. FRP material consists of polymeric matrix material and fiber reinforcement. In addition to carbon fibers, glass and natural fibers are applied for lightweight material. Different fiber types are chosen: short, long or endless fibers. Due to the chemical structure, polymer materials differ in a wide range compared to monolithic steel materials. The flow behavior is strongly temperature dependent. For the handling of FRP materials the characteristics of fiber and matrix material need to be known. The required knowledge is growing with further influences, e.g. varying fiber content or additional reinforcements, like metallic inlays. All these effects and interactions influence the forming behavior of the hybrid component. The combination of different materials for the generation of hybrid automotive components is a promising approach, see Behrens et al. (2017a), Behrens et al. (2017b), Behrens et al. (2017c). Herein the application of glass mat reinforced thermoplastic composite (GMT) material is focussed. The GMT is based on polyamide 6 and glass fibers with randomly orientation.

2. RHELOGY OF POLYMER MATERIALS

With reference to the GMT structure, plastic forming is strongly related to temperature. Applying thermoplastic material in manufacturing processes, knowledge of fluid process technology is required, because GMT material is handled in a polymer melt state (Eyerer et al., 2008). Due to this effect, the flow behaviour requires a distinct description different to monolithic steel blank. In this context the most significant parameter is the viscosity, which is defined as inner resistance against a constant loading (Eyerer et al., 2008). Viscosity depends on the process conditions, especially the occurring temperature. In literature, this type of material, which cannot be characterized by established physical and mechanical approaches are classified as non-newtonian fluids. For the description of the flow behaviour, viscosity η is presented as a function of shear rate $\dot{\gamma}$. Due to an expensive effort for the material characterisation, this relationship is used, even if it is not covering all effects (Giesekus, 1994).

Scientific work on the flow behaviour of GMT and its characterisation exist. Kau and Hagerman (1987) investigated compression molding process for sheet molding compounds to identify viscosity characteristics. Squeeze flow testing is a suitable approach for the estimation of flow characteristics of GMT material. In Kotsikos et al. (1996) injection molding of fiber reinforced polypropylene is considered and the flow behaviour is described taking into account anisotropy and non-newtonian flow effects by power law relationships. A basic approach to describe the flow behaviour is presented by Ostwald-de Waele equation (Giesekus, 1994):

$$\tau = K\,|\dot{\gamma}|^{(n-1)}|\dot{\gamma}| \quad (1)$$

In formula (1) τ represents the shear stress, $\gamma^\cdot$ the shear rate or rather velocity, K the consistence parameter and n the flow index. In case of a press rheometer setup the required pressure force depends on the resulting resistance in terms of shear and strain amounts (Oelgarth, 1997).

Figure 1 outlines the shear and strain amounts within a press rheometry flow process. For simplification and in case of extreme flow phenomena, wall slip zone is regarded as shear zone. In addition to the pressure values, further stress ratios need to be taken into account.

With reference to equation (1), the deformation tensor specification can be splitted in strain (D) and shear (S) ratio (Oelgarth, 1997):

$$\eta_D = 2^{n_D-1} K_D \left|\dot{\varepsilon}\right|^{n_D-1} \quad (2)$$

$$\eta_S = K_S \left|\dot{\gamma}\right|^{n_S-1} \quad (3)$$

With these terms a description of flow behavior is possible. The flow characteristics of polymeric materials are strongly temperature dependent and in general? described by means of viscosity and shear rate.

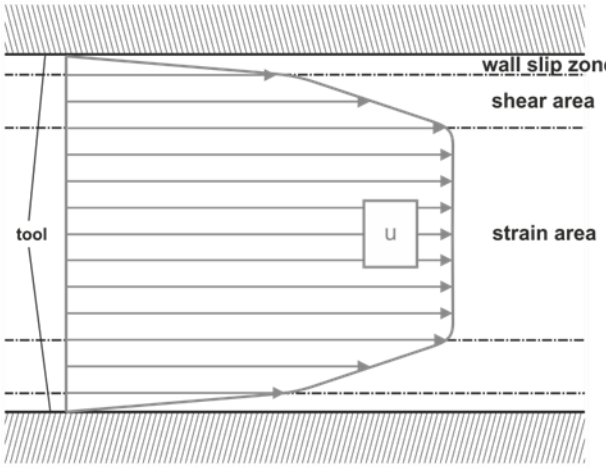


Fig. 1. *Representative sketch of polymer melt flow in press rheometry setup (according to Oelgarth, 1997).*

A concept for temperature dependence is presented by Cross-William-Landel-Ferry (1955). The behavior is described with estimation of a master curve and a shift factor α_T, see equation:

$$\log(\alpha_T) = \frac{8.86(T_B - T_S)}{101.6(T_B - T_S)} - \frac{8.86(T - T_S)}{101.6(T - T_S)} \quad (4)$$

where: T - current temperature, T_S - reference temperature, T_B - temperature from the experiment.

The factors 8.86 and 101.6 are determined by Cross-William-Landel-Ferry (1955) based on experimental investigations. For the experimental estimation of viscosity data rotational or capillary rheometer are state of the art. To enhance the usability in commercial software packages a flow curve based on the viscosity data representation is created, see (Hussain, 2013). Concerning numerical software packages, stress and strain data are often preferred as input data. The transformation of the viscosity data is done in Hussain (2013) with equations:

$$\bar{\sigma} = 3\eta(T)\dot{\varepsilon} \quad (5)$$

$$\dot{\varepsilon} = \frac{\dot{\gamma}}{\sqrt{3}} \quad (6)$$

where: $\bar{\sigma}$ - effective stress, η - viscosity, T - temperature, $\dot{\varepsilon}$ - strain rate and $\dot{\gamma}$ - shear rate.

For the viscosity analysis, linear stage of the logarithmic force displacement curve is used. Taking into account different punch velocities, the flow exponent n from equations (2) and (3) can be estimated by the gradient of press force characteristics. Furthermore with the determination of consistency parameters K_i (equations (2) and (3) a representation of viscosity versus shear rate can be obtained. More detailed transformation procedure for GMT material is presented in Behrens et al. (2018).

For GMT material no general standard procedures for the experimental estimation of flow behaviour exist. In addition there are several combinations of fibre and polymer material and the range of production fluctuations are higher compared to monolithic sheet material. Reliable flow behaviour information is not available from producers or databases. The presented existing literature differs in application fields and material combinations. Often circular plate geometries are used (Davis and McAlea, 1990), therefore it is difficult to generate reliable data due to friction, pressure, heat flow, etc. These influences have to be minimized in order to obtain accurate input data. To ensure reliable information for the flow behaviour of the applied GMT material, an experimental set-up has been created and press rheometry tests have been carried out within the current study.

3. EXPERIMENTAL RHEOLOGICAL CHARACTERISATION METHOD

Herein for the characterisation of the glass mat reinforced thermoplastic composites a rheometer tool set-up (see figure 2) is used to investigate the flow behaviour depending on the temperature. The investigations are carried out with a step of pre-heating of the samples to achieve a homogenous temperature distribution in the specimens. Afterwards the specimens are pressed with velocities of 1 mm/s and 3 mm/s, tool temperatures from 220°C up to 280°C and two different specimen thickness values. Figure 2 presents the experimental set-up with upper and lower tool geometries with inserted heating cartridges.

To describe the flow behavior of the GMT an additional analysis and subsequent transformation of the experimental data according to Hussain (2013) and Behrens et al. (2018) have to be perfomed. For the present contribution, in addition to the procedure in Behrens et al. (2018), an approach related to bulk metal forming characterisation test is applied. In Schommer et al. (2014) a press rheometry test with cylindrical samples is used to determine the flow characteristics of a sheet molding compound (SMC).

Assuming an incompressible material, constant temperature and load cell data a flow curve representation is generated. For the estimation of the flow characteristics, specimens with a dimension of 50 mm x 30 mm x 4.2 mm and a punch velocity of 1 mm/s are used. Taking into account the geometrical dimensions and boundary conditions, no length change in y-direction, an effective stress-strain curve can be determined.

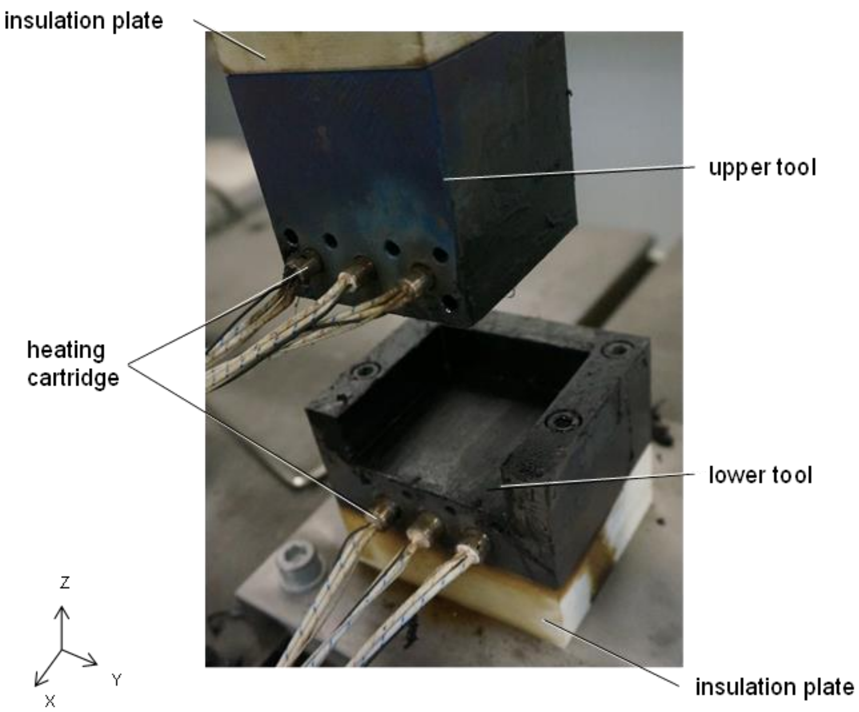
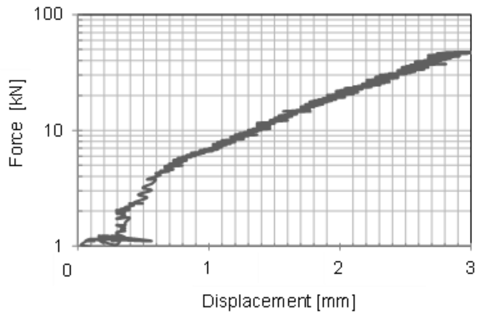
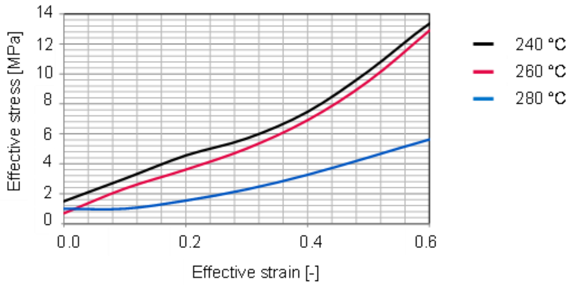


Fig. 2. *Experimental set-up for rheology investigations of GMT material.*

Figure 3a presents the force-displacement curve for the rheometry test at 206°C and figure 3b includes the estimated effective stress-effective strain curves for the GMT material at 240°C, 260°C and 280°C. For the temperatures 240°C and 260°C the results show similar characteristics with reference to the curve shape, for 280°C the curve shape indicates significantly softer material behaviour with lower stress values. Depending on the used polyamide and the fibre structure for higher temperatures, e. g. 280°C, the thermoplastic material exhibits a predominantly liquid like state.



a)



b)

Fig. 3. *Experimental force displacement curve at 260°C (a) and estimated flow curve representation for GMT material at 240°C, 260°C and 280°C (b).*

With the smoothed data for the force displacement values it is possible to identify a basic flow behavior description with reference to compression test analysis from bulk metal forming.

4. NUMERICAL SIMULATION

Taking into account boundary conditions of the press rheometry setup and material data a numerical simulation is carried out using the commercial software package LS-DYNA. Furthermore the evaluated viscosity data is used for finite element modelling with regard to fluid structure interaction (FSI). The FSI approach is based on an Eulerian-Lagrangian coupling algorithm using different mesh fields for the description of the fluid and the solid parts (Schommer et al., 2014). For the GMT material modelling, element free galerkin (EFG) method (Guo et al., 2010) is applied using precise remeshing procedure. As element formulation, adaptive element type 42 is chosen. EFG method for nearly incompressible materials on the one hand offers advantages in case of high distortions, moving boundaries (FSI) and adaptive procedure (Guo et al., 2010). On the other hand EFG formulation requires higher CPU cost. According to solution algorithm, EFG method adopts stress point integration and provides accurate surface representations (Karajan et al., 2014), which is beneficial for the numerical modelling of GMT.

Figure 4 shows the FE model for the simulation of the characterisation test of GMT material. Tool geometries are modelled as rigid with thermal conductive properties and for the GMT material EFG method is applied. Corresponding to the experiment, displacement in *y*-direction is suppressed. FE simulation of the related press rheometry characterisation test using a plasticity material model is performed. The objective of this FE simulation is the correct prediction of material flow depending on the boundary conditions.

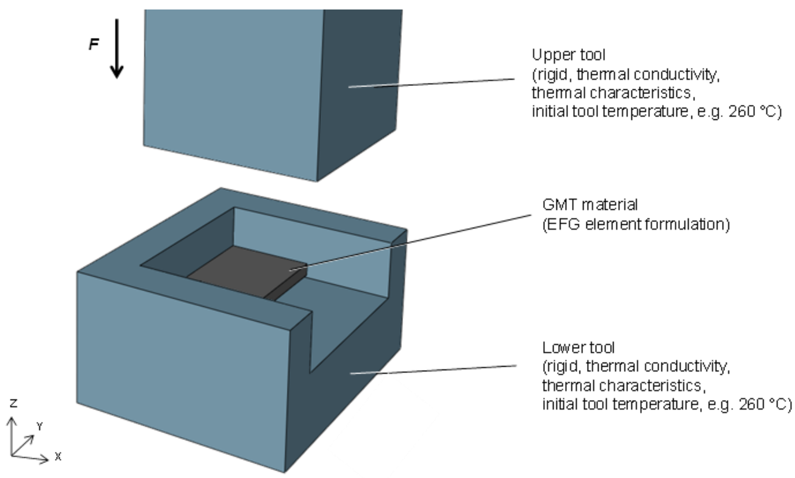
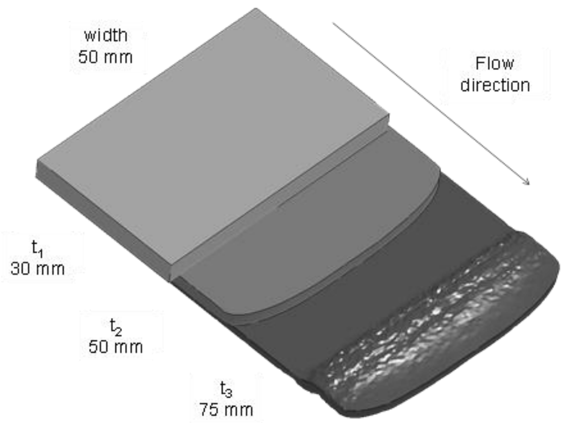


Fig. 4. *FE model for numerical simulation of press rheometry characterisation test for GMT material.*

5. RESULTS, DISCUSSION AND CONCLUSIONS

Focus of the FE simulation is the prediction of the material flow depending on punch speed and temperature influence. In figure 5 the resulting geometries from experiments and predicted specimen dimensions after forming by the FE simulation are shown. Figure 5 a) presents the material flow for three timesteps (t1, t2, t3) and the corresponding flow length. Figure 5 b) shows the final specimen geometry after processing from experiment and figure 5 c) presents an optical comparison of final geometry between FEA and experiment.



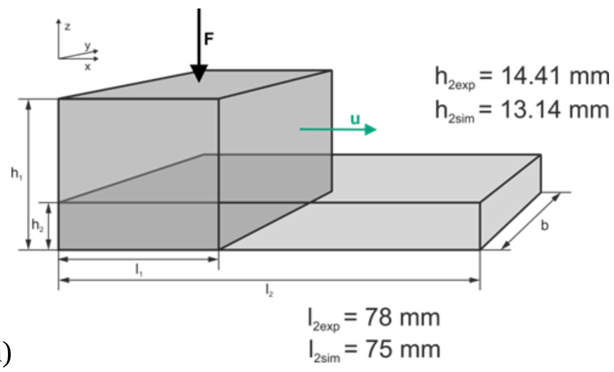
a)

b)

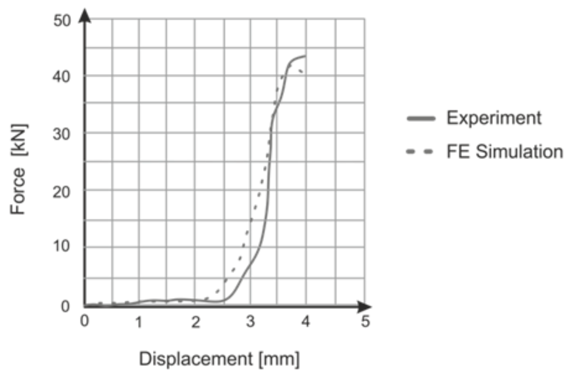
c)

Fig. 5. FE results for press rheometry simulation at different time steps (t_1, t_2, t_3) (a), experimental components after process (b) and geometry comparison between FEA and experiment for GMT material processing at 260°C (c).

Figure 6a shows the specimen dimensions of initial and final shape, figure 6b presents the corresponding force displacement curves. The length increases in the experiment up to circa 78 mm. After passing the tool length (see figure 2), a squeeze out effect occurs for the GMT material. This material accumulation can be predicted by the FE simulation. The final height values h2 are included in figure 6a. The specimen dimensions of the numerical simulation correspond to the experimental results. The material model is limited for the prediction of air inclusions and local squeeze out effects of the thermoplastic material, but overall applicable to predict the material flow of the GMT block.



a)



b)

Fig. 6. Process sketch including final geometry dimensions (FEA and experiment) (a) and force displacement curves for GMT material processing at 260°C (b).

Within the work for this contribution an experimental set-up for press rheometry tests has been designed and applied for composite material. The analysis procedure has been proved and can be used in FE simulations with the estimated data for this kind of material. The minimisation of influences concerning existing literature approaches has been done and the set-up can be used in future for similar characterisation tests for different kind of materials.

Taking into account the experimental and numerical results, an important contribution for the prediction accuracy in the FE simulation of GMT material forming has been provided. Moreover the influence of rotational tool motion on the polymer mold have to be evaluated within a parameter study.

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DOŚWIADCZALNA I NUMERYCZNA ANALIZA ZACHOWANIA SIĘ W CZASIE PŁYNIĘCIA HYBRYDOWYCH STRUKTUR WYTWORZONYCH W NIEKINEMATYCZNIE OGRANICZONYCH PROCESACH PRODUKCYJNYCH.

Streszczenie

Wyzwania stawiane sektorowi samochodowemu związane z ograniczeniem emisji CO_2 powodują zainteresowanie lekkimi elementami w rozwoju przemysłu. Tworzywa sztuczne wzmocnione włóknami (ang. Fibre reinforced plastics – FRP) są alternatywą dla monolitycznych stali. FRP z jednej strony pozwalają uzyskać wysokie wytrzymałości przy niższej gęstości, ale z drugiej strony wymagają nowych metod produkcyji. Połączenie różnych metod kształtowania w produkcji hybrydowych elementów jest jednym z możliwych rozwiązań. Charakterystyki kompozytu na bazie polimeru i stali są różne i dlatego potrzebne są szerokie badania własności materiałów i opracowanie odpowiednich metod matematycznego modelowania. W pracy wykonano badania własności kompozytu na bazie polimeru wzmacnianego szklanymi włóknami. Ponadto wykorzystano metodę elementów skończonych do projektowania wytwarzania hybrydowego elementu inkrustowanego metalem.

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