FINITE ELEMENT ANALYSIS FOR SHEET METAL REINFORCED HYBRID STRUCTURES PRODUCED VIA NON-KINEMATICAL CONSTRAINT MANUFACTURING PROCESSES

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Abstract
With reference to the challenges in the automotive industry like fuel economy or weight reduction, new hybrid materials are being developed and applied for established as well as new components. One approach to achieve less weight while retaining adequate mechanical characteristics is the combination of different materials [1, 2]. In [1] the advantages of hybrid structures consisting of fibre reinforced plastics (FRP) in combination with sheet metal inlays are investigated. For the manufacturing of these FRP-metal structures new innovative production concepts are needed. The present contribution deals with FE based process design of the manufacturing process for hybrid components with non-kinematical knitting rotation. Within the process, the metallic inlays will be entirely wrapped by the thermoplastic matrix. Using this method, a form- and material fitted structure is generated by process integration. Air locking defects can be suppressed by the rotational tool motion through an improved local contact pressure. Applying a rotational motion influences the flow direction and fibre orientation in positive manner. An extensive material characterization has been carried out. In order to describe the flow behaviour of the polymer component, viscosity data is needed. Therefore, experimental investigations are carried out and provided for the FE simulation.

1. Introduction

In the manner of facing the challenges in automotive sector regarding CO_2 emissons, lightweight applications are one approach. The temperature dependent flow behaviour of polymers with regard to viscosity and shear rate can be described with the approach by Cross-William-Landel-Ferry [3]. The viscosity data is used for the FE modelling to enable the application of Lagrange formulation [4] within the FE code, in which the nodes are coupled to the material deformation [5]. Regarding the varying material characteristics, different FE modelling techniques have to be applied, e. g. fluid structure interaction [4]. Taking into account the experimental and numerical results, an important contribution for the prediction accuracy in the FE simulation of hybrid component forming will be provided.

2. Material processing

To face the challenges coming along with lightweight application various materials and processes are investigated and used nowadays. Common materials are available in different variations of fibre reinforced plastics (FRP) also known as composites consisting of short or long fibres and polymer matrix. Fibres intensify the strength of the polymeric matrix and improve the mechanical properties of the composite structure. Besides glass fibre there are carbon, aramid and natural fibres. Depending on the variation of materials there are many process handlings [6]. An approach within automotive serial

production processes is the utilization of semi-finished products. 20 years after the establishment of sheet moulding compounds (SMC), glass mat reinforced thermoplastics (GMT) were invented and classified as high perfomance composites. With regard to the manufacturing process, GMT is heated up to melting temperature before forming [6, 7]. The mechanical properties are related to the fibre reinforcement [6] and as well the characterisitics depend on thermal influences, local pressures and velocities [7]. The objective of this contribution is the characterisation and analysis of flow behaviour of GMT material. The analysis in this contribution is related to GMT material with polyamid 6 laminate with randomly oriented glass fibers.

2.1. Polymer melt material

For the processing of forming applications of polymers there is a demand for molecular mobility. Duroplast and elastomer material start vulcanization and linking after forming. Therefore the material types hold an inherent stiffness. Due to their structure the plastification of thermoplast material is strongly coupled to the specific temperatures and fluid related processes. To achieve plastic deformation, thermoplastic material needs to be in melt state for process handling steps [8].

2.2. Rheology, viscosity characteristics and flow behaviour

With relation to the material characteristics of polymer melts, here GMT, viscosity is the major parameter to describe the forming behaviour. Viscosity is defined as inner material resistence against constant loading during extrusion [8]. Viscosity strongly depends on temperature [7] and in general is indicated by the shear rate. Referring to sheet metal forming processes and the integration of polymer materials, material behaviour is described by flow stress and plastic strain values [1, 9]. For GMT material a few research approaches for the estimation of rheology and flow characteristics exist. *Dweib* and *Brádaigh* [10] performed experimental studies and analysises for the shearing and extensional behaviour of GMT material under compression loading with non-lubricated mold plate surfaces. *Fisher* and *Birley* [11] determined viscous, elastic and yield parameters of sheet moulding compound using a parallel plate plastometer. In general the rheological behavior for polymer melts is given by viscosity curves with viscosity η versus shear rate $\dot{\gamma}$.
For the description of the viscosity dependence on the deformation velocities $\dot{\gamma}$ and $\dot{\varepsilon}$ a potential approach needs to be taken into account. The general form by *Ostwald-de Waele*, according to [12], is:

$$\underline{\underline{S}}^{*} = 2\,K\,\left|(2\underline{\underline{D}}:\underline{\underline{D}})^{\frac{(n-1)}{n}}\right|\underline{\underline{D}} \tag{1}$$

In formula (1) $\underline{\underline{S}}^{*}$ represents the stress tensor without isotropic pressure, $\underline{\underline{D}}$ is the tensor of deformation velocity, n the flow exponent and K is a consistency parameter. In case of press rheology the considered flow is defined by shear and strain ratio: $D_{ik} = \frac{1}{2}(\partial_i v_k + \partial_k v_i)$. For further details see literature [10, 11, 12]. The viscosity strongly depends on the temperature. Besides extensive material characterization tests with the approach by William, Landy and Ferry (WLF) [3] the temperature dependence can be included by generation of a master curve with relation to experimental data and with the estimation of a shift factor α_T the temperature dependent viscosity function is widely described.

$$\log(\alpha_T) = \frac{8.86(T_B - T_S)}{101.6(T_B - T_S)} - \frac{8.86(T - T_S)}{101.6(T - T_S)} \tag{2}$$

In formula (2) T is the current temperature, T_B is the temperature from the experiment and T_S is the reference temperature. The factors 8.86 and 101.6 are estimated in [3] basing on experimental data.
The tensor of deformation in formula (1) includes strain and shear dependent information.

With regard to [12] the viscosity η can be described depending on shear (*s*) and strain (*d*):

$$\eta_s = K_S|\dot{\gamma}|^{n_s-1} \qquad \eta_D = 2^{n_D-1}K_D|\dot{\varepsilon}|^{n_D-1} \tag{3}$$

Focused on investigations regarding deep drawing processes and forming operations a relation for stress and strain is often preferred, e. g. for the implementation in commercial FE software packages [13]. In [13] an approach is presented to transfer experimental viscosity data to an effective stress vs. strain rate representation. For the relations between viscosity and flow data formulation see formula (4).

$$\overline{\sigma} = 3\eta(T)\dot{\varepsilon} \qquad \dot{\varepsilon} = \frac{\dot{\gamma}}{\sqrt{3}} \tag{4}$$

In formula (4) $\overline{\sigma}$ is the effective stress, η is the viscosity, T the temperature, $\dot{\gamma}$ the shear rate and $\dot{\varepsilon}$ the strain rate. With formula (4) it is possible to describe the effective stress values versus strain rate with relation to viscosity and depending on temperature.

3. Material characterisation

Due to the large range of composite material combinations, in this work an extensive material characterisation for GMT material with 30 % glass fibre (thickness 4.2 mm and 8.4 mm) is performed in order to obtain exact data for the rheology characteristics and the related flow behaviour.

3.1. Experimental investigations

To ensure a precised data estimation a tool is designed and constructed for rheology investigations.

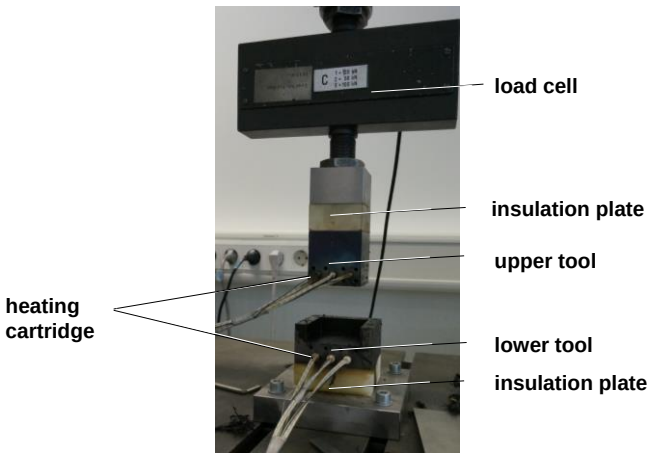

Figure 1. Experimental set-up for rheology investigations of GMT material

In figure 1 the tool for the material characterization is shown. The upper and lower tool geometries contain holes with different diameters for the integration of heating cartridges for the tool heating. The load cell detects force and displacement values during the process. Additionally, for reasons of process control temperature sensors are used to measure the temperature. The insulation plates are integrated in the set-up to guarantee an accurate measurement without heat conduction influences on the load cell. To generate an extensive material data basis, investigations with velocities 1 mm/s and 3 mm/s for the GMT material are performed. Tool temperature values are 220, 240, 260 and 280 °C. The specimen dimensions are 50 mm x 30 mm with thickness values of 4.2 and 8.4 mm. Within the investigations the heated GMT material is pressed with constant punch velocity.

3.2. Analysis of viscosity data

At first, the heating characteristics of the specimens are considered for different tool temperatures. As a result the specimens show a constant temperature after 180 s. The focus of the investigation is the estimation of accurate viscosity data for the applied GMT material. For all combinations of temperature and press velocity three tests are carried out.

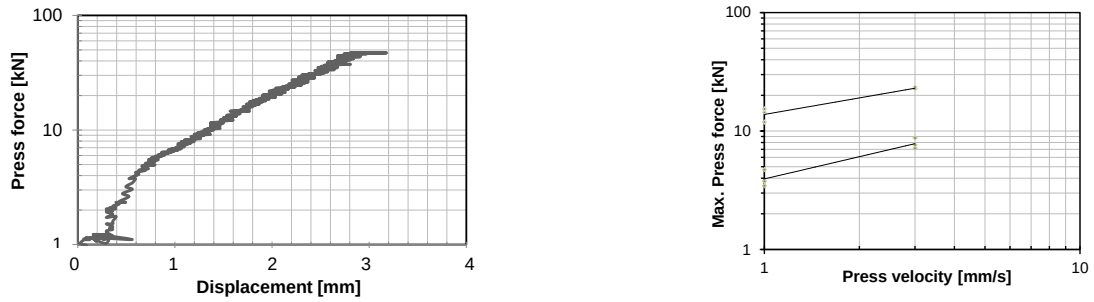

Figure 2. Experimental data of press rheology investigations for GMT material with a thickness of 4.2 mm at 260 °C: Exemplary force-displacement curve (left) at speed 1 mm/s and analysis approach for estimation of flow exponent (right) for different process stages

In figure 2 on the left hand the force displacement curve for a press rheology test for a GMT with 4.2 mm thickness for temperature of 260 °C and press velocity of 1 mm/s is shown. At the beginning there is a compression stage of the melt followed by a linear increase of the force and to the end the force decreases. For the analysis only the linear stage is taken into account [12]. According to *Oelgarth* the flow exponent *n* can be estimated from logarithmic representation of press force and press velocity for different height values based on the linear force increase area. The assumption of corresponding shear and strain exponents is made. Figure 2 (right) shows this depiction for the test case 260 °C with press speed of 1 mm/s and 3 mm/s. With the representation the flow exponent can be estimated from the gradient of the press force characteristic. For the the configuration at 260 °C a flow exponent of 0.458 is determined. The analytical description for press force conditions can be simplified as [12]:

$$\mathrm{F}_{s,\mathrm{theor}} = 2^{n_\mathrm{S}+1}\,\mathrm{K}_s\,\mathrm{B}\,\dot{h}^{\,\mathrm{n}_s}\left(\frac{2n_\mathrm{S}+1}{n_\mathrm{S}}\right)^{n_\mathrm{S}}\frac{\mathrm{L}^{n_\mathrm{S}+2}}{n_\mathrm{S}+2}\,\frac{\mathrm{L}^{n_\mathrm{S}+2}}{\mathrm{h}^{2n_\mathrm{S}+1}} \tag{5}$$

$$\mathrm{F}_{D,\mathrm{theor}} = 2^{n_D+1}\,\mathrm{K}_D\,\mathrm{B}\,\mathrm{L}\left(\frac{\dot{h}}{h}\right)^{n_D} \tag{6}$$

Within this description wall adhesion is taken into account and the flow profile is based on strain related central flow amount and sheared wall close films. In formula (5) and (6) the dimensions length *L* and weight *B* of the melt specimen are included as well as height h and velocity $\dot{h}$. K_i, n_i are the flow variables mentioned in chapter 2.2.. With the force relationship and the force behaviour it is possible to determine K_D, K_S. Using formula (3) and (4) a relationship regarding deep drawing characteristics mentioned in [13] is generated.

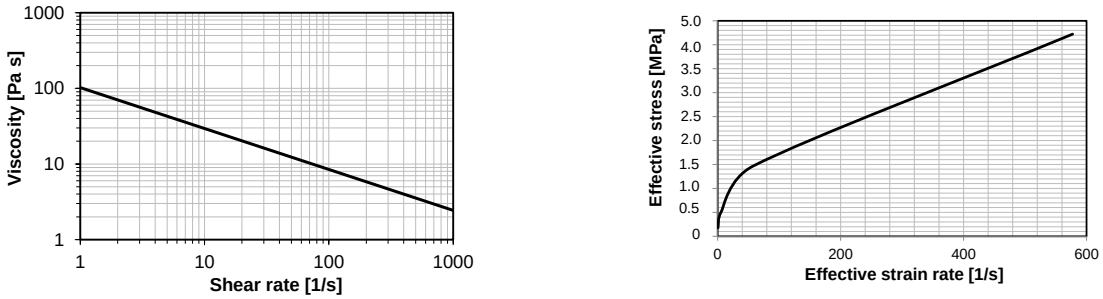

Figure 3. Results of the press rheology analysis for GMT material with 4.2 mm thickness at 260 °C: Vicosity curve (left) and estimated flow characteristics (right)

Figure 3 shows the estimated viscosity curve and the resulting flow curve representation for the GMT material for a process temperature of 260 °C.

3. FEA of the experimental characterization approach

The experimental results are used to build up an FE model with LS-DYNA of the simplified press rheology characterization approach. The dimension of tool and specimens as well as process temperature are similar to the test set-up in figure 1. For the FE simulation of the characterization approach a press speed of 1 mm/s is chosen and the GMT material is modelled with strain rate dependent plastic material with temperature influence based on the experimental data of chapter 2. The polymer is represented by an EFG (element free galerkin) formulation [14] as solid element. Rigid tools are used.

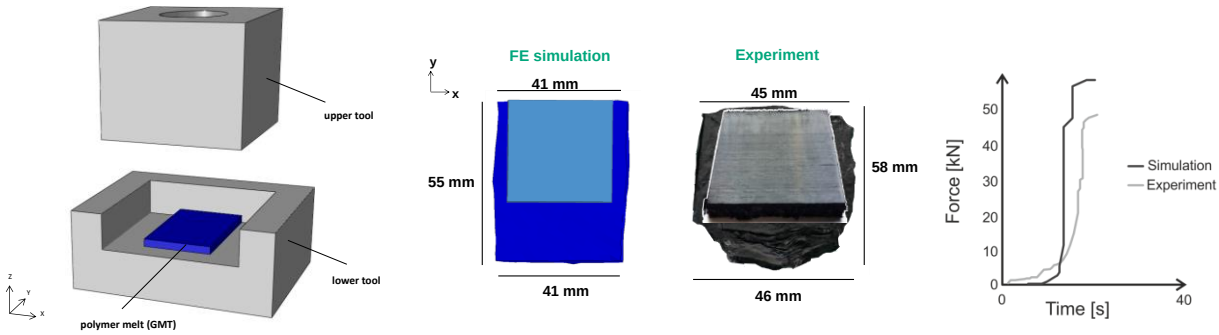

Figure 4. Numerical FE model for press rheology characterization test (left), numerical and experimental pressed polymer melt of rheology test with punch displacement 3 mm (middle) and force time curves of FE simulation and experimental investigation (right)

Figure 4 (left) shows the numerical model of the FE simulation of press rheology test. For the numerical simulation the software LS-DYNA is used. Figure 5 (middle) shows the resulting melt geometry after isothermal pressing of the polymer melt with secimens size 40 x 40 x 8.4 mm. The flow characterisitics from FEA and experiment show deviations. Right hand side of figure 5 the force time curve is shown. The punch force is marginally overestimated in the FE simulation. The flow behaviour in the FE simulation demonstrate a higher flow resistence. To overcome this effect, additional numerical optimization is needed.

5. Conclusions & Outlook

The focus of this contribution belongs to an experimental approach to investigate and determine the flow characterisitics for GMT material. To achieve this objective an individual experimental set-up is created and characterization tests are carried out. Afterwards an analysis with reference to literature is performed and the estimated flow behaviour is used for a simple FE simulation of the press rheology test. In future works the characterization test will be used for investiagations of various polymer materials. Within the experimental approach also further temperature variables, e. g. heat tranfer coefficient and elastic modulus are investigated. These results will be subject of future publications.

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