A NOVEL METHOD FOR MANUFACTURING OF HYBRID STRUCTURES MADE OF METALANDFIBER REINFORCED PLASTICS USING A MULTIDIRECTIONAL FORMING PROCESS

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Abstract

Hybrid materials are increasingly used in lightweight construction. The combination of metallic materials with fiber-reinforced plastics (FRP) can reduce weight and improve the mechanical properties of a component. FRP are known for their lightweight and corrosion resistance, while metals show high strengths and stiffnesses. In order to combine the advantages of both materials, it is possible to reinforce highly stressed segments of a metallic component with FRP. A novel method for manufacturing such hybrid metal-FRP composite structures using a multidirectional forming process is investigated. Thereby, a glass mat reinforced thermoplastic (GMT), consisting of a polypropylene matrix with 40% glass fiber reinforcement, is compression moulded on specific segments of a metallic component by means of a controlled multidirectional die. For this, finite element (FE) simulations are required to design a forming process close to an industrial application. In order to conduct such a numerical study of the material flow during forming, a precise characterization of the GMT is necessary. Therefore, isothermal compression tests were conducted using a parallel-plate rheometer at different temperatures ranging from 180 °C to 220 °C and varying squeeze rates from 0.05 mm/s to 2 mm/s. The experimental data is used to fit a material model for the FE simulations. To verify the material model for further simulations in the project, the compression process is simulated in ABAQUS using a Coupled Eulerian-Lagrange approach and the results are compared with the experimental data.

Keywords: Composite materials, numerical simulation, multidirectional forming process, glass mat reinforced thermoplastic

1. INTRODUCTION

The desire of enhanced structural performance and a reduced carbon footprint has led to an increase in the use of hybrid materials in the field of light weight construction. A method to address this topic is the combination of metallic materials with fiber-reinforced plastics (FRP). While FRP are known for their light weight and corrosion resistance, metals show high strengths and stiffnesses. Hence, a combination of metallic materials with FRP can reduce weight and improve the mechanical properties of a component [1]. This paper investigates a novel method for manufacturing such hybrid structures using a multidirectional forming process. The multidirectional forming process involves the wobbling, swiveling or rolling movement of a tool to create a workpiece contour. **Figure 1** shows the outcome of such a forming process, whereby a FRP is compressed on a specific segment of a component. In contrast to conventional pressing processes, only a small part of the tool is in contact with the workpiece at any time, allowing for incremental forming. This unique kinematics reduces forming forces compared to conventional processes and allows controlling the stress state in the component with more precise [2]. Furthermore, highly stressed segments of a component can be reinforced locally due to the unique kinematics [3].

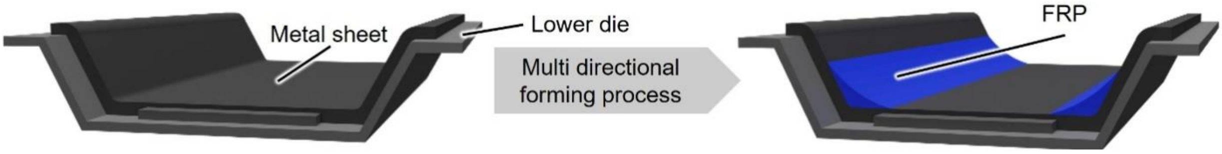

Figure 1 Schematic representation of the outcome of a multidirectional forming process. A FRP is compression moulded on the inner contours of the component

For the application of such a multidirectional forming approach, the process has to be designed using finite element (FE) simulations. In order to accurately compute the material flow during forming, a precise material model is essential. Therefore, the characterization of a glass mat-reinforced thermoplastic (GMT)is performed. A well-established method to determine the flow behaviour of GMT are squeeze flow tests in a parallel plate rheometer [3]. Thereby, GMT is compressed between two parallel plates at a constant temperature and squeeze rate, with the polymer melt flowing in a radial direction [4]. The flow behaviour can be determined by recording the forming force and displacement. The experimental data is modelled and implemented in a FE simulation. It is assumed that the material maintains a constant volume during forming. On the basis of a previous study by Althaus et al. (2024), it is assumed that the material is undergoing pure biaxial extension, whereby it slips completely off the tool surface [5]. This paper presents the characterisation of a GMT. The data obtained is used to develop a material model for the FE simulation in ABAQUS using a coupled Eulerian-Lagrange (CEL) approach. The model is then verified against experimental data.

2. MATERIALS AND METHODS

2.1 Experimental Setup

The rheological data of the GMT was obtained using a forming simulator DYNSJ5590 from Instron, as shown in **Figure 2**.

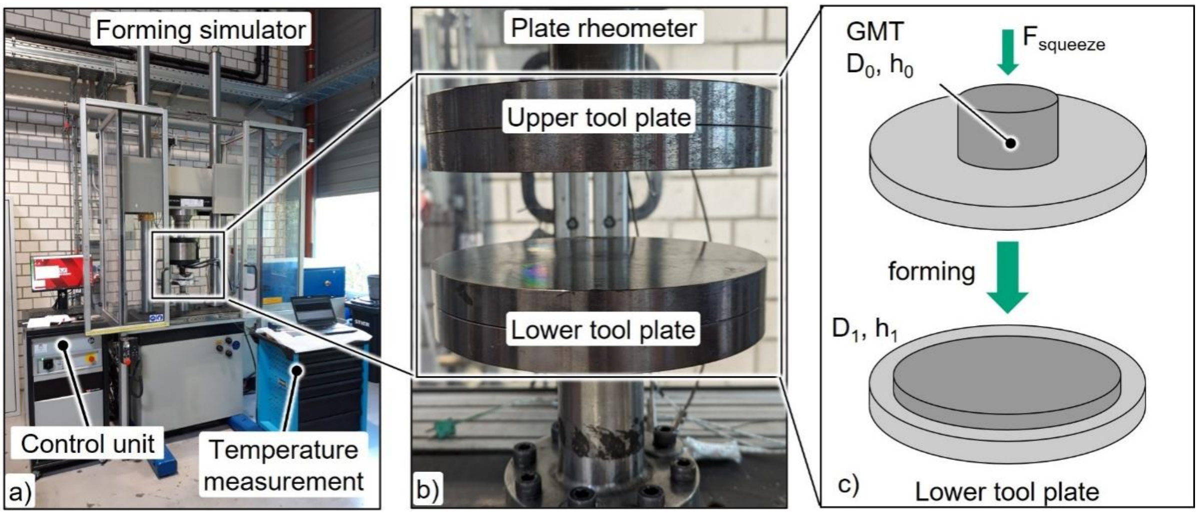

Figure 2 a) Forming simulator b) tool plates heated by integrated heating cartridges c) schematic representation of the compression moulding of GMT

The tool plates were heated using heating cartridges. The tests were conducted isothermally at temperatures ranging from 180 to 220 °C and varying squeeze rates between 0.05 and 2 mm/s. Each parameter combination was repeated three times. The GMT consists of a polypropylene matrix with 40% glass fiber reinforcement (StrongLite GMT RD40, BÜFA GmbH & Co. KG, Germany) and had a thickness of 4 mm. It was cut into specimens with a diameter of 50 mm. For testing, three specimens were placed on top of each other between the tool plates with an antiadhesive Polytetrafluorethylen (PTFE) foil between the specimens and the tool surfaces to reduce friction. With the attached measuring unit, the forming force and the displacement of the upper tool plate were measured.

2.2 Material Modelling

The experimental data was used to generate a material model for the numerical simulation. According to Kotsikoset al. (1996), the squeeze force can be calculated assuming a pure biaxial tension [6]. Rajak et al. (2021) incorporated this into their analysis, modeling the flow behaviour of FRP using the true stress as a function of the true strain and strain rate as shown in **Equation (1)** [1]. This method is used for the material modeling of the rheological data presented in this paper.

$$\sigma = \frac{F_{squeeze}}{A} = \frac{F_{squeeze}}{\frac{A_0 h_0}{h}} = \frac{F_{squeeze} h}{\pi R^2 h_0}, \qquad \varepsilon = ln\frac{h}{h_0}, \dot{\varepsilon} = \frac{u}{h} \tag{1}$$

with:

$F_{squeeze}$– squeeze force (N)
u– squeeze rate (mm/s)
A_0– initial GMT radius (mm)
R–radius (mm)
ε – strain (-)
σ – stress (MPa)
h – plate separation (mm)
$\dot{\varepsilon}$ – strain rate (1/s)
h_0 - initial specimen height (mm)

2.3 Numerical Model

In order to verify the material model, compression tests were simulated using the software Abaqus with a CEL method. The CEL approach combines the Eulerian and Lagrangian formulations to model problems involving fluid-solid interaction. It employs an Eulerian approach to model fluid behavior and a Lagrangian approach to model solid behavior. The coupling between the fluid and solid domains is achieved through interface conditions, which allow the transfer of forces, velocities and pressures between the domains[7].The simulation model consists of an upper and lower plate, the GMT specimen and an eulerian section, as schematically shown in **Figure 3**. In order to reduce the complexity of the simulation, the circular symmetry was used and only an eighth of the setup was simulated. The tools were defined as ideal rigid bodies with an element edge length of 1 mm and a pure slip behaviour at the surface of the dies was assumed. The eulerian section was meshed using an element edge length of 0.8 mm. The flow behaviour of the GMT was modelled using true stress–strain curves, obtained with equation (1).

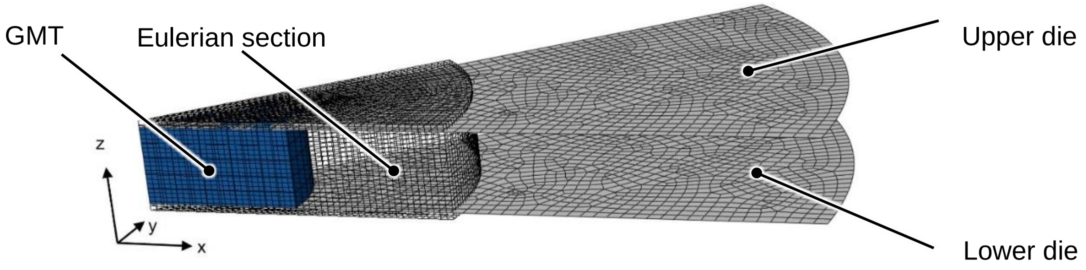

Figure 3 Numerical setup of the compression test

The generated models show good accordance to the experimental data with R^2 values between 0.9993 and 0.9997 indicating that the fitted model can be used for the FE simulations.

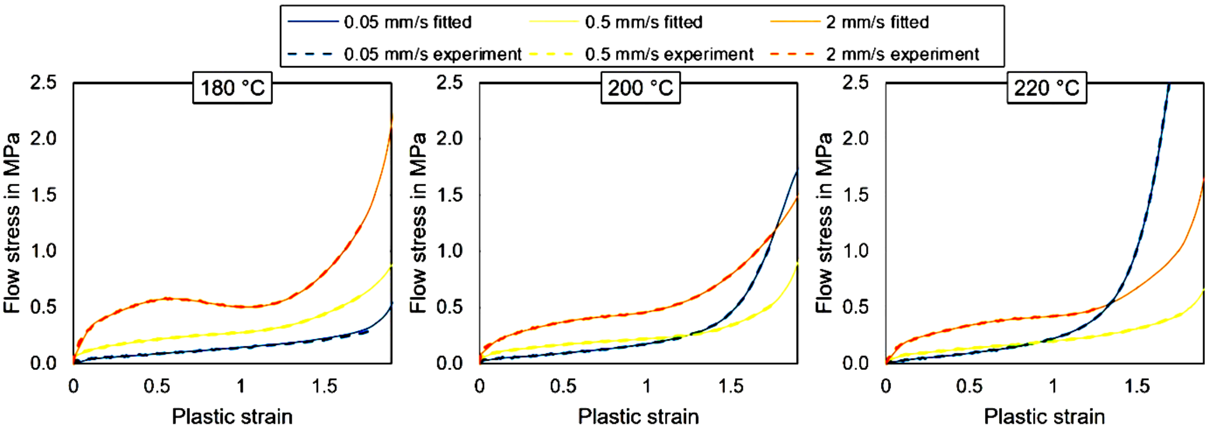

Figure 4 Flow curves of the GMT for different squeeze rates and temperatures. The experimental data is shown in comparison to the fitted model

The fitted data were implemented in Abaqus for the numerical simulations. In **Figure 6**, the numerical results for a squeeze rate of 0.05 mm/s are compared to the experimental data. The numerical results are in good agreement with the experimental data, with an RMSE of 0.01 for 180 °C and 200 °C, and 0.04 for 220 °C. This indicates that the generated material model can effectively predict the flow behaviour of the investigated GMT.

Table 1 Fitting coefficients and R^2 for biaxial extension

	180 °C			**200 °C**			**220 °C**		
	0.05 mm/s	0.5 mm/s	2 mm/s	0.05 mm/s	0.5 mm/s	2 mm/s	0.05 mm/s	0.5 mm/s	2 mm/s
p1	0.001	0.001	0.007	-0.001	0.002	0.001	-0.003	0.002	0.004
p2	-0.004	-0.002	-0.036	0.002	-0.010	-0.007	0.007	-0.009	-0.019
p3	0.005	0.002	0.049	0.009	0.007	0.015	0.014	0.008	0.012
p4	0.007	-0.002	0.044	-0.015	0.023	-0.005	-0.027	0.018	0.027
p5	-0.014	0.003	-0.153	-0.013	-0.022	-0.033	-0.013	-0.024	-0.022
p6	-0.003	0.016	0.068	0.028	-0.014	0.046	0.046	-0.011	0.018
p7	0.012	0.007	0.230	0.014	0.022	0.072	0.027	0.024	0.027
p8	0.001	-0.029	-0.192	0.001	-0.011	-0.058	0.016	0.003	-0.071
p9	0.048	0.063	-0.071	0.067	0.050	0.077	0.094	0.057	0.092
p10	0.104	0.240	0.574	0.114	0.189	0.408	0.121	0.156	0.382
R^2	0.9997	0.9997	0.9996	0.9997	0.9996	0.9993	0.9997	0.9997	0.9996

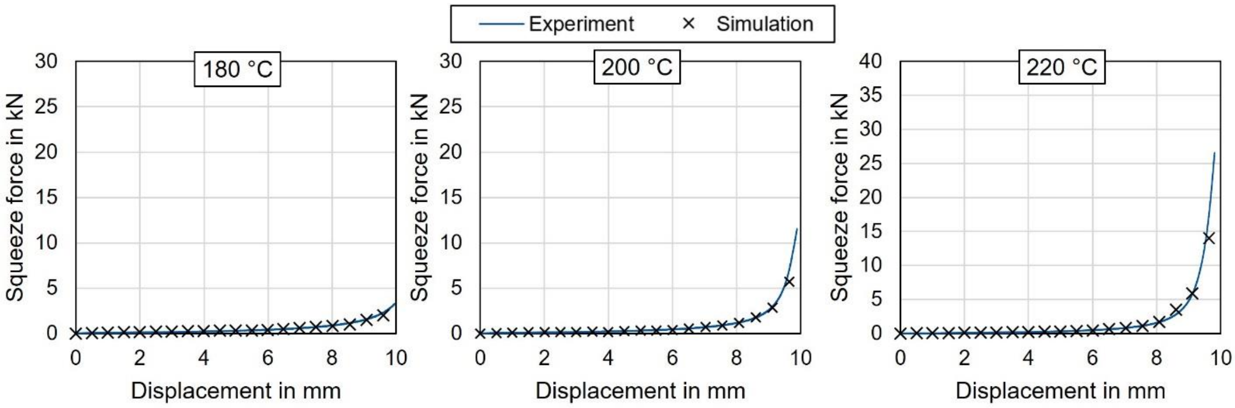

Figure 5 Comparison of the experimental and numerical squeeze force-displacement diagrams at a squeeze rate of 0.05 mm/s

3. CONCLUSION AND OUTLOOK

In this paper as a preliminary step for the process design of a novel multidirectional manufacturing process for hybrid metal-FRP structures, a material characterisation was conducted. For this purpose, the flow behaviour of GMT was investigated by means of compression molding tests. The obtained data were used to generate a material model for numerical simulations. The material model was then verified using experimental data. The results demonstrated a high level of agreement with an RMSE of < 0.04, indicating that the presented material model is suitable for the upcoming simulations of the process. In future work, the material model will be used to simulate the multidirectional forming process. The simulation can be used for the reduction of experimental trials, thereby reducing the time, costs, and materials required for the novel process design.

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REFERENCES

[1] RAJAK, D.K., PAGAR, D.D., MENEZES, P.L., LINUL, E. Fiber-reinforced polymer composites: Manufacturing, properties, and applications. *Polymers*. 2019, vol. 11, no. 10. DOI: 10.3390/polym11101667.

[2] ALTAN, T., NGAILE, G., SHEN, G. In: *Cold and hot forging. Fundamentals and applications*. Materials Park OH: ASM International, 2004.

[3] GROCHE, P., SCHEITZA, M., KRAFT, M., SCHMITT, S. Increased total flexibility by 3D Servo Presses. *CIRP Annals.* 2010, vol. 59, no. 1, pp. 267–270. DOI: 10.1016/j.cirp.2010.03.013.

[4] THATTAIPARTHASARTHY, K.B., PILLAY, S., VAIDYA, U.K. Rheological characterization of long fiber thermoplastics – Effect of temperature, fiber length and weight fraction. *Composites Part A Applied Science and Manufacturing*. October 2009, vol. 40, no. 10, pp. 1515-1523. DOI:10.1016/j.compositesa.2009.06.009.

[5] ALTHAUS, P. Rheological characterisation and modelling of a glass mat reinforced thermoplastic for the simulation of compression moulding. In: *Material Forming: ESAFORM 2024*, 2024, pp. 411–421.

[6] KOTSIKOS, G., BLAND, J.H., GIBSON, A.G., CHANDLER, H.W. Squeeze flow testing of glass mat thermoplastic material. *Composites Part A: Applied Science and Manufacturing.* 1996, vol. 27, no. 12, pp. 1195–1200.

[7] ZHOU, Z., ZHOU, T., ZENG, Z., LI, Z., LIAN, S., WANG, X. Numerical simulation prediction of gas trapping in aspheric lens molding based on coupled Eulerian-Lagrangian method. In *Proceedings Volume 12976, Eighth Asia*

Pacific Conference on Optics Manufacture and Third International Forum of Young Scientists on Advanced Optical Manufacturing (APCOM and YSAOM 2023); 1297607. DOI:0.1117/12.3000487 2023.

[8] DRÖDER, K., BEHRENS, B.-A., BOHNE,F., CHUGREEV, A., SCHULZE, H., WONNENBERG, B. Numerical and experimental investigation of thermoplastics in multi-axis forming processes. *Procedia CIRP*, 2019, vol. 85, pp. 96–101.