Author
Dipl.-Ing. Dmitry Gerasimov[1]
Jonas Wälder M.Sc.[2]

Co- Author
Univ.-Prof. Dr.-Ing. Dr. h. c. Mathias Liewald MBA [2]

Jochen Wellekötter[3]
Prof. Dr.-Ing. Christian Bonten[3]

Company/ Institution
QuantorForm Ltd[1], Institute for Metal Forming Technology[2], IKT[3]

Investigations regarding the simultaneous processing of metal and plastic using full forward extrusion

Determination of the predictive accuracy of the forming process via QForm software

When producing high performance parts, the combination of different materials opens up a wide range of functionality and application. Thus, in the last few years, the use of metals and plastics for hybrid structures has gained importance as their respective complementary characteristics can be of great benefit. In this study, FEA results of the combined full forward extrusion of metal and plastic will be presented as well as first experimental results. Objective of the numerical investigations is to ensure a complete fusion of the plastic, which can be achieved by having high temperatures during the forming process. Therefore, a parameter variation (DOE) via QForm is performed in order to detect essential parameters that have an influence on the occurring temperature. Further, first experimental results are presented that prove the practicability of the forming process and verify the results achieved in the numerical investigations. Apart from the indemnification of high temperatures, the aim of the numerical investigation using the QForm software is to achieve a reproducible und realistic plastic flow of the polymer material during the metal forming process. Center of attention will be the numerical investigation of novel forming processes as well as the comparison of the experimental results with the FEA study via QForm.
The project was founded by the Deutsche Forschungsgemeinschaft (DFG) with the title "Metall-Kunststoff- Fließpressen" and is a mutual project of the Institute for Metal Forming Technology (IFU) and the Institut für Kunststofftechnik (IKT).

Keywords: Extrusion, Plastic, Cold forming, Simulation, Finite Element Method

1. Introduction

Hybrid components are gaining more and more importance in the field of mechanical engineering due to the fact that weight constantly must be reduced, demands for special component properties are growing, and the pressure for lower manufacturing costs is rising. Due to the very different specific properties, a particular focus is on the use of hybrid parts made of plastic and metal. The plastics combine lower density, good thermal isolation, good media resistance, good damping properties, but have significantly lower mechanical properties. In contrast, metals have very good mechanical properties, high melting temperatures, good vibrational transmission, and a high electrical and thermal conductivity [1-3].

In serial production, producing hybrid components mainly takes place using two methods. In both variants the deformation of the metal parts takes place separately from the application of the plastic. In figure 1a) a component manufactured by form-fit joining is shown. This production variant always involves a number of operations: the manufacturing of the metal component, the manufacturing of the joining partner made of plastic, and a joining operation connecting the components (glue, clips, screw,...). The combination of complementary properties and the freedom of design is only partially present in this variant.

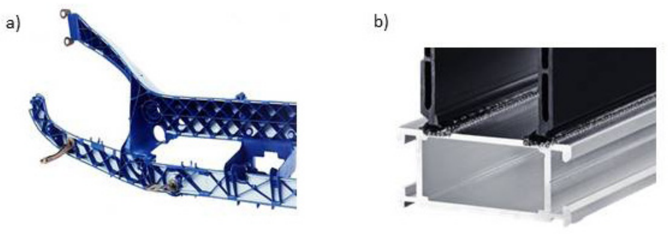

Fig. 1: Manufacturing of hybrid components by a) joining and b) injection molding around metal inserts

In figure 1b) another production possibility of hybrid parts is shown which is also widespread in the industry. As already listed in the manufacturing process, the metallic joining partner is made before the reunification of materials. Following, the finished metallic components are molded in liquid plastic. This ensures a positive connection of the two parts to be joined and thus, a high bonding strength. A disadvantage of this method is the high complexity and the strong restriction of the freedom of design because the metal body has to be inserted in the injection device of the injection molding machine. As the manufacturing before this process consists of several steps (forming, injection) [2-5].

1.1 Process
At the Institute for Metal Forming Technology (IFU) and the Institut für Kunstofftechnik (IKT) the newly developed manufacturing process for hybrid components takes place in only one single process step. In this new process, the plastic inserted into the metallic semi-finished product is in the form of granules. Enough heat is generated by the subsequent forming process so that a melting of the plastic granules occurs (see figure 2). This manufacturing approach opens up a fundamentally new component spectrum that brings new possibilities to the field of lightweight components, isolation, and high performance components. In the field of lightweight construction, it will be possible to further reduce metal thicknesses and partially replace the metal with plastic – without having restrictions regarding the overall stiffness of the component. Due to lower density of plastic (about 0.95g/cm3) thus a new lightweight construction potential in suitable components is available. Another new application is the production of NVH-components (noise, vibration, harshness). By the targeted implementation of a vibration- damping plastic layer, it becomes possible to produce solid-formed components, which have a reduced damping effect. Similar concepts, called damping plates, are already applied in sheet metal forming [6].

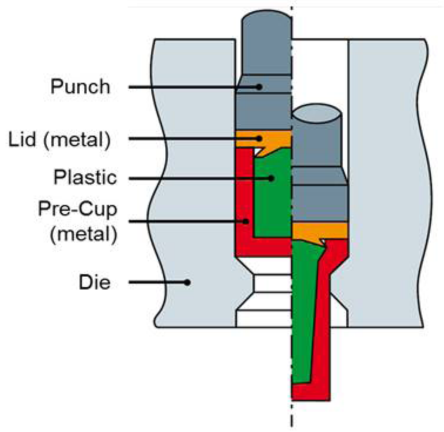

Fig.2: Scheme of the cup-backward-extrusion; left: initial state; right: process sequence during forming process

As already described, the University of Stuttgart is developing a new process route that allows processing plastic (molding) and metal (forming) in one process step. Therefore, the established full-forward extrusion is used. The resulting forming process is shown in figure 2, which is depicted on the left side of the forming process in the initial state and on the right side of the forming process after forming. Shown here is a constructed blank which consists of three parts, the metallic lid (orange), the metallic pre cup (red,) and the inserted plastic (green) in granular form. At the beginning of the extrusion process the plastic granulate is compressed (depending on particle size, pre-compaction,...) before the actual forward extrusion (VFP) starts with the required heat.

2. Polymers
The properties of polymers are fundamentally different from the properties of aluminum. This is particularly reflected in the significantly different characteristic temperatures like the melting temperatures, which can be regarded as advantage and disadvantage at the same time. On the one hand the temperature stability is considerably lower, on the other hand the processing requires less energy and the production is more cost- effective. The manufacturing of plastic components is usually performed on the melting of plastic granules when high temperatures and a high pressure occur. Due to pressure, the melted plastic flows into a tool in which it achieves its final shape and then cools down. In case of metal-plastic impact extrusion, the plastic is not heated by external energy sources. The whole energy for the melting process of the plastic must be generated by the high deformation during the impact extrusion. By a simulation of metal-plastic impact extrusion it can be determined whether the plastic phase melts. This significantly depends on the plastic used. Typical plastics such as polyethylene (PE) and polyamide (PA) differ in their melting point range of about 100°C (PE: ~110°C; PA: ~220°C [7, 8]. The temperature-dependent specific heat capacity of plastics can be used as the base of simulation and is determined by differential scanning calorimetry (DSC). Figure 5 shows an example of a DSC curve of PE with low density (Lupolen 1800 S, LyondessBasell Industries, Rotterdam, NL). The peak at about 120°C characterizes the crystalline phase of the plastic. Due to the melting of the crystalline structure, a large amount of energy is consumed whereby the power consumption increases. If the power absorbed by pure shear energy results in a temperature above the melting point of the plastic, the plastic phase melts and starts cooling down after completing the transformation into a new shape. Plastic melt behaves structurally. This means that, in contrast to the behavior of newtonian fluids, the viscosity decreases with increasing shear. With regard to the simulation, this behavior must be taken into account and can be converted because of the similarity to the flow behavior of metals in flow diagrams. For this purpose, experiments on rotational rheometer (SR 500 by Rheometrics Inc., Piscataway, NY, USA) at different shear rates are carried out at the IKT. The shear rates were varied from 1 s-1 to 100 s-1 at deformations up to 100% and were recorded at each moment. By analyzing this data, the flow curve can be calculated according to equation 1 [7]:

$$\bar{\sigma} = \sqrt{3} * \tau \qquad \varepsilon = \frac{\gamma}{\sqrt{3}} \quad (1)$$

$\bar{\sigma}$ resulting stress, ε elongation, τ shear stress, and γ deformation.

However, it must be mentioned that the rheometer tests are performed at relatively high temperatures (here 190°C for PE). The temperatures for the metal-plastic extrusion are not constant and are not necessarily in the same order. Therefore, tempered tensile and compression tests of plastics are performed at the same time.
The tempered pressure testing is currently performed at the IKT and delivers stress-strain curves which can also be integrated in the simulation as flow curves. For a wide temperature range from room temperature to melt-liquid area, the entire process in the simulation can be shown by combining the flow curves.

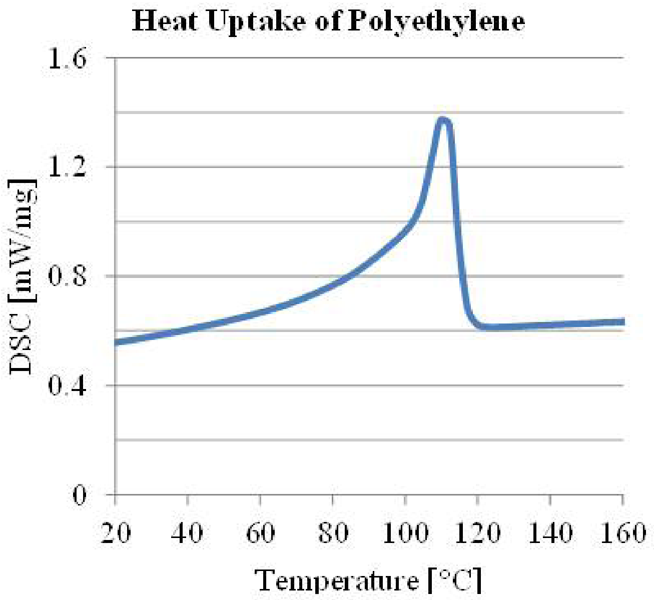

Fig. 3: Heat flow versus temperature of low density poly-ethylene at a heat rate of 10 K/min

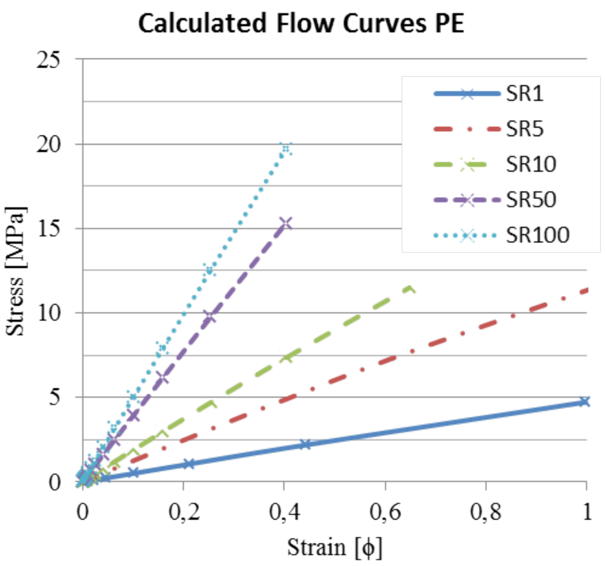

Fig. 4: Stress versus displacement for low density poly-ethylene (T = 190 °C), measured for different strain rates´1-100 s-1

Chapter 3 – Experimental investigations

In order to show the feasibility of the process, first experimental investigations were carried out. The used polymer is Polyethylene (melting point 110°C). The used raw part is made of aluminum EN AW 6082, has an initial height of 40 mm, and a drilled hole of about 12 mm. The final parts after being formed are shown in Figure 5.

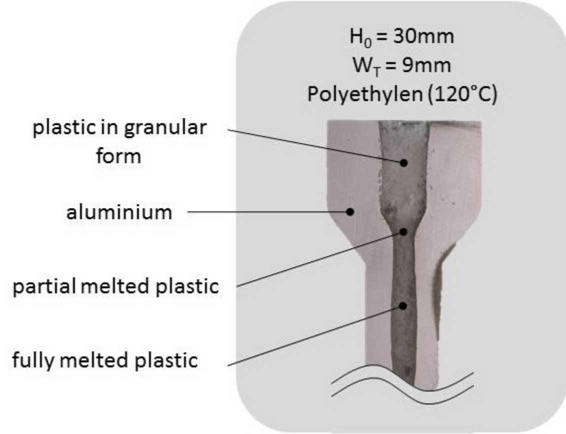

Fig. 5: Test part with three different melting sectors

On closer inspection, it can be noticed that the part consist of three areas. First, sector 1 which is the cylindrical sector above the forming zone. Second, the forming zone in the middle (sector 2), in which the forming of the hybrid part takes place and third, the pin of the component which passed the forming zone entirely (sector 3). In the upper sector, the plastic is in form of granulate, because the heat conduction through the plastic is too low (0.2 W/m*K) to introduce the required temperature in this area. In sector 2, a partial melting of the plastic can be reached. An increase of temperature takes place, initiated through the forming of the part made of metal. It is noticeable that the melting degree increases with progressively passing of the forming zone (which involves an increase of temperature). In the last sector, a complete connection of the plastic phase can be seen. In case of the Polyethylene, this becomes obvious by the entire disappearing of the structure which can be seen in sector one and two. Furthermore, regarding the geometrical dimensions, a thinning of the wall thickness can be observed. The wall with an initial thickness of 8 mm is reduced to 5.3 mm by ironing, whereas the inner diameter decreases from 12 mm to about 4 mm. The very first experiments show the feasibility of the new forming process. It is possible to satisfactorily process Polyethylene and high-fusing Polyamide using the heat development of a full-forward-extrusion process. In further investigations, simulations should be verified and the several influences of wall thickness, grain size, plastic goods, and ram speed should be analyzed, which cannot be determined entirely using numerical investigations.

4. Numerical investigations

4.1 Description of simulation model

The numerical simulation was carried out in the QForm software using the finite element method having the purpose of optimal parameter determination for extruding aluminum cups filled with granulate PE. Taking into account the axial symmetry, the 2D simulation of a meridional workpiece crosscut was performed. The triangular finite elements of low order with additional central nodes for approximation of velocity fields [8] are used for 2D tasks in QForm. The approximation of mean stress fields is carried out using a traditional method and the heat transfer process is calculated in QForm using the finite volume method. The Voronoi cells are used as finite volumes here.

QForm gives an opportunity to simulate a coupled deformation of several bodies made from different materials. The contact

surfaces of bodies cannot interpenetrate, but can slide relatively to each other when simulating such processes.
The viscoplastic model of material deformation was used in the simulation [9]. The Green´s theory for simulating non-compact materials was used to consider compacting of the granulate [10].vThe thermophysical properties of PE used in the simulation are described in chapter 2. The flow stress curves for AA 6082 and friction conditions between aluminium and steel tool were taken from references [11] and [12]. Friction condition between aluminum and PE are specified in chapter 4.2. The relative density of PE was taken equally to 0.5.

4.2 Verification of simulation model

Experimental results of the extrusion of aluminum cups filled with granulate PE are shown in chapter 3. The verification of initial data for the simulation was performed based on these results. The experimental and simulation results performed with the friction factor 0.9 (Siebel friction law) are shown in figure 6.

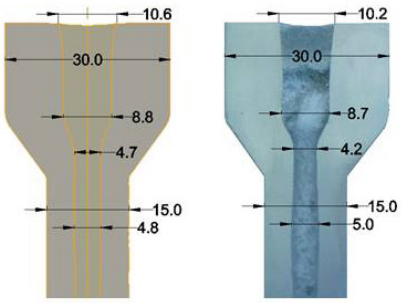

Fig. 6: Deformation of aluminium cup filled with granulated PE: experimental results (right) and simulation results (left)

As it can be seen, the simulation is in good correspondence with the experimental results. Some insignificant differences in form can be connected with the non-uniform compaction of granulated PE in the experiment. Therefore, the specified initial data is suitable for the following simulations.

4.3 Optimization of technological process

The main goal of the optimization is to define process parameters when the part of PE in the final product is at its maximum. The granulated PE has to be heated up to its melting temperature (120 °C) to melt and to get a solid structure after cooling down again.
The heating of PE up to the necessary temperature can be reached due to heat generation in PE as a result of deformation and due to heat transmission from the heated aluminum cup.
The heat rate per unit area generated on the workpiece surface due to friction with tool depends on workpiece sliding velocity in reference to the tool $\Delta V\tau$ and tangential stress τ:

$$q_{fr} = 0{,}5 \cdot \eta' \cdot \tau \cdot \Delta V^{\tau} \left[\frac{W}{m^2}\right]$$

With $\eta' = 0{,}95$ – friction heat generation efficiency.

The heat rate per unit volume generated in the workpiece due to deformation depends on the stress intensity σi
and the strain rate $\dot{\varepsilon}$:

$$q_{def} = \eta'' \cdot \sigma_i \cdot \dot{\varepsilon} \left[\frac{W}{m^3}\right]$$

With $\eta'' = 0{,}95$ – deformation heat generation efficiency.

In this case the strain rate value has the maximum effect on the heating process. Therefore, it is necessary to create optimal conditions with a maximum strain rate in the deformation zone. Two parameters were investigated in the context of this paper: the initial inner diameter d of an aluminum cup and the punch velocity V during extrusion.
The special function was used in simulation to investigate an average maximum temperature that is reached in each point of PE workpiece during the whole process including heating from aluminum cup after extrusion process (30 seconds). Several simulation results are shown in figures 7 and 8.

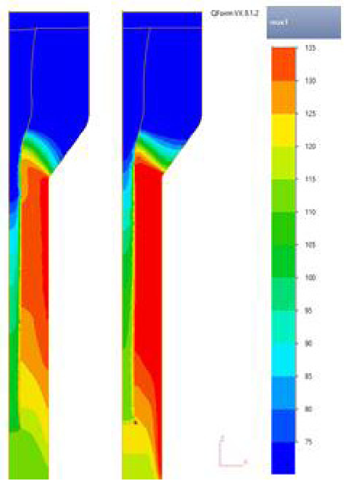

Fig.7: Maximum temperature distribution in compacted PE. Extrusion of aluminum cup with inner diameter d=12 mm and punch velocities v=50 mm/s (left) and v=150 mm/s (right)

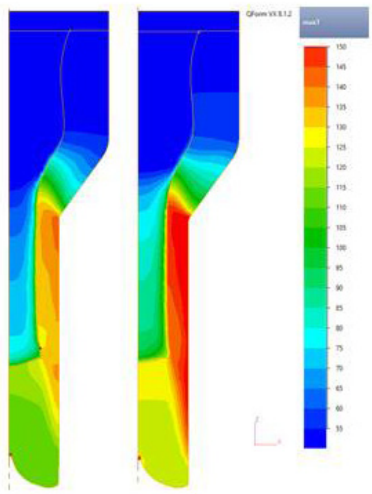

Fig. 8: Maximum temperature distribution in compacted PE. Extrusion of aluminum cup with inner diameter d=20 mm and punch velocities v=50 mm/s (left) and v=150 mm/s (right)
All simulation results are shown in table 1.

Table 1: Simulation results. Maximum temperature values of PE during the whole process for different combinations of initial inner diameter of aluminum cup and punch velocity.

Inner diameter, mm	Punch velocity, mm/s	Mean maximum temperature of PE during the entire process, °C	
		On the contact surface of PE	In the middle of the part
12	50	130	97
	100	135	101
	150	138	105
16	50	130	89
	100	135	95
	150	136	101
20	50	130	70
	100	135	77
	150	137	87

It can be seen from the simulation results that the melting temperature (120 °C) was reached only on the contact surface of PE. In the middle of the part, the melting temperature was not reached which is connected with the low thermal conductivity of PE. Increasing the punch velocity from 50 mm/s to 150 mm/s allows increasing the temperature in the middle of the part by 10 to 15 degrees for workpieces with different inner diameters.

Chapter 5 – Conclusion and outlook

This paper shows the results of the numerical simulations of the novel forming process which deals with the combined extrusion of metal and plastics. It is demonstrated that it is possible to dimension the process with numerical investigations, regarding the desired temperature. Furthermore, the feasibility of this process is shown.

The very first experimental attempts exhibit a satisfactory melting behavior of the plastic, based on the high initiated process temperature while forming. Future work will concentrate on improving the numerical simulation, on testing the application, and on inspecting and testing the components. Therefore, a novel material model should be implemented in the simulation software, which allows detecting a local melting of the plastic, regarding the currently prevailing state with the aim to depict the actual process as good as possible. In order to examine the mechanical properties of the produced part, several tests will be performed with emphasis on the occurring adhesive strength between both materials as well as on the analysis of the emerging melting degree.

References

1. W. Michaeli, O. Grönlund, A. Neuss, M. Gründler, J. Wunderle. Neuer Prozess für Kunststoff-Metall- Hybride, Kunststoffe 9, Page 136–140 (2010),
2. U. Endemann, S. Glaser, M. Völker, Kunststoff und Metall im festen Verbund, Kunststoffe 11, (2012), Pages 110–113
3. C. Bonten: Kunststofftechnik – Einführung und Grundlagen, Carl Hanser Verlag (2014)
4. M. Stumpf, Maßgenaues umspritzen metallischer Gewindeeinsätze, Maschinenmarkt, (2012)
5. W. Michaeli, W.M. Hoffmann.: Hybride Verbindungen, Kunststoffe 6, Page 50–53 (2009)
6. M.M. Matsco: Injection Molding and Metal Fabrication Combined, Design News 1, Page 96 (1996),
7. J.D. Bressan, U. Kirchhof, Construction and validation tests of a torsion test machine, Journal of Materials Processing Technology 179, Page 23–29, (2006)
8. C.H. Liu, S. Choudhry: Automated numerical simulation of metal forming using low-order triangular and tetrahedral elements, Simulation of Materials Processing: Theory, Methods and Applications, Pages 151-154 (2001)
9. S. Stebunov, N. Biba, A. Vlasov, A. Maximov: Thermally and Mechanically Coupled Simulation of Metal Forming Processes, Proceedings of the 10th International Conference on Technology of Plasticity, ICTP 2011, Pages 171-175 (2011)
10. Green R J, A Plasticity Theory for Porous Solids, International Journal of Mechanical Sciences, Vol. 14, Pages 215-224, (1972)
11. Wälder, J., Wellekötter, J., Felde, A., Liewald, M., Bonten, C.: Numerical investigations for simultaneously processing metal and plastic using impact extrusion . NUMIFORM, Troyes/Frankreich, (2016)
12. J.A. Schey, Metal Deformation Processes: Friction and Lubrication, Marcel Dekker, New York, Page 427 (1970)