Application of numerical simulation for lightweight design

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ABSTRACT

Due to the increasing lightweight construction efforts to reduce component weight and thus minimize the energy demand for mobilisation of moving masses, light metals or even plastic applications are growing in importance. In order to realise the process development with consideration of the material, its behaviour must be known. This paper aims to show the importance of numerical process design and how it can be validated with experiments. For the thermo-mechanical simulation to generate results with high accuracy, the use of real material data is necessary. Depending on the investigated process, different characterisation possibilities are available. Here, the compression test was carried out, for example, to determine the forming behaviour of aluminium (EN AW-6060) and magnesium alloys (AZ31) and for a polyamide without and with glass fibre reinforced (PA 6 and PA6-GF30) on elevated temperatures and strain rates of hot bulk forming processes. In this case, the sample position, especially in the case of the polyamide, received increased attention. Thus, it was found that glass fibre reinforced plastics (PA-GF30) can be compressed differently in the longitudinal direction than perpendicular to the extrusion direction. Furthermore, an enhancement of the forming limit and a reduction of the forming force with increasing temperature could be observed for all investigated materials. In addition to the forming behaviour, the thermo-dynamic material properties are at least just as important for the purposed thermo-mechanical process simulations. These were also determined by experimental simulation for the analysed materials in order to regard the internal microstructure. Then, the implementation of all these material data into the FE software simufact.forming V15 and MSC Marc/Mentat was carried out in order to predict a forging process as well as an additive manufacturing process for the semi-finished products. Finally, the calibration of the FE models took place to verify their accuracy. This is the

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first study undertaken to characterise the forming behaviour of plastics and to study the production of layered magnesium components for further forming processes.

Keywords: *Polyamide; Aluminium; Magnesium; Bulk Forming; Additive Manufacturing; Numerical Simulation.*

Introduction

The goal to reduce CO_2 is moving into all areas of daily life. The mobility sector has a strong influence on research, which is defined by political strategies. Weight reduction is a proven means to achieve this aim with components or moving masses in addition to optimizing the degree of efficiency or changing the drive concept. In general, this goal can be reached by topology optimization or material substitution. Above all, the application of lightweight materials (high strength materials or light metals) or material combinations constantly influence the forming technology with new challenges. On the one hand, higher-strength materials, which are often difficult to form, are used to reduce the dimension of the components for the same load. On the other hand, light metals are now being processed which have lower mechanical properties up to break but twice the specific strength of steel. Therefore, light metals are suitable as constructive lightweight construction concepts for non-crash-relevant applications. In order to process different alloys into complex components and at the same time produce a firm bonding, extrusion with all its sub-process types has proven to be suitable for the production of semi-finished products of hybrid (for example aluminium and magnesium) compounds to combine their advantageous properties. Magnesium is the lightest construction metal but has poor corrosion resistance. Aluminium, on the other hand, has high corrosion protection but also higher density. The numerical process simulation of the compound extrusion (magnesium core with “coated” aluminium) was used to fully understand the process and to determine the process limits for the metal alloys under consideration for the interface layer development [1–5]. The main focus was on the forgeability of the extruded hybrids while maintaining the interface layers [6–8]. An experimental and numerical evaluation of the process limits of a shortened process chain was used for the production of hybrid components by precision forging. The main focus was on the inductive heating of the hybrid semi-finished products [9, 10] while simultaneously firmly bonding within a few process steps, whereby the monolithic starting materials (cylinder and tube) were inserted before forming and not bonded [11].

In addition to conventional forming technologies, investigations have also been done on the additive manufacturing (AM) of monolithic and hydride materials with following forming process. The background of this effort is that the process-related errors of the AM are eliminated by the forming processes. However, this only lends itself to additive methods with a high build-up rate, otherwise the very time-consuming process chain is extended even further. In addition, in powder bed processes very complex geometries with possible undercuts can be produced, but subsequently the forming process is not possible. In wire and powder feeding methods, such as Wire Arc Additive Manufacturing (WAAM), 3D Plasma Metal Deposition (3D-PMD) or Laser Metal Deposition (LMD), the geometry as well as the microstructure can be improved by following a partial (hot) deformation. Initial investigations of the WAAM with inline hot forming have shown that the acicular-ferritic (needle-shaped) microstructure can be transformed into a refined polygonal microstructure. In addition, inner defects, such as pores, can be compacted and closed. Furthermore, subsequent forming increases the mechanical properties of the components. Rolling or forging can also be applied to eliminate geometric deviations of additive manufactured components, whereby the surface quality and tolerances can be increased compared to only printed solids. In this way, material combinations or geometries with graded properties which are not producible by using conventional manufacturing methods can be joined [12].

Whether it is the conventional or the modern manufacturing processes, there are ongoing efforts to perform a process development with the help of simulation to detect problems or failures in the early phase of the technology and process development itself. The most commonly used method is the finite element method (FEM). Taking into account defined boundary conditions (material data, process parameters, meshing etc.), the processes at the macroscopic as well as the microscopic level can be developed. Depending on the level of detail, more or less high demands are necessary as input data. In the following, the determination of the numerically relevant data (forming behaviour, thermal behaviour) and their influence on the simulation results will be presented and validated by means of laboratory tests under industry-specific conditions for different materials and processes.

Material Characterisation

For the description of material behaviour during a manufacturing process, the application of experimental simulation is a proven means. It is important that the material is characterised according to the investigated process. It is therefore essential that the microstructure (as-cast, deformed or heat-treated microstructure, optimally the solution state) and the load direction, temperature and strain rate are comparable to the real forming process. The most important material properties for a thermo-mechanical coupled process simulation are the temperature-dependent thermodynamic (thermal expansion, specific heat capacity, thermal conductivity) and the thermomechanical material properties (transversal contraction, flow curves, Young's modulus, etc.), which depend on the chemical composition of the material and on the microstructure. An important and easily measurable calibration value of the FEM is the forming force, and thus the flow curves for all materials were calculated on the basis of force-displacement curves during a cylinder compression test (regarding the sample position in the semi-finished product vs. the load direction and correction of the dissipation energy because of inner friction as well as the friction between die and material).

Aluminium EN AW-6060

The characterization of the aluminium alloy with the chemical composition (see Table 1) with respect to forming properties was performed in the dilatometer DIL 805A/D (Bähr Thermoanalyse GmbH now TA Instruments, Hüllhorst, Germany) in the temperature range of 350 °C to 450 °C with constant strain rates up to 10 s^{-1}. The recorded force-displacement curves from the cylinder compression tests (cylinder geometry: d5 x h10 mm) are the basis for the calculation of the flow curves (Figure 1, left) with the friction correction according to *Siebel* [13] and the temperature correction after principle of conservation of energy. To determine the specific heat capacity, the Multi-HTC96 from Setaram was used in which cylinder samples with d4.95 mm x h12 mm were tested (see Figure 1, right).

Table 1: Chemical composition of EN AW-6060 by optical emission spectrometry

Si	Fe	Cu	Mn	Mg	Zn	Ti	Na	Al
0.435	0.208	0.01	0.050	0.455	0.018	0.009	0.006	bal.

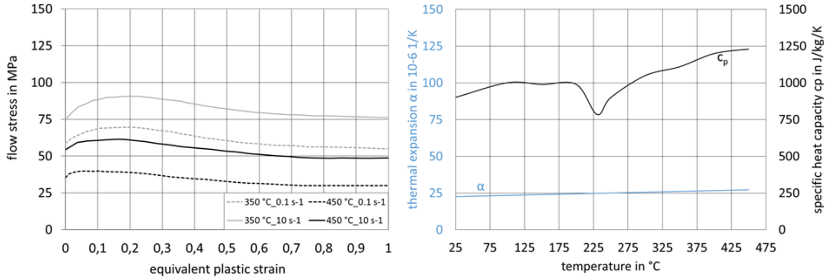


Figure 1: Determined thermomechanical (left) and thermodynamic (right; thermal expansion is from [14], specific heat capacity was measured) material behaviour of EN AW-6060

The forming behaviour depends on temperature and strain rate – with increasing temperature, flow stress decreases and an increasing strain rate at the same temperature increases the flow stress and shifts the curve maxima to a higher plastic strain. In the case of thermodynamic material data, it is noticeable that there is a discontinuity in the curve shape of the specific heat capacity. This indicates the dissolving of precipitates and can be typical for measurements in delivery condition. An additional heat treatment eliminates this phenomenon [15].

Polyamide

Due to the goal of integrating plastics in forming processes, the material data of the polyamide is essential. The classification is in unreinforced and glass fibre reinforced (GF30) polyamide PA6.

Cylinder compression tests (sample geometry d14 x h20 mm) were also used to determine the forming behaviour in order to analyse the material behaviour under compressive stress at different temperatures and strain rates. The analysed temperature and strain rate are based on the laboratory conditions for forging. In the later forging experiments, the plastic core is inserted into the aluminium preform/tube and heats up only by the heat transfer from the aluminium to the core material. Within 10 to 15 s handling time, the temperature of the plastic increases from room temperature to 90 °C inside the core and 130 °C near the contact area. The tests were realised at the universal testing machine Galdabin Quasar 50 kN with an optional compression cup (for isothermal test conditions in the tempered experiments) (Figure 2). The switch to another forming simulator was necessary because the other heated up the samples with conductivity or induction, which doesn’t work for plastics. At all contacting areas, a graphite spray was applied to the carbide compression plates to reduce the friction (μ=0.05) and the risk of adhesion.

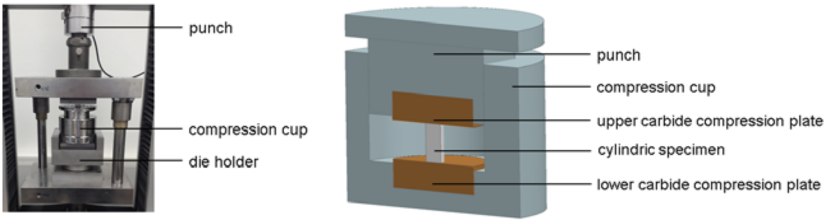


Figure 2. Setup for the compression tests (left: Galdabini Quasar 50 kN; right: compression cup for isothermal conditions)

The force-displacement curves were measured during the tests and were used for the flow curve calculation with the required friction and temperature correction. The temperature increase was 17 K (PA6) or 30 K (PA6-GF30) for the tests at room temperature. Figure 3 shows the forming behaviour of PA6 and PA6-GF30 with the division in vertical (orthogonal to the rode length) and in horizontal (along the rode length). The other material properties, such as density and specific heat capacity, are from the supplier data and from *Graf et al.* [16].

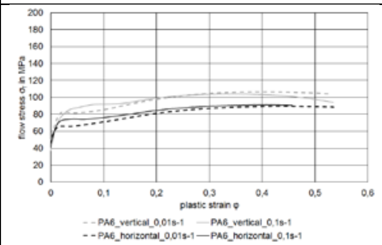
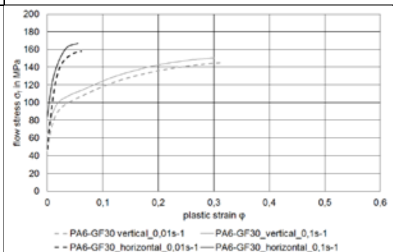
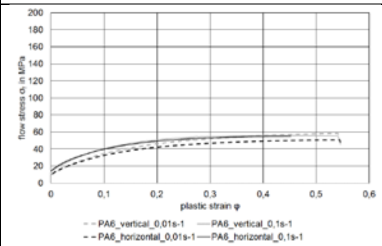
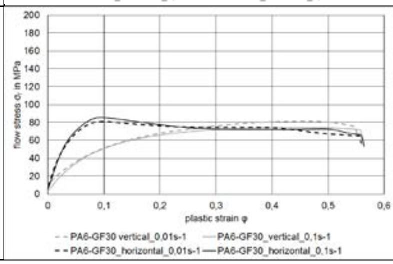
	Polyamid PA6	Polyamid with 30 % glass fibres PA6-GF30
20 °C		
100 °C		

Figure 3. Comparison of the forming behaviour of polyamide with (right) and without glass fibres (left) at different temperatures (20 °C in the upper line; 100 °C in the lower line) and for varied strain rates (0.01 s^{-1} and 0.1 s^{-1})

The analysis of the flow curves shows a deviation between the materials and between the sample orientations. For forming the glass fibre reinforced polyamide, a higher stress is required than for unreinforced polyamide. The materials have a curve shape similar to metallic materials. Furthermore, the sensitivity of the material can be determined for the strain rate especially at room temperature. With increasing strain rates, the flow stress also increases, but the influence at 100 °C is lower. The sample orientation is also decisive for the necessary forming forces, whereby a distinction between glass fibre reinforced and unreinforced polyamide is necessary. For the PA6, the vertical samples need higher flow stress for plastification than the samples in longitudinal direction. The sample position of PA6-GF30 is even more important due to the fibre orientation. It could be determined that the horizontal samples have higher flow stresses than the vertical samples. In comparison to the unreinforced polyamide a lower plastic strain was determined and a brittle behaviour at room temperature was detected. Therefore the maximum plastic strain for horizontal compressed PA6-GF30 was the lowest of all (Figure 3, top right). The glass fibre-reinforced polyamides can be formed much better at a higher forming temperature than at room temperature, which is reflected in the achievable plastic strain. The influence of the temperature on the plastic strain wasn't found in unreinforced polyamides.

Magnesium AZ31

For the characterization of the magnesium alloy, it should be mentioned that this material was investigated for additive manufacturing processes. In order to consider it with respect to the microstructural phenomena, a sufficiently high and thick wall of 15 layers was applied by cold metal transfer (CMT) welding [12]. Samples were machined from the wall to make cylinders (d5 x h10 mm) for the compression or dilatometer test as well as for the determination of the specific heat capacity (d5 x h0.5 mm). Hence, an as-cast microstructure could be considered in the test specimens, which is the representative used for carrying on the investigations. The chemical composition (Table 2) of the specimens was measured by optical emission spectrometry (OES).

Table 2. Chemical composition of the investigated magnesium alloy AZ31

Al	Zn	Mn	Cu	Si	Fe	Ni	Sn	Mg
2.763	1.09	0.386	0.002	0.015	0.005	0.001	0.003	bal.

The forming behaviour was determined under isothermal conditions in the dilatometer DIL 805 D/A (Bähr Thermoanalyse GmbH now TA Instruments, Hüllhorst, Germany) in the temperature range of 350 °C to 450 °C and with strain rates between 0.1 s^{-1} and 10 s^{-1} in order to regard the effects of plastification during cooling or for the later planned forming of the additive manufactured walls (using WAAM). The force-displacement curves recorded during the compression tests provide the basis for the calculated flow curves (Figure 4, left), whereby these machine data were subjected to a friction and temperature correction.

During the multiple heat treatments due to the layer-by-layer strategy, the component expanded thermally and "stored" the heat, while the coefficient of thermal expansion was measured in the DIL 805 D/A dilatometer and the specific heat capacity was analysed in the DSC-60 Differential Scanning Calorimeter from Mettler Toledo (Mettler-Toledo International Inc., Columbus, Ohio, USA) for the process-relevant temperature range up to the melting temperature (Figure 4, right).

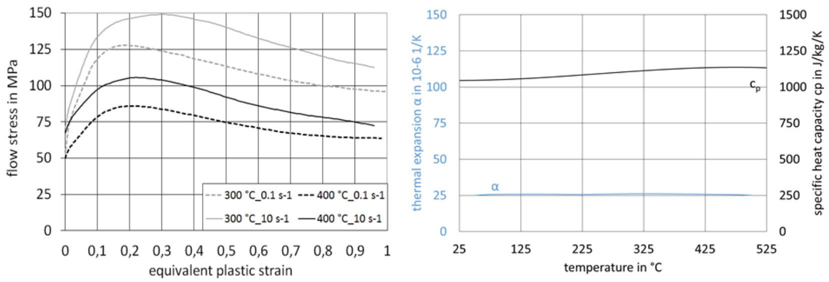


Figure 4. Determined thermo-mechanical (left) and thermo-dynamic (right) material behaviour of molten and solidified AZ31 wire

The evaluation of the flow curves shows that with increasing temperature, the flow stress increases and with simultaneous increase of the strain rate within a test temperature, the flow stress also increases and the maximum flow curve can be found at a higher plastic strain. The thermodynamic material data show a continuous increase in thermal expansion with increasing temperature as well as with the specific heat capacity increase.

Bulk Forming with Lightweight Materials

Aluminium Components

The forging of monolithic components has been successfully carried out for many decades and serves in the present experimental and numerical investigation only as a reference (regarding the force, weight) to the further developed hybrid compounds of aluminium and polyamide (see Figure 5).

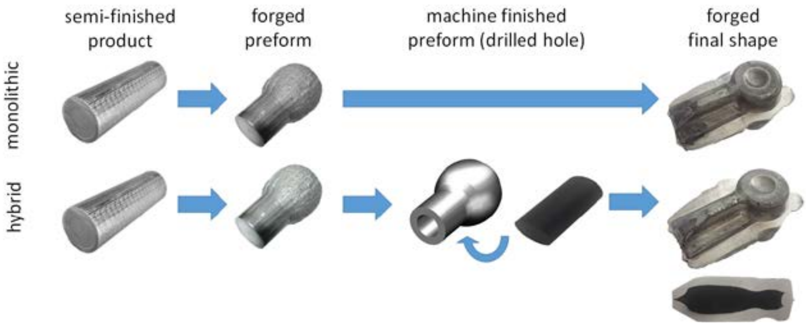


Figure 5. Investigated processes for monolithic and hybrid materials for the SMARTBODY

For these tests, the dies were heated to 220 °C so that the 400 °C hot semi-finished products (heated in the convection oven) did not cool too quickly. These extruded sections with D20 x H70 were pre-forged in a first die and then forged to the final contour in a second die. The pre-forging is necessary to pre-distribute the material so that there is sufficient material in the thicker part of the final gravure. Both tool sets were integrated on hydraulic presses in order to form specimens with a ram speed of 80 mm/min.

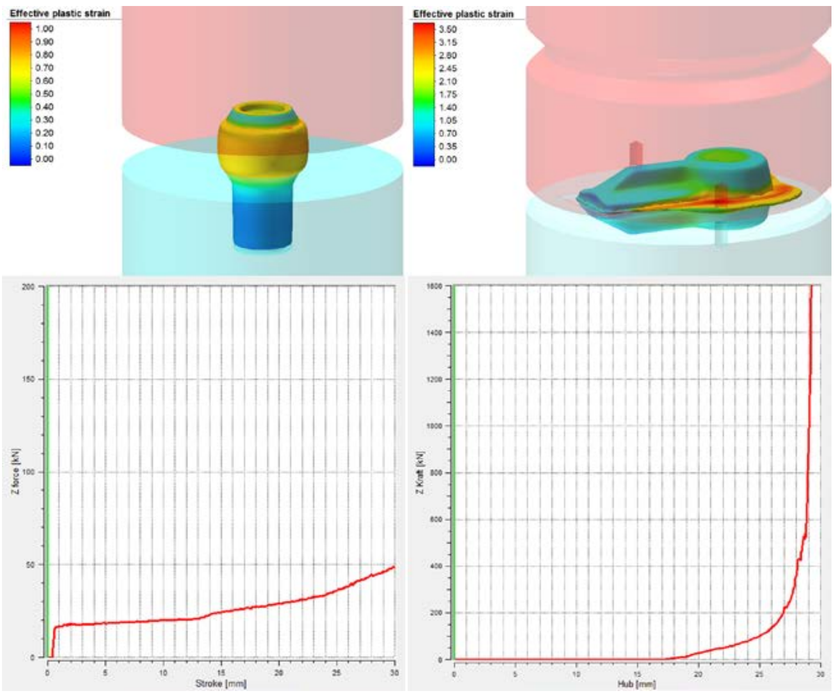


Figure 6. Simulated effective plastic strain and forces of forging the preform (left) and the final shape (right) at hydraulic press with 80 mm/s and initial temperature of 400 °C

The numerical challenge in this process was on the one hand in the material modelling, because the material data were determined for these tests and implemented in the FE software *simufact.forming v15*. On the other hand, mesh stability posed a significant numerical challenge as well. In order to save computing time, the upsetting process (1st step) was regarded as an axially symmetrical 2D model with Advanced Front Quads (element length of 0.5 mm) and these results were extended up to a 360°-model in order to calculate the subsequent process step of component forging as a full 3D model with Tet elements (2 mm edge length). The focus of the calculations was on calculating the force in order to determine whether the component could be produced with the whole process chain on the existing presses with the selected process parameters (see Figure 6). In addition, the geometric comparison of the component with regard to die filling and flash was carried out.

A comparison of the calculated and the measured forging force for the final shape shows a good accuracy with 1400 kN at the real press (was the maximum for the hydraulic press) and 1457 kN in FE software *simufact.forming v15*. One reason for the good accordance is the consideration of the determined thermomechanical and thermodynamic behaviour of the material EN AW-6060.

Aluminium-Polyamide Hybrid Components

This technology had also some experimental and numerical challenges. The technology described above is currently regarded as a discontinuous route. This means that the upsetting took place in a first forming heat (450 °C), the components were machined after cooling to room temperature in order to get a blind hole into the preform and then heated again. After reaching the forming temperature of 400 °C (in a later continuous process, the forming temperature in the second step is as low as in the first step), the polyamide (5 mm shorter than the hole depth) was inserted into the existing hole and then forged. Only by heat transfer from aluminium is the polyamide heated up. In the early development phase of this technology, FEM were used to determine on which side the hole had to be drilled so that the polyamide didn't get squeezed out during forging. Because the aim was that the aluminium coated complete the polyamide core of the forging – also after deburring. The final FEM result shows that the hole with a diameter of 20 mm was drilled 40 mm deep in the narrow diameter of the preform. Due to the use of plastics with a lower strength than the aluminium component, the resulting forming force is lower as compared to the monolithic version. In addition, the geometric design of the demonstrator component could be well-represented numerically (see Figure 7).

Figure 7. Forging of hybrid SMARTBODY (left: FEM; middle: real forging; right: cut over the length, black: polyamide; grey: aluminium)

In table the resulting forces are compared between monolithic and hybrid material for the finale process step – the finished forging.

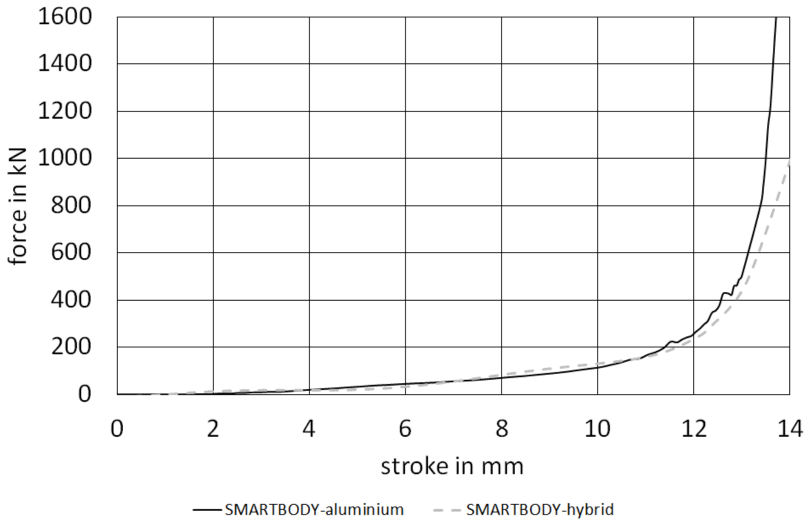


Figure 8. Comparison of the forging force for a monolithic aluminium alloy EN AW-6060 and a hybrid aluminium-plastic compound of EN AW-6060 and PA6

Due to the lower strength of the plastic core, a substantially lower forging force is necessary for a complete shaping of the demonstrator compared to the monolithic aluminium component. Hence, resources can be saved during the application by the reduced weight, but also in the production of hybrid components less energy is necessary.

Additive Manufacturing with Lightweight Materials for Semi-Finished Products

In this section, methods will be presented to produce semi-finished products from light metals for incremental forming processes by means of wire-based additive manufacturing.

The investigations focused on geometrically simple magnesium semi-finished products (Figure 8, left), which will be subsequently formed incrementally by flow-forming. The surface can be levelled and the properties further improved through the hot forming of the additive magnesium tube. The tubes have a diameter of 60 mm and 20 layers, which was realized with continuous movement by a combination of circles. The offset in z-direction took place immediately after the completion of the underlying circle. The used welding technology was the CMT method with the following process parameters: wire feed = 5.0 m/min; welding speed = 40 cm/min; layer offset = 1.7 mm; current = 45–55 A, voltage = 11–12 V; shield gas = 15 l/min Argon.

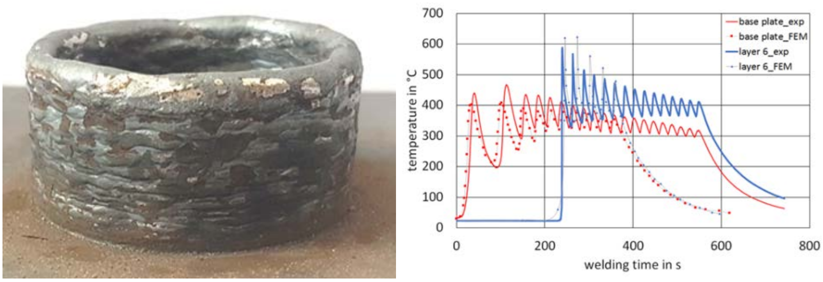


Figure 9. Magnesium WAAM tube (20 layers) and the comparison of measured and simulated temperature field

In addition to the experimental feasibility analysis, thermo-mechanically coupled simulation with *MSC Marc/Mentat 2018* of the tube manufacturing process (see Figure 8, right) and the transfer of results from a welding simulation to a FE forming simulation *simufact.forming v15* by using the material data with consideration of the real microstructure were also carried out. The main focus was on the geometry transfer, including distortion, and the residual stresses. The additionally necessary thermodynamic material data (e.g., melting temperature, thermal conductivity etc.) are used from *Miehe* [17]. The modelling strategy is based on the element birth technique, in which the geometry (based on the metallographically determined shape) is predefined and the deactivated elements get physical properties when the material-specific melting temperature falls below the specified value for the first time after heat [12].

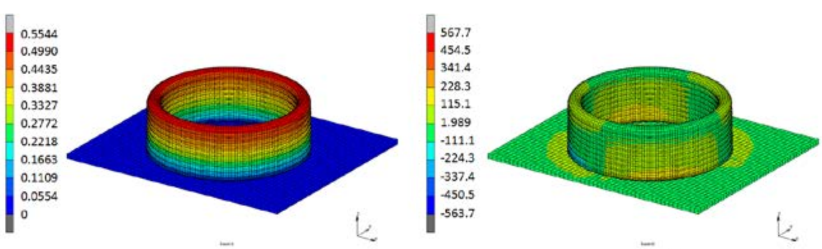


Figure 10. Simulated WAAM of magnesium cube up to room temperature (left: displacement; right: xy stresses)

The experimental and numerical comparison of the temperature development in different areas of the component or at the base plate shows a very good agreement with the implemented material properties in the *MSC Marc/Mentat* (Figure 8, right). Due to the high computing time, only 6 layers of the real 20 layers were considered in the FEM. However, the maximum temperatures (although technically difficult to detect due to the inertia of the thermocouples type K) and the cooling behaviour could be analysed. Based on this, the prediction of component displacement (Figure 9, left) or the thermal induced residual stresses (Figure 9, right) can be possible.

The fact that a subsequent forming of additive components was investigated at first for an inline hot forming process (rolling) of one weld seam demonstrated that a combination of welding and hot forming could homogenize the mechanical properties and increase the ductility by 20 %. This results from the refinement of the microstructure during the forming process (recrystallization). These findings were then transferred to an additively produced wall, although no inline hot forming was currently carried out (see Figure 10).

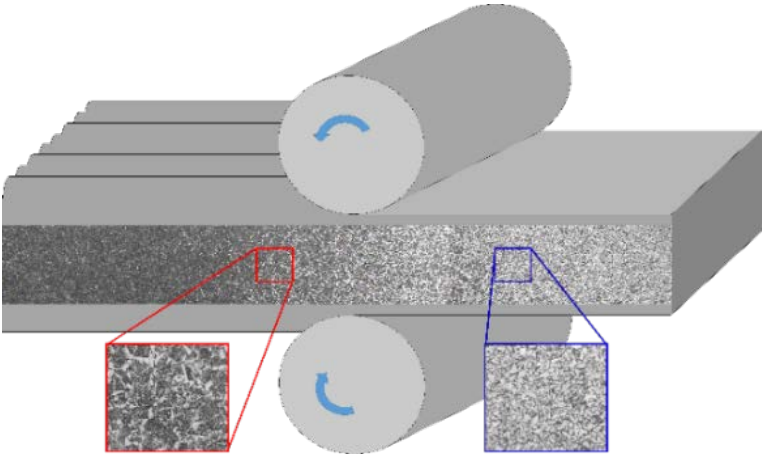


Figure 11. Change of microstructure in a hot rolled WAAM wall

The processes that took place were decoupled, i.e., WAAM then cooled down to room temperature, reheated, hot forming. The evidence of a material change by process combination is already applied for steels.

Summary

In the present article some examples for the application of light metals and hybrid structures could be shown, whereby the focus of the investigation was on the numerical process simulation and/or process design by consideration of real thermo-mechanical and thermo-dynamic material data (flow curves, heat capacity, thermal expansion etc.).

For the reduction of moving masses, new fields of application in the field of component production as lightweight construction were pointed out. These included, on the one hand, forging processes in which a comparison was made between monolithic aluminium components and their production from an aluminium-polyamide compound. The demonstrator component under investigation could be made over 10 % lighter by using polyamide as the core material. The whole process was predicted with the FE software *simufact.forming V15*. Hence, the determination of the thermo-mechanical and thermo-dynamic properties under process relevant parameters was done for the metal but also for the polyamides (PA6 and PA6-GF30). Therefore, the forming forces as well as the real material flow can be predicted and the possible process limits detected. Thus, error-free components were forged, and the potential of lightweight design for hybrid structures could be detected.

In order to meet the requirements of lightweight materials in the field of additive manufacturing, in contrast to other studies, no aluminium or titanium alloys except magnesium were investigated. The technology used is mainly for simple contours, for example for semi-finished products for further forming processes, suitable because of its high build-up rate (1500 cm^3/h) in combination with high material utilisation. In order to design these multi-layer welding processes properly, all necessary thermo-mechanical and thermo-dynamic material properties of the magnesium wire AZ31 were determined and implemented in the FE software *MSC Marc/Mentat*. Thus, the semi-finished products could be produced with less distortion. The focus was on a detailed thermo-mechanical transient simulation in order to predict the microstructure development with the resulting mechanical properties in further investigations. However, this only works if the simulation calculates the correct temperature distribution in the component.

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