Numerical Development of a Tooling System for the Co-Extrusion of Asymmetric Compound Profiles on a Laboratory Scale

N. Heimes[1,*], J. Uhe[1], S. E. Thürer[2], H. Wester[1], H. J. Maier[2], C. Klose[2] and B.-A. Behrens[1]

[1] Leibniz Universität Hannover, Institut für Umformtechnik und Umformmaschinen, An der Universität 2, 30823 Garbsen, Germany
[2] Leibniz Universität Hannover, Institut für Werkstoffkunde, An der Universität 2, 30823 Garbsen, Germany
*Corresponding heimes@ifum.uni-hannover.de

Abstract. In order to reduce the weight of vehicles and their CO_2-emissions and to increase driving range, new ways of producing hybrid material compounds must be developed to tailor the properties of the part exactly to the intended use. Lateral angular co-extrusion (LACE) offers the possibility to produce hybrid profiles. In the past, this process was used to extrude flat magnesium-titanium profiles and after further development, co-axial aluminium steel profiles.
In this study, the numerical development of a tooling system for the production of asymmetric hybrid semi-finished products extruded using LACE is presented. The co-extruded profiles, consisting of an L-profile made of steel (AISI 5120) that is filled with aluminium alloy EN AW-6082 on one side, will subsequently be formed to hybrid transverse control arms by die forging. The tool design is initially carried out for a laboratory scale extrusion in order to gain basic knowledge about the process and to quantify the influence of the different process variables like ram velocity or extrusion ratio.

Keywords: Co-extrusion; FEM; Tailored forming; Aluminium-steel compound.

1 Introduction

Depending on the volume ratio, a hybrid component made of light metal and steel is significantly lighter than mono-material parts made of steel, while still offering sufficient stiffness. One possibility of combining light metals, e.g. aluminium and steel is co-extrusion. Co-extrusion processes can be divided into two main categories according to the type of extrusion billet [1]. On the one hand, modified extrusion billets with reinforcing elements integrated in the billet matrix material or hybrid extrusion billets can been used. In this case, both matrix material and reinforcement are plastically deformed. For example, Foydl *et al.* investigated the extrusion of discontinuously reinforced extrusion billets of the aluminium alloy EN AW-6060 which were drilled along

the symmetry axis in order to fill in cylindrical, conical or spherical steel elements [2].The second possibility is the use of conventional extrusion billets, which are combined with reinforcing elements like steel wires or flat profiles. The reinforcing elements are fed to the deformation zone from outside the extrusion tool. Consequently, only the matrix material is plastically deformed. Chatti *et al.* used modified chamber tools to extrude aluminium profiles from EN AW-6060 together with wires made of AISI 304 steel [3]. Pietzka *et al.* succeeded in embedding steel wires in a magnesium matrix and was able to embed up to eleven wires in a co-extruded profile [4]. Grittner *et al.* investigated the lateral angular co-extrusion of flat aluminium titanium compound profiles using conventional aluminium billets. Therefore, the aluminium alloy was redirected at an angle of 90° within the tool and joint with the titanium profile in the welding chamber [5]. Based on the process described by Grittner *et al.* a LACE process for aluminium EN AW-6082 and steel AISI 5210 was developed to produce coaxial aluminium steel profiles which, are formed to hybrid bearing bushings in the further course of the process chain within the Collaborative Research Centre 1153, see Fig. 1 [6, 7].

In order to expand the range of applications for components that can be produced by LACE and to demonstrate the potential of the technology, a co-extrusion process is to be designed for asymmetrical hybrid profiles, which are subsequently formed into hybrid control arms by die forging, see Fig. 1. Based on the geometry of the transverse control arm, the intermediate stages after die forging and extrusion were designed inversely. For the production of hybrid asymmetrical profiles it is particularly challenging that there is no comprehensive form closure. The bond is mainly formed by material closure. At this, it is of great importance to consider the geometrical and process-related limits of the different technologies.

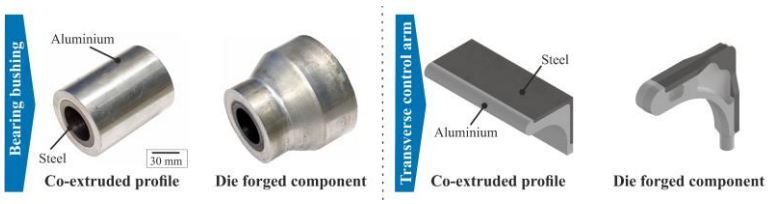

Fig. 1. Co-extruded semi-finished profile and die forged component, left: bearing bushing, right: transverse control arm

Numerical modelling has become state-of-the-art as an initial step in designing and further improving extrusion and co-extrusion processes as it enables to study the material flow and influence of process variables under various conditions and, thus reduces the number of experimental tests and saves resources [8, 9]. In addition, the actual values of local parameters like temperature or contact pressure are often difficult to obtain or not measurable during extrusion processes. In the present study, an FE model of the LACE process to produce asymmetrical hybrid profiles is established to investigate a possible tool design for co-extrusion experiments on a laboratory scale and to gain knowledge about the influence of the tool geometry and process variables on the resulting hybrid profile.

2 Numerical Investigations

2.1 Model Setup

The commercial FE software FORGE NxT 2.1 was used to model the co-extrusion process. To limit the computation time, the existing symmetry was considered and only the half of the 3D FE model was examined, see Fig. 2a. The billet is placed in the container and pressed into the upper die *via* the press ram. At this point, the aluminium contacts the wedge, which redirects the material flow by 90° to the extrusion direction. The wedge does not only deflects the flow of aluminium, but together with the lower die it forms a feed channel, which guides the L-profile into the welding chamber. The feed occurs at an angle of 80° to the extrusion direction. The L-profile is filled with aluminium in the welding chamber and leaves the tool as a hybrid profile *via* the die opening.

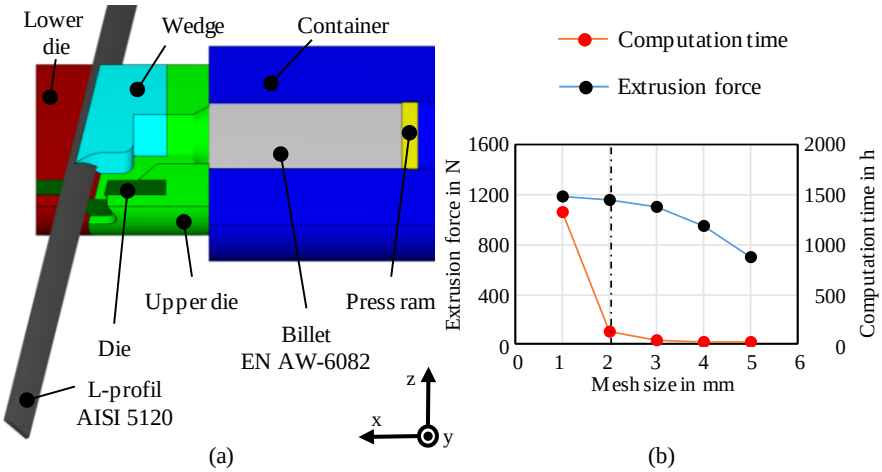

Fig. 2. Half 3D FE model of the assembly (a) Mesh study (b)

Both, the accuracy of the calculated results and the computation time are strongly dependent on the selected minimal element size. Based on the results of a preliminary mesh study, a minimum element size of 2 mm was used for the numerical investigations resulting in 177,000 tetrahedron volume elements in total. Thus, a sufficiently high accuracy and a reasonable computing time of approx. 125 h was achieved, see Fig. 2b. A further refinement of the mesh increases the simulation time by a factor of eleven, with only minimal increase in the accuracy of the results. For the mesh study, only the mesh size of the aluminium was used, as it has a significant influence on the resulting extrusion force, which is the most important criteria for the design of the process. Since the L-profile is very thin and long compared to aluminium, a mesh size of 1.5 mm was chosen. In the area of the chamber tool and the die a refinement box was used to reduce the mesh size to 0.5 mm. With six elements over the profile thickness the results over

the thickness can be represented sufficiently accurate. The tools were modelled as rigid bodies for the described investigations.
Due to extensive plastic deformation during the co-extrusion process, two remeshing criteria, a periodic initiated remeshing criterion with a fixed remeshing after 20 steps as well as an automatic size criterion to refine the mesh of the workpiece according to the curvature of the die in the contact area, were applied. Tresca's friction model was used to describe the frictional behaviour between billet and tools. According to the findings of a previous study, the friction factor was set to 0.95, which describes the high adhesion tendency of aluminium well [10]. A bilateral sticking condition was assumed for the interface between the aluminium billet and the L-profile, since the L-profile is only displaced due to the contact with the aluminium. For the heat transfer coefficient, a value of 35 kW/m^{2}K was chosen according to literature [11]. The ambient temperature was set to 50 °C. For an accurate prediction of thermomechanical material behaviour during the co-extrusion process, flow curves of both the aluminium alloy EN AW-6082 and the case hardening steel AISI 5120 were experimentally determined by means of uniaxial cylindrical upsetting tests and implemented in the FE software as a function of strain, strain rate, and forming temperature [10].
A numerical process design study was performed to determine a suitable tool geometry and process parameters for the experimental investigations. Therefore, different tool geometries and their influence on the material flow were analysed. After the selection of a suitable tool geometry, the extrusion ratios were varied to determine their influence on the extrusion force and the profile geometry. The extrusion ratio was calculated from the cross sectional area of the aluminium billet at the beginning of the process and the aluminium cross section of the hybrid profile. In order to vary the extrusion ratio, the contours of the die were adapted while maintaining the same L-profile thickness. By varying the profile thickness, the aluminium surface is changed in the profile cross section. To ensure a better comparability of the results of different reinforcement contents, the die contour must be adjusted accordingly so that the extrusion ratio remains the same. In addition, the influence of the ram velocity on the extrusion force requirement was investigated. Finally, the die contour was varied to improve the bond formation between aluminium and steel by clamping the L-profile. The process parameters used for the numerical-parametric study are summarised in Table 1.

Table 1. Process dimensions and parameters

Dimension	Value	Parameter	Value
Billet length	120 mm	Billet temperature	530 °C
Billet diameter	56 mm	L-profile temperature	20 °C
L-profile length	800 mm	Tool temperature	450 °C
L-profile thickness t_h	3, 5 mm	Ram velocity v	2, 4 mm/s
L-profile legs length	20 mm	Extrusion ratio ψ	3.8:1, 5.3:1, 8.1:1

2.2 Results and Discussion

First, the geometries of the chamber tool, more specifically the wedge and upper die geometry, were varied. Figure 3a shows tool variant A, where a flat redirection of the material flow was chosen for the wedge in combination with a slope at the upper die as transition to the die. In variant B, the redirection of the material flow consists of a hemisphere and the transition from the upper die to the die consists of a radius, see Fig. 3b. The evaluation of the velocity in z-direction shows that in variant A a more pronounced dead zone is formed at the wedge. A larger dead zone is desirable to ensure that the aluminium from inside the billet flows and, thus no impurities such as oxides or lubricants enter the joining zone between aluminium and steel. At the transition from the upper die to the flat die, the variant B forms a larger dead zone. However, a dead zone is not necessary there, as the material is removed in the finishing machining process.
Decoupled simulations of tool load were carried out to identify possible weak points within the components. For both variants, the 1st principal stresses do not show any extreme values that would indicate a risk of crack formation. The evaluation of the force-time curves also shows no significant differences. Due to the material flow and easier manufacturing, variant A with a flat wedge and sloping transition was selected for further investigation.

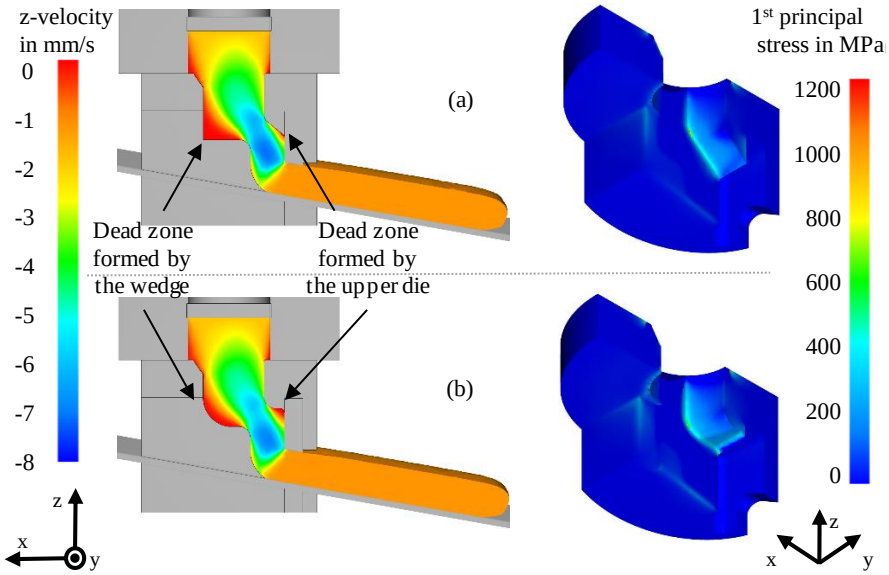

Fig. 3. Velocity in z-direction and die analysis for tool variant A (a) and variant B (b)

In the next step, the extrusion ratio was varied by changing the aluminum content while maintaining a constant L-profile thickness of 3 mm. Figure 4a-d show the extruded profiles in side view with the respective temperature field, in Fig. 4 a,b,d the ideally straight L-profile is visualised in pink to illustrate the bending. The smallest extrusion ratio of 3.8:1 shows a slight bending of the profile in negative z-direction as shown in

Fig. 4a. With a higher extrusion ratio to 5.3:1 the bending of the profile increases, see Fig. 4b. At the maximum extrusion ratio of 8.1:1, the L-profile was deformed until necking occurs which leads to an abortion of the computation. The contact temperature is the equal for all variants at approx. 460 °C. The L-profile heats up very quickly due to the small profile thickness. With an extrusion ratio of 3.8:1, the profile heats up faster in the feed channel than with an extrusion ratio of 5.3:1. The varying heating is due to the different exit speeds. As the extrusion ratio increases, the exit speed of the profile increases and, thus reduces the contact time in the feed channel. The increased temperature of the profile in the channel in Fig. 4c is due to the fact that the temperature is shown at a press height H_p of 60 mm. Due to the tool contact in the channel, the L-profile always heats up in the same way, regardless of the extrusion ratio, until the aluminium fills the welding chamber. Subsequently, the L-profile is pressed out of the die together with the aluminium so that the following L-profile has less time in the channel to heat up. The higher deformation of the L-profile for larger extrusion ratios correlates with the increased contact normal stress. Contact normal stresses of up to 600 MPa were determined for the extrusion ratio ψ of 8.1:1, for ψ of 5.3:1 stresses up to 460 MPa and for the smallest extrusion ratio ψ of 3.8:1 a contact normal stress of 370 MPa was determined. The flow stress of AISI 5120 at the present contact temperature of 460 °C is 550±30 MPa [10]. The deformation of the L-profile at the extrusion ratio of 8.1:1 can therefore be explained by exceeding the flow stress of the material. Increasing the ram velocity will not result in an increased bend of the profile, see Fig. 4a,d. Only the heating of the L-profile in the feed channel is reduced by increasing the ram velocity.

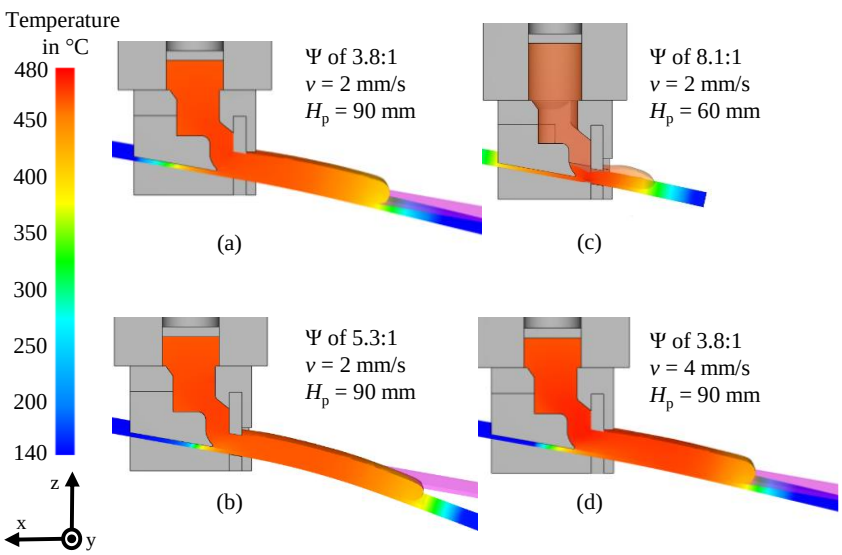

Fig. 4. Profile geometry and temperature distribution for varying extrusion ratios (a-c) and extrusion velocity (d) for an L-profile with a thickness of 3 mm

One possibility to increase the flow stress would be to reduce the contact temperature by decreasing the process temperatures of the aluminium and the heated tools. However, a reduction of the temperature is not recommended for two reasons. Firstly, the resulting extrusion force would increase and thus, possibly exceed the maximum force of the extrusion press. On the other hand, the formation of a material compound between aluminium and steel is impeded at lower temperatures. However, this is of crucial significance for the strength of the compound profile. The calculated extrusion force-time curves are plotted in Fig 5a. Dashed lines represent the force curves with an L-profile thickness of 5 mm, all the other curves represent results with a profile thickness of 3 mm. All curves show a similar characteristic course and differ only in the time shift due to varying extrusion velocity and the maximum extrusion force resulting from the variation of the extrusion ratios. Due to the design of the tooling system, different steps are visible in the extrusion force curve. First, the aluminium billet is upset to the container diameter, whereby the force increases only slightly. The subsequent first increase in force to 400 N marks the diameter reduction in the upper die. The aluminium is now pressed further into the tool, whereby the force remains constant until the aluminium reaches the wedge's redirection. As the wedge is deflected towards the die, the force increases slightly to approx. 800 N. The last steep rise marks the contact phase between the aluminium and the L-profile up to the stationary force plateau, which describes the extrusion. In the stationary phase, the force requirement decreases continuously due to the decreasing friction surfaces of the aluminium billet in the container. An increase in the extrusion ratio leads to an increase of the required extrusion force, as shown in the comparison of the courses with a ram velocity of 2 mm/s in Fig. 5a.

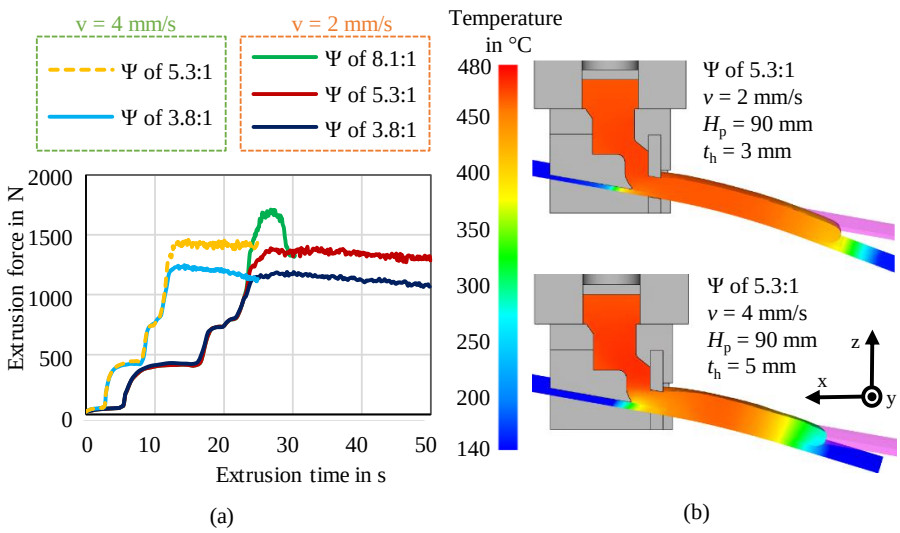

Fig. 5. Force-time curves for the variation of extrusion ratio, ram velocity and profile thickness (a) profile geometry and temperature distribution for a profile thickness of 5 mm and 3 mm (b)

The drop in extrusion force after an extrusion time of 28 s at an extrusion ratio of 8.1:1, is caused by the necking of the L-profile due to the large extrusion ratio. However, an increase in ram velocity only leads to a slight increase in the maximum extrusion force, comparing the two curves for an extrusion ratio of 3.8:1. To increase the profile straightness, the profile thickness was increased to 5 mm and the mean extrusion ratio of 5.3:1 was simulated with a press velocity of 4 mm/s. The thicker L-profile in combination with the increased ram velocity is intended to compensate for the profile bending, as the profile heats up more slowly and the bending stiffness is increased. When using the thicker L-profile, the die geometry has to be adjusted to achieve the same extrusion ratio as with the 3 mm profile. The resulting extrusion force for a profile thickness of 5 mm is slightly higher, but still on a comparable level to the force requirement for a 3 mm profile. The slightly higher force level is due to the higher ram velocity. Fig. 5b shows the extruded profile for an L-profile thickness of 5 mm and 3 mm. By increasing the profile thickness, the bending could be significantly reduced. However, a slight curvature can be seen, so that if the extrusion ratio is increased to 8.1:1, no necking is to be expected, but rather a strong curvature of the profile. The contact temperature dropped to 420 °C due to the thicker L-profile, since the larger volume results in the L-profile extracting more heat from the aluminium. Simulated cross-section of the hybrid profile with an extrusion ratio of 5.3:1 with a profile thickness of 5 mm is shown in Fig. 6a. The section was taken 30 mm after exiting the tool at the final press height H_p of 100 mm. The extruded profile deviates only slightly from the target geometry, which can be explained by the expansion of the aluminium after exiting the die. The aluminium completely fills the cavities of the L-profile, so that no hollow spaces are created in the profile.

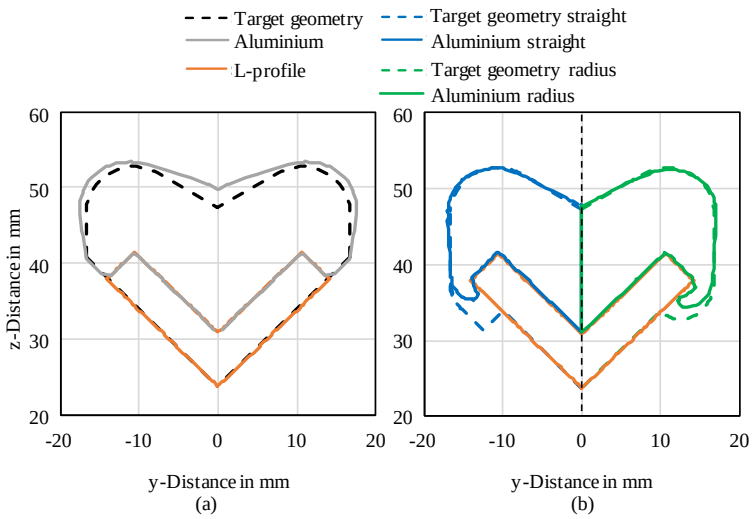

Fig. 6. Simulated profile cross-section ψ of 5.3:1, v = 4mm/s, t_h = 5mm (a), profile cross-section for variation of die geometry (b)

The clamps are not completely filled in both variants. The reason for the incomplete filling might be that the lower die, which guides the L-profile, is aligned flush with the die. This allows the aluminium to flow directly into the die without filling the form completely. The incomplete filling reduces the pressure in the welding chamber and thus, the expansion of the aluminium after leaving the die is decreased. In order to fill the clamp, the contour of the lower die should not be flush with the die. By offsetting the lower die contour, a pronounced welding chamber is formed, so that enough pressure is generated for complete forming.

3 Conclusions and Outlook

In the scope of this work, the numerical design of a lateral angular co-extrusion (LACE) process for the production of asymmetrical aluminium-steel compound profiles was presented. An FE model was built up and used to examine the influence of different tool geometries and process parameters on the developed LACE process. It was established that the extrusion ratio has a strong influence on both the maximum extrusion force and the profile straightness. Furthermore, it was shown that with an L-profile thickness of 5 mm the straightness is increased.
Based on these results, an extrusion tool system will be manufactured for experimental investigations on a 2.5 MN extrusion press on a laboratory scale. The numerical model will be validated on the basis of the experimental results. For better filling of the clamp geometries, a larger welding chamber will be added to improve the composite quality.

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