Forging of eccentric co-extruded Al-Mg compounds and analysis of the interface strength

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Abstract. Within the subproject B3 of the Collaborative Research Center 692 it has been shown that Al-Mg compounds with a good bonding quality can be produced by hydrostatic co-extrusion. During processing by forging, the aluminum sleeve is thinned in areas of high strains depending on the component geometry. To solve this problem an eccentric core arrangement during co-extrusion was investigated. Based on the results of FE-simulations, the experimental validation is presented in this work. Rods with an offset of 0.25, 0.5 and 0.75 mm were produced by eccentric hydrostatic co-extrusion. Ultrasonic testing was used to evaluate the bonding quality across the entire rods. For the forging investigations the basic process Rising was chosen. The still good bonding quality after forging was examined by dye penetrant testing and optical microscopy.

For an optimal stress transfer between the materials across the entire component, a sufficient bonding between the materials is essential. To evaluate the interface strength, a special bending test was developed. For the conception of the bending specimens it was required to analyze the Rising specimens geometry. These analyses were performed using a reconstruction of the geometrical data based on computer tomography (CT) investigations. The comparison with the numerically determined Rising specimen geometry shows good correlation. Parametric Finite Element Analyses of the bending test were used to develop the load case and the specimen geometry. By means of iterative adaption of load application, bearing and specimen geometry parameters, an advantageous stress state and experimentally applicable configuration were found. Based on this conception, the experimental setup was configured and bending tests were performed. The interface strength was determined by the calculation of the maximum interlaminar interfacial tension stress using the experimental interface failure force and the bending FE model.

1. Motivation
The challenge of using composites and compounds is in creating a sufficient bonding between the materials. However, not only an existing bonding is important but also a reliable transfer of stresses in operation, especially for components for industrial or safety applications. By using aluminum and magnesium as compound materials, both goals could be reached. The production by hydrostatic co-extrusion – with AZ31 as core material and AA-6082 as sleeve material – results in a complete bonding [1]. The bonding could be maintained during further processing by forging [2]. The interface strength was investigated with different methods and high interface strengths were found, but with a high variation [3, 4]. Furthermore, another effect occurred at components with asymmetric cross
sections which were forged by Rising as shown in figure 1. In areas of high strains – increased by an opposing material flow – the flank thickness of the sleeve material is reduced [2]. This could become a problem, if the sleeve material breaks up. Then, the stresses would be applied to just one material which means the loss of the compound. Additionally, corrosion could start damaging the magnesium core. To increase the flank thickness and to enhance the field of application of the compounds, an eccentric core arrangement during co-extrusion was investigated.

![Critical flank thickness](image1)

**Figure 1.** Transversal cross section of a component with centric core arrangement forged by Rising with reduced flank thickness in the region of high strains.

2. Part I – Production and Processing

2.1. Introduction

The idea of an eccentric co-extrusion was developed by FEUERHACK [2] and a schematic presentation of the process is given in figure 2a. Thereby, the eccentric arrangement of the magnesium core is given by an offset of center axes Ω of the aluminum and the magnesium billet. It can be calculated with equation 1 and the extrusion ratio ψ, if d are the diameters of the pressing billet respectively rod.

\[
ψ = \frac{d^2_{\text{billet}}}{d^2_{\text{rod}}} = \frac{d^2_{\text{billet}}}{d^2_{\text{rod}}}
\]

The offset leads to a minimum (smin) respectively maximum (smax) wall thickness of the aluminum sleeve as shown in figure 2b. FEUERHACK investigated eccentric co-extrusion with five different offsets within the pressing billet in the range of 1 to 5 mm numerically. The further processing of the eccentric rods was also numerically investigated. Therefore, FEUERHACK chose the basic forging process Rising to compare the results with the former used centric core arrangement. He showed, that with increasing the offset, the critical flank thickness also increases [2].

![Eccentric co-extruded rod](image2)

**Figure 2.** a) Schematically presentation of the eccentric hydrostatic co-extrusion process, and b) the cross section of a co-extruded eccentric rod.
Based on the numerical findings of FEUERHACK the experimental validation is presented in this article. Therefore, rods with an offset of center axes of 0.25, 0.5 and 0.75 mm were produced.

2.2. Experiments

2.2.1. Eccentric hydrostatic co-extrusion. The extrusion experiments were performed at the Compound Extrusion Products GmbH in Freiberg, Germany. The production of eccentric pressing billets and rods are based on the experimental experience in co-extrusion of Al-Mg compounds with a centric core arrangement. In opposite to the assumption of FEUERHACK, the core diameter is 58 mm instead of 60 mm due to technical limitations of processing a loose fit between the materials. Thus, the comparability of the numerical and experimental results is limited. Table 1 gives a summary of the calculated values of the experimental setup used in this work.

| All dimensions in mm | Offset | $s_{\text{min}}$ | $s_{\text{max}}$ |
|----------------------|--------|------------------|------------------|
| Pressing billet       | 0      | 11               | 11               |
|                      | 1      | 10               | 12               |
|                      | 2      | 9                | 13               |
|                      | 3      | 8                | 14               |
| Co-extruded rod       | 0      | 2.75             | 2.75             |
|                      | 0.25   | 2.5              | 3.0              |
|                      | 0.50   | 2.25             | 3.25             |
|                      | 0.75   | 2.0              | 3.5              |

The parameters – with an extrusion temperature of about 300 °C and a plunger velocity of 3.6 mm/s – for eccentric co-extrusion were the same as used for a centric co-extrusion with a tapered extrusion die. As sleeve material the aluminum alloy AlMgSi1 (AA-6082) and as core material MgAl3Zn (AZ31) were used. A detailed description of the co-extrusion process of Al-Mg compounds can be found at KITTNER [1]. The bonding quality of the rods has been examined by ultrasonic testing. With this nondestructive method the rod could be verified entirely. In addition, the interface formation was evaluated by optical microscopy.

2.2.2. Forging. The forging experiments were performed on a 1000 kN eccentric press (Raster-Zeulenroda) with the same forging die and process parameters as used by FEUERHACK [2]. Specimens with a length of 40 mm were cut off from the co-extruded rod and heated at 350 °C for 30 minutes prior to forging. For significant results, the correct positioning of the specimens into the forging die is important. The specimens have to be rotated that $s_{\text{min}}$ and $s_{\text{max}}$ are in a six o’clock position (figure 2b). The lower the offset, the more difficult the positioning, due to an optical identification of $s_{\text{min}}$ and $s_{\text{max}}$. For lubrication an aerosol with a composition of MoS$_2$ and graphite was applied to the upper and lower die prior to forging. The specimen temperature was about 300 °C and the die temperature 200 °C. After forging, some components were cut in longitudinal or transversal direction for an investigation by dye penetrant testing and preparation for optical microscopy. In addition, a comparison of CT data of the component geometry and simulation results was performed. Therefore, new simulations with the adapted core diameter of 58 mm were necessary. The experimental CT investigations are described in part II of this paper, but the results of the comparison between simulation and experiment are presented under paragraph 2.3.2.
2.3 Results and discussion

2.3.1. Eccentric hydrostatic co-extrusion. By using ultrasonic testing, the bonding quality across the entire rod could be evaluated. This method was used for co-extruded Al-Mg rods by LEHMANN [3] at first. The ultrasonic emitter/receiver is positioned on the lateral area of the rod. Thus the ultrasonic waves are spread across its cross section. In case of a non-bonding condition, the emitted ultrasonic waves are reflected at the interface resulting in a strong peak after a short runtime. If there is a sufficient bonding most of the ultrasonic waves pass the interface and only a small part is reflected. This leads to a smaller, but still significant peak – when the interface is passed – and to one larger peak indicating the bottom echo. By this characteristic echo signals the corresponding areas could be qualitatively identified and were marked on the rods, as can be seen in figure 3.

Figure 3. Developed view of a rod with a qualitatively indication of the bonding quality investigated by ultrasonic testing; red areas indicate no bonding and green areas a good bonding.

To give an overview of the experiments, the results of the specimens with the largest offset (0.75 mm within the rod) are presented. The investigated rods had a completely formed bonding with exception of the beginning of the rods. A poor bonding quality in this area was also shown by KITTNER [1] due to an unsteady material flow in the beginning of the co-extrusion process. To characterize the interface formation, specimens for optical microscopy were prepared in longitudinal and transversal direction. The good bonding quality – detected by ultrasonic testing – could be confirmed by this investigation. A faultless interface with a thickness of about 1 µm has formed completely, as the macro- and microstructures in figure 4 show. This is in accordance to the results that have been found during co-extrusion with centric core arrangement [1] and have been expected.

Figure 4. Microstructural investigations confirmed the good bonding quality: a) transversal and b) longitudinal cross section, c) and d) corresponding microstructures.
2.3.2. Forging. During the forging process no peculiarities could be observed compared to forging with a centric core arrangement. After cutting the forged compounds, a dye penetrant test was performed on the longitudinal and transversal cross section. The transversal cross section shows no macroscopic damage of the interface at the observed area. But in the longitudinal cross section a damage of the interface is indicated in the \( s_{\text{min}} \) region (figure 5b). Due to the material flow in longitudinal direction the interface is fragmented as it has been found by FEUERHACK [2]. He described the fragmentation process of compounds with a centric core arrangement by four levels. The indicated damage in figure 5b corresponds to level three in his classification. In this level, the previously fragmented interface is elongated due to the material flow in longitudinal direction. Thereby, the fragments drift away from each other and voids develop between them. If the forming pressure and elongation are high enough, the materials are pressed into the voids again [2]. In the present case, the forming process is completed before the materials can be pressed into this voids as shown in figure 5d and 5e. Thus, they are detected by the dye penetrant test.

Figure 5. Comparison between the cross sections of a Rising specimen with a) centric core arrangement and b-c) offset of 0.75 mm within initial billet show a shifted Mg-core, d-e) Microstructures of fragmented interface areas detected by dye penetrant testing.

Comparing the longitudinal cross sections of a component with no offset (figure 5a) and with an offset within the initial billet of 0.75 mm (figure 5b), it can be seen, that the Mg-core is shifted. The critical flank thickness in the component with centric core arrangement is in range of 160 to 170 \( \mu \text{m} \). For the component with an offset of 0.75 mm within the initial billet the flank thickness is in range of 400 to 450 \( \mu \text{m} \) (figure 5c). Thus, the flank thickness could be increased by the eccentric core arrangement. The results of the comparison between simulation and experimental results are in a good conformity. For a better comparison a model based on STL (Standard Tessellation Language) was derived from the CT-data, as well as from the geometry of the simulation results. Figure 6 shows the outline of the component cross sections in transversal (figure 6a) and longitudinal (figure 6b) direction. The blue lines indicate the real component identified by CT. The red lines indicate the component based on the simulation results. At the transversal cross section it can be seen, that the outer outlines do not match exactly. This is due to information losses during data transformation and a limited precision in the positioning of both datasets. The differences are about 0.1 mm, which is very small. The modelled material behavior is based on flow curves identified by compression tests at three different temperatures and strain rates. Nevertheless, it cannot reproduce the real material flow exactly. Thus, a
higher deviation of both datasets occurs in the upper region and in the flash region. Additionally, in FE-simulations, the material behavior is supposed to be more rigid than in reality. The deviation can also be seen at the material flow in longitudinal direction. Due to this problem the critical flank thickness in the simulation is thinner than in the experiment. The deviation of the resulting geometries of simulation and experiment at this point is about 0.1 mm. In general the deviations are in range of 0.1 to 0.6 mm depending on the position of the measurement.

![Figure 6](image)

Figure 6. Comparison of the datasets of a component with an offset of 0.75 mm within the initial billet, blue lines indicate the CT-data, and red lines indicate the simulation model.

3. Part II – Strength of the interface

3.1. Introduction

For the further manufacturing of the forged billet and application of the structural component it is essential to achieve a sufficient bonding. Therefore, it was necessary to analyze the material in the forged state. In the presented investigations, Rising specimens described in paragraphs 2.2.2. and 2.3.2. were analyzed. Interlaminar tensile stresses are particularly critical for the interface. Hence, in previous investigations special bending tests were used to characterize the tensile strength of the interface [3, 4]. For that reason, a new bending configuration which is adapted to the special requirements was developed and applied.

3.2. Geometry reconstruction

For the conception of the load case and the specimen geometry it was required to know the geometry of the Rising specimen. Thus, investigations using computer tomography (CT) were performed. In these analyses Rising specimen with an offset of 0.75 mm of the initial billet were examined. An example of the primary results of the CT investigation is given in figure 7.

![Figure 7](image)

Figure 7. Example of CT data of a Rising specimen, offset of the initial billet: 0.75 mm: a) 3D model, b) Transversal cross section in the middle part (CT analyses performed by CWM GmbH, Chemnitz, CT scanning resolution: voxel edge length $\approx 55 \mu m$).
As final result, the geometrical data were transformed into a 3D STL model of the core and sleeve. Hence, beside the outer contour, the interface geometry can be determined. The STL file was imported into the software Paraview 4.3.1 for analysis and editing to compare the geometry with the results of the simulation and to develop the bending specimen geometry. The comparison of the CT and numerical geometry is given in paragraph 2.3.2. An example of the analyzed transversal cross section of the Rising specimen and the position of specimen extraction is shown in figure 8. The general design and proportions of the bending specimen were developed using numerical simulations, see paragraph 3.3. Based on one exemplary reconstructed geometrical data, a parametrical finite element model of the bending specimen was configured. For the determination of strength values the measured transversal geometry of the specimens after manufacturing was used.

Figure 8. Example of reconstructed STL data of a Rising specimen in Paraview, offset of the initial billet: 0.75 mm: a) Separated 3D model, b) Transversal cross section in the middle part, position of the bending specimen.

3.3. Development of load case and specimen geometry

Generally, many configurations of load cases are conceivable for the determination of the interface strength. In previous investigations different specimen geometries and loading devices were applied, see [3, 4]. Every version of bending configurations considered the requirements of the respective geometry of the semi-finished product or the further processed component. In case of the Rising specimen presented in this paper, the interface geometry is complex. The wall thickness of the sleeve is strongly varying within the transversal cross section. Therefore, it was required to find a part for an applicable extraction of bending specimen. For all analyzed configurations, the section adjacent to the middle section (in longitudinal direction) in the upper part of the Rising specimen was chosen, see figure 8b. A small specimen width enables a separation of three specimens from the limited middle section. Due to the small cross section of the bending specimen geometry it was reasonable to use a punch loading with supporting bearings without pre-stressing instead of the clamping system which was used in [3]. For that reason, a symmetrical three point bending loading device was developed.

The conception of the load case and the specimen geometry was performed using parametric finite element analyses (FEA) with ANSYS 14.0. The 3D model includes a monolithic specimen based on the reconstructed geometrical data with linear elastic material behavior (one material: elastic parameters of Al). This approach provides a stress value which occurs in the direct adjacency of the interface. The complicated stress distribution due to stress singularities at the interface edge is not included. Analytical investigations to the Al-Mg interface edge resulted in very weak stress singularities [3]. Thus, it can be concluded that this approach is legitimate. The criteria for developing the load case and dimensioning the specimens which were considered in the FEA are: high interlaminar tensile stress at the interface, limited v. Mises equivalent stress in the adjacent region of the load application and bearings and a controllable handling of the specimens while manufacturing and test preparation. The resulting FE model including the symbolic boundary conditions as well as an
An example of the longitudinal normal stress distribution are given in Figure 9. Although the model includes only one material (Al), the interface contour is considered. Beside the calculation of the interfacial stress at the bottom of the specimen, the modeling of the interface contour enables further stress evaluations (not presented in this paper). For the variation of the specimen geometry the parameters of the model can be adapted. The maximum tensile stress is located at the interface at the bottom, due to the symmetrical configuration. As a result of the deviation from the elementary bending theory it is shown that the position of the neutral axis is varying depending on the x-coordinate (not constant in the middle of the specimen height). Furthermore, the parametric numerical model is the basis for the interface strength determination presented in paragraph 3.5.

**Figure 9.** a) 3D FE model, loadcase, b) Stress distribution $\sigma_x$ on the surface of the specimen (minimum stress is limited to -60.2 MPa, white areas).

3.4. Experimental setup, preparing and performing of the bending tests
The tests were performed using Rising specimens with an offset of 0.25, 0.50 and 0.75 mm of the initial billets. Three bending specimens were separated from the middle section of each analyzed Rising specimen by wire eroding with subsequent grinding (example, see Figure 10a). Furthermore, a maximum of three Rising specimens per variation of the offset value were investigated. To detect possible pre-existing defects at the interface, dye penetrant tests were performed. By means of damage detection some specimens had to be separated out which could not be mechanically tested. The material with the offset of 0.5 mm showed a particularly high damage ratio.

**Figure 10.** a) Example of a bending specimen W x H x L= 2.5 x 2.5 x 8.5 mm (W…width) – nominal geometry, b) Experimental setup of the bending test.
The bending device which is shown in figure 10b was assembled in a 100 kN testing machine of Zwick/Roell, using a 5 kN load cell. Two linear bearings were used to provide the displacement degree of freedom in longitudinal direction (x-direction) of the specimen. To support the specimen at defined sections, two prisms are bonded with the top of the linear bearings. The loading punch is connected to the traverse of the testing machine. To achieve a sufficient accuracy, the position of load application (punch) and bearings (supporting prisms) is marked on the surface of the small specimen. The bending tests were performed at room temperature with a punch velocity of 3 mm/min until interface failure occurs. As a consequence of different offset values, the sleeve thickness at the bottom of the specimens is in a range of 3.25 to 4.15 mm.

3.5. Results and discussion
After reaching the maximum force value at interface failure, an abrupt force decrease occurred, which is an indication of brittle failure behavior. It correlates with the previous results of interface strength investigations with similar Al-Mg compounds at room temperature [3, 4]. The experimental determined maximum forces are used as input value for strength determination. Furthermore, the specific transversal geometry of the specimens which is varying because of the individual grinding process was considered. For the strength calculation the FE model of the bending test was used. In table 2, the results of the interface strength (including the average value $\sigma_{IF}$) for the different offsets 0.2, 0.50 and 0.75 mm of the initial billets are given. The average strength of the specimens with offset 0.75 mm shows a higher level compared to the material with an offset of 0.5 and 0.25 mm. Generally, high variation of the interface strength between specimens of the same offset configuration is observed. The lower strength values (e.g. 11 MPa, see table 2) could indicate that these specimens are already damaged at the inner section of the interface which could not be detected by dye penetrant tests. Furthermore, the average interface strength is in the range of the values determined in [4]. Additional to the fundamental investigations in [3], by means of the presented Rising tests it was demonstrated that the interface of the co-extruded rods can be successfully deformed in further manufacturing steps.

Table 2. Determined interface strength $\sigma_{IF}$ of Al-Mg specimens forged by Rising with different offsets of the initial billets.

| Offset [mm] | Number of bending specimens | $\sigma_{IF \, min}$ [MPa] | $\sigma_{IF \, max}$ [MPa] | $\sigma_{IF \, av}$ [MPa] |
|-------------|----------------------------|---------------------------|---------------------------|---------------------------|
| 0.25        | 7                          | 11                        | 66                        | 39                        |
| 0.5         | 2                          | 37                        | 49                        | 43                        |
| 0.75        | 9                          | 36                        | 89                        | 61                        |

4. Summary and outlook
With the new process eccentric hydrostatic co-extrusion, rods with an offset of center axes up to 0.75 mm could be produced. Investigations on the bonding quality by ultrasonic testing and optical microscopy showed a complete bonding as expected. Further processing by the forging process Rising revealed a good formability of these compounds. In addition, the critical flank thickness could be increased from about 170 µm to 450 µm (compounds with offset 0.75 mm). A comparison of FE-simulation an experimental results show a very good conformity. Based on this results, the offset will be increased up to 1.25 mm in future investigations.

The interface strength of material forged by Rising was analyzed using a new developed bending test which was configured by means of FEA and geometrical investigations. The results of the bending tests show a wide range of strength values up to 89 MPa. Compared to compounds with an offset of 0.25 and 0.5 mm the material with offset 0.75 mm shows higher strength values. Subject of further investigations could be the analysis of strength variations at different positions in the Rising specimens. Furthermore, possible reasons of the strength variations should be examined.
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