Interfacial strength analyses of Al/Mg compounds using bending tests

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Abstract. In the Collaborative Research Center 692, subproject B3 Al/Mg compounds are investigated. The hydrostatic co-extruded compounds presented in this paper were further manufactured by the forging process Rising. To continue the first investigations of Rising specimens regarding interface strength, a bending test developed in a previous project period was used. The specific load case and the bending specimen geometry considers the requirements concerning the special geometry of the Rising specimen. Based on experimentally determined failure forces (maximum forces), the stress state for the investigation of the interface strength was calculated by means of the elementary bending theory extended with a numerical determined correction factor. The numerical analyses were based on a parametric FE model of the load case. Crack initiation was caused by the maximum interlaminar interfacial tension stress. In the demonstrated investigations co-extruded compounds with different ratio of core material (Mg) in the transversal cross sectional area of the initial billet were analyzed. A particular feature of the investigations is the interfacial strength analysis of a subset of Rising specimens in different areas of the transversal cross section. This was enabled by using compounds with larger sleeve thickness due to a lower Mg ratio. Thus, in this case a more extensive characterization could be performed. The results show higher strength values for Rising specimens with the largest sleeve thickness compared to the other investigated configurations.

1. Introduction
The requirement of weight saving becomes more and more important in several fields of industry, e. g. automotive [1] and aircraft. Therefore, lightweight materials and structures are essential to consider in product development processes. Aluminum and magnesium provide high lightweight potential with advantageous mechanical properties. In the Collaborative Research Center 692, subproject B3 Al/Mg compounds are developed and analyzed regarding production process and the resulting bonding quality, strength of the basic materials, interfacial strength, residual stresses, fracture mechanical properties as well as formability [2, 3, 4, 5, 6]. The material was produced by hydrostatic co-extrusion [7]. The production of Mg/Al macro composites by co-extrusion can also be found in [8]. Special focus of the actual investigations is on further manufacturing processes of the Al/Mg compounds. Within the research project, the fundamental forging processes Upsetting, Spreading and Rising are analyzed. The investigations presented in this paper include the analysis of Rising specimens. The actual standard configuration features a Mg ratio of the transversal cross sectional area of 53% of the initial billet. Using this configuration, in areas of high strains the flank thickness of the sleeve is reduced [5]. To enlarge the sleeve thickness in these critical sections of the Rising specimen, concentric co-extrusion rods with lower Mg ratios of the transversal cross sectional area were used as
semi-finished product for the forging process Rising instead of the eccentric version presented in [6]. Continuing these investigations, the specimens were analyzed concerning interfacial strength.

2. Production process of the analyzed material

2.1 Hydrostatic co-extrusion
The initial rods of the investigated Rising specimens were produced by hydrostatic co-extrusion at CEP GmbH, Freiberg. In figure 1 the general principle of the production process is given. Details of the co-extrusion process of Al/Mg compounds can be found in [2]. The force is transmitted by the pressure medium which is surrounding the bi-material billet. Thus, the billet is pressed through the die, which results in the compound.

Figure 1. Principle of hydrostatic co-extrusion.

The materials used were the lightweight alloys AZ31 and AA6082. The aluminum alloy was used as sleeve material and assumes function of structure and corrosion protection of the magnesium alloy. In table 1 essential parameters of the rod production by co-extrusion (Mg ratio of the transversal cross sectional area, diameters of the rod \(d_{\text{sleeve}} / d_{\text{core}}\), degree of deformation \(\phi\), punch velocity \(v_{\text{punch}}\) and the extrusion temperature \(T_{\text{extr}}\)) are given. As a new feature, the Mg ratio (core ratio) of the transversal cross sectional area was reduced and varied to achieve a larger sleeve thickness in critical zones of the cross section, see [5]. Furthermore, the sleeve thickness in the other zones of the transversal cross section is enlarged as well using this configuration. Hence, the core diameter was reduced compared to the actual standard configuration of 14.5 mm. Another strategy of improving the sleeve and core geometry is the eccentric co-extrusion of the two materials, see [5,6].

Table 1. Essential extrusion parameters of the initial rods.

| Mg ratio [%] | \(d_{\text{sleeve}} / d_{\text{core}}\) [mm] | \(\phi\) [-] | \(v_{\text{punch}}\) [mm/s] | \(T_{\text{extr}}\) [°C] |
|-------------|---------------------------------|----------|-----------------|------------------|
| 47          | 20 / 13.75                      | 2.77     | 3.6             | 300              |
| 29          | 20 / 10.75                      |          |                 |                  |

2.2 Forging process Rising
The Rising experiments were performed by the Professorship of Virtual Production Engineering (within the subproject B3). Following the procedure presented in [6] the forging processes were performed with the same parameters as used by FEUERHACK [5]. The co-extruded initial billets with a length of 40 mm were forged by means of a 1000 kN eccentric press (Raster-Zeulnenroda) and the upper and lower die, see figure 2 a). The achieved specimen temperature was of about 300 °C and the die temperature of about 200 °C. For lubrication a composition of MoS\(_2\) and graphite was applied to the surfaces of the upper and lower die. An example of the transversal cross section is given in figure 2 b).
3. Bending tests

3.1 Specimen separation and preparation
Bending tests were performed to determine the interfacial strength. The separating of the bending specimens was done by wire eroding from the middle part of the Rising specimens, see figure 3 a). At first, 3 slices were separated. In a second step, the bending specimen geometry was manufactured out of the slices. In all Rising components, bending specimens were separated from the upper part of the transversal cross section (bending specimen 1 in figure 3 b)). In case of the configuration with a Mg ratio of 29 %, bending specimens from the lower part were eroded additionally (bending specimen 2 in figure 3 b)) to analyze the strength of the lower interface of the Rising specimens. After wire eroding the specimens were analyzed by dye penetrant test to detect samples with interface damages which were separated out and not mechanical tested. Subsequent to damage detection the specimens were grinded.

3.2 Experimental setup and procedure
The bending tests were performed in a 100 kN testing machine of Zwick/Roell. The three point bending load case was developed based on FE analyses already in previous investigations, given in [6], see figure 4 a). Thus, for the experiments the same bending device which is assembled in the testing machine and the same testing procedure as presented in [6] was used, see figure 4 b). The force
is applied by means of a punch and measured by a 5 kN GTM load cell. Two prisms which are bonded to linear bearings enable the symmetric floating bearing of the specimen with the degree of freedom of displacement in longitudinal direction. The interface at the lower surface intersects the line of load application. The bending experiments were performed with a punch velocity of 3 mm/min until interface failure occurs at maximum force.

![Diagram](image)

**Figure 4.** a) Load case, specimen – nominal geometry: $W \times H \times L = 2.5 \, \text{mm} \times 2.5 \, \text{mm} \times L$ (width $W$, height $H$, length $L = 8.5\ldots11.5$ mm, depending on the configuration), supporting distance $l = 3$ mm, b) Bending device and specimen.

### 3.3 Evaluation of experimental data

As a result of brittle interface cracking, the force $F$ is decreasing abruptly after reaching the maximum value. The interfacial crack initiation is caused by the maximum interlaminar tensile stress $\sigma_{x \text{ max}}$ at the bottom of the specimen which occurs in the middle plane (regarding to the width), see figure 5. Due to the load case there is no superposition of interlaminar shear stress at this position. If the interface strength is reached, the crack is initiated with subsequent instable crack propagation until the whole interface has failed. Therefore, the maximum value of the interlaminar tensile stress in longitudinal direction of the specimen equals to the interface strength $\sigma_{IF}$ (interfacial tensile strength). Because of deviations to ideal bending beam conditions caused by the special geometry, the calculation of stresses was performed using the equation of the elementary bending theory extended with a correction factor $C$, see equation (1). For interfacial strength calculation, the maximum forces $F_{\text{max}}$ determined in the bending tests were used.

$$\sigma_{x \text{ max}}(F_{\text{max}}) = C \frac{3l}{WH^2} F_{\text{max}}$$  \hspace{1cm} (1)
Figure 5. Example of the stress distribution $\sigma_x$, calculated by means of the FE Model of the bending load case (minimum stress is limited to -60.2 MPa, white areas) [6].

$C$ was calculated using the result of the linear bending theory and the solution of the FE model of the bending load case which was developed and already used in previous investigations. Details to the model are given in [6]. For the specimens geometry the correction factor $C$ equals to 0.937. An example of the stress distribution $\sigma_x$ is given in figure 5.

3.4 Results and discussion

In table 2 the determined averaged interface strength $\sigma_{IF_{av}}$ is given. The upper interface (IF) is associated with bending specimen 1 and the lower interface with bending specimen 2 in figure 3. The specimens, which were separated from the material with a Mg ratio of 47 % show moderate averaged interfacial strength values with good correlation to the results of the Rising specimens with eccentric co-extruded initial rods [6], see figure 6. Furthermore, good correlation can be observed to the interfacial strength of bending specimens which were separated from rods which were further processed by free axial and radial upsetting [4]. For the Rising specimens with lower Mg ratio which causes a larger sleeve thickness, the averaged interfacial strength value is much higher (nearly factor 2). This leads to the hypothesis of an increasing interfacial strength by an increasing sleeve thickness in normal direction of the analyzed interface section. The same trend was observed in the investigations given in [6], see figure 6 (the larger the offset, the larger the sleeve thickness on the upper side). Furthermore, the results show lower averaged strength values of the lower interface compared to the upper interface of the Rising specimens (Mg ratio of 29 %). Nevertheless, the strength of this lower interface is on a high level.

Generally, the scattering of the strength values is high (figure 6), which corresponds to the previous investigations regarding these special Al/Mg interfaces [3, 4, 6].

| Mg ratio [%] | Number of bending specimens | Interface | $\sigma_{IF_{av}}$ [MPa] |
|-------------|-----------------------------|-----------|-------------------------|
| 47          | 8                           | upper     | 50                      |
| 29          | 6                           | upper     | 97                      |
|             | 9                           | lower     | 76                      |
4. Summary
Interfacial strength investigations were performed with Al/Mg compounds which were further processed by the forging process Rising. Continuing previous investigations of the research project, Rising specimens with reduced Mg ratio were used (enlarged sleeve thickness at the critical flanks). For strength determination bending tests were performed. Interfacial strength values were calculated using the experimental maximum bending force and the elementary bending theory extended with a correction factor, which was determined by means of a FE model of the load case.

The material with the lowest Mg ratio (largest sleeve thickness) showed the highest level of interfacial strength. Furthermore, the interfacial strength of the lower interface of this configuration is lower but on a high level as well. In case of the material with Mg ratio of 47 % good correlation to the previous results can be observed. The scattering of the strength values is high. In further investigations concerning the interfacial strength, bending specimens of the initial rods of the configurations of [6] and of the Rising specimens presented in this paper will be analyzed.

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