Manufacturing Al/Mg composite materials

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Abstract

The manufacturing of innovative lightweight materials and their further processing by forming allows functional dimensioning of components in addition to lightweight design. Accordingly, workpieces can be produced that have locally differing component properties. The new lateral extrusion process of composites produces near net shape lightweight composites. This process application is particularly useful when producing corrosion-resistant Al/Mg composites since it facilitates combining the favorable strength/weight ratio of magnesium with the favorable corrosion behavior of aluminum. The composite interface area is of specific significance in this respect. The presented method initiates diffusion processes with phase reformation to obtain a firmly-bonded metal joint.

Keywords

Al/Mg composite materials, interface formation, encapsulating lateral extrusion

1 INTRODUCTION

The growing need for energy-efficient mobility requires the consistent implementation of lightweight construction principles. An effective measure to achieve this objective is the use of new materials if comparable component properties can be ensured at low weights. Magnesium alloys are particularly suitable as lightweight construction materials due to their excellent strength/weight ratio. However, the high susceptibility of these materials to corrosion prevents their widespread use in vehicle manufacturing. Corrosion-resistant metal coating systems provide effective protection against corrosion attacks. Two or multilayer composites with layer thicknesses up to several millimeters depending on requirements can only be achieved by mechanical processes. The best known processes applied in technology are roll or explosion cladding and extrusion / extrusion molding. Unlike other coating techniques in which targeted modification of material and functional properties remains limited to sections close to the surface, these processes allow the manufacture of structure-optimized semi-finished products. In addition to lightweight construction, further processing of such light metal composites by forming allows load-adequate dimensioning of components. In the field of composite manufacturing, the strive to produce near net shape components while reducing the number of manufacturing stages at the same time results in the development of novel processes, such as lateral extrusion. Using this process, geometries with rotating flanges or multiform secondary shaped elements molded transversely to the component axis can be produced as composite components with adjusted functional properties.

The interface is of special significance when manufacturing composites by forming. A joint with adequate strength can only be expected if substance transport across phase interface can be initiated between the two materials of the composite so that there is a predominantly firmly-bonded joint. The findings of our studies on lateral extrusion of composites presented below will show that such a bond is possible between aluminum (FCC lattice) and magnesium (HCP lattice) despite the different lattice structures. For example, the formation of a pronounced diffusion zone between an AZ31 magnesium forging alloy and a standard EN AW 6060 aluminum alloy could be proven under specific technological conditions.

2 DESCRIPTION AND APPLICATIONS OF THE LATERAL EXTRUSION PROCESS FOR COMPOSITES

The lateral extrusion process for composites facilitates the manufacture of metal composite components according to design principles that are typical of lateral extrusion. The two applications or component embodiments described below can be distinguished based on the build-up of layers that can be produced.

Variation 1 – Encapsulating lateral extrusion of composites

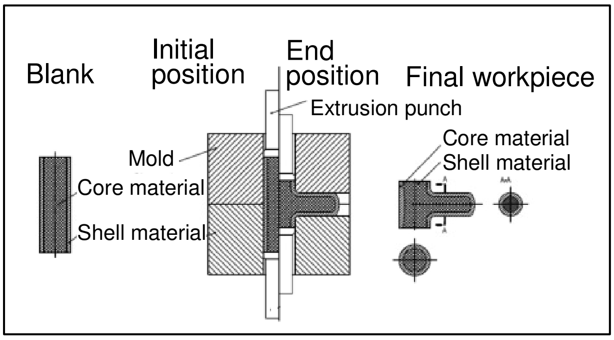


Figure 1: Principle of the encapsulating lateral extrusion process for composites (variation 1)

In this process variation, workpieces can be produced from one material that is almost completely clad with another or several other materials (Figure 1). The initial slug preferably is a cylindrical two- or multi-layer semi-finished product. The metal layers are arranged concentrically as shown in Figure 1. The slug is pressed into the die using a lateral extrusion tool by applying pressure. Figure 1 shows the principle of the process as an example of molding a cylindrical secondary shaped element onto an encapsulated composite material.

Variation 2 – Layered lateral extrusion of composites

This process allows the combination of two or more materials in such a way that a layered structure is obtained. The slugs in this process preferably are two or more cylindrical rod sections made of a material combination that is suitable for the respective application (Figure 2). These are also formed under pressure using the tool system described for Variation 1 (Figure 2).

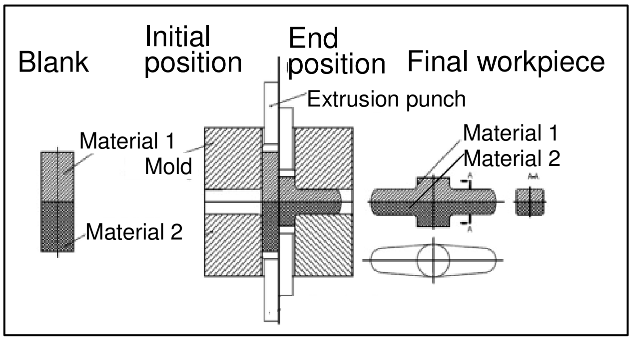


Figure 2: Principle of the layered lateral extrusion process for composites (variation 2)

The paper presents the work and results of experiments based on a variation 2 test set-up. They allow for more basic insights and are the preliminary for future investigation of test set-up based on variation 1.

The material combination used for the manufacture of a composite by lateral extrusion has to meet the following basic demands:

- Materials with sufficient plastic deformability
- Individual components with similar flowing behavior
- Meet the chemical and physical condition for diffusion in a solid state

Lateral extrusion allows the manufacture of components with adjusted material and functional properties. Near net shape workpieces can be produced that have locally differing component properties. This process application is particularly useful when producing high-strength corrosion-resistant Al/Mg composites since it helps to combine the favorable strength/weight ratio of magnesium with the favorable corrosion behavior of aluminum.

Vehicle construction can be viewed as a promising future application for the encapsulating lateral extrusion of composites. In addition to vehicle manufacturing and mechanical engineering, significant fields of application for the lateral extrusion of composites include:

- aerospace industry
- electrical and power engineering
- sports equipment and leisure industry.

3 STUDIES ON INTERFACE FORMATION

Previous research results confirm that the chemical prerequisites for diffusion in the solid phase are met in an aluminum/magnesium pairing [1] [2]. Normally, substance transport across phase interface is possible only if the system is comprised of a series of mixed crystals. In addition to this elementary condition, the diffusion process is influenced by a multitude of external factors that must be quantified for a target-oriented influencing of bonding mechanisms. This becomes feasible only if process-specific parameter fields can be transformed into differentiated quantitative models. The greatest advantage as compared to the common process-oriented view is the general applicability of the expertise gained. Such an approach requires a sophisticated description of the factors acting locally within the interface by means of measurable variables.

Besides chemical prerequisites, the following restrictions are decisive for initiating a solid-state reaction: an almost "ideal" contact between the reactants, a high degree of disorder in the lattice structure, and supply of an amount of energy (the so-called threshold energy) [3]. Controlled influencing of technological parameters that allow maximum interface area increase under high compressive normal stresses is therefore fundamental for producing composites by forming. The newly formed surface breaks open diffusion-reducing oxide and adsorption layers, dramatically increases the number of atomic disorders and promotes the required approximation of the contact materials. Another decisive factor is the forming temperature that determines the flow behavior of the composite components and provides the required amount of energy for activating the substance transport.

The aim of this study was to develop an experimental setup that implements the creation of a composite material in a way that allows a variation of defined parameters and thus the interpretation of microstructural changes in the boundary layer. The more basic method of layered lateral extrusion process is better suited for this study, since the interface evolves as a plane surface and thus allows much easier control of parameters in the tests as well as a two-dimensional model in idealized mathematical description of surface evolution.

In order to link the composite formation to the forming process a FE model was created. Forming process characteristics such as temperature distribution, local surface enlargement and normal stresses were described and analyzed with respect to their effect on composite formation.

The verification of the resulting composites has been completed by a microstructure analysis of the boundary layer and the determination of the bond strength in shear test.

3.1 Test arrangement for producing composites

The test arrangement described below (Figure 3) established the preconditions for ascertaining interface reactions between aluminum and magnesium under forming conditions [1]. The test arrangement is based on the process principle of lateral extrusion. The aluminum or magnesium specimen are in heatable mold halves and they are formed by two punches moving towards each other so that a pressing process is developing.

The mould halves are mounted between two spring stacks and are moved along such that they are in the middle between the two punches, if the forming conditions are the same for the two specimen in each mold. Under this precondition a symmetrical plane of division and a composite specimen with a pin offset by 180° is created. In this case the boundary layer between the materials is in the die parting line.

Differing deformation ratios in under- and upper tool, for example caused by different flow properties (flow stress) of the composite partners can lead to a difference in the forming start of the two materials. In this case the boundary layer is not in the parting line of the die and the pins are formed asymmetrically.

The tool has a temperature control system with an overall heating power of 1,500 W for maintaining the mold temperature. In addition to the mold temperature υ_M, the test arrangement allows a defined variation of the relative formation rate of the newly formed surface area ε_A, the compressive stress in the interface σ, and the forming speed dφ/dt. The applied plunger force as a function of forming path can be measured using a piezo crystal load cell and a cable-operated sensor.

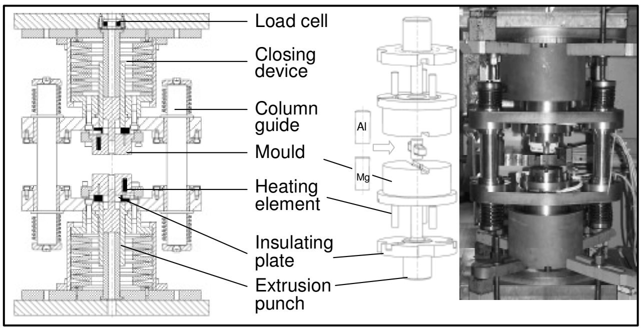


Figure 3: Test arrangement for generating and analyzing the interface between aluminum and magnesium

The aluminum and magnesium specimen were prepared by machining of commercially extruded material bars. The face planes of the specimen were turned and, at a surface roughness of R_z = 6.3 µm, no further mechanical pre-treatments were carried out. Before the start of the experiment the aluminium alloy AlMgSi1 was subjected to solid-solution heat treatment (530°C / 60 min / cold water quenching).

Studies of the microstructure and of the interface as well as the determination of the mechanical properties were conducted with specimens manufactured under the following test conditions:

- Material pairing: AZ31 / AlMgSi1
- Specimen geometry: Ø 19.7 mm x 42 mm
- Specimen temperature υ_P: 450°C
- Mold temperature υ_M: 300°C
- Pin cross section: 14x15 mm²
- Plunger speed: const. 5 mm/s
- Forming press kinematic: position controlled

To determine deviations from the technological test conditions, the plunger forces of every fifth test were evaluated within the test series. The shapes of force-displacement curves displayed in Figure 4 vary only slightly, i.e. significant deviations in the test conditions can be excluded.

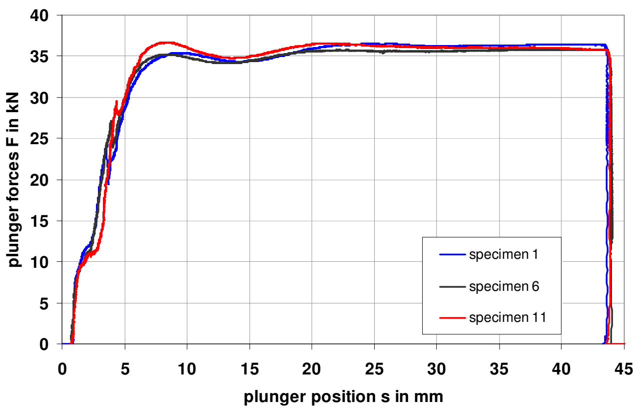


Figure 4: Plunger force determined during the lateral extrusion of an Al/Mg composite

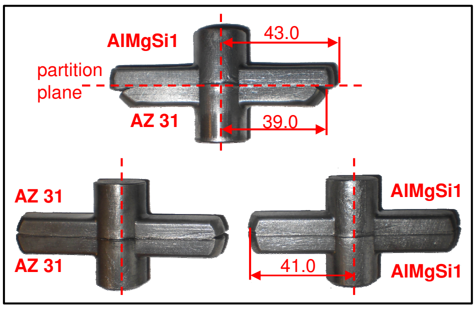


Figure 5: Composite specimens with different material pairing

Figure 5 shows an exemplary composite specimen for the test series. It shows an asymmetrical shape of the pins that is typical of this material combination under the test conditions described. The reason for this are the different yield stresses of the two materials at the beginning of the process resulting in the premature plasticizing of wrought aluminum alloy and thus the 'advancing' of the aluminum. This becomes clear from the specimens in Figure 5 showing two reference specimens (AZ31-AZ31; AlMgSi1-AlMgSi1) for comparison. Here, the pins were formed symmetrically due to matching yield stresses.

3.2 Analysis of the test conditions using FEM

The process described was modeled in the FEM simulation systems FORGE, version 2008, and simufact.forming.SFM, version 8.1. The design data of the test facility provided the basis for the simulation model with rigid tools. The elastic deformation of the active parts and the generation of a temperature field within the tools were not taken into account. The simplification regarding the temperature build-up appears justified due to the fact that both the mold and the workpiece are kept at forming temperature by a temperature control system. A material description according to Hensel, Spittel was selected in view of the variable material behavior during the forming process. This provided an opportunity to analytically describe the flow behavior of the materials as it is influenced by temperature, forming degree, and forming speed. It was proven based on geometrical characteristics such as pin length, length of dead zone, and material advance that the simulation result and the real forming process match. In addition, the process forces were adjusted. Selected results of the various simulation runs are presented below; knowledge of these results helps considerably in understanding the conditions that prevail in the interface when the composite is formed [4].

- A continuously growing comparative forming degree was found that assumes the value φ_V = 4.6 until the pins are fully molded. (Figure 6, right)
- At an initial tool and sample temperature of 350°C and a punch speed of 2.5 mm/s, the temperature increase due to the forming process is 10 K (Figure 6, left). When the traversing rate drops to 1.0 mm/s, the heat input decreases to 5 K. When the specimen temperature (450°C) is clearly higher than the tool temperature (350°C), the temperature in the forming zone drops (420°C).
- In the forming zone, the normal stresses between the composite partners range from 130 N/mm² to 180 N/mm².
- The aluminum alloy exits from the forming zone first as the forming tests show. The outlet speed is 3.8 mm/s.

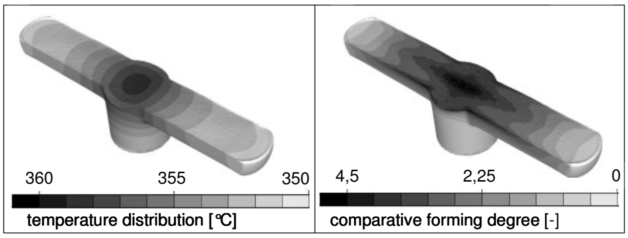


Figure 6: Temperature distribution (left) and comparative forming degree (right) in the interface during lateral extrusion of composites [4]

3.3 Characterization of the interface

3.3.1 Analysis of the microstructure

The SEM image confirms that a homogeneous interface is formed between magnesium and aluminum under the test conditions described (Figure 7, top). The electron contrast in backscattering mode (BSE) shows that the interface is formed at a width of less than 2 µm by two phases. The different composition of the interface could be confirmed using an overlay mapping (two-dimensional element concentration distribution) of the elements aluminum and magnesium (Figure 7, middle). The composition consists of an aluminum-rich and a magnesium-rich phase at a width ratio of two to one. The grid parameters were determined using X-ray diffraction analysis (XRDA) for unambiguous identification of phases. The interface thus consists of the body-centered cubic $Al_{12}Mg_{17}$ and the face-centered cubic Al_3Mg_2 phases (Figure 7, bottom). These are two intermetallic phases that are known from the aluminum-magnesium two-material system. [1]

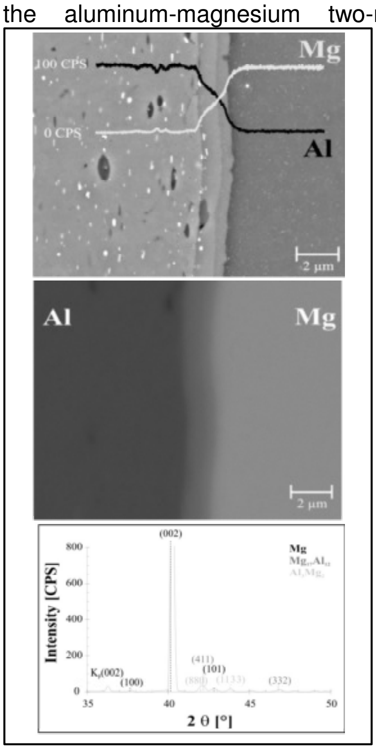


Figure 7: Microstructure of the interface: SEM image of the interface showing the element distribution in percent by weight (top); EDX analysis in mapping mode (middle); X-ray diffraction analysis (XRDA) with identified interface phases Mg17Al12 and Al3Mg2 (bottom) [1]

3.3.2 Analysis of mechanical properties

A special test arrangement was designed to determine the mechanical properties of the Al/Mg composite enabling the application of a tangential load to the interface by an outer force F (Figure 8). The sample was taken from the middle of the formed composite specimen with a sample length a=15mm and sample high b=15mm.

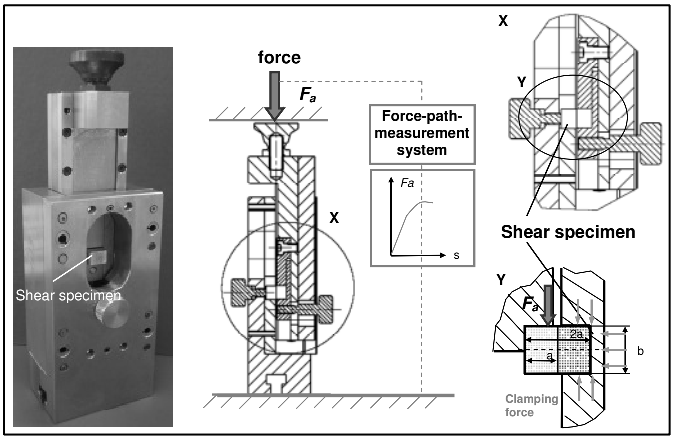


Figure 8: Testing device for experimental identification of the compound strength (shear-tension test); left side: device with shear specimen; right side: schematic visualization of the test design.

The induced load is in correspondence with the norm DIN EN ISO 14273 applicable as shear-tension tests. Characteristic of the mechanical properties of the composite, therefore, is the experimentally determined compound strength τ_V. The strength τ_V corresponds to the external force strength F_a per unit of geometric area A_g of the boundary layer, at which value the failure of the bond occurs (equation 1).

$$\tau_V = \frac{F_a}{A_g} \qquad \text{equation 1}$$

A value for the real strength of the bond, termed adhesion strength τ_H, which is calculated as inherent force F_i per real bond area A_w (equation 2), can not be determined experimentally.

$$\tau_H = \frac{F_i}{A_w} \qquad \text{equation 2}$$

Thus, the experimental set-up only allows a comparative study of the experimentally accessible compound strength, requiring constant test conditions.

Crucial for the comparative assessment of the composite sample is therefore the maintenance of constant experimental conditions.

The specimen is kept in position by a clamping jaw which fastens the specimen in vertical position and a fastener which prevents a tilting of the specimen in horizontal direction. Thus the clamping conditions were kept constant for all samples.

The shear samples were taken axisymmetrically as shown in Figure 9 (left), i.e. the interface was situated in the symmetrical plane of the shear samples. In order to determine the composite strength until fracture, the samples were subject to a continuously increasing test force. The force was increased at a constant test speed of 1 mm/s. The result of the shear test was a force-displacement curve characteristic of the mechanical properties of the composite material (Figure 9, right). The evaluation of shear displacement at fracture point and the maximum test force at this point allows predictions on the formability and composite strength of the composite material. Maximum shear forces F_{amax} up to 20 kN have been observed at a shear distance s_B of 2.0 mm.

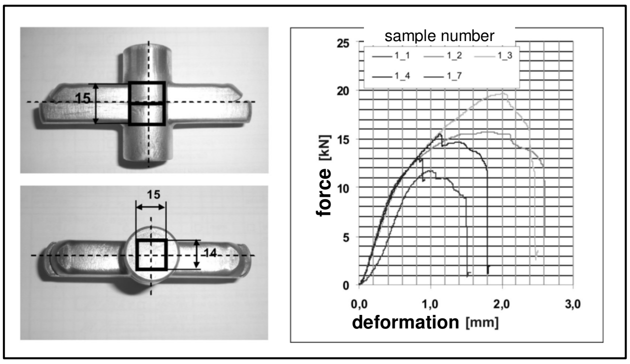
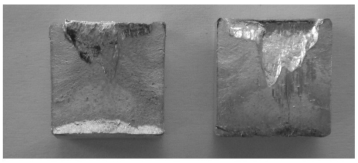


Figure 9: Position of shear sample in the laterally extruded Al/Mg composite (left); shear test force-displacement curves (right)

The boundary layer is characterized by a brittle deformation behavior [1], but the determined values also contain a ductile component, caused by fracture sections partially in the base metal due to non-ideal boundary layer evenness and symmetricality (Figure 10).



sample number:	1_3
shear force $F_{a\,max}$:	20 kN
position at fracture s_B:	2.0 mm
compound strength τ_V:	93 N/mm²

Figure 10: Surfaces of a sheared sample

Very high composite strengths of up to 93 N/mm² were determined. These, however, are below the theoretical shear strength of AlMgSi1 with τ_B = 210 N/mm² and AZ31 with τ_B = 130 N/mm² [5] [6]

4 CONCLUSIONS

Lateral extrusion of composites is a process that allows the near net shape manufacture of structure-optimized components in accordance with the typical design directives of lateral extrusion. A major field of application for this new method is the manufacture of steering system parts. A firmly-bonded joint is required to ensure sufficient bonding strength in the composite. The findings of our lateral extrusion of composites studies show that the substance transport across the phase boundary is possible. Phase reformation in the interface area of the composite specimen as a result of diffusion processes was proven using SEM and XRDA analyses. The bond strength of the composite was tested in a specially designed test facility. Further studies will focus on the systematic variation of individual parameters to study their influence on the microstructure and facilitate the controlled setting of desired composite properties.

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