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The original version of this article supplied to AIP Publishing contained an error in the press ratio. In the experimental procedure of the manuscript, the following sentence was incorrect: “With a diameter of 55 mm for the aluminium billet, 15.2 mm for the steel rod and an opening diameter of 28 mm for the die, the press ratio equalled 9:1.” “9:1” is incorrect. The correct ratio is “6:1”. (For the calculation of the press ratio, an opening die diameter of 25 mm was assumed by mistake. This resulted in miscalculated press ratio of 9:1. For the used die with an opening diameter of 28 mm the correct press ratio equals to 6:1.). This has been corrected in the revised version published on 23 February 2018.

Co-Extrusion of Semi-Finished Aluminium-Steel Compounds

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Abstract. The combination of light metals and steels allows for new lightweight components with wear-resistant functional surfaces. Within the Collaborative Research Centre 1153 novel process chains are developed for the manufacture of such hybrid components. Here, the production process of a hybrid bearing bushing made of the aluminium alloy EN AW-6082 and the case-hardened steel 20MnCr5 is developed. Hybrid semi-finished products are an attractive alternative to conventional ones resulting from massive forming processes where the individual components are joined after the forming process. The actual hybrid semi-finished products were manufactured using a lateral angular co-extrusion (LACE) process. The bearing bushings are subsequently produced by die forging. In the present study, a tool concept for the LACE process is described, which renders the continuous joining of a steel rod with an aluminium tube possible. During the LACE process, the rod is fed into the extrusion die at an angle of approx. 90°. Metallographic analysis of the hybrid profile showed that the mechanical bonding between the different materials begins about 75 mm after the edge of the aluminium sheath. In order to improve the bonding strength, the steel rod is to be preheated during extrusion. Systematic investigations using a dilatometer, considering the maximum possible co-extrusion process parameters, were carried out. The variable parameters for the dilatometer experiments were determined by numerical simulation. In order to form a bond between the materials, the oxide layer needs to be disrupted during the co-extrusion process. In an attempt to better understand this effect, a modified sample geometry with chamfered steel was developed for the dilatometer experiments. The influence of the process parameters on the formation of the intermetallic phase at the interface was analysed by scanning electron microscopy and X-ray diffraction.

INTRODUCTION AND MOTIVATION

Nowadays, technical components must comply with a variety of technical requirements such as low weight, compact design, enhanced functionality or increased life-time in order to create more efficient products. Given the individual material properties, these requirements can often no longer be met by mono-material components produced by conventional production processes. Clearly, one promising approach to enhance product quality is to combine different materials, locally adapted to the demands of the product. In this way, the different material properties such

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as high mechanical strength, enhanced wear resistance, or low density can be exploited.

The overarching goal of the Collaborative Research Centre 1153 is the development of novel process chains for the production of hybrid solid components by “Tailored Forming”. In conventional manufacturing processes for hybrid components, the materials are joined during or after the forming process. By contrast, Tailored Forming will lead to hybrid components using semi-finished products consisting of two or more different materials joined prior to the main forming process. The process chain discussed in this study begins with a lateral angular co-extrusion (LACE) process [1] to combine the aluminium alloy EN AW-6082 and the case-hardening steel 20MnCr5 (Fig. 1). A subsequent die forging process will form the hybrid bearing bushing with a wear-resistant sliding surface, which will be then finished by machining. In order to achieve the overall goal, the process chain needs to be framed by design, construction, simulation and quality control steps [2].

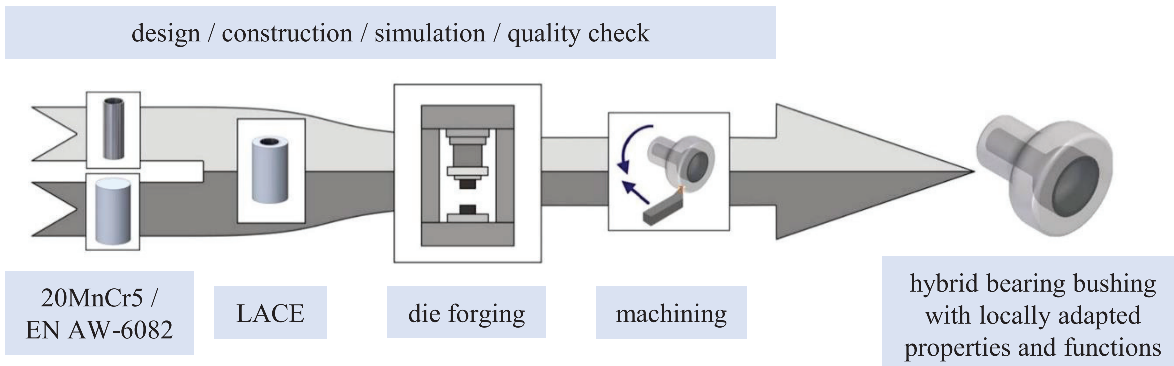


FIGURE 1. Novel process chain to manufacture a hybrid bearing bushing consisting of aluminium and steel, starting with a LACE process, followed by subsequent die forging and machining processes [2]

The production of metallic composite materials via co-extrusion has been the subject of intensive research for several decades. In general, there are two different process variants of co-extrusion. On the one hand, the reinforcing elements can be integrated within the extrusion billet. Thus, by extrusion of the reinforced billet both the matrix material and reinforcement will be formed [3]. On the other hand, the reinforcing element, e.g. steel-wires, can be fed from outside the die into the deformation zone [4]. Here, only the matrix material is plastically deformed and the reinforcement remains essentially unchanged. In a related study, a modified equal channel angular pressing process, which was termed “LACE”, enabled the co-extrusion of asymmetric aluminium-titanium compound profiles. Specifically, a titanium profile was fed laterally at an angle of 90° to the deformation zone. The aluminium was extruded perpendicular to the titanium profile and redirected inside the tool in order to produce an asymmetric compound profile [5]. In the present paper, the production of coaxial hybrid semi-finished compounds consisting of aluminium and steel using LACE is presented.

EXPERIMENTAL PROCEDURE

The objective of this investigation was the development of a process for the production of coaxial aluminium-steel compound profiles with a central continuous steel reinforcing element. For the determination of suitable process parameters, 20MnCr5 steel rods were used to facilitate the initial extrusion experiments, which were performed using a laboratory extrusion press with a maximum press force of 2.5 MN (Müller engineering). The tool concept for the determination of the process parameters is shown in Fig. 2. The tool enabled extrusion of the aluminium alloy EN AW-6082 at an angle of 90° between the punch direction and the profile’s exit port. This allowed for a continuous feed of the steel rods into the welding chamber, with the movement of the steel rod being caused only by the friction between steel and aluminium. With a diameter of 55 mm for the aluminium billet, 15.2 mm for the steel rod and an opening diameter of 28 mm for the die, the press ratio equalled 6:1. A supporting channel inside the tool prevented tilting of the steel rod during feeding.

The chemical composition of the materials employed in the present study were analysed via spark spectrometry (Spectromaxx from Spectro). The results obtained are summarised in Tables 1 and 2. The billets and the extrusion block were preheated to 500 °C for 2 h and the temperature of the steel rod equalled room temperature at the beginning of each experiment. The die and the container were also preheated to 500 °C. A ram speed of 0.5 mm/s was used during the experiments.

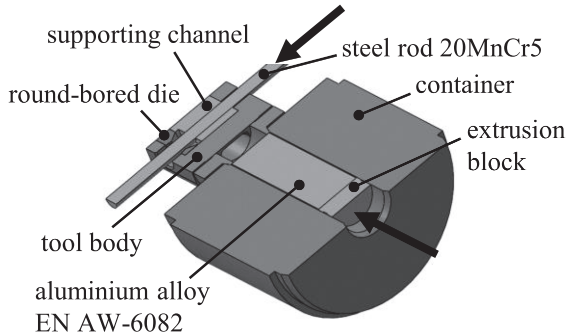


FIGURE 2. Schematic sectional view of the LACE process with a redirection of the aluminium alloy by an angle of 90°

TABLE 1. Chemical composition of the aluminium alloy EN AW-6082 in wt.-%

Material	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
EN AW-6082	1.34 ± 0.005	0.20 ± 0.006	0.06 ± 0.001	0.77 ± 0.003	0.91 ± 0.008	0.02 ± 0.0003	0.13 ± 0.0008	0.23 ± 0.0009

TABLE 2. Chemical composition of the steel 20MnCr5 in wt.-%

Material	C	Si	Mn	Cr	S
20MnCr5	0.21 ± 0.008	0.25 ± 0.002	1.19 ± 0.01	1.11 ± 0.006	0.03 ± 0.002

Joining of aluminium and steel at elevated temperatures can lead to intermetallic phases. The formation of intermetallic phases in compound forging of steel-aluminium composites and their dependence on the process parameters was investigated in different studies [6, 7]. As intermetallic phases have a great impact on the mechanical properties and the quality of the aluminium-steel joint [8], experimental investigations were carried out on a quenching dilatometer DIL 805A/D+T (TA Instruments) in order to determine the influence of the process parameters on the development of intermetallic phases in the joining zone. The experimental setup of these investigations is schematically shown in Fig. 3 (a). In order to analyse and quantify the development of intermetallic phases in the described co-extrusion process, aluminium and steel specimens were compressed considering various relevant boundary conditions of the process such as temperature, pressure, and holding time. Two steel cylinders with an aluminium cylinder at the centre were heated up by inductive heating and then pressed with a defined constant force. After a given period of time, the specimens were quenched with nitrogen. A steel sleeve was used to obtain higher stresses than the yield stress of aluminium. First investigations showed the presence of an aluminium oxide layer between the deformed aluminium and the steel cylinder, but no intermetallic phases were detected. Thus, an elimination of the oxide layer was performed using modified geometries in the subsequent experiments (Fig. 3 (b) and (c)). With these modified geometries, the aluminium oxide layer is sheared off because of the large deformation of the aluminium, which resemble the conditions present in the LACE process.

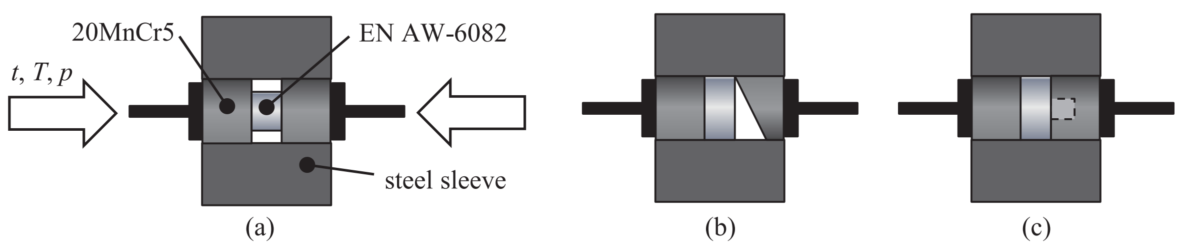


FIGURE 3. Schematic of dilatometer tests using different steel specimens, (a) cylindrical, (b) chamfered, (c) bored

The parameters for these experiments were determined based on numerical simulation because the actual local values like temperature or contact pressure in the welding chamber are difficult and sometimes not possible to determine during the co-extrusion process. Therefore, numerical simulations with different extrusion parameters such as ram speed, temperature, and press ratio were carried out to determine the particular temperature, contact pressure, and contact time between aluminium and steel. For the numerical investigations, the commercial FEA system simufact.forming 13.3.1 was used to simulate the extrusion process. The tools were modelled as rigid components and the flow behaviour of the billet material was defined using the integrated material database of simufact.forming. As a first approach, the steel rod was modelled as a rigid-body with heat flow in order to reduce computation time. Because of the symmetry, only one-half of the objects was modelled.

The initial billet temperature and the temperature of the tool were varied between 480 °C and 560 °C, while the ram displacement was varied between 0.3 mm/s and 1 mm/s. For the description of the frictional behaviour between the billet and the tool, the constant shear model (Tresca's friction model) was used. A friction factor of 0.8 was chosen between the billet and the tool according to literature [9]. For the co-extrusion parameters examined, contact pressures between 140 MPa and 400 MPa, aluminium temperatures between 390 °C and 460 °C, and contact durations from 3 s to 18 s were obtained. In the initial experimental trials, the maximum possible set of parameters was employed. Therefore, a temperature of 540 °C and a compressive force of 5890 N were used in the dilatometer experiments shown in this study. The holding time and the heating time were each chosen to be 240 s to ensure a uniform heating of aluminium and steel during the experiment.

For the microstructural investigations, the specimens from the dilatometer experiments as well as samples taken from the hybrid profile using wire-cut electrical discharge machining were prepared metallographically normal to their longitudinal axis and the cross section, respectively. The interface was analysed by scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDS) using a Supra 40VP from Zeiss. Images were recorded using secondary and backscattered electrons. X-ray diffraction (XRD) was performed with a D8 Discover featuring a Våntec 500 2D-detector from Bruker AXS using CoK_α radiation (35 mA, 45 kV). For the measured profiles, a scan range of 40° 2θ to 115 ° 2θ, an increment of 15° and a scan time per step of 120 s was chosen. The analysis was performed using the crystallographic database PDF2-2010.

RESULTS AND DISCUSSION

A hybrid semi-finished profile was manufactured using the LACE process (Fig. 2). The relative movements between aluminium and steel resulted in a strong contact of the steel rod's surface with the extruded aluminium alloy. The aluminium profile was extruded to a total length of 540 mm and an outer diameter of 28 mm, enclosing the steel rod in the profile, which had a diameter of 15.2 mm. Examinations of the bonding area were conducted using cross sections from the hybrid profile. Light microscopy showed a gap between the different materials at the front end of the profile. This gap was no longer detectable macroscopically after a distance of 75 mm from the front end of the aluminium profile. This position as well as the extrusion direction are marked in Fig. 4.

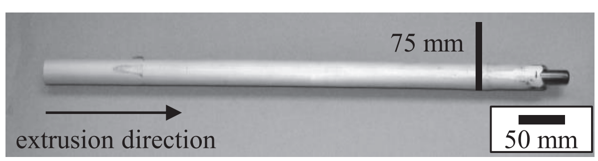
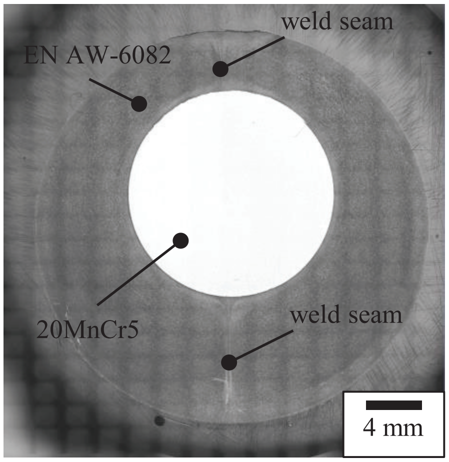
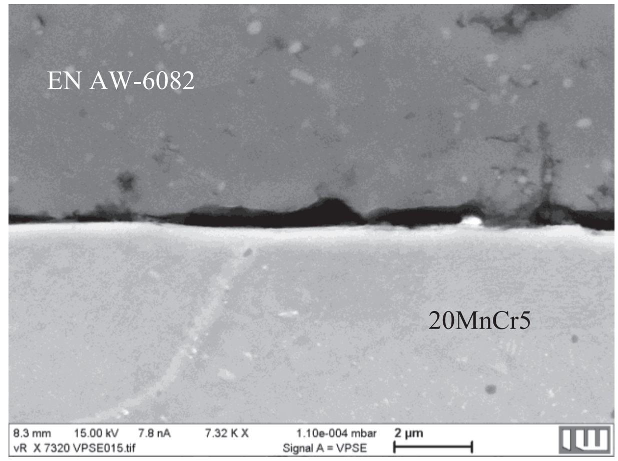


FIGURE 4. Co-extruded aluminium steel profile with a total diameter of 28 mm and a total aluminium length of 540 mm

As shown in Fig. 5 (a), the steel reinforcement was not positioned truly coaxial inside the profile due to its loose fit in the support. However, the supporting channel successfully prevented tilting of the rod in the die. The position of the longitudinal weld seam was determined using a H_2SO_4/HF etching solution. In the initial segment of the hybrid profile the weld seam was displaced, which may be caused by an uneven aluminium flow during the filling of the die. The displacement of the weld seam decreased during the extrusion process, resulting in a completely symmetric position after about 75 mm of extruded aluminium, as shown in Fig. 5 (a). While the bond between aluminium and steel appeared fully closed in the light optical investigations, a small gap of up to 400 nm could still be detected in the SEM after a profile length of 390 mm (Fig. 5 (b)).



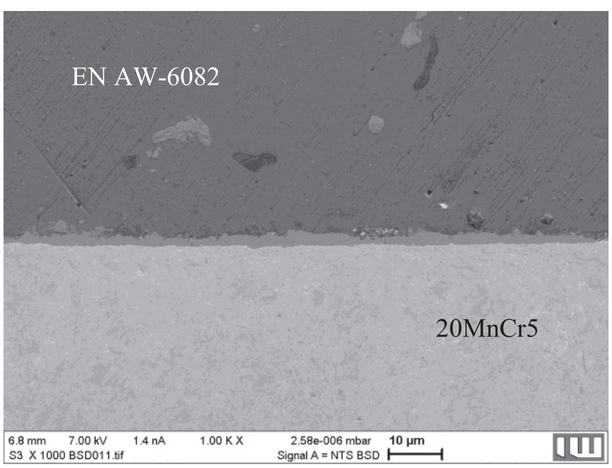
(a)



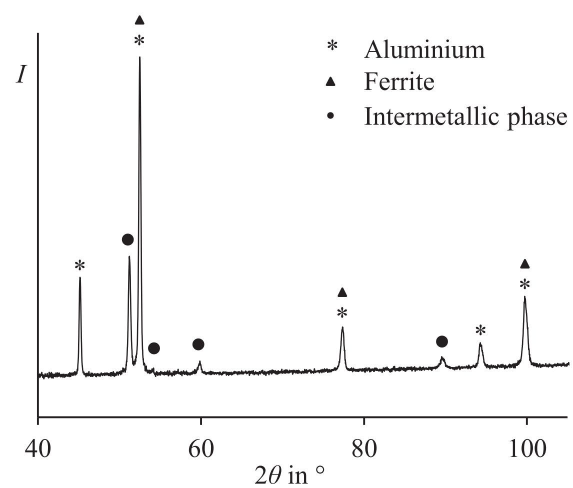
(b)

FIGURE 5. (a) Light optical image of the cross section after a profile length of 75 mm; (b) SEM image of the interface between EN AW-6082 and 20MnCr5 after an aluminium length of 390 mm

In order to create a metallurgical bond between both materials it seems necessary to heat the steel rod in future extrusion experiments. In order to validate this assumption, experiments with a quenching dilatometer were performed using a material temperature of 540 °C and a compressive force of 5890 N. The results of these experiments conducted in the dilatometer are displayed in Fig. 6, exemplarily for the chamfered specimen (Fig. 3 b)). As shown in Fig. 6 (a) an intermetallic phase with a thickness between 2 µm and 7 µm was detected in the SEM using the backscattered electron detector (BSD). The XRD profile (Fig. 6 (b)) fits with the patterns of aluminium (PDF 00-003-0932) and ferrite (PDF 03-065-4899) [10]. The additional peaks at 50°, 54°, 60° and 90° 2θ indicated an Al_xFe phase (PDF 00-001-1265). The corresponding EDS analysis revealed an atomic ratio of 3:1 between aluminium and iron in the intermetallic phase seam, which suggests the presence of an Al_3Fe phase. As mentioned in [11], this brittle intermetallic phase should be rather thin in order not to degrade the bond at the interface. For the envisaged application, this is of paramount importance, as the hybrid needs to withstand the subsequent die forging.



(a)



(b)

FIGURE 6. Aluminium (EN AW-6082) and steel (20MnCr5) dilatometer specimen compressed for 240 s at 540 °C with 5890 N; (a) BSD image of the interface; (b) XRD pattern of the interface with main peaks for aluminium and steel and additional peaks from an intermetallic phase

SUMMARY AND OUTLOOK

Based on the results presented in this study, the following conclusions can be drawn:

- The break-up of the initial oxide layer present on the aluminium is required in order to establish a firm bond to the steel as demonstrated in dilatometer experiments.
- After an extrusion of 75 mm of aluminium, the interface of the hybrid profile appeared macroscopically fully closed. However, a gap of about 400 nm could still be detected in the SEM further along the length of the profile.
- Dilatometer experiments demonstrated that pre-heating of the steel seems to be a viable approach to enhance the bonding between aluminium and steel during the LACE process.
- SEM analysis revealed that an intermetallic phase with a thickness of 2 µm up to 7 µm can be established under suitable process conditions in the dilatometer experiments. EDS and XRD analysis suggest that this phase is Al_3Fe phase.

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