INFLUENCING THE MECHANICAL PROPERTIES OF PRE-JOINED HYBRID SEMI-FINISHED PRODUCTS BY IMPACT EXTRUSION

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Abstract

Hybrid components are made by combining two or more different materials and used in applications where monolithic components are not suitable due to their limited functionality or performance. Combining steel and aluminium in a technical component for power transmission provides the advantages of locally improved strength and reduced weight. However, the joining zone is critical for the component's performance because of brittle intermetallic phases which may develop. Therefore suitable measures must be taken to achieve a sufficient bond strength. The further forming of pre-joined hybrid semi-finished products allows the joining zone to be positively influenced, both geometrically and mechanically. In this study, components consisting of steel (20MnCr5) and aluminium (EN AW-6082) were first joined by friction welding and formed using three different impact extrusion processes to increase the joint interface area in the compound. In order to evaluate the influence on the bond quality, scanning electron microscope (SEM) images, impact bending tests and tensile tests were carried out. Depending on the adjusted interfacial area enlargements, an influence on the formation of the intermetallic compound and on the mechanical bond strengths could be observed. In contrast to specimens with an unaffected joining zone geometry after forming, those with a developed spherical joining zone and thus an enlarged interface (up to 36 %) achieved higher bond strengths (up to 17 % for tensile load; 42 % for impact load) and were characterised by local joint surfaces without a brittle intermetallic compound.

Keywords: Tailored Forming, friction welding, impact extrusion, bond strength, intermetallic compound

1. INTRODUCTION

Lightweight technology has become increasingly important in various industries such as aerospace or automotive due to the need for improved fuel efficiency and reduced environmental impact. Since monolithic components are limited in their function by the properties of the selected material, other concepts are needed to extend the functional spectrum. The use of different materials in one component enables the adjustment of load-adapted functional areas, which can be designed accordingly depending on the application. With the combination of e. g. steel and aluminium, a weight-reduced component with locally higher-strength and wear-resistant areas can be created. When processing dissimilar materials, an interface is created which generally represents the weak point in the component. Therefore, the main goal is to enhance the joining zone properties with regard to the mechanical strength and emerging intermetallic phase. One possibility is the enlargement of the joining zone interface through optimised material flow. A novel approach for the production of hybrid components with an enlarged joining zone surface is the process chain called Tailored Forming, in which a joint is first created by a suitable joining process such as friction welding and then improved by a further forming step.

2. STATE OF THE ART

There are several approaches to combine dissimilar materials within one component. Some studies investigated joining by forming in order to combine different bulk materials. Liewald et al. experimentally investigated the backward cup extrusion of C15 and EN AW-1050 and achieved sufficient bond qualities by form fitting [1]. Groche et al. focused on the welding process of dissimilar materials by cold extrusion. Although steel is difficult to cold weld, a sound bond could be achieved while the contact normal stress and the interface enlargement surpass particular values [2]. Alternatively, it is possible to add an additional heating step to equalise the yield stresses for better joining zone properties. Wohletz et al. extruded specimens of C15 and EN AW-6082 under elevated temperatures to influence the material flow. The bond strength could be increased at steel temperatures of 600 °C and aluminium temperatures of 200 °C [3].

Whereas in the case of compound forging the joining zone is created through the forging step itself, other approaches aimed to further process the pre-existent joining zone through an additional material flow. The concept of combination and further processing is already widely established as tailored blanks in sheet metal forming [4]. In bulk metal forming, on the other hand, there have only been a few studies on the joining and forming of hybrid materials. Foydl et al. used hot compound extrusion to reinforce aluminium blocks with steel wires. The subsequent die forging of the specimens did not reduce the joining interface quality indicating a good workability [5]. Similar findings were provided by the research of Domblesky et al. in means of friction welding and upsetting of dissimilar material combinations such as aluminium and copper or steel and copper [6].

The pairing of steel and aluminium has a poor welding suitability using conventional welding methods due to the divergent physical properties, which is why suitable joining methods are necessary. A suitable process is rotatory friction welding due to low joining temperatures, which in this case are below the melting temperature of aluminium. Intermetallic compounds (IMC) with a thickness greater than 1 µm significantly reduce the bond strength due to their brittleness in steel and aluminium pairings [7]. Since IMC occur when joining dissimilar materials, it must be ensured that these do not exceed this certain thickness. An increased growth of intermetallic compounds at long friction times and high joining temperatures could be observed in several investigations [8]. At low intermetallic compound thicknesses of about 350 nm, as in the friction welding of AW6061 to AISI 1018 in the study by Taban et al., bond strengths up to 250 MPa could be achieved [9].

Derived from the state of art, this study focuses on the joining zone enlargement of pre-joined steel-aluminium pairings by a subsequent forming step. Different impact extrusion processes such as hollow forward extrusion (HFE), cup backward extrusion (CBE) and cup backward full forward-extrusion (CBFFE) are used in the context of Tailored Forming. The different material flow directions and specimen geometries have an influence on the adjustable surface enlargement in the interface and thus also on the joining zone properties. With the aid of tensile tests and impact bending tests, the mechanical strength and ductility of the joining zone are evaluated. The IMC is an important influencing factor with regard to the joining zone, which is why the properties are examined further using SEM images.

3. PROCESS CHAIN

3.1 Tailored forming

The Tailored Forming process chain enables the production of a functionally adapted hybrid hollow shaft with a lightweight character (**Figure 1**). Higher-loaded areas are made of the high-strength steel alloy 20MnCr5, while the remaining part is made of the age-hardenable aluminium alloy EN AW-6082. The materials are welded together at the end faces in the first step using rotary friction welding. This is followed by either cup backward extrusion (CBE), cup backward full forward extrusion (CBFFE) [10] or hollow forward extrusion (HFE) [10,11] under elevated temperatures to produce a near-net-shape preform, which is then given its functional surfaces by machining.

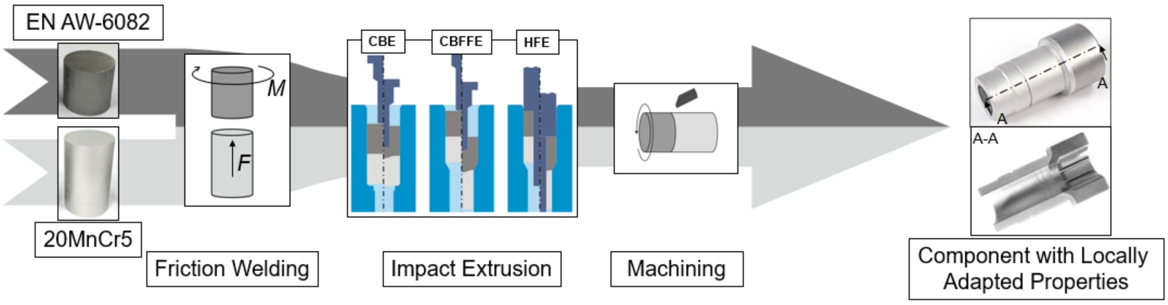

Figure 1 Tailored Forming process chain to create a hybrid hollow shaft

3.2 Friction welding

First, the semi-finished products are joined together in a serial arrangement by rotatory friction welding on the KUKA Genius Plus friction welding machine with parameters chosen according to a previous study [10]. To achieve a defect-free bond, the welding surfaces are machined and cleaned of residues with ethanol. After joining, the samples were then shortened to a length of 72 mm (22 mm steel, 50 mm aluminium) for CBE and CBFFE and a length of 70 mm (35 mm aluminium, 35 mm steel) with an inner diameter of 16 mm for HFE.

3.3 Impact welding

Before impact extrusion, the friction-welded semi-finished product is heated on the steel side with the aid of an inductive heating concept, as in previous investigations [10]. After completion of the heating step, the sample is transferred into the forming tool by an automated robot handling system. Impact extrusion was carried out on a LASCO type SPR 500 screw press with three different forming tools, which are shown schematically in **Figure 1**. The forming forces were measured using strain gauges, to be able to compare the required forming forces. In order to evaluate the influence of the different processes on the IMC and mechanical properties, SEM images, tensile tests and impact bending tests were carried out.

4. RESULTS AND DISCUSSION

4.1 Force and temperature measurements

A suitable induction heating profile with a duration of 22 s for HFE and 25 s for CB(FF)E with a power of 24.2 kW and a frequency of 14 kHz was empirically determined by measurements with thermocouples type K (**Figure 2 a)**). The temperature of the steel rises to about 900 °C within 9 s for HFE respectively 12 s for CB(FF)E and is saturating from that point because the curie temperature is reached. As a result, the magnetic properties worsen, which is why a further 10 s of heating are needed to rise to 950 °C in both cases. The temperature differences after transfer to the forming die are 410 K for CB(FF)E and 500 K for HFE. Due to the different workpiece geometries and the resulting 3 s longer heating time, the aluminium temperature is at 390 °C for CB(FF)E and 50 °C higher compared to HFE (340 °C). An increase in the heating duration was not applied due to too high temperatures in the aluminium and hence the danger of reaching the liquid phase.

Due to different material flow directions and cross sections, the forces vary depending on the process (**Figure 2 b)**). In CBE, only the steel is formed by a punch into a cup with d = 16 mm. This is also the case with CBFFE, but after the cup forming there is also a reduction of the aluminium area from 40 mm to 32 mm, which is why the force curve rises again at 0.11 s and reaches a maximum of 450 kN. Due to the transition to an additional full forward material flow the cross-section to be formed is larger. Therefore, there is a higher force required overall compared to CBE. HFE also reduces the diameter from 40 mm to 32 mm with an additional bore hole of 16 mm and is carried out with a counterpressure of 160 MPa to avoid tensile stresses, which are negligible in the other processes. Since a counterpressure is used and the largest steel and aluminium cross-sections are formed, the process forces are the highest at 875 kN for HFE [11].

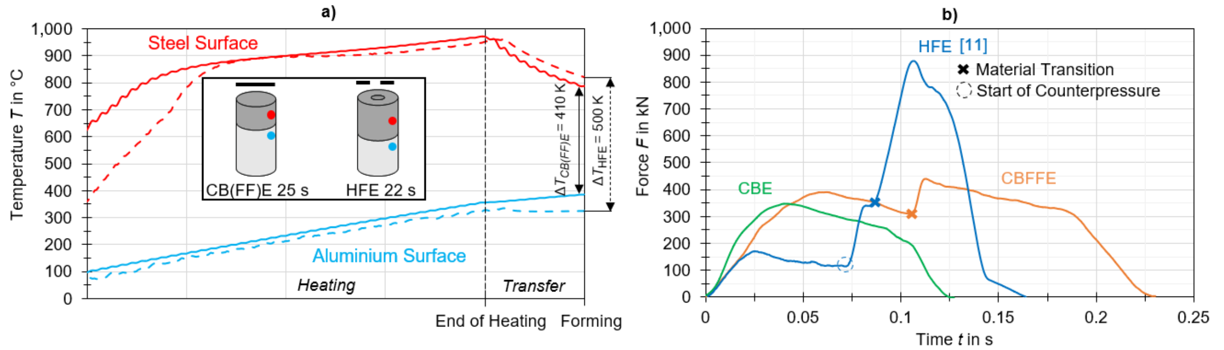

Figure 2 a) Temperature-time-curves during induction heating of semi-finished workpieces, **b)** Force-time-curves of the different impact extrusion processes

4.2 Mechanical tests and SEM imaging

After impact extrusion, the samples were cross-sectioned longitudinally and prepared metallographically for further SEM examinations, which were carried out with a Zeiss Supra VP 55 scanning electron microscope. All samples are characterised by a homogeneous IMC at the edge (**Figure 3**, area 1). Compared to the other two processes with an IMC thickness of 600 nm to 1 µm, HFE specimens have a smaller IMC thickness of 400 to 600 nm. This may be due to the sample geometry. For both CBE and CBFFE, the bonding surface between steel and aluminium before forming is larger compared to HFE due to the lack of an inner diameter, which is why excessive heat input into the joining zone area is beneficial during heating (**Figure 2 a)**). This allows the IMC to grow. For both CBE and CBFFE, the IMC thickness in area 2 is in the range of approx. 900 nm. Compared to a flat joining zone, surface enlargement of approx. 36 % was achieved with CBE and 26% with CBFFE. Due to the higher degree of deformation and the greater surface enlargement the IMC breaks up and is no longer continuous. As a result, the two materials separate and weld to each other locally. The breaking and re-welding of the joining zone results in the formation of local, metallic joints, which can be compared to the tearing of oxide layers, analogous to cold pressure welding [12]. In the centre (**area 3**), no IMC is visible in either of the backward extrusion processes. The material flows from the inner area to the outer peripheral zones. Since the IMC has a low ductility, it tears open in the centre and is carried outwards by the material flow. However, if the surface enlargement is too low, welding of the materials is not guaranteed, which is why defects occur (**Figure 3**, area 3 CBFFE). The specimens were tested under tensile load on the Zwick/Roell Z250 universal testing machine. Both full and hollow test geometries were used in order to be able to compare the hollow and backward processes with each other (**Figure 4**). The geometries were defined based on the final contour of a hollow shaft (**Figure 1**) and modified with corresponding functional surfaces to enable clamping in test adapters. The results of the tensile tests support the aforementioned thesis of local juvenile connections. On the fracture surfaces of the tensile specimens, aluminium attachments can be seen in the areas with larger joining zones and consequently broken IMC. Both in the descending area and in the centre, sound bonds are present for CBE (**Figure 3**), which is why an average component strength of 222 MPa is achieved. With insufficient surface enlargement, the samples show a brittle fracture, which is accompanied by hardly any aluminium attachments. In this case, the joint quality depends heavily on the connection between the brittle IMC and the interface material on each site.

Furthermore, the ductility of the generated components was investigated. Impact bending tests were carried out on the pendulum impact tester PSW-Losenhausen 150 J at room temperature with a sample geometry of 27.5 mm x 5 mm x 5 mm. Specimens, which were extruded by CBFFE, fell apart during preparation. Due to the relatively thick IMC, which is in the range of the critical phase seam thickness of 1 µm [7], and the lower surface enlargement, which was not sufficient for a new formation of juvenile joints, it can be assumed that local defects were present. These were responsible for failure given the small joining zone cross-section of the test specimens. However, when comparing the two processes HFE and CBE, despite large deviations an improvement of the ductility from 56 to 75 J due to the surface enlargement can also be seen (**Figure 4**).

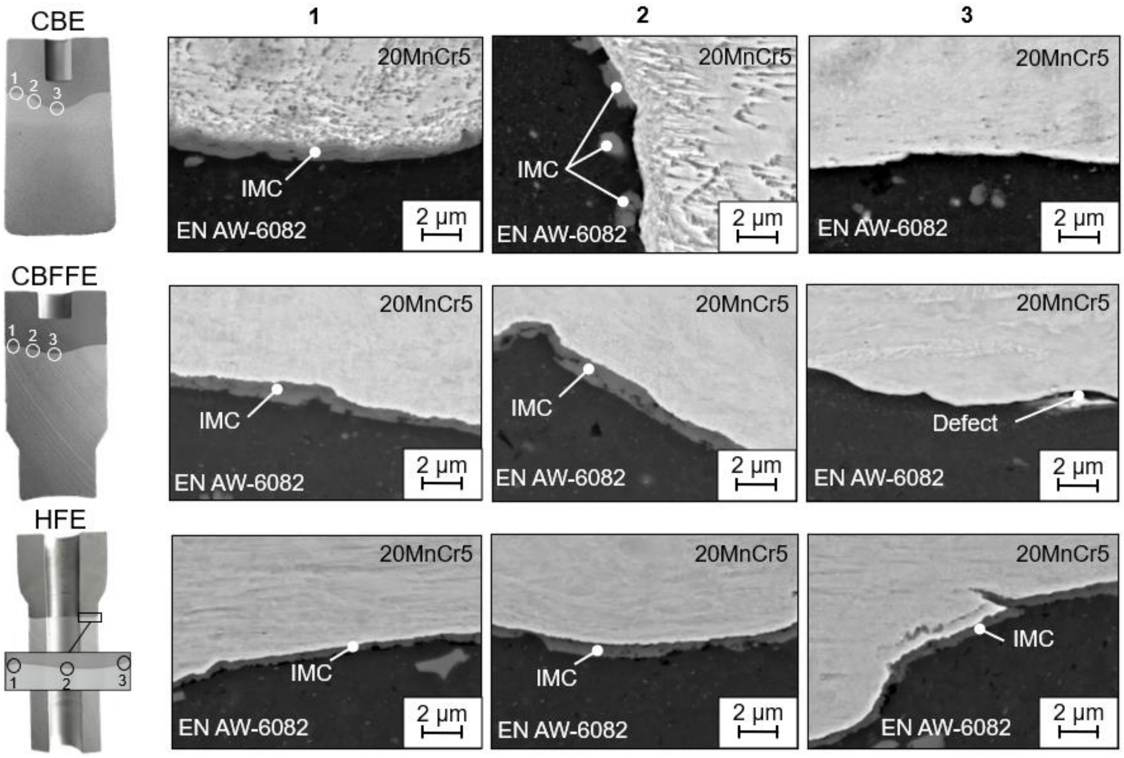

Figure 3 SEM Images of cross-sectioned specimens

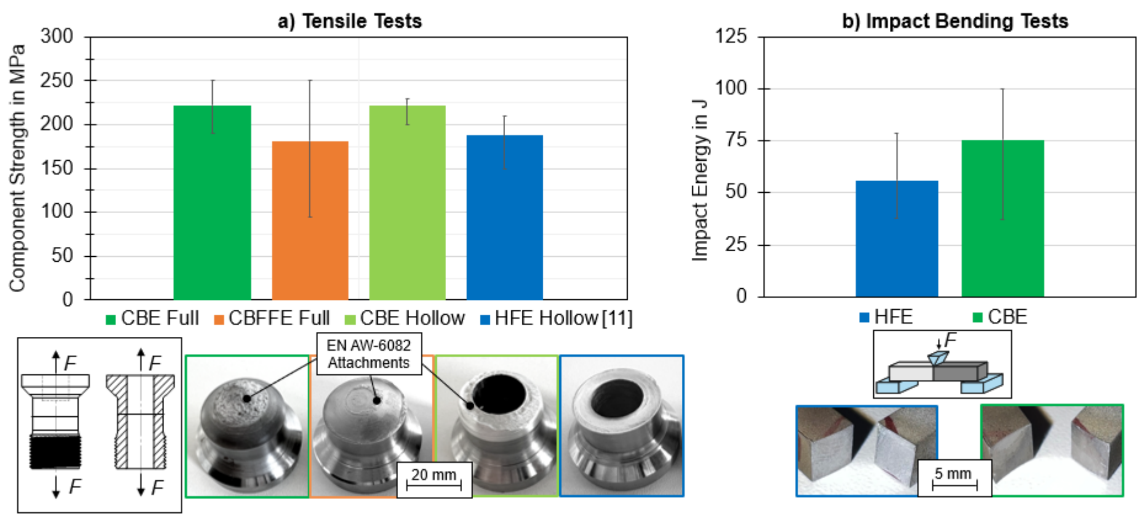

Figure 4 Mechanical properties and fracture surfaces of **a)** tensile tests and **b)** impact bending tests

5. SUMMARY AND OUTLOOK

The setting of larger joining zone surfaces is possible through the use of subsequent impact extrusion processes under elevated temperature and has a positive effect on the mechanical properties of the components. The rupturing of IMC and the re-welding of juvenile steel and aluminium areas increases both the strength under tensile load and the ductility. With a spherical shape and a sufficiently high surface enlargement of 36 %, the specimens produced with CBE achieved a strength increase of 17 % under tensile load and 42 % under impact load. In order to further increase the bond strengths in the future, it is recommended to set larger degrees of deformation in the joining zone. With CBE, this is possible by using larger cup punches so that the surface of joints without IMC is increased.

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