COMPARISON OF THE JOINING ZONE DEVELOPMENT OF HYBRID SEMI-FINISHED PRODUCTS AFTER DIFFERENT EXTRUSION PROCESSES

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Abstract

The use of hybrid semi-finished products made of aluminium and steel enables the production of components with locally adapted properties, i.e. high strength and wear-resistance with reduced weight. In the scope of this work, different impact extrusion processes for the forming of friction-welded hybrid semi-finished products consisting of steel (20MnCr5) and aluminium (EN AW-6082) were developed and experimentally implemented. The resulting material flows were intended to enable different joining zone geometries as well as to evaluate the influence of a thermo-mechanical treatment during the impact extrusion process on the quality of the joining zone. For this purpose, a full-forward extrusion, cup-backward extrusion, combined cup-backward-full-forward extrusion and a hollow-forward extrusion process were investigated. The evaluation of the resulting component quality was carried out based on metallographic images, which provide microstructural information about the forming-related influence on the friction welded joining zone. Based on the characteristic values determined, a correlation between the reproducibility and quality of the joining zone properties and the type of impact extrusion process is deduced. The backward extrusion processes have proven to be the best processes in terms of influencing the joining zone geometry. Further, the effect of forward extrusion showed no significant influence on the joining zone geometry, even resulting in a reduction of the joining zone formation in the combined cup-backward-full-forward extrusion process.

Keywords: Multi material components, friction welding, impact extrusion, joining zone properties, tailored forming

1. INTRODUCTION

Lightweight construction is playing an increasingly central role in terms of environmental protection and the associated difficulties in reducing global CO_2 emissions. It is a key technology for energy saving, as well as for driving comfort or safety within the automotive industry. With the help of multi-material concepts, it is possible to create load-adapted components, in which areas are functionally subdivided. This can save weight and minimise harmful emissions. In the case of electric vehicles, the driving range can be enhanced due to the improved efficiency resulting from the lower weight [1]. A promising innovative process chain to meet the increasing requirements is the tailored forming approach. Whereas in the conventional process, joining takes place after forming, in tailored forming a joint is first created using a suitable process such as friction welding, which is then influenced and enhanced by forming. Therefore, in the following investigations, the suitability of various impact extrusion processes is examined in order to gain a better understanding of the influencing factors for the improvement of the component qualities.

2. STATE OF THE ART

In sheet metal forming, pre-assembled semi-finished products are already in use in the form of tailored blanks [2]. With regard to bulk forming, the process chain still needs to be developed in order to fully utilise the potential of pre-assembled hybrid components. Processes that are suitable for joining dissimilar bulk materials exist in different forms. One approach is the direct joining of two semi-finished products by impact extrusion, in which the specimens are formed together without prior bonding. Liewald et al. investigated form-fitting backwards can extrusion of C15 and EN AW-1050. It was possible to create an axial bond between the different materials, where a clear friction dependency could not be observed [3]. Groche et al. studied the welding process of steel and aluminium by cold extrusion [4]. It was shown that, in addition to the heat treatment, the surface condition plays a major role in the creation of a strong bond. In literature, mainly extrusion at room temperature for hybrid parts has been investigated. As an extension to cold extrusion, hot extrusion was experimentally investigated in the study by Wohletz et al. [5]. The heating enables the equalisation of the different yield stresses of steel and aluminium. The temperature influence and the resulting changed material flow on the joining zone was observed by varying the workpiece temperature. Despite relatively high deviations, the bond strength remains equal or even increases at higher temperatures in comparison to cold forming. The best results achieved were at 600 °C for the steel side and 200 °C for the aluminium side.

There are various possibilities for pre-assembling work pieces prior to forming. Many material combinations are not suitable for conventional welding due to their different melting temperatures. Therefore a potential joining process for hybrid components can be friction welding, in which a stationary and rotating component are joined together below the melting temperature through relative motion and pressure. The friction itself generates heat, which leads to recrystallization. Combined with the applied high local plastic strain, fine-grained microstructures occur in the joining zone [6]. However, when different materials are joined, intermetallic phases may emerge. Due to their brittleness, intermetallic phases above a certain thickness have a negative effect on the joining zone, which is why attention must be paid with regard to hybrid compounds. Ideally, the creation of an intermetallic layer should be suppressed, as their formation primarily results in a reduction of the bond strength [7].

So far, relatively low emphasis has been placed on joining and subsequent hot forming of bulk metal components. Tekkaya et al. investigated the process route of joined and formed steel-reinforced aluminium profiles resulting in good bond strengths [8]. Similar to this, Foydl et al. developed a hot compound-extrusion process, in which steel reinforcements are inserted into aluminium billets to create strengthened components [9]. However, the reinforcing steel elements used are comparatively small and do not serve as a fully separate functional areas. Therefore, only the effect of particle reinforcement is studied, which is why further investigations on bulk parts are necessary. Domblesky et al. investigated the feasibility of bi-metallic friction-welded preforms and demonstrated good workability and potential for use in bulk forming applications based on open die forging using material combinations as aluminium and copper or steel and copper [10]. In contrast to this, a more challenging joining of a hybrid material pairing is considered in this work. While previous numerous investigators primarily studied the cold extrusion of hybrid semi-finished specimen or hot extrusion without prior bonding, the following paper deals with hot extrusion of hybrid parts including steel (20MnCr5) and aluminium (EN AW-6082). In previous work, mainly the full forward extrusion process of steel/aluminium at room temperature has been studied.

By considering different impact extrusion processes (full-forward extrusion, hollow-forward extrusion, cup-backward extrusion, combined cup-backward-full-forward extrusion) for friction welded hybrid semi-finished specimen, the direction of material flow as well as the initial geometry are varied. Therefore, possible differences can be observed with regard to the influence on the joining zone geometry.

3. TAILORED FORMING PROCESS CHAIN

In the first step, two cylindrical work pieces with a diameter of 40 mm are joined in a serial arrangement by friction welding, see **Figure 1a**. This is followed by hot impact extrusion, in which the specimens are first heated inductively, see **Figure 1b**. After heating, the work piece is automatically placed in the extrusion die with the help of a robotic gripper and is then formed by the force of the extrusion punch. Afterwards, the sample is pushed out by the ejector and then removed manually. The specimen is quenched in water, first on the initially heated steel side and then on the aluminium side, before being completely inserted into the quenching bath. The heat input in the steel is significantly higher, which is why it is cooled down first. Four different extrusion processes are used in this study, which differ in terms of their material flow direction (forward, backward) and/or their geometry (full, cup, hollow). The presented process chain varies in terms of different tool systems and the resulting final geometries of the extruded specimen after the impact extrusion step in **Figure 1c** including either full-forward extrusion (FFE), hollow-forward extrusion (HFE), cup-backward extrusion (CBE) and combined cup-backward-full-forward extrusion (CBFFE).

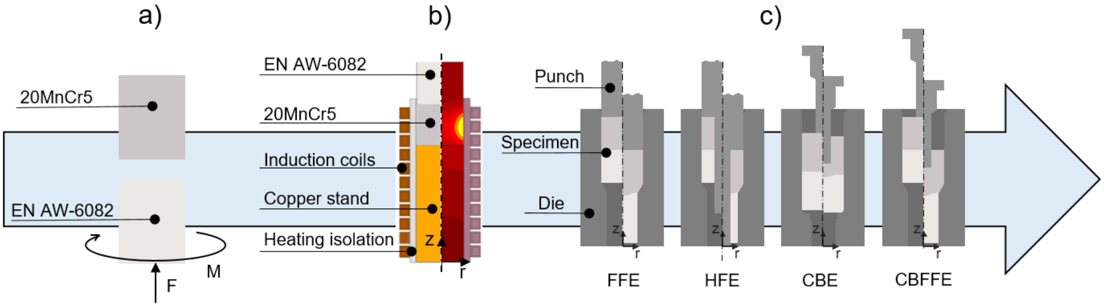

Figure 1 Tailored forming process chain
a) friction welding **b)** inductive heating **c)** impact extrusion including full-forward extrusion (FFE), hollow-forward extrusion (HFE), cup-backward extrusion (CBE), cup-backward-full-forward extrusion (CBFFE)

3.1 Friction welding

The semi-finished products made of steel (20MnCr5) and aluminium (EN AW-6082) are first friction welded in a serial arrangement using the parameters shown in **Table 1**. Preparatory measures before friction welding include machining and cleaning of the welding surface, eliminating negative influencing factors such as dirt or major surface roughness, especially on the steel side [11]. With the selected parameters, only the aluminium deforms due to its low strength. Possible impurities on the aluminium side are swept outwards, so that the surface condition of the aluminium does not play a significant role compared to the steel side [12]. After friction welding, the welding flash is removed by turning. Furthermore, the specimens are shortened to the appropriate length of 100 mm for full forward extrusion and 70 mm for the other processes used.

Table 1 Parameters used for friction welding

Billet diameter (mm)	Relative friction path (mm)	Frictional force (kN)	Press force (kN)	Press time (s)
40	4	150	251	2

3.2 Induction heating and impact extrusion

The heating of the hybrid component is necessary to equalise the diverging flow stresses of the dissimilar materials. For this purpose, the steel side is heated to approx. 900 °C with the help of an inductive coil, while the aluminium remains outside and is not exposed to direct inductive heating, see **Figure 1b**. Heating is carried out using a 40 kW mid-frequency generator (TRUMPF TruHeat MF3040) with a frequency range from 5 kHz to 30 kHz. The induction coil consists of eleven rectangular windings, which generate a magnetic field to heat up the specimen inside the coil. An exemplary temperature curve is shown in **Figure 2**.

After heating, the sample is automatically extracted by the robot gripper. The transfer time from the induction coil to the extrusion die is 5 s. After insertion, the punch moves down and forms the hybrid sample depending on the process through the particular active tool elements seen in **Figure 1c**. All extrusion processes were carried out using a LASCO type SPR 500 screw press with 280 mm s^{-1} impact velocity. After extrusion and subsequent quenching in water, the samples were cut lengthwise and examined metallographically using etching according to Kroll (3 ml HF + 6 ml HNO_3 + 100 ml H_2O). This enables a characterisation of the joining zone with regard to the geometric formation as well as potential defects that occur after extrusion.

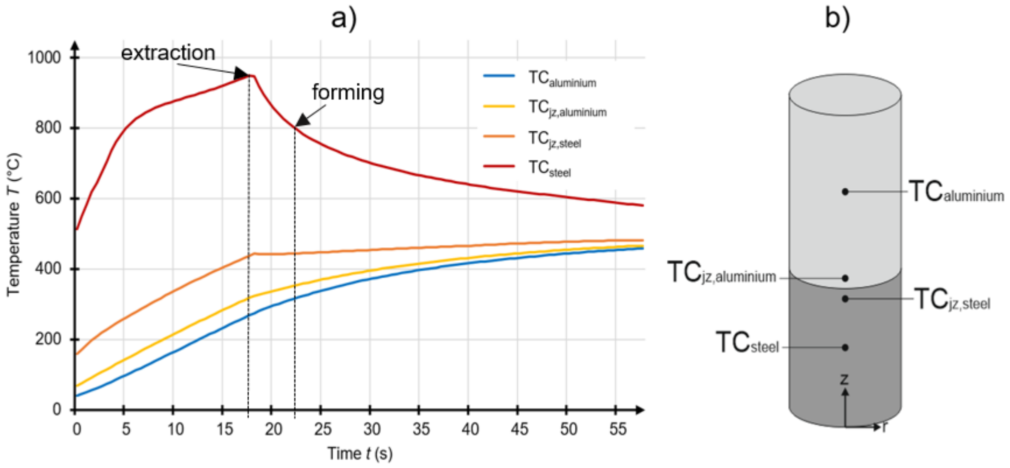

Figure 2 Inductive heating
a) qualitative heating curve of the hybrid specimen, **b)** location of the thermocouples (TC)

4. RESULTS AND DISCUSSION

Metallurgical images of the different impact extruded cross-sectioned samples are shown in **Figure 3** and **Figure 4**.

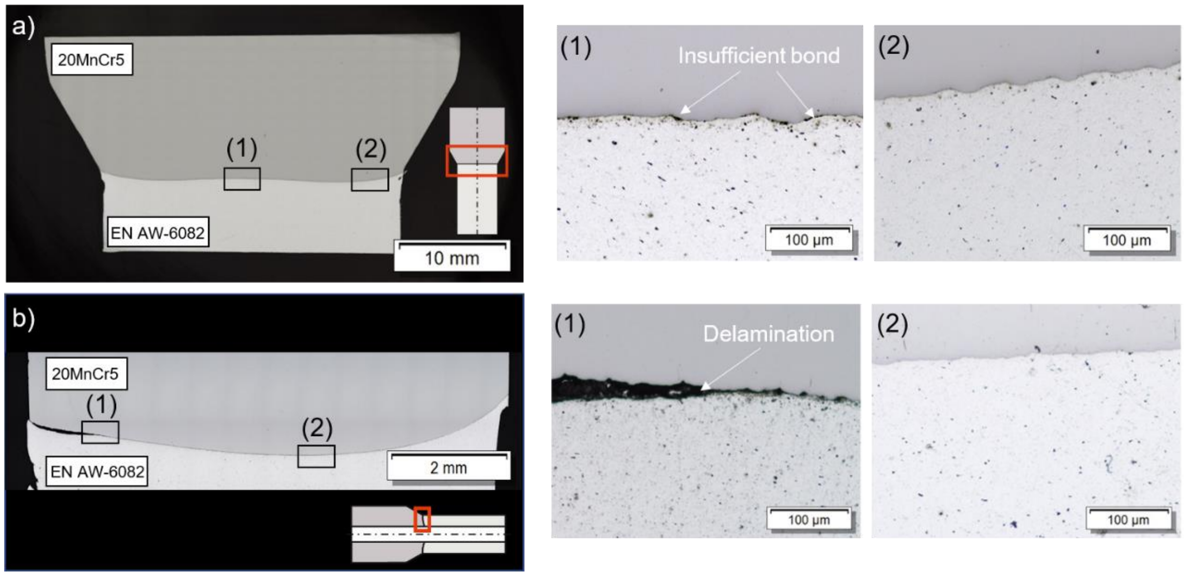

Figure 3 Metallographic images of a friction-welded specimen after
a) full-forward extrusion, **b)** hollow-forward extrusion, (1) centre region near the blank, (2) edge area

After full-forward extrusion, a plane joint zone can be seen, which, apart from marginal wave-like areas, does not have any distinctive points, see **Figure 3a.** In the middle **(1)** there are flaws which indicate an insufficient bond, whereas in the edge area **(2)** a sound bonding has been created. The centre point in the friction welding process is characterised by low rotational speeds and is therefore generally defined as a weak point. Since there is no central material flow on the steel side in the extrusion process, no surface enlargement occurs. Therefore, the centre is not affected by forming. A possible reason for the lack of change in geometry could be a low yield stress of the aluminium due to the temperature influence from the heated steel side during the heating and the transfer period to the extrusion die, see **Figure 2**. This results in a favoured material flow on the aluminium side due to the large difference in the yield stresses and the ratio of deformation resistances between steel and aluminium. The steel acts as a full punch and mainly deforms at the extrusion shoulder. In **Figure 3b** a specimen after hollow-forward extrusion is shown, with the inner diameter on the left of the image section and the outer shell on the right. Due to the large clearance fit of the inner blank diameter an unguided material flow leads to a delamination in the left joining zone area **(1)**. Due to the different friction conditions between the rod and the inner hole of the specimen as well as between the die wall and the outer specimen surface, an outwardly curved joining zone is formed, which indicates higher friction on the die wall than on the rod. In the outer area of the hollow profile **(2)**, a good bond can be seen in the close-ups due to a guided material flow and the higher rotational speeds from the friction welding process leading to better initial bonding in outer areas [11].

In both cup-backward extrusion (see **Figure 4a**) and the combined cup-backward-full-forward extrusion process (see **Figure 4b**), the joining zone geometry is significantly influenced and has a spherical curvature after forming, which correlates with surface enlargement. This enables brittle intermetallic phases to be thinned out and thus potentially increase the surface of metallic contact between steel and aluminium for a better bond. In the comparison of both processes, a reduced distortion of the joining zone can be observed in the combined process due to the additional forward-moving material flow. In contrast to forward extrusion, a defect free joint could be created in the centre as well as at the edge.

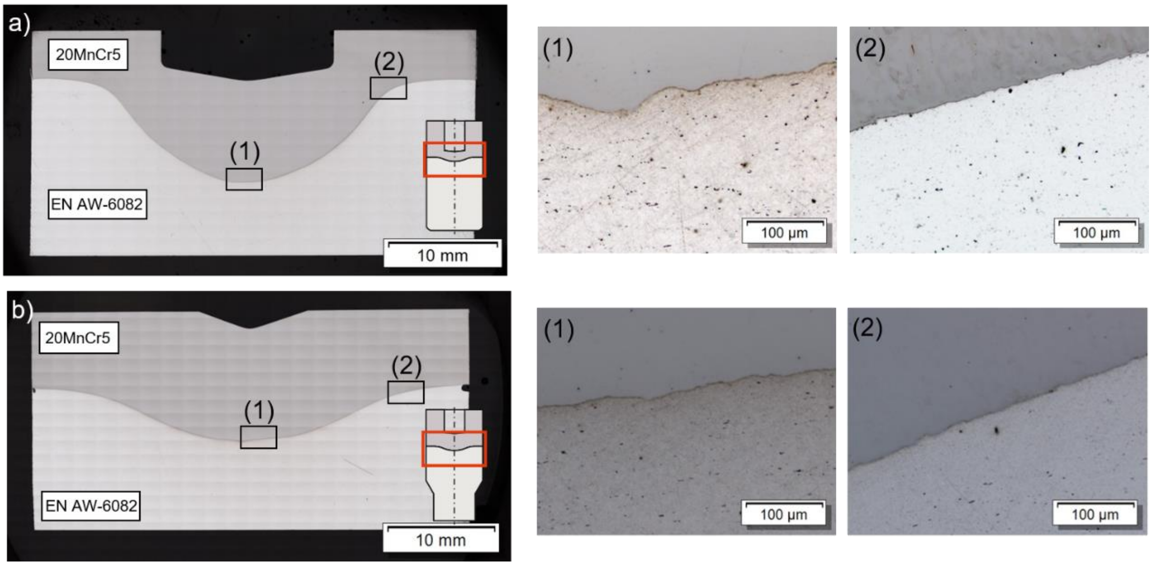

Figure 4 Metallographic images of a friction-welded specimen after: **a)** cup-backward extrusion, **b)** combined cup-backward-full-forward extrusion, (1) centre region, (2) edge area

In the extrusion processes analysed, a geometric change of the joining zone could only be achieved through a deformation induced by the punch. In the absence of material flow against the punch direction (z-direction), the steel does not deform, which is why only marginal geometric changes were achieved in the forward extrusion processes.

5. CONCLUSION AND OUTLOOK

By using different extrusion processes, it is possible to influence the joining zone geometry of steel/aluminium hybrid components to different degrees. In full forward extrusion, the joining zone is only marginally effected by the forming operation. The reason for this is the high yield stress difference between steel and aluminium resulting from the low temperature gradient caused by the conductive heating of the aluminium side after local induction heating during transfer and forming. Hence, the material flow mainly takes place in the aluminium as long as the steel is not deformed by the punch itself, as it is in the case of the cup extrusion processes. A surface enlargement in the joining zone area, which could potentially thin out intermetallic phases, therefore only occur in backward extrusion processes. This statement has yet to be validated and can be verified with the help of mechanical tensile tests and SEM images in future investigations.

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REFERENCES

[1] TEKKAYA, A.E., MIN, J. Special Issue on Automotive Lightweight. *Automotive Innovation*. 2020, vol. 3, pp. 193-194.

[2] MERKLEIN, M., JOHANNES, M., LECHNER, M., KUPPERT, A. A review on tailored blanks - production, applications and evaluation. *Journal of Materials Processing Technology*. 2014, vol. 214. no. 2, pp. 151-164.

[3] LIEWALD, M., DOERR, F., KANNEWURF, M. Form-closed joining by cold forging - Investigations of form-closed joining of aluminium and steel by backward-cup-extrusion. *wt Werkstatttechnik online* 104. 2014, pp. 620-624.

[4] GROCHE, P., WOHLETZ, S., ERBE, A., ALTIN, A. Effect of the primary heat treatment on the bond formation in cold welding of aluminium and steel by cold forging. *Journal of Materials Processing Technology.* 2014, vol. 214. pp. 2040-2048.

[5] WOHLETZ, S., GROCHE, P. Temperature influence on bond formation in multi-material joining by forging. *Procedia Engineering*. 2014, vol. 81. pp. 2000-2005.

[6] FAHRENWALDT, H.J. *Practical Knowledge of Welding Technology: Materials, Processes, Manufacturing*. Braunschweig/Wiesbaden: Friedr. Vieweg & Sohn Verlagsgesellschaft mbH, Braunschweig/Wiesbaden 1994.

[7] YILMAZ, M., CÖL, ACET, M. Interface properties of aluminium/steel friction-welded components. *Materials Characterization*. 2003, vol. 49, no. 5, pp. 421-429.

[8] BEHRENS, B.-A. TEKKAYA, A.E., KOSCH, K.-G., FOYDL, A. KAMMLER, M., JAEGER, A. Manufacturing of steel-reinforced aluminium parts by co-extrusion and subsequent forging. *Key Engineering Materials* 2014, vol. 585. pp. 149-156.

[9] FOYDL, A., PFEIFFER, I., KAMMLER, M., PIETZKA, D., MATTHIAS, T., JAEGER, A., TEKKAYA, A.E., BEHRENS, B.-A. Manufacturing of Steel-Reinforced Aluminium Products by Combining Hot Extrusion and Closed-Die Forging. *Key Engineering Materials*. 2012, vol. 504-506, pp 481-486.

[10] DOMBLESKY, J., KRAFT, F., DRUECKE, B., SIMS, B. Welded preforms for forging. *Journal of Materials Processing Technology*. 2006, vol. 171, pp. 141-149.

[11] MA, H., QIN, G., DANG, Z., GENG, P. Interfacial microstructure and property of 6061 aluminium alloy/stainless steel hybrid inertia friction welded joint with different steel surface roughness. *Materials Characterization*. 2021, vol. 179, 111347.

[12] NEE, A.Y.C. *Handbook of Manufacturing Engineering and Technology*. London: Springer-Verlag, 2015.