Materials Research Proceedings 41 (2024) 792-801 https://doi.org/10.21741/9781644903131-87

Influence of enlarged joining zone interfaces on the bond properties of tailored formed hybrid components made of 20MnCr5 steel and EN AW-6082 aluminium

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Keywords: Friction Welding, Hot Forging, Tailored Forming, Joining Zone, Spray Cooling

Abstract. Hybrid material compounds offer an extension of the technological application range of monolithic components by combining positive material-specific properties. In the case of steel and aluminium, a load-adapted component with high strength areas and a reduced weight can be created. Tailored Forming enables the joining zone created by a pre-joining process to be modified and enhanced by a subsequent forming step. Derived from previous studies, an enlarged joining zone interface through spherical joining zone curvature and an equalisation of yield stresses through an inhomogeneous induction heating with partial cooling are necessary to achieve a defect free bond with high strength and ductility. In order to further enlarge the joining zone interface and hence to increase the surface ratio of juvenile welding spots without brittle intermetallic compounds, different local plastic strains are induced. Additionally, an alternative spray cooling concept is used to evaluate the effect of steeper temperature gradients on the bond quality. Rotary friction welded specimens made of 20MnCr5 steel and EN AW-6082 aluminium are cup backward extruded with different extrusion ratios using punch diameters of 22 mm and 30 mm. Metallographic images, SEM analysis and hardness tests of cross-sections are used to evaluate the bond quality with regard to the joining zone formation, occurring defects and the resulting intermetallic compound. With cooling, higher yield stresses could be set in the aluminium, which counteract material failure even with larger punch diameters due to a higher deformability. However, the surface enlargement of the joining zone is reduced. Despite the higher surface enlargement in uncooled specimens, insufficient bonds were achieved due to existing cracks in the aluminium in or near the joining zone interface, as well as significant thicker intermetallic compounds.

Introduction

In a world characterised by constant progress and innovation, lightweight construction is becoming progressively important to optimise technical high-performance components. This paradigm shift in industrial applications not only promises a weight reduction, but also a load-adapted design to overcome the limitations of monolithic components. Hybrid material concepts enable structures to be designed to conserve resources and also opens up new horizons for sustainable mobility, increased efficiency as well as a variety of applications in a wide range of industries. The combination of different material properties is already a well-established practice in sheet metal forming, commonly referred to as tailored blanks, and is extensively applied in the construction of automobile bodies. Joined sheets created from steel with varying qualities, thicknesses, strength or surface coatings are shaped in a final step to create specific elements e. g. b-pillars with high strength and also sufficient elongation capacity to ensure safety in the event of a crash [1].

State of the Art

The concept of hybrid components has already been applied to bulk metal in numerous studies in terms of compound forging, where a joint is created between two semi-finished products by forming itself [2]. Compound forging requires a certain plastic deformation and consequently an increase in surface area in order to create a sufficient bond. In the case of a bonding between steel and aluminium, oxide layers are broken up according to the Bay model so that metallic contacts and consequently covalent Al-Fe compounds can subsequently form along the interface [3]. In the studies by Groche et al. [4] and Peter et al. [5], the steel alloy C15 and the age-hardenable wrought aluminum alloy EN AW-6082 were joined by cold forming using a cup backward extrusion process. The surface enlargement of the joining zone, which has a positive effect on the bond due to oxide cracking, could be significantly influenced by the heat treatment condition and the surface roughness of the different materials. Alternatively, it is also possible to set a temperature gradient between the bonding partners, which leads to an equalisation of the different yield stresses during forming. By varying the workpiece temperatures for steel at 600 °C and aluminium at 200 °C, Wohletz and Groche [6] achieved equal or even higher bond strengths in comparison to cold compound forging. Wang et al. [7] studied the deformation mechanisms and mechanical properties in aluminium-steel bimetallic gears produced by hot compound forging. The temperature of the aluminium core was varied between 300 and 500 °C. The steel, which was formed into the external gear rim around the core, was at a temperature of 850 °C. At higher temperatures, it is more difficult to break up the oxides, as the softened aluminium induces insufficient severe plastic deformation. The best bond strengths were achieved at an aluminium temperature of 300 °C, as the oxides were broken up and pushed into the aluminium base material due to the sufficient strength of the aluminium resulting in an oxide-free interface area.

Further investigations were carried out using a combined manufacturing process for hybrid materials consisting of pre-joining and subsequent forming at elevated temperatures. In this case, the forming is not used to join the semi-finished products, but to geometrically influence the component to gain a final contour preform and in particular to thermomechanically enhance the joining zone properties. In the studies of Behrens et al. [8] or Foydl et al. [9], a combined process of extrusion and die forging was developed to enhance the mechanical properties of co-extruded profiles by embedding reinforcing steel fibres in an aluminium matrix material. However, it is also possible to create load adapted components with strictly divided areas made of different materials with complementary properties. In this regard, Domblesky et al. [10] joined hybrid semi-finished products made of copper and steel or copper and aluminium with rotary friction welding in a serial arrangement. Subsequently, the specimens were forged under hot working conditions. The hybrid parts showed a sufficient workability and are comparable to the base materials in terms of yield and tensile strength. Various studies have applied this novel Tailored Forming process chain to produce hybrid high-performance components with load-adapted areas made of steel and aluminium [11, 12]. By using pre-joined components with a material bond in a subsequent forming step, the aforementioned problem of oxides in the joining zone can be avoided and sufficiently high bond strengths can be achieved. Rotary friction welding has proven to be a suitable joining process, in which the strength-reducing oxides can be removed from the joining zone by the plastic deformation of aluminium that occurs during the process [13]. Excessive growth of the brittle intermetallic compound (IMC), which forms in the interface due to the insolubility between steel and aluminium, is not initiated by the low heat input. According to Herbst et al. [14], seam thicknesses of 0.07 µm occur in friction welded specimens made of 20MnCr5 and EN AW-6082, which are well below the critical values of 1 µm, that significantly reduce the bond strength. It is assumed that the existence of an IMC is necessary for a sufficient bond. Maximum bond strengths are achieved with an IMC thickness of 0.5 µm in several investigations [15].

Different extrusion processes were developed and investigated with regard to the bond strength and ductility [16]. Cup backward extrusion proved to be the most suitable process for producing a hybrid hollow shaft due to the greatest influence on the joining zone geometry and consequently the mechanical properties [17]. By using an inductive heating concept with an additional immersion cooling, the temperature gradient between steel and aluminium could be significantly increased in a full forward extrusion process, which led to an improved equalisation of the yield stresses. In this case, the aluminium did not fail in the process, which is why cracks along the joining zone could be largely prevented [16]. Furthermore, in the course of this, an alternative spray cooling was theoretically designed for impact extrusion in the study by Ince et al. [18]. With this concept, greater temperature gradients can be achieved by avoiding the Leidenfrost effect.

Based on the findings presented, the combination of cup backward extrusion combined with an enhanced cooling strategy to achieve a beneficial forming temperature gradient shows high capability to utilise the full potential of the Tailored Forming process chain. This study focuses on cup backward extrusion at elevated forming temperature with partial spray cooling to study the interactions between surface enlargement, the emerging IMC and the resulting interface.

Materials & Methods

As in previous studies [15], the material pairing of steel (soft-annealed 20MnCr5) and aluminium (EN AW-6082 T6 condition) is used for the Tailored Forming process chain to produce a load-adapted hollow shaft with high strength areas and reduced weight (see Fig. 1). In order to create a material bond, the semi-finished products with a diameter of D = 40 mm are joined by means of rotary friction welding using the parameter set and the procedure described in a previous study [17]. During the process, only the aluminium deforms plastically, as it has a lower strength compared to steel. The resulting aluminium welding flash is removed by machining and the hybrid samples are prepared with a steel length of 22 mm and an aluminium length of 50 mm for the subsequent cup backward extrusion.

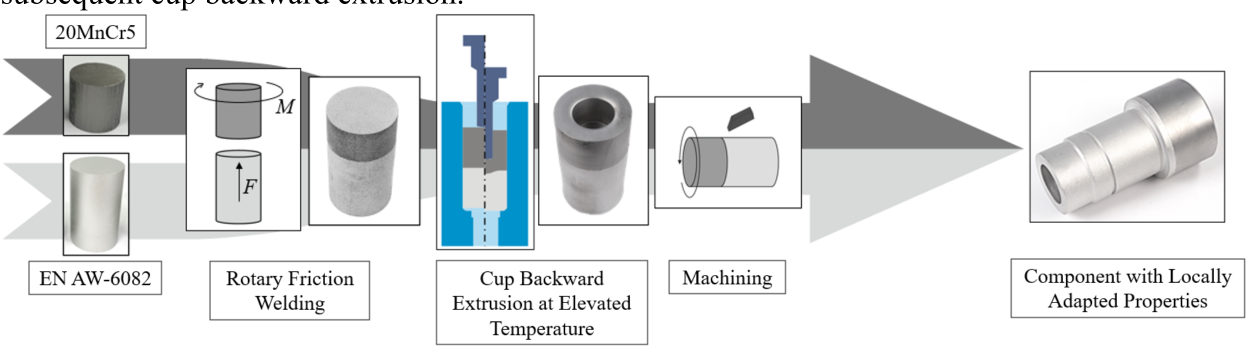

Figure 1. Process chain of Tailored Forming for a hollow shaft

Prior to the forming process, the hybrid semi-finished workpiece is inductively heated on the steel side in order to create a temperature gradient between steel and aluminium, and consequently an equalisation of the yield stresses. Two heating concepts, with and without cooling on the aluminium side, are used to investigate the influence of the temperature gradient on the joining zone properties. With the shorter component length used here, thermal conduction is even more critical compared to longer sample geometries for full forward extrusion in previous studies [16-18], as only a small volume of steel needs to be heated to a forming temperature of 900 °C. The aluminium with high thermal conductivity must be kept as cool as possible to avoid overheating and melting. As shown in Fig. 2 a) the steel area is heated, while the aluminium is cooled by a sprayed mixture of pressurised air and water from four nozzles [18] using the parameters in Table 1. As the heating of the steel core is only possible by heat conduction due to the skin effect, heating is carried out within 34 s (uncooled) respectively 37 s (cooled) in four stages with decreasing power addition at a frequency of 15.9 kHz to generate a homogeneous temperature distribution. Temperatures were measured using thermocouples type K. To determine the influence of the heat input on the aluminum side, hardness tests are carried out with friction welded samples with and without cooling after induction heating and quenching without forming.

Table 1. Parameters used for spray cooling

Water		Air	
Pressure in bar	Mass Flow in l/min	Pressure in bar	Mass Flow in m^3/h
0.7	1.2	0.8	6.8

Cup backward extrusion is carried out on a Lasco SPR 500 screw press. All transfer steps are robot-assisted to ensure reproducibility in the time-sensitive process. At the start of the automated forming process, the sample is inserted into the induction coil by a robot gripper for inductive heating with and without cooling. Once heating is complete, the material is removed automatically from the coil and transferred to the die (see Fig. 2 b)). Subsequently, the punch is pressed into the steel part of the specimen with an impact velocity of 280 $mm \cdot s^{-1}$. By varying punch diameters between D = 22 mm or D = 30 mm, different cross-sectional changes of 28.8% respectively 53.5% are induced.

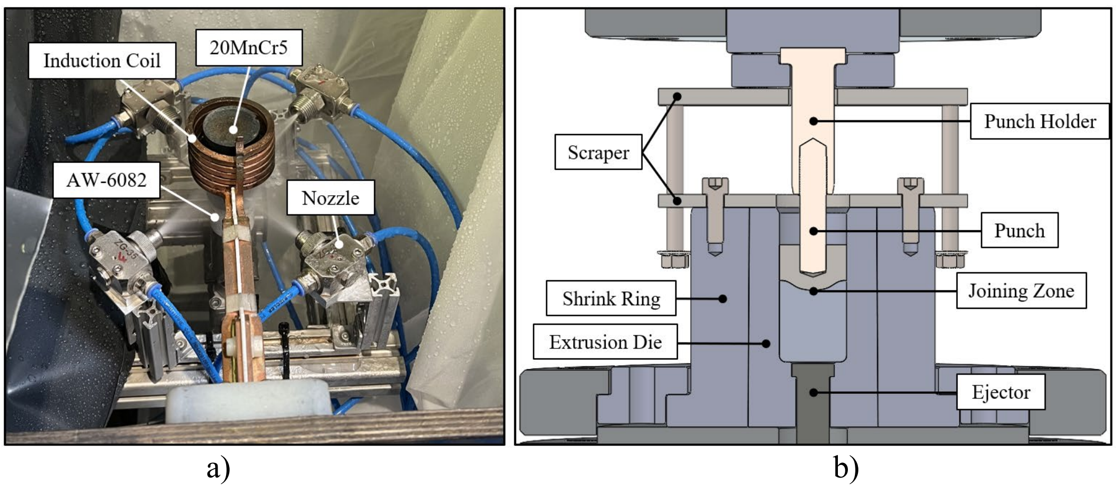

Figure 2. Experimental set-up: a) induction heating with spray cooling, b) Tool system for cup backward extrusion

After forming, the samples are quenched in water. To avoid thermal cracking, first the aluminium is quenched for 1 s, then the steel for 10 s and the aluminium for 10 s with two repetitions each, before the entire specimen is completely immersed to reach room temperature. The samples are then cut lengthwise to measure the inner and outer diameter D_o, the depth of the joining zone h, the radius r and the width a of the spherical segment (see Fig. 3 a)) to calculate the surface enlargement A_{Jz}. The joining zone consists of a spherical shape with a surface A_S and a nearly unformed circular ring A_R, which was taken into account as well. The modified surface area A_{Jz} is calculated approximately using the following equation:

$$A_{J_z} = A_S + A_R = \pi \cdot \left[(2 \cdot r \cdot h) + \left(\frac{D_O^2 - (2 \cdot a)^2}{4}\right)\right] \quad (1)$$

Light microscopic and SEM images as well as EDX analyses are performed on the cross sections using a field emission scanning electron microscope Supra VP 55 to evaluate the influence of cooling effect and the different cross-sectional changes on the joining zone geometry as well as the emerging IMC. The existence of a material bond is examined in different positions (see Fig. 3): in the edge area R0, descending area R1 and R2 as well as in the centre M1 and M0. The local test geometry has a rectangular cross-section of 2.5 mm x 2.5 mm with a length of 8.5 mm and is extracted for each variant at the specified locations using wire eroding. Extracting local areas acts as a test method and allows an evaluation of correlation between surface enlargement, the IMC thickness and the existence of a resulting bond.

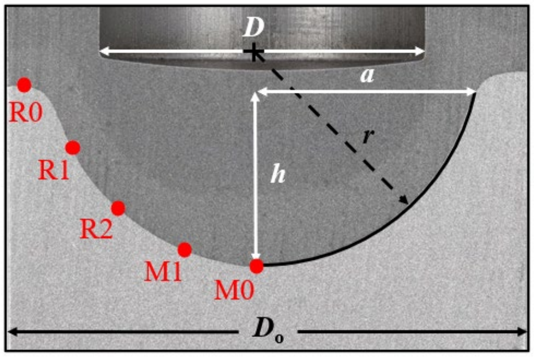

Figure 3. Geometric quantities and test positions for a material bond

Results & Discussion

When using spray cooling, there is a significant temperature drop of 314 °C in the aluminium centre Tc_1 (see Fig. 4). In this case, the central steel temperature Tc_2 could even be increased from 800 °C to the necessary 900 °C by adjusting the power profile and heating times, as the aluminium temperatures are well below the melting point due to prevention of excessive heat through the cooling effect. Therefore, the overall temperature difference can be increased by 116 % from 343 °C to 742 °C. The effect of cooling can be clearly seen in the hardness measurements (see Fig. 5). The aluminium base material of the uncooled variant has an average hardness $\bar{x}$ of 77 HV and indicates softening due to excessive heat input. In comparison, cooled samples have an average hardness $\bar{x}_+$ of 92 HV. As long as temperatures of 200 °C are not exceeded for durations of 30 minutes with the alloy EN AW-6082, no strength reductions are to be expected [19]. These two conditions are met in this case, which is why the initial heat treatment condition T6 (97.5 HV10) can be largely maintained by the use of spray cooling. The lower temperatures also have a significant effect on the yield stress in the forming process, which at higher values also require higher forming forces to enable the material to flow (see Fig. 6). The forming resistance of the aluminium is increased by the cooling during the process and requires a significantly higher forming force of $F = 867$ kN for $D = 30$ mm, which is 38.5% lower without cooling and reaches a value of $F = 626$ kN. A comparison of the punch diameters also shows a difference. As larger volumes have to be formed at $D = 30$ mm, the forming forces required are generally higher with an increase by 104.6% compared to $D = 22$ mm.

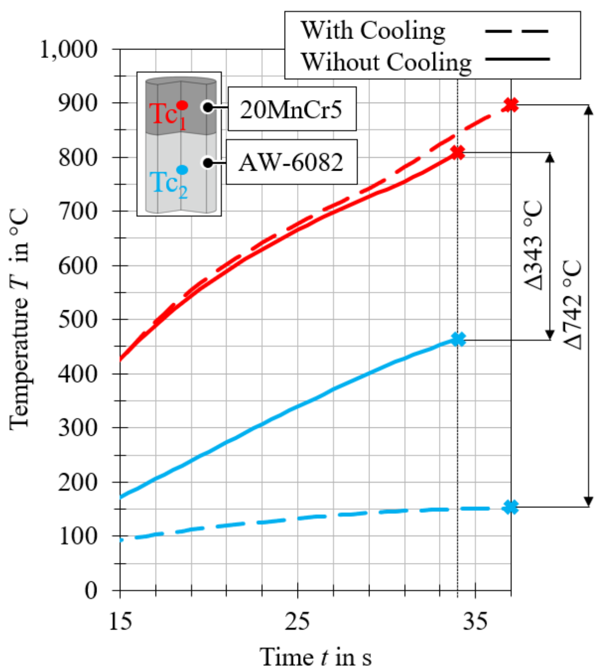

Figure 4. Temperature-time-curves for cooled and uncooled specimens

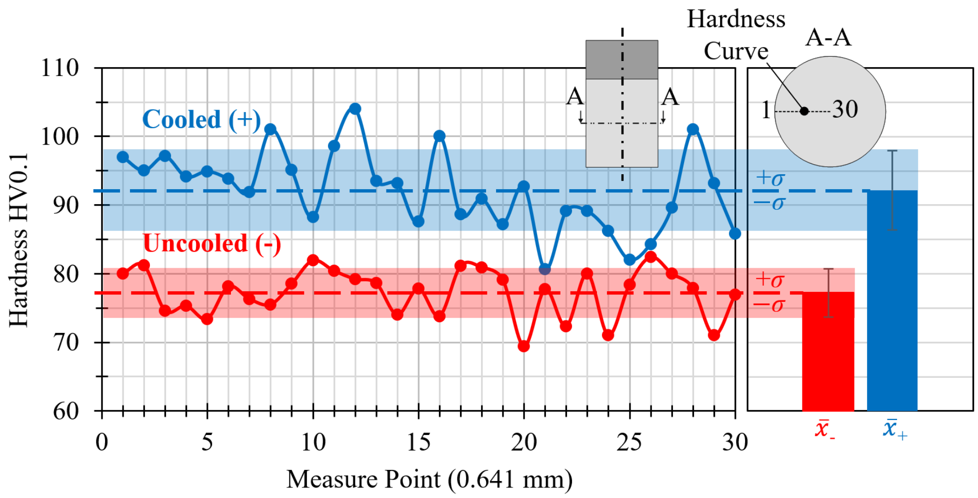

Figure 5. Hardness curves in the aluminium base material

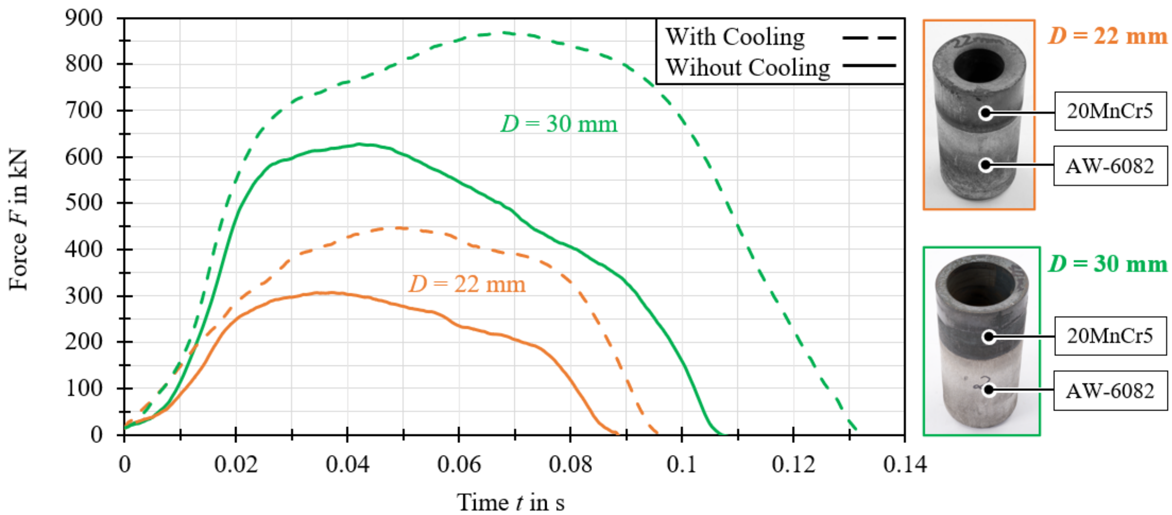

Figure 6. Force-time curves of the cup backward extruded specimens

Depending on the punch diameter and cooling strategy used, different joining zone geometries occur (see Fig. 7). For uncooled variants, the increased temperature of over 450 °C (see Fig. 4) in the aluminium leads to reduced yield strength, which is why the steel area presses into the underlying aluminium during the forming process and gives the joining zone a spherical contour. As a result, a surface enlargement of 52.7% (D = 30 mm, uncooled) is achieved compared to the reference surface (1320.3 mm^2), which is only friction welded (see Tab. 2). When cooling is used, the joining zone is less pronounced and is accompanied by a surface enlargement of only 5.9% (D = 30 mm, cooled). The same phenomenon is observed for D = 22 mm, but to a higher extent although a significantly smaller punch cross section (ratio: 53.7%) was used. Reason for this is a higher penetration depth, which, in contrast to D = 30 mm, was guaranteed by sufficient available press energy. The increased cross-section paired with the higher yield stress due to the cooling requires higher forming forces, which were not set in this case. Nevertheless, the cross-sections can be compared with each other on the basis of their percentage surface enlargement.

In the absence of cooling, damage, both in the base material itself and along the IMC is observed, especially in the edge areas a) and g). Depending on the position, IMCs of different thicknesses occur, which reach their maximum in the edge area R0 for all variants. With increasing surface enlargement towards the centre, the IMC becomes thinner. On the one hand, this may be due to the inhomogeneous temperature distribution in the radial direction, which is favoured by the skin effect during inductive heating. Higher temperatures occur at the edge, which correlate with thicker IMC. However, the decrease of IMC thickness is intensified by the local increase in surface area towards the core. From studies in which steel and aluminium were joined by compound forging, a decreasing oxide layer content with increasing local plastic strain was also observed [5], which is comparable to the IMC mechanisms occurring here. In the middle, a bond without IMC can be seen in the cooled variants. Two possible scenarios are imaginable for the formation of a bond in the centre:

- *Scenario 1*: The friction welding process generally results in inferior joint qualities in the centre due to the low relative speeds [13]. In friction welded variants, cracks are present in the centre and are enlarged due to the different thermal expansions of the materials while inductively heated. Subsequent forming counteracts this and creates a material bond in positions c) and i) with IMC and f) and l) without IMC. Due to the significantly greater heat input in the uncooled variants, growth of the IMC is initiated during or after forming. The previous defect is thus closed by the reshaping and an IMC is formed by diffusion.
- *Scenario* 2: A bond with IMC results from the friction welding process. If an IMC exists, it is either enlarged by inductive heating or breaks apart due to the thermal expansion. If the IMC is intact, it is broken up by the surface enlargement due to the low ductility and flushed outwards by the backward material flow during forming. In outer areas such as e), this leads to an accumulation of the IMC. As a result, juvenile welding surfaces are formed in central areas, which are joined together within forming. This is comparable to the breaking up of oxide layers during cold pressure welding [3]. This phenomenon of IMC rupturing was also observed in a previous study in which punch diameters of D = 16 mm were used without cooling [16]. In contrast to larger diameters of 22 mm and 30 mm, however, no IMC was observed for uncooled variants in the centre.

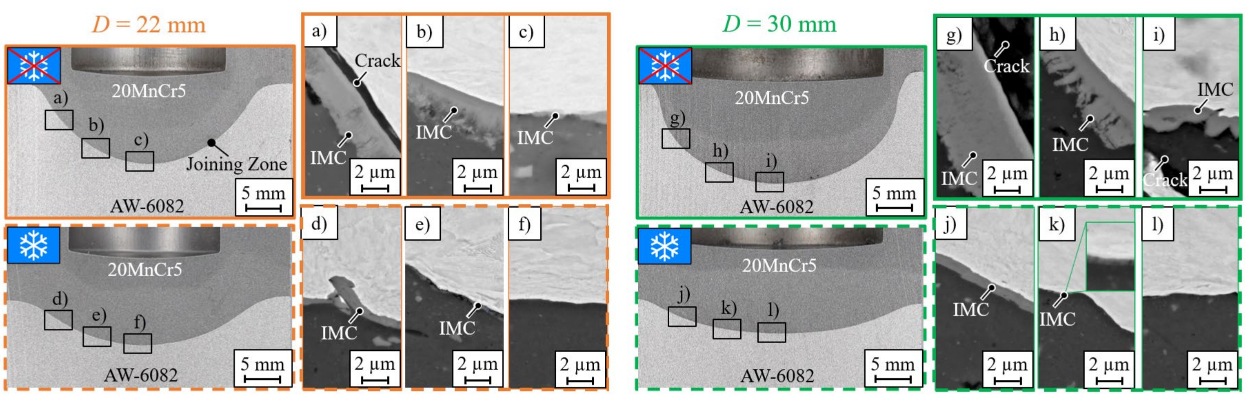

Figure 7. Cross sections and SEM images of the different variants with and without cooling

Intermetallic brittle phases such as $FeAl_3$ or Fe_2Al_5 in particular occur when exposed to heat for a short time. Other types of Fe_xAl_y such as Fe_3Al or FeAl can be excluded due to the short heating time caused by inductive heating [20]. The observed IMC for uncooled variants exhibits lamellar structures in the positions b) and h). This indicates the formation of the Fe_2Al_5 phase, which emerge at temperatures above 500 °C. By cooling of 500 to 350 °C, the typical rod-shaped phases of the Fe_2Al_5 turn into $FeAl_3$ [20, 21]. In the edge area, where the IMC is particularly thick, two different phases can be seen both optically by different colouring due to electron backscattering in the SEM image and in the EDX analyses due to different aluminium contents. The steel-side phase has an aluminium content of 68 at.-%, which would indicate the Fe_2Al_5 phase. The aluminium-side phase has a content of 74 at.-% and is indicative of the $FeAl_3$ phase [20]. In uncooled variants, the formation of only continuous $FeAl_3$ is suspected due to the lower temperature range of below 350 °C, which is why only one phase can be detected in this case. In the studies by Herbst et al. [14], significant growth of the IMC was only observed at temperatures from 540 °C upwards. As it is only possible to measure the temperatures shortly before forming, therefore a reasonable assumption is, that the aluminium has exceeded this critical temperature due to heat conduction during transfer and especially during forming. The increased contact area of the punch with $D = 30$ mm in the interface leads to faster diffusion, which is why the IMC thickness b is significantly greater with $b = 6.4$ µm than at $D = 22$ mm with $b = 3.1$ µm. In addition to the use of cooling, the related change in cross-section is therefore another important influencing factor with regard to the IMC formed and consequently the bond strength. In conclusion, the larger contact area and the greater contact pressure during forming causes a stronger growth of the IMC, which can only be prevented by cooling, if larger punch diameters are used.

Table 2. Joining zone surface enlargement ΔA_{Jz} and IMC thickness b for different variants

<table>
<tr><th>D [mm]</th><th>Cooling Strategy</th><th>D_0 [mm]</th><th>h [mm]</th><th>a [mm]</th><th>r [mm]</th><th>A_{Jz} [mm^2]</th><th>ΔA_{Jz} [%]</th><th colspan="3">b [µm]</th></tr>
<tr><td>0.0*</td><td>Uncooled</td><td>40.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>1320.3</td><td>0.0</td><td colspan="3">n.e.</td></tr>
<tr><td>0.0*</td><td>Cooled</td><td>40.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>1320.3</td><td>0.0</td><td colspan="3">0.7</td></tr>
<tr><td rowspan="2">22.0</td><td rowspan="2">Uncooled</td><td rowspan="2">41.0</td><td rowspan="2">4.0</td><td rowspan="2">5.1</td><td rowspan="2">14.9</td><td rowspan="2">1709.1</td><td rowspan="2">29.5</td><td>a)</td><td>b)</td><td>c)</td></tr>
<tr><td>3.1</td><td>2.9</td><td>1.0</td></tr>
<tr><td rowspan="2">22.0</td><td rowspan="2">Cooled</td><td rowspan="2">41.0</td><td rowspan="2">2.3</td><td rowspan="2">5.5</td><td rowspan="2">23.6</td><td rowspan="2">1470.3</td><td rowspan="2">11.4</td><td>d)</td><td>e)</td><td>f)</td></tr>
<tr><td>1.0</td><td>0.1</td><td>n.e.</td></tr>
<tr><td rowspan="2">30.0</td><td rowspan="2">Uncooled</td><td rowspan="2">41.0</td><td rowspan="2">4.8</td><td rowspan="2">6.3</td><td rowspan="2">20.0</td><td rowspan="2">2016.4</td><td rowspan="2">52.7</td><td>g)</td><td>h)</td><td>i)</td></tr>
<tr><td>6.4</td><td>3.5</td><td>1.0</td></tr>
<tr><td rowspan="2">30.0</td><td rowspan="2">Cooled</td><td rowspan="2">41.0</td><td rowspan="2">1.6</td><td rowspan="2">6.2</td><td rowspan="2">39.6</td><td rowspan="2">1398.1</td><td rowspan="2">5.9</td><td>j)</td><td>k)</td><td>l)</td></tr>
<tr><td>1.0</td><td>0.1</td><td>n.e.</td></tr>
</table>

*friction welded & not formed

During preparation of rectangular geometries for local bond testing mainly samples without cooling fell apart (see Tab. 3). Friction welded variants (1), (2) without an additional forming step were inductively heated and quenched afterwards to investigate the isolated effect of the heat input on the bond. Due to excessive growth of the IMC, which in turn leads to cracks within the joining zone, the uncooled and unformed sample (1) already fell apart after heating and quenching. Therefore, no bond exists in any position. If cooling is used, the growth of the IMC can be largely suppressed, which is why a bond in position R0, R1, R2 and M1 is present for (2). As previously mentioned, the cooled and unformed sample (2) has a central defect, which is why there is no bond in the position M0. However, this can be compensated for by forming with additional cooling (4), (6).

Table 3. Existence of a material bond depending on position R0, R1, R2, M1, M0

Variant \ Position	R0	R1	R2	M1	M0
(1) Uncooled + Not Formed	No Bond	No Bond	No Bond	No Bond	No Bond
(2) Cooled + Not Formed	Bond	Bond	Bond	Bond	No Bond
(3) 22 Uncooled	No Bond	Bond	Bond	No Bond	No Bond
(4) 22 Cooled	Bond	Bond	Bond	Bond	Bond
(5) 30 Uncooled	No Bond	Bond	Bond	No Bond	No Bond
(6) 30 cooled	Bond	Bond	Bond	Bond	Bond

In the absence of cooling, only specimens in positions R1 and R2 could be extracted of cup backward extruded samples (3), (5). Although, there is a visible bond with an IMC thickness of 1 µm (see Fig. 7) in the centre M0, a premature failure due to small test dimensions occurs. The reason for this is the brittle nature of the very thick IMC, which is occasionally accompanied by cracks in the joining zone regarding the SEM images (see Fig. 7). When cooling is used, at the edge area R0 or in central regions such as M1 or M0 bonds are sufficient enough to withstand the extraction without damage. The positive effects of cooling on the bond are therefore clearly visible and seem to be necessary for defect-free forming.

Summary & Outlook

In this study, cup backward extrusion of pre-joined hybrid components made of steel and aluminium was investigated with regard to varying punch diameters and heating concepts. Both factors are important control variables in the forming process and have a significant influence on the bond quality due to the sensitive and narrow process windows. A cooling of the aluminium part during the inductive heating process allows the setting of larger temperature gradients and consequently an adjustment of the yield stresses in the forming process. Defects in the aluminium base material that would otherwise occur both outside and inside the joining zone can be prevented. Furthermore, the growth of the IMC is suppressed, which has a positive effect on the local material bond along the interface.

In order to further investigate the influence of the cooling concept and enlargement of the joining zone on the component properties, it is advisable to carry out local tensile tests based on the extracted test cross-sections used in this study. Furthermore, service life tests are necessary to check whether a heat treatment is necessary for sufficient performance. Supplemented by future numerical simulations, a transferability of the correlation between surface enlargement, resulting IMC and increase in bond strength to similar processes within Tailored Forming is ensured.

Acknowledgments

The results presented in this paper were obtained within sub-project B03 of the Collaborative Research Centre 1153 “Process chain to produce hybrid high performance components with Tailored Forming” funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – SFB 1153 TP B03 – 252662854. The authors thank the DFG for the financial support of this project and the subproject A02 for the SEM/EDX investigations.

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