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Investigation of the joining zone formation of impact extruded hybrid components by varied forming sequence and partial cooling

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Abstract. Hybrid material concepts enable the combination of beneficial properties of different materials to extend the limited potential of monolithic components. When it comes to steel and aluminium, a wear-resistant and a lightweight metal are combined to produce a weight-reduced high-performance component with load-adapted areas. A method to create hybrid gear shafts is a novel approach called Tailored Forming. The process chain consists of joining e. g. by friction welding and subsequent impact extrusion under elevated temperature. Before forming, an axial temperature gradient is set in the serial arranged semi-finished products to adjust the different yield stresses of the dissimilar materials through induction heating of the steel part. The subsequent forming is intended to positively influence the joining zone thermo-mechanically and geometrically. However, prior work indicated a limitation of the influence on the joining zone in forward rod extrusion. Therefore, approaches are being researched that enable a stronger formation of the joining zone geometry to influence the resulting bond qualities through surface enlargement. A forward rod extrusion process of friction welded hybrid semi-finished products made of 20MnCr5 (AISI 5120H) combined with EN AW-6082 (AA6082) was carried out experimentally. Complementary to prior investigations, in which mainly the aluminium section was reduced through the die angle followed by the steel, the forming sequence of the materials was reversed to increase the joining zone surface with variation of the forming path. Additionally, a cooling of the aluminium side was realized through an immersion cooling to adjust maximum temperature gradients and further equalize the different yield stresses. Hardness tests, metallographic and SEM images of cross-sections were taken to evaluate the bond quality with regard to the temperature influence, joining zone formation, occurring defects and the resulting intermetallic compound (IMC). Impact extrusion with initially steel formed followed by aluminium resulted in a spherical formation of the joining zone and consequently in greater surface area, but also lead to partial defects in the IMC. The partial cooling of the aluminium allowed higher temperature gradients to be set, thus reducing defects through improved material flow in the joining zone.

Introduction

An effective use of resources is becoming more crucial to deal with rising energy prices as well as increased environmental responsibilities. Monolithic components have their material-specific restrictions, thus new concepts and production techniques must be created to meet the rising standards. Monolithic materials cannot always meet the ever-more-complex and occasionally conflicting criteria put on lightweight constructions. One option to address these demands for lightweight concepts and attain a required load-adapted functionality is through hybrid components, which utilize different materials. In the case of steel and aluminium, the positive mechanical properties are combined to produce a high-performance component with low weight.

Using the example of a hybrid gear shaft, aluminium can serve as a structural element, while steel is used in a power transmitting area [1].

State of the Art

Within sheet metal forming, especially for the automotive industry, application-adapted hybrid semi-finished products called tailored blanks have been widely used since their development by ThyssenKrupp in 1983 [2]. Due to the local adaptations such as a local variation of the sheet thickness or sheet material, the components are optimised for a subsequent forming process or the end application [3]. This concept can also be applied to bulk metal forming. Contrary to compound forging of hybrid materials, where the joining is realised by forming [4-6], the hybrid semi-finished products are first pre-joined and then further processed by forming in order to positively influence the joining zone. The combination of joining and forming has been addressed by some studies for similar and dissimilar material pairings. For instance hot forging of cladded work pieces consisting of two different steel alloys using upsetting tests was investigated numerically and experimentally by Wang et al with regard to material distribution and the effect of friction [7]. Furthermore, in the studies by Foydl et al, an extrusion process was developed, in which aluminium profiles were reinforced by steel wires. For further processing into connecting rods, the components were cut to size and used as semi-finished products for a die forging process [8]. Basic research into joining by friction welding and subsequent upsetting of solid hybrid components made of copper and aluminium or steel and copper was carried out by Domblesky et al. The results obtained from upsetting indicate a good workability of hybrid materials [9].

Based on the concept of the studies mentioned, the new approach called Tailored Forming enables a production of load-adapted high-performance components by forming pre-joined hybrid semi-finished products. The process chain can differ in terms of joining processes used such as friction welding, lateral angular co-extrusion (LACE) or cladding and subsequent forming processes such as impact extrusion or die forging [10].

The joining zone of the two hybrid materials is usually the weakest area, where the failure of the component occurs. Therefore, the basic motivation is the enhancement of the weak point through suitable measures such as reducing tensile stresses and thus defects by a pressure superimposition [11-13], an adjustment of the yield stresses by a viable heating strategy [14] or improvement of the stress state by an inversed forming sequence [15]. The last two aspects mentioned have a direct influence on the shape of the joining zone, which results in an increase of bond strength and quality through surface enlargement [15] and influencing IMCs, which in general are characterised by their brittleness. The creation of a sufficiently sound bond is the setting of the lowest possible IMC thickness, which should not exceed a certain thickness. According to Herbst et al. sufficiently narrow IMC thicknesses smaller than 1 µm indicate high bond strengths, while for thicknesses greater than 1 µm, the strength decreases significantly [16]. A sufficiently sound bound can be achieved through a subsequent forming operation. During the impact extrusion of serially arranged hybrid semi-finished products, it is crucial that the yield stress differences between the two materials are as small as possible. In this way, a high local degree of forming can be achieved and influence can be exerted on the joining zone geometry. If the yield stress difference between steel and aluminium is too high, the local deformation is not sufficient and the different materials flow one after the other into the extrusion shoulder with only a parallel displacement of the interface. In previous work [17], the influence on the joining zone properties after friction welding and impact extrusion under elevated temperatures of steel-aluminium billets was investigated. In various forming processes such as backwards cup (full forward) extrusion or hollow forward extrusion, it was possible to geometrically influence the joining zone so that larger joining zone surfaces were created. In the case of forward rod extrusion, however, the joining zone did not change and remained flat, almost as it was after friction welding (see Fig. 1). Since in forward rod extrusion no additional compressive stress is initiated by forming tools as in the other processes investigated, the axial temperature gradient is particularly important in the case in order to set the previously mentioned local deformations resulting in a spherical shape of the joining zone [17]. Due to this, a larger temperature gradient must be set in order to further equalise the yield stresses and also to influence the joining zone geometry. This is possible e. g. by actively cooling the aluminium.

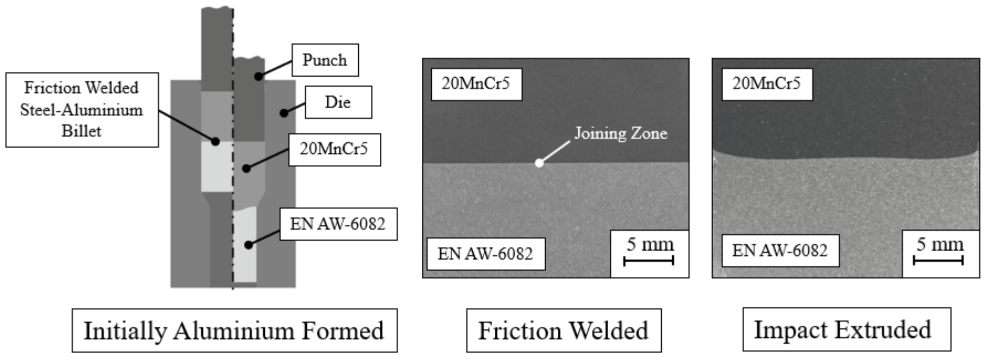


Fig. 1. Joining zone after friction welding and forward rod extrusion.

According to Gumm an increased flow rate of the centre material is observed if the harder metal undergoes the forming process first. In case the softer material is pressed through the die first, lower pressures in the forming zone and a formation of cavities in in the joining zone of compound forged components is observed [15]. Therefore, the sequence of materials is another crucial factor to further enhance the joining zone geometry through an improved stress state in the forming zone. Another aspect to reduce unwanted tensile stresses is the application of a pressure superimposition. Particularly in cold extrusion of hybrid materials, fractures occur inside the component due to differing yield stresses, which can be significantly reduced by this measure with the similar effect of the selection of material sequence [11-13]. However, this does not have any influence on the surface enlargement [17], but is required to ensure the reduction of defects.

Deriving from the state of the art, a pressure-superimposed forward rod extrusion with partial aluminium-side cooling is carried out within the scope of this study by means of Tailored Forming. Furthermore, contrary to the previous work, the material sequence is inverted so that the steel is formed first followed by the softer aluminium. In order to reproduce the formation of the joining zone and the resulting surface enlargement, the forming path is varied. The two heating strategies (without vs. with cooling) are compared with regard to the joining zone formation. The process changes enable an improvement of the mentioned joining zone characteristics. The friction welded and impact extruded steel-aluminium bonds are evaluated by means of metallographic images and hardness tests. Furthermore, the resulting IMC is characterised by SEM images and EDX analyses. The process changes enable an improvement of the joining zone characteristics.

Tailored Forming for the Production of a Hybrid Transmission Shaft

The process chain of Tailored Forming (see Fig. 2) first includes friction welding of the hybrid material pair consisting of steel (soft-annealed 20MnCr5) and aluminium (EN AW-6082 T6 condition) in a serial arrangement. Then the joined semi-finished products are formed in a forward rod extrusion process with prior inductive heating, which in the context of this study takes place both with and without immersion cooling. This is followed by machining to produce the final component, which is characterised by a load-adapted material distribution. The process chain of Tailored Forming has already been used in earlier work to create customised, hybrid machine parts in serial and coaxial arrangements like axial bearing washers or bevel gears [10].

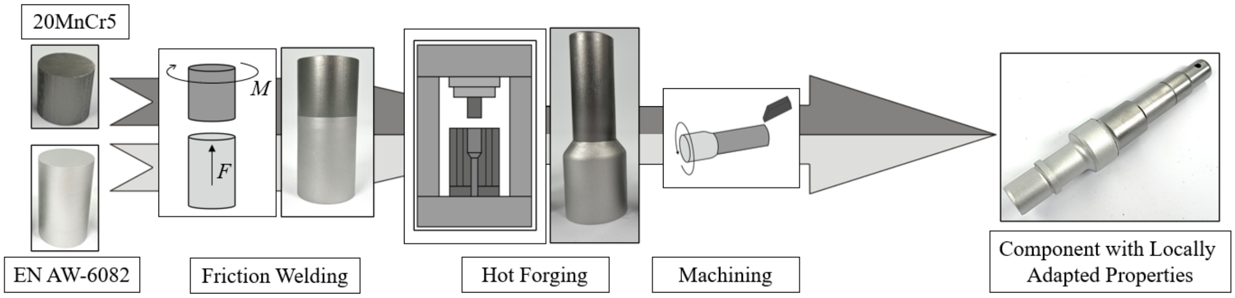
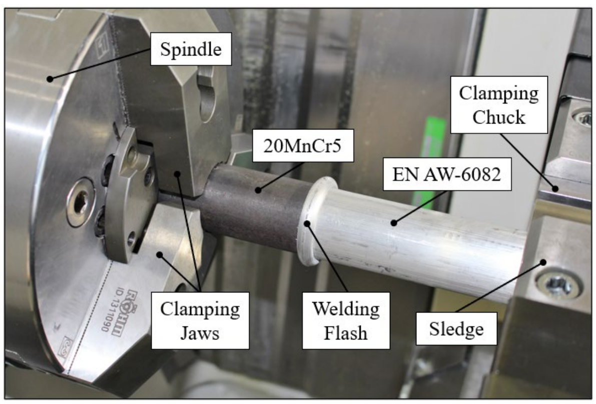


Fig. 2. Process chain of Tailored Forming for a hybrid shaft with reversed forming sequence.

Rotatory Friction Welding

Before joining, the welding surfaces of both semi-finished products made of 20MnCr5 and EN AW-6082 are first machined and cleaned with ethanol to remove irregularities and impurities. After preparation, the materials are immediately joined on the KUKA Genius Plus friction welding machine with the experimental set-up and parameters shown in Fig. 3.



Parameter	Value
Billet Diameter D	40 mm
Rotation speed n	1500 rpm
Relative Friction Path s_R	4 mm
Friction Pressure p_F	120 MPa
Upsetting Pressure p_U	200 MPa
Upsetting Time t_U	2 s

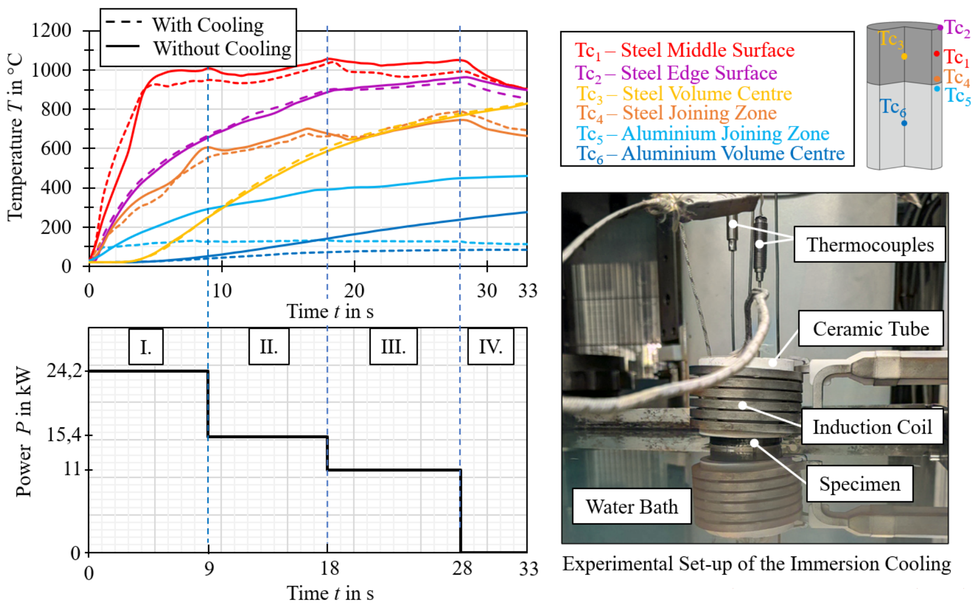
a) b)

Fig. 3. Rotatory friction welding: a) experimental set-up, b) investigated parameters.

The parameters were chosen according to the previous work [18] and are designed to prevent unnecessary shortening and to set low temperatures in order to keep the emerging intermetallic phase as small as possible. The steel rotates at a speed of n = 1500 rpm on the spindle side, while on the sledge side the aluminium is rubbed against it with a relative friction path of s_R = 4 mm at a friction pressure of p_F = 120 MPa. After completion of the friction phase, the upsetting phase takes place with an upsetting pressure of p_U = 200 MPa and an upsetting time of t_U = 2 s. The resulting welding flash consists of aluminium as only this material is plastically deformed in the process due to its lower strength compared to steel. After the process, the welding flash is removed by machining and the specimens are shortened to a length of 105 mm (42 mm steel, 63 mm aluminium) for the subsequent impact extrusion process.

Inductive Heating and Immersion Cooling

With the help of an induction coil, the friction-welded hybrid component is heated partially to equalise the significantly different yield stresses of steel and aluminium before the forming process. In order to achieve a favorable flow behavior, an inhomogeneous temperature distribution in the hybrid semi-finished product is necessary. According to simulations and material data, the yield stresses at steel temperatures of 900°C or higher and aluminium temperatures of 20°C are approximately the same level [14]. Due to the time required to heat up and process the component in combination with the thermal conduction during this time, it is not technically possible to reach this ideal equalisation for the forming process. The aim is therefore to achieve the largest possible temperature gradient between the two materials. To investigate the influence of the temperature gradient on the material flow, the heating is carried out with and without partial cooling of the aluminium side before forming. During the heating phase, the steel side is in the induction coil, which consists of six rectangular windings. The magnetic field is generated by a 40 kW mid-frequency generator (TRUMPF TruHeat MF 3040) with a frequency range between 5 - 30 kHz. The edge of the aluminium part is at the same level as the lowest coil winding and is cooled by the surrounding water when used with immersion cooling (see Fig. 4).



a) b)

Fig. 4. Partial heating: a) measured temperatures during induction heating with and without immersion cooling, b) positions of the thermocouples (Tc) and experimental set-up.

The temperature curves shown in Fig. 4 were determined during induction heating without subsequent forming using six thermocouples Type K. Induction heating takes place in segments I to III, where the power is continuously reduced in each stage to counteract overheating close to the surface. After a total of 28 s, the induction heating is finished and the sample is moved out of the coil by a pneumatic cylinder in segment IV so that an automated robot gripper can transfer the sample into the tool with a transfer time of approx. 5 s. By using the immersion cooling, significantly lower temperatures of 84°C instead of 237°C without cooling (Tc_6) are set in the aluminium part of the sample, while the steel temperatures at $t = 28$ s remain the same for both heating strategies reaching nearly 800°C (Tc_3). When comparing the material centres (Tc_3 and Tc_6), a temperature gradient of 694 K can be set with the help of cooling, while only 532 K are achieved without cooling. This corresponds to an increase of approx. 30.5%. An estimated yield stress of about 250 MPa for steel and about 140 MPa (uncooled) and 175 MPa (cooled) for the aluminium is set for strain rate of $\dot{\varphi} = 10$ 1/s and $\varphi = 0.4$.

Impact Extrusion

The forward rod extrusion of the specimens was carried out on a Lasco SPR 500 screw press and took place immediately after the transfer from the induction heating in the tooling system seen in Fig. 5a). To reduce tensile stresses inside the component, a counterpressure $p_{Counter}$ = 160 MPa was generated by four gas springs, which are connected to the counter punch via a transverse beam. The process is designed in such a way that the counterpressure acts on the component shortly before the joining zone passes the extrusion shoulder.

To observe the influence of the forming process on the geometric shape of the joining zone, the immersion depth of the punch was varied in a range of 8 mm with a step width of 2 mm. The relative forming path *s* (see Fig. 5 b)) describes the distance of the joining zone beyond the lower extrusion shoulder. In the case of a negative value for *s*, the joining zone has not passed the lowest point of the impact extrusion shoulder.

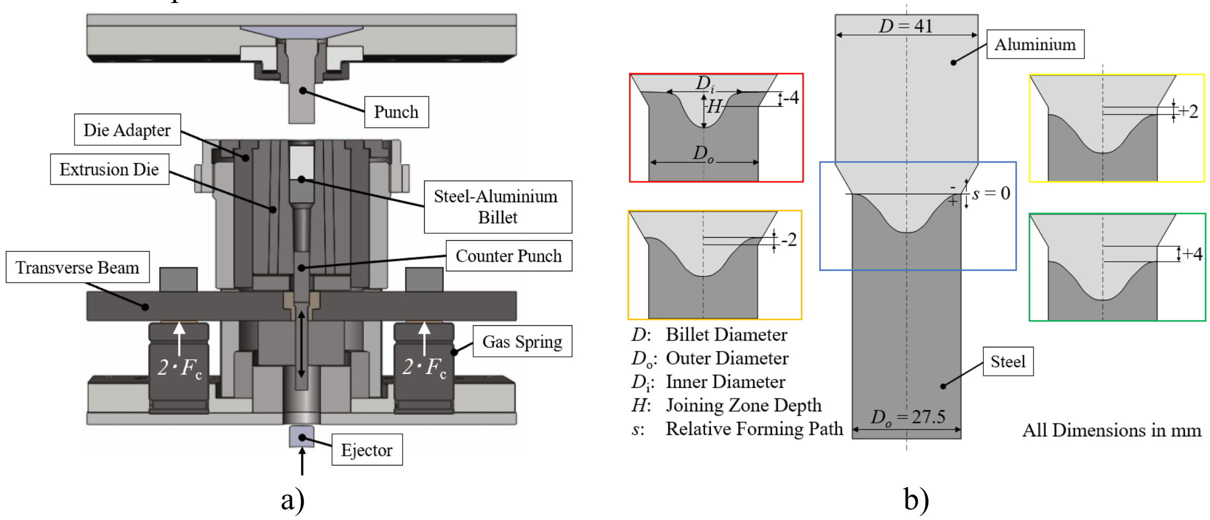


Fig. 5. a) Tooling system for forward rod extrusion [19], b) Formation of the joining zone geometry after impact extrusion depending on the relative forming path s.

After forming, the samples were quenched in a water bath. To avoid thermal cracking, first the aluminium was quenched for 1 s, then the steel for 5 s and again the aluminium for 5 s, before the entire specimen was completely immersed for another 20 s. The samples were then cross-sectioned to measure the inner and outer diameter such as the depth of the joining zone to calculate the surface enlargement. The joining zone has a paraboloid geometry, which is why the modified surface area A_{JZ} was calculated approx. using the following equation:

$$A_{Jz} = \frac{\pi\cdot(\frac{D_i}{2})}{6\cdot H^2}\left[\left(\left(\frac{D_i}{2}\right)^2 + 4\cdot H\right)^{\frac{3}{2}} - \left(\frac{D_i}{2}\right)^3\right] + \frac{\pi}{4}(D_o^2 - Di^2) \quad (1)$$

At a relative forming path *s* = -4 mm, the joining zone has not yet fully passed through the impact extrusion shoulder, which is why the paraboloid geometry is not found over the entire cross-section. Therefore, the unformed circular ring (D_o - D_i) was taken into account in the calculations. Samples with *s* = +4 were further prepared metallographically. Light microscopic and SEM images as well as EDX analyses were performed using a field emission scanning electron microscope Supra VP 55 to evaluate the cooling effect and the forming sequence on the joining zone geometry and quality as well as the emerging IMC.

Results and Discussion

The joining zone depth *H*, which contributes significantly to the surface enlargement, increases with higher relative forming paths *s* and reaches its maximum for *s* = +4 (see Fig. 6). In this case a joining zone surface of $A_{JZ} = 1010.11$ mm^2 is obtained which corresponds to a surface enlargement of approx. 70% compared to the unaffected, flat joining zone after friction welding or with initially aluminium formed. The measured and calculated values for each variation are shown in Table 2. As the joining zone is passing through the extrusion shoulder, steel forms a funnel, dragging the materially bonded aluminium along with it. The material is drawn more strongly into the centre due to the locally varying forming speed and forms the funnel shape in the absence of subsequent material flow. With increased relative forming path *s*, the effect mentioned becomes stronger, which is why the shape of the joining zone between steel and aluminium is characterised by a steadily increasing joining zone depth *H*.

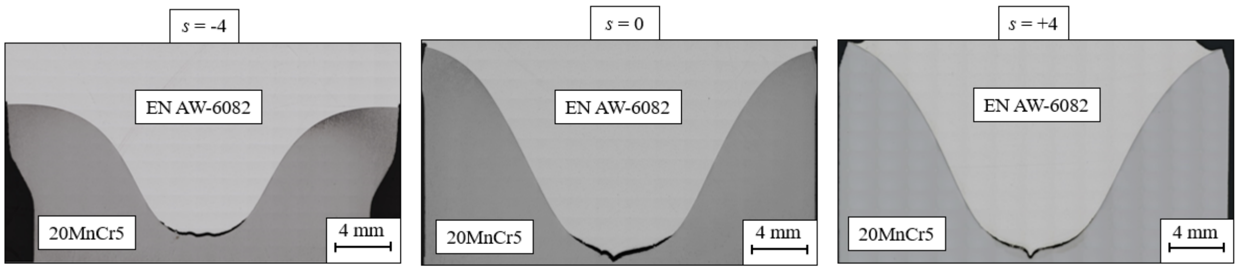


Fig. 6. Exemplary images of the joining zone formation for s = [-4, 0, +4].

Table 1. Comparison of the surface enlargement depending on relative forming path s.

Initially Formed Material	Relative Forming Path *s* [mm]	Inner Diameter D_i [mm]	Outer Diameter D_o [mm]	Joining Zone Depth *H* [mm]	Joining Zone Surface A_{JZ} [mm^2]	Surface Enlargement [%]
Aluminium	4	27.5	27.5	0	593.96	0
Steel	-4	21.8	27.5	9.5	803.44	35.2
Steel	-2	27.5	27.5	12.35	943.67	58.88
Steel	0	27.5	27.5	12.9	968.58	63.07
Steel	2	27.5	27.5	13.3	986.92	66.16
Steel	4	27.5	27.5	13.8	1010.11	70.06

The occurring defect in the centre of the specimen is caused by the funnel formation, which usually occurs in monolithic semi-finished products due to a lack of subsequent material flow at the end of the forming process [20]. A locally weak bond in the centre of the joined materials before forming is pre-existent, due to low relative friction speeds in the friction welding process. Combined with an increased forming speed in the centre and differing yield stresses, a detachment of the two materials is very likely. The defect can mostly be avoided if the extrusion takes place with high friction between the extrusion die and the specimen [21]. In this regard the use of a counterpressure can set the required stress state [11-13]. Since the gap was nevertheless observed during the tests carried out, it can be assumed that the set of a counterpressure $p_{Counter} = 160$ MPa is not sufficient to completely compensate the tensile stresses acting in the joining zone.

The greater temperature gradient caused by the immersion cooling (see Fig. 4) provides a better equalisation of the yield stresses, thus a lower deformation resistance ratio and therefore a less pronounced paraboloid shape. Furthermore, the constriction of the aluminium is largely prevented (see Fig. 7) so that, unlike the sample without cooling, no gap extends over the entire circumference of the component surface near the joining zone. Due to the improved material flow, the central defect is also slightly reduced from 132 µm to 53 µm, but cannot be completely prevented. The influence of the partial cooling is also reflected in the measured hardness (HV0.1), which show an average increase of 12 HV from 61 HV without cooling to 73 HV with cooling for the aluminium. The hardnesses in the steel are subject to relatively large deviations, but also increased slightly on average by 8 HV from 283 HV to 291 HV.

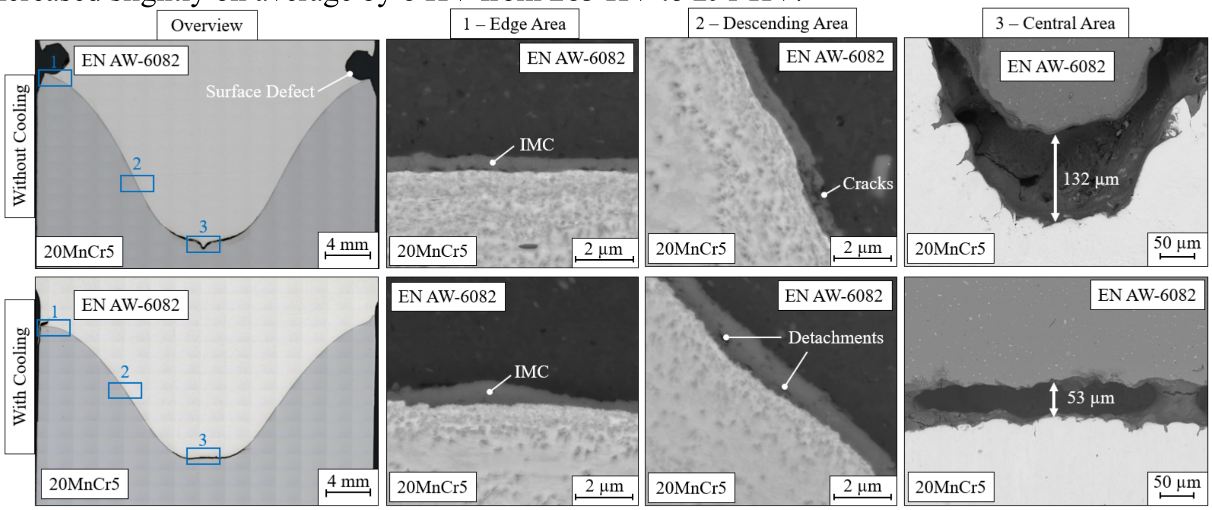


Fig. 7. Metallographic and SEM images of the joining zone (s = +4 mm) without and with cooling with a counter pressure of $p_{Counter}$ = 160 MPa.

Regardless of the used heating strategy, the formed IMCs have been influenced by the surface enlargement leading to a relatively homogenous structure. The thickness in the edge area as well as in the descending area is varying between 0.6 to 0.8µm. Near the central area, the brittle IMCs are destructed after forming due to the detachment between the two materials. The IMC thicknesses in the edge area are approx. in the same size range compared to the thicknesses in the central area, which is why no thinning of the IMC can be certainly observed due to the surface enlargement. However, since the IMC does not exceed the critical thickness of 1 µm [16] combined with the increase in surface area compared to a flat joining zone, a potential improvement of the bond strength can be assumed.

As expected, the chemical composition in the joining zone was not influenced by the cooling. An EDX line scan of the specimen without cooling at a forming path of s = +4 mm (see Fig. 8) is exemplary shown in Fig. 8. A diffusion and hence a deposition of manganese and silicon into the area of the joining zone with a concentration of up to 5 wt.% is seen, indicating the existing IMC.

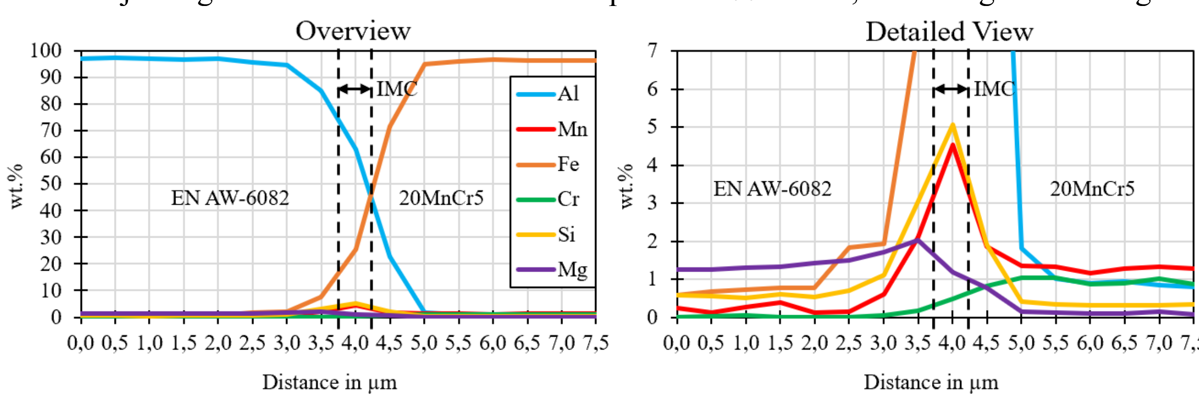


Fig. 8. EDX analysis of the descending area for a specimen without cooling (s = +4 mm).

Summary
In this study, a forward rod extrusion process was used which, based on preliminary work, focused on the forming sequence and the use of partial cooling for the aluminium side. The variation of the forming path showed a material flow-related increase of the surface enlargement of up to 70%. Furthermore, the complete passing of the joining zone through the impact extrusion shoulder resulted in defects near the surface as well as on the interior, which could be reduced with the help of the improved material flow through immersion cooling. A homogenous formation of the IMC is ensured in the enlarged areas. Partial detachments or cracking of the IMC was observed regardless of cooling in the areas with increased surface area, especially in the centre at the highest material flow rates. For future work, the counter pressure should be increased further in order to compensate the tensile stresses that occur for a defect-free bond. Furthermore, mechanical tests should be carried out to prove that the enlarged surface also improves the bond strength of the joining zone. To investigate the possible adjustable maximum temperature gradients, selecting other cooling strategies such as air-spray cooling should be considered.

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