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Fabrication of steel-aluminium parts by impact extrusion

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ABSTRACT

The impact extrusion of axially arranged steel-aluminium billets was studied in this research. Two different bi-material billet concepts were considered: discrete and prejoined billets. Discrete billets were formed in order to achieve a joint through plastic deformation. Prejoined billets were created by friction welding beforehand and their behaviour under plastic deformation was investigated. Pressure superposition was utilised to improve the resulting bond strength by changing the stress state in the joining zone during forming. Depending on the magnitude of the applied counter pressure, the resulting bond strength could be influenced positively. It was also shown that the effect of die shoulder angle was not significant for the achieved bond strengths. The findings suggest that elevated billet temperatures can eliminate the need for counter pressure.

1. Introduction

The issues of climate change and environmental degradation have become increasingly relevant for the manufacturing industry during recent years. Both legal regulations and interest in new technologies, such as electromobility, have expanded the demands for more efficient machine elements. Lightweighting, for instance, can be achieved through multi-material designs. Since components generally do not experience uniform loads in use, steel and aluminium can be used for areas subjected to higher and lower loads, respectively. The combination of steel's high strength and aluminium's low density within a hybrid machine component enables a functional design that can provide the required strength at a lower weight. According to Tekkaya and Min, lightweight technologies, such as the use of advanced high-strength steels, Al and Mg alloys, carbon fiber-reinforced polymers and hybrid metal-polymer composites, will continue to play a crucial role in the automotive industry in the future [1]. This eventually necessitates the further development of innovative joining and forming processes to employ the right material in the right place (Fig. 1).

Cold pressure welding describes joining at room temperature, which allows two similar or dissimilar materials to be joined together. The plastic deformation required for coalescence is achieved through high compressive forces. Fahrenwaldt et al. state that – unlike friction welding – no intermetallics are formed in cold pressure welding, as the process is carried out at room temperature [2]. For a successful execution of the cold pressure welding, welding surfaces should be in close contact in the beginning. Under the application of high degrees of plastic deformation, the oxide layers, which are of brittle nature, break up and the virgin base metals come into direct contact and form a metallurgical bond [3]. Materials such as copper or aluminium are particularly suitable for cold pressure welding. Their good formability results in a higher surface expansion profile in the joining zone, which facilitates the fracture of oxide films.

The bond strength that can be achieved via cold pressure welding is equal to the strength of the softer base metal. During impact extrusion, however, even a higher strength can be achieved through the accompanied work hardening of the softer base metal. Lange et al. characterised impact extrusion by high material utilisation, high productive capacity as well as its ability to promote work hardening for manufacturing value-added products [4]. This makes cold extrusion a suitable process to manufacture lightweight steel-aluminium components. Groche et al. studied the influence of process variables on the welding of steel and aluminium by cold extrusion [5]. The billets' initial microstructural states, height ratio as well as the treatment of welding surfaces were investigated. They found that the precipitation hardened state of aluminium alloys are more suited for processing than the soft annealed state if the intention is to obtain a sound bonding behaviour with steel.

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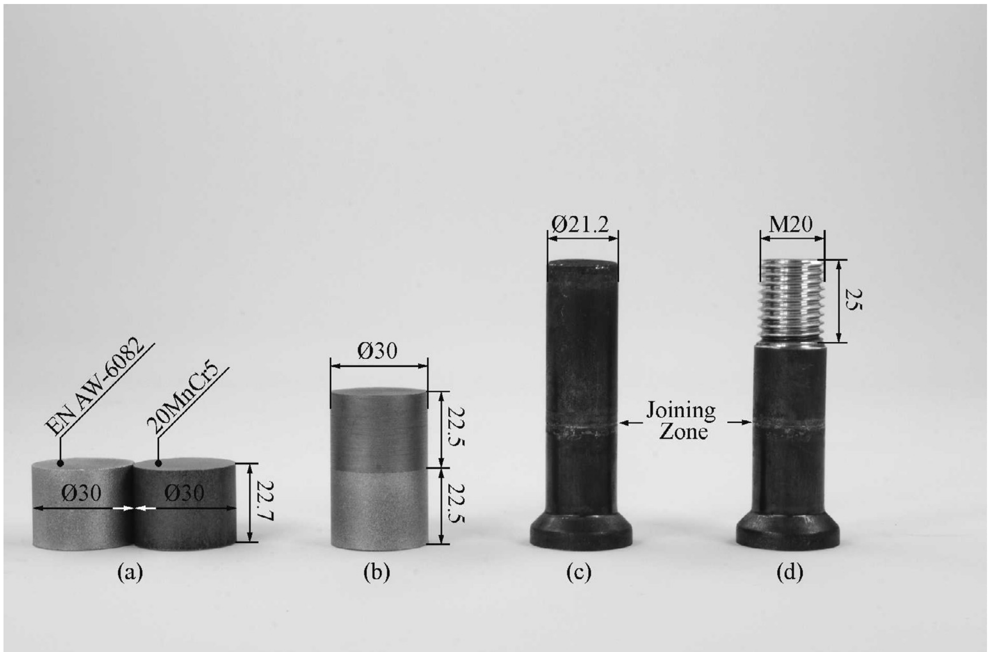

Fig 1. (a) Discrete billets; (b) prejoined billets; (c) extruded workpiece; (d) specimen for tensile test.

Some studies tackled the question of whether working at elevated temperatures can be favourable for bond formation. Wohletz and Groche investigated the influence of individual workpiece temperatures on the interface between C15 steel and EN AW-6082 aluminium alloy [6]. A design of experiments was applied that involves different initial temperatures. These ranged from 20 to 600 °C for steel and from 20 to 200 °C for aluminium. It was shown that a good bond could be achieved for certain combinations of temperatures, whereas other combinations led to cracks or imperfect joining zones. Kriwall et al. studied the joining of sheet steel and bulk aluminium by deformation [7]. Prior to the joining process, a zinc coating was applied in the joining zone by hot dipping. Forming experiments were carried out in a temperature range between 220 and 375 °C taking into account the behaviour of the zinc layer at elevated temperatures. The most promising results could be obtained at 350 °C. The forming tools were also heated to this temperature to avoid the disadvantages resulting from the heat dissipation during the process.

Defects can develop in the workpiece during impact extrusion processes and affect the product properties in a negative way. Balasundar and Raghu have dealt with the formation of funnel-shaped flow defects in forward rod extrusion [8]. They found that the formation of a so-called funnel is dependent on the area reduction and cone angle of the extrusion die. Increased friction could also prevent the onset of defect formation. Valberg et al. also showed how surface material relocates into the interior of the workpiece and induce a typical funnel defect [9]. They gave a detailed explanation of the mechanism based on simulation results. Ko and Kim studied the occurrence of central bursts, also referred to as chevron cracks, in forward rod extrusion [10]. They reported that by choosing appropriate values for area reduction and die shoulder angle, the stress state can be influenced to prevent such defects. Provided that the process takes place under identical frictional conditions, reducing the area change and increasing the die shoulder angle would result in central bursting in the workpiece.

Many researchers utilised stress superposition as a means to control defects occurrence in metal forming. Wagener et al. could produce defect-free parts from materials that are typically brittle at room temperature [11]. They used a counter punch acting on the tip of the extrudate to shift the stress state to compression during deformation. Soyarslan and Tekkaya also reported that material formability can be increased by applying counter pressure [12]. They could show that chevron crack sizes depend on the magnitude of applied counter pressure and become smaller with increasing pressure. Cracks completely disappear after a certain threshold, which was around 200 MPa for 100Cr6 workpiece material used in the study. Choi et al. claimed that the following parameters influence the formation of chevron cracks: area reduction, die shoulder angle, friction, properties of workpiece material [13]. Hoche et al. stated that the application of counter pressure affects the residual stress distribution considerably and thus can be used as a method for controlling product properties without a significant change in the processing time [14]. Ossenkemper et al. dealt with forward rod extrusion of steel casings filled with aluminium cylinders [15]. Application of counter pressure appeared to have no influence on the expansion of the steel-aluminium interface, but the contact pressures here could be altered.

Friction welding is another suitable process to join steel and aluminium. Ma et al. investigated varying rotation speeds between 1100 and 1700 rpm and friction pressures between 120 and 180 MPa in the friction welding of X5CrNi18-10 stainless steel and EN AW-2014 aluminium alloy [16]. They showed that the highest tensile strength of 325 MPa is obtained when the heat generation is kept at an intermediate level. In addition, an increase in the size of the intermetallic phases was observed at higher occurring temperatures, which resulted in lower bond strength as well as poorer corrosion behaviour. Herbst el al. also reported that shorter contact times and low heat input are the factors favouring the bond strength of friction welded steel-aluminium joints [17]. They presented an almost linear decrease of the resulting bond strength with increasing thickness of the intermetallic phases. Behrens et al. investigated the bond strength of conical shaped surface geometries. Compared to flat surfaces, they were able to improve the bond strength from 252 to 294 MPa by using a 30° inclined surface [18].

The studies in the field have so far dealt with the hybrid extrusion of steel and aluminium, the influencing variables, the defects that arise and possible countermeasures, such as the application of pressure superposition. In the Collaborative Research Centre CRC 1153 'Tailored Forming', a wide variety of material combinations and manufacturing processes are being researched with the aim of producing bimetallic machine parts. So far, many promising results have been achieved for similar material combinations [19,20]. This study is concerned with a dissimilar material combination: steel and aluminium alloy. Impact extrusion at room temperature was carried out with two different bi-material billet concepts: discrete and prejoined billets. Pressure superposition was utilised to prevent defects and improve the bond properties. The results were compared with the previous results at elevated temperatures.

2. Material and methods

The workpiece materials used in the study are a case hardening steel 20MnCr5 (AISI 5120) and a wrought aluminium alloy EN AW-6082 (AA6082). 20MnCr5 is usually case hardened to provide good wear resistance with core toughness. EN AW-6082 includes magnesium and silicon as main alloying elements and is favoured due to its good strength-to-weight ratio after T6 heat treatment. The 20MnCr5 steel material was supplied soft annealed, while the EN AW-6082 was delivered in T6 condition.

2.1. Preparation of bi-material forging billets

Bi-material billets were manufactured by friction welding 20MnCr5 with EN AW-6082. The steel and aluminium rods were face turned to ensure the relatively fine welding surfaces are plane-parallel to each other. This was followed by ultrasonic cleaning of the welding surfaces. A holder was placed over the cleaner that allows mounting multiple workpieces. Welding surfaces were submerged in an alcohol based cleaning agent and the ultrasound was switched on for three minutes with a frequency of 40 kHz at 120 Watt. After ultrasonic cleaning, the agent residue was given time to evaporate from welding surfaces and the workpieces were mounted in the friction welding machine.

With a rotational speed of 1600 rpm, 130 MPa friction pressure was applied and the aluminium was allowed to shorten 4 mm after which the workpieces were pressed with a forging pressure of 225 MPa. During friction welding, steel remains practically rigid, whilst aluminium undergoes severe plastic deformation and the oxidised top layer is displaced to the flash. The friction leads to an increase of the temperatures in the joining zone. The generated heat rapidly dissipates from the joining zone. The dissipation is more rapid in the aluminium because of its high thermal conductivity. Control of the heat generation is crucial and excessive heat should be prevented; because high temperatures can lead to an unfavourable growth of brittle intermetallic phases in the joining zone. Thus, the selection of a short friction time or alternatively a shorter axial shortening with high friction pressure was preferred in this study.

After friction welding, the flash developed around the joining zone was removed by turning. Subsequently, the workpieces were cut off by sawing and then face turned to the required length. Sandblasting with steel shots was used to roughen the surfaces and to facilitate a better adhesion of a lubricating layer. A MoS_2 based lubricating coating was applied by dipping on the billets.

The discrete workpieces were prepared differently, all surfaces of every individual steel and aluminium billets were coated with the same lubricating layer as the friction welded ones. Immediately before extrusion, one end face of each pairing billet was face turned and a cleaning agent was applied to remove any possible residues. Steel and aluminium billets were then stacked inside the extrusion die with the turned surfaces facing each other.

2.2. Impact extrusion

Forward rod extrusion is a compressive stress dominated forming process; yet the stress state of a material point in the workpiece can also be subjected to tensile stresses with progressing deformation. As far as the extrusion of bi-material workpieces is concerned, tensile stresses cause the aluminium to separate from the steel and thus adversely affecting the bond strength. Separation can take place either completely or partially, the latter being especially critical if it develops in form of an internal defect, which cannot be detected through visual inspection. In order to maintain the bond between steel and aluminium, tensile stresses in the joining zone should be minimised or eliminated. To this end, forming experiments were carried out by using an impact extrusion tooling system with a fitted counter pressure superposition mechanism. The intention here is to superpose compressive axial stresses in the workpiece – in the opposite direction of material flow – to control the stress state in the joining zone [21].

The mechanism involves a transverse beam, two nitrogen gas springs and a counter punch. Two identical gas springs support the beam at both ends. The counter punch is in contact with the transverse beam at the centre through conical mating surfaces. They therefore have a synchronised downward motion. The counter punch was precisely dimensioned to make contact with the tip of the extrudate just as the joining zone enters the plastic deformation zone. The applied forces are then transmitted into the gas springs via the transverse beam. The gas springs' vertical lifting force generates the necessary pressure superposition in the bi-material workpiece. Once the initial force of the springs is overcome, the system starts to move in the material flow direction. With increasing spring stroke, the magnitude of counter force increases as dictated by the spring stiffness. Both the initial force and the spring stiffness are dependent on the filling pressure of gas springs that is adjustable. The two counter pressures of 150 and 300 MPa are the averaged values of initial and end forces divided by the cross sectional area of the reduced section of the extruded part.

Two double reinforced extrusion dies were used in the forming experiments. Both have a cross section reduction of 50 %, but differ in their cone angles. One has an angle of $2\alpha = 90°$ and the other has $2\alpha = 135°$. Below the extrusion dies, multiple pressure plates are situated. The top plate is interchangeable according to the diameter of the extrudate. The intermediate plate has no contact with the workpiece and is used for centring and guiding of the counter punch. Bottom plate has a transverse opening and houses the transverse beam whilst axially supporting the components above it. All these axially floating modular tooling components are tightened through an axial pressure generated by an internally threaded locking ring mating the housing.

The forming experiments were carried out on a hydraulic press. The bi-material billets were at room temperature at the beginning of forming. The selection of a relatively slow ram speed of 10 mm/s led to a reasonably low temperature increase in the bi-material workpiece due to plasticity induced heat and in doing so thermal loads on the joining zone could be refrained. Formed workpieces were ejected from the extrusion die by using the die cushion.

2.3. Product testing

Tensile testing was performed on bi-material workpieces with the intention of bond strength determination after extrusion. Machining operations around the joining zone were intentionally avoided in order not to remove any bonded steel-aluminium interface. Thus, the test specimens did not have a standardized dog bone shape with a reduced gauge length. This is a reasonable approach, because bond strengths are sought and the compliances

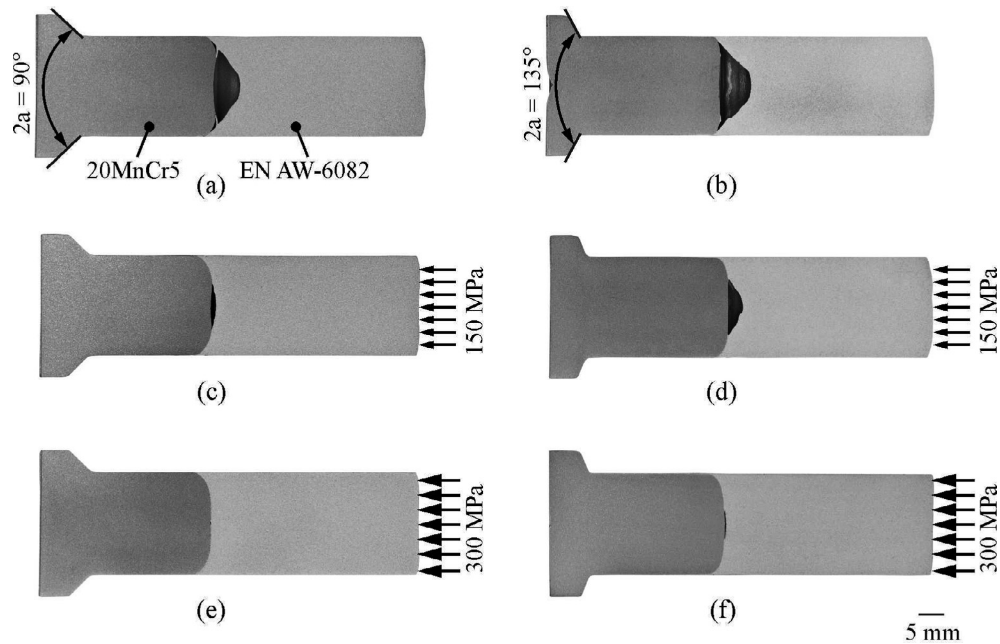

Fig 2. Joining zones influenced by dies' cone angle and applied counter pressure: (a-b) without counter pressure; (c-d) with 150 MPa counter pressure; (e-f) with 300 MPa counter pressure.

resulting from the absence of a gauge length are acceptable and have no influence on the strength results. Besides their nonstandard geometry, the specimens were too small in length to be clamped in the available tensile testing machine. This necessitated the design and fabrication of auxiliary parts for clamping. With regard to clamping the butt-side, the conical surface of the extruded workpiece was utilised for force transmission. The specimen was placed in a threaded female adapter that includes a conical surface to hold and centre the specimen. A male adapter with an extended gripping area is then bolted in the female. Clamping the extrudate-side was achieved through a M20 thread machined at the tip of the extrudate and a matching female adapter with extended gripping area. Fig. 1 shows the parts related to the different process steps.

For comparison, tensile tests were also performed on friction welded workpieces. Unlike extruded specimens, friction welded specimens had a standardized dog bone geometry. The welded workpieces could be chosen long enough to define a gauge length of 70 mm. The testing diameter was reduced from 30 to 25 mm. By this means, any possible break in the gripping area could be prevented.

Tests were executed with a crosshead speed of 0.2 mm/s until fracture. It should be noted that the obtained bond strength results refer to the measured extrudate cross section (Ø21.2 mm) and friction-welded specimen cross section (Ø25 mm). Local strength values vary from centre to edge.

In order to reveal the joining zones, the extruded workpieces were sectioned longitudinally by using wire-cut electrical discharge machining. The sectioned halves were subjected to glass bead blasting to obtain a burnt-free surface and photographed.

3. Results and discussion

No major surface defects were observed after visual inspection beside a marginal funnel formation at the butt side of the workpieces extruded with the $2\alpha = 135^{\circ}$ die. The used tribo-system resulted in a good surface quality. No galling was observed, neither on workpiece nor on die surfaces. All joining zones were situated in the reduced section, almost at the same axial position. The tips of the extrudates became more flattened with increasing counter pressure. Aluminium did not flow in the gap between the counter punch and mid-plate even at the highest counter pressure of 300 MPa.

The sectioned workpieces extruded from prejoined billets are shown in Fig. 2. In all workpieces, a separation at the joining interface is visible and its size is dependent on the applied counter pressure. The size of the central gap decreases with increasing counter pressure. But even for $2\alpha = 90^{\circ}$ and 300 MPa counter pressure, a small gap of 110 μm can be observed at closer look. This is associated with the fact that at the very centre of prejoined billets no bonding is achieved through friction welding as there is no relative movement here in the friction phase.

In all the presented combinations, the gaps became more pronounced, in both height and width, with increasing cone angle of the extrusion die. For instance, the gaps' heights, i.e. the axial separations along the central axis, were measured 5.9 mm and 7.2 mm, for no counter pressure (Fig. 2-a and 2-b) and 1.1 mm and 3 mm for 150 MPa counter pressure (Fig. 2-c and 2-d), with $2\alpha = 90^{\circ}$ and $2\alpha = 135^{\circ}$ dies, respectively. For 300 MPa counter pressure, the gap's width is considerably longer (5.5 mm) for $2\alpha = 135^{\circ}$ die (Fig. 2-f).

A distinct phenomenon is observed in the specimens extruded without counter pressure. Aluminium split up on 3/4 of the radius and a tiny portion of it stuck onto the steel surface. A secondary gap was formed in the outer region for $2\alpha = 90^{\circ}$ (Fig. 2-a). A closer look is necessary to recognise aluminium traces on steel for $2\alpha = 135^{\circ}$ (Fig. 2-b). This indicates that the local bond strength was probably the highest in this particular location, albeit the holding interface was forced to separate substantially with only the edges providing parts' integrity.

Fig. 3 shows the resulting bond strengths obtained by tensile tests. Minimum tensile strength of EN AW-6082 according to DIN EN 755-2 and bond strength of friction welded specimens are also shown as reference values. Disregarding the occurred cracks, it is apparent that by varying the cone angle the geometry of the join-

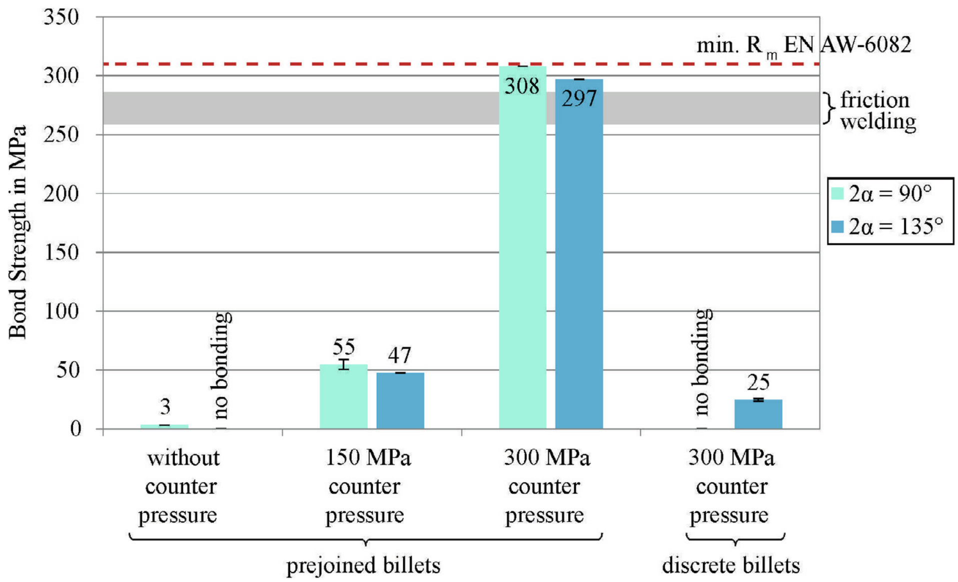

Fig 3. Bond strengths of steel-aluminium joints after cold extrusion, three samples each.

ing zone could not be influenced, as can be seen in Fig. 2-e and 2-f. Thus parameters that play a crucial role in improving the bond strength, such as surface expansion, are invariable through cone angle variations. Therefore, the cone angle did not affect the strength results in this study.

The counter pressure superposition has a positive influence on the bond strength. The bond strength of prejoined billets was actually significantly worsened by extrusion if the counter pressure is not high enough. The specimens extruded without counter pressure had practically no bonding at all. Almost all specimens broke during the machining process. Applying 150 MPa counter pressure could improve the bond strength by about 50 MPa, which yields an 81 % decrease with reference to friction welded specimens. The strength results conform with the cracks observed in the joining zone images. Though, 300 MPa counter pressure could produce a 10 % improvement in the bond strength towards friction welded specimens. It should be noted that M20 threads were broken at ca. 290 MPa in two of the three specimens from these combinations whilst the joining zones remained intact after the test. This implies a bond strength that is higher than 290 MPa for these specimens, although they were taken out for the calculation of the mean values.

The details regarding the processing of prejoined steel-aluminium billets at elevated temperatures were given in [22]. The simulated temperature distribution and the induction heated billet are shown here in Fig. 4-a. Tensile tests carried out on the specimens extruded with inhomogeneous temperature distribution exhibited necking in the EN AW-6082. The joining zone remained intact after the tests. The tensile strength was appr. 160 MPa. This is much lower than the given minimum tensile strength of aluminium in the precipitation hardened T6 state. The heat input through induction heating provokes a softening in the aluminium. An additional precipitation hardening was carried out for aluminium to regain its properties. This involved solution-

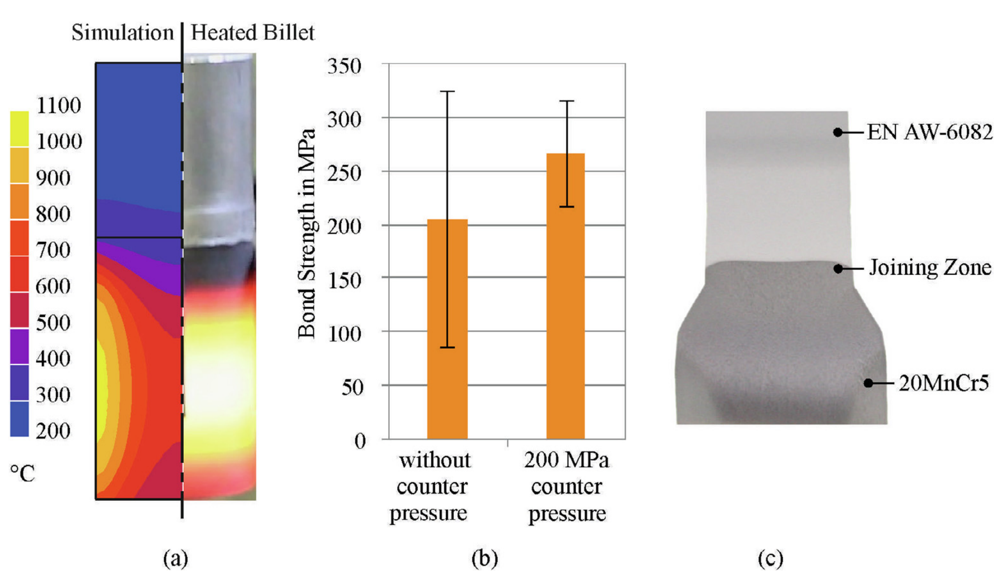

Fig 4. (a) Induction heated hybrid billet; (b) bond strengths of steel-aluminium joints after extrusion at elevated temperatures; (c) joining zone extruded without counter pressure (sample size of four).

izing at 500 °C for 40 min, quenching in water and then artificial ageing at 150 °C for 24 h. The tensile tests were repeated on the heat treated specimens whose results are shown in Fig. 4-b.

By applying 200 MPa counter pressure, the bond strength could be increased by 30 % over the conventionally processed specimens without counter pressure. High deviations were observed, especially when no counter pressure was used in the extrusion. It should be investigated in detail whether these deviations are resulting from the intricate thermal history of the specimens. As distinct from the cold extruded specimens, no macro gaps were observed in the joining zones of warm extruded specimens (Fig. 4-c). For the specimen extruded without counter pressure, however, central micro cracks were revealed under the light microscope [22].

4. Conclusion

In this study, impact extrusion of bi-material steel-aluminium billets was investigated. Besides conventional extrusion, counter pressure superposition was applied on workpieces and its influence on the resulting product properties was studied. Aluminium alloy EN AW-6082 and steel 20MnCr5 were used as workpiece materials. Two different forward rod extrusion dies with the same area reduction but two different cone angles were employed in the study.

In conventionally extruded parts, relatively large gaps occurred in the centre of the part. These defects led to low or no bond strength at all. By using counter pressure during extrusion, the gaps became smaller, but a complete elimination was not possible. The resulting bond strengths were found to agree with joining zone images. A clear trend was observed in bond strength with respect to counter pressure: the greater the applied counter pressure, the higher the bond strength becomes. By using a counter pressure of 300 MPa, an increase in the tensile strength up to 308 MPa could be obtained.

In the comparison of discrete and prejoined billets, a clear disadvantage became prominent for the billets that were previously not friction welded. It is shown that discrete parts can yield only a low bond strength despite using a counter pressure of 300 MPa, whilst without counter pressure, no bond could be produced. This implies the importance of prejoining since the problems regarding surface cleanliness can be addressed efficiently.

The occurrence of gaps in the joining zone could be eliminated when the extrusion was carried out at elevated temperatures. Using counter pressure made no difference in the geometry of the joining zone. Central cracks in the micro-scale were observed in the specimens extruded at elevated temperature without counter pressure. The resulting bond strengths also agree with these observations. High deviations suggest that the cracks might have occurred in only some of the specimens. In addition to the possibility of achieving complex geometries and processing a wider range of materials, utilising heated steel-aluminium billets can produce good bonds without having to use the pressure superposition. Furthermore, the heat input can contribute to the diffusion between the metals. Using prejoined billets is especially advantageous here, as the generation of any oxide layer in the joining zone can be hindered.

In summary:

- The impact of the cone angle on the bond strength shrinks with increasing counter pressure
- Cold forward extrusion of discrete billets can achieve a bond by utilising counter pressure
- The bond strength of prejoined cold extrusion parts increases with counter pressure
- Heating the steel before extrusion with counter pressure resulted in a good bond strength, but needs further investigation

CRediT authorship contribution statement

Bernd-Arno Behrens: Supervision, Funding acquisition. **Johanna Uhe:** Writing - review & editing, Project administration. **Furkan Süer:** Writing - original draft. **Deniz Duran:** Writing - original draft, Conceptualization, Methodology, Investigation. **Tim Matthias:** Writing - review & editing, Conceptualization. **Ingo Ross:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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