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Characteristics of joining and hybrid composite forging of aluminum solid parts and galvanized steel sheets

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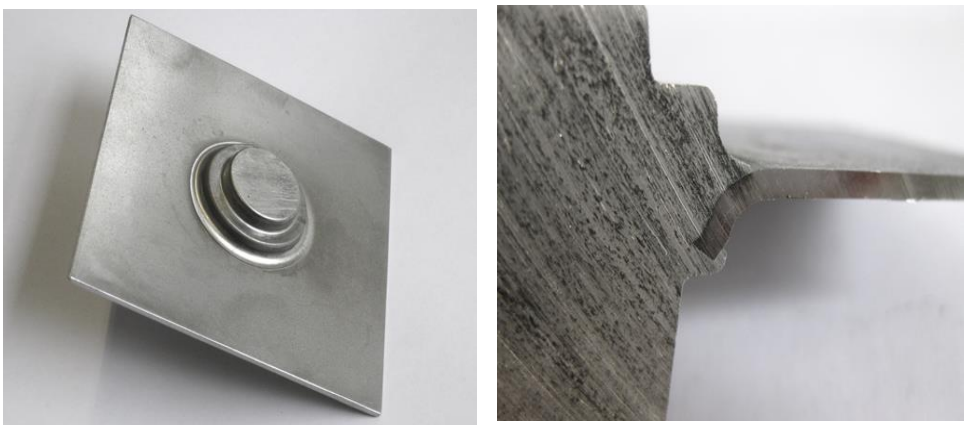
Abstract. In lightweight construction, light metals like aluminum are used in addition to high-strength steels. However, a welded joint of aluminum and steel leads to the precipitation of brittle, intermetallic phases and contact corrosion. Nevertheless, to use the advantages of this combination in terms of weight saving composite hybrid forging has been developed. In this process, an aluminum solid part and a steel sheet were formed in a single step and joined at the same time with zinc as brazing material. For this purpose, the zinc was applied by hot dipping on the aluminum in order to produce a connection via this layer in a forming process, under pressure and heat. Due to the formed intermediate layer of zinc, the formation of the Fe-Al intermetallic phases and the contact corrosion are excluded. By determining the mathematical relationships between joining parameters and the connection properties the strength of a specific joint geometry could be adjusted to reach the level of conventional joining techniques. In addition to the presentation of the joint properties, the influence of the joining process on the structure of the involved materials is also shown. Furthermore, the failure behavior under static tensile and shear stress will be shown.

1. Introduction

To save weight in constructions and to reduce the consumption of resources during production process and operation multi-material designs are being used more and more frequently. The components are adapted to the loads, so the best material is used at the point of loading. As aluminum has a low density and steel a high degree of strength these two materials are particularly suitable for a multi-material design. However, this poses some challenges for the joining technique because the used materials have different mechanical and metallurgical properties. As soon as aluminum and iron come into contact in the molten state they form brittle intermetallic phases. Furthermore, the difference in electronegativity of the two materials leads to contact corrosion. To join these two materials despite their properties mechanical joining processes like riveting, clinching, etc. or gluing are frequently used. But also connections with metallic continuity are possible as several studies have shown. Meco et al. investigated the influence of the intermetallic phases and the width of the heat affected zone as a function of the temperature during the laser beam welding process of aluminum and steel. They showed that a narrow heat-affected zone with a low proportion of intermetallic phases is as damaging to the strength as large pronounced phases themselves, [1]. Kashani et al. showed that the strength of the compound increases when the size of the intermetallic phases is less than 10 microns, [2]. Zhang et al. investigated the influence of zinc in the grinding of aluminum and steel. They found that the zinc from the coating of the steel sheet has a positive influence on the formation of the intermetallic phases and thus on the strength, [3].

Engelbrecht et al. developed parameters for a laser soldering process to avoid a melting of both materials. In this case, aluminum and steel should also be isolated from each other as it can also lead to the formation of intermetallic phases in the solid state, [4]. Reisgen et al. also examined the formability of an arc-blended mixed aluminum / steel compound, [5]. In addition, hybrid composite forging has been developed, [6–8]. In this process, the two materials are joined to each other without transition to the molten state in a material-tight manner. The peculiarity of the method is that only one process step for forming and producing the connection is necessary. So far, this was done separately. Such a connection shows figure 1. Figure 1b) clearly shows the mechanical clamping of the created joint.



a) b)

Figure 1: a) hybrid forging joint; b) micrograph of the joint

This process is now transferred to the joining of aluminum solid parts with galvanized steel sheets. Cause zinc has a positive influence on the formation of the phases, an intermediate layer was considered to realize the compound. In the first step, the aluminum solid parts were coated with zinc. In the second step, the galvanized aluminum was bonded to the galvanized sheet steel under pressure and temperature.

Table 1: Material properties of AlMg4,5Mn and Dx54+Z

For the experiments the aluminum alloy AlMg4,5Mn and steel grade DX54 + Z (thickness 1 mm) is used. The material characteristics are listed in table 1. For the joining process, the yield strength and compressive strength of the AlMg4.5Mn were additionally determined.

	tensile strength	Yield strength	Young's Modulus	Breaking elongation	compressive yield strength
AlMg4,5Mn	329 MPa	223 MPa	92.400 MPa	14,36 %	328 MPa
DX 54+Z	260 MPa	120 MPa	210.000 MPa	36 MPa	-

Table 2: chemical composition of AlMg4,5Mn

Al [%]	Mg [%]	Mn [%]	Fe [%]	Si [%]	Cr [%]	Zn [%]	Cu [%]	Ni [%]
94,3	4,489	0,515	0,3042	0,1555	0,0796	0,0470	0,0403	0,0020

The chemical composition of the aluminum material is listed in table 2. This material has a good weldability and corrosion resistance. Therefore, it is often used in apparatus, container and vehicle. Due to the good low temperature properties and seawater resistance this alloy is also used in shipbuilding.
The DX 54 is a hot-dip galvanized deep-drawing steel that is mainly used in vehicle construction.

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2. Hot dipping of Aluminum

To apply the zinc layer on the aluminum stud the process of hot dipping steel was transferred. The bolts were left in the furnace for 20 minutes at 420 °C in the zinc melt. The molten zinc used corresponds to a near-eutectic zinc-aluminum alloy to avoid melting of the bolt edges due to the low-melting eutectic. The classification of the melt in the phase diagram is shown in figure 2. It is composed of 17% aluminum and 83% zinc and is therefore a hypoeutectic alloy. The melting temperature of this composition was found to be 378 °C. Figure 2 also shows micrographs of the hypereutectic and eutectic composition in the cut. The layer thickness of the zinc coating on the aluminum is between 50 and 150 microns. Below this layer, a diffusion layer is formed during coating in which the zinc content decreases with increasing distance to the surface. **Figure *3*** shows the aluminum bolt with the zinc layer on the left. The cross section of this layer can be seen in the right part of the figure.

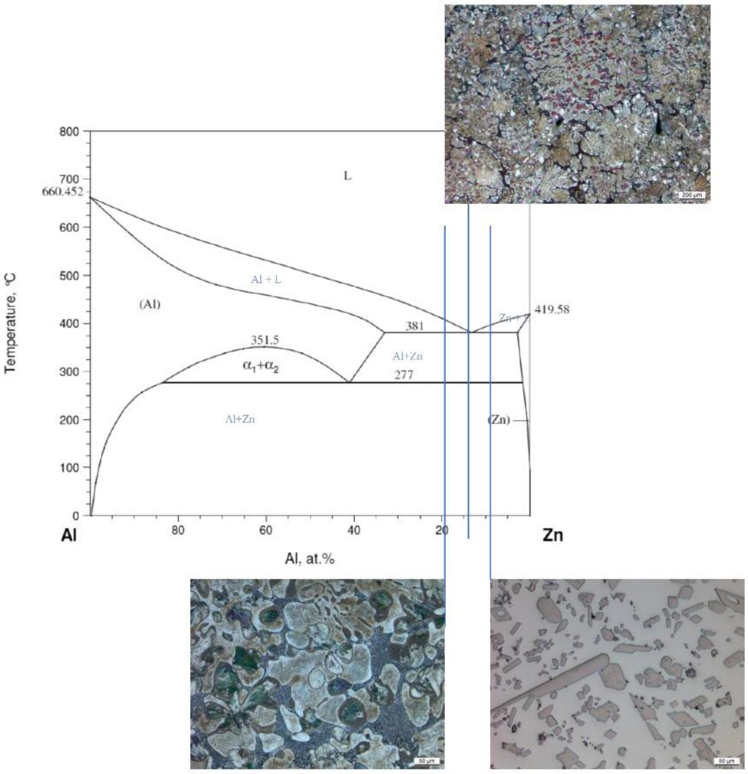

Figure 2: Phasediagram of Al-Zn; Source: Materials Science International Services GmbH

The layer thickness can be adjusted by stripping the liquid melt after removal from the zinc bath. The investigation of the coating in the scanning electron microscope with the energy-dispersive X-ray spectrometry (EDX) clearly showed that a nearly pure zinc layer was formed, which increasingly grows in the course of the bolt with aluminum.

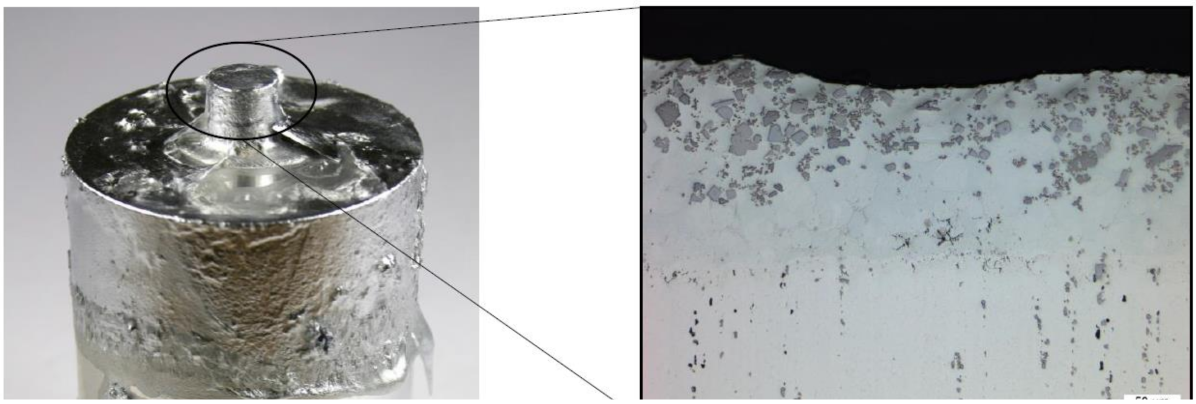

Figure 3: Zinc coating on aluminium

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3. Joining of the aluminum and the galvanized steel sheets

The joining tests were carried out with a tensile compression test bench in an oven. The experimental setup is shown in figure 4. The aluminum studs were hung from the upper punch in a die and heated by natural convection for 20 minutes before the joining process was performed.

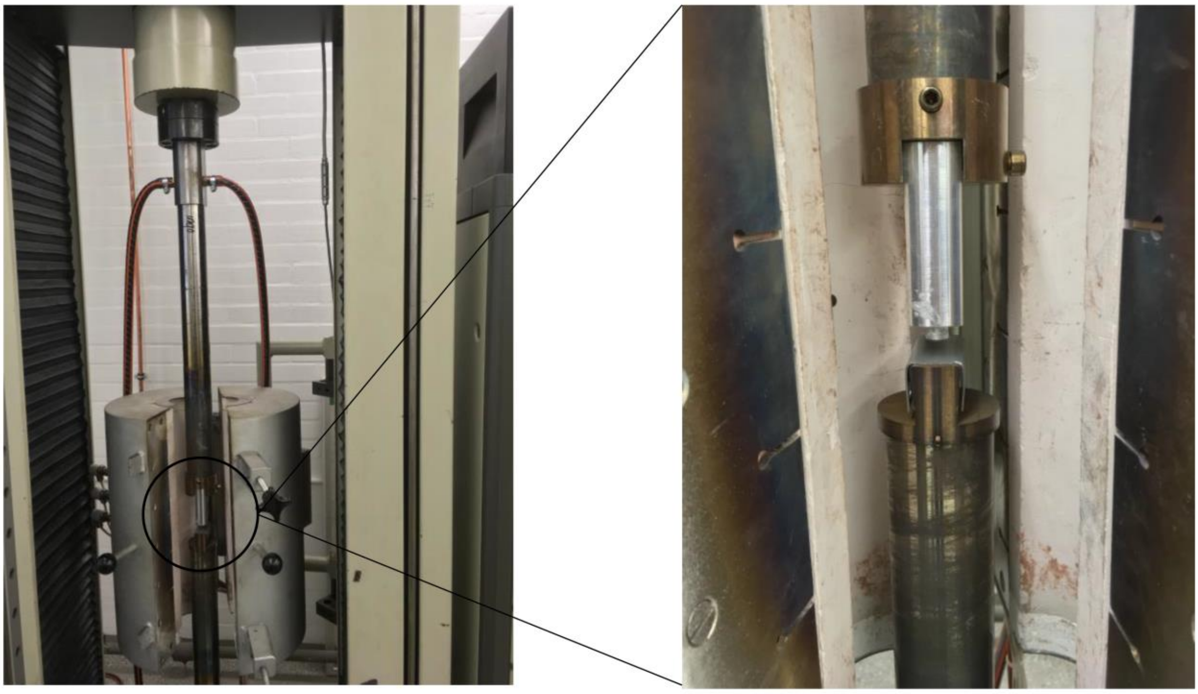

Figure 4: Testing setup

On the lower punch, the produced steel sheet samples were placed on a die. The sheets were also pre-heated. After the preheating time, the punches were used to approach the predetermined force at the specified speed. The parameters were varied with the aid of a D-optimal test plan to make an adequate statement about the process window with the lowest possible number of tests. The parameter field is shown in table 3.

Table 3: Joining parameters

Oven temperature in °C	Specimen temperature in °C	Punching speed in mm/min	Punching force in kN
375 - 500	220-375	5-18	15-40

The head tensile strengths of the individual samples were subsequently determined by tensile testing.

4. Results

The applied force and the introduced heat lead to a metallic continuity of the zinc layers of both specimen halves. Figure 5 shows a cross section of the joining area. The joint of the two materials over the zinc layer is clearly recognizable here. The diffusion layer is also visible, which is located in transition of the zinc layer to the aluminum base material.

The base material of the DX54 + Z has not got influence from the zinc during the joining process. The structure has been completely preserved compared to original state.

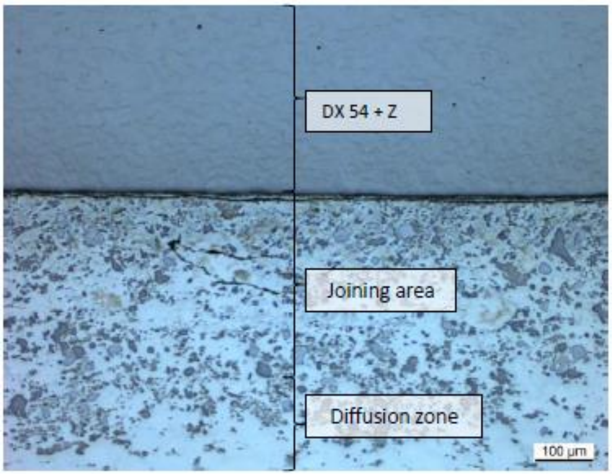

Figure 5: Joining area

The chemical composition of the joining area is shown qualitatively in the SEM image in figure 6, clearly to see is the abrupt decrease in iron content and the immediate increase in zinc and aluminum content. The proportion of aluminum in the connection zone is only slightly lower than the zinc content, but much lower than in the case of the parent material. The amount of iron in this area is close to zero. This shows that no diffusion of the iron has taken place and the associated formation of the brittle intermetallic phases has been prevented. The composition of the chemical elements in the joining zone suggests that a cohesive zinc-zinc compound was formed which was formed from the two zinc layers on the base materials. The lower melting point of the zinc also prevents the formation of intermetallic phases as the base materials do not have to be melted.

Furthermore, the resulting intermediate layer leads to the shielding of the materials, whereby the contact corrosion is also prevented.

The geometry of the tensile specimens produced in the joining process is shown in figure 7.

The cross sections in figure 7 show the used materials before the joining process. The two zinc layers are clearly visible. While the zinc layer on the steel sheets is a few microns thick the layer thickness on the aluminum is between 50 and 150 microns.

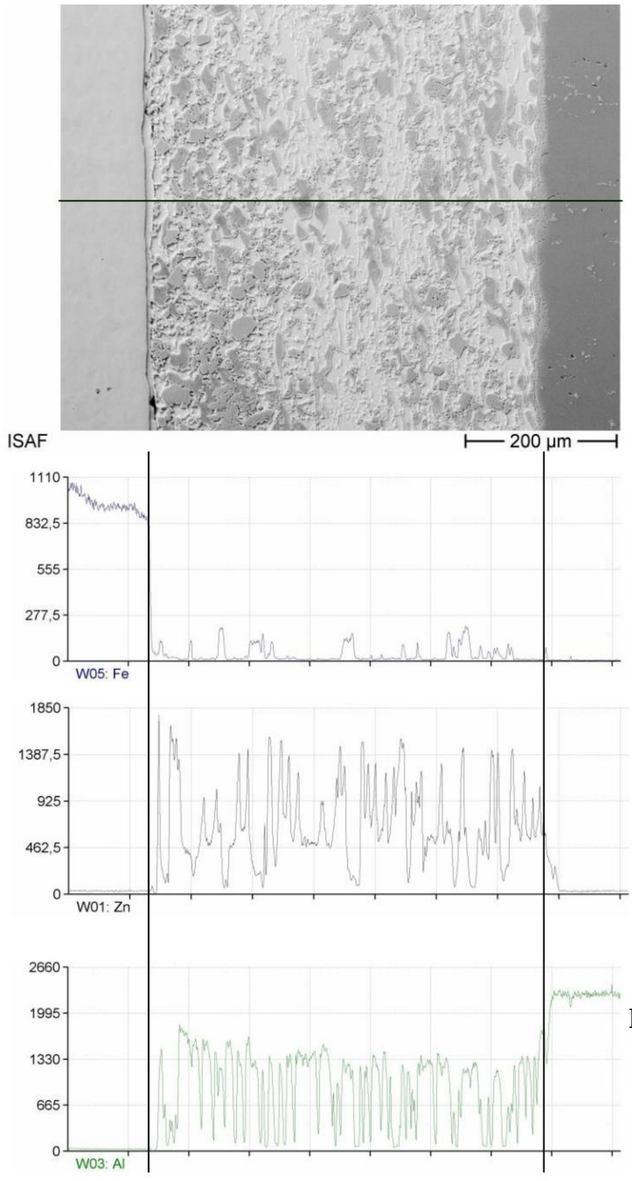

Figure 6: SEM-EDX analysis of the join-

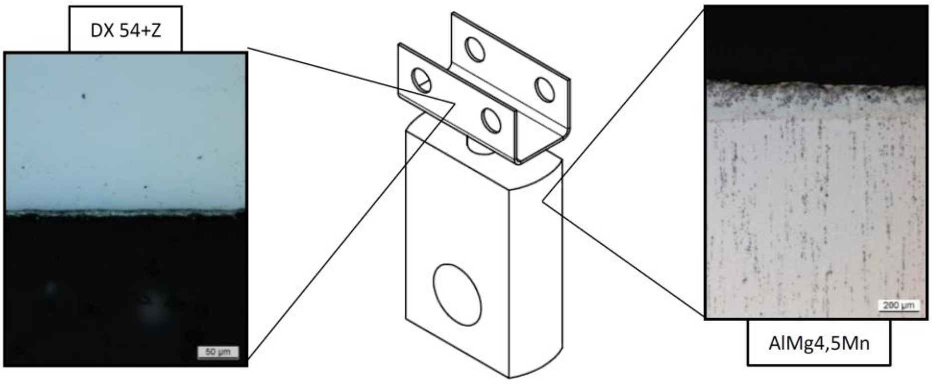

Figure 7: Specimen geometry and micrographs of the used materials

The force-displacement curves determined in the tensile test for the samples, which were joined at oven temperatures between 410 and 500 ° C, are shown in figure 8. The measured surface temperatures of the specimens before the joining process were between 220 and 375 °C. This corresponds approximately to the melting temperature of the near-eutectic molten zinc used for coating. As expected, the zinc layer was returned to the molten state at this temperature. This means that under the given process conditions no metallic continuity could be generated as no liability or solidification had occurred at removal from the oven. Cooling in the oven would not be expedient because the determined process parameters and relationships should be transferred to a forging process. Despite of this fact, the temperature-controlled cooling will be part of subsequent investigations.

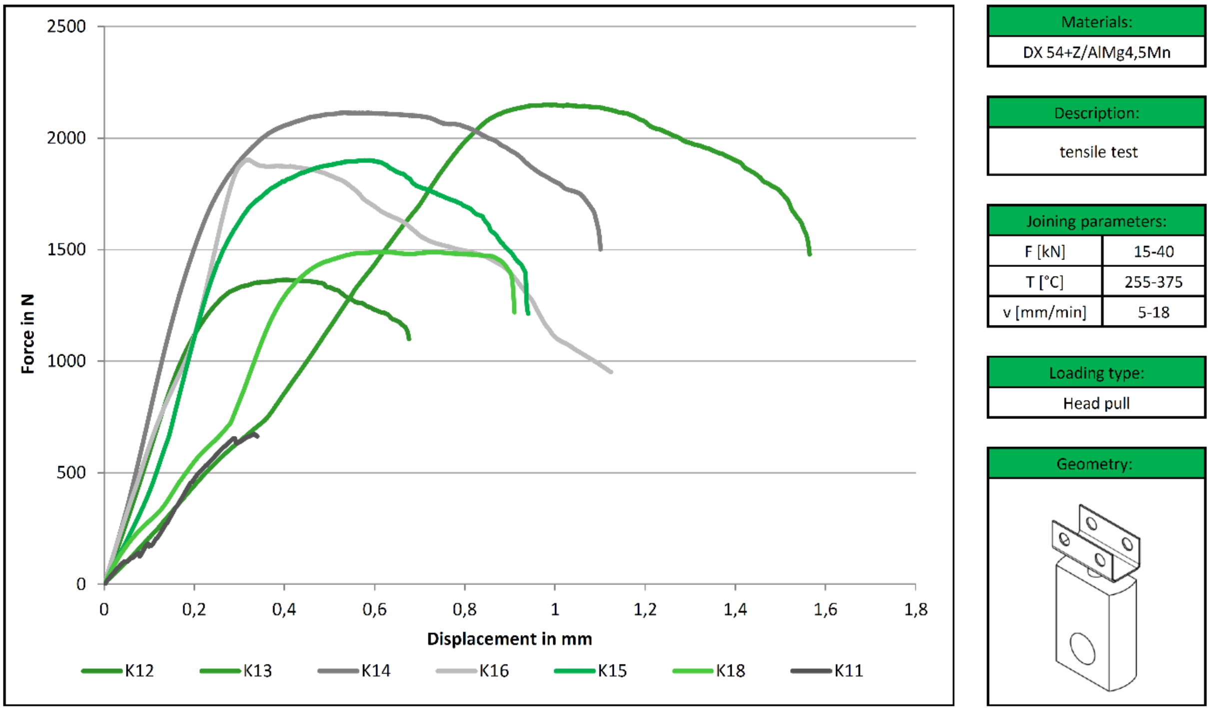

Figure 8: Force-displacement curves of specimens

The highest force is borne by the specimens joined at a temperature of 330 °C, a force of 27.5 kN and a punch speed of 11.5 mm/min. The measured specimen temperature on surface of the zinc was about 330 °C.

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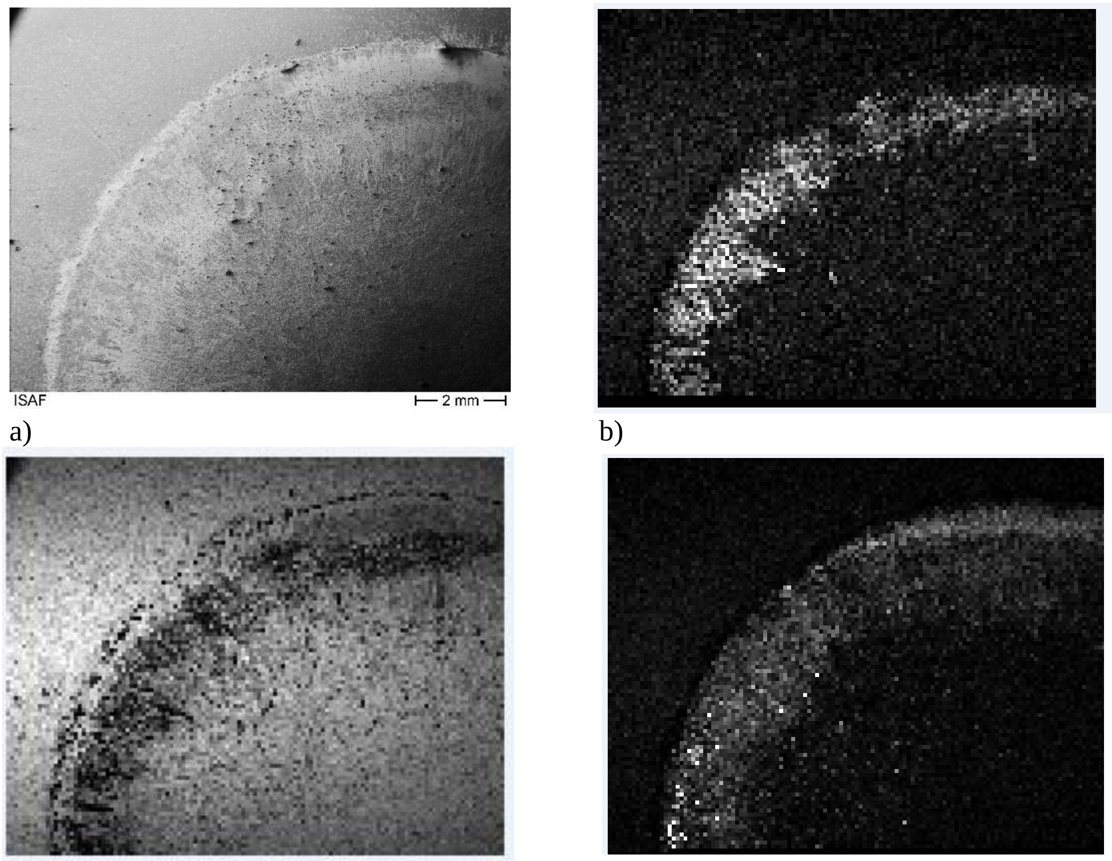
The tensile tests were carried out after complete cooling of the samples. The fracture surfaces were also subjected to an EDX analysis after the experiments to obtain the distribution of the elements over the attachment surface and thus to be able to characterize the metallic continuity. Figure 9 shows the analysis



a) b) c) d)

Figure 9: a) REM picture of the fracture area; b, c, d) Elementanalysis of Fe, Zn, Al

of the fracture surface on the steel side with the SEM. The distribution of the elements iron, zinc and aluminum (figure 9 b-d) clearly shows the transition of the materials in the attachment zone. Thus, a cohesive connection has been created which withstands forces of up to 2.1 kN.

The evaluation of the degree of deformation as a function of the joining parameters resulted, as expected, in a proportional relationship. The tensile strength, however, shows no correlation as a function of the joining parameters. However, it was assumed that, as with all thermal joining processes, a minimum energy must be introduced to produce a metallic continuity. This energy is composed on the one hand of the introduced heat and on the other hand of the forming energy. The heat energy was calculated by the mass of the bolts, the heat capacity of the aluminum and the temperature difference. The contribution of the deforming energy goes back to the generated plastic deformation. The transformation energy or deformation work is converted up to 95% into heat, which implies a connection between temperature change at the joint and compression, [9]. Therefore, the deformation energy was derived from the very good correlation of the compression ratio and the joining parameters and calculated using the integral of the force-displacement data from the joining process.

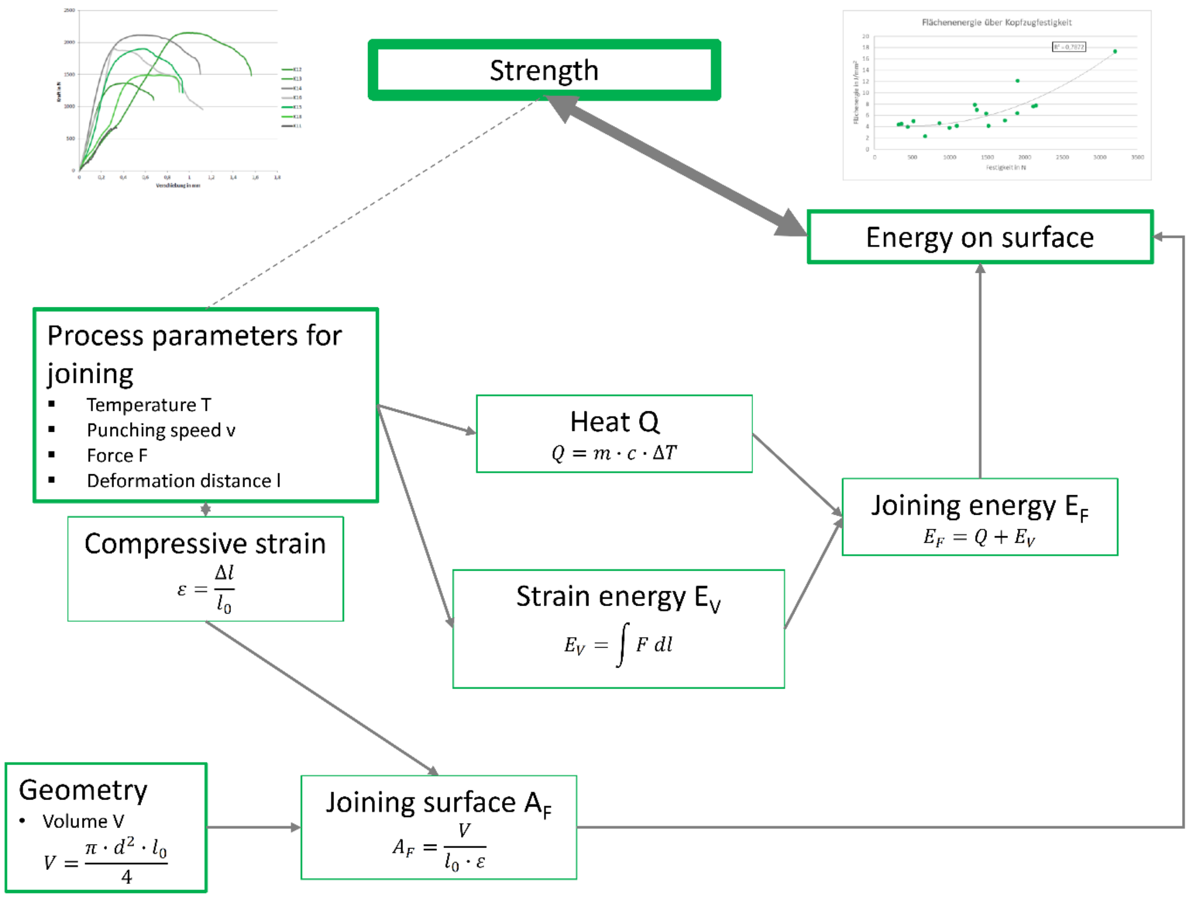


Figure 10: Analysis of correlation

The actual joining surface was calculated by means of the compression ratio from the volume of the aluminum bolt. The actual joining surface is used to normalize the introduced total joint energy, in the sum of deformation work and heat energy. The normalized energy values were plotted against the

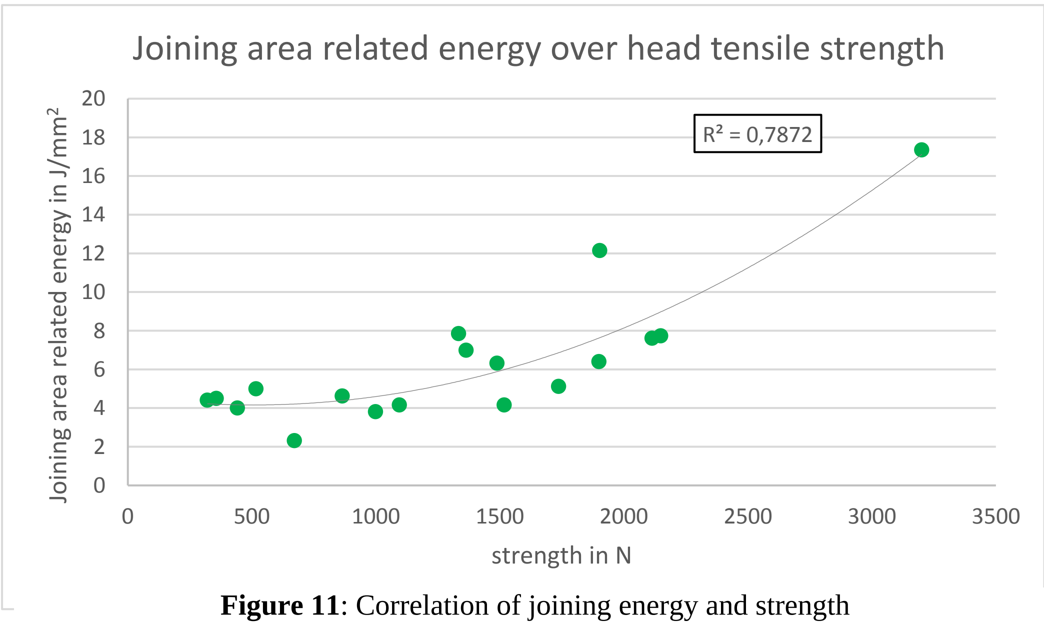


Figure 11: Correlation of joining energy and strength

determined head tensile strength values and are shown in figure 10. Furthermore, the degree of normality $R^2 = 0.7872$ was calculated via the trend course, in the form of a quadratic relationship. The established and described relationships are shown in figure 11.

5. Conclusions of joining tries

Within the scope of the presented work two significant results have been developed so far.
First, aluminum was galvanized using the hot dip process and the parameters for this process were determined. The influence of the composition of the molten bath was checked and improved by an iterative process. The adhesion of the layer is dependent on the immersion time and the temperature. The layer thickness can be adjusted after removal by stripping. Analysis by SEM and micrographs revealed that during galvanizing, a diffusion layer in the aluminum sets, thereby eliminating the oxide layer.
As a second result, parameters were developed for producing a material connection between the zinc-plated aluminum bolt and the galvanized steel sheet. This could also be detected by SEM and micrographs. This analysis also showed that the two base materials were hardly affected.
The determined strength values are comparable with the values of punctiform geometries produced with conventional joining methods. The comparison of the values from the literature with the data obtained in the experiment (figure 12) shows that the head tensile strength of the compound corresponds to the thermal joining method, [10–12]. Furthermore, it is above the level achievable with mechanical joining methods.

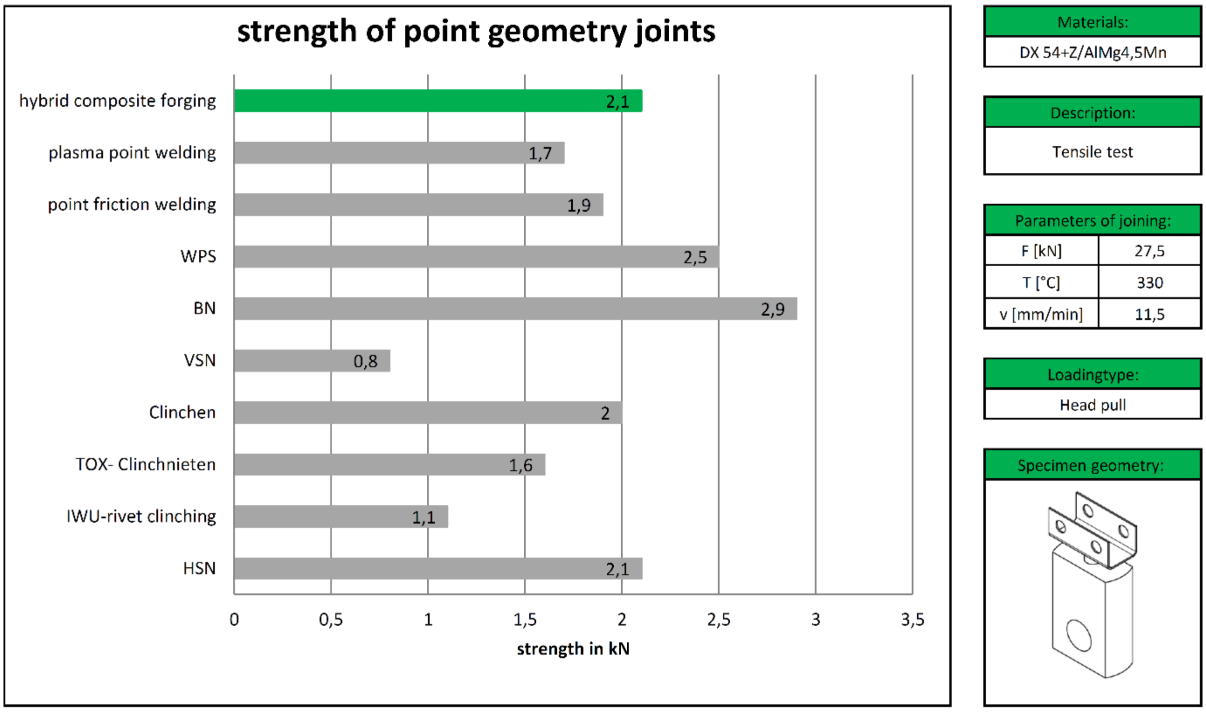


Figure 12: Comparison of ultimate strength of different joining techniques

The determined relationships clearly show that a minimum energy must be applied to create a metallic continuity. With increasing joining energy and a concomitant increase in the compression ratio an increase in strength can be achieved to a certain extent. An in-depth evaluation and validation of these relationships should enable the economical production of the joint in industrial production in the medium term.

6. Investigation of parameters for hybrid composite forging by FE-simulations

The research on the forging operation of hybrid composite forging is made subsequently to the galvanization of the aluminum part. To identify suitable parameters for hybrid composite forging finite-element simulations were conducted with FORGE NxT 2.1. A cylindrical aluminum bulk part, material AlMg4,4Mn0,7Cr, with a diameter of 10 mm and a hight of 20 mm and a steel sheet, material DD11, with a diameter of 30 mm and a height of 1 mm are the connecting partners of the forging process. The temperature of the forging tools was set to 250 °C. As friction conditions the “Coulomb limited Tresca model” was chosen with high friction conditions (μ = 0,3).
On the bulk aluminum part the top layer is defined as a different type of aluminum to simulate the effect of the zinc layer as a first appraoch, as material data for Zinc was currently not available in sufficient quality. Furthermore, simulations above the melting point of zinc lead to simulation errors as it gets liquid. The material description for the hot forming operation is based on the flow curve equation by HENSEL and SPITTEL.
To identify suitable parameters for the forging process different temperatures of aluminum and steel are investigated. In addition, the velocity of the presses is a parameter that was varied between 3 mm/s and 300 mm/s, which represent a spectrum of different industrial presses. Table 4 shows the different investigated parameters.

Table 4: Used simulation parameters for investigation of the joining zone

Temperature aluminum (°C)	Temperature steel (°C)	Velocity (mm/s)
450	20	3
500	200	300
550	400	

The temperature distribution within the aluminum in the joining zone after forming was investigated. At the forging process with v = 300 mm/s the highest temperature is above 550 °C, for v = 3 mm/s the highest temperature is below 312 °C (see figure 13 and figure 14) Thus, the higher press velocity leads to a more irregular temperature distribution and to significant higher temperature in the joining zone (figure 13) than the low press velocity.

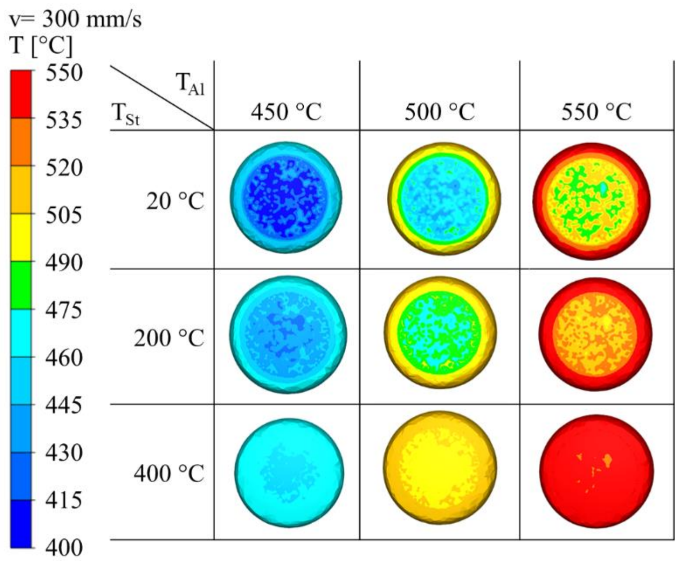


Figure 13: Comparison of the temperature distribution of the aluminum part in the joining zone at the end of forming with 300 mm/s at different temperatures of aluminum and steel at the start of the forming process

Figure 13 shows that especially with a bigger difference between the starting temperatures of aluminum and steel the temperature distribution is increasingly irregular. This effect can be observed when the results of the simulations with T_{St} = 20 °C are compared to the results of the simulations with T_{St} = 400 °C. The simulations with T_{St} = 400 °C show a more homogenous temperature distribution.
As seen in figure 14 a lower press velocity leads to a more homogenous temperature distribution in the joining zone. This can be seen when the results in figure 13 are compared with the results in figure 14.

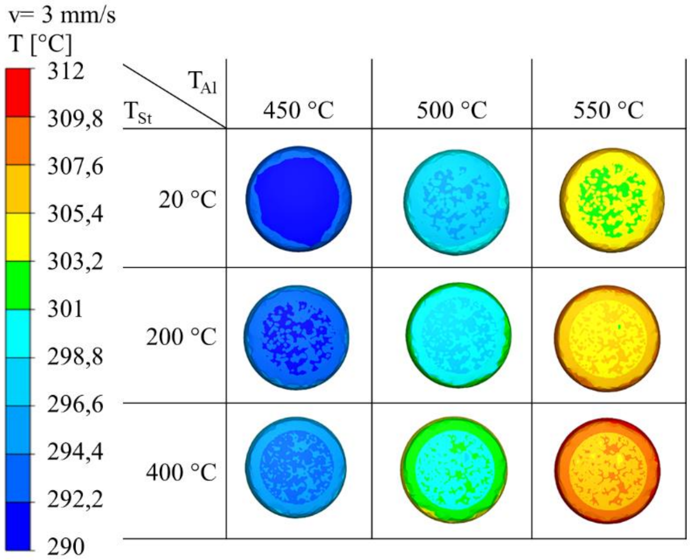


Figure 14: Comparison of the temperature distribution of the aluminum part in the joining zone at the end of forming with 3 mm/s at different temperatures of aluminum and steel at the start of the forming process

In simulations in which the low press velocity was used, the temperature of the tools has significant influence on the temperature of the connecting partners. In figure 14 the figure of temperature distribution of the simulation T_{Al} = 450 °C and T_{St} = 400 °C shows that the temperature of aluminum at the end of forming is below 296.6 °C. This decrease in temperature occurs due to heat transfer to the dies and to the ambient medium and is more present when a low press velocity is used.

In general the simulations showed, that the temperature decreases from the outer areas to the middle of the joining zone. The irregular temperature distribution in the joining zone is a difference between simulations with a defined layer of different material on the bulk aluminum part and simulations with only bulk aluminum (figure 15).

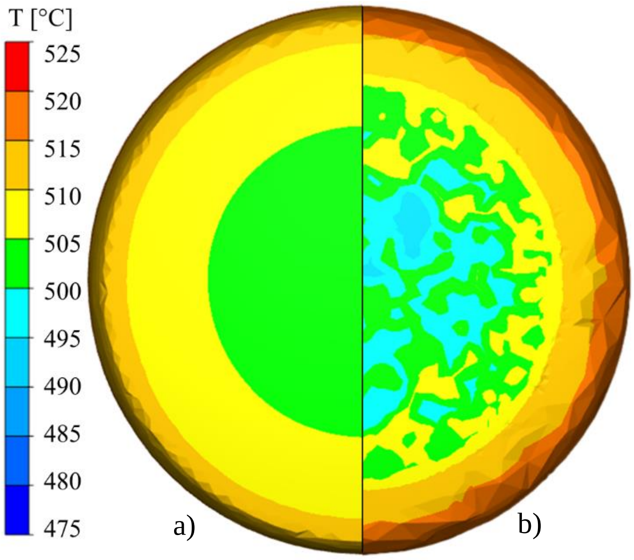


Figure 15: Temperature distribution in the joining zone of the aluminum part a) without defined layer of different material and b) with a layer of different material in the joining zone with T-Al: 500 °C, T-St 400 °C and press velocity of v = 300 mm/s

In simulations without a defined layer of different material the temperature decreases form the outside of the joining zone to the middle of the joining zone. Figure 15 shows the comparison of the temperature distribution of a simulation without (figure 15 a) and with a defined layer of different material in the joining zone (figure 15 b) for a forming simulation with the parameters T_{Al} = 500 °C, T_{St} = 400 °C and a press velocity of 300 mm/s. The irregularities in the temperature distribution in the simulations with a defined layer of different material might occur due to problems with remeshing of the top layer. The real temperature distribution can be investigated with experimental tests. An irregular temperature distribution may lead to an inhomogeneous joint.

In the joining zone a homogenous temperature distribution shall be attained, so the joint is homogenous as well. The temperature distribution can have an influence on the distribution of elements in the joining zone as shown in figure 9. To achieve a homogenous temperature distribution lower temperature difference between aluminum part and steel sheet will be investigated in further simulations. For example simulations where the temperature of aluminum part and steel sheet are below the melting point of zinc will be made. Especially the temperatures shown in table 3 will be examined. Furthermore, a variation of press velocity between 3 mm/s and 300 mm/s will be investigated, e.g. 50 mm/s, 100 mm/s and 150 mm/s. Results of simulations with these parameters are expected to lead to homogenous temperature distribution in the joining zone that will investigated in experimental trials and tested further.

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