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Numerical and experimental investigation of flat-clinch joint strength

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Abstract

The striving for energy savings by lightweight construction requires the combination of different materials with advantageous properties. For joining sheet metal components, clinching offers a good alternative to thermal joining processes. In contrast to thermal joining processes, the microstructure in the joining zone remains largely unaffected. Conventional clinch joints, however, have a protrusion on the underside of the joint, which restricts their use in functional and visible surfaces. Flat-clinching minimizes this disadvantage by using a flat anvil instead of a die. Due to the flatness on the underside, it can be used in visible and functional surfaces. This paper deals with the increase of joint strength by using an auxiliary joining element (AJE) in the second forming stage. To achieve optimum improvement in the joint strength of an aluminum Al99.5 H14 sheet metal joint and to save costs, the AJE was varied numerically in terms of volume, material and basic shape. The geometric parameters (e.g., interlocking f and neck thickness t_n) do not allow direct derivation of the joint strength. For this reason, the 2D clinch model was extended for the first time to include 3D load models (cross tension, shear tension). To validate the numerical results, optimized flat-clinch joints with AJE and the associated load tests were implemented experimentally. The numerical models were used to improve the process development.

Keywords Flat-clinching · Finite element analysis (FEA) · Joining by forming · Joint strength · Joining elements · Auxiliary joining elements (AJE)

1 Introduction

By combining advantageous properties of different materials, energy can be saved in the sense of lightweight construction. In addition to heat-inducing processes, mechanical joining processes have gained in importance in recent years, as the microstructure is largely retained during joining.

The form-closed clinch joint is formed by a punch penetrating the joining partners and subsequent upsetting of those [1]. The form closure and force fit are formed by widening [2]. Clinching can be used to join different sheet thicknesses with an overlap connection. The process is considered to be easy to automate, clean and well reproducible. The high material variety and the low preparation effort for the joints are particularly noteworthy. In addition to materials of the same and different types, clinching also allows coated materials to be joined. Conventional clinch joints, however, have a process-related protrusion on the underside, which restricts their use in visible and functional surfaces.

In recent years, special clinching processes have been developed to enable more material combinations. Many works dealt with the production of a one-sided functional surface [3]. Flat-clinching, developed and patented at Chemnitz University of Technology [4], minimizes the external protrusion on the joining surface facing away from the punch by using a flat anvil instead of a shaping die. As a result, the interlocking f is formed completely within the material plane (see Fig. 1). The use of a flat anvil also eliminates the complex axis alignment of punch and die. The flat-clinching process is thus less sensitive to angular errors, which can occur especially at higher process forces due to the elastic bending up of the C-frames [5]. In addition to the interlocking f, the key geometric values of a clinch joint also include the neck thickness t_n, the bottom thickness t_b and the protrusion height p.

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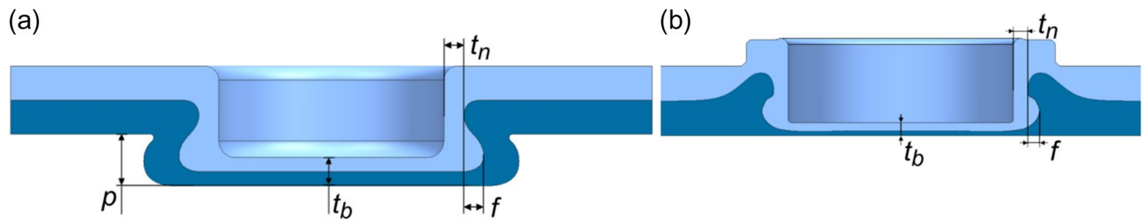


Fig. 1 Comparison of joint cross sections [4] **a** conventional clinch joint **b** flat-clinch joint

In flat-clinching the material is no longer displaced out of the sheet plane into the forming die, but flows in radial direction. Only compressive stresses occur in the bottom area of the clinching point and tensile stresses occur in the neck area, which are caused by the axial rise of the material. Due to this more advantageous stress state compared to conventional clinching, flat-clinching can also be used to permanently join materials that are more sensitive to tensile stress, such as wood and corrugated cardboard [6]. The flatness of the underside extends the use in visible and functional surfaces. With flat-clinching, sheets with a total sheet thicknesses of up to 5 mm can be joined. With higher sheet thicknesses, the interlocking can no longer be large enough to achieve a durable joint. To avoid the occurrence of the anvil-side protrusion while at the same time influencing the material flow in such a way that an interlocking is formed within the material plane, relatively high blank holder forces are required. Therefore, the forming forces during flat-clinching are higher compared to conventional clinching.

In recent years, many researchers have investigated the influence of geometrical tool parameters on the flat-clinch joint. Chen et al. focused on the blank holder [7] in addition to Beyer [4]. Chen et al. confirmed the results of Beyer that the increase of the blank holder force decreases the material flowability, furthermore Beyer dealt with the blank holder contour. Kumma et al. also investigated the blank holder force and additionally the edge radius of the blank holder [8]. Both parameters influence the interlocking f and the neck thickness t_n of the joint.

Sabra Atia and Jain analyzed the effects of tool parameters such as blank holder contour and the influence of process parameters on the material flow behavior of dieless clinch joints. They evaluated the effects in relation to joint strength [9]. In addition to the tool parameters, different sheet thickness configurations were also analyzed. Han et al. investigated other process parameters, such as punch opening angle, blank holder radius, and punch speed, both experimentally and numerically [10]. The results showed that the blank holder radius has a significant influence on the clinch joint, while the punch opening angle and blank holder corner radius have a minor influence on the clinch joint.

This paper deals with the increase of joint strength by using an auxiliary joining element (AJE). The auxiliary joining element is an additional element designed to increase the interlocking f and stabilize the neck thickness t_n. Flat-clinching with AJE was developed by Gerstmann [5] for a punch diameter of 5 mm and a cylindrical AJE.

A second clinching stage is added to the process, whereby a flat-clinch joint with interlocking f is formed between the upper sheet and lower sheet in the first clinching stage (see Fig. 2a–c). In the second clinching stage, the AJE is inserted

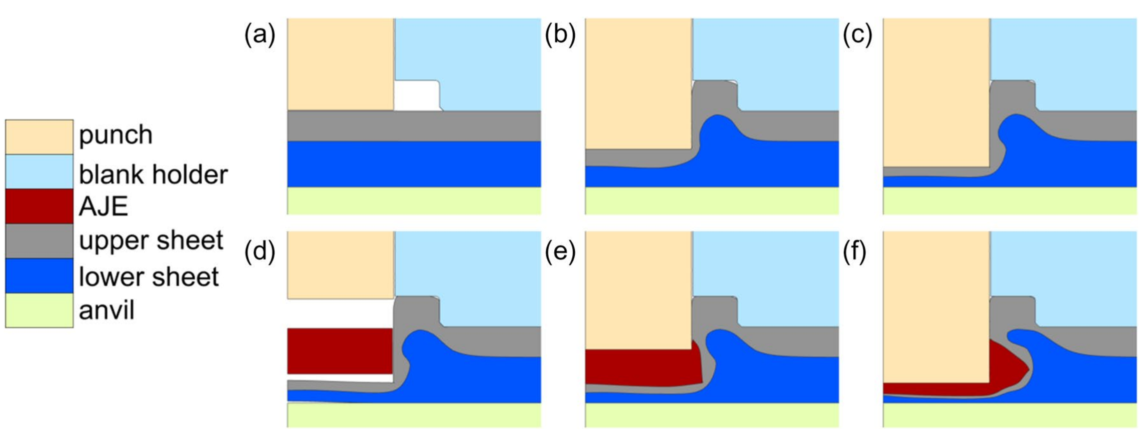


Fig. 2 Material flow of two-stage flat-clinching with AJE

(see Fig. 2d) and subsequently formed. The AJE is first upset until it is reaching the inner wall of the clinch joint before it flows radially. An interlocking f_{AJE} is formed between the AJE and the upper sheet (see Fig. 2e) and the interlocking f between the upper and lower sheet is reduced in the meantime and the neck area is displaced before the interlocking f increases (see Fig. 2f).

The following section explains the procedure for performing the reference tests and the calibration. The preliminary tests help to calibrate the numerical models so that the AJE variation can subsequently be carried out numerically. The numerical analysis complements experimental investigations at low cost and reduces the need for expensive prototypes and experiments [11].

2 Reference test and calibration

Reference tests with and without AJE help to implement the numerical modeling of the flat-clinching process. For the production of the flat-clinch joints, the universal C-frame stand press DFG 500/150E from the Eckold GmbH & Co. KG was used. Aluminum Al99.5 H14 (EN AW-1050A) with a sheet thickness of 1.0 mm and 1.5 mm was used as the starting material due to its low strength and very good cold formability. The following process parameters were used: cylindrical punch with 7.0 mm diameter, a blank holder force of 39 kN and a bottom thickness of 0.65 mm (both in the first and second process stage; t_{b1} and t_{b2}). The blank holder force and the bottom dead center of the punch are set in the machine control. During the clinching process, the force is recorded with a type 9104A measuring washer from Kistler Instrumente GmbH. The generated charge is converted into electrical voltage by a 1-channel charge amplifier type 5011A from Kistler Instrumente GmbH and recorded with the help of an ALMEMO 809 measuring module from Ahlborn GmbH. The punch movement is measured by an inductive displacement transducer FWA 150-T from Alhorn GmbH on the piston rod of the servo motor. After the clinching process, the bottom thickness is measured by means of a micrometer gauge. The cylindrical AJE with a height of 1.5 mm and a diameter of 6.9 mm were produced by shear cutting from an Al99.5 H14 sheet metal for the reference tests.

For numerical implementation of the joining process, the experimentally determined force curves (blank holder and punch force) and the geometric characteristic values (see Fig. 3) served as a calibration basis. In the numerical model, the blank holder force and the tool geometries were defined as input. Punch force and geometric characteristics of the clinch joint are comparison values after the clinching process to evaluate the quality of the numerical model. The geometric parameters were measured by macro sections using an optical microscope. Figure 3 shows the overlay of the separation lines obtained from the macro sections of the individual flat-clinch joints.

Figure 4 shows the geometric values which are necessary for flat-clinch joints with AJE (bottom thickness t_b, interlocking with AJE f_{AJE}, interlocking f, neck thickness with AJE t_{nAJE}, neck thickness t_n, neck thickness on the blank holder side t_{nBH}). The area of the bottom sheet tongue (see Fig. 4-left) is described with the geometric values maximum rise height of the bottom sheet h_{anv} and radial distance to the maximum rise height of the bottom sheet t_{anv}. To take batch-dependent fluctuations in the mechanical properties of the sheets into account in the numerical process design, flow curves were determined for all sheet thicknesses by means of the plain strain upsetting test.

For the numerical models of the load analyses, reference flat-clinch joints were tested for cross tension and tensile shear with the universal testing machine Galdabini Quasar 50 kN of the company Galdabini (S.P.A.). Specimen dimensions and test speed of 10 mm/min were taken from DIN ISO 16237 and DIN EN ISO 12997.

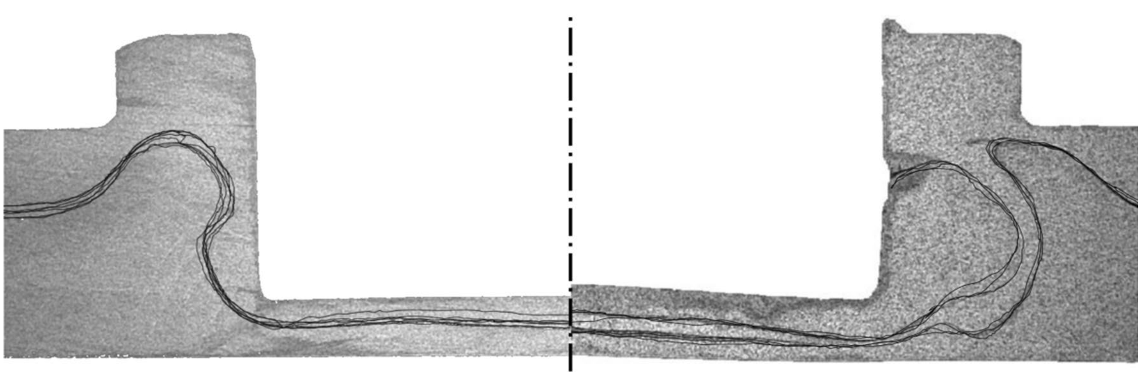


Fig. 3 Separation lines of the conventional flat-clinch joint (left), and the flat-clinch joint with AJE (right)

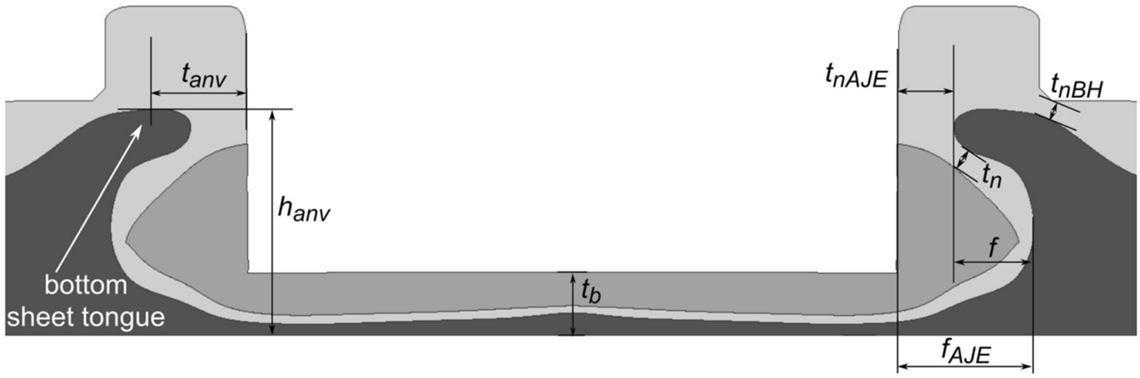


Fig. 4 Geometric characteristics of a flat-clinch joint with AJE

3 Simulation model description

The clinching process was simulated in the FEA software Simufact Forming 16.0. The geometries of the punch and blank holder were imported via a corresponding CAD-interface. Flat-clinching is typically modeled as a 2D axisymmetric model (see Fig. 5) due to the rotationally symmetric joint geometry. The punch movement was modeled as a hydraulic press, while a real characteristic load curve was assigned to the blank holder.

All joining partners were meshed with MARC element type 10, using the Advancing-Front-Quad-Mesher (element size of 0.2 mm for the lower sheet and 0.1 mm for the upper sheet and the AJE). The whole model contains about 9000 elements. The complex material flow during flat-clinching results in a complex stress state. During the process, the contact normal stresses strongly vary and therefore require the use of the combined friction model. The low contact normal stresses at the beginning of the process allow the use of Coloumb's friction model. As the process progresses, the contact normal stress increases and the Coloumb friction law no longer reflects reality in a physically correct manner. The Coloumb model must be limited with the combination of Tresca's law [4, 5]. As can be seen in Fig. 6, flat-clinching can be modeled with sufficient accuracy. The comparison of the geometric parameters of the numerical simulation with the experiment are shown in Fig. 7.

The geometric values for flat-clinching with AJE alone do not allow direct derivation of the joint strength. Due to the change in position of the decisive variables when using an AJE, such as interlocking *f* and neck thickness t_n, the previous relationships (interlocking particularly decisive for cross tension load, neck thickness for shear tensile load) no longer apply. For a qualitatively assessment of the joint strength, numerical 3D models for cross tension (see Fig. 8) and tensile shear loading were created (see Fig. 9).

The more complex forming during the load analysis can no longer be modeled using a rotationally symmetry, so that a 3D model for cross tension and tensile shear loading is necessary. For this purpose, the results from the 2D joining process, including complete forming history, were transferred to 3D and adopted as an initial condition. This transformation leads to a cylindrical geometry of the clinch joint. To simulate the rectangular sheets used

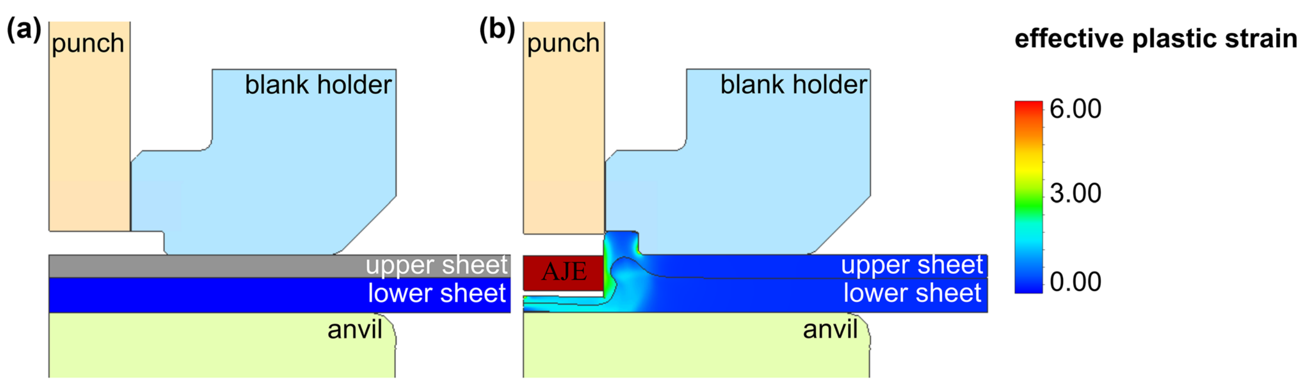


Fig. 5 Flat-clinching model **a** conventional flat-clinching (1st stage) **b** with AJE and forming history of upper and lower sheet from 1st stage (2nd stage)

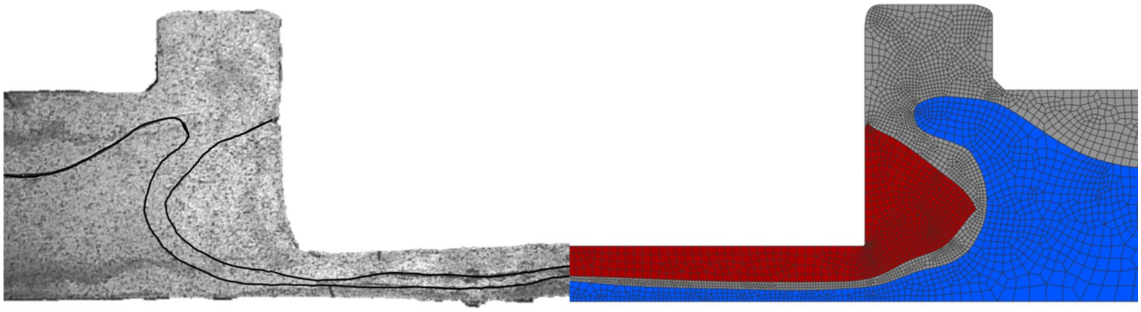


Fig. 6 Cross-section of a flat-clinch joint with AJE from experiment (left) and simulation (right)

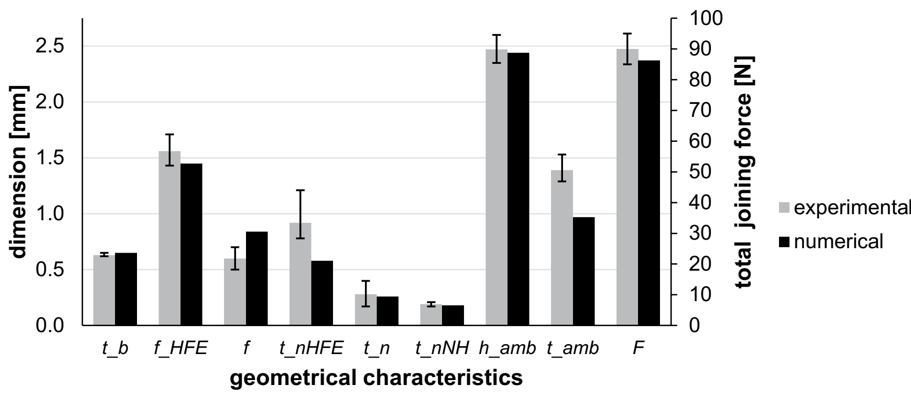


Fig. 7 Comparison of the geometric characteristic values from experiment (left) and simulation (right)

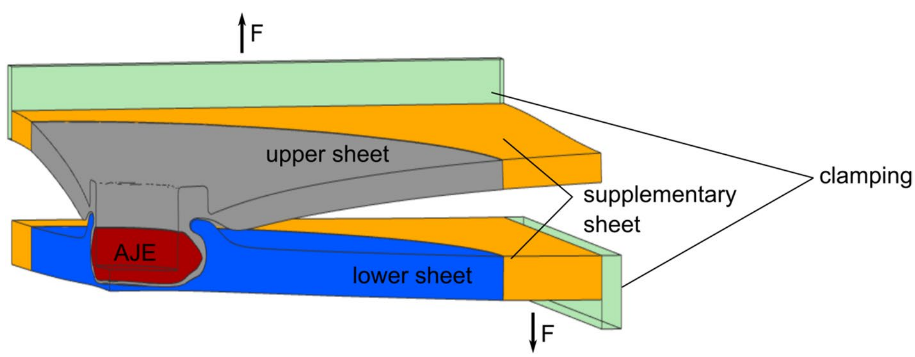


Fig. 8 Numerical cross tension model including load direction

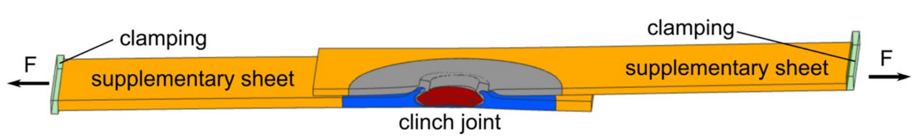


Fig. 9 Numerical tensile shear loading model including load direction

in the test (based on DIN ISO 16237 and DIN EN ISO 12997), supplementary sheets were added (see Figs. 8, 9). To improve the contact modeling between the clinch joint and the supplementary sheet, the clinch joint was trimmed to a fixed outer diameter. The reduced diameter of the clinch joint in 2D was selected in such a way that no strain hardening could be detected in the outer region and thus no falsification of the results (see Fig. 10). Moreover, the glued contact to the supplementary sheets did not result in any additional strain hardening in the contact area. In addition, the model was expanded to include clamping devices, which were connected to the supplementary sheets by glued contact. A fully adapted 3D joining simulation would result in an enormous increase in computation time, so the load simulations were carried out as partially symmetrical. A symmetry angle of 90°

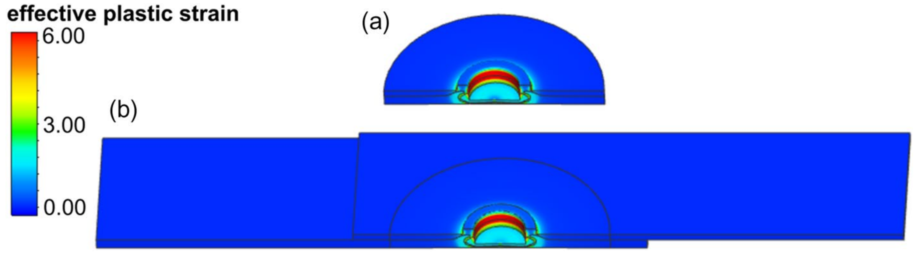


Fig. 10 Illustration of the supplementary sheets **a** before adjusting the diameter **b** after reducing the diameter and attaching the supplementary sheets

was selected for the cross tension test and an angle of 180° for the tensile shear loading test.

For the load tests, all components were remeshed with the Tet-Mesher (tetraeder 134, element size of 0.8 mm for the lower and upper sheet, 0.3 mm for the AJE, 1.0 mm for the supplementary sheets) including refinement boxes (level 1) in the joining zone, while retaining the complete forming history and, as in the joining simulation, the mesh was additionally refined in the joining zone. The whole model contains about 246,000 elements for the cross tension and 500,000 elements for the tensile shear loading. In contrast to the joining process, the contact normal stress changes not so complex during the cross tension and tensile shear loading, so that the friction can be modeled in a simplified way as according to Coulomb. The displacement of the clamping devices was applied via restraints at the real speed of 10 mm/min. These models allow qualitative comparison of the joint strength of flat-clinch joints. Calculations were made only up to the maximum force without obtaining an accurate damage prediction.

4 Parameter variation

To improve the joint strength, the use of auxiliary joining elements designed to increase the interlocking f and stabilize the neck area t_n was investigated by means of numerical simulations. The volume was varied in terms of height and diameter, and the material and basic shape were also changed. To infer the first relationships, only a bottom thickness combination ($t_{b1} = t_{b2} = 0.65$ mm), which forms a good average between the smallest possible (0.4 mm) and the minimum necessary bottom thickness (start of interlocking at 1.25 mm), was selected here. To evaluate the improvement, the geometrical characteristics were investigated in addition to the numerical load models. A cylindrical AJE of Al99,5 H14 with a diameter of 6.9 mm and a height of 1.5 mm was used as a reference AJE. In addition to the numerical investigations, some numerically improved flat-clinch joints were verified experimentally.

4.1 Volume variation

As a first step, the volume of the cylindrical AJE was changed and the influence of the changes on the joint strength was investigated. The initial height of the AJE was varied while keeping a constant diameter of 6.9 mm. From a technological point of view, a minimum initial height of 0.5 mm is relevant. 3.0 mm was defined as the maximum value, since the area from the clinch point to the upper edge of the clinch joint offers the largest space for additional material with approx. 2.8 mm. The specimen height was varied in steps of 0.5 mm. The geometric values were derived from the numerically gained cross sections. With lower height, the interlockings f and f_{HFE} were lower and the tongue of the bottom plate was displaced less radially outward (radial distance t_{anv}) (see Fig. 11). From the simulation of the cross tension and tensile shear test of the different heights, the height of 1.0 mm showed the greatest improvement in strength.

The change in position of the bottom sheet tongue (see Fig. 4), which is caused by a larger material feed of the AJE (see Fig. 12), results in a lower cross tension load capacity. The strength of a flat-clinch joint depends on the interlocking f and the neck thickness t_n. With the use of the AJE, these values shift and new important values are added, such as the neck thickness t_{nBH} on the blank holder side due to the radial displacement of the tongue of the bottom plate. In principle, additional material leads to an increase of the interlocking f, depending on the initial height of the AJE. However, the interlocking f and the joint strength are not directly dependent on each other, as is the case with conventional flat-clinch joints. This trend was also demonstrated experimentally.

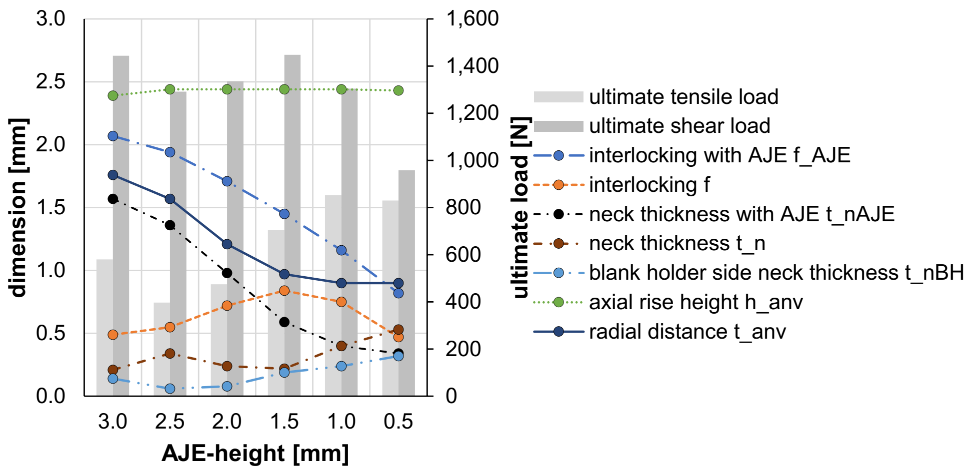
In addition to the initial height, the diameter of the AJE was also changed numerically from 4.0 to 6.9 mm. In the experiment, however, a smaller diameter cannot be implemented, because central positioning cannot be guaranteed. The simulation showed that no separate investigation of the diameter for the volume change is necessary. The differences in geometrical and mechanical parameters are negligible, so that the investigation of the initial height of the AJE is sufficient. Since the AJE with smaller diameter first spreads before it touches into the clinch joint wall, the states of the heights can be compared with those of the diameter. The difference in strength due to the work hardening caused by the spreading of the AJE-material is hardly noticeable when evaluating the geometric characteristics and the total joining force. So that when considering the volume change in aluminum Al99.5 H14, the consideration of the height for the volume change is sufficient.

4.2 Material variation

As a further point of investigation, the AJE-material was varied, using steel DC04 and the aluminum alloy AlMg3. The cylindrical reference AJE with a diameter of 6.9 mm and an initial height of 1.5 mm was selected as the test shape. Figure 13 gives an overview of the geometrical and mechanical characteristics for the different AJE-materials.

With the materials DC04 and AlMg3, a circumferential groove was formed in the simulation in the area of the punch radius (see Fig. 14). This was also observed in

Fig. 11 Geometrical and mechanical characteristics for different AJE-heights



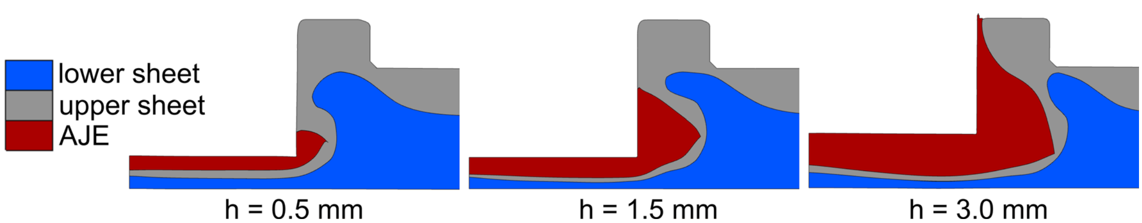
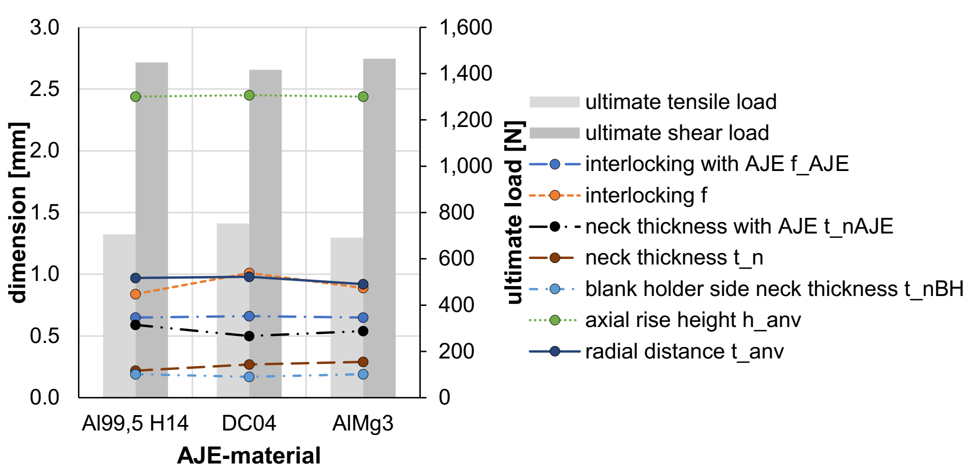


Fig. 12 Cross sections for different AJE-heights

Fig. 13 Geometrical and mechanical characteristics for different AJE-materials



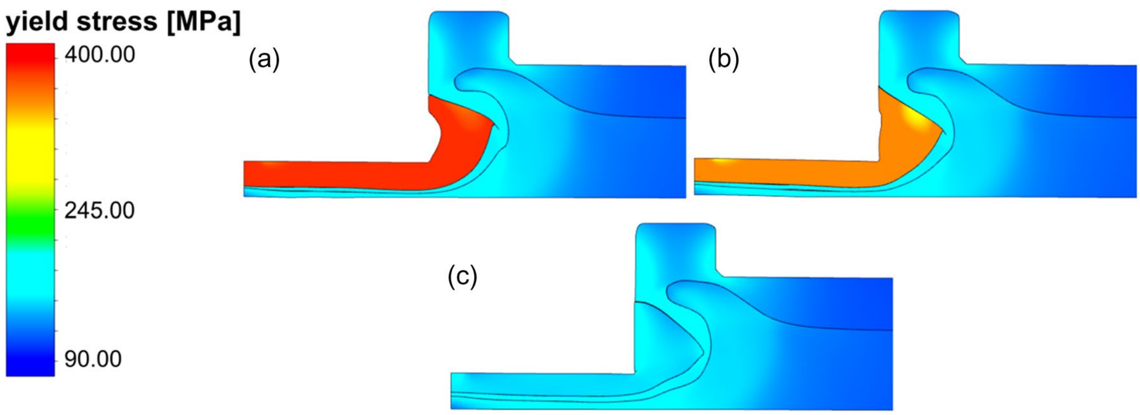


Fig. 14 Work hardening difference of various AJE-materials **a** DC04 **b** AlMg3 **c** Al99.5

the experiment. However, the geometric properties hardly changed. In the experiment, the thinning of the bottom area resulted in a lower loading capacity, while in the simulation the loading capacities remained the same. Since the sheet material has a lower strength, this material is increasingly displaced, while the AJE material remains in the bottom area. In addition, the neck thickness t_{nBH} on the blank holder side comes more into focus as a weak point than in the other investigation points.

4.3 Variation of the basic shape

In addition to the cylindrical shape of the AJE, cone and truncated cone were investigated (Fig.15). The advantage of these basic shapes, which are rotationally symmetrical, is that the AJE reinforces the clinch joint evenly in all directions. To ensure comparability, all bodies had the same volume.

The truncated cone angle was also varied. The simulations showed that the angle does not influence the geometrical and mechanical characteristic values. This corresponds to the trend that can be seen with the smaller diameters. Here, again, the material first spreads out before it is displaced radially outward. Therefore, all following investigations were carried out with a constant angle.

The cross-sections of all flat-clinch joints with different AJE shapes are almost the same, which is also reflected in the evaluation of the geometrical and mechanical properties (Fig. 16).

In principle, no improvement in the load-bearing capacity against cross tension could be achieved in the experiments for any of the investigated parameters. The changes in the geometric parameters with the use of the AJE are more severe than expected. The cylindrical reference AJE shows the best load capacities.

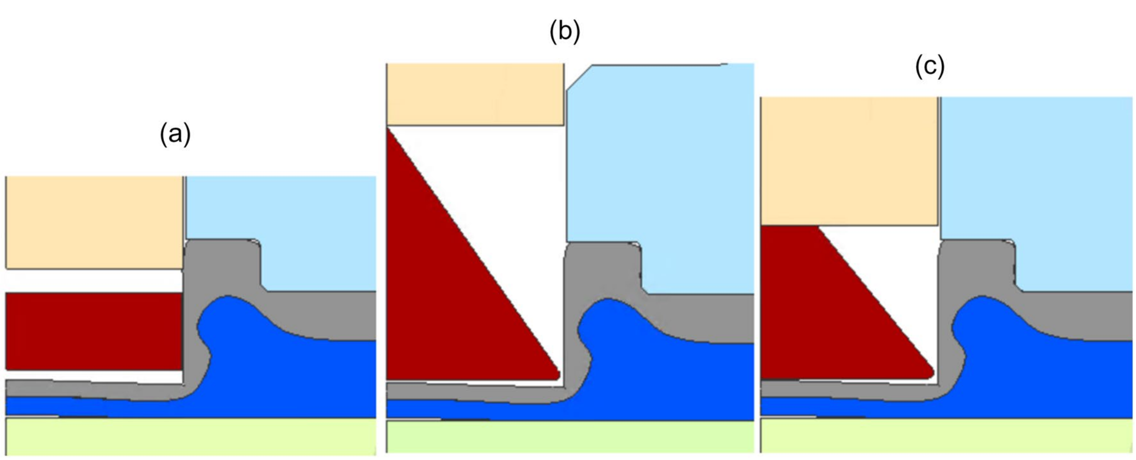


Fig. 15 Different basic shapes of AJE **a** cylinder **b** cone **c** truncated cone

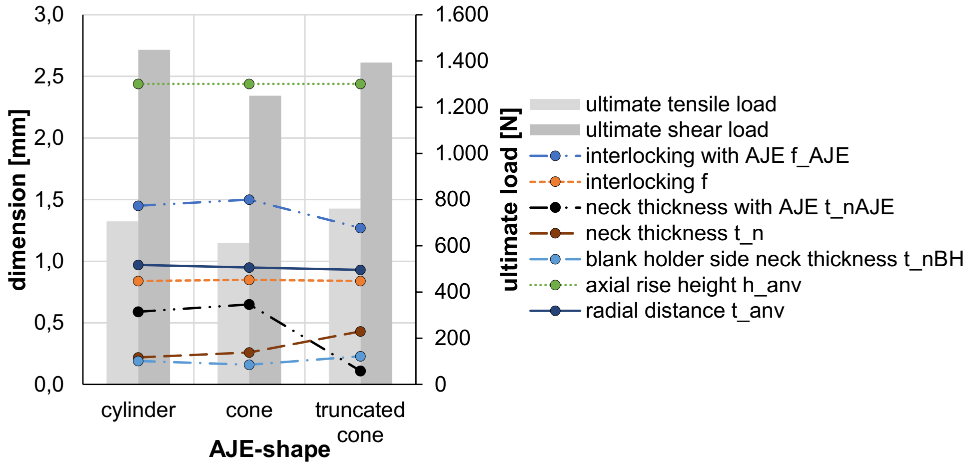


Fig. 16 Geometrical and mechanical characteristics for different AJE-shapes

5 Conclusion

In this paper, the use of an auxiliary joining element (AJE) in a 7 mm flat-clinch joint at a bottom thickness combination of $t_{b1} = t_{b2} = 0.65$ mm was investigated. The AJE is expected to increase the interlocking f and stabilize the neck area t_n, resulting in an improvement of the joint strength. For the numerical investigation, reference tests were carried out with macro sections for the evaluation of the geometrical characteristics and cross tension and tensile shear tests for the mechanical characteristics. The AJE was varied in terms of its volume, material selection and shape, and the influence on joint strength was investigated numerically.

Since the geometric parameters from the numerical 2D joining process do not allow a clear conclusion to be drawn on the joint strength, 3D load models were created for cross and shear tension. With these models, a qualitative comparison of the different flat-clinch joints was possible. From the numerical analysis it can be seen that lower AJE volumes do not change the actual cross section of a flat-clinch joint. With increasing volume, the position of the bottom plate tongue moves, so that the basic relationships for joint strength no longer apply. The increase in the interlocking f causes a displacement of the bottom plate tongue, so that new weak points are added, such as the neck thickness t_{nBH} on the blank holder side. The load capacity against cross tension can thus not be improved.

With the use of different materials for the AJE, the cross-section hardly changes. The thinning of the bottom area increases as the material with the lower strength is primarily displaced. In addition, a circumferential groove was formed in the area of the punch radius, which offers more surface for dirt accumulation, for example.

By varying the shape, a slight improvement in terms of tensile shear strength could be achieved for the cone. However, the production of the cone is particularly time-consuming in contrast to the cylinder. The extent to which the costlier production offsets the benefit of the improvement in joint strength must be decided depending on the application. The use of an AJE in a flat-clinch joint can in principle lead to an improvement in joint strength. However, the evaluation of the geometrical characteristics is not sufficient to allow an estimation of the joint strength.

Since flat-clinching with its flatness on the underside extends the use of the clinch joints to visible and functional surfaces, other methods for improving the joint strength will be investigated in the future.

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