

Further Development of an Adaptive Joining Technique Based on Friction Spinning to Produce Pre-Hole-Free Joints

Christian Wischer^{1,a*}, Werner Homberg^{1,b}

¹Paderborn University, Forming and Machining Technology, 33098 Paderborn, Germany

^acw@luf.upb.de, ^bwh@luf.upb.de

Keywords: Friction spinning, versatile process chain, friction riveting, mechanical joining

Abstract. Mechanical joining processes are an essential part of modern lightweight construction. They permit materials of different types to be joined in a way that is suitable for the loads involved. These processes reach their limits, however, as soon as the boundary conditions change. In most cases, these elements are specially adapted to the joining point and cannot be used universally. Changes require cost-intensive adaptation of both the element and the process control, thus making production more complex. This results in high costs due to the increased number of auxiliary joining element variants required and reduces the economic efficiency of mechanical joining. One approach to overcoming this issue is the use of adaptive auxiliary joining elements formed by friction spinning. This article presents the current state of research on pre-hole-free joining with adaptive joining elements. The overall process chain is illustrated, explained and analyzed. Special attention is paid to demonstrating the feasibility of pre-hole-free joining with adaptive joining elements. The chosen mechanical parameters are subsequently listed. Finally, a comprehensive outlook of the future development potential is derived.

Introduction

The world of manufacturing technology is changing. The increasingly stringent regulations imposed on governments require adjustments to products enabling them to be manufactured as effectively as possible with the smallest possible carbon footprint. This constitutes an essential point, especially in times of global process chains and ever shorter product life cycles. The automotive sector, which is crucial to many national economies, is facing considerable challenges. The ever-stricter requirements for maximum emissions of climate-damaging greenhouse gases are forcing OEMs to adjust the efficiency of their value chains and cut back on energy requirements [1] [2] [3] [4].

One approach to reducing the overall energy requirement is to minimize the moving masses by employing lightweight construction appropriate to the load [5]. This approach pursues the goal of combining the properties of different materials and implementing their properties in the best possible way [3]. It does, however, pose significant challenges for joining technology and especially for multi-material constructions [6]. This engineering approach can only be implemented to a limited extent using conventional thermal joining processes. The reason is to be found in the creation of intermetallic phases, which reduce the strength of the joint and cause it to become brittle [4]. Proven techniques such as resistance electrode welding no longer meet the requirements when employed alone, and hence other solutions must be considered.

The processing industries have found a solution in mechanical joining techniques. These allow different materials to be joined together without the temperature influence affecting mechanical properties [6]. The group of mechanical joining techniques offers various methods for joints of a varying nature in terms of accessibility or the need for an additional auxiliary joining element [4] [10] [14]. For each joining task, there is usually a particularly well-suited process, specially adapted to the requirements of the joint [4]. However, this specialization also incurs challenges. Clinching, for example requires ductile materials and thus restricts the processable material combinations [6] [15]. When it comes to fiber-reinforced plastics, the joining process decreases their load bearing capacity, because the structure is disrupted or weakened during the joining process [15]. Similar restrictions

apply to processes that require additional auxiliary joining elements, such as self-piercing riveting (SPR) or full-punch riveting. Of economic interest are processes that require access to the joint from only one side and no pre-punching of the components. Such joints can conceivably be achieved through flow drill screwing [4] [12] [14] [15].

This technique is widely used to form load-bearing structures from dissimilar materials, especially in the case of space-frame constructions. This process uses a rotating, bolt-shaped auxiliary joining element to penetrate components and form a thread in the resulting draft. The relative movement between the rotating additional joining element and the fixed parts generates heat through friction [14]. The heat supports the penetration of the joining element by reducing the flow stresses in the component and hence the process forces. Furthermore, the thread-forming elements of the auxiliary joining element also enable the joint produced to be detached, if necessary, in the event of damage. Here, the specially adapted joining elements limit the convertibility of the process to different materials, including thin sheet materials [11] [12].

One approach to overcoming these limitations is the use of adaptive friction elements formed by friction spinning. This innovative process uses friction-induced heat to create additional joining elements, suitably adapted to the application, from uniform semi-finished products. Both the geometric shape and the mechanical properties of the auxiliary joining element can be adapted to the specific requirements of the joint. These adaptive elements are suitable for joining components that are accessible from either side, both with and without a pre-hole. Of particular economic interest are those joining processes that allow joints to be joined together without pre-holing. By eliminating the need for a separate pre-holing operation, the overall process time is reduced and thus the output quantities too.

This paper presents experimentally generated results on how joining with adaptive friction elements can contribute to meeting the needs of lightweight construction. The first characterization focuses on pre-hole-free joining with adaptive friction elements. Initial investigations, which were carried out in [17], used aluminum as the initial material for the adaptive auxiliary joining elements employed to join pre-holed sheets to one another. For an efficient process design, these should be kept as lean as possible.

This paper thus focuses on pre-hole-free joining, which removes the need for the additional step of pre-holing. This requires a switch in the material used for the adaptive auxiliary joining elements from aluminum to steel in order to achieve the necessary heat resistance during the joining process. The joint quality of pre-hole-free joined EN AW 6016 aluminum sheets and FSJC made of C45E is subsequently evaluated. This is done based on the interlock formation and shear tensile strength of joined pairs of sheets. In addition, the forces and moments required to generate the joint are recorded to identify and analyze characteristic phases. The aim of the research is to perform an initial analysis of the characteristics of pre-hole-free joining. The information obtained then provides initial knowledge for further research.

Process Principles

In order to join components with adaptive friction elements, comprehensive knowledge of the process sequence is required. Overall, the process comprises two stages. The first stage involves generating adaptive friction elements, and the second takes in joining with adaptive friction elements. **Fig. 1** displays the two stages of the novel joining method. To demonstrate its versatility, a selection of possible designs for adaptive friction elements and the associated process parameters are shown in the center.

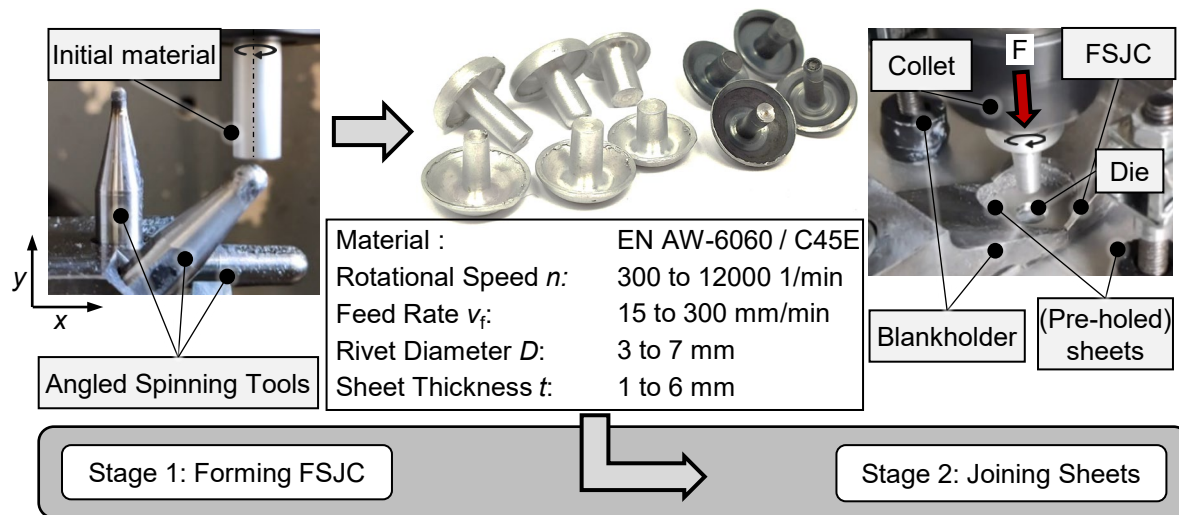


Fig. 1 Process stages for joining with adaptive Friction Spun Joint Connectors (FSJC)

The central mechanism of the joining process is the generation of heat by friction. The temperature input reduces the necessary flow stresses and thus the forming forces in the first and second stages. This approach is not limited to a specific material and is suitable for producing FSJC from steel or aluminum alloys. Sheets made of steel and aluminum alloys can be joined both with and without pre-holing [16] [17] [18].

Stage 1: Forming adaptive FSJC

This subsection describes the generation of adaptive auxiliary joining elements from a uniform initial rod material. Its sequence is illustrated in **Fig. 2**. Each cycle starts with the positioning of the rotating semi-finished product on the fixed tool according to the desired radius. Subsequently, the tool is immersed in the semi-finished product in order to locally reduce the flow stresses in the semi-finished product. Next, the cylindrical rivet shaft is formed by an axis-parallel feed movement. Finally, the manufactured FSJC and the tool are detached from each other, and the additional element is finished and ready to be used for joining components.

Adaptations are made to the rivet shape and mechanical properties from one rivet to the next, according to the requirements for each joint. This is achieved through specific modulation of the process parameters. Depending on the material, different procedures are suitable for influencing the strength of the joint. Either through a targeted temperature input via the process parameters [18] or by direct partial quenching during generation of the elements.

Variations in sheet thickness, like those encountered when using tailored blanks, can be responded to directly by adjusting the length of the auxiliary element and, if necessary, its diameter.

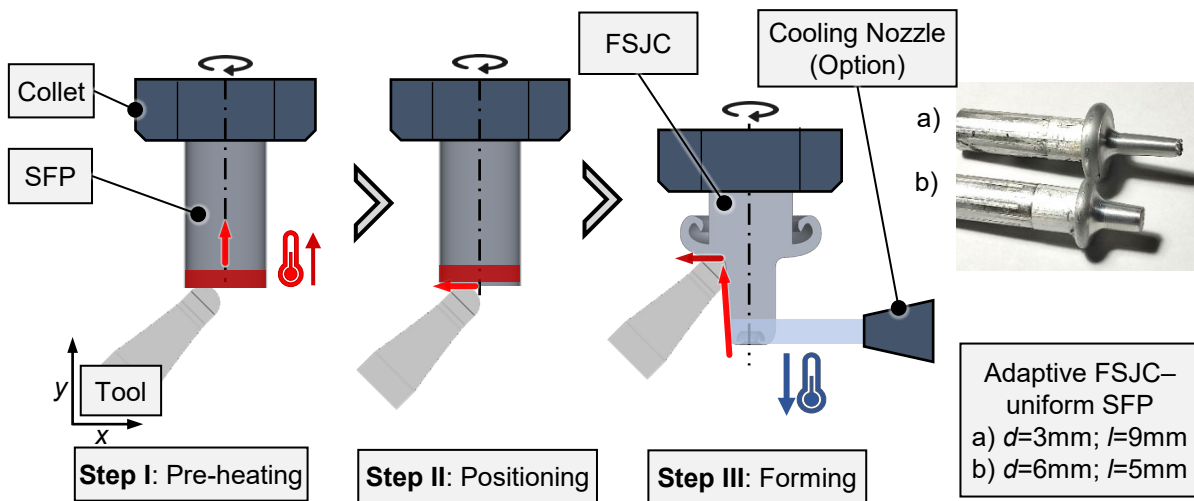


Fig. 2 Process principle for forming adaptive joining elements

Stage 2: Joining with FSJC

Subsequent to the generation of the FSJC in Stage 1, these can be used to join together pairs of sheets. In principle, joining with adaptive JE is suitable for joining pre-holed and non-pre-holed components. Whether pre-holing is necessary, however, depends on the material of the FSJC. Aluminum alloys, for example, are unsuitable for penetrating sheet metal and require an additional pre-holing operation to create a joint. Because of their material-specific characteristics, steel joining elements are suitable for joining components without pre-holing. This process variant is especially appropriate for the cost-efficient joining of components in dissimilar materials or with different sheet thicknesses. Fig.3 illustrates the sequence.

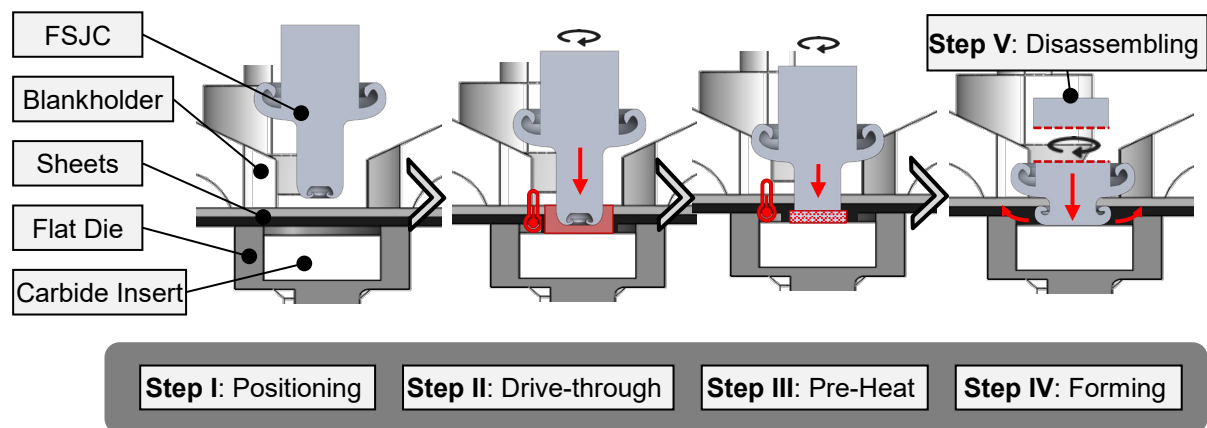


Fig. 3 Process principle: Joining with FSJC

Each joining cycle begins with the positioning of the auxiliary joining element generated in Stage 1 at the position of the intended joining point just above the sheet pairs (Step I). The second step involves rotating the FSJC to heat the sheets locally to promote penetration. This procedure is similar to flow drilling and generates a pull-through from the suppressed material of the sheets. At the beginning of the third step, the sheets are fully penetrated, and the steel joining element's tip is guided onto the flat die surface and pre-heats the element itself. Immediately after initial contact, the rotational speed of the FSJC is increased to create as much friction-induced heat as feasible in the shortest possible time. After the yield stresses of the auxiliary element have been locally reduced, a coaxial feed stroke follows, which upsets the tip of the auxiliary joining element (Step IV). The upsetting material encloses the draught and finally forms the load-bearing interlock. Once the final position has been reached, the rotation stops, and the FSJC can be separated by machining during disassembly (Step V).

Experimental Setup

In order to be able to form adaptive auxiliary joining elements and characterize their joining properties, a suitable setup is required (**Fig. 4**). This setup can allow an initial process characterization of joining with adaptive joining elements. The central feature is a horizontally attached milling spindle manufactured by Weiss Mosbach Germany. With a maximum speed of 14,000 rpm, this spindle provides the rotational energy necessary to form adaptive auxiliary joining elements from different materials. Furthermore, the necessary feed movements are carried out by means of cross support without any clearance. This is numerically controlled by a Siemens Sinumerik 840SL and thus enables the flexible contour shaping of the adaptive joining element through simple modification of the NC code.

To be able to reproduce the entire process chain, two constructive devices are required. First, a suitable tool concept is required for generation of the FSJC (**Fig. 4**). The angle-adjustable tool holder depicted is designed to accept rod-shaped tools via an ER16 interface. Shown in the center is an interchangeable fixture for joining shear tensile specimens. This fixture includes a central bore to take punch-shaped dies. Of particular interest in novel mechanical joining processes are the forces and torques that occur.

A load cell is provided to measure the process forces acting during the process phases. This is located below the joining station of the assembly. It enables process-integrated recording of the forces and torques that act during joining and the generation of the adaptive joining elements.

The strain-measuring force transducer of the ME Systems Technology K6D175 50kN/5kNm/UP13 converts the acting forces and torques into an electrical signal. The values are amplified by an HBM data acquisition system (QuantumX module MX440B) and recorded by an additional computer. Based on the measurements, the acting process parameter influences can be analyzed in order to optimize the process and tool design.

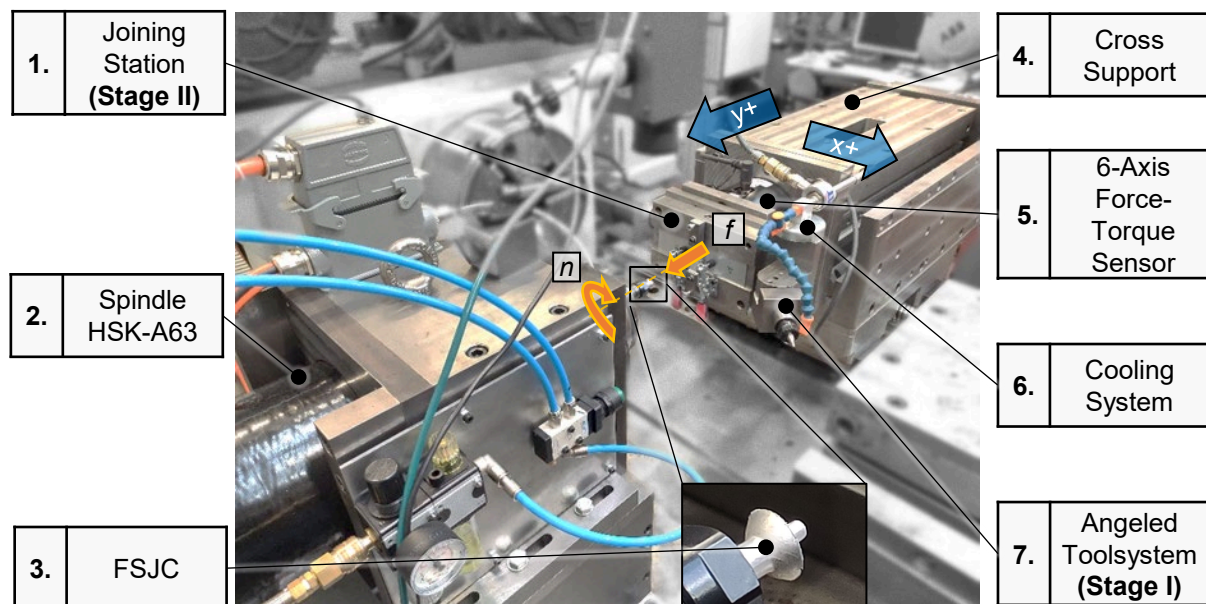


Fig. 4 Experimental setup

Experimental Procedure

Our results presented below are the most significant results from a parameter study carried out in advance. The parameters used in this study varied the speed and feed rate during the setting operation (Stage 2, Step 4), while keeping the upsetting distance constant.

The parameter set shown in Table 1 was chosen, since it represents the best ratio between the acting force and the process time.

Table 1 Material specification and process parameters

Process Parameter		Material	
RPM	Drive-through: 14 000 rpm	Joining element	C45E initial rod $d_0 = 8\text{mm}$ FSJC $d_1 = 4,5\text{mm}$, $l_1 = 7\text{mm}$
	Forming: 10 000 rpm		
Feedrate	Drive-through: 150 mm/min	Sheet	EN AW 6016 T6 dimension: $105 \times 45 \times 1\text{mm}$ overlap $l_u = 16\text{mm}$
	Forming: 100 mm/min		
Upsetting	Distance: 5 mm		

By way of an example, the results presented demonstrate the feasibility of pre-hole-free joining with adaptive auxiliary joining elements and deliver approaches for future characterization. The overall conditions are listed in **Table 1**. This specifies the materials used and their dimensions together with the specific process parameters used to produce the samples.

In order to be able to assess the joint quality, suitable characteristic values are required. The quality of the joints was evaluated on the basis of three different criteria. First, the joining force characteristics. The progression of the joining force F_z and torque M_z over the process time was determined using the above-mentioned force transducer (**Fig. 4**). These data provide information, for example, on the geometry formation, the material condition in the forming zone and the expected joining force. Another important aspect is the joint geometry realized. This is determined by a cross-section cut. This section allows conclusions to be drawn about the effect of process parameters on the cross-section geometry and the strength of the bond. Furthermore, knowledge can be gained about the material flow during the setting process, allowing conclusions to be drawn regarding the quality of the tool design. Finally, the shear tensile strength according to DVS/EFB-3480-1 is mentioned as an important indicator for the joint strength achieved, based on the typical force-displacement curves.

Joining force characteristic

To contribute effectively to the design and joining of lightweight constructions, substantiated knowledge of all the acting forces and torques is indispensable. This basic data can be used to appropriately design equipment and processes and thus to use resources as efficiently as possible. One such characteristic curve is shown in **Fig. 5**. According to the sequence shown and described in **Fig. 3**, the joining cycle begins with the coaxial positioning of the friction element in the desired joining position. The actual joining process begins when contact is made between the rotating auxiliary joining element and the surface of the cover sheet. Immediately, an increase in the applied torque to approx. 6 Nm can be identified, with a low load of 300 N. After the sheets have been penetrated, the torque decreases by a third to 4 Nm. In the next stage of the joining process, the FSJC, now rotating at maximum speed, comes into contact with the fixed, plane die made of carbide. This moment is clearly identifiable from the peak in the acting axial forces of about 8 kN and a slight increase in the torque.

After sufficient thermal energy has been generated and the tip of the steel auxiliary joining element has softened, the axial forces drop to a quarter of the maximum value of 2 kN, and a largely constant torque curve is present over the entire third phase. At the end of the fourth phase, an increase comes

about in the axial force and applied torque. At the beginning of the fifth phase, the feed and rotation stop, so that the joined shear tensile specimen can be removed and examined further.

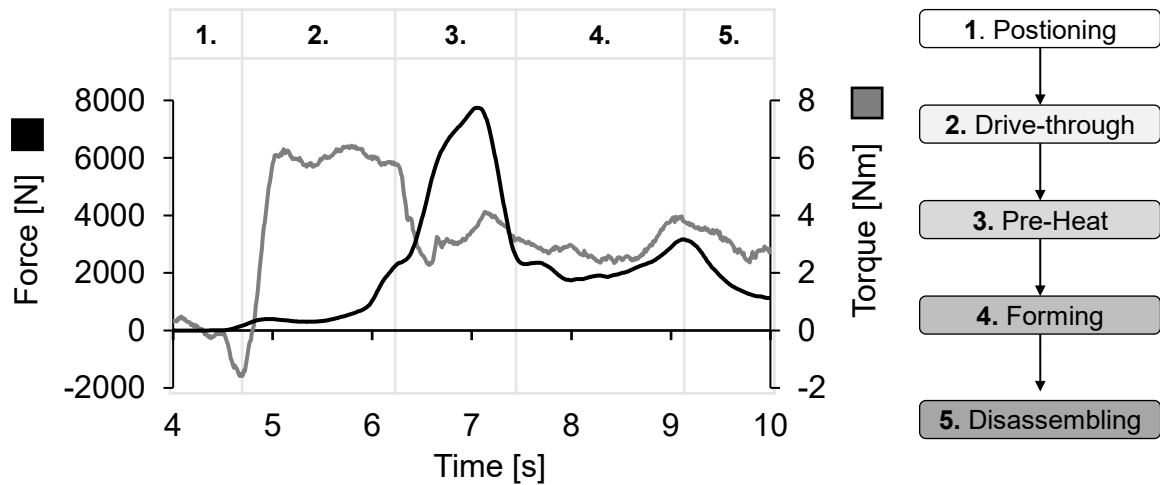


Fig. 5 Qualitative course of the joining (axial) force F_z and torque M_z over process time

It is evident that the general level of the joining force is significantly lower than that of other, conventional mechanical joining processes like SPR or clinching for the given boundary condition and parameter constellation [10].

Cross section analysis of a joint connection

To obtain deeper process insight, an exemplary cross-cut specimen is displayed in **Fig. 6**. As a result, structures that contribute to the mechanical strength become visible, and conclusions can be drawn about the process control.

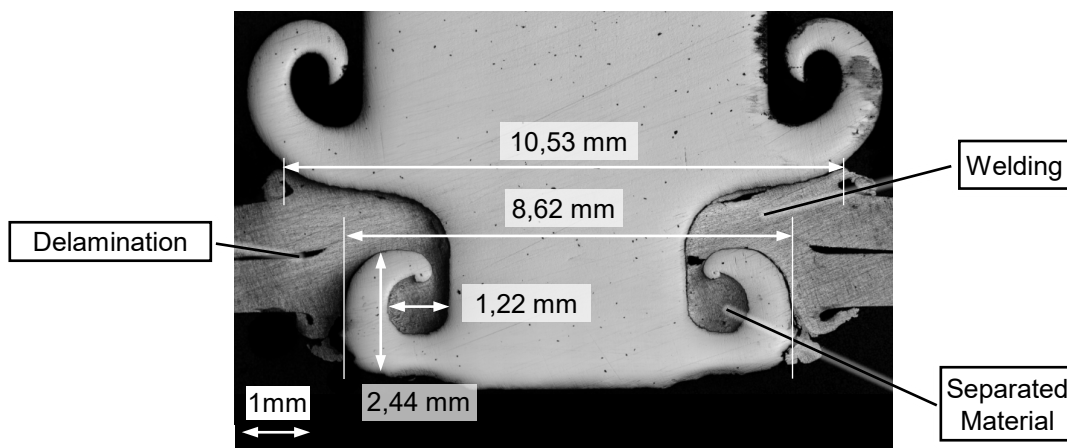


Fig. 6 Exemplary cross section joint connection

First of all, a slight delamination of the sheet materials can also be identified. This characteristic is essential in the case of hybrid joining techniques, since the layer thickness of the adhesive would be influenced. The friction-induced temperature input of the friction adhesive into the base material must also be considered. In **Fig. 6**, welding of the sheet materials can be seen near the setting head. While this effect does not take the form of a mechanical joining process, it will increase the strength of the joint due to the increased frictional and material bonding. When it comes to the structural integrity of the sheet metal, it is noted that the base sheet has been partially cut by the rotating steel auxiliary joining element. Since the material has been upset, this will not effectively contribute to the load-bearing capacity, especially under head tension.

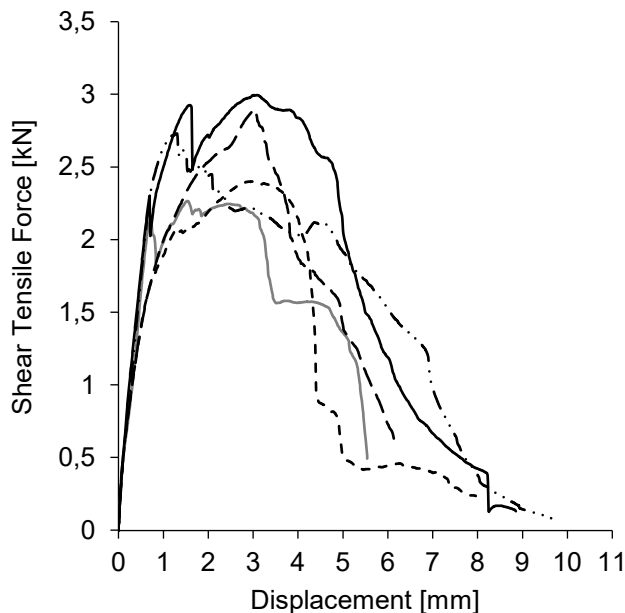
Low head tensile strengths might be expected depending on the test direction, and especially the joining direction. The reason may be found in the closing head's shape. After the maximum diameter has been reached, it decreases again until just short of the initial shaft.

The setting head comes into contact with the cover plate, thus maximizing the contact area between the element and the cover plate.

A similar strength and pull resistance would be achieved with a smaller upsetting distance without altering the integrity of the sheet structure. Examining the variation of the upsetting distance will be an interesting approach for further investigations.

Mechanical Strength

Of particular importance for a joining process is a well-founded understanding of the mechanical strengths that are attainable. This is particularly important with a view to safety-relevant applications. Shear-tensile specimens were thus prepared and destructively tested for an initial characterization of the mechanical properties according to DVS/EFB-3480-1: Testing of properties of mechanical and hybrid (mechanical/bonded) joints. This international standard defines the general test conditions, the test geometries and the test speeds applied to mechanically joined joints and joints made of steel and non-ferrous metals in the workpiece thickness range up to $t \leq 4.5$ mm.



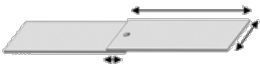
Test type and sample geometry	
Shear tensile test	
According to DVS/EFB-3480-1	
Test boundary conditions	
Testing machine: Zwick Z020	
$v_t=10$ mm/min	
Sample number: 5	
Sheet materials	
EN AW 6014 T6, $t= 1\text{mm}$	
EN AW 6014 T6, $t= 1\text{mm}$	
Joining element	
C45E, $d_1=4,5\text{mm}$, $l=7\text{mm}$	
Die geometry	
Flat die: diameter= 14mm, depth= 2mm	
Process parameters	
see Table 1	

Fig. 7 Force-displacement diagram of lap shear in the experimental series (each curve represents one specimen)

To compare the load capacity and the strength, characteristic values such as the maximum shear tensile strength F_{\max} and the corresponding displacement S_{\max} are defined in the test instructions. Higher values represent a greater energy absorption capacity. The second value, $0.3S_{\max}$, describes the residual load-bearing capacity of the joint or, more precisely, the possible displacement while maintaining at least 30% of the maximum shear tensile strength.

Fig. 7 displays the resulting force-displacement curves of five destructively tested shear tensile specimens. The process parameters used to generate the specimen are shown in the table on the right. On closer examination of the curves, it is clear that the strength of the specimens is comparable in the experimental series. The curve paths do, however, differ strongly in some cases.

The reason was found to be in the formation of the interlock inside the sheet structure. Since the upsetting material of the FSJC partially separates the lower plate, similar shear tensile strengths are achieved, but not load-bearing capacities.

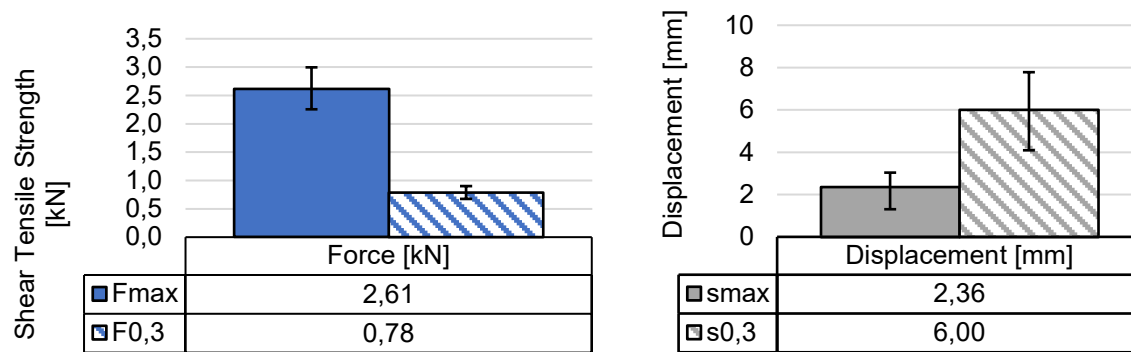


Fig. 8 Representation of the characteristic sizes of a shear-tension connection according to DVS/EFB-3480-1

This is clearly shown through the analysis of the characteristic values of mechanical joining processes shown in **Fig. 8**, based on five destructively tested shear tensile specimens. These bar charts represent the mean values of the respective test variables, supplemented by indicators reflecting the range of the results. The displacement required for the maximum force and the residual load shows an increased scatter. The maximum force F_{\max} was reached after a displacement of approx. 2.36 mm and, after a further 3.7 mm, 30% of the maximum value was still present, although the base plate had already broken.

Summary

The experimental results presented in this paper prove the feasibility of the pre-hole-free joining of components using FSJC.

After a comprehensive introduction to the novel joining process, an initial process characterization was provided in order to evaluate and illustrate the quality of the joint. The data were analyzed, and conclusions drawn about the underlying process control. Initially, the forces and moments required to create the connection were plotted over the processing time by way of example. An analysis of the curves indicates that the maximum forces and torques determined are significantly lower than those of conventional piercing joining processes. Phases that offer potential for process control can also be identified. To obtain a deeper knowledge of the process, a sample cross-section was analyzed so as to be able to assess the quality of the joint and the process parameterization in addition to the externally visible variables. Based on the corresponding cross-section, it became apparent that an excessively high upsetting distance reduces the integrity of the joint. Furthermore, the upset FSJC is seen to flow to the outside and the inside.

After the maximum interlock of the joint has been attained, the upset material curls to the inside, partially cutting through the base sheet and reducing its mechanical strength.

This becomes particularly clear from the third parameter, the mechanical shear tensile strength and the contact pattern of the joint. The maximum shear tensile strength corresponds to the aluminum sheets used, since these represented the fracture point in the constellation investigated. The strength and the energy absorption capacity determined were subject to significant scatter in the evaluated maximum and residual load capacities.

Key Findings

- Feasibility of pre-hole-free joints with adaptive joining elements
- Upset distance is decisive for a sustainable connection

Outlook

The data obtained provide a solid foundation for further developing the pre-hole-free joining of formed elements by friction pressing. In particular, experimental investigation of the die design can effectively contribute to increasing the quality of the joint. The pull-through is enclosed specifically

by increasing the distance between the bottom of the base sheet and the die surface. In this way, the rotating steel auxiliary joining element is prevented from affecting the sheet structure and thus reducing the load-bearing capacity. It is also feasible to implement load-optimized and direction-optimized strength control. This is made possible by a modified die design. Combined with the consistent expansion of joinable materials, joining with additional joining elements generated by friction pressure can effectively open up future lightweight construction potential and conserve our natural resources.

Acknowledgements

The authors would like to thank the DFG (German Research Foundation) for funding TRR 285-Project-ID 418701707, subproject C03.

References

- [1] Lambiase, F.; Scipioni, S.I.; Lee, C.-J.; Ko, D.-C.; Liu, F. A State-of-the-Art Review on Advanced Joining Processes for Metal-Composite and Metal-Polymer Hybrid Structures. *Materials* 2021, *14*, 1890, <https://doi.org/10.3390/ma14081890>
- [2] K. Mallick, Advanced materials for automotive applications: an overview J. Rowe (Ed.), Advanced materials in automotive engineering, Woodhead Publishing, Oxford (2012), pp. 5-27, <https://doi.org/10.1533/9780857095466.5>
- [3] Geoffrey, D.: Materials for Automobile Bodies, Kap.2: Design and material utilization, Elsevier, S. 17-91 (2012), <https://doi.org/10.1016/B978-0-08-096979-4.00002-5>
- [4] Geoffrey, D.: Materials for Automobile Bodies, Kap.6: Component assembly: materials joining technology, Elsevier, S. 17-91 (2012), <https://doi.org/10.1016/B978-0-08-096979-4.00006-2>
- [5] Merklein, M.; Johannes, M.; Lechner, M.; Kuppert, A.: A review on tailored blanks-Production, applications and evaluation. In: Journal of Materials Processing Technology 214 (2), S. 151-164, 2014, <https://doi.org/10.1016/j.jmatprotec.2013.08.015>
- [6] Martinsen, K., Hu, S. J., & Carlson, B. E. (2015). Joining of dissimilar materials. *CIRP Annals*, 64(2), 679–699, <https://doi.org/10.1016/j.cirp.2015.05.006>
- [7] Junying Min, Jingjing Li, Yongqiang Li, Blair E. Carlson, Jianping Lin, Wei-Ming Wang, Friction stir blind riveting for aluminum alloy sheets, *Journal of Materials Processing Technology*, Volume 215, 2015, Pages 20-29, ISSN 0924-0136, <https://doi.org/10.1016/j.jmatprotec.2014.08.005>.
- [8] Li, Yongbing & Wei, ZeYu & Wang, Jiao & Li, YaTing. (2013). Friction Self-Piercing Riveting of Aluminum Alloy AA6061-T6 to Magnesium Alloy AZ31B. *Journal of Manufacturing Science and Engineering*, <https://doi.org/10.1115/1.4025421>
- [9] Yunwu Ma, Sizhe Niu, Huihong Liu, Yongbing Li, Ninshu Ma, Microstructural evolution in friction self-piercing riveted aluminum alloy AA7075 T6 joints, *Journal of Materials Science & Technology*, Volume 82, 2021, Pages 80-95, <https://doi.org/10.1016/j.jmst.2020.12.023>.
- [10] K. Mori, N. Bay, L. Fratini, F. Micari, A.E. Tekkaya, Joining by Plastic Deformation *CIRP Annals - Manufacturing Technology*, 62 (2013), pp. 673-694, <https://doi.org/10.1016/j.cirp.2013.05.004>
- [11] Pina Cipriano, G., Ahiya, A., dos Santos, J.F. et al. Single-phase friction riveting: metallic rivet deformation, temperature evolution, and joint mechanical performance. *Weld World* 64, 47–58 (2020), <https://doi.org/10.1007/s40194-019-00803-3>

-
- [12] Miguel Costas, David Morin, Johan Kolstø Sønstabø, Magnus Langseth, On the effect of pilot holes on the mechanical behaviour of flow-drill screw joints. Experimental tests and mesoscale numerical simulations, *Journal of Materials Processing Technology*, Volume 294, 2021, 117133, <https://doi.org/10.1016/j.jmatprotec.2021.117133>
- [13] Johan Kolstø Sønstabø, David Morin, Magnus Langseth, Testing and modelling of flow-drill screw connections under quasi-static loadings, *Journal of Materials Processing Technology*, Volume 255, 2018, Pages 724-738, <https://doi.org/10.1016/j.jmatprotec.2018.01.007>.
- [14] Meschut G, Janzen V, Olfermann T. Innovative and highly productive joining technologies for multi-material lightweight car body structures. *J Mater Eng Perform* 2014; 23(5): 1515–23, <https://doi.org/10.1007/s11665-014-0962-3>
- [15] Pragana, J. P. M., Silva, C. M. A., Bragança, I. M. F., Alves, L. M., & Martins, P. A. F. (2018). A new joining by forming process to produce lap joints in metal sheets. *CIRP Annals*, 67(1), 301–304, <https://doi.org/10.1016/j.cirp.2018.04.121>
- [16] Lossen, Benjamin & Homberg, Werner. (2016). Friction spinning – Twist phenomena and the capability of influencing them. 1769. 070001. 10.1063/1.4963454., 2016 <https://doi.org/10.1063/1.4963454>
- [17] C. Wischer, E. Wiens, W. Homberg. Joining with versatile joining elements formed by friction spinning, *Journal of Advanced Joining Processes*, Volume 3, 2021, <https://doi.org/10.1016/j.jajp.2021.100060>.
- [18] Wiens E, Wischer C, Homberg W, eds. Development of a Novel Adaptive Joining Technology Employing Friction-Spun Joint Connectors (FSJC).; 2021, <https://doi.org/10.25518/esaform21.4682>