Joining with Friction Spun Joint Connectors – Manufacturing and Analysis

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Abstract. Nowadays, the production of modern lightweight structures, like a body in white structure requires a wide variety of mechanical joining processes. To fulfill the various demands, mechanical joining processes and joining elements (JE) are used. Very often, they are adapted to the application, which leads in turn to a numerous of different variants, high costs, and loss of the process chain versatility. To overcome this drawback, an innovative approach is the usage of individually produced and task-adapted JE, the so-called friction spun joint connectors (FSJC). These connectors can be modified in shape as well as in material properties. This flexibility offers high potential for lightweight design but also increases the necessary analytical effort regarding the forming process as well as the manufactured joint’s properties. Therefore, a new analysis strategy based on the Finite-Element-Method (FEM) is proposed, which numerically determines the local load bearing capacity within a given joint in order to identify the critical regions for load transfer. The process of joining element manufacturing and the analysis strategy will be described in detail and optimization results of the joints are shown. Numerical results are discussed and possible recommendations for joint manufacturing are derived.

1. Introduction and state of current research

One of the greatest challenges of our time is to limit the global temperature rise caused by human-induced climate change. Since the beginning of the industrial age, emissions of climate-damaging greenhouse gases have been increasing continuously, and with them global temperatures. A large share of these gases are emitted by the transport sector [1]. One approach to reduce emissions can be found in the mass reduction of vehicles moved and thus of the required energy. In order to accomplish this goal, the automotive industry focuses on high-resolution, load-optimized lightweight construction [2]. By using a diverse range of materials, it is possible to produce lightweight structures that are suitable for the given loads without any compromises in terms of vehicle safety. In order to implement this strategy, an adapted manufacturing strategy is required, in particular with regard to the intended joining techniques. For joining dissimilar materials, thermal processes such as resistance spot welding quickly reach their limits and restrict the design options regarding possible material combinations [3].
Hence, there has been a notable rise in mechanical joining processes in recent years, especially in car body construction, to join different materials reliably and efficiently. However, not all techniques are suitable for every application. Clinching, for example requires ductile joining components, otherwise cracks are noticeable [3]. The joining elements of the self-piercing riveting processes are usually specifically designed for their intended use. Different sheet thicknesses or material combinations usually require special joining elements or tool adaptation of the die geometry or process control.

From a design perspective, increasing numbers of different joining points within a given structure also require new approaches in the design process. With regard to increasingly shorter product life cycles, analytical methods are time-consuming and costly when it comes to dimensioning joints to meet load requirements[4]. In industrial practice, therefore, computer-aided pre-selection is increasingly being used in order to provide a suitable joining process at an early phase in the production development process.

Currently, during the design process, the optimization of the joining element and the structure are considered separately. The optimization of quantity and distribution of joining elements is done based on experience or supported through artificial intelligence. Also, topology optimization and size optimization are used. In mechanical joining, Finite-Element-Analysis (FEA) can be used for process design [7] and to select a suitable tool geometry combination [8]. When designing components and their joints, choosing the number and distribution of joining elements is very important. Possible procedures for this are ranking based on selection, size optimization or topology optimization [9]. For the design of individual joining points, it is possible to determine the loads acting on joining points based on an overall structure such as a car body [10]. Due to the large number of joining points, these are represented for this purpose by simplified models such as a beam which is coupled by a rigid body bushing to the shells or one single beam with a tied node to surface contact and constrained bending degrees of freedom [11]. The stiffness of the simplified model of the joint is calibrated on the basis of real joints. The loadings from the overall structure can then be used in the next step for the detailed analysis of individual joints. The overall motivation is to design and arrange the joining points in such a way that the load on the component and the joint are distributed as evenly as possible. Since currently the design of the joint and the components are considered separately, the interdependencies between the mechanical loads on the component and the joint are rarely considered during the optimization process.

In this context, it is desirable to take the component adaptation and the distribution of the joints into account in order to prevent their oversizing. This requires flexible joining elements (JE) and a flexible joining process, as well as the support of design methods to assess the load distribution in the component and joining element. The method presented in this paper focuses on the analysis of the load distribution of the riveted connection. The approach for the evaluation of the load-bearing behavior is based on a change of the deformation energy depending on a local reduction of the Young's modulus. This makes areas of the joint that contribute less to the load transfer identifiable and uncovers geometric optimization potentials of the joint.

One solution for the manufacturing of such flexible JEs is the use of adaptive joining elements formed by friction spinning. The shape and mechanical properties of the joining elements (FSJC) are adjustable according to the joining point specifications. Compared to other mechanical joining processes that use friction-induced heat to join metal sheet pairs from identical materials, this method offers the ability to join different materials, at most sheet thicknesses without the need to modify the die geometry. In an exemplary study, the geometry of the rivet is varied and the jointed connection is analyzed by using the new developed method, which provided an opportunity to identify potentials for minimizing oversizing in the design and manufacture of the FSJC.
2. Process principles
In order to form adaptive joining elements, it is suitable to use the friction-induced heat for forming the FSJC from a uniform initial material. This so-called friction spinning process increases the formability of the material through a locally limited temperature increase, and thus reducing the flow stress and the forming forces [4-6].

The presented process shown in Figure 1 includes of two stages. Firstly, the manufacturing process to form an adaptive FSJC from a rotating semi-finished rod, see Figure 1 a). This FSJC can be used immediately for joining preholed sheets in the second stage. Finally, the joined sheets can be used for tensile test to analyze the mechanical properties of the FSJC. Figure 1 b) shows a selection of different part geometries, including different angled tips, hollow and grooved shafts and different-shaped heads. Geometry combinations of these can be formed using the same universally applicable forming tool.

2.1. Stage 1: Forming adaptive FSJC
Figure 2 shows the principal process sequence for forming a load-adapted FSJC. During the manufacturing process, the semi-finished product (SFP) rotates to induce heat through a two-dimensional relative motion between the SFP and the fixed tool. The necessary rotational motion is provided by a motor spindle, movements by numerically controlled, motor-driven axes. In order to form adaptive elements from the semi-finished product, suitable high-temperature tools are required. The decisive factor is that the melting point of the tool material is higher than that of the JE material. For aluminum alloys, common tool steels are suitable, while steel connectors requires carbides due to the high temperatures of $\vartheta > 800 ^\circ C$. Fastening the SFP during forming is ensured by a collet, clamped in spindle. First successful investigations primarily use aluminum alloys but also steel to form suitable FSJC.
Figure 2. Process principle forming adaptive FSJC – SFP \( D_0 = 8 \text{mm} \) – Universal tool R3-45°

Each forming process begins with the immersion of the rotating circular SFP (EN AW-6060 T6) into the rigid tool (1.3343). The relative movement pre-heats its tip by frictional heat and increases the formability of the SFP (step I). This is followed by the second and third phases of the forming process, which determine the shape and dimensions of the FSJC. For forming, the rotating semi-finished product is positioned as seen in Figure 2 (step II) depending on the intended diameter. Subsequently, the length of the FSJC is formed by a relative movement parallel to the rotational z-axis (step III). Both its diameter and length are customizable specifically to the mechanical requirements of the joining point. Furthermore, the FSJC inner structure can be modified by an adapted, optional process control strategy. Targeted cooling at the connectors base permits local hardening (step III). Consequently, the JE is usable to join pre-holed sheets of variable thickness or material.

2.2. Stage 2: Joining Process

Just like the forming process (Figure 2) of the FSJC, the joining process also benefits from the innovative approach of the friction spinning. Due to the frictional heat generation and the resulting reduction of the flow stress, the joining forces required to form the closing head are reduced and enhance the interlock. To create the joint, a die is required which is filled by the plasticized base of the FSJC and form the locking head as a die positive and its dimensions.

Figure 3. Process principle using solid FSJC (EN AW-6060 T6) and a spigot die, joining pre-holed 1 mm aluminum sheets (EN AW-6014 T4)

The joining process (Figure 3) starts with step I: The coaxial positioning of rotating FSJC in relation to the holes in the pair of sheets (EN AW-6014 T4). To pre-heat the rivets base, the element is axially pressed onto the tip of a fixed spigot die. Following in step II a short 0.5 s dwell time and the associated local temperature input, the closing head is formed in step III. This is done by a coaxial feed stroke, the FSJC is forced into the cavity of the die until the interlock has been formed. The dies spigot has a
decisive task in this process. On the one hand, the material flow is steered in a defined direction. On the other hand, the coaxial position of the FSJC to the die is ensured during the forming process. In order to increase the force fit, an additional short movement is proceeded, compressing the FSJC shaft and enhance the connections quality enhancing the frictional force and stiffness.

The connections attainable mechanical strength is affected by various factors. Probably the most important is the intended material for the FSJC. Aluminum is less complicated to process compared to steel due to its low strain reduction temperatures. Steel has a significantly higher mechanical strength and thus enables additional manufacturing options, especially with regard to pre-hole free joining operations. It is possible to pierce through pairs of sheets, similar to flow drilling, so that the closing head can then be formed with the benefit of friction-induced heat. Another factor affecting the attainable mechanical strength is the diameter of the pre-holes. Independently of the diameter of the adaptive FSJC, this effects on the connections shear tensile strength. In turn to the compression of the FSJC during the forming of the closing head in stage IV, the expansion is bounded by the pre-holing of the sheets. The load-bearing cross-sectional area is equivalent to the perforation. The cross tension strength is affected in particular by the shape and volume of the die, which defines the shape of the closing head. Its diameter forms the load-bearing interlock, while the depth defines the peeling resistance.

Figure 4 displays cross sections of possible joining options. Large sheet thicknesses a) can be joined as well as multilayer connections b). By replacing the die as shown in b) and c), it is also possible to change the geometry of the closing head. Additionally, it is also possible to make changes in the design of the closing head. This allows adjustments to the mechanical properties and material flow behavior.

![Figure 4. Connections of variable thickness, number of sheets and materials by an adaptive aluminum FSJC, a) St-Al, b) St-Al-St, c) St-St (*Setting head optimization has not occurred yet)](image)

3. Numerical analysis of the local load bearing capacity

The presented process offers the possibility to influence both the production of the JE and the joining process itself. Supporting methods in the design process are required for the flexible design of the FSCJ and the joint connection. The focus here is on reducing oversizing. For an analysis of the load bearing capacity of the JE a FE-model was set up using MSC Marc. A quasistatic 2D axisymmetric FEA of the connections of two 1 mm thick sheets under tension loading was used for the investigations. During the analysis, the size of the rivet was stepwise reduced and the change of the deformation energy in the joining connection was analyzed. As a reference rivet for the investigations, the FSCJ shown in Figure 5 a) was used. It has a diameter of 10 mm and a length of 7 mm. Figure 5 b) shows the rivet modified by a hole with a diameter $D_1$ of 1 mm. The third version is shown in Figure 5 c). The diameter of the hole $D_1$ was increased to 2 mm and the length $l$ of the rivet was also shortened from 7 mm to 5.25 mm. To simulate the load on the joint, the lower sheet was fixed and a displacement $\Delta z$ of 0.01 mm was applied to the upper sheet. The production of the rivet and the connection were not considered in the simulation. Therefore, an ideal rivet geometry was assumed for the numerical investigations.

![Figure 5. a) Reference rivet, b) Rivet with hole, c) Rivet with increased hole and shortened length](image)
A new approach based on the consideration of the deformation energy as a function of a change in stiffness was developed for the evaluation of the load-bearing behavior of the joined connection. The calculation of the proposed post size $\Delta W$ is done by a user subroutine according to Figure 6. In the first time step, all elements will be assigned a Young's modulus of 100% and the deformation energy for the entire system is calculated. The energy calculated in the first increment is used as the reference energy $W_{\text{ref}}$. In the next step, an element is assigned a reduced Young's modulus of 95% and the deformation energy $W_i$ for the entire system is calculated. The difference $\Delta W$ between the reference energy $W_{\text{ref}}$ and the energy for the respective increment $W_i$ is determined and in the next step, $\Delta W$ is allocated to the weakened element. The calculation is repeated until all elements have consecutively been assigned a reduced Young's modulus and the change in deformation energy has been calculated and mapped to each respective element. The result $\Delta W$ can be plotted as a false color plot and can be interpreted as follows: A large value implies that the deformation energy of the overall system drops significantly. This can be explained by the reduced stiffness of the considered element and means that this element contributes a lot to the load transfer. Thus, the areas that contribute more to the load transfer can be identified by a large energy difference.

**Figure 5.** Test case cross tension test using a 2D axisymmetric FE-model, a) Basic FSJC, b) Modified FSJC with 1 mm hole, c) Modified FSJC with 1 mm hole and shortened length

| 1st increment | all elements 100% Young's modulus |
|---------------|-----------------------------------|
| Calculation of the deformation energy as a reference $W_{\text{ref}}$ |
| 2nd increment | one element 95% Young's modulus |
| Calculation of the deformation energy for the 2nd increment $W_i$ |
| $\Delta W = W_{\text{ref}} - W_i$ |
| $\Delta W$ allocated to the weakened element |
| ith increment | ith element 95% Young's modulus |
| Calculation step of the 2nd increment is repeated for all elements |

**Figure 6.** User subroutine calculation procedure for calculating the change of deformation energy

Figure 7 compares the results of the change in deformation energy for the three rivet geometries. When comparing the unmodified rivet geometry in Figure 7 a) with the modified variant shown in
When comparing the initial variant in Figure 7 a) and the rivet with 2 mm hole and shortened length in Figure 7 c), a lower value for $\Delta W$ in the contact areas between rivet and sheet metal (highlighted with a red circle) can be determined for the modified variant. This means that, in comparison, variant c) with the lower values in the contact area has a lower deformation energy. This is due to the reduced size and stiffness of the rivet and a more distributed load transfer over a larger area. The smallest FSJC has less stiffness than the other variants due to the reduced size. By reducing the rivet size, there is also a reduction in the total energy. If this is also taken into account when comparing the variants, it means that in percentage terms, measured against the total energy, there is a larger drop in the deformation energy for variants b) and c). However, overall the rivet contributes comparatively less to the load transmission and could be reduced even further. In all three variants, the sheets contribute the main part to the load transfer.

For further comparison, the FSJC can also be viewed without the sheet metal. Differences in the contact areas between the rivet and the sheet metal can be confirmed as already shown in Figure 7. It can also be confirmed that the entire rivet only has a minor contribution to the load transmission. When comparing the ranges of $\Delta W$ values for the individual variants in Figure 7 and Figure 8, $\Delta W$ assumes smaller values for only the rivet without the sheets, see Figure 8. Due to the lower values of $\Delta W$, it can be inferred that the rivet contributes less to the joint connection in total. Thereby, the small value indicates a smaller contribution to the load transmission. As in Figure 7, no distinctive differences could be found between variant a) and b) when considering the energy change in Figure 8. In version c), smaller changes in energy compared to version a) and b) were observed. By reducing the stiffness, the load transfer is redistributed to several areas.
In summary, the rivet size has been reduced, but the overall contribution of the rivet to the load transfer is still small and can be further adjusted to reduce oversizing and achieve a more uniform load transfer.

4. Summary and Outlook
In this paper, the innovative approach to join with individually manufactured and task adapted FSJC was presented. These connectors can be modified both in their shape and in their material properties. This flexibility offers completely new possibilities in terms of lightweight construction, but also increases the effort required to analyze the process as well as the properties of the manufactured joint. To overcome this, a new analysis strategy based on the FEM was proposed to numerically determine the local bearing capacity in order to identify important areas for load transfer of the joint. In a study, the rivet geometry was changed in two stages and analyzed with the new method based on the change of its deformation energy. This enables the possibility to identify potential for adapting the rivet geometry. Based on these results, it would be feasible to make the rivet hollow on the inside and to use a tube instead of a solid material as the semi-finished product for the production of the FSJC. Overall, it was shown that the rivet is not the main load transfer element and that there is potential to investigate the rivet geometry further to counteract oversizing.

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