Versatile self-piercing riveting with a tumbling superimposed punch

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Abstract. Increasing resource efficiency is a major challenge and affects almost every aspect of social and economic life. The mobility sector in particular is responsible for a large share of primary energy consumption and is increasingly in the focus of public interest. One possibility to adress these challenges is to reduce the vehicle weight by means of lightweight construction technologies such as multi-material systems. These assemblies consist of workpieces with different mechanical and geometrical properties, which poses a major challenge for joining technology. Mechanical joining processes such as semi-tubular self-piercing riveting are often used in the production of these assemblies, but due to their process characteristics, they are rigid and can only react to changing process variables to a limited extent. One way to increase the versatility of self-piercing riveting is to superimpose a tumbling kinematics on the punch. During tumbling, an angular offset of the punch axis to the tool axis is set and the contact area between punch and workpiece is reduced. In this work, investigations were carried out to determine how the tumbling strategy, consisting of the parameters tumbling angle, tumbling onset and tumbling kinematics, affects the material flow of the rivet element. For this purpose, experimental tests are conducted with the typical materials of conventional multi-material systems and the geometric joint formations are determined by means of macrographs.

Key findings

- Analysis and identification of the significant influencing parameters of the tumbling strategy on the process combination and their interactions
- Evaluation of possibilities of a targeted material flow control to influence the geometric joint formation

Introduction

The energy and climate crisis demands a more efficient use of resources and technology. A major part of this ongoing change has to take place in the mobility sector [1]. Stricter limits for CO_2 emissions were imposed recently [2]. One way of increasing efficiency in automotive engineering is weight reduction [3]. Especially the battery weight in electric vehicles can be partially reduced this way [3]. Since the body in withe is an important part of the vehicle's total weight, efforts are often focused on replacing conventional steel used in body design with lightweight materials such as aluminum, fiber-reinforced plastics or high strength steel [4]. Reducing the overall mass of a passenger car with an internal combustion engine by 100 kg can save about 0,5 l of fuel per 100 km [5]. In addition to reducing weight and increasing efficiency, the mechanical strength and crash behaviour of a vehicle can also be improved by the selective use of materials [4]. This approach is generally called multi-material design [3]. The spectrum of materials used in this strategy includes light metals, such as titanium or aluminum, as well as plastics and composites [6], up to ceramics [7]. Due to the different chemical, mechanical and thermal properties of these materials, joining technology is one of the greatest challenges of multi-material design [6]. While conventional thermal joining processes reach their limits when it comes to joining dissimilar materials [8], mechanical joining technologies such as semi-tubular self-piercing riveting (SPR) are becoming increasingly important [9]. Since SPR is a rather rigid process with limited flexibility, it cannot comply with the increasing demand for rapid response to individual product configurations [3]. One way to improve the variability of SPR is to superimpose the process with a tumbling kinematics on the punch. The punch is tilted by a certain angle, which reduces the contact area between the tool and the workpiece [10], as shown in Fig. 1b). As a result, the joining forces are reduced, and the process limits are increased [11], due to a higher number of parameters. Furthermore, the flexibility and versatility of the process can be enhanced [3].

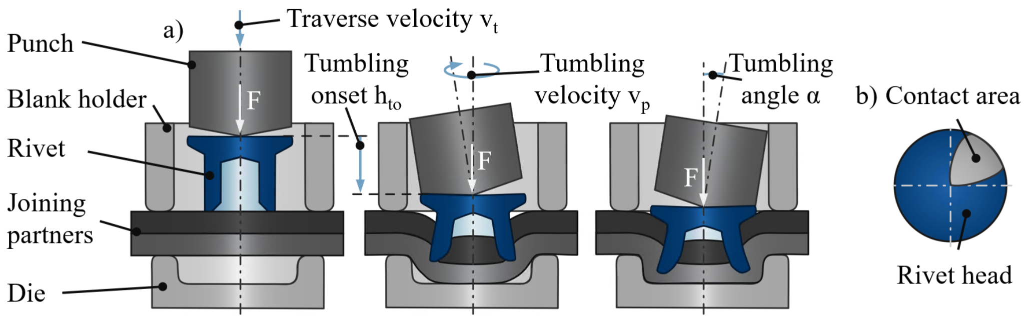
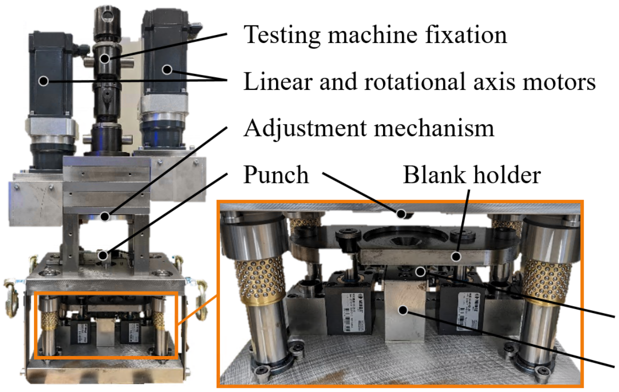


Fig. 1. a) Components and process parameters [13] of semi-tubular self-piercing riveting with tumbling punch and b) resulting contact area.

At present, the potential of this process combination cannot be exploited to its full extent, since no holistic understanding about the correlation of the process parameters with the geometrical joint formation of the SPR joints exists. To improve the process knowledge, an extensive series of experiments was planned and executed, analyzing the effects of various parameters and tumbling strategy combinations based on macrographs. Therefore, the tumbling angle α, the tumbling speed v_t, the tumbling kinematics, and the tumbling onset h_{to} were varied. These parameters are further illustrated in Fig. 1a) and are explained in more detail below. The results of the analysis provide a basis for the efficient use of the process combination to achieve a higher versatility. In particular, conclusions regarding the process and material flow control in semi-tubular self-piercing riveting are drawn.

Tumbling Self-Piercing Riveting Process

For the investigation of the process combination of a tumbling superimposed semi-tubular self-piercing riveting process, the tool shown in Fig. 2 is utilized. The tool design provides the ability to investigate a variety of parameters of the joining and tumbling strategy [3]. The core of the tool setup is the combination of a rotating and a linear axis, which enables predominantly rotating and linear kinematic models to be executed and a free path planning of the contact surface between punch and rivet head can be implemented. Furthermore, the adjustment mechanism for the tumbling angle and the punch movement is excluded from the force path of the tool, thus enabling highly dynamic movements. The tool is installed in a conventional universal testing machine of the type Walter-Bai, which performs the tool stroke in the z-direction. As materials for the investigations, the steel HCT590X with a sheet thickness of t_0 = 1.5 mm and the aluminium alloy EN-AW6014 with a sheet thickness of t_0 = 2.0 mm are selected. Due to their mechanical and geometric properties, these two materials and sheet thicknesses represent common multi-material systems and their challenges for joining technology. The die type used is a flat die with a diameter of 8.5 mm, a depth of 1.7 mm and a draft angle of 5°. The rivet element is a C-rivet with a shaft diameter of 5.3 mm and a rivet height of 5.0 mm from industrial applications.



Parameter	
Rivet	C 5,3 x 5 H4
Die	FM_85_2117
Punch-side joining partner	HCT590X+Z t_0=1.5 mm
Die-side joining partner	EN AW-6014 t_0=2.0 mm
Traverse velocity v_t	10 mm/min

Fig. 2. Semi-tubular self-piercing riveting tool with detail views and tool parameters.

The investigations are carried out to identify the influences of individual parameters and their interactions with each other. For this purpose, the four process parameters of the tumbling strategy consisting of the tumbling angle α, the tumbling velocity v_t, the tumbling kinematics and the tumbling onset h_{to} are varied and evaluated. An overview of the variations of the process parameters are shown in Fig. 3. The tumbling angle is investigated in three stages. As a lower limit, the tumbling angle α = 1° is selected, since at an angle of α = 0° no tumbling angle is applied and the process is similar to a conventional semi-tubular SPR process. As a result, no correlations can be identified between the tumbling and the joining process. The upper limit of the investigated tumbling angles is set at α = 5°. Previous studies have shown that in certain circumstances cracks in the rivet shaft of multi-material systems occur at angles higher than α = 5° [3]. For a finer gradation, the tumbling angle α = 3° is also investigated. Furthermore, the tumbling kinematics is varied as a process variable. A distinction can be made between predominantly rotating and predominantly linear movements. For the rotating kinematics models, circular and spiral kinematics are applied. The two models differ mainly in the adjustment of the maximum tumbling angle, which is approached in the first revolution in case of circular kinematics and is built up over the entire joining process in case of spiral kinematics. As a predominantly linear kinematics model, the kinematic shown in Fig. 3d) is investigated, which has fundamentally different motion characteristics. The motion has a significantly higher proportion in the radial direction and thus affects the material flow during the joining process.

a)

Parameter			
Tumbling angle α	1°	3°	5°
Kinematics	Circle	Spiral	Linear
Tumbling speed v_p	180 °/s		360 °/s
Tumbling onset h_{to}	3.0 mm		4.5 mm

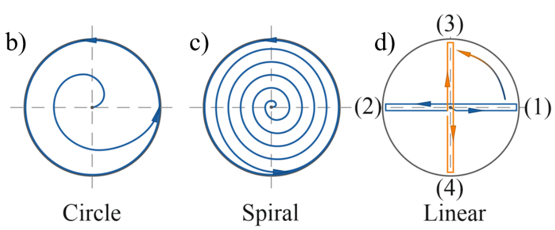
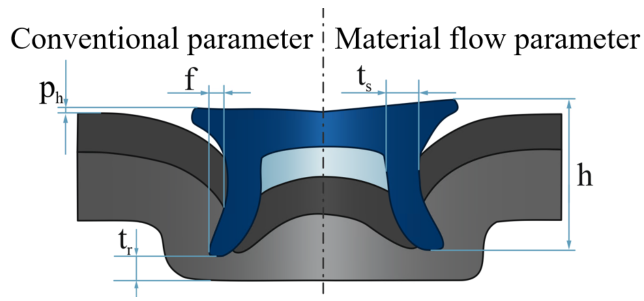


Fig. 3. a) Overview of the process parameter variation and schematic illustration of b) circular c) spiral and d) linear kinematics.

As a further process parameter, the influence of the tumbling velocity on the joining process is investigated. This parameter is varied in the steps 180 °/s and 360 °/s. Since the traverse speed, which generates the z-stroke of the punch, is constant at v_t = 10 mm/min, an increase in the movement speed enhances the distance moved by the contact surface during the joining process, which can be described in terms of the number of revolutions in case of a rotating movement pattern. For the investigations with linear kinematics, the same path speeds are applied as for the rotating models. The fourth parameter of the tumbling strategy is the tumbling onset. As shown in Fig. 1a), the tumbling onset corresponds to the stroke of the punch from the first contact with the rivet to the start of the tumbling motion. It is selected based on the process phases of conventional semi-tubular SPR with $h_{to} = 3.0$ mm and $h_{to} = 4.5$ mm. A tumbling motion of the punch before the cutting phase of the punch-side joining partner is completed causes a large angular misalignment of the rivet in the joint. Therefore, the influence of an onset of the punch movement during spreading with $h_{to} = 3.0$ mm and setting with $h_{to} = 4.5$ mm is examined. The process phases are identified during sampling with a tumbling angle $\alpha = 0°$ using force signals [12].

In the investigation, a total of three tests per parameter combination are conducted in order to identify statistical and process uncertainties. In total, the test setup comprises 108 tests. The geometric joint formations, shown in Fig. 4, are determined to evaluate the influences of the individual parameters on the joint and their interactions. For this purpose, macrographs are prepared and the standard geometric parameters relevant for the joint quality are determined. These consist of the undercut, the rivet head end position and the residual sheet thickness [13].



	Parameter
f	Undercut
h	Rivet height
p_h	Rivet head end position
t_r	Residual sheet thickness
t_s	Shaft thickness

Fig. 4. Geometric joint parameter for conventional and material flow parameter.

The investigations are also intended to identify and determine the material flow components. For this reason, the maximum rivet shaft thickness is measured in order to be able to identify radial material flow components in the joint. Furthermore, the rivet height is determined, which also provides insights into the effects of the individual parameters on the joint.

Evaluation of the Influencing Parameters

To determine the influence of the parameter variation, the rivet head geometry was analysed using 3D images. Fig. 5 shows three profile geometries of rivet heads, which differ in the tumbling angle. The other parameters remain constant. Therefore, the circular kinematics, the tumbling onset of $h_{to} = 3.0$ mm, and the tumbling velocity of $v_p = 180$ °/s were chosen since the influence of the tumbling angle can be visualized best with this configuration. The colours of the rivet heads indicate how far the rivet extends above the surface of the punch-side joining partner. It is evident that the rivet head sits significantly lower when the tumbling angle is increased. Accordingly, by using a greater tumbling angle it is possible to directly regulate the rivet head end position for example to obtain a plane surface of rivet head and joining partner. The planarity improves with increasing angle and the conical shape caused by the punch is reduced.

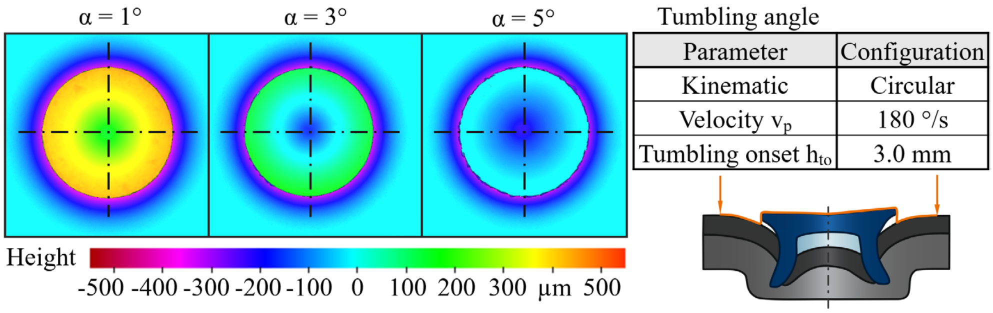


Fig. 5. Analysis of the rivet head geometry with varying tumbling angle.

Thus, it can be determined, the rivet head end position decreases when the tumbling angle is increased. In order to identify process characteristics about the material flow, the residual sheet thickness is examined. Fig. 6 shows the correlation of the residual sheet thickness with the kinematics, the tumbling angle, and the tumbling onset. Since the tumbling velocity has shown hardly any influence on the residual sheet thickness, both velocities are included in the average values plotted. It can be stated that the tumbling onset has a major influence on the residual sheet thickness when circular or spiral kinematics are applied. The linear kinematics leads to significantly more inhomogeneous results and is therefore statistically unstable. If tumbling starts after a 3.0 mm stroke, the residual sheet thickness increases with the tumbling angle. The difference from $\alpha = 1°$ to $\alpha = 3°$ is significantly greater compared to the variation from 3° to 5°. However, if the tumbling starts at $h_{to} = 4.5$ mm, the residual sheet thickness remains almost constant and is barely affected by other parameters. This means that the effect of the tumbling angle on the residual sheet thickness is a characteristic attribute of the tumbling punch, which only occurs if the effective tumbling process is sufficiently applied. It can be seen that not only the onset but also the duration of the tumbling has a significant influence on the geometric joint formation.

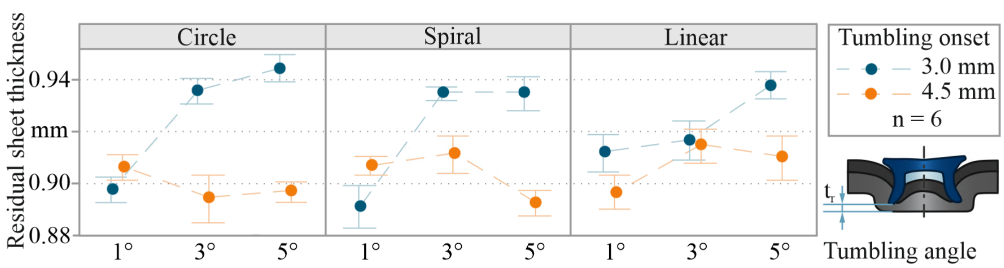


Fig. 6. Average residual sheet thickness depending on kinematics, tumbling angle and onset.

The fact that the residual sheet thickens as the tumbling angle increases contradicts decreasing rivet head end position. Hence, the tumbling punch must result in a deformation of the rivet. Therefore, the rivet height and the thickening of the rivet shaft were investigated to identify the direction of the material flow. Fig. 7 shows the correlation of the rivet height with the kinematics, the tumbling angle, the tumbling velocity, and a constant tumbling onset. It is apparent that the rivet is significantly compressed as a large tumbling angle is selected. The residual sheet thickness can therefore increase as the change in the rivet height is greater than the change in the rivet head end position. The figure also indicates that the deformation of the rivet is significantly less when linear kinematics are used. This shows that the effects of the tumbling punch are not well utilized by linear kinematics. Additionally, it can be seen that increasing the tumbling velocity leads to an enhanced rivet height change, especially with a large tumbling angle. To understand the effect of the velocity on the joint, process limits can be examined. If the tumbling velocity is increased infinitely, the tumbling process is equal to the conventional SPR. Accordingly, a very high velocity neutralizes the effects of the tumbling punch. A similar case applies to a tumbling velocity approaching zero. Hence, there must be an interval, in which the tumbling velocity ideally amplifies the effects of the tumbling punch however, detailed investigations with additionally varying velocities of the traverse are required therefore.

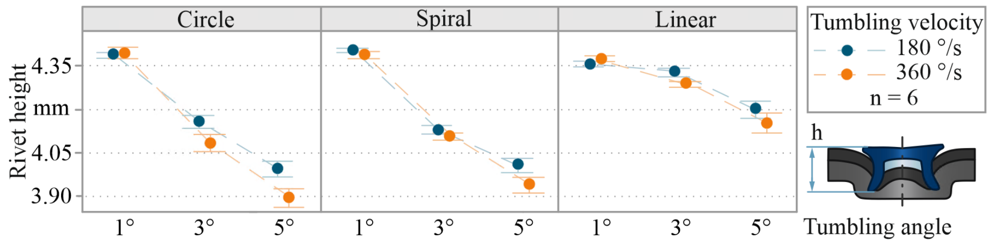


Fig. 7. Average rivet height depending on kinematics, tumbling angle, and tumbling velocity.

A reduction in rivet height leads to a partial radial material flow. The thickening of the rivet shaft increases the clamping effect of the joint and improves the force fit. Fig. 8 can be used to estimate the material flow. The outlines of rivet geometries extracted from the macrographs are shown. The reduction of the rivet height as well as the thickening of the rivet shaft by increasing the tumbling angle can be clearly seen in Fig. 8a). A significant part of the material flows radially inwards, as there is a flow constraint to the outside. The thickening of the rivet shaft also influences the undercut of the joint. For instance, the analysis showed that the undercut does not increase any further above a tumbling angle of $\alpha = 3°$, since the shaft thickening pushes the lowest and innermost point of the punch-side joining partner, at which the undercut is measured, further outward. This effect can be observed particulary well, when taking the average undercut for circular kinematics with 3.0 mm tumbling onset as an example. When the tumbling angle is increased from $\alpha = 1°$ to $\alpha = 3°$, the undercut changes from $f_{1°} = 0.32$ mm to $f_{3°} = 0.37$ mm. However, if the angle is further increased to 5°, the measured undercut even decreases slightly, resulting in an average value of $f_{5°} = 0.35$ mm.

In Fig. 8c) the influence of the kinematics is shown. While the outline is barely distinguishable for circular and spiral kinematics, the outline of the linear kinematis stands out from the other two kinematics, especially on the left side. As shown before, the rivet height remains greater with this kinematics. As a result, the radial material flow is reduced and the rivet shaft barely thickens. Also, the rivet head end position remains higher and the rivet foot is pushed outwards significantly less compared to the other kinematics. Thus, it can be confirmed that the effects of the tumbling punch vary in intensity due to the selection of the kinematics.

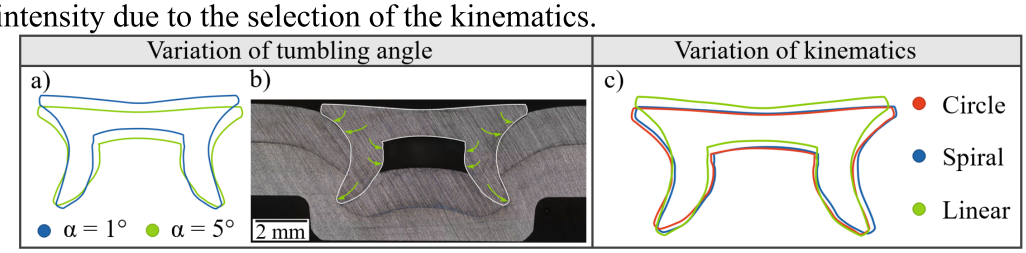


Fig. 8. Comparison of rivet outlines depending on a) tumbling angle and c) kinematics to determine b) material flow behaviour using 3.0 mm tumbling onset and a velocity of 180 °/s.

Summary

In this work, a semi-tubular self-piercing riveting process with superimposed tumbling kinematics on the punch was investigated. This involved deliberately varying the tumbling strategy in order to examine the effects of the process parameters tumbling angle, kinematics, tumbling onset and tumbling velocity on the geometric joint formation. In addition to the conventional geometric parameters such as rivet head end position, residual sheet thickness and undercut, the rivet height and the thickness of the rivet shaft were analysed to obtain findings on the material flow. It can be stated that the rivet geometry can be significantly influenced by the selected parameters, especially by the tumbling angle. When varying the tumbling kinematics, the circular and spiral kinematics show similar results. The linear kinematics weakens the effects of the tumbling punch and partly causes statistically uncertain results. Accordingly, the following findings refer primarily to the predominantly rotational kinematics.

The analysis of tumbling onset showed that the characteristics of tumbling are less identifiable when onset is delayed. This is particularly important for the residual sheet thickness since it can only be affected by the tumbling angle when the tumbling onset is in an early process stage. This understanding improves the flexibility of the process, as different sheet thickness combinations can thus be joined without having to exchange the die or the rivet. In general, a low rivet head end position is targeted in semi-tubular self-piercing riveting, ensuring that the surface of the rivet head and the punch-sided joining partner form a plane surface. It can be identified that the rivet head end position can be improved by increasing the tumbling angle. Furthermore, it was determined that an early tumbling onset in combination with a large tumbling angle and a high tumbling velocity cause a reduction of the rivet height. This leads to a thickening of the rivet shaft and thus to radial material flow. As a result, the force fit of the joint can be strengthened and the load-bearing capacity affected.

The results of this work provide a solid basis for the process control of tumbling semi-tubular self-piercing riveting. Nevertheless, some aspects offer further research potential. For example, due to the thickening of the rivet shaft the undercut can no longer be increased above a certain tumbling angle. However, since the undercut is decisive for the joint strength, the correlation between these two parameters could be investigated in more detail. Furthermore, there is potential for varying the kinematics, as only one configuration per kinematics was examined here. To separate the effects of tumbling onset and tumbling duration more precisely, it would also be interesting to conduct experiments with a tumbling motion only in the respective process phase. In addition, it is advisable to analyse the significance of the radial material flow for the load-bearing capacity and the joint strength of the connection in more detail.

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