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Combination of versatile self-piercing riveting processes

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Abstract. Due to economic and ecological framework conditions, a resource-saving utilization of raw materials and energy is becoming increasingly important in particular in the mobility sector. For the reduction of moving masses and the resources consumed, lightweight construction technologies are part of modern production processes in vehicle manufacturing, for example in the form of multi-material systems. Challenging in the manufacture of multi-material systems especially in view of changing supply chains is the variety of materials and geometries that bring conventional joining processes to their limits. Therefore, new processes are required, which can react versatile to process and disturbance variables. A widely used industrial joining process is semi-tubular self-piercing riveting, which is however a rigid process. To increase the versatility, the two newly established processes multi-range self-piercing riveting and tumbling self-piercing riveting are combined and the capabilities for targeted material flow control are united. Therefore, an innovative two-stage process based on the combination is introduced in this paper. The rivet is set with the multi-range self-piercing riveting process with an overlap of the rivet head and then formed by a tumbling process. Further, a specific adaptation of the tumbling strategy is used to investigate the possibility of reducing cracks in the rivet head. Thereby, different tumbling strategies are used and similar geometric joint formations are achieved to compare the results.

Introduction

The ecological, economic and social developments of the last years require a major focus on resource-saving technologies and the increase of efficiencies in many areas [1]. In particular, the mobility sector is undergoing a major transformation, as this sector is responsible for approximately 26% of CO_2 emissions in the European Union, measured in 2019 [2]. One way to reduce energy consumption over the entire product life cycle, regarding both the production and the use of vehicles, is the deployment of lightweight construction technologies. This often involves the use of multi-material systems, which are characterized by the fact that they comprise components that have different mechanical and geometric properties [3]. The mechanical properties vary due to different materials used, and the geometric properties are dimensioned according to local requirements and consequently differ. This is reinforced by the vulnerability of global supply chains, which is also noticeable in lightweight materials due to the crisis. However, the manufacture of these systems requires the ability to join a variety of different components with varying materials and geometries and places all the greater demands on the flexibility of joining processes in more and more versatile process chains. [4]. These requirements are a major challenge for conventional joining processes currently in use, such as semi-tubular self-piercing riveting [5]. Due to its process design, this method is a rigid joining process that can only react to process and disturbance variables to a very limited extent [6]. In order to adapt the joining process to changed

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boundary conditions, a change of the tools or the auxiliary joining part used is necessary [7]. However, these changes also result in a decrease of the process efficiency. To avoid a change of tools, versatile processes that can react flexibly to changing conditions are required. In order to address the challenges of future production systems with a large number of variants and to increase the adaptability of the joining processes, the two processes multi-range semi-tubular self-piercing riveting [8] and tumbling self-piercing riveting [9] were investigated. The schematic process layouts of both processes are shown in Fig. 1.

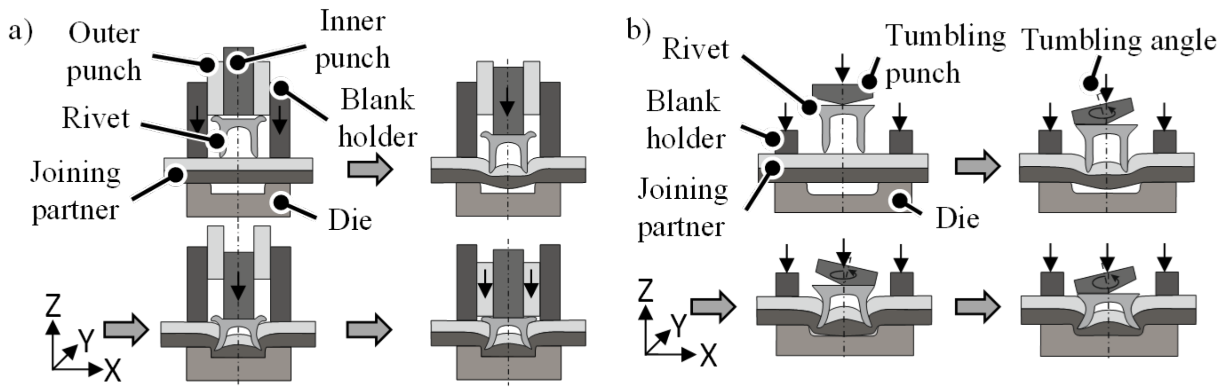

Fig. 1 Multi-range self-piercing riveting a) and tumbling self-piercing riveting b)

Conventional semi-tubular self-piercing riveting is a mechanical joining process for which double-sided access to the workpiece is required. The process design allows joining of similar and dissimilar materials such as steel, aluminum and fiber composites [10]. In addition, no pre-hole operation is necessary, the process can realize fast cycle times and achieves high static and fatigue joint strengths [11].

Using the process with multi-range tubular self-piercing rivet, shown in Fig. 1 a), the setting of the rivet is followed by a forming process, which forms the rivet head after setting onto the punch-sided sheet. Therefore, an inner and an outer punch is required. Due to the subsequent forming of the rivet head, the rivet can be adapted to the respective thickness of the joint. Just like the conventional self-piercing riveting process, a form-fit and force-fit connection is created, which allows high joint load-bearing capacities, which are comparable to conventionally produced joints, to be achieved for pure aluminum [4] and multi-material joints [12]. The studies mentioned, were able to show, that the induced linear material flow was able to join sheet thickness variations of more than 1 mm. However, it was found that, especially with low sheet thicknesses, air inclusions occurred between the rivet head and the punch-side joining partner. These might have a negative effect on following process steps such as a cathodic dip painting. Closing this gap was not possible due to cracking in the rivet head area that occurs at high degrees of deformation.

The tumbling semi-tubular self-piercing riveting process, shown in Fig. 1 b), is a combination of a tumbling process and conventional self-piercing riveting [9]. Tumbling is an incremental forming process that has its origins in cold forging. Characteristic of the process is the tumbling movement of the punch, which is described by an angular offset of the punch axis relative to the rest of the tool axis [13]. Together with a conical shape of the punch, the angular offset, which describes the tumbling angle, results in a reduction of the contact area between the punch and the workpiece. Thus, a higher surface pressure is achievable and large forming operations can be realized with a comparably low force level [14]. Furthermore, due to the reduced contact area, a kinematic model can be applied, which specifically controls the movement of the contact area on the workpiece in order to achieve increased material flow control and thus a process-side influence on the workpiece. The targeted movement enables both an influence on the geometry and on the mechanical properties by strain hardening. By combining both versatile joining approaches, more opportunities to influence the process are expected and a specific shaping of the rivet head can be achieved.

Materials and Methods

In the research, an aluminum EN AW-6014 is used, which is an alloy of aluminum, magnesium and silicon. The material is applied in many components of the body-in-white and critical outer skin applications in the automotive industry. Therefore, the material is a component of multi-material systems in many applications and thus adequately represents them. The material is characterized by good formability and hemming behavior, as well as good paint bake response. For the punch-side joining partner, a sheet thickness of t_0 = 1.0 mm and for the die-side joining partner, a sheet thickness of t_0 = 2.0 mm was selected.

The rivet element used is an adapted rivet geometry, which is modified for the multi-range joining process and has a material protrusion at the rivet head. This material protrusion is embossed by the outer punch in the conventional process and, thanks to the additional material, enables better joining suitability for greater total sheet packages. The selected die has a standard geometry from the industrial environment from type FM 095 2116 with a diameter of 9.5 mm and a die depth of 1.6 mm.

As a joining strategy based on the process combination, a two-stage process is selected. The first three process phases of conventional self-piercing riveting, consisting of clamping the joining partners, piercing the punch-side joining partner and flaring the rivet, are carried out with the multi-range tool, as shown in Fig. 2. The subsequent tumbling process is applied to completely form the joint and to shape the rivet head by increasing the radial material flow to the punch-side joining partner.

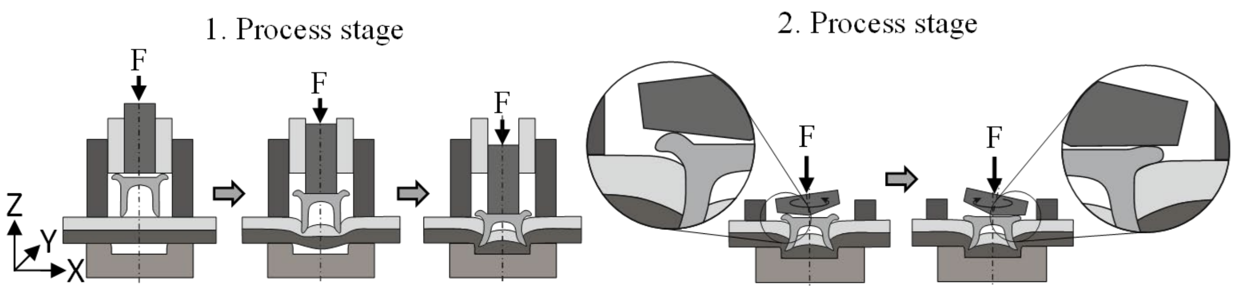

Fig. 2 Process combination of multi-range and tumbling self-piercing riveting

In order to investigate the joining process, which combines a linear and a tumbling kinematic, the specimens are joined successively using two joining systems. To set the joint, a joining system, which was presented in [15], with extended punch-sided tool actuator technology was used (see Fig. 3). It is based on a column guided frame. The lower tool contains the die, which provides the cavity needed to create the interlock. The upper tool includes an inner and an outer punch for the setting and forming process as well as a blankholder. Servoelectric drives are used to control the two punch movements with individual motions and independently parameterized force-displacement profiles. For the first process stage in this investigation, only the inner punch and the blank holder are used.

For the second process stage, a tool is used, which was presented in [9] and can be seen in Fig. 3 b). In this tool, which is mounted in a universal testing machine, the self-piercing riveting process can be superimposed by a tumbling kinematic of the punch. This is achieved by combining a rotational and a linear axis. The linear axis is installed on a rotating table, and thus the rotation and linear motion can be used to approach any point on a circle by any path. This makes the tumbling kinematics completely freely configurable and different tumbling strategies can be investigated.

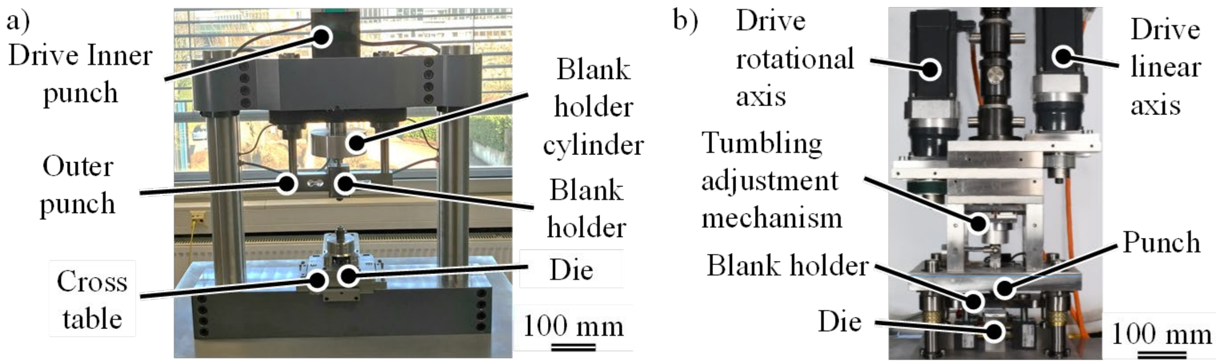

Fig. 3 Tool setup of multi-range self-piercing riveting a) and tumbling self-piercing riveting b)

The tumbling strategy consists of the parameters tumbling angle, tumbling kinematics, tumbling velocity and tumbling onset. The tumbling angle is defined by the inclination of the punch axis to the tool axis and a larger tumbling angle results in a reduced contact area. In Fig. 4 shown on the left, the tumbling angle is set by one rotation from the neutral position after the first contact between the punch and the rivet. Another possibility is to set the tumbling angle before the initial contact and thus reduce the contact pressure of the punch in the rivet head center, shown in Fig. 4 in the middle. The tumbling kinematic shows the movement of the contact surface on the rivet head and can be individually adapted. In a circular kinematic, the tumbling angle is kept constant after reaching the maximum, whereas in a spiral kinematic the tumbling angle increases over the entire joining process and reaches its maximum at the end of the process, depicted in Fig. 4. The tumbling velocity is not varied in the tests, since it only results in the number of rotations during the joining process. The tumbling onset at which the angle is set also plays a subordinate role because the onset should be after the first two process phases consisting of clamping and cutting.

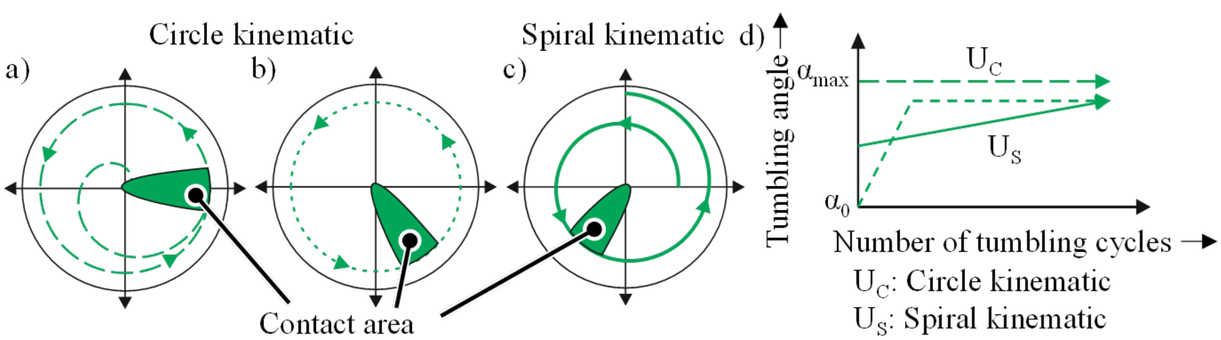

Fig. 4 Tumbling kinematic of the tumbling strategy used (a: Circle kinematic set by one rotation, b: circle kinematic set before joining, c: spiral kinematic, d: Representation of the tumbling angle over time for the kinematics used)

In order to investigate the influence of the tumbling strategy on the formation of cracks in the rivet head, macrographs of joints that are realized using different strategies are analyzed. Moreover, the achieved characteristic joint parameters, including the undercut, the rivet head end position and the residual sheet thickness are assessed to ensure the comparability of the evaluation of the crack formation depending on the tumbling strategy.

Results

In a first process stage, the rivet elements are set into the joint with the inner punch of the multi-range tool. The stroke of the punch is selected to ensure that the rivet head has a protrusion, as in previous investigations with the tool. In experiments with the multi-range tool, the outer punch would then form the protrusion of the rivet head on the sheet metal on the punch side, but this causes the challenges already described. Here, however, the effective mechanism of the tumbling punch is used to form the protrusion to the joining partner through the use of targeted material flow control and to completely form the joint. In this investigation, different configurations of the tumbling strategy are applied and different levels of sophistication of the adaptation of the tumbling strategy are presented to demonstrate the possibilities with the versatile joining process. First, a conventional tumbling strategy with a circle kinematic and a tumbling angle of 6° is applied and then the joint is evaluated using a macrograph. Fig. 5 shows the section through the center plane of the riveted joint. Significant cracks are in the center of the rivet head and at the protrusions. The crack in the rivet head is located centrally and is directed toward the tubular volume. In addition, a cavity can be identified on the upper side of the rivet head, as it is characteristic of tumbled joints. This deformation is caused by the conical punch, that due to its geometry, has a very small contact area between the punch and the rivet as the process begins. The contact is reduced only by adjusting the tumbling angle afterwards. The crack in the center is caused by the punch geometry, as this causes significant bending stresses on the rivet head.

At the start of the process, the rivet head first comes into contact with the punch tip due to its conical shape and applies a force. When the punch comes into contact, the adjustment mechanism begins to approach the tumbling angle, however, this requires a full revolution during which the punch is moved in the z-direction. From the tumbling velocity ω = 240 °/s and the traverse speed, which describes the displacement of the punch in z-direction with v = 10 mm/min, a punch travel in z-direction of h = 0.25 mm results until the tumbling angle is completely adjusted. Thus, at the beginning of the process, the total force of the punch passes over the rivet head center into the joint. Furthermore, cracks can be identified on both sides at the rivet head protrusion. This damage to the rivet element at the rivet head is also due to the tumbling kinematics and the tumbling angle. The selected tumbling angle α = 6° causes a significant reduction of the contact area and a high surface pressure at the rivet head protrusion. Furthermore, a combination of radial and tangential material flow due to the tumbling motion and the large tumbling angle is causal for significant material deformation.

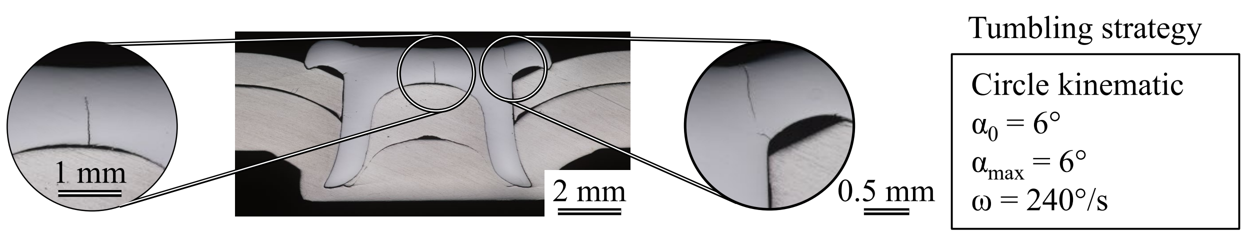

Fig. 5 Macrograph with detail views of joint set with standard tumbling strategy

To reduce the formation of cracks in the rivet head, the tumbling strategy is adapted based on the causes of the cracks that have occurred. With its mechanical design and customized control system, the tool offers all opportunities to adjust the tumbling strategy to the changing peripheral conditions. The cause of the cracks in the rivet center is the initial contact of the punch with the rivet head and the subsequent force applied. To prevent this effect of the conically shaped punch, the tumbling angle is set to the maximum angular position of the process before the initial contact between punch and rivet head. For a reduction of cracking at the rivet head projection, the maximum tumbling angle in the joining process is lowered to α = 5° to reduce the surface pressures. In addition, the punch is also accelerated to its maximum tumbling velocity ω = 240 °/s before the onset of the process to prevent inhomogeneous deformations at the rivet protrusion. In Fig. 6, a macrograph is shown in the center plane of the riveted joint connected with the adapted tumbling strategy. The results show no cracks appearing at the rivet head center and a significant reduction in crack size at the rivet head protrusion. The lack of initial contact of the punch on the rivet head reduces the bending stress in the rivet head and no indentation occurs on the rivet head.

The 1° lower maximum tumbling angle has the effect of reducing the stress peaks at the rivet head protrusion and preventing a complete cracking of the auxiliary joining elements as seen before.

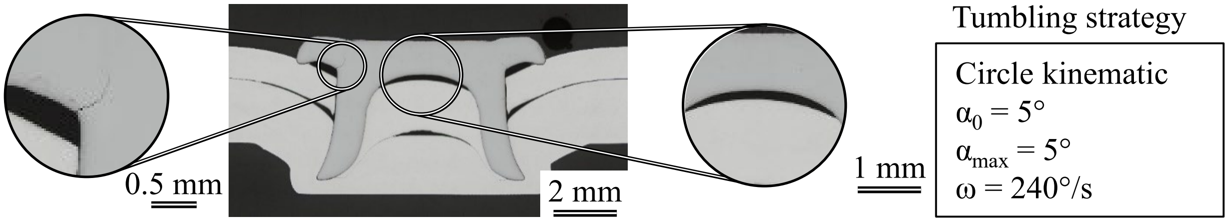

Fig. 6 Macrograph with detail views of joint set with adapted tumbling strategy

However, the tumbling strategy contains further parameters with which the joining process and thus the material flow and stress distribution can specifically be controlled. Alongside the tumbling angle, the tumbling kinematic has a significant influence on the resulting joint. Circular kinematics have a constant tumbling angle throughout the entire process, except for the setting phase of the angle. In the case of spiral kinematics, which are also predominantly rotating kinematics, the tumbling angle increases during the entire process and reaches its maximum deflection at the end of the process. This results in a constant increase in the tumbling angle and a lower deformation of the rivet head per revolution. Decreasing the deformation of the rivet head protrusion per increment is intended to reduce the probability of cracking and to form a defect-free joint.

Since initial contact at $\alpha = 0°$ in the rivet head center of the punch is also to be prevented in these experiments, the tumbling angle at the start of the process is selected at $\alpha = 4°$. This causes a spiral contour of the contact surface on the rivet head without causing initial contact in the rivet head center. Fig. 7 shows a macrograph of the joint of a connection set with spiral kinematics. The joint shows no cracks in the rivet head, either in the rivet head center nor at the rivet head protrusions. As with the adapted circular kinematics, there is no punch contact in the center, hence no cracking in this area occures. The results also show that moving the contact area in a radial direction in the form of a tumbling angle increase reduces the sensitivity to cracking. The maximum tumbling angle in the spiral kinematics is the same as in the adapted circular kinematics, but the comparatively slow buildup of the angle is less critical for the rivet head protrusion.

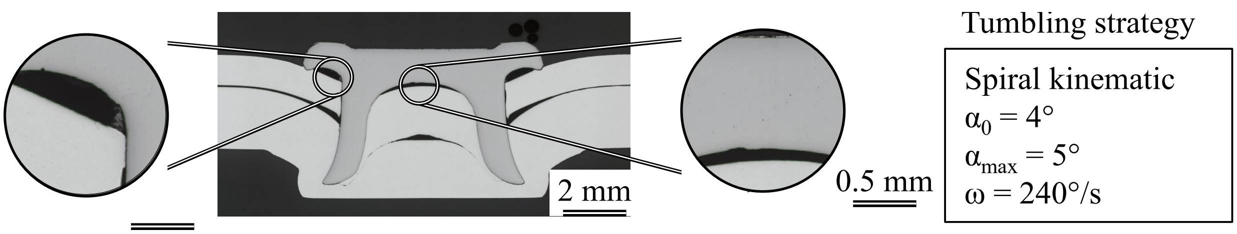

Fig. 7 Macrograph with detail views of joint set with versatile tumbling strategy

For a comparison of the results of the individual kinematic models, the geometric joint formation is considered because the individual parameters have specific influences on the joint and similar characteristics must be provided to allow a comparison of the formation of cracks. The values in Fig. 8 are averaged results over the right and left measured values because the macrographs do not show any angular offsets of the rivets. For each combination, only one test is shown, since the deviations of the results observed are negligible. The undercut is shown to be high for both kinematic models with a slightly reduced level for the spiral kinematics. This reflects previous findings [9] when comparing circular to spiral kinematics, but both kinematic models are at a similar level. The rivet head end position also shows results with a low maximum difference of 0.04 mm for the investigated variants. The differences can be explained by the variation of the tumbling onsets. In the 6° tumbling, the punch is in the 0° position at the beginning, whereas in tests with 5°, the punch is already at the maximum tumbling angle at the first contact between punch and rivet, thus causing a greater deformation of the rivet head protrusion. The difference in residual sheet thickness can also be explained by the adaptation of the tumbling strategy. With a continuously increasing angle, a larger radial material flow and a smaller axial material flow component are obtained. As a result, the rivet element is driven less into the joint and an increased residual sheet thickness results with a maximum difference to the other kinematic models of 0.04 mm. The results show similar geometric joint formations for all three tumbling strategies and are therefore suitable for comparison of the tumbling strategies.

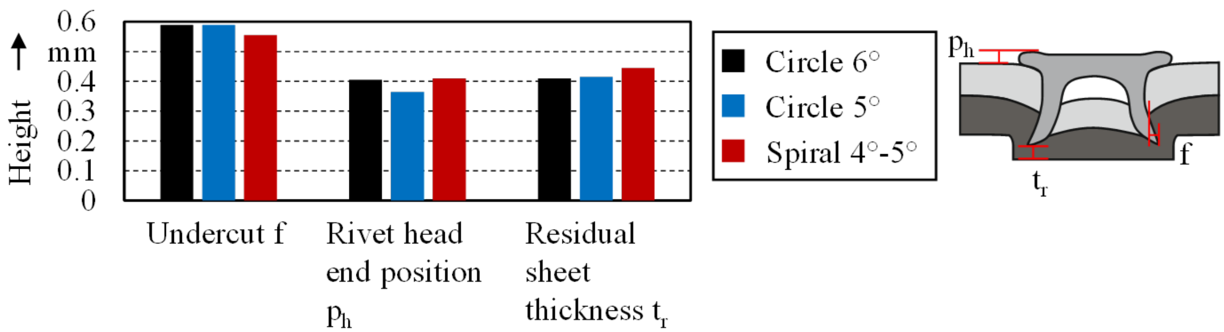

Fig. 8 Geometric joint formation of joints with varying tumbling strategies

The investigations show the increased versatility of the process combination by uniting the two processes into a two-stage joining process. The first process stage enables the rivet to be set precisely without deforming the rivet head in the radial outward area. Further, it is possible to increase the application options and the material flow control by adapting the process parameters of the tumbling strategy. The process combination allows a significant influence to be exerted on the shape of the joint without having to change the die or the rivet geometry. Additionally, the risk of the occurrence of cracks in the rivet head can be reduced and thus defect-free joints can be realized by adapting the tumbling strategy. By combining the two operating principles, the characteristic properties of the two processes can be combined. These are characterized in the case of multiple linear actuation by axial and in the case of tumbling semi-tubular self-piercing riveting by radial control of the material flow, which enables the tubular volume to be adjusted.

Summary and Outlook

In the investigations on a combination of versatile semi-tubular self-piercing riveting processes, a two-stage process consisting of a multi-range self-piercing riveting process and a tumbling self-piercing riveting process has been set up and evaluated. After setting the rivet to a constant rivet head height above the punch-side joining partner with the inner punch of the multi-range tool, the rivet head protrusions are formed onto the punch-side joining partner with a tumbling punch. For the second process stage, different tumbling strategies were investigated with a variation of several parameters. The results show that by adapting the tumbling strategy, the sensitivity of the rivet heads to cracking can be reduced while achieving nearly consistent geometric joint properties. Consequently, by combining the two processes, the versatility can be increased and new opportunities for joining technology can be created. However, closing the cavities under the rivet head protrusion is shown to be a challenge. Therefore, further investigations and adaptations of the tumbling strategy are necessary to realize the required crack-free joining. Further, the load bearing capacity is a very important feature of joints and should be investigated. This can be tested using the shear tensile and cross tensile test.

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