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Innovative mechanical joining processes in versatile process chains - potentials, applications and selection procedures

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Abstract. Mechanical joining processes have gained extensive importance in recent years. In contrast to temperature-based processes, mechanical joining approaches allow the joining of dissimilar materials such as steel and aluminum. What most of the processes have in common is that they are often designed for a specific combination of materials and sheet thicknesses. Consequently, the versatility of these processes is limited. This article will therefore provide an overview of four innovative manufacturing processes, which allow a higher adaptability than conventional mechanical joining processes. In this context, the basic strategies, their applications as well as their advantages and limitations are presented. The contribution closes with a summarizing evaluation and an outlook.

Introduction

In many industrial sectors, there is a trend towards lightweight construction and the reduction of CO2 emissions [1]. One of the most important strategic approaches is the targeted combination of lightweight materials such as high-strength steel, aluminum and fiber-reinforced plastics. A major challenge, however, is the selection of a suitable joining technique. Due to the different melting points, it is often not possible to use thermally based processes [2]. Therefore, mechanical joining methods have gained extensive importance in recent years. In addition to approaches such as cold welding, self-pierce riveting, mechanical clinching and joining by forming in particular have a great potential for technological application [3]. Thereby, it has already been shown in the past that these methods are suitable for joining high-strength steels with aluminum [4]. Groche et al also show the great potential of the technologies, but point out that the influencing variables and process limits are not yet fully understood and it is therefore difficult to predict the final properties [5]. Nonetheless, these processes can be used to achieve highly productive joining processes, which are particularly important for automotive engineering [6]. Due to the different requirements, there are currently a large number of different process variants, which are compared, for example, in terms of their application possibilities [7]. To address these challenges, in the following four innovative processes are presented and evaluated, which allow an increase in the versatility.

Mechanical joining without auxiliary elements

Mechanical joining without auxiliary elements is a joining process consisting of a two-stage process in which pin structures, produced by forward extrusion from the sheet metal plane are used to join dissimilar materials. This process has proven to be suitable to join materials such as high-strength steel and aluminum [8], as well as steel and fibre-reinforced plastics. Pin structures are already used to increase the strength of metal/fibre reinforced plastic joints. However, often forming processes are not used to manufacture these pins. Instead, manufacturing processes such as powder bed fusion, direct energy deposition or moulding processes are used. Cold extrusion has several advantages compared to these processes. On the one hand, the pin structures have a high strength due to the strain hardening during the extrusion process and, on the other hand, the process can be integrated into existing manufacturing processes with additional weight savings as no auxiliary part is necessary. The two-stage process consists of the pin extrusion from the sheet metal plane and the subsequent joining process, whereby two different process routes are used, the direct pin pressing and the caulking. In the former, the extruded pin is pressed into an unperforated joining partner and forms an undercut due to the compression within the joining partner. In the latter, the pin structure is inserted through a pre-punched joining partner and thus the pin head is upset.

In the first step, the pin must be formed by extrusion from the sheet metal plane. This process requires a multi-acting tool in which the blank holder and punch can be controlled independently. The blank holder prevents the sheet from bulging during cold extrusion and reduces the amount of radial material flow. First, the blank holder pressure is applied, followed by an axial punch movement. The punch penetrates the sheet and displaces the material both axially downwards into the die cavity and laterally outwards into the sheet metal plane limited by a mechanical stop. The punch penetration depth thereby regulates the displaced material and consequently the pin height.

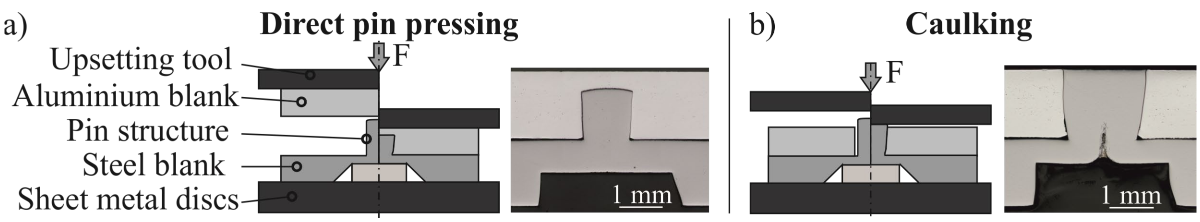

Figure 1: Schematic illustration of the cold extrusion process according to [9]

Furthermore, due to the higher plastic deformation of the material at a higher punch penetration depth, the strain hardening of the material increases, which has an influence on the mechanical properties of the pin and thus on the subsequent joint. For the same reason, the ratio of the punch cross-sectional area to the cross-sectional area of the pin structure also influences the strength of the pin structure. The pin structures are used in the subsequent step for joining using caulking or direct pin pressing (Fig. 1) [9]. Depending on the joining strategy, different pin heights are required, since caulking requires a pin height that is higher than the initial sheet thickness of the joining partner. With direct pin pressing, pin heights can be used that are both smaller and larger than the sheet thickness. However, the pin height plays a crucial role in the formation of the undercut, which is particularly important for the cross tension strength and prevents the joint from unbuttoning under shear loads. Fig. 1b) schematically shows the process sequence for caulking. The pin structure is placed in the pre-punched joining partner and placed between conventional upsetting tools. The punch indentation, which occurs during pin forming, needs to be supported to prevent damage or bending back of the pin. Subsequently, the upper upsetting track moves axially and upsets the pin, which results in a radial material flow and the pin initially expands in the head area. This creates an undercut and a therefore a form-fit connection. With direct pin pressing, shown in Fig. 1a), no pre-punched joining partner is required. Here, the punch indentation is first supported and the component is then placed between conventional upsetting tools. The joining partner is subsequently placed over the pin structure, followed by an axial movement of the upper upsetting tool downwards, causing the pin to penetrate the joining partner which displaces the material axially upwards. Due to the joining operation and the penetration of the pin into the joining partner, the pin is upset, whereby the pin creates an undercut. The greater the initial pin height, the more the pin is compressed, which has a positive effect on the cross tension strength. When considering connections in which continuous fibre-reinforced thermoplastics (CFRT) are used as joining partners, the general joining process changes depending on the joining strategy. In this case, particular attention must be paid to the fibre-friendly insertion of the pin. Therefore, when using fibre-reinforced plastics with a thermoplastic matrix for caulking, the joining partner is first heated locally to improve the fibre movability and is subsequently pierced with a mandrel. In contrast to drilling, this significantly reduces fibre damage, which has a positive effect on strength. Subsequently, the pin is inserted through the perforated joining partner and upset, analogous to the caulking of metal/metal joints. When metal pin structures are pressed directly into CFRTs, the matrix is also first heated thermally to increase the movability of the fibres. Different heating strategies such as infrared radiation, vibration or ultrasound can be used for heating. In this way, the fibres should rearrange around the pin structures and avoid pre-damage which could reduce the load capacity of the joint. In [10], fibre orientation mechanisms were investigated using different pin diameters and head geometries when joining metal pins with CFRTs using direct pin pressing. The pin structure is then pressed into the heated matrix and the joint is reconsolidated and cooled under pressure to fill the void zones created by the pressing process with matrix and fibers.

Joining with adaptive friction elements

Joining with adaptive friction elements is a process for the positive and non-positive joining of sheet metal semi-finished products. Individually manufactured friction elements as auxiliary joining parts allow the joint to be modified in terms of dimensions as well as geometric and mechanical properties. The joining process considered here is divided into two sub steps (Fig. 2a).

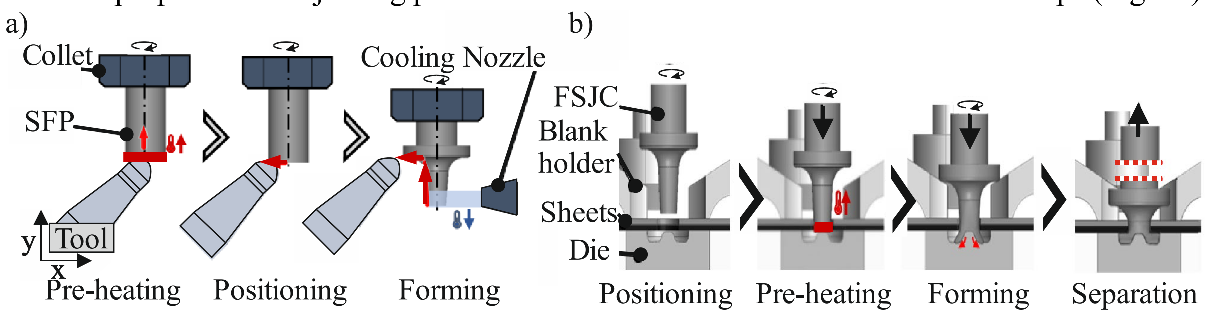

Figure 2: Production of adaptive friction elements/auxiliary joining part

First, the auxiliary joining part is produced. A wire section is set in rotation as the starting material. Contact with a tool generates friction and thus heat. This causes the material to be plasticized locally in the area of tool engagement. The contour of the shank and the head of the auxiliary joining part is formed by appropriate tool movements. Due to the kinematic shape generation, a high degree of changeability with regard to geometry and dimensions can be achieved. [11]

Since heat is introduced into the auxiliary joining part by means of friction, temperature profiles can be realized, if necessary in combination with cooling processes, which can be used in the sense of heat treatment. In this way, the microstructure and thus the mechanical properties of the material can be specifically adjusted, for example by martensitic hardening. The temperature control can be individually controlled, in particular by feed movements and the speed of the tool or semi-finished product as well as the use of coolants, which results in a high degree of variability. [12]

After the auxiliary joining part has been produced, it is fed to the joining point, as shown in Fig. 2b). By rotating the auxiliary joining part while the joining partners are stationary, an opening can be made in the joining partners as required to produce the joint, comparable to flow drilling. In this way, pre-punched or pre-hole-free sheet-metal semi-finished products can be joined. The rotating auxiliary joining part then comes into contact with a stationary die, so that heat is generated by local friction and plasticizes the lower area of the auxiliary joining part. Due to the now high forming capacity, an undercut can be formed by axial repositioning so that a form-fit joint is produced. The high variability of the joining technology described here results in particular from the individual design of the auxiliary joining parts. Wire-shaped semi-finished products made of various metallic materials with different diameters can be used. Furthermore, dimensions and geometry of the auxiliary joining part can be individually adapted by kinematic shape generation. The mechanical properties of the auxiliary joining part are determined by the range of materials that can be used, which can be further modified by individual thermal or thermomechanical treatments. Appropriately, customized auxiliary joining parts are suitable for covering a wide range of joining points. Thanks to an adjustable auxiliary joining part length, sheet metals of different thicknesses (t = 1-6 mm) made of numerous materials can be joined in any sequence, without any preferred direction, with positive locking and in some cases also with frictional locking. Pre-piercing of the semi-finished products can be largely dispensed, especially if hardened auxiliary joining parts are used. At present, however, accessibility of the joint on both sides is required. The load-bearing capacity of the joint can be specifically influenced in particular by the diameter, the head or undercut geometry and the strength of the auxiliary joining parts used.

Versatile self-piercing riveting (V-SPR)

Due to its high load-bearing capacities, a wide range of application and high process robustness, semi-tubular self-piercing riveting, which is also one of the mechanical joining processes, is being frequently used [13]. However, the increasing number of material-thickness combinations and the current rigidly designed tool systems, result in the need for a large number of rivet-die combinations to fulfil the different joining tasks [14]. In order to increase process efficiency and effectiveness, new versatile joining strategies are required, which can react to the changes mentioned above. One possibility to achieve this versatility is based on combining a new joining system technology with increased punch-sided tool actuator technology with multi-range capable semi-tubular self-pierce riveting which was presented by [15] and shown in Fig. 3a).

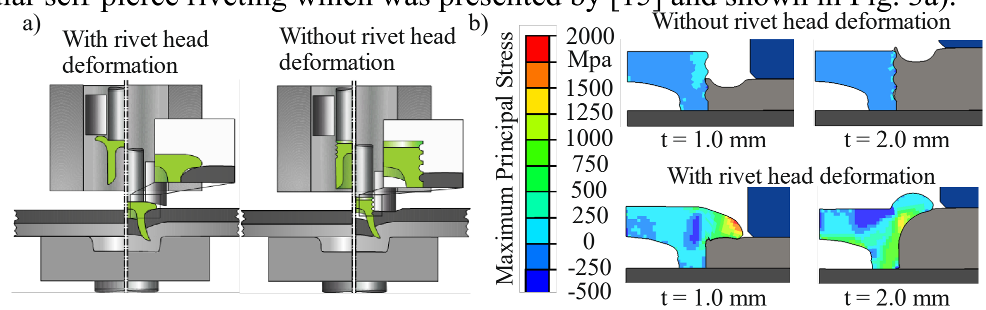

Figure 3: Process sequence for the versatile self-piercing riveting process

The joining system presented enables a joining process (inner punch) and a forming process (outer punch) to be carried out by means of independently controllable punch movements. The forming process is required in order to adapt the rivet to the respective sheet thickness combination. This can be done in two different ways: With and without rivet head forming. If a rivet with head forming is used, the protrusion of the rivet head is formed to the respective sheet thickness. The punch-sided material is formed into annular ring grooves which are located in the head area of the rivet, if a rivet without head forming is used. Both rivet concepts are presented in Fig. 3a). The feasibility of the new mechanical joining process was evaluated using a previously validated numerical axisymmetric 2D-substitute model, which focused the rivet head formation [16]. Therefore, only the upper part of the joint consisting of the punch-sided sheet and the rivet head is modeled. Subsequently, the two rivet concepts were tested with different punch-sided sheet thicknesses (1.0 mm and 2.0 mm) in order to verify their adaptability to changed boundary

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conditions (Fig. 3b)). Both rivet concepts enabled the formation of the joint for both thicknesses. However, the simulations also showed that the rivet with head deformation leads to an increased stress concentration in the head area.

Tumbling self-piercing riveting process

An industrially often used joining process is the semi-tubular self-piercing riveting, which is characterized by a very robust design with short process times. However, the joining process is also comparatively rigid and the tools used can only adapt to the process to a very limited extent in order to be able to react to disturbances and process variables [2]. A forming process with a large number of degrees of freedom and a great potential for increasing process control is tumbling. The bulk metal forming process is characterized by a tumbling punch with a conical shape that tilts out of the tool axis. This tilting causes a reduction of the contact area between the punch and the workpiece and can be used to intentionally control the material flow. One parameter of the tumbling strategy is the tumbling angle. It causes a reduction of the contact area with increasing angle and thus a lower required forming force [17]. Another component is the kinematic with which the tumbling punch is positioned on the rivet head [18]. This can be applied in the form of a circle, a spiral, by radial tilting and as multi-blade kinematics. The different kinematic models are characterized by a varying material flow in the forming operation and thus it can be used in a specific pattern. In addition, the number of revolutions, the ramp-up phases until the maximum tumbling angle is reached and the rotational or linear speed of the tumbling punch can be adapted [19]. The integrated tumbling process into the self-piercing riveting process allows an increased degree of reaction to process and disturbance variables and the production of tailored joints shown in Fig. 4.

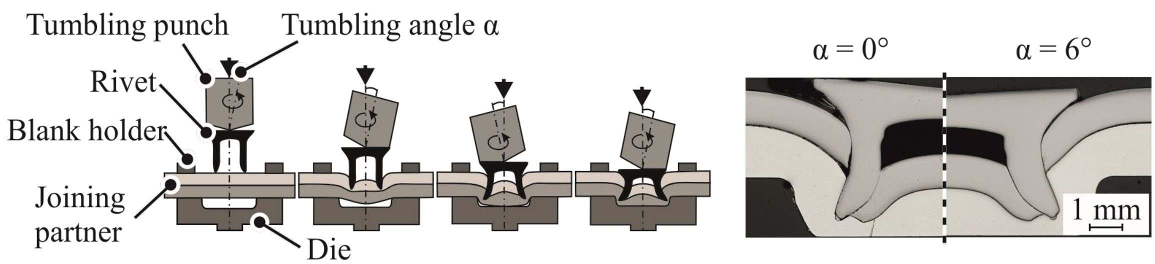

Figure 4: Schematic tumbling self-piercing riveting and influence of varying tumbling angles

The combination makes it possible to combine the advantages of the two processes and to expand the process window. The increased number of process parameters in a tumbling riveting process can be used to react to influences such as varying mechanical and geometric properties with targeted material flow control. Furthermore, a freely configurable tumbling strategy enables an in-situ adaptation of the process route, which makes it possible to react during the joining [19].

Discussion and evaluation of versatility in innovative joining processes

The innovative joining processes shown previously are characterized by individual features in the process design. They provide varying potentials for extending the possibilities of influence before or during the joining process to increase the versatility. The investigations show that the versatility is achieved on different process levels and thus different approaches for applications are feasible. A distinction can first be made according to the process stage. In the pin joining, friction element joining and versatile self-piercing riveting processes, an adaptation to the joining task is performed in an earlier process stage. The versatility of pin joining for metal/metal connections arises in particular in the first process stage, the extrusion of the pin structures. Here, by varying the process parameters and boundary conditions, it is possible to directly influence, the subsequent mechanical joint properties and, in addition, the joinability of the pin joints. Thus, by adjusting the pin height, it is possible to adapt to variations in sheet thickness and changed joining partner properties, and also to react to the mechanical requirements of the joint by adjusting the number of pins.

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Investigations of the influences of the process parameters have shown that the pin height can be directly influenced by varying different process variables [1]. Experimental investigations in [6] on the influence of different pin heights on the joint properties under shear load have shown that due to the increasing strain hardening during the extrusion process, the strength of the pin structures increases with the pin height and, analogously, the strength of the joint itself. The maximum load capacity of the joint depends directly on the diameter of the pin structure. However, it was shown based on investigations on different pin geometries with different pin cross-sections that under otherwise identical process conditions, a smaller pin cross-section in relation to the forming punch has a higher shear strength in relation to the cross-section compared to a pin with a larger cross-section. This shows that an increased flow resistance into the die or deformation resistance due to a reduced pin cross-section leads to an increase in strain hardening, especially in the pin base, where a metal/metal pin connection usually fails under shear load. These investigations show that an increase in the versatility of pin joining is achieved by the extrusion process. The individual adaptation of the extruded pin structures enables an extended range of possible joining applications.

Joining with adaptive friction elements also includes a preceding process stage. The high variability of the joining process is in particular due to the individual design of the auxiliary joining elements used. Wire-shaped semi-finished products made of various metallic materials (e.g. aluminum, steel) with different diameters (currently 5-14 mm) can be used for these. Furthermore, dimensions and geometry of the auxiliary joining part can be individually adapted by kinematic shape generation (diameter 3-12 mm, length 4-15 mm, head shape, etc.). The range of materials that can be applied, which can be further modified by individual thermal or thermomechanical treatments determines the mechanical properties of the auxiliary joining part. Appropriately, customized auxiliary joining parts are suitable for covering a wide range of joining points. Thanks to an adjustable auxiliary joining part length, sheet-metal semi-finished products of different thicknesses (t = 1-6 mm) made of numerous materials can be joined in any sequence, i.e. without a preferred direction, with positive locking and in some cases also with frictional locking. Thus, as in pin joining, the increase in versatility is achieved by adapting geometric or mechanical properties of the joining component. Pre-piercing of the semi-finished products can be largely dispensed with, especially if (in-process) hardened auxiliary joining parts are used. The load-bearing capacity of the joint can be specifically influenced in particular by the diameter, the head or undercut geometry and the strength of the auxiliary joining parts used. There are characteristic similarities to pin joining as well, with direct pin pressing and caulking with a pre-hole in the joining partner.

In semi-tubular self-piercing riveting, the versatility can also be increased by a geometric adaptation of the auxiliary joining elements. However, the auxiliary joining part is not adapted individually for the joint, but the spectrum of joining capabilities is enlarged by targeted adaptations of the geometry. In addition to the adaptation of the geometries of the joining components, an increase in the versatility is achieved by extending the influence from the process control side. The tool design is modified and the number of process parameters is increased by integrating additional sensors and actuators. With a targeted adjustment of these parameters, the material flow can be controlled and it is possible to react to disturbance variables. In the case of versatile semi-tubular self-piercing riveting, process-side control is provided not only by the adapted rivet geometry, but also by the internal and external punches. By adapting the process route, influence can be exerted on the resulting geometric joint formation and the joining range of multi-material systems can be extended [17]. The investigations show an influence of the tumbling strategy on individual characteristic features of the joint. The influence of the tumbling kinematics on the joining process is further investigated in [18], which shows a decrease of the joining forces with increasing tumbling angle. For the kinematic models applied, it can be stated that a more gradual adjustment of the tumbling angle causes the force-displacement curves to increase more uniformly. As a further process parameter, the tumbling velocity is investigated in [19] in the form of the rotation speed of the tumbling punch for a circular and spiral kinematics. The results show a uniform formation of the rivet head end positions with increasing rotation speed. Overall, the findings show that the process combination consisting of a self-piercing riveting process superimposed by tumbling kinematics can increase the possibilities for influencing the process. By adapting the tumbling strategy, the characteristic features relevant for the joint can be specifically controlled and adapted to the joint to be manufactured. The resulting increased material flow control can thus be applied to expand the range of feasible joints and significantly increase the adaptability of the process.

Two superordinate approaches to increase versatility can be identified in innovative joining processes. On the one hand, a wider range of joining tasks can be achieved through the targeted and individual adaptation of geometric and mechanical properties of the joining components. However, a further distinction must be made here whether the joining components are individually adapted for each joining task, as in pin joining and friction element joining, or whether the possible forming operations on the auxiliary joining element are increased, as in the case of versatile semi-tubular self-piercing riveting. On the other hand, the joining process itself can be influenced by the targeted control of adapted tool systems.

Summary and Outlook

In the context of the investigations, it was shown that it is possible to react to fluctuations in the process with the help of versatile joining processes. This is demonstrated by the three processes presented: mechanical joining without auxiliary elements, joining with adaptive friction elements, versatile and tumbling self-piercing riveting. The results of the investigations show the different characteristics of the versatility of the individual processes. It is demonstrated how the versatility is achieved and how it can be applied in the manufacture of the joints. For joining with pin structures, the versatility is particularly in the manufacturing process of the pins. By specifically controlling the geometry and mechanical properties of the pins, the joining spectrum can be expanded. Joining with adaptive friction elements is characterized by the individual design of the auxiliary joining parts. Thus, as with pin joining, the adaptability of the joining technology is also extended for this joining process in an earlier process stage. The same is applied to the use of adapted rivet geometries in versatile semi-tubular self-piercing riveting. Here, however, the influence on the process is additionally increased by a special tool design. In tumbling semi-tubular self-pierce riveting, the versatility is increased during the joining process by targeted control of the material flow. In future investigations, this adaptability is to be increased even further. In this context, for example, the development of real-time capable models appears to be of great interest in order to enable in-situ control of the joining processes. Furthermore, the analysis of joining technologies under industrial conditions appears to be of significant importance. On the one hand, it should be analyzed how the mass of the tools can be reduced in order to be able to use them in combination with an automated robotic system. On the other hand, it should be investigated how the production time can be reduced. Finally, the application properties with regard to corrosion and fatigue strength must be assessed.

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References

[1] K. Martinsen, S.J. Hu, B.E. Carlson, Joining of dissimilar materials, CIRP Annals 64 (2) (2015) 679–699. https://doi.org/10.1016/j.cirp.2015.05.006

[2] D. Li, A. Chrysanthou, I. Patel, G. Williams, Self-piercing riveting-a review. Int J Adv Manuf Technol 92 (5-8) (2017) 1777–1824. https://doi.org/10.1007/s00170-017-0156-x

[3] K.-I. Mori, N. Bay, L. Fratini, F. Micari, A.E. Tekkaya, Joining by plastic deformation. CIRP Annals 62 (2) (2013) 673–694. https://doi.org/10.1016/j.cirp.2013.05.004
[4] Y. Abe, T. Kato, K. Mori, Self-piercing riveting of high tensile strength steel and aluminium alloy sheets using conventional rivet and die. JMPT 209 (8) (2009) 3914–3922. https://doi.org/10.1016/j.jmatprotec.2008.09.007
[5] P. Groche, S. Wohletz, M. Brenneis, C. Pabst, F. Resch, Joining by forming—A review on joint mechanisms, applications and future trends. JMPT 214 (10) (2014) 1972–1994. https://doi.org/10.1016/j.jmatprotec.2013.12.022
[6] G. Meschut, V. Janzen, T. Olfermann, Innovative and Highly Productive Joining Technologies for Multi-Material Lightweight Car Body Structures. JMEP 23 (5) (2014) 1515–1523. https://doi.org/10.1007/s11665-014-0962-3
[7] J. Varis, Economics of clinched joint compared to riveted joint and example of applying calculations to a volume product. JMPT 172 (1) (2006) 130–138. https://doi.org/10.1016/j.jmatprotec.2005.09.009
[8] D. Römisch, M. Kraus, M. Merklein, Experimental Study on Joining by Forming of HCT590X + Z and EN-AW 6014 Sheets Using Extruded Pin Structures. JMMP 5 (1) 2021. https://doi.org/10.3390/jmmp5010025
[9] D. Römisch, M. Kraus, M. Merklein, Investigation of Different Joining by Forming Stratgies when Connecting Different Metals without Auxiliary Elements. KEM 883 (2021) 19–26. https://doi.org/10.4028/www.scientific.net/KEM.883.19
[10] J. Popp, T. Kleffel, D. Römisch, T. Papke, M. Merklein, D. Drummer, Fiber Orientation Mechanism of Continuous Fiber Reinforced Thermoplastics Hybrid Parts Joined with Metallic Pins. Appl Compos Mater 28 (4) (2021) 951–972. https://doi.org/10.1007/s10443-021-09892-0
[11] C. Wischer, E. Wiens, W. Homberg, Joining with versatile joining elements formed by friction spinning. Journal of Advanced Joining Processes 3 (2021) 100060. https://doi.org/10.1016/j.jajp.2021.100060
[12] C. Wischer, W.Homberg, A contribution on versatile process chains: joining with adaptive joining elements, formed by friction spinning. Prod. Eng. Res. Devel. 16 (2-3) (2022) 79–88. https://doi.org/10.1007/s11740-021-01094-8
[13] DVS/EFB, Self-pierce Riveting – Overview: Sonderverfahren (2019).
[14] X. He, I. Pearson, K. Young, Self-pierce riveting for sheet materials: State of the art. Journal of Materials Processing Technology 199 (1-3) (2008) 27–36. https://doi.org/10.1016/j.jmatprotec.2007.10.071
[15] F. Kappe, M. Bobbert, G. Meschut, New Approach for Versatile Self Piercing Riveting: Joining System and Auxiliary Part. KEM 883 (2021) 3–10. https://doi.org/10.4028/www.scientific.net/KEM.883.3
[16] F. Kappe, C.-R. Bielak, V. Sartisson, M. Bobbert, G. Meschut, Influence of rivet length on joint formation on self-piercing riveting process considering further process parameters. ESAFORM (2021). https://doi.org/10.25518/esaform21.4277
[17] S. Wituschek, M.Lechner, Investigation of the influence of the tumbling angle on a tumbling self-piercing riveting process. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications 236 (6) (2022) 1302–1309. https://doi.org/10.1177/14644207221080068
[18] S. Wituschek, F. Kappe, M. Lechner, Investigation of the influence of varying tumbling strategies on a tumbling self-piercing riveting process. Prod. Eng. Res. Devel. 16 (2(2022) 353–362. https://doi.org/10.1007/s11740-021-01099-3
[19] S. Wituschek, M. Lechner, Versatile tool design for a tumbling self-piercing riveting process. The 12th Tooling Conference & Exhibition, Tooling 2022, (2022) 499–506.