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Review on mechanical joining by plastic deformation

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ABSTRACT

Mechanical joining technologies are increasingly used in multi-material lightweight constructions and offer opportunities to create versatile joining processes due to their low heat input, robustness to metallurgical incompatibilities and various process variants. They can be categorised into technologies which require an auxiliary joining element, or do not require an auxiliary joining element. A typical example for a mechanical joining process with auxiliary joining element is self-piercing riveting. A wide range of processes exist which are not requiring an auxiliary joining element. This allows both point-shaped (e.g., by clinching) and line-shaped (e.g., friction stir welding) joints to be produced. In order to achieve versatile processes, challenges exist in particular in the creation of intervention possibilities in the process and the understanding and handling of materials that are difficult to join, such as fiber reinforced plastics (FRP) or high-strength metals. In addition, predictive capability is required, which in particular requires accurate process simulation. Finally, the processes must be measured non-destructively in order to generate control variables in the process or to investigate the cause-effect relationship. This paper covers the state of the art in scientific research concerning mechanical joining and discusses future challenges on the way to versatile mechanical joining processes.

Introduction

The need for flexible and versatile joining processes for the joining of multi-material systems is constantly increasing due to the trend towards lightweight structures driven by the increasingly strict climate targets. In order to reduce emissions and energy demand, especially in the mobility sector, the reduction of vehicle weight is a major factor in achieving these goals. Currently, there are a number of different joining processes, which can only be used to a limited extent for joining multi-material systems (Mori et al., 2013). These are often too restrictive and inflexible to react quickly to changing requirements when joining dissimilar materials. Furthermore, unequal stiffness, chemical incompatibility and different thermal expansion coefficients in particular pose problems for these joining processes. Additionally, the often poor weldability of dissimilar metals is a challenge for conventional joining processes. For this reason, there are efforts to develop new, innovative joining processes or to further develop existing joining processes that are characterized by their versatility and can thus react to batch variations or changing process conditions. Versatility here refers to the ability of process chains to adapt to requirements beyond the -originally planned extent (flexibility). The versatility of process chains results in increased requirements on joining technology, which can only be met if the joining technology itself also becomes versatile. Mechanical joining processes offer the clearest opportunities to create versatile joining processes due to their low heat input, robustness to metallurgical incompatibilities and various process variants.

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Mechanical joining processes and their classification

Overview

In the course of the energy crisis in the 1970s, efforts were made to reduce automobile weights with the aim of reducing fuel consumption. It became apparent that new body concepts such as aluminium bodies could hardly be produced with resistant spot welding. Mechanical joining techniques therefore became a focus of attention. Main principles for the use of mechanical joining technologies in automotive engineering were laid down in the 1980s as part of a collaboration between the institute LWF, headed by Ortwin Hahn, and industrial partners in a working group, called AK Clinchen, headed by S. Singh from AUDI (Schröder, 2006). A classification is required to categorize the large number of mechanical joining processes. The classification of the processes according to the fundamental joining mechanisms form-fit, force-fit and material-fit is not appropriate because, for example, all these bonding mechanisms can occur simultaneously in clinch joints. The classification according to the standard DIN 8593 is not based on the process-specific requirements of the joint and is also not considered sufficient here. Based on their research and development work, Hahn and Klemens developed an alternative classification of mechanical joining processes. For this purpose, essential distinguishing features are utilized in the sense of an ordering scheme. A main distinguishing feature is the requirement of an auxiliary joining element. For processes with an auxiliary joining element, the necessity of a pre-hole as well as the required accessibility are used as further classification features. In processes where no auxiliary joining element is used, the main distinguishing features are whether a cutting operation is part of the process and the shape of the joint (Hahn and Klemens, 1996).

A revised version of the classification scheme is shown in Fig. 1, where function carriers and multi-stage processes are not considered, non-round joint shapes are combined and recent developments are added. In this paper, the focus is on industrially established and productive processes as well as on particularly promising process innovations which both require large formed parts to be joined.

Joining with auxiliary joining element

Self-piercing riveting

Self-piercing riveting (SPR) mentioned in DIN 8593–5 is a mechanical joining process without thermal input and is of particular interest for the joining of two or more materials with auxiliary joining element. SPR is a one-step process and a non-detachable joint is created (Chrysanthou and Sun, 2014). As shown in Fig. 2, the setting of a riveted joint requires a die, a punch and a blank holder. The entire process sequence can be divided into four stages. First, the blank holder, which encloses the rivet, fixes the parts to be joined on the die. Due to the further feed of the punch, the rivet penetrates the punch-sided sheet, creating its own pre-hole. The rivet undergoes plastic deformation and expands radially into the die-sided sheet, resulting in the formation of an interlock. As a result of this, a force-fit and form-fit connection is created. Finally, the punch and the blank holder reset to their initial position. The quality of a SPR-joint can be determined using various parameters. amongst the most important, which influence the load-bearing capacity of the joints, are the interlock (*f*), the rivet head position (pH) and the minimum die-sided material thickness (t_r), which can be seen in Fig. 2 (DVS/EFB, 06.08.18).

The current understanding of the process allows the production of semi-tubular riveted joints with a wide range of material thickness and strengths (see Fig. 3). Böllhoff, for example, invented the HDII-rivet with a more solid geometry design compared to the standard rivet in order to be able to join sheets with strength of up to 1700 MPa. By the countersunk head, which is drawn far to the base of the rivet, a certain multi-range capability with regard to material thickness is given (Hornbostel, 2010). The U-rivet, invented by Tucker, also allows to join sheets made of ultra-high-strength materials on the punch-side with strengths of up to 1600 MPa. This rivet is characterised by a significantly reduced half-hollow volume. The rivet head was designed very flat, in order to reduce bending effects (Bartig and Wissling, 2017).

The prerequisite for this wide range of joining possibility is the correct selection of both, the rivet and the die. Drossel and Jäckel (Drossel and Jäckel, 2014), show the influence of the geometric properties of the die on the joint formation. The quality-relevant characteristics are significantly influenced by the die depth. A reduction of the die depth could cause an increase of the interlock. A greater rivet length can further enhance this effect. However, an increase of the interlock is usually accompanied by a reduction of the minimum die side material thickness. In addition, interactions between the rivet length and the die depth can lead to damage of the rivet (Kappe et al., 2021). Conditioning of the parts to be joined can improve the joining properties when using materials with low ductility. Zhao et al. (Zhao et al., 2020), showed that additional heat treatment of a cast aluminium alloy before joining can significantly reduce the occurrence of cracks in the closing head. However, this leads to a continuous reduction in the shear strength. The use of ring groove dies which were specially developed for joining cast aluminium can also lead to an improvement in joint formation as well as a reduction in cracks (Böllhoff Group, 2021). Further research work

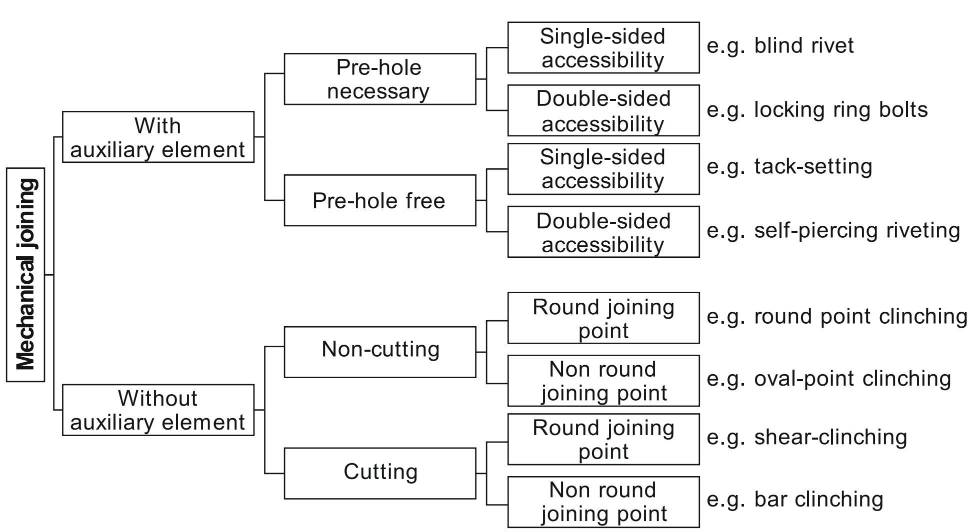

Fig 1. Systematic classification of mechanical joining techniques with and without auxiliary joining element according to (Hahn and Klemens, 1996).

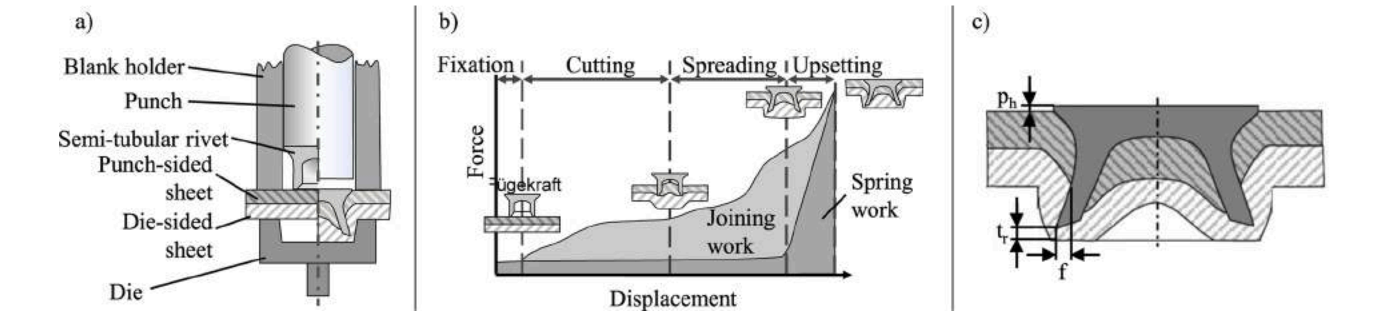

Fig 2. a)Tooling for SPR, b) Process sequence for self-piercing riveting and exemplary joining force-displacement curve, c) Quality-relevant characteristics of a SPR-joint (DVS/EFB, 2018).

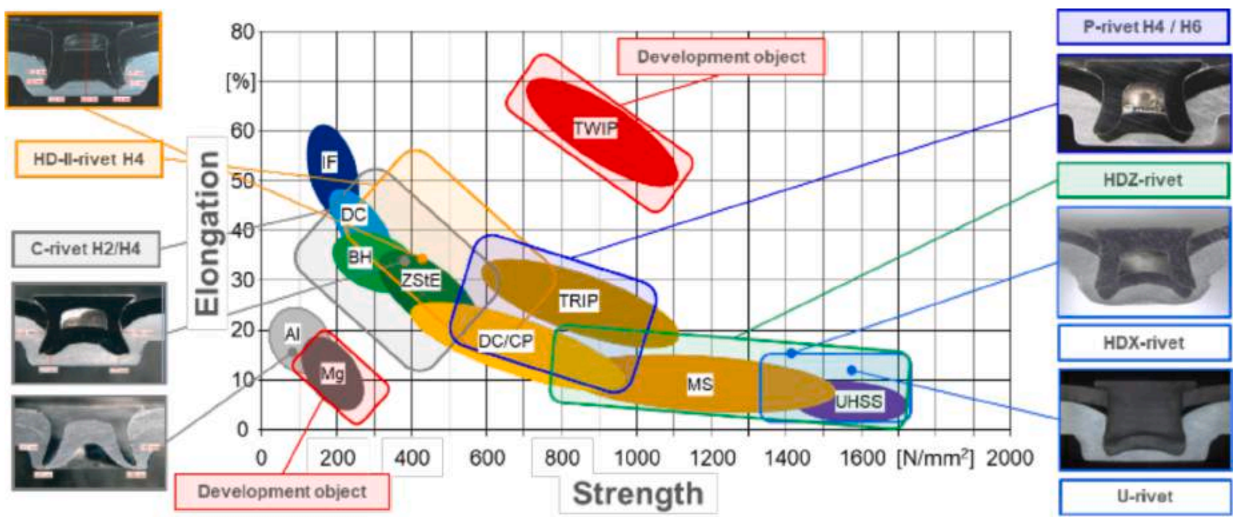

Fig 3. Application range of different rivet geometries according to material strength and elongation according to (DVS/EFB, 2018).

should focus on increasing flexibility and developing versatile processes to enable the process to respond to changing boundary conditions and to reduce the number of rivet/die variants required.

A completely different approach regarding the rivet geometry is using double-sided self-pierce riveting (Kato et al., 2001). In this variant of self-pierce riveting, the rivets are made from tubes with chamfered ends that are placed in-between the sheets to be joined and are subsequently pierced through the sheets in a single stroke. Flaring of the rivet ends during piercing ensures the creation of an undercut that holds the sheets tightly together (Fig. 4).

The main challenge of double-sided self-pierce riveting is the positioning and alignment of the rivets and the capability of creating good undercuts in sheets with different mechanical strengths. These topics have been recently addressed (Alves et al., 2021) using flat-bottom holes that are preliminary machined in the sheet with greater mechanical strength. Here the rivets are inserted before being pierced through the two sheets and by using different chamfered angles α at the upper and lower tube ends to compensate the greater or lesser difficulty of piercing through the sheets with higher or lower mechanical strength.

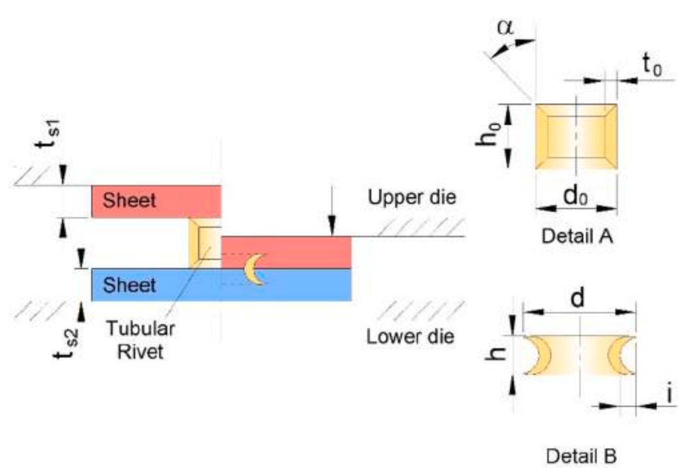

Fig 4. Double-sided self-pierce riveting at the beginning (left) and end (right) of the process with details of the tubular rivet before ('A') and after ('B') plastic deformation. (Alves et al., 2021).

Tumbling self-piercing riveting

The conventional joining process of self-piercing riveting is based on a linear translational movement of the active tool elements. This characteristic makes the joining method a rather rigid process with limited degrees of freedom given by the tool geometry. Adapting the process to varying process and disturbance variables is limited, however, new challenges in joining technology require an increased versatility and thus new joining methods and procedures. To extend the process limits of self-piercing riveting an orbital forming kinematic of the punch can be integrated into the joining process. Orbital forming is according to (Groche et al., 2007) an incremental bulk forming process based on tilting the punch axis out of the tool axis by a tumbling angle α, as it is shown in Fig. 5 in combination with a self-piercing riveting process. The usually conical shape of the tumbling punch results in a partial deformation of the workpiece and the characteristic orbital kinematic.

The increase of the tumbling angle is analogue to an increase in the

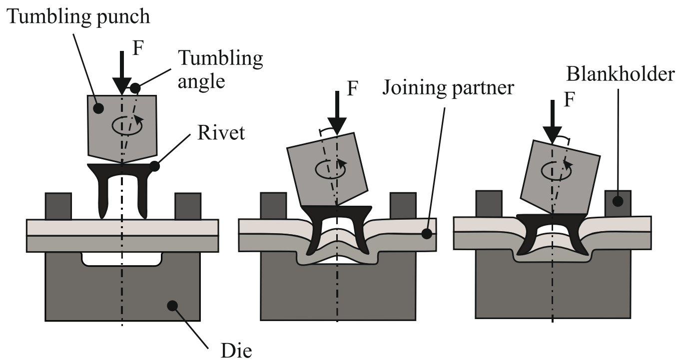

Fig 5. Tumbling self-piercing riveting process according to (Wituschek et al., 2021).

forming force due to a reduction of the contact area between the punch and the workpiece (Merklein et al., 2012). An important component of orbital forming is the tumbling strategy in the context of orbital kinematics. The tumbling kinematics can be divided into four different types according to (Merklein et al., 2012): circle, straight-line, spiral and daisy, which are shown in Fig. 6.

The tumbling strategy has a significant influence on the forming behaviour of the workpiece. For example, a circular motion enables uniform forming over the entire workpiece (Plancak et al., 2012). The combination of a tumbling process with a self-piercing riveting process was investigated in (Thoms, Six et al., 2003). An orbital and a radial riveting process were examined which are characterised by circle and rosette-shaped kinematic of the tumbling punch. The material combinations investigated consist of a deep-drawing steel and two micro alloyed and dual-phase steels. The results of the research work show a reduction in the joining force of 40–55% compared to conventional self-piercing riveting. Using this joining method, equivalent joints can be created in terms of geometric characteristics, joint strengths and failure behaviour. Furthermore, no significant differences on the rivet head surface could be determined. (Di Bella et al., 2018) analysed the quality of a joint produced by means of an orbital riveting process with a circle shaped kinematic. The materials used are an aluminium alloy EN AW-6082-T6 and a carbon steel A570. Tests on the durability of tumbling riveted joints in a salt-water environment with varying time intervals and material combinations were carried out. The investigations showed that an influence on the joining point of both can be detected. The combination with the aluminium joining partner on the punch side leads to unbuttoning, whereas the combination with a steel joining partner on the punch side leads to bearing failure. Applications for tumbling riveting are numerous, especially in the industrial sector and can be divided into orbital riveting and radial riveting. The differences are varying tumbling kinematics, however, current applications of this process combination use constant tumbling strategies and tool angles. The potential of tumbling riveting can be shown, but current process combinations are rigid and cannot react to disturbance and process variables. This is the point of focus for new research projects that address a versatile tumbling riveting process. To shift the process limits and to create tailored joints an in-situ adaption of the tumbling kinematic and the tumbling angle can improve the joint quality. Therefore in (Wituschek et al., 2021) a versatile tool design is presented and the influence of the tumbling strategy on the joint formation is investigated. Experimental investigations on the tumbling self-piercing riveting process in (Wituschek and Lechner, 2022)about the influence of the tumbling angle show an increasing undercut with higher tumbling angle.

Friction riveting

Besides the mechanical joining processes carried out at ambient temperature, alternative approaches have been developed, that use friction-induced heat to join components. In comparison to other friction based joining techniques, like friction element welding, it is not intended to weld the element with the sheet materials. The process sequence is generally similar for all the presented methods. To generate a pre-hole-free connection, a rotating auxiliary joining element penetrates the sheet material to form an extruding hole. The relative movement between the two components heats up the materials and reduces the flow stresses and thus the joining forces. This can be used to drive through sheets, create an interlock or form a thread in the sheet material (ARNOLD UMFORMTECHNIK GmbH & Co. KG, 2020).

Most common in industrial applications is flow drill screwing (Fig. 7). This technique uses friction-induced heat to reduce the sheet material's flow stresses with the aim of forming a bearing thread. The resulting connection is detachable and requires access from one side (EJOT, 2018).

In addition to screw-shaped joining elements, alternatives were developed which form the bearing interlock by forming the auxiliary joining element. For example (Min et al., 2015) used a modified blind rivet to join sheets together without pilot holes. (Li et al., 2013) and (Ma et al., 2021) used a friction element with a similar geometry to self-piercing rivet. A new approach to join plastics was presented by (Gagliardi et al., 2018) and (Pina Cipriano et al., 2020). The rod-shaped friction element made of aluminium immerses a plastic material and then locally melts at the surface. Due to the material accumulation in the centre of the element, the tip expands and forms the interlock. With regard to materials, friction based joining techniques offer a wide range of options, combinations, layers and sheet thicknesses (EJOT, 2010). Similar material combinations and multi-material structures are also possible, even in combination with structural adhesives. These techniques are not limited to ductile metals, include high strength steel materials, castings or magnesium alloys (Miller et al., 2006). Provided a

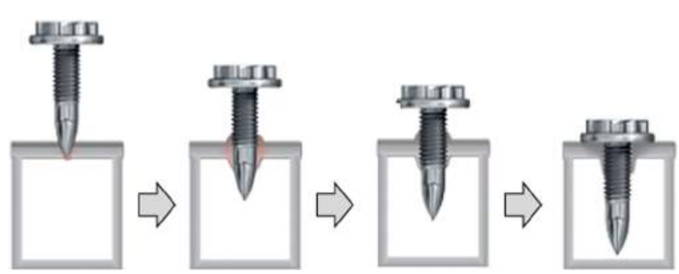

Fig 7. Process sequence of Flow Drill Screwing according to EJOT (EJOT, 2018).

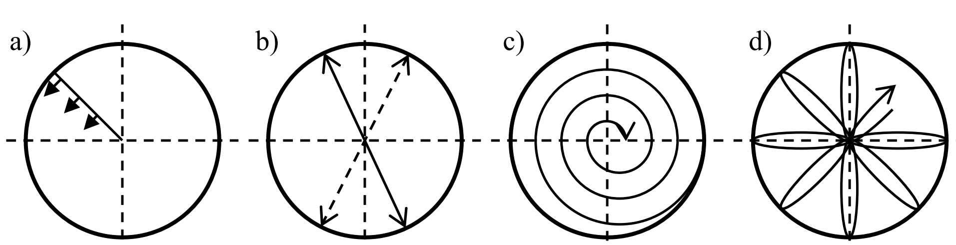

Fig 6. Tumbling kinematics, (a) circle, (b) straight-line, (c) spiral and (d) daisy.

special process design or an adapted joining element, fibre-reinforced engineering plastics like CFRP are processable (Lambiase et al., 2021). Nevertheless, there are important aspects to consider: Friction-based joining processes are associated with a temperature input. This effect influences the microstructure and the mechanical properties of the sheet material and joining element.

(Ma et al., 2021) and (Costas et al., 2021) found that the microstructure of the sheet materials around the connection is significantly finer due to recrystallization during processing. For aluminium alloys, Costas et al. (Costas et al., 2021) investigations showed that the hardness in the heat-affected zone is reduced. An influence investigation of pre-holing on mechanical properties was performed by (Policena et al., 2019) and (Sønstabø et al., 2018). The results showed that pre-holing significantly affects the tendency to delamination, the mechanical properties of the connections and its fracture pattern. If pre-holing is provided, the sheet material fails, otherwise the joining element fails. Also, pre-holing the cover sheet increases the ductility of the connection and decreases the maximum shear tensile strength of a joint. No significant influence has been identified for an acting head tensile load.

To extend possible application fields, a multitude of investigations with different subjects are performed. One important approach can be found in the joinability of alternative materials. For example, (Miller et al., 2006) and (Biermann et al., 2017) studied the flow drilling of magnesium and aluminium casting alloys and the influence of tool tempering on the machining result. Similar developments should be performed and knowledge should be transferred to other techniques. There is also a need for investigations on joining behaviour. Further process control strategies are needed to ensure the required joining properties. Knowledge obtained from (Skovron et al., 2015) and (Su et al., 2018) about process design must be applied to other methods. These results can be used to improve the design of the technical properties of the joint to meet the needs of the application. However, despite all the advantages of friction-based joining processes, their flexibility is limited. Joining elements are usually specially adapted to their area of application. Thus, a change in the process boundary conditions requires a costly process adaptation. A promising development is presented by (Rostek et al., 2020) and (Wischer et al., 2021) introducing an adaptive friction based joining technique. Formed by friction spinning the joining elements are tailored to the joining point's requirements. This approach is also suitable to reduce process forces in joining processes. Sheets are easier to penetrate, and the forces required to form the closing head are reduced.

Joining without auxiliary joining element

Friction stir welding

Friction Stir Welding (FSW) is a solid-state joining method taking advantage of a non-consumable tool stirring action and restrained heat input generated by friction at tool/workpiece interface. The FSW technique represents an appropriate option for hard-to-weld materials, such as aluminium alloys. Ahmed et al. (Ahmed et al., 2021) investigated on the weldability of EN AW-2024-T4 and EN AW-7075-T6 as skin and stringer respectively for T-butt joints manufactured by FSW. The microstructure of these joints can be seen in Fig. 8. Different tool rotational speeds were adopted by keeping a constant welding speed of 50 mm/min. W-shaped hardness profiles along the centre line of the skin of the welds were obtained, with the highest level recorded at 600 rpm thanks to proper balance between heat generation and cooling rate. Raturi et al. (Raturi et al., 2019) carried out a study on tool pin profile, process parameters and preheating effect on EN AW-6061/ EN AW-7075 friction stir welds. Tool pin profile and tool rotational speed resulted to be the most prevailing factors in FSW welds quality in terms of tensile strength and flexural load, while preheating procedure eased material deformation ahead the moving tool, thus, improving material flow.

FSW of Al-Mg alloys shows remarkable advantages, such as higher energy saving, cost reduction and high suitability for tailored material

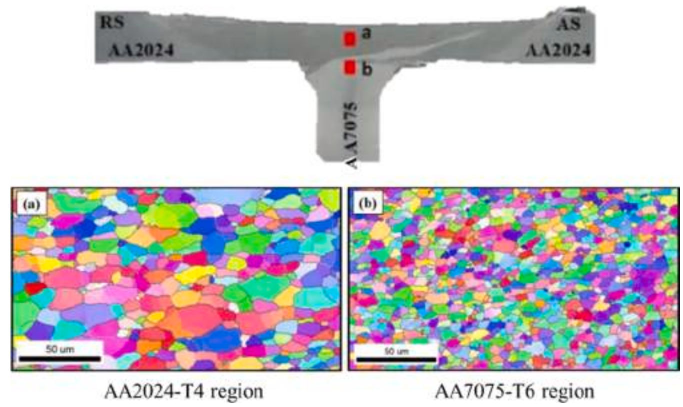

Fig 8. Microstructure and mechanical properties of dissimilar friction stir welded EN AW-2024-T4/ EN AW-7075-T6 T-butt joints. (Ahmed et al., 2021).

design in specific applications. On the other hand, Al–Mg joining is characterised by the development of intermetallic compounds (IMCs), leading to a decrease in the mechanical properties of the weld and representing a drawback to be limited. Starting from the above considerations, Mehta et al. (Mehta et al., 2019) evaluated the water cooling effect on IMCs formation in FSW of EN AW-6061/AZ31B dissimilar alloys. Compared to conventional FSW process, higher tensile strength as well as higher joint efficiency were recorded for the water-cooled case, suggesting a lower IMCs formation due to a better heat removal. Zhao et al. (Zhao et al., 2021) compared conventional FSW and ultrasonic vibration enhanced FSW (UVeFSW) of EN AW-6061-T6/ AZ31B-H24 alloys, finding an IMCs thickness reduction on the whole Al/Mg bonding interface by ultrasonic vibration adoption.

In the cases of Al-Ti, Al-Steel and Al-Cu IMCs formation shows up, reducing the mechanical performances of the joint. FSW as a solid-state operation can reduce the number of produced IMCs. Shehabeldeen et al. (Shehabeldeen et al., 2021) welded different FSW EN AW-6061-T6/Ti6Al4V joints to analyse the effect of tool rotational speed on microstructure and mechanical properties, proving that high RPM values lead to Al/Ti interface layer thickness increase and causes brittle phases of IMCs that deteriorate the joint structure. Yu et al., 2020 (Yu et al., 2020) employed ultrasonic vibrations in FSW of EN AW-6061/Ti-6Al-45 to reduce tool wear and enhance interfacial reaction. As Al-Steel dissimilar FSW welds are regarded, Derazkola and Khodabakhshi (Derazkola and Khodabakhshi, 2020) studied the formation and growth of the IMCs layer at the Al-Fe interface during EN AW-5005-O/St-52 low carbon steel FSW process by comparing experimental data with a thermo-mechanical model. For sound/defect-free dissimilar welds, it was found that the lower thickness of the IMC layer can enhance the dissimilar weld mechanical performance, with a maximum joint efficiency of approximately 90%. On Al-Cu welds, Hou et al. (Hou et al., 2020) studied dissimilar FSW butt joining of EN-AW6061/Cu at different tool offset values. Authors found out that decrease in tool offset determines a higher material intermixing in the stir zone, providing more reaction between them to form more IMCs, reducing weld mechanical properties.

As a further proof of FSW potential in joining of dissimilar materials, Li et al. (Li et al., 2020) successfully welded AZ31B/Ti-6Al-4 V dissimilar alloys by friction stir lap welding (FSLW) obtaining a 89.2% joint efficiency with respect to that of the AZ31B base material. The increasing demand of composite and hybrid structures made by polymer/metal joints can possibly be fulfilled using FSW.

Derazkola and Khodabakhshi (Derazkola and Khodabakhshi, 2020) performed a Fed friction-stir (FFS) process of EN AW-2024 aluminium alloy and polycarbonate (PC) by adding reinforcing alumina nanoparticles through the weld stir zone (SZ), reducing the difference in mechanical strength of aluminium and polymer base materials, thus showing a beneficial influence on the formation of a sound dissimilar weld. Derazkola and Simchi (Derazkola and Simchi, 2019) performed a sound T-joint Poly methyl methacrylate (PMMA)/EN AW-5754 by FSW process, concluding that the main welding mode was macro/micro-mechanical interlocking and chemical interactions between aluminium fragments and ramus with PMMA. Fig. 9 shows the process as well as a micrograph of a PMMA/EN AW-5754 joint. Overall, several open issues regarding FSW techniques are still under evaluation within the international scientific community. The effective addition of powder materials to locally improve the mechanical properties of the joints just close to the solid bonding surface appears to be one of the most promising and at the same time challenging attempts.

Clinching

Clinching is defined in DIN 8593 (DIN, 2003a-09) as the joining of two or more overlapping sheet metal, tube and / or profile parts by forming at least one joining partner using a punch and die. This involves a partial intersperse of the joining partners, with the sheet material being partially displaced out of the sheet plane by shear forming (DIN, 2003b-09), followed by subsequent stamping so that a joint is produced by radial material flow (Fig. 10). Additional elements are not used, although additives or auxiliary materials (Voelkner and Bräunling, 1997) may be required depending on the joining partners.

The clinching processes offers a wide range of variants, which are fundamentally described and categorized in (DVS EFB, 2012). These variants are separated according to their geometry into round and beam-shaped, the process steps required for joining into single-step and multi-step and into cutting and non-cutting clinching processes. The generated clinch joints are based on the principles of form- and force-closure, which Groche elaborates in (Groche et al., 2014), with a dominating form-closure component. Under certain conditions, according to Riedel (Riedel, 1997), there can also be a material closure or, according to (Füssel, Großmann et al., 2014), it can be created specifically. In single-step processes, the joint is produced by punch or die in an uninterrupted translational stroke (Fig. 11). In multi-step processes, (Chen, 2018) punch and die perform several successive translational strokes, some of which are in opposite directions. The joining process can be controlled by displacement or force. In accordance to the requirements, the joint properties are set by geometric design of the tools (Doege and Behrens, 2007) or by design of the joining process (Füssel et al., 2014).

The setting process (Fig. 11) starts after parts to be joined have been fixed by the blank holder (Step 1), the punch passes through the parts to be joined (Step 2) until it reaches the bottom of the die (Step 3). In the further course, the increasing joining force causes a thickness reduction of the parts to be joined (Step 4), whereupon a radial material flow is initialized and fills the die contour (Step 5). This radial material flow leads to the formation of the undercut between the joining partners. In the return stroke (Step 6), the blank holder acts as a stripper (Step 7). Depending on the design of the forming die, the joining element can be formed in closed dies or in split dies, whereby these differ in the stress state generated (Gibmeier et al., 2002) around the joints. In addition to a purely translational punch movement, there are alternative drive kinematics for generating clinch joints, which pursue the approach of reducing the joining force or reduce cold pressure welding effects between clinching tools and especially Al-Alloys as joining partners. In this case, impact or shock-like pulses are superimposed on the translational punch movements (Thoms, Kalich et al., 2003). In these drive kinematics, an impact mechanism in combination with the translationally moved punch generates the force effect on the parts to be joined. A similar system for clinching has an additional mass-spring unit (Kraß, 2004). The basis of the reaction force reduction in this process is the combination of two measures. On the one hand, an oscillating pulse-shaped joining force introduction is used and, on the other hand, a vibration isolation of the tool system is realized, which leads to a decoupling of the joining forces effective at the joining point from the reaction forces acting on the frame of the setting device. Another variation of the clinching process uses the specific punch kinematics of radial joining presses (Thoms, Kalich et al., 2003). In radial clinching, the punch is deflected according to a rosette or similar path, always passing through the zero position. In orbital clinching, the punch is deflected by a certain angle and rolls along a circular path. In both kinematics, however, the punch does not rotate around its own axis.

In addition to the use of low-frequency superposition pulses, high-frequency vibrations in the range of ultrasonic can be used in forming processes as described in (Panknin and Siegert), (Pohlman and Lehfeldt, 1966), (Severdenko and Kosobutski, 1975) and (Cheeke, 2012). The use of ultrasonic in forming processes leads to the useful effects of a reduction of friction between the workpiece and the tool, shown in (Pohlman and Lehfeldt, 1966) and (Siegert, 2003) and the reduction of the forming force explained in (Heßeln and Wanner, 2014). The coupling of kinetic energy with thermal energy (Beyer et al., 2006) in laser beam assisted clinching (Osten et al., 2014) enables semi-hot

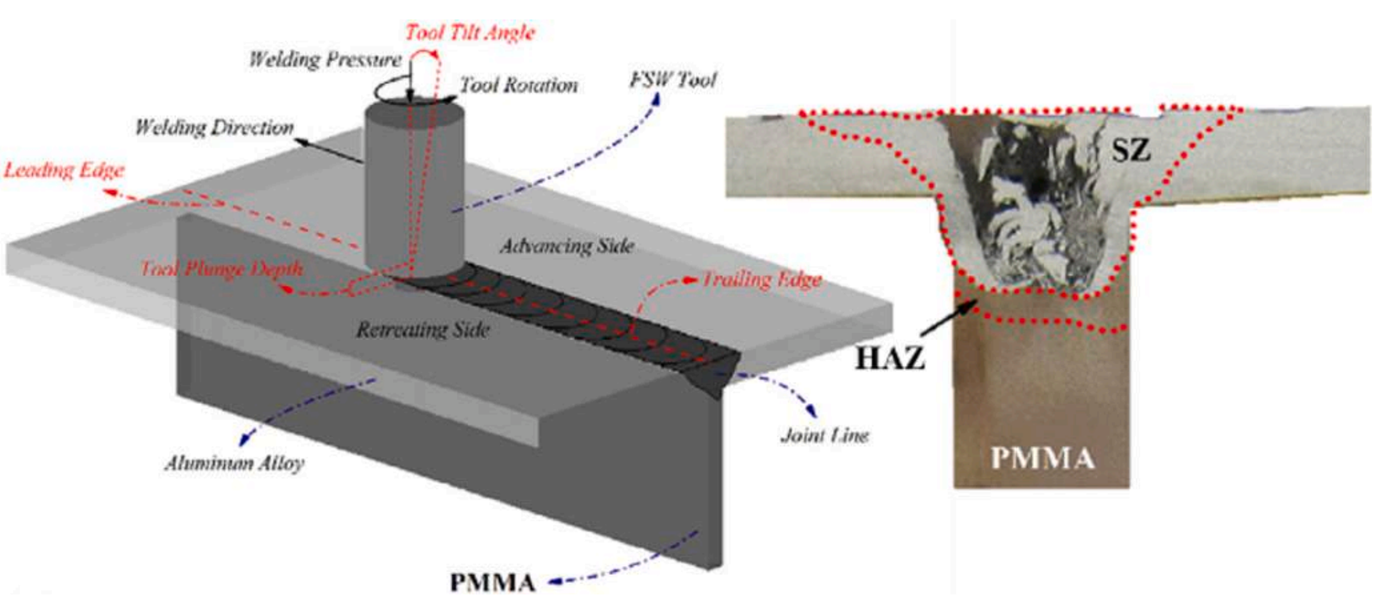

Fig 9. Dissimilar friction stir welding of T-joints (Derazkola and Simchi, 2019).

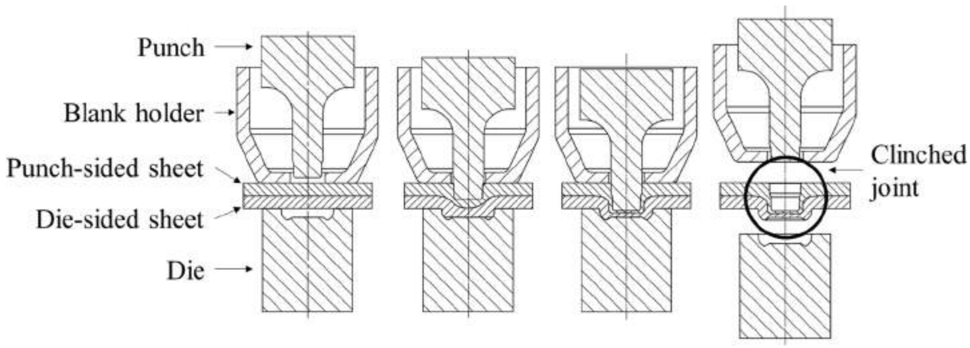

Fig 10. The process sequence of the Clinching process.

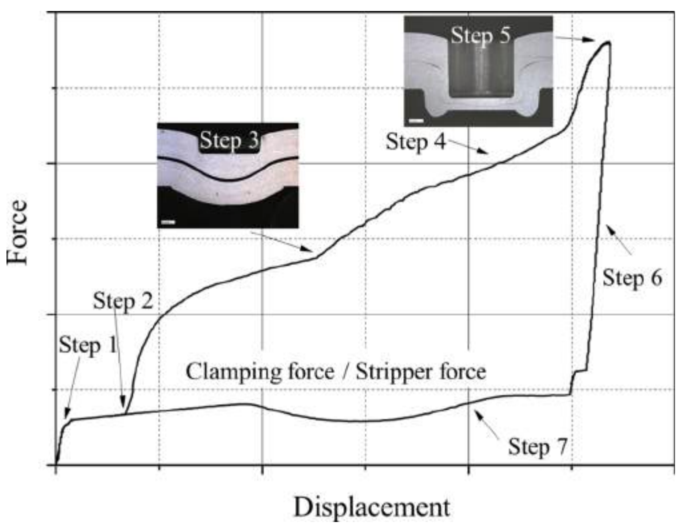

Fig 11. Force-displacement-curve for the clinching process.

forming (Neugebauer et al., 2003). This semi-hot forming reduces the process forces and increases the deformation capacity of the joining partners (Neugebauer et al., 2003). This additional thermal energy can also be introduced alternatively in the form of induction or resistance heating (Thoms V. and Timm M., 2002), with the same objectives. If the clinching suitability of the parts to be joined is set locally by the thermal energy prior to clinching (Meschut et al., 2014), the joining process can also be performed as a cold forming operation. The mechanical joint properties are essentially determined by the size of the joining element (nominal diameter), neck thickness, undercut and work hardening. The formation of these parameters depends on the geometry of the joining tools, the bottom thickness, the joined materials and their arrangement. As a preferred variant according to (DVS EFB, 2012), the thicker joining partner and the joining partner with the higher strength should be arranged on the punch side. If this is not possible, a compromise design of the joint can be made. The neck thickness generated by the tool selection correlates directly with the shear tensile strength, whereas the undercut correlates with the peel tensile and head tensile strength. Quality assurance can primarily be achieved by force and displacement monitoring of the clinching process (Fig. 11). Here it is possible to evaluate the entire process graph or only individual areas of interest, e.g. the maximum force or the punch displacement at the start of the return stroke. The evaluation of the joining element formation can be carried out non-destructively or destructively. In the case of the external quality characteristics, an assessment is made via the visual appearance with a view to the bottom thickness, a symmetrical clinch point formation, crack free surfaces of the joining parts and, when using coated semi-finished products, damage to the coating. In non-destructive quality control, the dominant parameter, bottom thickness, is measured. If the tool geometries are known, this measurement can be used to infer the parameters such as undercut and neck thickness, which can only be inspected destructively. Other possibilities for non-destructive testing of the quality-determining parameters are ultrasonic measurement of the bottom thickness (Schneider et al.), computer tomographic recording qualitatively in (Füssel et al., 2014) and quantitatively in (Köhler et al., 2021a) of the joint, or measurement of the electrical resistance (Jiang et al., 2015).

In general, the mechanical properties and, in particular, the forming capacity of the joining materials are important for clinching. According to (DVS EFB, 2012), materials with an elongation at break of UE $\geq$ 12%, a yield or proof stress ratio YS / TS $\leq$ 0.7 and a tensile strength of TS $\leq$ 600 MPa are currently considered to be well suited for clinching (DVS EFB, 2012). If the components to be joined do not comply with these recommendations, joining can also be realized by means of a case-by-case design or by adapting the clinching process. If the joining component materials are suitable for clinching according to (DVS EFB, 2012), dissimilar joints can be clinched in addition to pure metallic component materials, as Eshtayeh explains in general in (Eshtayeh et al., 2016). The metallic materials represented by steels of various structures and strengths. Aluminium, magnesium, copper and their alloys primarily represent the non-ferrous metals. In case of aluminium alloys, rolled alloys represent the dominant portion of the semi-finished product types. Aluminium die casting materials as described in Behrens (Behrens et al.) can also be clinched. Magnesium, as described in (Daxin Han et al., 2021) and copper and copper alloys, as described in Füssel (Füssel et al., 2019), can be made as single-grade and mixed compounds. Abe in (Abe et al., 2008) and Lee in (Lee et al., 2010) present the joinability of aluminium alloys and high strength steels, also adapting the clinching process according to (Abe et al., 2012) in the form of the die tools. The clinching processes in their variations additionally enable the joining of further material combinations in the form of metallic and non-metallic components, as shown in (Lüder et al., 2014) especially for wood-based materials. In the case of mixed joints of metallic (Wen et al., 2016) and non-metallic joining partners, general remarks on aluminium alloys, steel materials (Lee et al., 2014) or magnesium in combination with plastics (Meschut and Schmal, 2018) or carbon fibre-reinforced polymer are presented in (Dawei et al., 2018). Liu describes the influence of the manufacturing parameters on the properties of the joints in metal-plastic combinations in (Liu et al., 2020).

If the components to be joined are not suitable for clinching, the clinching process can be adapted or the components to be joined can be converted to a state suitable for clinching. Neugebauer presents these measures for materials that are difficult to form in (Neugebauer and Scheffler, 2006), Jäckel (Jäckel et al., 2017) for materials with limited ductility, Lin in (Lin et al., 2020) in the form of heat input restricted locally to the joint, and Chen in (Chen et al., 2017) for a modified clinching process. Jäckel combines in (Jäckel et al.) these approaches of process modification and heat input for joining 7xxx aluminium alloys.

The joinable component thicknesses range from thin sheets and foils with a total thickness of 0.3 mm in (Behrens et al., 2012) to component thicknesses of 20 mm in (Israel et al., 2013). Chen cites additional studies on the influence of component thickness in (Chen et al., 2018). Metallic coatings such as various types of zinc coatings, e.g. hot dip galvanized in (Abe et al., 2009) or electrogalvanized in (Hahn et al., 1999), or tinned copper materials (Füssel et al., 2019) can also be joined. Clinching of organically coated semi-finished products e.g. coil coated materials or powder coated materials according to (Hahn et al., 1999) with standard or modified tools or also according to (Mende, 2006) based on active media is possible. The aim of the modified clinching processes is to maintain the functions of the coating, such as corrosion protection and decoration.

Shear-Clinching

The development of shear-clinching by Busse et al. (Busse et al., 2010) extends the process boundaries of clinching to low-formable metallic material. The great advantages of shear-clinching compared to the common methods, such as clinching with pre-hole, are the elimination of the positioning and the pre-hole operation. As shown in Fig. 12, the shear-clinching die consists of a movable anvil and several mutually movable lamellae with inner edge radius of less than 0.5 mm.

The punch unit is made of a blank holder, an inner punch and a spring-loaded outer punch with a hemispherical (Busse et al., 2010) or cone-shaped (Graser et al., 2019) outer contour. During the joining process, the die-side joining partner is shear-cut, while the punch-side joining partner is penetrated by defined decoupled inner punch. This creates a form-fitting and non-positive joint. Meschut and Weikelmann (Meschut and Weikelmann, 2017) provide an overview of the application limits of shear-clinching. In principle, the joinability is mainly limited by the die-side joining partner. For the shear-clinching, the mechanical properties of the die-side joining partner should lie between TS = 359 MPa, UE = 34.5% and TS = 1202 MPa, UE = 10.2%. That means that the typical dual-phase steels or press-hardened steels can be joined using shear-clinching. Hörhold et al. (Hörhold et al., 2016) indicate that shear-clinching of ductile aluminium with press-hardened 22MnB5 has comparable mechanical properties under quasi-static loads as clinching with pre-hole. The load-bearing capacity of the shear-clinching joint increases with the enhanced tensile strength of the punch-side joint partner (Wiesenmayer et al., 2020). In addition, the joint load-bearing capacity is influenced by the specimen geometry (Hörhold et al., 2017). The reason for this is that the specimen stiffness and the edge distance vary with different specimen geometries, which influences the material flow in the punch-side joining partner during the joining process. Han et al. (Han et al., 2019) confirms that the edge distance can also influence the load-bearing capacity of the joint when joining multi-element specimens. To avoid loss of load-bearing capacity, a minimum edge distance of 22 mm should be ensured during shear-clinching of EN AW-6016 (2.0 mm) with 22MnB5 (1.5 mm). Like most joining by forming techniques, distortion should not be neglected. Han et al., 2018 (Han et al., 2018) show that the displacement of the punch-side joining partner can be eliminated by adapting the joining sequence.

Furthermore, global bending of the shear-clinched specimen as well as joint gaps between the joining positions can be additionally reduced by modifying the punch geometries (Han et al., 2018). To improve understanding of the distortion mechanisms in shear-clinching and to simplify tool development in terms of reducing specimen distortion, Han et al. (Daxin Han et al., 2021) has demonstrated a method for three-dimensional modelling of the shear-clinching process. Based on this framework, the shear-clinching can be further developed for joining narrow flanges. Further research should focus on joining novel materials, e.g. FRP, so that the application range of the shear-clinching can be further expanded.

Pin joining

In this paper, a pin structure is defined as a small rod protruding from the surface of at least one joining partner, which can be embedded in the second joining partner. Thereby, the pin is a macroscopic structure with a defined geometry and typically has a diameter and height of at least one millimetre. The aspect ratio height to diameter is typically larger than one. Oftentimes pins have a cylindrical cross section, however other cross sections, such as rectangular (Heimbs et al., 2014) can be found. Pin-like structures are comparable to pin structures in terms of dimensions, but the defined geometry can only be partially reproduced.

Pins or pin-like structures can also have substructures with significantly smaller dimensions. Distributed over the joint's surface, they can increase the bond strength of polymer-metal joints but also function as primary feature to create such joints. The mechanical anchors created by the infiltration of the surface structures are assigned to mechanical adhesion and as a result of increased surface area higher force can also be transmitted through specific adhesion (Heimbs et al., 2014). Substructures can either be irregular and produced for example via blasting (Lucchetta et al., 2011), pickling (Chan-Park et al., 2001), etching (Bischof, 1993), anodizing (Marinelli J. M., Lambing C. I. T., 1994) or other electrochemical processes (Kleffel and Drummer, 2017) or regular and predominately produced via laser structuring processes (Heckert and Zaeh, 2014). In order to achieve a good load transfer undercuts orthogonal to the joining surface are beneficial (Kleffel and Drummer, 2017).

Current manufacturing processes of pin structures

Pin structures for joining dissimilar materials can be produced by various processes, which can be categorized as moudling, additive, subtractive and formative manufacturing processes. moudling processes are primarily based on metal injection moudling (MIM). The Helmholtz-Zentrum Geesthacht (Ferri et al., 2012) patented a process called MIM structuring, which is based on the MIM process to produce metal moldings with structured surfaces. However, the components are limited regarding their mechanical properties, due to a residual porosity of up to 4.4% (Feistauer et al., 2016). This can be reduced to nearly 0% by a subsequent hot isostatic pressing step (Heaney, 2019). Additive processes are also frequently used to produce pins. These include additive manufacturing (AM) processes such as powder bed fusion (PBF)

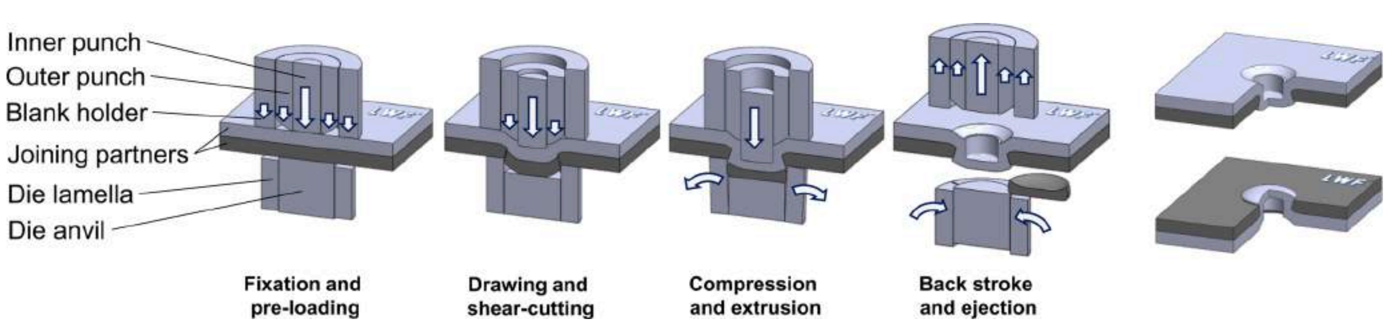

Fig 12. Process sequence and setup of the tool for shear-clinching (Daxin Han et al., 2021).

(Plettke et al., 2014) or direct energy deposition (DED) (Graham et al., 2014), as well as welding processes like cold metal transfer (CMT) or arc percussive micro-welding (APMW) (Oluleke et al., 2013). Due to the layer-by-layer production, AM processes have the advantage of a high degree of design freedom. Furthermore, complex geometries and undercuts can be realized. In (Plettke et al., 2014) PBF with a laser beam as the energy source was used to build pins of AlSi10Mg and Ti6Al4V on a base material, which were then used for joining with fibre-reinforced plastics (FRPs). DED can utilize wire or metal powder fed into a laser beam to create welding paths, forming the part. In (Graham et al., 2014) this process was used to produce pins with a diameter of 1 mm and a height of 3 mm, which took about 10 s per pin.

CMT is a variation of gas metal arc welding and was introduced by the Austrian company Fronius in 2004. Due to a special wire feed system combined with a high speed control system to regulate the arc length, the heat input and the material transport can be controlled (Pickin and Young, 2006). Thus, different pin head geometries, such as spherical, cylindrical or spike-like pin heads can be realized. The effect of these geometries on the tensile shear strength when joining stainless steel 304 L with carbon fibre-reinforced plastics were investigated in (Ucsnik and Kirov, 2011). For one pin with a diameter of 1.2 mm and a height of 1.6 mm a process time of about 3 s is necessary (Hopmann et al., 2017).

Subtractive processes for pin manufacturing include classical machining or micro-machining processes and the Surfi-Sculpt process. This process was developed at the welding institute (TWI) by Dance and Ewen (Dance and Kellar, 2010), in which an energy beam (electron or laser beam) is used to locally melt material on the surface and redistributes this material through a relative movement of the energy beam, creating protrusions and intrusions on the surface. In this way, different geometries can be realized (Kellar and Smith, 2006). With micro milling pins are manufactured by removing unnecessary material through processes such as milling, turning, or grinding. In (Di Giandomenico, 2014), micro-milling was used to structure titanium components and create different pins, which were then joined with FRPs with a thermoplastic matrix. Besides the processes mentioned, formative processes such as friction stir forming (Saju and Narayanan, 2020) and cold extrusion from the sheet metal plane (Kraus et al., 2019) are used for pin manufacturing. In friction stir forming, a rotating tool is used to extrude material axially from a sheet material into a previously created opening in the joining partner, resulting in a cylindrical pin. Depending on the die geometry, different pin head geometries, such as classic rivet head geometries, can be realized (Saju and Narayanan, 2020). By separating pin production and joining operation, pin geometries for joining metal and FRPs can be produced as well (Conte et al.). In (Kraus et al., 2019), cold extrusion is used to extrude pin structures from the sheet metal plane. For this purpose, a blank holder force is first applied to the sheet followed by axial material extrusion into a die using a punch. An illustration of the pin cold forming process can be seen in Fig. 13.

In this way, different pin diameters and geometries can be manufactured. The advantage of this process is the possibility of creating several pins in one stroke, as well as the process-related work hardening of the pin structures, which has a favourable effect on the pin strength. In addition, the process can be easily integrated into existing industrial manufacturing processes.

Developments of metal- metal joints

Joining with pin structures is of great interest, especially in the field of metal/FRPs, which is why a lot of research is being conducted in this field. However, pins also offer great potential for joining dissimilar metals. Especially in the case of cold formed pins, no additional auxiliary element is needed for the joining operation and the pin is formed from the base material, resulting in weight reductions. Additionally, joining with pin structures offers advantages in terms of the process versatility, as the pin height and number of pins can be adjusted in order to adapt to batch variations and specific strength requirements for the joints. Based on a similar principle, resistance element welding with upset auxiliary joining elements (Meinhardt et al., 2019) can be mentioned for joining dissimilar metals as well. In this work, steel sheets made of Cr249La, were joined using auxiliary elements made of Cr240La steel with carrier sheets made of Al5-Std and with Al6-Out. In the tensile shear test, shear strengths of 3.2 kN, 4.5 kN and 4.0 kN respectively were achieved (Meinhardt et al., 2019). In (Kraus et al., 2019) cold extruded pins of DC04 with a diameter of 1.32 mm were used for joining with EN AW-6016 to compare the tensile shear strengths of caulked and directly pressed pins. Both joining processes are illustrated in Fig. 14.

The pressed-in samples achieved a maximum strength of 363 N compared to 702 N for the caulked samples due to the significantly lower form-fit formed during direct pin pressing (Kraus et al., 2019). In (Römisch et al., 2021), the effect of the pin height on the tensile shear strength of direct pin pressing was investigated. Here, pins made of a dual phase steel (DP600) with a diameter of 1.5 mm and pin heights of 1.08 mm, 1.45 mm and 1.86 mm were joined with EN AW-6014-T4 sheet (thickness t_0=1.5 mm). The 1.08 mm pins achieved a maximum shear strength of 766 N. By increasing the pin height to 1.45 mm and 1.86 mm, the maximum shear strength could be increased by 22.5% to 938 N and 33.7% to 1025 N respectively. (Kraus and Merklein, 2020) simulated the effect of the number of cold formed pins of a DC04 steel with a diameter of 1.32 mm on the tensile shear strength. Here, up to a 3 × 3 Matrix a linear correlation of the strength with the number of pins could be shown, which was experimentally validated in (Römisch et al., 2021) on multi-pin structures with two pins. With a higher pin count of 15 pins (5 × 3) the maximum tensile shear force is only 14.3 times higher than the single pin, due to an increased bending moment at high tensile shear forces (Kraus and Merklein, 2020).

Developments of metal - polymer joints

To create metal-composite hybrid parts, pin reinforced joints with thermoset based composites are known and well described in the literature. Thereby, the integration of the pin into either dry fabrics prior to impregnation processes via "vacuum assisted resin infiltration" (Ucsnik et al., 2010) or "vacuum assisted resin transfer moudling" (Graham et al., 2011) or pre-impregnated sheets (Parkes et al., 2014) takes place before the matrix curing. In several studies a significant reinforcement could be shown, when pin reinforced samples were compared to adhesively joined references. An increase of the maximum force in the range of approx. 37% (Smith and Wylde, 2005) over 52.3% (Ucsnik et al., 2010) up to 650% (Parkes et al., 2014), and the energy absorption before failure of up to approx. 3000% (Ucsnik et al., 2010) could be

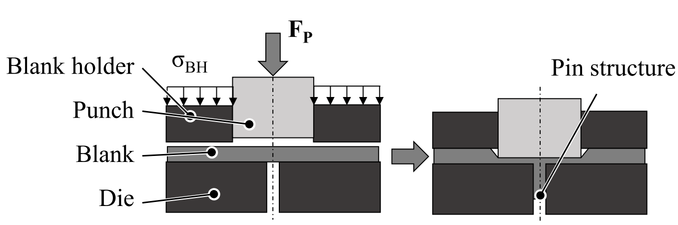

Fig 13. Illustration of the pin extrusion process according to (Römisch et al., 2021).

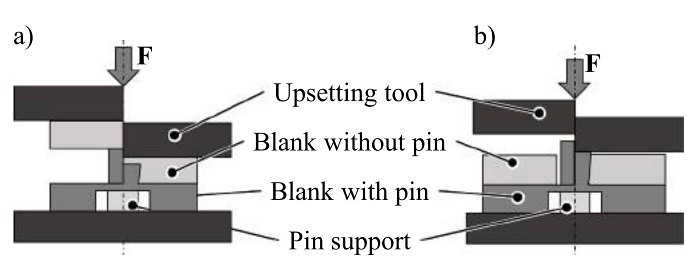

Fig 14. Process routes for joining with cold formed pin structures. (a) Direct pin pressing, (b) caulking.

shown. One major advantage is, that fibers are not cut but rearranged around the pin structures leading to improved mechanical properties (Eberl et al., 2017). Due to irreversible curing processes, joining must take place during manufacturing of the part and a subsequent joining operation is impossible. An approach to create metal-composite joints via subsequently inserted pin structures is the use of continuous fibre reinforced thermoplastics (CFRT) of which the matrix can be molten to achieve fibre flexibility (Meyer J. and Johns M., 2013). The pins can then be inserted into the composite while fibers rearrange around the pin. Both direct pin pressing as well as caulking processes as described above for metal/metal joints are applicable.

To heat the matrix, different strategies, mostly already known in polymer welding, are applicable. Hot air (convection) has shown to be effective to heat the CFRT component prior to pin insertion (Thakkar R., 2014). Thereby, a disadvantage is that a precise definition of the heated area is difficult to be achieved. The use of infrared radiation in combination with masks to define the irradiated area has proven to be an effective way to create a locally limited molten zone (Popp et al., 2021). The challenge hereby lies in the need to melt the matrix through the thickness without overheating the irradiated surface. A fast way to heat the matrix is the use of ultrasonic vibration. However, in these studies, fibre breakage can be seen which potentially weakens the CFRT component and joint strength (Feistauer et al., 2020).

Other heating strategies used in polymer-polymer and/or polymer-metal welding, but not yet experimentally investigated in pin joining are: inductive heating (Velthuis et al., 2007) (AlMg3/Carbon Fibre_Polyamide 66), (Roesner et al., 2011) (1.4301 stainless steel/Polycarbonate, Polyamide 66, Glass fibre Polyamide 66) laser radiation with the subtypes of transmission joining (Amend et al., 2013) and heat conductive joining (Rodríguez-Vidal et al., 2016), friction press joining (Wirth et al., 2014), and friction vibration heating. In the current state of the art metal polymer caulking, pins are pushed through the heated CFRT sample (Kraus et al., 2019), where it shows superior strength (270 N) in comparison to direct pin pressing (118 N). In contrast to this, it could also be possible, to use pre formed holes as described by Hufenbach et al. in (Hufenbach et al., 2018) through which the pin can be inserted prior to caulking.

Additionally, pin-like structures show high potential for adhesion incompatible polymer-polymer joints, as investigated in studies for lap joint (Wolf et al., 2017) and butt joint connections (Wolf et al., 2019). The generation of structures as well as heating of the second joining partner take place via friction vibration energy in each case. The bond quality is influenced, amongst others, by the pin-like structure itself (Wolf and Drummer, 2021) as well as the second joining partner (Wolf et al., 2019). The use of pin-like structures enables bond strengths of up to 82% of the base material strength of the weaker material, related to the cross-sectional area of the pin-like structure (Wolf and Drummer, 2020).

Joining by plastic instability

Joining by plastic instability is based on the development of plastic instability waves and formation of compression beads in thin-walled tubes subjected to axial compression. Alves et al. (Alves et al., 2011) explored the formation of compression beads separately, or in

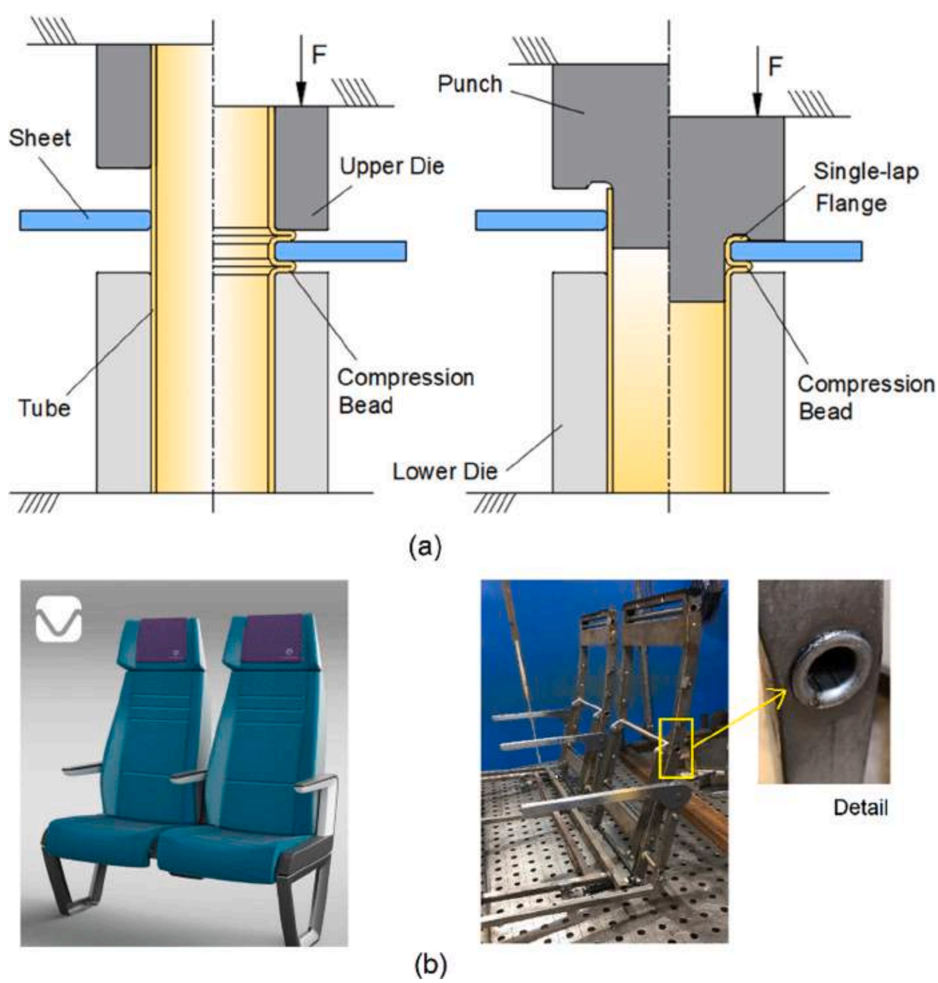

Fig 15. (a) Utilization of compression beads in joining by plastic instability of sheet to tubes and (b) application in the fabrication of the metallic structure of a train passenger seat (Modseat, 2017).

combination with tube end flaring to produce sheet-tube form-fit connections perpendicular to the longitudinal tube direction (Fig. 15).

The process was subsequently extended by Alves et al. (Alves and Martins, 2012) to inclined sheet-tube connections after redesigning the upper and lower dies to force the plastic instability waves to match the desired angle of inclination. Fig. 16 includes a schematic representation of the process and a photograph of a sheet-tube connection between two dissimilar materials with very different mechanical strengths. Subsequent work by Viehweger et al. (Viehweger et al., 2013) concluded about the risk of having crack initiation at the inner radius of the compression beads in materials with limited formability at ambient temperature. The problem was further investigated by Sizova et al. (Sizova et al., 2017) who proposed an alternative geometry (designated as ‘arrow bulge’) for the compression beads with the objective of reducing the overall level of damage and preventing the risk of cracking (Fig. 17). The arrow-bulged compression beads are triggered by plastic instability like the axisymmetric or inclined compression beads, but its special shape is obtained by introducing a conical frustrum inner wall on the upper die.

Sviridov et al. (Sviridov et al., 2017) proposed heating the forming area where compression beads are formed to avoid cracking. They proved the feasibility of the procedure by producing crack-free compression beads in a E235+*N* steel tube subjected to local inductive heating (600 °C-700 °C), which failed by inner cracking when formed at ambient temperature.

Despite the above-mentioned developments the process has been mainly circumscribed to tube-sheet connections. Extension to profiles namely, to extruded aluminium profiles, is an open topic that needs to be addressed to enlarge the application portfolio of the process. An interesting approach to consider in this extension is the use of ‘weakened areas’ (Wehrle et al., 2014) that are commonly applied in the design of crash absorbing structures. In fact, by reducing the wall thickness of the profiles in local selected areas, it will be possible to control the location where the compression beads will form, and to compensate the different plastic flow kinematics of the material located at the corners and side walls of the profiles. The utilization of compression beads resulting from plastic instability of tubes subjected to axial compression was also applied in the connection of tubes-to-tubes by means of form-fit joints. Two different processes were specifically developed for this purpose (Fig. 18).

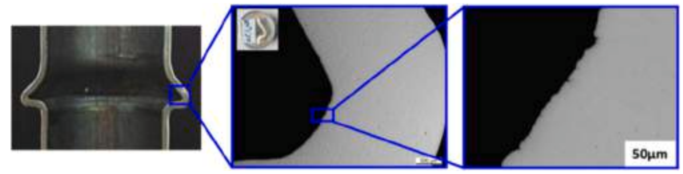

Fig 17. Cross-section of a tube showing an arrow-bulged compression bead and magnification details showing the absence of cracks at the inner radius (Sizova et al., 2017).

The first process developed by Alves and Martins (Alves and Martins, 2012) is targeted to tube branching solutions, which are widely used in plumbing, air conditioning, refrigeration, and process piping, amongst other applications. The process makes use of asymmetric compression beads that are created by axial compression of tubes between flat parallel platens using dies with curved contours that match the diameter of the main tube to be fixed to the branch tube (Fig. 18a). The second process developed by Alves et al. (Alves et al., 2014) is focused on the joining of tubes by their ends and consists of a sequence of two plastic

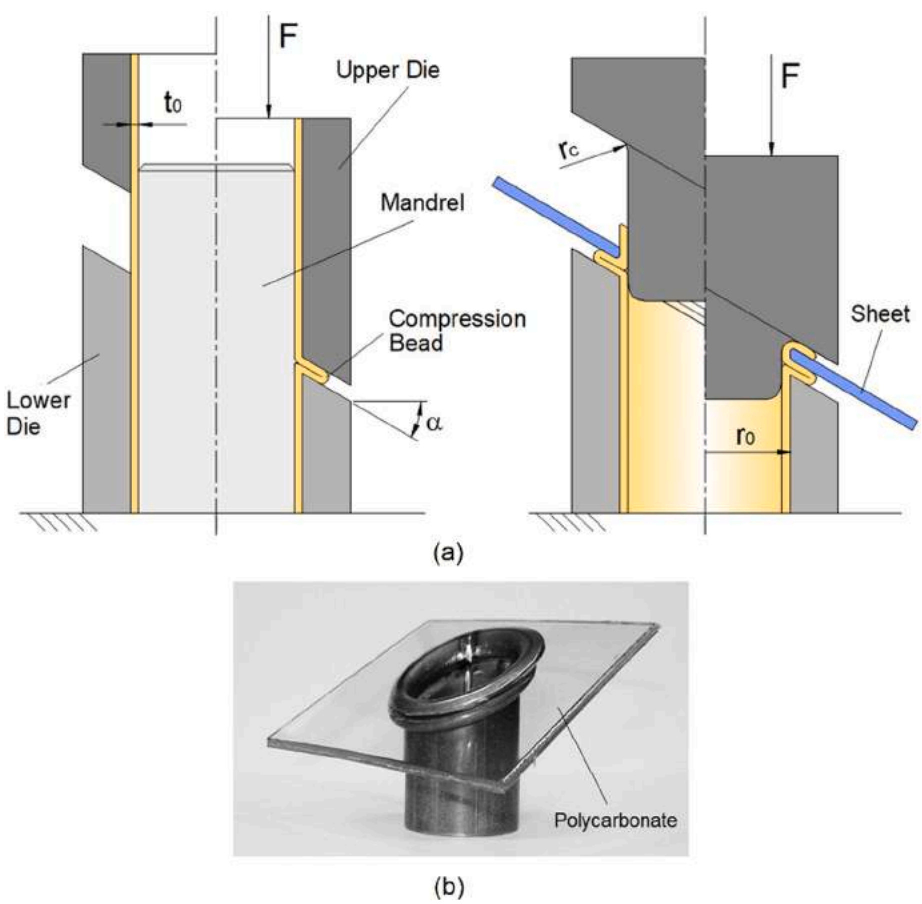

Fig 16. (a) Utilization of inclined compression beads in joining by plastic instability of sheets to tubes and (b) application in a connection between a steel tube and a polycarbonate sheet.

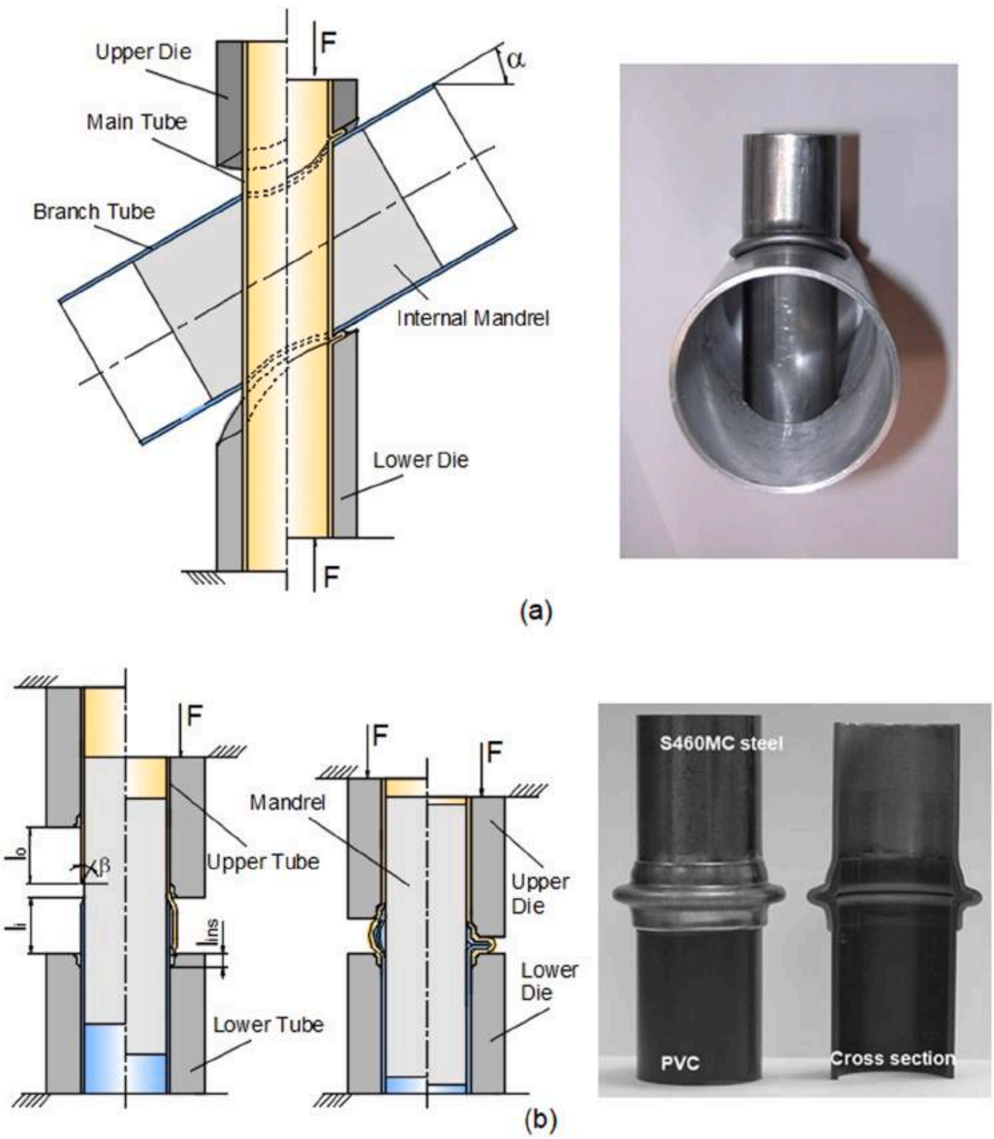

Fig 18. Joining by plastic instability applied to (a) tube branching and (b) to the connection of tubes by their ends.

deformation modes (expansion and plastic instability) in a single press stroke (Fig. 18b). As seen in the figure, the first deformation mode (expansion) is accomplished by pressing the upper tube against the chamfered end of the lower tube, which acts as a tapered punch. Once the upper tube diameter is expanded along its unsupported height *lo*, further pressing results in plastic instability of both tubes and in the creation of a mechanical interlocking built-upon two overlapped compression beads. Subsequent investigations by Yu et al. (Yu et al., 2018) confirmed the applicability of the process and suggested its hybridization by combination with adhesive bonding to produce joints with sealing and anti-rusting requirements for pipeline applications.

The process can also be used to connect tubes made from dissimilar materials, but when the mechanical strength of the tubes to be joined is very different, the expansion of the stiffer tube must be performed in a mandrel instead of being accomplished over the chamfered end of the lower tube. One of the main challenges regarding the numerical simulation of joining by plastic instability with dissimilar materials namely, metals and polymers, is the difference of up 20% that can easily be found between the flow stress in compression and tension of ductile polymers. Appropriate models making use of special purpose yield criteria (Caddell et al., 1974) that account for the effect of hydrostatic stress are required.

Joining by sheet-bulk forming or boss forming

Lap joints produced by welding, adhesive bonding, fastening, self-pierce riveting, clinching, and hemming are commonly used to join sheets or plates partially placed over one another. Clinching and hemming do not require the use of auxiliary elements, but their working principles can often limit their applicability. Clinching, for example, only works with thin sheets and should not be used in high-stress applications because the resulting joints do not provide the same level of security as that of welded or self-pierced joints. Hemming and bending of tabs (Mraz, 2015) are limited to sheets with thicknesses up to 5 mm to facilitate bending and should preferentially be used in materials with small elastic spring back to limit recovering (and loosening) after being bent. In addition to what was mentioned above both clinching and hemming give rise to material protrusions above and below the sheet surfaces.

Pragana et al. (Pragana et al., 2018) introduced a new joining process based on the combination of partial cutting, bending and form-fit joining by means of sheet-bulk forming (Merklein et al., 2012). The process is schematically shown in Fig. 19a-c and can produce strong lap joints with all the plastically deformed material contained within the thickness of the two sheets. In a recent work, Pragana et al. (Pragana et al., 2020) propose its application to the fabrication of hybrid busbars made from

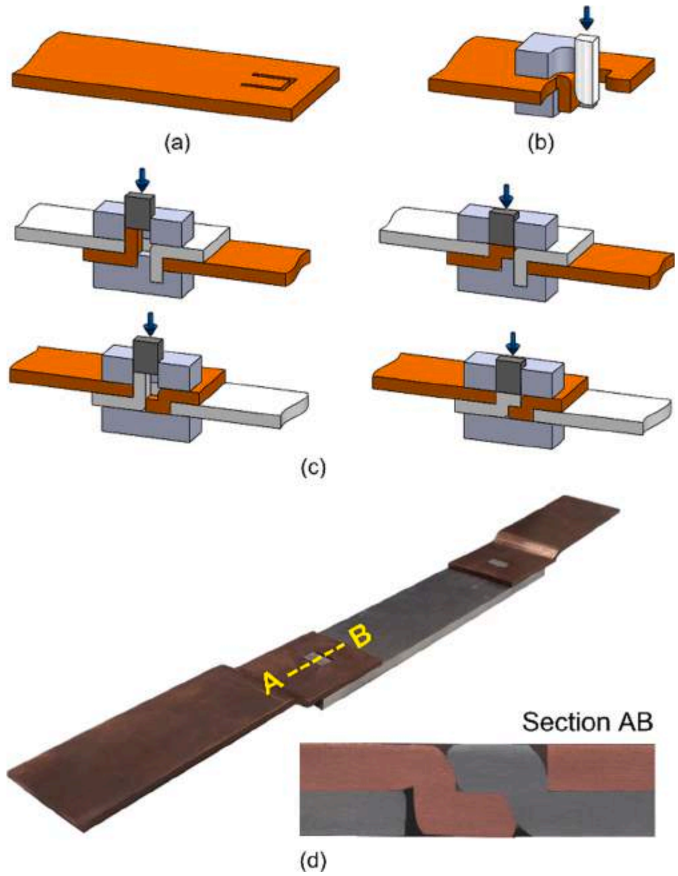

Fig 19. Joining by sheet-bulk compression: (a) partial cutting, (b) bending and (c) form-fit joining by sheet-bulk compression. Application to hybrid busbars with detail of the cross-sectional joint is shown in (d) (Pragana et al., 2018).

copper and aluminium strips (Fig. 19d).

The process shown in Fig. 19 was recently improved by replacing partial cutting with wire electro discharge machining by lancing to facilitate its implementation in a progressive tool with multi-station dies (Reichel et al., 2021). However, the application of joining by sheet-bulk compression to produce hybrid busbars for the distribution of electric power in vehicles and industrial installations requires looking beyond manufacturing and mechanical performance. In fact, studies must also focus on proper design strategies to ensure good electric current flow in both conductors and low electric resistance of the joints (Reichel et al., 2021).

Joining by boss forming has been specifically developed for the connection of tubes to sheets and of rods to sheets or hubs. Fig. 20 includes details of two of these developments that were recently proposed in the literature. The first of these developments due to Afonso et al. (Afonso et al., 2020) combines boss forming with upsetting to produce tube-sheet connections. Boss forming by partial compression of the tube wall thickness along the longitudinal direction is firstly applied to pile-up material into an annular flange (Fig. 20a) and upsetting of the free tube end against a sheet with a bevelled hole is subsequently used to obtain a form-fit mechanical interlocking (Fig. 20b). The process has been successfully applied to connect metallic, sandwich and polymer sheets to metallic tubes (Fig. 20c).

The other development made by Brosius and Guilleaume (Brosius and Guilleaume, 2020) makes use of cross-rolling to connect rods to hubs. As shown in Fig. 20d, the hub is fixed to the rod by the material of the rod that is piled-up and moved against the hub by a combined axial and rotational movement of two pairs of V-grooved rolls. The process has been successfully applied to connections involving metallic rods and metallic and ceramic hubs. The connection of rods to sheets has also been considered by Narayanan (Narayanan, 2018) and by Alves et al. (Alves et al., 2019). The first work (Narayanan, 2018) clamped the rod in a rotating lathe chuck and made use of a compression tool to incrementally pile up material and fix the sheet to the rod. The second work (Alves et al., 2019) is an extension to rods of the working principle that the same authors had previously developed for tubes (Fig. 20a-b).

A challenge facing joining by sheet-bulk compression, joining by boss forming and mechanical joining of dissimilar materials in general, is the problem of corrosion, as corrosion plays an important role in the service life of the joints. However, the topic has not been systematically addressed in the literature and the overall number of papers in the field is still scarce (Abbas et al., 2020).

Self-pierce riveting of tubes to sheets

Solid rivets that go completely through the tubes and blind rivets that only go partially are commonly used to connect sheets to tubes along their longitudinal direction (Fig. 21a). Self-pierce riveting of tubes to sheets (Alves et al., 2020) allows connecting sheets to the tube ends without auxiliary elements (Fig. 21b). The process consists of positioning and pushing a tube with a chamfered end (e.g. with a geometry like that of a rivet) through a sheet to obtain a mechanical interlocking i that holds the tube and the sheet tightly together (refer to the detail in Fig. 21b). Compared to welding, self-pierce riveting of tubes to sheets offers the advantage of avoiding the heat-cooling cycles that give rise to distortions, residual stresses, and metallurgical changes.

The process allows connecting sheets to tubes made from dissimilar materials at ambient temperature by means of invisible joints that are hidden inside the sheets (i.e., there are no material protrusions above and below the sheet surfaces). The support ring and the chamfered angle α of the tube end (Fig. 21b) plays a key role in the overall mechanics of joining. The support ring prevents failure by buckling of the tube wall when the tubes are pushed against the sheets. The chamfered angle α influences material flow during piercing and flaring of the tube through the sheet. Small values of α (e.g., $\alpha = 15^\circ$) give rise to inner curling and to the formation of 'fishhook-like' interlockings that are difficult to control and very sensitive to variations in the fillet radius of the tube end (Fig. 22). High values of α (e.g., $\alpha = 60^\circ$) do not allow the tube end to flare and to create a mechanical interlocking. In fact, further pushing of the specimen would give rise to buckling instead of piercing and flaring.

In their work, Alves et al. (Alves et al., 2020) suggest the utilization of chamfered angles $\alpha = 45^\circ$ to obtain good mechanical interlocking between the sheets and the tube ends.

In contrast to conventional self-pierce riveting of sheets, the process requires no use dedicated tools, nor there are limitations related to maximum thickness of the sheets to be joined. The main drawback of self-pierce riveting of tubes to sheets is related to the fact that the mechanical strength of the tube must be higher than that of the sheet. A solution to connect low strength tubes to high strength sheets that needs to be investigated is the possibility of first machining a dovetail ring hole in the sheet and then compressing the tube into the dovetail ring hole to produce a mechanical interlocking. The idea closely follows that of injection lap riveting (Ferreira et al., 2021), and requires the sheet made from a higher strength material to behave as a die into which the softer tube ends will be injected by axial compression.

Potential and challenges of the current processes and process analysis

This chapter deals with interdisciplinary topics related to the joining processes described. In particular, challenges for mechanical joining technologies in versatile process chains are addressed. From the authors' point of view, these are possibilities for increasing flexibility, dealing with materials that are difficult to join (FRP, high-strength), the applicability of process simulation and non-destructive testing methods.

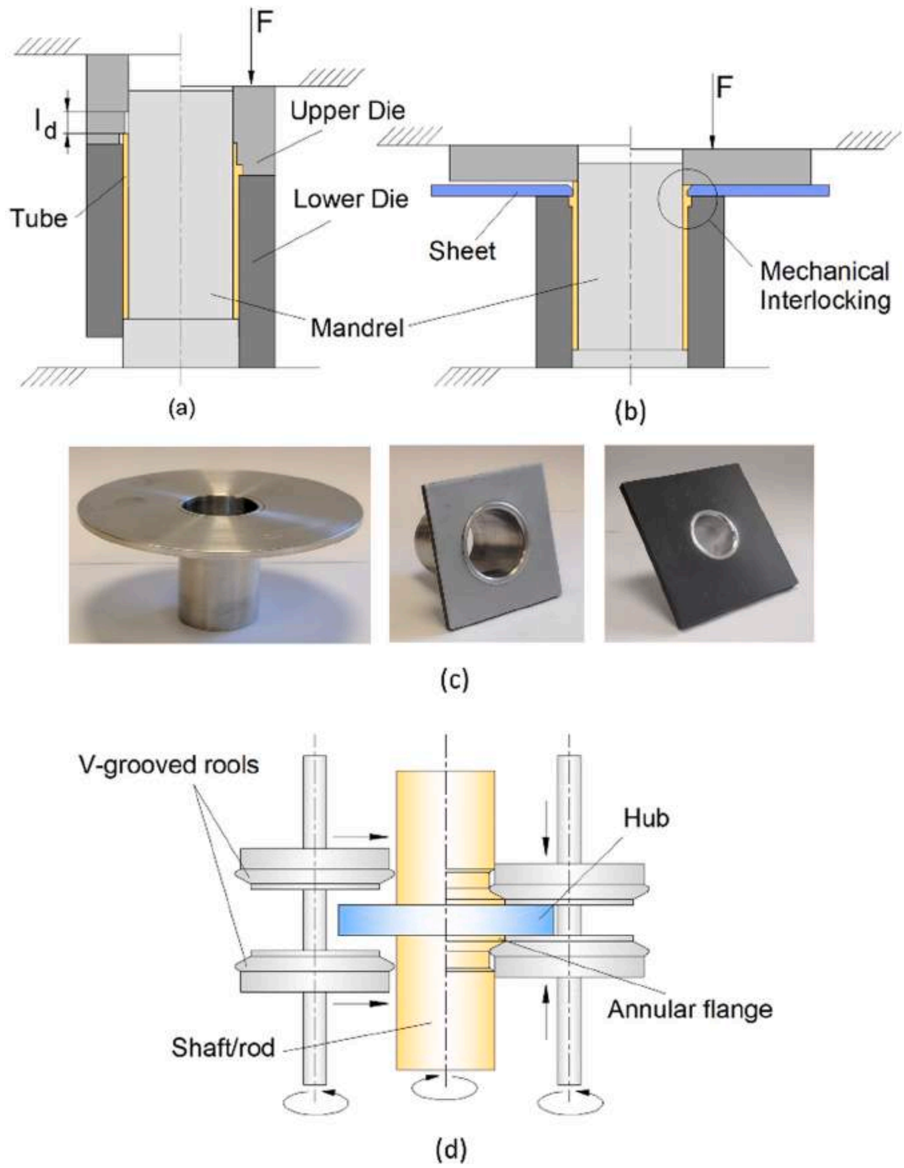

Fig 20. Joining by boss forming. (a) Boss forming of the annular flange followed (b) by upsetting of the free tube end against the sheet surface (c) to produce tube-sheet connections between metallic tubes and metallic, sandwich and polymer sheets. (d) Fabrication of hub-rod connections by a combined axial and rotational movement of two pairs of V-grooved rolls. (Alves et al., 2021).

Increasing flexibility

There are a number of possibilities to extend the application limits of the current rigid joining systems and thus to enable flexible joining systems. The possible adaptations relate to auxiliary joining elements as well as modified process routes and adapted joining systems. The following subsections present examples of industry-driven innovations for increasing the flexibility of mechanical joining processes.

Adaptive tools

Adaptive modification of the tools is one way of increasing the flexibility and cost-effectiveness of mechanical joining processes. Weikelmann (Weikelmann, 2015) presented a die with a lowerable die base for clinching processes. In this case, the depth of the die is adapted to the corresponding joining task before the joining process by relative movement of the base element. Subsequently, the base element is fixed and the joining process can be carried out. This adaptive adjustment allows joining of different material-thickness combinations with one die without prior die change, thus shortening cycle times and enabling greater flexibility. Drossel and Jäckel (Drossel and Jäckel, 2014) presented a die with a lowerable die base for the self-piercing riveting process. This die concept was developed for the application of materials with low ductility. In their investigations they showed, in addition to the possible adaption to changing boundary conditions, that the joint formation can be supported and cracks avoided by inducing compressive stresses in the riveting zone.

Adaptive processing route

When using high-strength or ultra high-strength materials, the danger of rivet damage when setting the joint increases due to the high strength of the material. In the case of press-hard steels in particular, the rivet foot can be compressed when the joint is set. (Meschut et al., 2014) showed, that local conditioning of the joining zone can prevent the rivet from collapsing and thus increase the process limits of the SPR-technology. Economic use for ultra-high-strength steels can thus be made possible while maintaining the overall component properties.

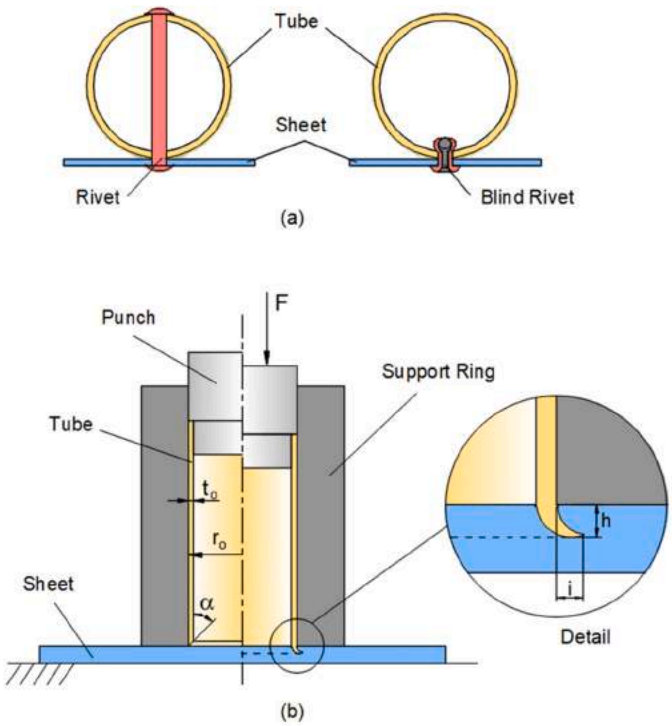

Fig 21. (a) Connecting tubes to sheets (a) along their longitudinal direction by means of solid (left) and blind (right) rivets and (b) by self-pierce riveting of tubes to sheets (Alves et al., 2020).

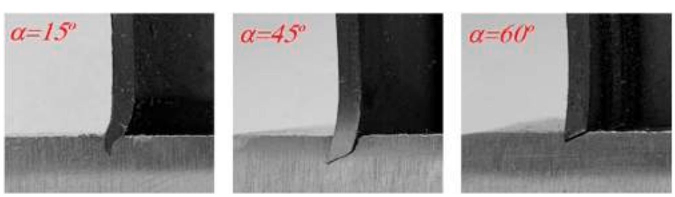

Fig 22. Experimental cross-sections of joints fabricated by self-pierce riveting of tubes to sheets with different chamfered angles α of the tube ends.

Flexible auxiliary joining element

Another possibility for increasing flexibility is the development of new, flexible auxiliary joining elements. These can extend the process limits but also partly enable a reduction in process forces or the number of auxiliary joining element variants required for joining different material-thickness combinations. In their study, Uhe et al. (Uhe et al., 2020) develop an auxiliary joining element for the self-piercing riveting process with a stress-optimized geometry. The geometry enables a joint made of high-strength steels on both the punch- and die-side as well as a joint made of high-strength steel as punch-sided and aluminium as die-sided material. Previously, two different rivet geometries were required for these joints. Kotercova and Briskham (Kotercova and Briskham, 2019) presented a rivet with a reduced shank and head diameter. This can reduce the joining force and allows the joining of narrower flanges, thus increasing the lightweight design. Some multi-range capability can be achieved with T-rivets (Trinick, 15.01.2015). The hollow design of the rivet shank increases the shank volume to accommodate the punched slug, allowing some flexibility with regard to thickness changes.

Flexible joining system

The further development of existing joining systems enables flexible joining processes to be set up and thus increases resource efficiency. Lang and Draht (Lang and Draht, 04.08.2005) developed a joining system that combines the joining of at least two materials by clinching as well as riveting process. The joining system can be adapted to the corresponding joining requirement and the appropriate joining process can be selected. Despite many research efforts, much potential for shaping mechanical joining technology in a versatile way still remains unexploited.

Fibre rearrangement

The range of mechanical joining technologies of metal and fibre-reinforced plastic joining partners have a wide range as (Galińska and Galinski, 2020) in general and (Lambiase et al., 2021) showed for clinching processes. Depending on the matrix material group (thermoplastic or thermosetting) and the chosen process conditions, the occurring phenomena during joining strongly depends on the matrix viscosity. In this respect, the behaviour varies between fluid-like (in case the process temperature exceeds melting temperature or a processing before chemical crosslinking) and solid-like (at room temperature or already crosslinked). Accordingly, fibres can move and deform through the matrix or obey composite specific failures modes in the solid case (cf. (Cuntze and Freund, 2004)).

A scale-specific approach to describe the behaviour for fabric-reinforced materials while processing were made by (Long, 2007) with the definition of five deformation mechanisms. In (Boisse, 2015) the deformation behaviour of different textile architectures during processing at a mesoscopic level are presented. A detailed review of forming phenomena and defects for pre-impregnated and dry fabrics are given in (Azzouz et al., 2021). Those more general studies do not take into account the local phenomena during mechanical joining processes. Joining processes with local forming of the FRP lead to a change in the internal material structure compared to the initial state. The methods to investigate the initial and resultant inner material structure and fibre path can be done by micrographs (c.f. (Lambiase and Paoletti, 2018), (Lee et al., 2014)) and CT-analysis (Meschut et al., 2014) (Gröger et al., 2021). The observed deformation and failure modes of the single fibres during joining are summarized in Fig. 23. The in-plane (Fig. 23a) and out-of-plane modes (Fig. 23b) can superimpose and lead to fibre failure (FF) (Fig. 23c) caused by fibre tension and bending. The tension stress occurs by friction between relative moved fibres and clamp effects of the textile architecture, e.g. ondulation. Due to the fact that FRP just can be in a liquid (melted/unlinked) state locally, the fibres are also clamped in the non-melted or already solidified area. Whereas FF by bending is induced by compression and shear load.

The in-plane phenomenon of fibre reorientation and shifting can be observed for unidirectional FRP around bolts, pins and moulded holes (Fig. 24a). The displacement of the fibres in transverse direction to the initial fibre path leads to a decomposition and matrix rich zones in front and behind the obstacle. In perpendicular direction the fibres are compacted resulting in an increased local fibre volume content (FVC). Those phenomena can be seen at pinning processes by (Parkes et al., 2014) for additive manufactured titanium pins or by (Eberl et al., 2017) for titanium pin-insertion process for FRP. Also for continuous fibre reinforced thermoplastic (TPC) for clinched joints in (Seidlitz et al., 2014) the phenomena are observed. Since the local heating via friction the fibres are clamped in the non-melted area, FF and interfibre failures (IFF) occurs in the joining zone. For multi-layered FRP the areas of high and low FVC are forming according to the initial fibre orientation. Due to the overlapping crossed fibres tangential the obstacle areas of high FVC occurs (Fig. 24b). Caused by the straight fibre path around the hole, matrix rich zones are formed.

These phenomena were investigated by (Hufenbach et al., 2012) for moulding hole forming based on FRTP with glass fibre reinforcement and for carbon fibre reinforcement in (Roth et al., 2020). The in-plane reorientation of the fibres in a bidirectional fabric was also observed in a developed partial thermo-forming process by (Lahr). The sliding and the shearing of the fibres are similar to the deformation mechanism of

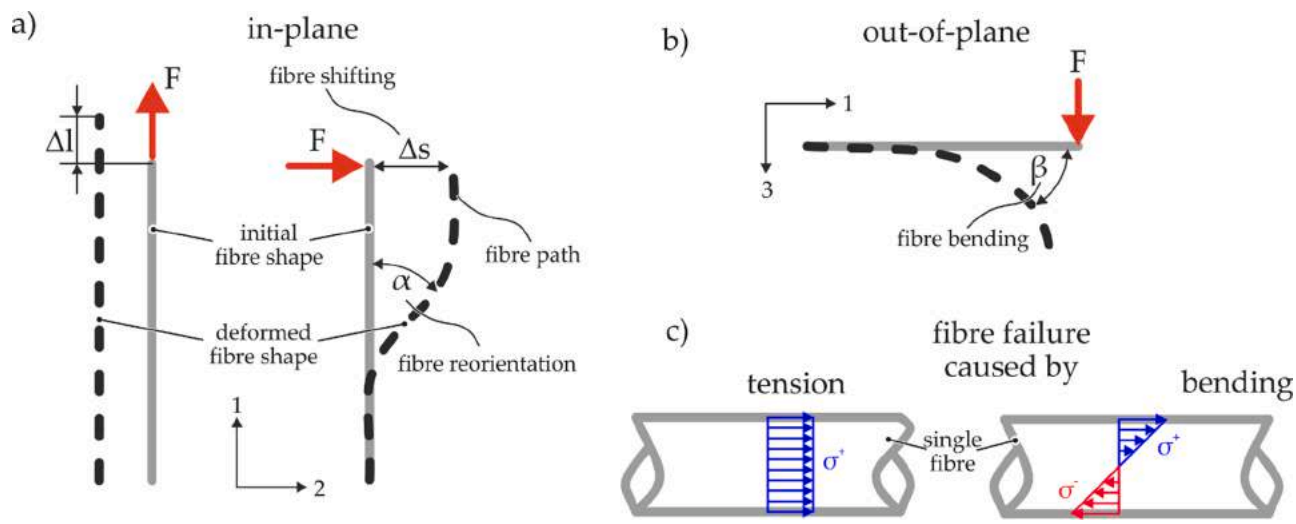

Fig 23. Fibre deformation and failure modes in forming processes.

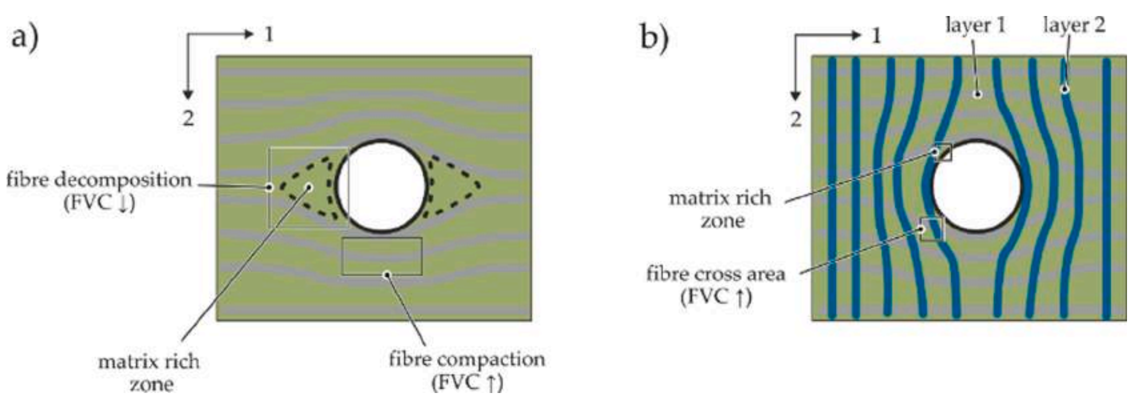

Fig 24. Schematic of the resultant in-plane material structure for a) unidirectional and b) multi-layered FRP.

(Long, 2007) in the heated joining zone. The out-of-plane fibre rearrangement is characterised by fibre bending. The bending direction is caused by the tool movement and illustrated in Fig. 25 and leads to fibre compaction at the top of the tool or the obstacle and the matrix rich zones in the feed area.

This phenomenon can be seen both in the bladder-assisted moulding process proposed by (Barfuss et al., 2018) and in further investigations by (Würfel et al., 2020). The phenomena occurring in the joining process can superimposed by in-plane and out-of-plane effects. In the direct pin pressing process (Kraus et al., 2019) and in the further investigation of the process by (Popp et al., 2021), a distinct fibre displacement was reported. In Fig. 25 (Feistauer et al., 2020) a fibre rearrangement in both in-plane- and out-of-plane direction can be seen. Caused by the ultrasonic movement of the pins just to heat up the area of the TPC next to the pin, the fibres can only rearrange against the tool motion.

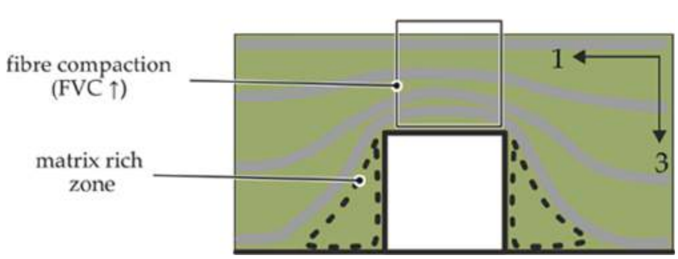

Fig 25. Resultant out-of-plane material structure for a unidirectional reinforced FRP.

A detailed description of the 3-dimensional rearrangement is made by (Brown et al., 2015). A thermally-assisted piercing process in thickness direction of a pre-impregnated unidirectional tape of TPC with local heating area around the pin is analysed (Fig. 26). The micro-scale material structure shows thinning and thicking of the orthogonal layers

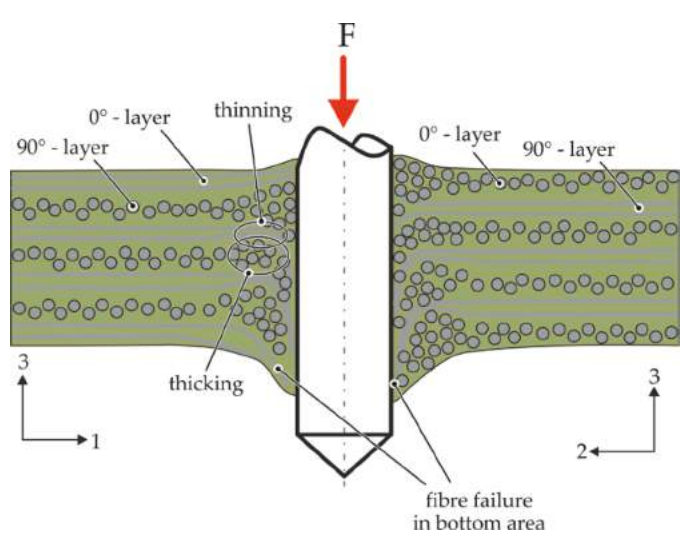

Fig 26. Illustrated resultant material structure of pinning process after Brown2015 (Brown et al., 2015).

around the pin caused by bending and reorientation processes. In the thermoactivated pinning by (Hufenbach et al., 2012) the phenomena occur for a fabric reinforced composites. Both observed during the piercing process, the softened matrix is extruded in pin direction especially at the entry and the exit of the pinning zone. This leads to an increasing laminate thickness and a fibre distortion around the pin. Additionally, the heating zone is localized just around the pin so that the fibre movement is restricted to the softened matrix area. Due to the fibre displacement in pin direction, the fibre strain increases and especially in the exit zone FF occurs (Hufenbach et al., 2012). Furthermore, by varying the heating zone and the process temperature it has be shown that increasing the heating area and process temperature the fibre movement increases. This tends to more voids and resin rich zones (Brown et al., 2015).

A further mechanical joining technology of clinching is carried out with sheets of metal and FRP. An overview of the wide range of clinching technologies for joining metal and continuous FRP is given in (Gröger et al., 2021). The fibre rearrangement depends on used matrix system (thermoplastic or thermosetting) and the given thermal assistance for increasing the ductility of the matrix. The thermal assistance could be given in a defined manner (Vorderbrüggen et al., 2019) and (Gude et al., 2015) or friction induced by tool rotation (Lambiase and Paoletti, 2018) and (Seidlitz et al., 2014). Caused by the heated matrix, for a thermoplastic matrix fibre bending in insertion direction of the punch is observed in the punch feed area (Gröger et al., 2021).

Also in the process of thermoclinching by (Gude et al., 2015) and (Gude et al., 2019) with an initial fibre cut before or during the process, the fibres are bent through the pre-hole of the metal sheet by a pin. In contrast, (Lin et al., 2018) identifies delamination in this punch feed area of the joining zone. Both, (Gröger et al., 2021) and (Lin et al., 2018) observed a material structure in the bottom and ring channel area which is driven by compression, flow pressing and excessive bending. This lead to cracks, debonding and fibre fractures.

Clinching of TPC without thermal assistance is characterised by FF and delamination as shown in (Vorderbrüggen et al., 2019). Also for thermoset matrix without pre-holes (Lambiase and Ko, 2017) and with pre-holes (Lambiase and Paoletti, 2018) delamination occur. Induced by the radial material flow of the metal join partner a buckling in the composite occurs in (Lambiase and Paoletti, 2018), which leads to delamination and FF while bending. Another phenomenon is the imprint of the used CF in metal bulge.

An advanced joining technology is the embedding of inserts investigated by (Troschitz et al., 2019). These inserts can be used for welding (Troschitz et al., 2020) or clinching (Gröger et al., 2021). In (Troschitz et al., 2019) a detailed CT-analysis of a global heated GF/PP multi-layer composite is presented. The analysis of the resultant shows an inhomogeneous complex material structure. The fibres are reoriented and shifted in-plane and bent in out-of-plane pin motion direction. Due to the down warded pin movement and the counter wise motion of the counterpunch to push the bended fibres in the undercut, which leads to a diffuse fibre orientation around the insert. Caused by the global heating an increase of the laminate thickness, FF or IFF are not observed. It can be assumed that no clamping effects occur due to global heating.

A joining process with an auxiliary element is the self-riveting process. The very common joining technology (Li et al., 2017) with further developments in simulation and process design was investigated by different authors (c.f. (Hirsch et al., 2017) (Leconte et al., 2020)). The piercing process at room temperature is characterised by bending in out of plane direction. Caused by the solid behaviour both fibres and matrix and due to the bending and the contact pressure of the rivet FF, IFF or matrix cracks occur in the joining zone.

In conclusion, fibre rearrangements take place in all joining processes or necessary preliminary steps and at all scales in the composites. The joining direction is along the thickness direction of the composite. FF and IFF can occur when the flexibility is not sufficient due to a limited heating area, less process temperature or exceeding the maxima fibre strain.

All joining technologies are characterized by fibre deformation in tool motion direction and an in-plane fibre shifting and reorientation (cf. Fig. 23). The main challenge is the prediction of the internal material structure during the joining process. At this time, all authors use micrographs or CT-analyses at increasing joining force levels to determine the phenomena. However, all methods have a lack of information regarding 3D material structure (micrograph) or the correct local FVC in the joining zone. CT-analysis is also dealing with artefacts and the limitation of resolution depending on the specimen dimensions.

Challenges with high strength materials

In view of the increasing importance of lightweight design and multi-material design, the combination of high strength materials and lightweight materials is essential. In this way, it is possible to reduce the vehicle weight and thus pollutant emissions with regard to environmental protection, while the growing requirements related to the passenger safety can be met at the same time. In contrast to thermal joining techniques, whose application in this case is limited due to the different melting points of the dissimilar materials like aluminium alloys and steels, mechanical joining technologies such as self-piercing riveting offer the possibility of realising such multi-material joints (Abe et al., 2006). However, there are still major challenges when joining high strength steels. The resulting difference regarding the strength of aluminium alloys and high strength steels has a great impact on the joinability of the materials (Mori, 2014). Therefore, the material mix becomes more difficult. In this context, the punch-sided or die-sided arrangement of the high strength steel also plays a major role. The use of steel on the die side in particular is challenging, as a sufficient ductility of the die-sided material is a necessary prerequisite. Additionally, the strength of the sheet material has an impact on the flaring behaviour of the self-piercing rivet in the die-sided sheet. As a consequence, high demands are imposed as regards the rivet materials used for joining high strength steel. The rivets must exhibit an adequate strength but must provide a sufficient ductility at the same time to enable the rivet flaring. Another challenge arises when different material combinations with high strength steel are to be joined, whereby the punch-sided or die-sided arrangement of the sheets are varied. Uhe et al. (Uhe et al., 2020) demonstrated that for the joining of the aluminium alloy EN AW-5083 on the punch side and the high strength steel HCT780X on the die side on the one hand and HCT780X on both sides on the other hand different conventional types of rivets are required and that there is a risk of cracks occurring in the transition area between the rivet shank and the rivet head.

As a result of the challenging aspects previously described, several typical defects can occur when joining high strength steels using self-piercing riveting. The buckling and the fracture of the rivet shank represent major problems (van Hall et al., 2014). In case of using high strength steel on the punch side, the excessive compression of the rivet shank is problematic and can lead to the fact that the punch-sided material is not even pierced (Mori et al., 2006). The sheet thickness of the punch-sided high strength steel also has an influence on the joinability in this context. With rising sheet thickness, the risk of the compression, the bending and finally the fracture of the rivet shank rises (Mori et al., 2006). As concerns the use of steel on the die side, the fracture of the lower high strength steel sheet and the separation of the sheets during joining are common defects (Mori et al., 2006). Furthermore, the flaring of the rivet is considerably more difficult (Martinsen et al., 2015). This in turn can result in an insufficient formation of the interlock that is a relevant characteristic joint parameter and that in the end has an influence on the joint quality and the achieved joint strength. In (Abe et al., 2009) it is shown that a reduction of the interlock, which is important for the joint formation, is related to an increasing strength of the die-sided high strength steel sheet.

The joinability of material combinations including high strength steel is limited by the occurrence of the described typical defects. However, the joinability can be influenced by different factors. In general, several influencing factors can be identified, which have an impact on the joinability especially of material combinations with high strength steel. Besides factors like the mechanical properties of the sheet materials that are to be joined and the sheet thickness, the main aspects concern the die that is used during the joining process and the geometry as well as the mechanical properties of the rivets that are utilised. There exists a large number of different dies for joining. The choice of a suitable die depends largely on the sheet materials to be joined. The shape of the die, a flat die or a die with a mandrel for instance, influences the flaring of the rivet during the joining process and thus the formation of the interlock. Therefore, the choice of the die generally has a great impact on the joint quality and the achievable joint strength (Li, D. Z. et al., 2012).

The rivet geometry is another key factor regarding the joinability. It is especially decisive in case of joining high strength steels, as the piercing process and the subsequent rivet flaring can be influenced by choosing an appropriate rivet geometry in order to achieve a joint formation with assured quality (Philipskötter and Hahn, 2006). In particular, the geometry of the rivet foot has an impact on the piercing of the punch-sided material as it is shown in (Li et al., 2013). Additionally, the angle of the foot chamfer is relevant because the piercing process may be impeded if the angle is too small, while an insufficient rivet flaring may be caused by an angle that is too large. Another geometric parameter that is of importance is the rivet length. Even though the choice of the rivet length is primarily dependant on the sheet thickness of the sheets to be joined, even small differences regarding the rivet length can affect the achievable joint. This is particularly the case when high strength steel is used on the die side. If the rivet length is too low, the rivet flaring is more difficult, while the use of a too long rivet can lead to the fracture of the die-sided sheet (Abe et al., 2009). However, Sun (Sun, 2014) showed that the joint formation can be considerably improved and the joint strength can be increased when joining a 5000 series aluminium alloy and steel with a tensile strength of about 600 MPa by increasing the length of the utilised rivets from 6.0 mm to 6.5 mm. Nevertheless, an increase in rivet length may not only result in an improved rivet flaring and interlock formation but may also be associated with a reduction of the minimum die-sided material thickness (Kappe et al., 2021). This is a relevant characteristic joint parameter that has to be taken into account and must meet the required quality standards, too. Moreover, the risk of buckling and fracture of the rivet shank is higher when using a rivet with a longer rivet shank, which is why the rivet length should be chosen carefully.

Besides the rivet geometry, the mechanical properties of the rivets are of special importance. The strain hardening behaviour of the material of which the rivets are manufactured, for instance, influences the joining process and characteristic joint parameters such as the minimum die-sided material thickness (Mucha, 2011). In (van Hall et al., 2014) investigations on the variation of the rivet hardness and its effects on the joining of the high strength steel USIBOR® 1500 and a heat treated 6000 series aluminium are presented. While the use of rivets providing a hardness below 550 HV led to the buckling of the rivet shank, rivets with hardness values of more than 550 HV exhibited fractures (van Hall et al., 2014). These findings emphasise the high requirements that apply for rivets and rivet materials, which are to be used for the joining of high strength steels. An increase in strength is needed in this case to prevent the buckling of the rivet shank but the decrease in ductility that is generally associated with it has a negative effect and can be the reason for the occurrence of fractures. As a consequence, the choice of an appropriate rivet material is challenging when high strength steels are to be joined.

Against this background, there are some approaches that aim to improve the joint formation and joint quality when joining high strength steels and that also provide an important basis for the further expansion of the process limits in the future. These approaches can be divided into approaches that are related to the joining process and approaches that are related to the rivets that are used for joining. Regarding the process-related approaches, the adaption of the die that is used for joining has been the subject of various studies in the past years. Mori et al. (Mori et al., 2006) modified the shape of the die and successfully used it to join high strength steel with a tensile strength of 980 MPa by self-piercing riveting. This approach was furthermore applied to the joining of three sheets including high strength steel and an aluminium alloy (Abe et al., 2008) but there also were limitations regarding the punch-sided or die-sided arrangement of the high strength steel sheet (Mori et al., 2014). A new die concept that includes a movable die element is presented in (Drossel and Jäckel, 2014). Due to the combination of an outer die ring and an inner movable die element, the stress state during the self-piercing riveting process is changed and the joining of materials with limited ductility is facilitated (Drossel and Jäckel, 2014). A new joining concept for self-piercing riveting with solid rivets is self-locking self-pierce riveting, which is presented in (Sartisson and Meschut, 2017). By modifying the solid rivets with an embossing contour that makes the embossing ring on the die unnecessary, the joining of the ultra high strength steel 22MnB5 with aluminium alloys is realised (Sartisson and Meschut, 2017). An approach for extending the process limits for self-piercing riveting with semitubular self-piercing rivets is the local heat treatment of the sheet, which also allows the joining of 22MnB5 even on the die side, as the ductility of the material is increased in the area of the sheet, where the joint is positioned (Meschut et al., 2014). In (Lou et al., 2013) it is shown that the joint formation during joining of high strength steel with a tensile strength of up to 800 MPa and a 6000 series aluminium alloy can be improved by applying a direct current during the riveting process. Another method to improve the joint quality is to integrate an electromagnetic system during the self-piercing riveting process, which enables the joining at high speed (Jiang et al., 2019). As a consequence, an increased interlock can be achieved when joining carbon fibre reinforced plastic (Liang et al., 2019).

In addition to the approaches which concentrate on the adaption of the riveting process, there exist further concepts related to the rivets that are utilised for the joining operation, in detail the rivet geometry, the rivet material and the mechanical properties of the rivets. Modified self-piercing rivets can be used in order to improve the joint formation and to overcome existing process limits. The Böllhoff RIVSET® HDX rivet provides not only an adapted rivet foot but also an elevated hardness, which is why it can be used to join punch-sided press-hardened steel (Böllhoff, 2021). Kraus et al. (Kraus et al., 2020) presented a novel self-flaring rivet geometry that includes a rivet shank consisting of several mandrels and that is thus designed to facilitate the rivet flaring when joining aluminium alloys and high strength steels.

A new approach regarding the rivet material is the use of high strain hardening steels such as high nitrogen steels (Kuball et al., 2020). This provides the opportunity to eliminate the heat treatment and coating as conventional post process steps during the rivet manufacture, as the new rivets provide an adequate strength and corrosion resistance without these process steps. As a consequence, the graded mechanical properties after the forming of the rivets remain intact, which offers the possibility to produce tailored rivets according to the specific requirements during joining. As the tool loads during the rivet forming are challenging high due to the high strain hardening of the material, however, appropriate forming strategies are needed like the forming at elevated temperatures (Kuball et al., 2020). A suitable process and tool concept that is also essential is presented in (Kuball et al., 2020). By using the new rivets, joints meeting the quality standards are realisable for different material combinations consisting of the high strength steel HCT780X and the aluminium alloy EN AW-5083 (Uhe et al., 2021a). Furthermore, in (Uhe et al., 2021b) it is shown that an adequate joint strength is achieved when using the new rivets made of high nitrogen steel. Therefore, the new approach not only leads to the fact that the energy-intensive and time-consuming process chain during the rivet manufacture can be shortened but also that even challenging material combinations with high strength steel can be joined. In the future, this will also offer the chance to manufacture a variety of different rivets with tailored, graded properties as against conventional rivets exhibiting homogeneous properties after the heat treatment.

Applicability of process simulation

Process designs and the related process parameters for mechanical joining identified in a pure experimental way have only a limited validity which is contradicting the aim of versatile process chains (Meschut and Menne, 2018). Therefore, the simulation of manufacturing processes is usually used and established in research as well as in industry in order to avoid a huge number of cost-intensive real experiments (Bonte et al., 2008). The aim of such simulations or virtual experiments can be for instance a first feasibility study regarding manufacturability (Tekkaya and Martins, 2009). A much more sophisticated simulation result quality would be the fatigue behaviour of a joint under real loading condition including the product properties, which result from the joining process itself. Depending on the requested result, the effort in modelling of the joining process differs significantly. Due to that, the examples and application of numerical approaches shows a great variety which will be described in the following section.

Simulation types and achievable results

Simulation of the process is commonly performed using a Finite-Element-Analysis (FEA) which utilizes the finite-element-method (FEM) (Bathe, 2002). One reason for that is the broad applicability of the FEM itself and the availability of commercial codes. Another aspect is the achievable accuracy of the desired results, especially when different materials are used, which behaves anisotropic during deformation or during usage, complex three dimensional stress states are present, or a multi-scale modelling of the complex damage behaviour is required (Gude et al., 2015). A good overview about using FEA for mechanical joining is given by Eshtayeh and Hrairi in (Eshtayeh and Hrairi, 2016). They described about the strong influence of material properties as well as friction modelling on the resultant geometry of the joint. Additionally, damage behaviour was pointed out as an interesting issue for future research. Especially for self-piercing riveting this effect must be included in order to model the process steps as well as the joint strength appropriately. However, one big disadvantage of this type of numerical simulation is the long computation time, which increases with the quality requirements (Lafarge et al., 2021). To drop down the computation time, improvement of the numerical procedure is not sufficient and analytical simulations as a traditional approach come more into picture nowadays because of the applicability in closed-control loops (Lafarge et al., 2021). Israel describes in an initial research work the use of analytical models to describe a low demanding result like the force-displacement curve in thick sheet clinching (Israel, 2014). The subsequent calculation of joining forces in radial clinching (Breckweg, 2007) confirms the fundamental suitability of the analytical model for clinching technology in general. Despite the fact that the achievable quality is usually significantly reduced compared to the one resulting from FEM, single results like the force vs. process time can be determined with sufficient accuracy. The success and accuracy of such approaches varies greatly with the assumptions made. Therefore, these approaches are specific developments and solutions and are not widely spread.

Beside the limitation of the accuracy, large deformation in the joining process, present in Friction Stir Welding (FSW), can lead to problems and errors in the simulation using conventional FEA (Behrens et al., 2016). For this purpose, mesh free methods like smoothed particle hydrodynamics (SPH) or element-free Galerkin method (EFGM) are developed in the past and are successfully applied in production technology. All these strategies can be used for feasibility studies, sensitivity studies, process parameter identification, and the determination of product properties as described in the following for some of the most used mechanical joining processes.

Simulation of clinching

One early published numerical investigation of clinching using the FEA was done in 1994 by Klasfauseweh (Klasfauseweh, 1994). Due to the numerical issues like mesh-coarseness and limited computational capacity, the investigations were mainly used to show general effects and tendencies. With the ongoing developments in hardware, mesh refinement techniques and material description, the results can be improved in short period. In 2006 Gårdstam showed the possibilities of FEM for joining in automotive industry (Johannes Gårdstam, 2006) but with limitations in describing the fracture phenomenon as well as the drawback with availability of reliable material data at very high equivalent strain levels.

Also at this time, most simulations were done for axisymmetric arrangements which neglects the anisotropic behaviour (Hamel et al., 2000). He summarised the development in numerical modelling of the clinching process in 2010 (He, 2010) and Gerstmann and Awiszus discussed the numerical possibilities for a hybrid process, which shows large similarities to clinching: the flat-clinch-bonding (Gerstmann and Awiszus, 2020). Typical results of these investigation were material displacement, strains and stresses as well as material failure by crack initiation. Drossel et al. analysed in 2014 the clinching process by FEA regarding typical geometrical features like interlock and bottom thickness, which are not measureable without destruction of the probe. Additionally, they made successful sensitivity studies of the tool geometry features (Drossel et al., 2014). Chenot et al. showed and discussed the possibility of optimising the clinching process via FEA in (Chenot et al., 2011) regarding force-displacement curve and geometrical shape. They got a good similarity between the numerical and experimental data depending on the chosen parameters. Another topic in modelling of joining is damage as a material effect to describe the process failure. Tekkaya et al. showed different theories and approaches and discuss the results amongst other thing for the clinching process (Tekkaya et al., 2020). One major drawback of this theory is the difficult identification of damage parameters, similar to the determination of material parameters in general. This makes applicability of the already available FE-code implementations limited to universities and research institutes, resulting in a more retrospective identification of fundamental effect than using it in the design phase for virtual identification of process parameters, joint geometry, and joint strength in advance of production process.

Simulation of self-piercing riveting

Due to the cutting portion simultaneously to the plastic deformation process during joining of two sheets with an additional rivet, the above mentioned effect of damage is essential for the reliable simulation of Self-Piecing Riveting (SPR) and the corresponding results like force-displacement-curve or the strength of the joint as the relevant property (Fayolle et al., 2014). Li et al. gave a comprehensive review about the self-piercing riveting in general and in detail about the aspects of numerical simulation by means of FEM (Li et al., 2017). They describe the necessity of 3D-models for modelling testing procedures as well as the requirement for large strains in material characterisation tests. Furthermore, the sensitivity of the friction law – either with physical and unphysical values for Coulombs friction law – and the dependency of the results on the mesh refinement and remeshing strategy were shown. The modelling of material separation in the cutting part of the process via remeshing or element deletion is shown as a typical strategy which can cause errors at higher strain levels (Bouchard et al., 2008). Additional to this, the friction law can lead to wrong results as shown (Li et al., 2017). Especially for SPR, where the contact pressure reached high values, Hönsch et al. (Hönsch et al., 2018) use successfully a combined Coulomb Shear-factor-law, which brings together the physical levels of friction forces at small and large contact pressures. Because sliding at high pressure contact is limited by the shear stress of the material, several authors interpret this by Trescas law of yielding. Gerstman et al. (Gerstmann and Awiszus, 2020) also uses this approach, but for another mechanical joining process – flat clinch bonding – which underlines the physical meaning of modelling type due to its process transferability. The problems in the numerical simulation of self-pierce riveting also apply to other processes such as self-pierce riveting of sheets to tubes and double-sided self-pierce riveting, which are also based in working principles built upon plasticity, friction, and ductile fracture.

Friction stir welding

An extreme level of strain, strain rate, and temperature is exceeded in friction stir welding (FSR). Strains up to 5, strain rates up to 9 s^{-1} (Arora et al., 2009), and temperatures at 80% of the melting temperature for aluminium are achievable (Assidi et al., 2010). For such conditions a model is required, that covers the mechanical as well as the thermal aspect in a coupled thermomechanical FE-Model (Hamilton et al., 2010). For modelling the large strains, which causes extensive mesh distortion and would yield in large simulation time due to few remeshing steps in the simulation run, two modelling strategies are meaningful: a) Arbitrary Lagrangian Eulerian (ALE) simulation or b) meshless approaches like mentioned above in chapter 3.5.1. Both strategies are widely used and provide reliable results after the calibration of the model, see (Assidi et al., 2010) for Eulerian and ALE approaches. The advantages regarding the simulation quality of a typical FEA is ensured, but switching between the Eulerian and Lagrangian consideration of the meshed region requires a big portion of simulation time and makes the solution quite cost intensive. The second mentioned variant with meshless approaches is directly suitable for large strains, but the stable explicit meshless approaches are again time intensive. Therefore, coupled models with the FEM are becoming popular, nowadays. Xiao and Wu presents in (Xiao and Wu, 2020) such a strategy and presented another approach for direct coupling of the meshed and the particle region. They presented very good results regarding the temperature distribution and discussed the occurring numerical errors.

Conclusion process simulation

As written in many papers, the numerical simulation is a powerful tool for process design and development in research and industry. Besides the above mentioned possibilities, some work has to be done to bring the simulation strategy more into application. First of all, robustness of simulation tools has to be ensured (Tekkaya et al., 2009) despite the fact, that a high stabilization leads to foolproofness, which can result in problems like miss-interpretation of questionable numerical results. Nevertheless, a stable simulation tools by a meaningful pre-choice or self-adapting of numerical parameters is the key factor for acceptance in application. Secondly, testing strategies for getting material data easily has to be provided. This includes reliable data for deformation, damage, and friction. Especially the high strain levels and the changing conditions at frictional surfaces like normal pressure, sliding speed, and surface roughness are challenging in modelling and testing. Nevertheless, simulation quality and hardware performance is continuously increasing and both are the prerequisites for a new type of simulation, which comes more into favour – sensitivity study for evaluation of process robustness. As long as the physical effects are modelled well and the simulation results are similarly sensitive to the parameters like the experiment, the quantitative values of the simulations are of minor interest. Only the tendency of the observed result, e.g. neck thickness in clinching, is important to get the information about parameter sensitivity and process robustness in general. But this leads to the requirement of physic-based models instead of data-driven modelling approaches.

Non-destructive testing

Optical inspection

For process and quality analysis of mechanical joints, a broad variety of destructive and non-destructive testing (NDT) methods is applied. The initial evaluation of mechanical joints is usually conducted via visual inspection (Varis and Lepistö, 2003) and direct measurement of geometrical characteristics such as the bottom thickness at clinch points (DVS®/EFB, Februar 2012). This is often accompanied by the comparison of the force-displacement curve during manufacture with a reference curve in order to detect quality deviations (Haque et al., 2012). Above that, several optical NDT methods are applied for process and quality analysis. In case of self-piercing riveting, digital image processing can be used to determine whether the rivet is seated correctly in the joining machine or identify defect joints (Johnson et al., 2007). Digital image correlation measures strain fields at the joint, which can be correlated with the damaging behaviour, e.g. in-situ shear-lap tests in self-piercing riveted joints (Gay et al., 2017) and in bolted joints (Haris et al., 2017). Shearography - as an optic interferometry based method – can also be used to detect defects in bolted joints (Hung et al., 2000).

Thermography

To monitor process temperature during joining, passive thermography is established (Amancio, 2007). Active thermography, on the other hand, is a feasible method for detecting defects and imperfections in joining zones (Leicht et al., 2018). Here, common excitation methods are optical waves or pulses induced by a laser or lamp as well as ultrasonic and eddy current excitation (Menner et al., 2010). Numerous studies on quality inspection by means of thermography are published, in particular for clinched and riveted joints with different material combinations (cf. Table 1). Most investigations address the detection of cracks and imperfections or loose rivets. In addition, thermography is also used during destructive testing of joints, for instance in case of investigating the fatigue limit of riveted joints (Li et al., 2012).

Radiographic testing

For detailed geometry and structure analyses, computed tomography (CT) is established. Here, a three-dimensional image of an object is reconstructed with X-ray projections taken from several angels (Carmignato et al., 2018). Both homogeneous materials e.g. casted aluminium (Al) (Nicoletto et al., 2012) and heterogeneous materials e.g. fibre reinforced plastics (FRP) (Böhm et al., 2015) are investigated with CT. In the field of joining, CT is used to investigate geometrical quality characteristics such as the neck thickness of clinched joints (Raguvarun et al., 2014). Furthermore, CT provides the opportunity to detect defects and investigate the material structure inside the joining zone, as shown for drilled holes (Pejryd et al., 2014) and moulded holes (Hufenbach et al., 2012) as well as embedded inserts (Troschitz et al., 2019) and of semi-tubular self-piercing rivets (Meschut et al., 2014) in FRP. Furthermore, damage phenomena can be analysed in-situ CT. Investigations have been carried out, for instance, for adhesively bonded riveted single lap joints of FRP-Al (Füßel et al., 2016), pinned glass FRP (Hufenbach et al., 2012) and clinched Al-Al joints (Köhler et al., 2021b).

Table 1
Investigations on quality inspection by means of thermography for mechanical joints.

Excitation method	Type of joint	Material combination / Literature
Optical	Riveted	Al/Al (Zweschper et al., 2001), Al/Al (Zweschper et al., 1998), Al/CFRP (Riegert et al., 2002), Al/GF-PA (Gay et al., 2017)
	Clinched	Different material combinations (Srajbr et al., 2011)
Ultrasound	Riveted	Al/Al (Zweschper et al., 2001), Al/Al (Stamm et al., 2021), Al (Dillenz et al., 2000), St/St (Swiderski and Hlost, 2014), Al/CFRP (Riegert et al., 2002), CFRP (Dillenz et al., 2000), Metal/Metal (not specified) (Dillenz et al., 2000)
	Clinched	Different material combinations (Srajbr et al., 2011)
Eddy current	Riveted	St/St (Swiderski and Hlost, 2014)
	Clinched	Different material combinations (Srajbr et al., 2011)

In Fig. 27 the direction of force is marked with red arrows.

Vibration based methods

Thermography, radiographic testing, and their counterparts, such as vibration-based (global techniques) and wave propagation-based (local techniques), provide a basis for a similar revolution in NDT. The global technique uses long wavelength and the changes in the vibration characteristics of a system to identify damage phenomena (Scott William Doebling et al., 1998). He et al. performed experimental modal analysis to investigate the frequency response of cantilevered clinched beams. The results show that the higher the number of clinch points, the higher the natural frequencies (He et al., 2013). In a subsequent study they could obtain similar results deploying experimental forced vibration analysis (He et al., 2014). Dong et al. investigate the harmonic response of self-piercing rivet (DONG et al., 2010). With the help of a shaker and vibration transfer function, Park et al. predicted the spot weld's stiffness (Park et al., 2019).

The main disadvantage of the global technique is its insensitivity to minor flaws. On the contrary, the local technique benefits from a short wavelength to enable high sensitivity in damage detection (Bhalla et al., 2005). A model of the entire measurement system is often used to evaluate the results of the experiment (Schmerr, 1998). Eckhardt et al. proposed a method and a toolset to measure the bottom thickness of the clinch point during the process using ultrasonic pulse-echo (Schneider et al.). Köhler et al. utilized computed tomography and local technique to characterize clinch points with different bottom thicknesses (Köhler et al., 2021). Le et al. combined a magnetic camera with an ultrasonic probe to automate the self-piercing rivet joint's inspection. They detected the corrosion cracks using A-scan and B-scan ultrasonic (Le et al., 2016).

Other NDT methods

Other methods for non-destructive testing rely on electrical current. In the eddy current testing method, an electrically conductive object is subjected to an alternating magnetic field. Defects alter the eddy current paths (van Drunen and Cecco, 1984), allowing e.g. to identify the location and size of damage around a bolt in fatigue testing (Sun et al., 2021). Especially, mid-bore and corner cracks can be detected (Underhill and Krause, 2011). Furthermore, it is used to detect simulated failures such as corrosion or grinded notches in the proximity of holes in aluminium rivet joints using aluminium sheets (Janovec et al., 2019).

Beside this clinch joints can be evaluated by measurement of electrical resistance (Jiang et al., 2015) using the 4-wire method (cf. Fig. 28). Here, the connection resistance and the performance factor (ku - factor) are essential quality criteria to evaluate the binding mechanisms of force-closure and material-closure (Füssel, Großmann et al., 2014) and consequently, the clinch point's quality. This method is also suitable for quality determination on self-pierce riveted and blind

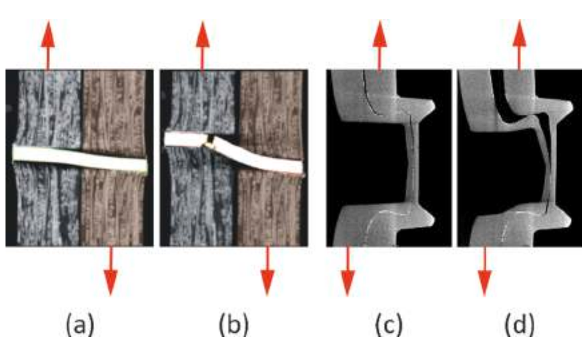

Fig 27. In-situ CT of deformation (a) and failure (b) (Hufenbach et al., 2012) of a pinned FRP lap shear specimen and in-situ CT of the initial deformation (c) and deformation prior to unbuttoning (d) in a clinch point (Al-Al-specimen) (Köhler et al., 2021b).

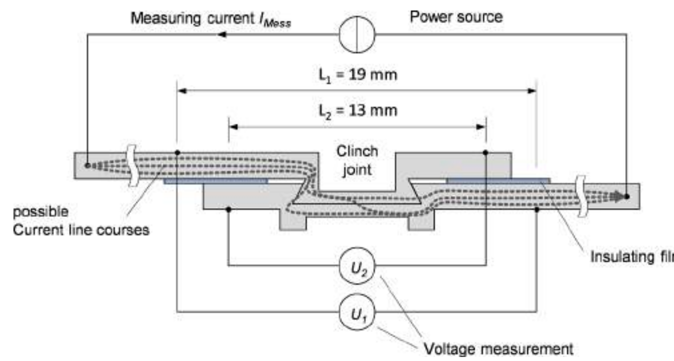

Fig 28. Measuring principle for determining the connection resistance (four-wire method) according to (Füssel, Großmann et al., 2014).

riveted joints (Schlegel et al., 2019).

NDT methods have long been used in industry for monitoring process and product quality. One of the main applications in the field of mechanical joining is the detection of defects and imperfections in joining zones. Furthermore, a detailed understanding of process and failure phenomena is increasingly in focus to improve and validate process and structural simulations.

For the application of a measuring method, the location and size of the considered defects and the phenomena as well as the size of the examined structure are decisive. Established NDT methods usually allow either the inspection of a large volume at low resolution (e.g., thermography) or very high resolution for a comparatively small measured volume (e.g., CT). In addition, the measurement methods differ in the required measuring time. Methods with short measuring times are predestined for inline application in the production process (e.g. vibration based methods). In contrast, local high-resolution methods, such as CT, require long measuring times and are therefore mostly used offline for the analysis of individual joining zones. The combination of local high-resolution with temporal high-resolution methods represents a great potential for efficient detailed analysis of joining zones in the future. In addition, the challenge of increasing flexibility and versatility of joining processes for multi-material systems can only be met by further adaption and optimization of the NDT methods.

Disassembly and recyclability

This increasing complexity of the designs and the associated joining techniques are leading to impurities and material losses due to joints in recycling processes like shredder based processes (Soo et al., 2018). For a sustainable use of hybrid structures, it is necessary to be able to separate hybrid compounds in a targeted manner (Lu et al., 2014). An overview of separation processes in car body construction, which are also used for mechanically joined joints, is presented in (Hahn et al., 2006), where a distinction is made between cutting processes, such as drilling and milling, dividing processes, such as chiselling, or thermal processes, such as flame cutting.

Conclusion and future challenges

The presented review shows the diversity of different mechanical joining processes and their different applications as well as limits in terms of joinability. This results in a high degree of complexity, which must be manageable for the user. It becomes more challenging when there are parameter fluctuations in the mechanical joining process chain. In this case, most of the processes reach their limits and can only be adapted to the new joining processes with great effort. Based on the experimental and numerical simulation investigations, long-lasting processes are better understood than younger processes or modifications of processes. Nevertheless, most of the processes are comparatively well understood. However, there are still major challenges with regard to the choice of desired methods and models for the description of work hardening at high strain levels, tribology and failure behaviour and mechanisms of the materials. Moreover, there are issues in dealing with 3D numerical simulations concerning the high degrees of deformation, damage or even mesh-free methods. In this regard, no methodology or process design has been established to ensure the joinability of the materials. In fact, the current methods are based on trial and error and subsequent numerical validations.

Nevertheless, the proposed approaches are to be based on simple calculation methods to ensure easy applicability. Generally, the main limit of pre-hole-free joining processes is the joining of high-strength materials such as high-strength steels and aluminium alloys. This applies in particular to the mechanical joining of hybrid material-thickness combinations with large differences in the strength of the joining parts. In addition, new processes are required for the mechanical joining of fibre-reinforced plastics in combination with metals without pre-hole and critical damage response. This means that the suitability of some joining processes for joining of ultra-high-strength materials needs to be examined. In order to guarantee the characteristics of the joints and components, there is an additional need for non-destructive testing methods for the monitoring of these processes and especially for quality inspection of safety-relevant mechanical connections.

However, the challenge for all mechanical joining processes is the limited adaptability, which has not been taken into account so far but will be required gradually in the future. Therefore, there is a need to adjust the existing mechanical joining processes and to improve the prediction capabilities in such a way that the safety in the design process is no longer increased even if the process chains change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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