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Mechanical joining of high-strength multi-material systems – trends and innovations☆

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Abstract. In conjunction with mechanical joining processes. Mechanical joining processes play a key role for the realization of multi-material lightweight structures, which are essential with regard to environmental protection. However, joining of dissimilar high-strength materials is challenging due to the varying properties of the joining partners and due to their high flow stresses and often limited ductility. Thus, the evolution of established processes as well as the development of innovative and highly productive joining technologies are necessary. Requirements for a highly volatile production environment are versatility, flexibility, resilience and robustness. Within this contribution, current trends and innovations related to selected mechanical joining processes for enabling the material mix are outlined in order to point out opportunities to address these requirements in the future. In this context, joining using cold formed pin structures is presented as a promising approach for connecting dissimilar materials like metals to fibre-reinforced plastics. Furthermore, it is shown how the shear-clinching technology can be combined with a process-adapted application of locally limited heat treatment in order to promote the joinability and control the material flow during joining. A novel approach for reducing process forces and expanding process windows is the use of ultrasonic assistance for mechanical joining operations, which is demonstrated by the example of a nut staking process with superimposed high frequency oscillation. As concerns the widely used self-piercing riveting technique, current research activities relate not only to the further development of the joining process itself, for example by combining self-piercing riveting and tumbling, but also to the use of new rivet materials like high strain hardening stainless steels. In addition, the evolution towards mechanical joining 4.0 against the background of data-based process control in conjunction with of mechanical joining processes is also subject of the considerations.

Keywords: joining / forming / high-strength materials / multi-material design / sustainability / versatility

1 Introduction

Nowadays, more than ever, society has a responsibility to pave the way to a sustainable future. The climate change affects all areas of society, from politics to economics and science. The European Union passed the European Climate Law that sets the framework for achieving climate neutrality within the European Union by 2050 including the target of reducing greenhouse-gas emissions by at least 55% by 2030 in comparison to the year 1990 [1]. This also has an impact on the mobility sector. For instance, a regulation has been established that sets CO_2 emission standards for new passenger cars and requires manufacturers to pay an excess emissions premium if their average specific CO_2 emissions exceed the permitted emissions [2]. This leads to increased cost pressure for manufacturers, with the effect being intensified by the increasing demands on the variety of products as well as on the vehicle safety. To meet these challenges, innovative approaches are needed that relate to both products and production processes. An opportunity for this is provided by sustainable lightweight approaches. This is made even clearer by the fact that around 40% of the total vehicle weight can be attributed to the car body [3]. A reduction of the vehicle weight leads to a reduced fuel consumption and thus reduced CO_2 emissions [4], which represents an important step towards zero-emission mobility. The weight reduction without reduction of the vehicle safety can be achieved with the aid of multi-material design [5]. For this reason, mechanical joining technologies are of particular importance in this context, as they allow the combination of dissimilar materials, like high-strength steels and aluminum alloys, and their favorable properties, while thermal

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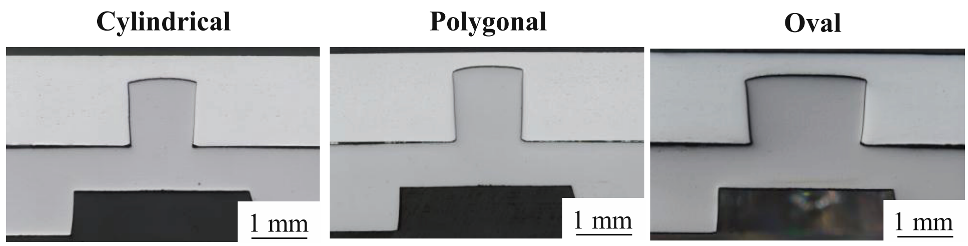


Fig. 1. Micrographs of exemplary pin connections made of DP600 and EN AW-6014 using different pin geometries according to [10].

joining methods have their limits in this case [6]. A multitude of joining technologies have been developed over the past years against the background of increasing requirements.

The current challenges for mechanical joining technologies include the processing of innovative materials with increasing strengths that are constantly being further developed. This aspect is also addressed by Ang in [7] for the mechanical joining technology of self-piercing riveting, where high strengths place correspondingly high demands on the rivets. The joining of dissimilar high-strength metals and fibre-reinforced plastics, for instance, also is challenging in this regard, as it is demonstrated in [8]. This results in new process limits that need to be overcome. Furthermore, lightweight concepts and multi-material systems demand flexible and efficient joining processes. Long and energy-intensive process chains pose a problem with respect to the goal of increased environmental protection and sustainability. The potential for saving resources has not yet been exhausted. Additionally, there is a lack of flexibility in case of disturbance and varying process variables, which is why rigid processes and tool designs reach their limits. This is also identified in [9] as one of the core challenges for joining technologies existing nowadays. Consequently, there is a need for more adaptive processes that are robust against external influences and allow appropriate process control. Against this background, in order to point out key aspects that can be used to address the aforementioned challenges, this paper provides an overview of current trends in mechanical joining of high-strength multi-material systems, whereby the focus is laid on the joining processes that are described hereafter. In the field of joining without auxiliary element, novel approaches are presented in connection with joining using cold formed pin structures and short-term heat treatment assisted shear clinching. Moreover, the potentials of utilizing ultrasonic assistance are expounded for mechanical joining technologies in general and using the example of a nut staking process in particular. Additionally, with regard to joining with auxiliary element, advances in self-piercing riveting are considered. This comprises self-piercing riveting using rivets made of high strain hardening stainless steels instead of conventional rivet materials as well as joining by orbital forming with focus on the combination of self-piercing riveting and tumbling. As joining operations are usually integrated into longer process chains, the determination of arising deviations and influencing factors across the entire process chain plays a major role. For this reason, approaches for data-based process control in the context of mechanical joining processes are also discussed.

2 Latest trends in mechanical joining

2.1 Joining using cold formed pin structures

Pin joining is a joining process that has the potential to join a range of materials, including dissimilar metals and metals to fibre reinforced plastics. The process involves the use of pin structures, which are inserted into the joining partner to be joined. Exemplary pin joints can be seen in Figure 1. A pin is an extension of a joining partner with a height/diameter ratio between around 0.8 and 2 mm, which is inserted into the second joining partner for the transmission of forces by means of a form-fit and, in some cases, a force-fit [9]. In contrast to a rivet, a pin is significantly smaller and a fixed component of a joining partner.

Adhesive bonding is often used to join dissimilar materials such as carbon fibre-reinforced plastics and aluminum, for example for aerospace applications [11]. However, due to the different thermal expansion coefficients of the materials, additional stresses can occur in the joint [11]. Nevertheless, especially in the area of joining fibre-reinforced plastics (FRP) and metals, pins are already being used which are usually attached to the surface of the metallic component. These are inserted into the FRP components and are intended to increase the strength of the joints. In [12], additively manufactured pins made of titanium (Ti-6Al-4V) in a 6×6 matrix were applied to a substrate and joined with carbon fibre-reinforced thermosets and tested mechanically by means of tensile tests. These were then compared with conventional co-bonded compounds, whereby an ultimate strength of up to 6.5 times higher could be achieved. In addition to the powder bed fusion (PBF-LB) process used in [12], the direct energy deposition (DED) process [13] is another additive manufacturing process that can be used to produce pins that are used to produce joints. In this context, the cold metal transfer (CMT) process can also be mentioned, which is a welding process in which the welding filler material is used to attach pins to the component surface. Different pinhead geometries, such as spherical, cylindrical or spike-like geometries can be created [14]. In addition to additive manufacturing processes, moulding processes such as metal injection moulding (MIM) [15], micro-machining [16] or the Surfi-Sculpt process, where a laser or electron beam is used to redistribute material on the surface of the components into different geometries, such as pins or wedge shapes [17], can be used to manufacture pin structures. Apart from the above-mentioned techniques, investigations are also being carried out to produce pins for joining dissimilar materials by cold extrusion from sheet

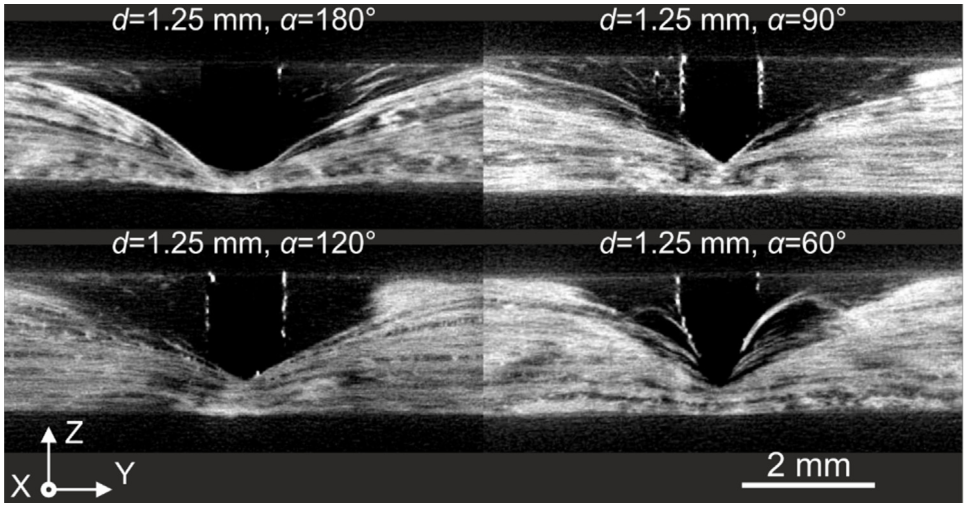


Fig. 2. CT image of the fiber rearrangement of a GF-PP sample after joining with pins with different pin head geometries [21].

metal [18], as this process has advantages over the processes mentioned in terms of speed, mechanical properties and integrability in existing process chains. The feasibility of extrusion of pins from the sheet metal plane was demonstrated by Ghassemali et al. [19] and Hirota [20].

In this context, however, thermoset matrix materials are often used to produce hybrid joints that are reinforced using pins. However, investigations are also being carried out to produce hybrid components from a metallic component with pins and fibre-reinforced components with a thermoplastic matrix. In [21], fibre rearrangement mechanisms were investigated during the direct pin pressing of additively manufactured cylindrical pins with varying pin head geometries made of 316L with glass-fibre reinforced polypropylene (GF-PP) using computed tomography (CT) analyses. The resulting fibre rearrangement can be seen in Figure 2. Before joining the components, the PP matrix was heated locally in the joining zone to melting temperature by infrared heating to enable fibre movability and thus reduce fibre damage.

In [22], based on the investigations in [21], the influence of the pin head geometries and different pin diameters on the joint strength were investigated. It was shown that a flat pin head compared to sharp pin heads has a positive effect on the load-bearing capacity under shear load and that smaller diameters have an advantageous effect on less abrupt component failure. In order to investigate the influence of pin structures with an undercut geometry on the load-bearing capacity of the joint and the filling of the undercut during joining, pins with varying undercuts were joined with GF-PP in [23] by means of direct pin pressing and investigated mechanically and with micrographs. The undercuts could be sufficiently filled with matrix and fibres during joining and had a positive effect on the load-bearing capacity under pull-out load compared to a cylindrical pin without undercut. In addition to varying undercut geometries, the geometry of extruded pins made of DP600 when pressed directly into GF-PP was also investigated in [24] in order to investigate the influences of polygonal, oval and cylindrical pins on the joint formation and the load-bearing capacity of the joint. It was shown that a cylindrical pin is advantageous for an isotropic behaviour of the joint, but a polygonal pin can be advantageous especially under a predominant loading direction. As an alternative joining method to the direct pin pressing of extruded pins with GF-PP, caulking was investigated in [25]. In caulking, the pin is inserted through a pre-punched joining partner and upset from the head side in order to create a form fit and thus the connection. Here, both the hole forming with regard to the fibre rearrangement mechanisms and different percentage upsetting of the pins during caulking were investigated (c.f. Fig. 3). It was shown that no damage to the fibres occurred due to the hole forming of the FRP. In addition, the load-bearing capacity of the joint was increased by a higher percentage compression of the pin structure during joining [25].

The focus of the work already presented was on the joining of Metall/FRP joints, as the use of pins is more widespread here. However, there are also efforts to use cold extruded pins from the sheet metal plane for joining dissimilar metals. The feasibility of this has already been demonstrated by Kraus et al. [18], who were able to show that extruded pins made from DC04 are suitable for direct pin pressing and caulking with EN AW 6016. Figure 4 shows the process sequence of pin joining of metal/metal and metal/FRP connections with pin extrusion and the two joining strategies with direct pin pressing and caulking.

In [27], Römisch et al. investigated the influence of varying pin heights and pin numbers on the joint formation and strength when directly pressing DP600 pins with EN AW-6014 T4. It was shown that with increasing pin height an increase of the undercut as well as the load bearing capacity of the joint was observed. In addition, the joint strength was shown to increase linearly with the number of pins. In [10], the pin geometry was also varied in addition to a varied height in order to analyse the influence on the load-bearing capacity when directly pressed into EN AW-6014. This showed that especially the ratio between punch cross-section and pin cross-section has an influence on the strain hardening in the pin during pin extrusion. With an increasing ratio, the flow resistance into the die and the

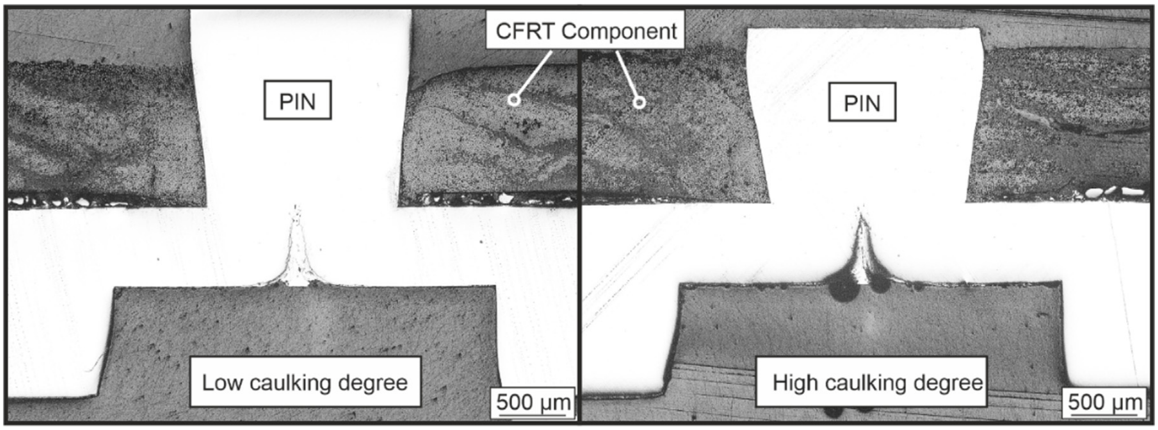


Fig. 3. Micrographs of caulked pin joints of DP600 and GF-PP with different degree of upsetting of the pin [25].

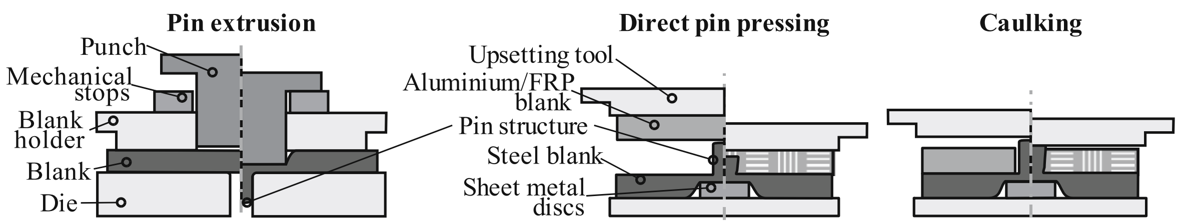


Fig. 4. Process sequence of pin joining with pin extrusion and the two joining strategies direct pin pressing and caulking according to [26].

deformation resistance increases, which leads to a stronger strain hardening and consequently higher shear strength of the pin and thus of the joint. In addition, in [28], data-driven methods were used to analyse the pin extrusion process with regard to relevant process properties in order to improve the predictability of the resulting pin height. Subsequently, in Römisch et al. [29], the entire process chain of pin joining of metal/metal joints, up to the mechanical joint characterisation, was numerically investigated and analysed and optimised with regard to process robustness. In order to increase the joint strength and the versatility of the joint, the extrusion of multi-pin structures was investigated in [26] in order to examine the influence of a simultaneous extrusion of a 3×4 pin array. Here, a pin height dependent on the position of the pins in the array was shown. Due to the process, local sheet thinning occurs during pin extrusion, which can vary depending on the pin height used. This can lead to sheet thinning which is so severe, especially with high pins, that it is not the pin that shears off but the remaining sheet that fails. For this reason, investigations were carried out in [30] to increase the local material thickness in the pin forming zone by orbital forming. Here, the local thickening not only increased the residual sheet thickness compared to conventional pin extrusion, but also increased the pin height due to the strain hardening caused by the orbital forming. Regarding the possibilities for influencing the subsequent joint, which result from pin joining with cold extruded pins, the pin height should be mentioned in particular. This not only affects the properties of the subsequent joint due to the work hardening in the pin, but also influences the joint formation and the joinability of different sheet thicknesses of the joining partners.

2.2 Short-term heat treatment assisted shear clinching

Regarding the joining of high-strength materials, their limited formability is challenging for established processes. Thus, new technologies have to be developed and manufacturing strategies have to be adapted in order to enhance process limits and to enable the joining of high-strength materials. The innovative shear-clinching combines shear-cutting and clinching (Fig. 5) and enables the joining of dissimilar high-strength materials in a single stage process [31].

During the joining sequence, the die-sided joining partner is indirectly shear-cut. Therefore, even ultra-high strength materials like hot stamped 22MnB5 can be processed [32]. After the cut, the upper sheet is drawn into the cut hole and then laterally extruded to form an interlock. The joint geometry is mainly influenced by the geometry of the tools like the diameter of the anvil, the diameter of the inner punch and the shape of the outer punch for which hemispherical [31], conical [33] and stepped [34] geometries were used. Within the process, the upper joining partner is subject to high strains. Therefore, the process is limited by the properties of the punch-sided sheet material [35]. It was shown that the high-strength alloy AA7075 cannot be joined without failure in the artificially aged T6 temper due to the limited formability of the alloy in this condition [33].

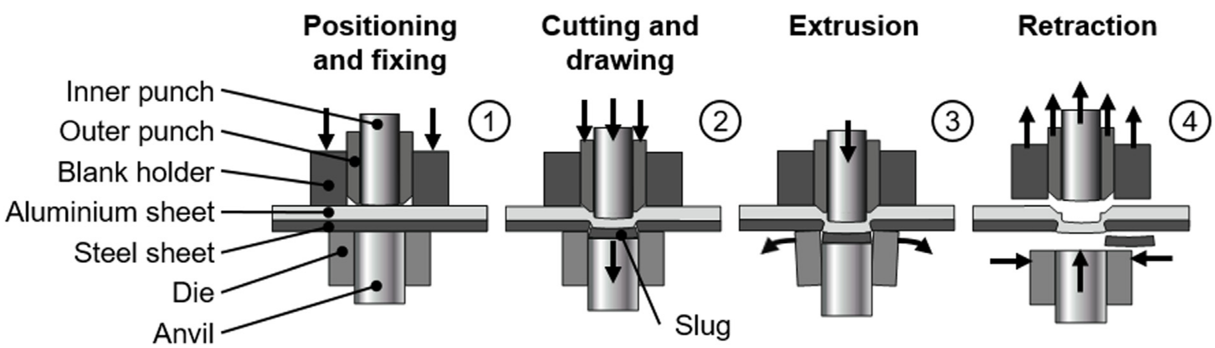


Fig. 5. Shear-clinching process according to [31].

Approaches to increase the forming limits of high-strength materials are forming at elevated temperatures and the performance of a heat treatment prior to forming operations in order to set favorable mechanical properties. The clinching of hard to form materials at elevated temperatures was shown by Hahn et al. [36] for magnesium AZ31 and by Lambiase [37] for aluminum AA6082. In [38], Jäckel et al. presented the joining of die-sided AA7021 T4 in a semi-tubular punch riveting process after heating the sheet via induction. The increased temperature leads to the reduction of flow stresses and therefore to a facilitated material flow. Moreover, the ductility of the materials enhances, too. Both factors contribute to the enhancement of the forming limits. Downsides of joining at elevated temperatures are the more complicated part handling and the necessity for special tool materials [39]. The named challenges can be avoided, when a heat treatment is performed prior to joining, which is then conducted at room temperature. Requirement is that the processed materials allow the defined setting of mechanical properties by heat treatments. For hot stamped 22MnB5 and clinching, this approach was shown by Meschut et al. [39]. By heating the material up to 850 °C for 4 s, the martensitic microstructure is locally transformed into a ferritic-perlitic structure, which leads to a reduced strength and increased ductility. In this condition, the steel can be joined with punch-sided AA6016 T4 without failure.

The strength of hardenable aluminum alloys is based on precipitations, which obstruct the movement of dislocations. By solution annealing, the precipitations are temporarily dissolved, whereas by natural and artificial ageing, the structure and size of the precipitations can be influenced, altering the mechanical properties of the alloy [40]. By a retrogression heat treatment, precipitations can also be temporarily and partly dissolved [41]. In comparison to solution annealing, the temperatures are lower and times are shorter. Therefore, the dissolution of the precipitations is incomplete. However, the mechanical properties are still affected by the heat treatment [41].

In [42], Jäckel et al. have shown the clinching of punch-sided high-strength AA7075 T6 after a retrogression heat treatment at 250 °C for 3 s. The same approach was shown for die-sided AA7021 T4 and semi-tubular punch riveting. In this case, the sheet was heated to 150 °C for 3 s. The short-term heat treatment allows the reduction of flow stress and therefore the subsequent joining at room temperature with increased forming limits. However, due to natural ageing, the joinability may be limited in time [43].

Graser et al. [33] have shown the shear-clinching of punch-sided AA7075 T6 after a short-term retrogression with die-sided HCT780X and hot stamped 22MnB5. By enhancing the forming limits of hardenable 7xxx aluminum, shear-clinching enables the joining of high-strength steel and aluminum. A laser was used as heat source, which allows the flexible application of small-scale heat treatment layouts and therefore the control of the material flow during the joining sequence in order to improve the joint geometry and strength.

The temperature during the retrogression has a high influence on the resulting mechanical properties of AA7075 [44], as different precipitations are dissolved at different threshold temperatures [45]. Increasing heat treatment temperatures cause the enhanced softening of AA7075 T6 (Fig. 6). However, in [44], the ductility is not increased in comparison to the T6 temper.

Yet, due to the facilitated material flow, the alloy can be joined without failure in the shear-clinching process. Requirement is the sufficient softening of the alloy as the strength of the upper sheet material is the main influencing factor for the joinability [35]. In [44], it was shown that starting from 300 °C, softening is distinct. Yet, crack-free joining was only possible for 350 °C and 400 °C. For 300 °C, cracks were still initiated during the joining sequence. In [33], joining of AA7075 T6 was possible after a retrogression heat treatment at 300 °C. However, a different batch of AA7075 was used. Principally, a lower temperature and therefore less softening is favorable for the joint formation as the undesired radial material flow during shear-clinching is reduced by a higher strength of the punch-sided material [35] and the joint formation is principally improved [44]. In addition, a higher material strength leads to higher load-bearing capacities (Fig. 7) [44]. Thus, in [44], despite the initiation of cracks, the highest joint strength was still achieved for a heat treatment temperature of 300 °C.

When the heat treatment is locally applied, temperature and therefore strength gradients can be induced in the sheet plane and locally varying mechanical properties can be set. Figure 8 shows the temperature and hardness distribution for two different spot geometries. For the extensive heating of the specimen, homogeneous softening

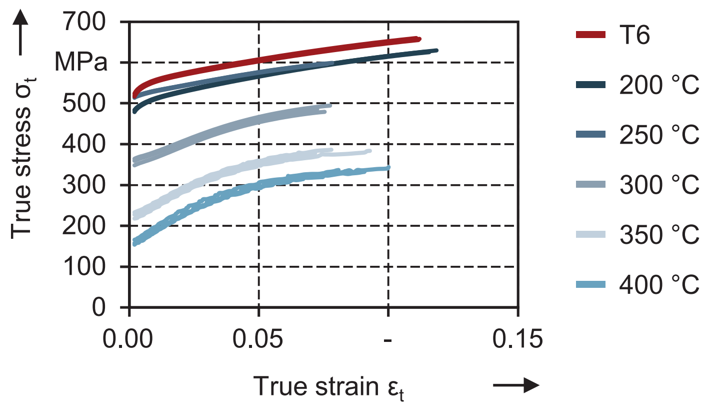


Fig. 6. True stress-true strain curves for the T6 temper and after a short-term retrogression at different temperatures according to [44].

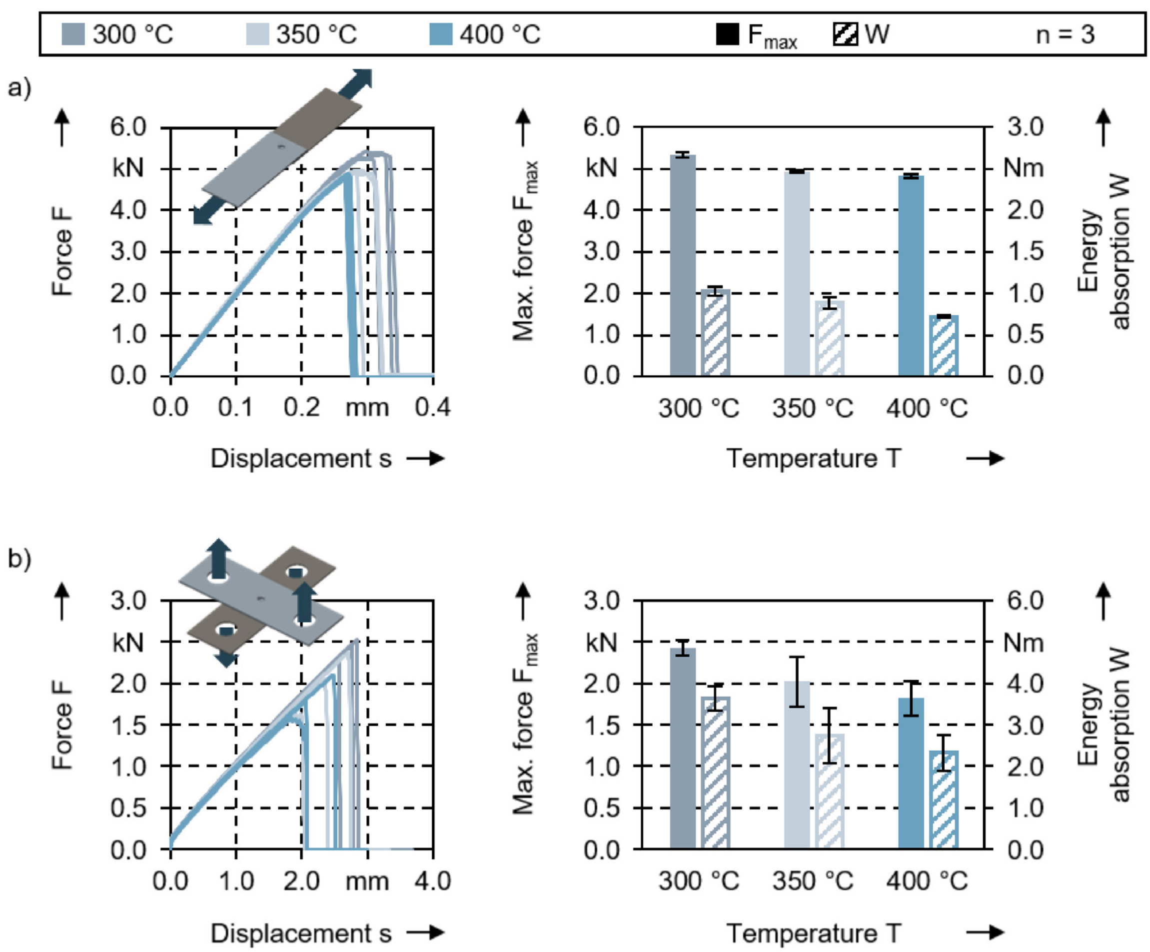


Fig. 7. Joint strength in dependence of temperature during retrogression and the load direction for (a) shear tensile load and (b) tensile load according to [44].

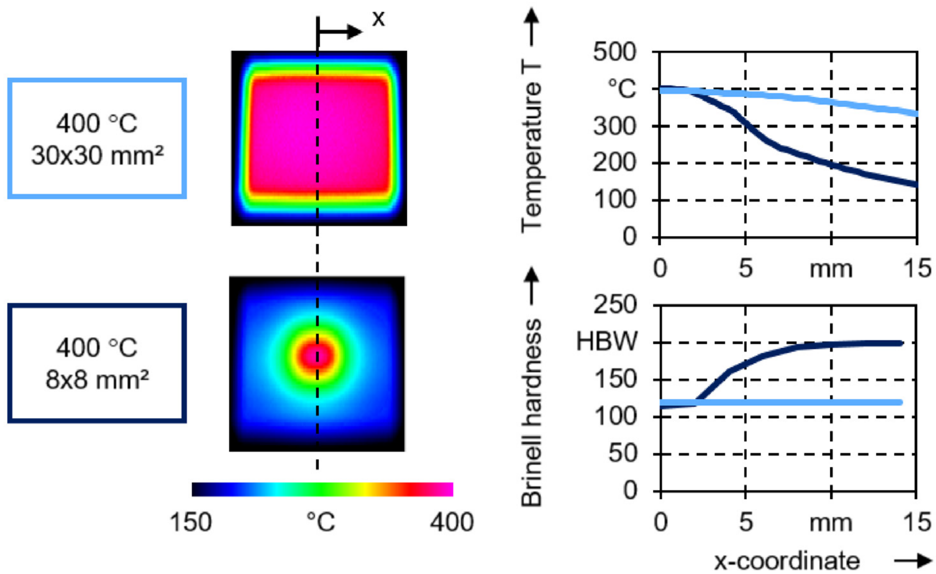


Fig. 8. Hardness gradients as result of a locally limited heat treatment according to [33].

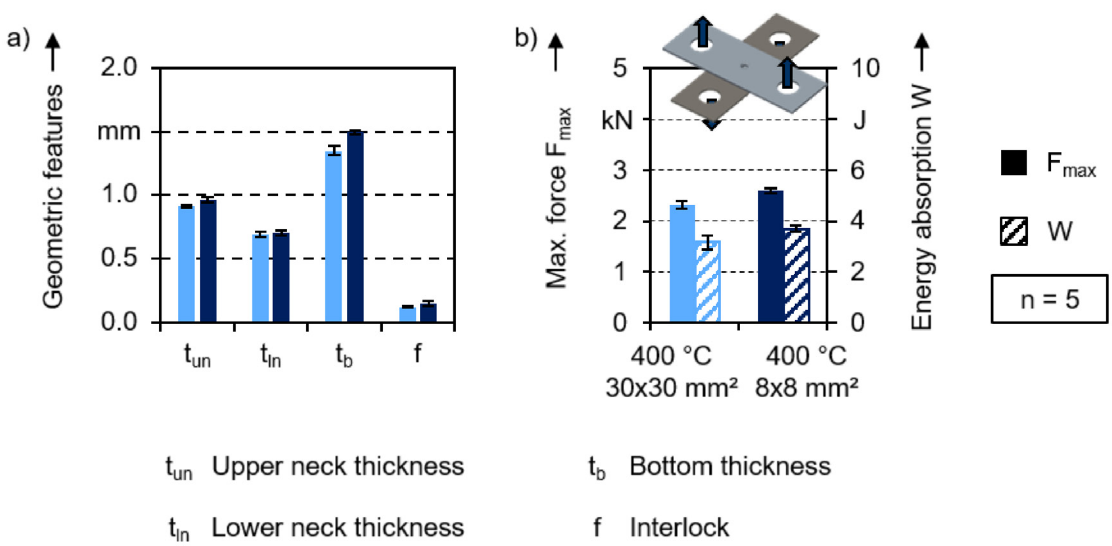


Fig. 9. (a) joint geometry and (b) joint strength under tensile load of shear-clinched AA7075 T6 (2.0 mm) and 22MnB5 (1.5 mm) after a retrogression at 400 °C with varying spot geometry according to [33].

is reached. In contrast, by limiting the heated area to the scale of the active tool elements, a defined hardness gradient is set.

The interaction of softened and not-softened areas influences the material flow [33]. By limiting the heat treatment to the contact zone of the inner and the outer punch, the surrounding not-softened material serves as armoring, which prevents the upper sheet from excessive radial material flow away from the joining zone [33]. As result, the formation of critical geometric features of the joint is improved, which leads to an increase of the joint strength (Fig. 9). Thus, a local short-term retrogression heat treatment does not only promote the joinability of high-strength 7xxx aluminum in joining by forming processes but also allows the control of the material flow by a process-adapted application of locally limited heat treatment layouts in order to improve the joint characteristics. The main influencing factor is the layout-dependent local temperature.

2.3 Ultrasonic-assisted joining

Frequently, the joining of sheet metals and bulk components requires detachable joints. Conventional screw joints depend on a pre-piercing operation of the sheet metal as well as a challenging part handling for screws, nuts and washers. Therefore, detachable joints demand more efficient joining processes. Self-piercing fasteners, which are directly installed into the sheet metal, offer the potential for facilitating this time-consuming and costly

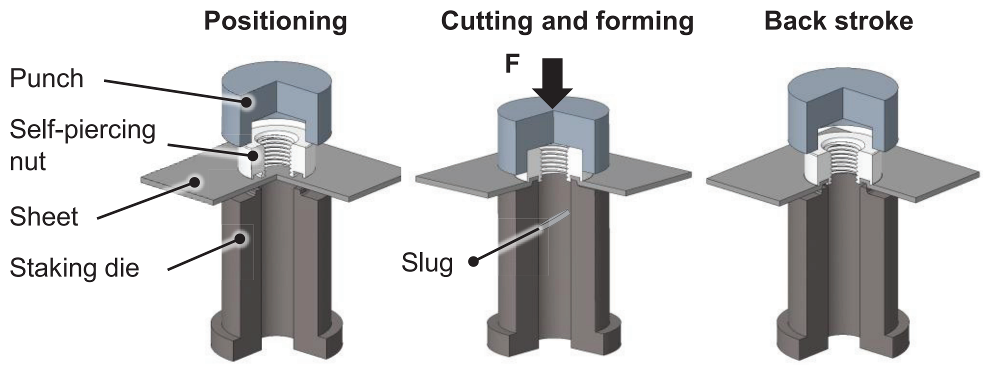


Fig. 10. Installation of a self-piercing nut into a sheet metal according to [47].

task and are becoming increasingly important. Figure 10 depicts the installation process of a self-piercing nut. According to Weiss [46] the following characteristic process steps are distinguished. Firstly, the self-piercing nut and the sheet are positioned onto the staking die. Then the punch presses the nut directly into the sheet metal and the self-piercing pilot penetrates the sheet, which leads to an initial shear cutting in combination with the die. Further punch infeed brings the outer collar of the nut and the blank into contact. The outer collar penetrates the sheet until the radial ribs touch down on it and compress it in combination with the die. This way, a radial and tangential material flow is induced and initiates the interlock forming, which is additionally enhanced when the nut body also touches the blank. Eventually, a form and force fit joint is created and the slug is sheared off between the self-piercing pilot of the nut and the cutting edge of the die. Since C-framed pliers are commonly used for the fastener installation, the maximum joining force is limited and further decreases with increasing length of the pliers' legs. This restricts the application to the edge areas of the blank. Thus, innovative methods to extend existing process limits are needed.

An innovative approach to enlarge process windows for distinct kinds of forming processes is the utilization of ultrasonic assistance. Superimposing a high frequency oscillation to the tool movement causes an immediate material softening that enables forming with reduced forces and thus lowered workpiece and tool loads. First investigations in the field of ultrasonic-assisted forming date back to Blaha und Langenecker in 1955 [48]. Driven by the potential to reduce forming forces considerably, numerous studies focused on ultrasonic-assisted forming. For example, Izumi et al. confirmed the ultrasonic-based softening effect for copper, magnesium, brass, lead, aluminum alloys and mild steels [49]. The transferability of the effect on distinct high strength steel and titanium alloys is given in [50]. Moreover, superimposing various forming processes such as wire drawing [51], deep drawing [52] and extrusion [53] with a high frequency oscillation proved the beneficial softening effect for industrial processes. Volume and surface effects explain the underlying softening mechanisms [54]. Volume effects refer to an enhanced dislocation movement as well as an intensified specimen heating due to the acoustic energy input while surface effects mean reduced friction. However, the underlying mechanisms involved are still the subject of current research.

In the context of mechanical joining, only a few studies investigated the effect of ultrasonic assistance. Wanner et al. [55] achieved promising results when superimposing a 20 kHz oscillation on a clinching process. In comparison to conventional joining, the maximum process forces were reduced by 15% and 20% for aluminum-aluminum and steel-steel combinations, respectively. The findings in [56] support the results of Wanner et al. and indicate a proportional softening due to an enhanced sample heating. Moreover, the integration of the ultrasonic system into C-framed pliers as well as the formation of sound joints with strengths comparable to conventional formed joints demonstrate the feasibility for industrial use cases. Further investigations in the context of ultrasonic-assisted clinching were carried out in [53] and [57]. In contrast to aforementioned studies, the superimposed oscillation caused a metallic bonding between the joining partners. As a result, the joint strengths improved significantly. The varying joint formations are explainable based on the different experimental setups. Once the sample is located in the node and once in the anti-node of the superimposed oscillation. Only in the anti-mode position sufficient vibrational energy is introduced into the joint to form a metallic bonding [53].

Present studies regarding ultrasonic-assisted joining processes clearly confirm the ultrasonic-based softening effect and thus the potential to improve existing processes and establish innovative process strategies. Nevertheless, mainly clinching was investigated and there is a lack of knowledge concerning joining processes with auxiliary elements. Presumably, the more challenging process management due to the additional element causes this research gap. Libby [58] analyzed an ultrasonic-assisted riveting process. A conclusion regarding the force reduction cannot be drawn since no reference process was presented. Wang et al. [59] superimposed a transverse ultrasonic oscillation on the riveting process. Focusing on the joint quality, they found a more uniform expansion of the rivet shaft and derived improved mechanical properties due to the ultrasonic assistance. Increased hardness and yield load of lap joints riveted with superimposed oscillation support

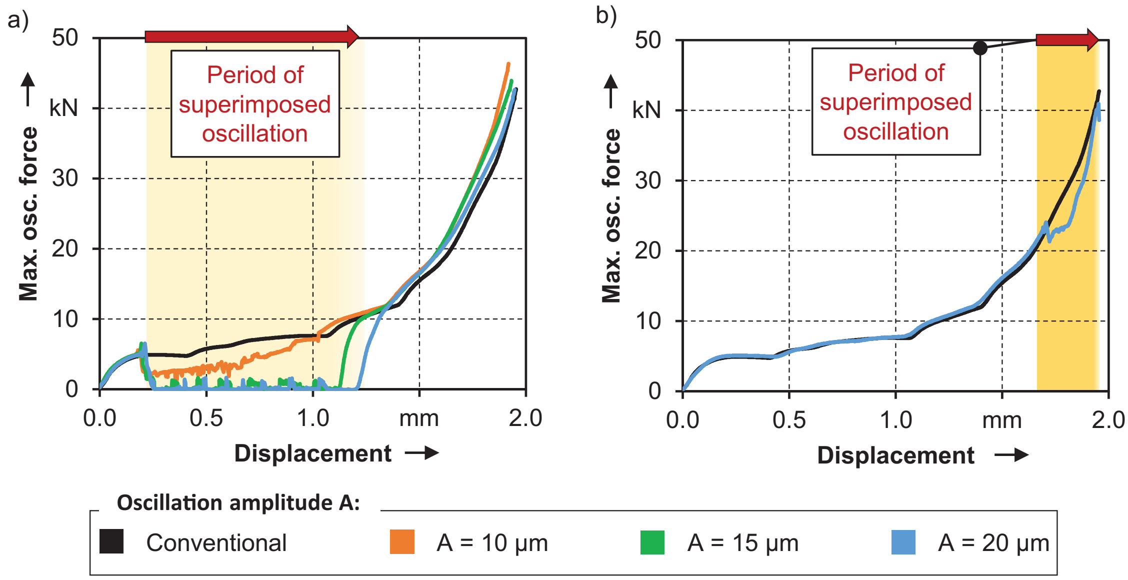


Fig. 11. Force-displacement-curves for ultrasonic-assisted staking of self-piercing fasteners: (a) Superimposing early process stage; (b) Superimposing final process stage according to [60].

these findings. Jäckisch and Merklein [60] conducted a comprehensive experimental investigation regarding ultrasonic-assisted joining with auxiliary elements. Focusing on the identification of the process characteristics for the novel fastener staking process, they superimposed different process steps with varying oscillation amplitudes (Fig. 11). Superimposing a high frequency oscillation of 20 kHz considerably changes the process characteristics. With increasing amplitude A, the force reduction becomes more prominent. They identified a threshold between 10 µm and 15 µm, where the stable contact condition between the tools and the joining partners switched to an irregular contact state. This means the temporary separation of the tools and the workpieces. Consequently, the process force exhibits periods of 0 N (Fig. 11a). Ultrasonic-assisted ring staking experiments by Leicht et al. [61] support these findings. They determined a state of cyclic contact shifts and periods of loss of contact. The inherent elastic deflection of experimental setups explains this amplitude-dependent effect. When the elastic deflection is lower than the oscillation amplitude, the tool's oscillation against the staking direction leads to a temporary loss of contact. Superimposing the high frequency oscillation during the final process stage of the fastener staking that is characterized by the interlock forming with elevated process forces, the effect of loss of contact is inhibited since the elastic deflection is greater than the oscillation amplitude [60]. Moreover, the force reduction compared to the conventional staking process is less pronounced (Fig. 11b). Similar to ultrasonic-assisted upsetting [49], the attainable process force reduction in ultrasonic-assisted nut staking is mainly determined by the oscillation amplitude.

Superimposing a high frequency oscillation on the staking process of self-piercing fasteners not only affects the process management but also the joint formation and strength. Characteristic form elements are the neck thickness and the interlocks. The application of ultrasonic assistance results in a similar formation of these elements as determined for the reference process. Moreover, interlock forming can be improved (Fig. 12a). Regarding the shear cutting of the blank, a reduced rollover depth is assumed based on the investigations in [62]. This way, more material is forced into the nut cavity and thus the interlock is increased. However, the maximum load bearing capacity determined in push-out tests is of the same level as conventionally produced joints (Fig. 12b), since failure predominantly occurs in the neck area. Consequently, enhanced interlock forming is ineffective for this testing method [60].

2.4 Joining by orbital forming

Conventional mechanical joining processes are distinguished by their process characteristics and the design of the joining tools as very robust, but also very rigid [63]. As a result, these processes can only react to a very limited extent to changing constraints such as process or external disturbance variables [9]. Particularly in the manufacture of multi-material systems, these rigid process properties represent a major challenge, since different workpieces have to be joined, which are made of different materials and thus have varying mechanical properties, as well as different geometric properties, such as varying sheet thicknesses [64]. A mechanical joining process often used in the industrial environment is semi-tubular self-piercing riveting, in which a connection is created by forming two joining partners and an auxiliary joining part, illustrated in Figure 13 [63].

After clamping the joining partners, the rivet element is driven by the punch, initially cuts through the punch-side joining partner and then flares. This creates an undercut of the rivet between the rivet shaft and the punch-side sheet metal [65]. As can be seen from the process diagram, the

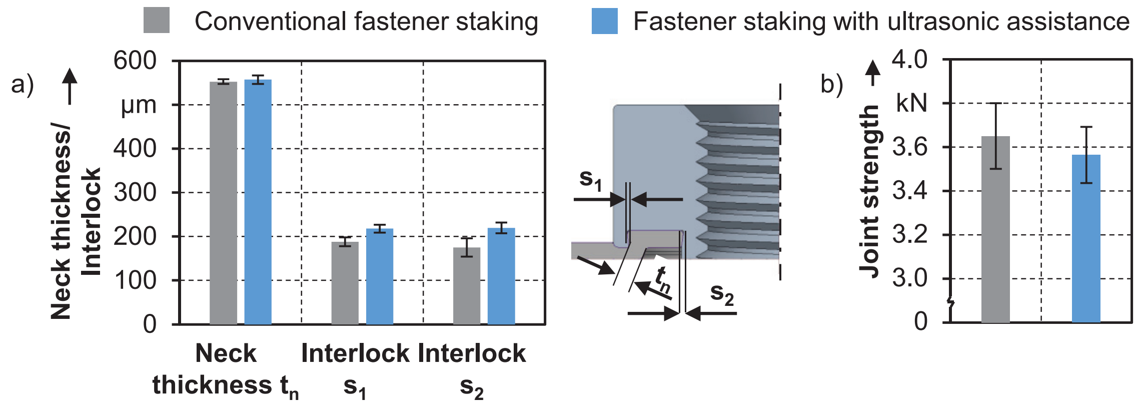


Fig. 12. Characteristics of conventionally and ultrasonic-assisted produced joints: (a) Joint formation (b) Joint strength according to [60].

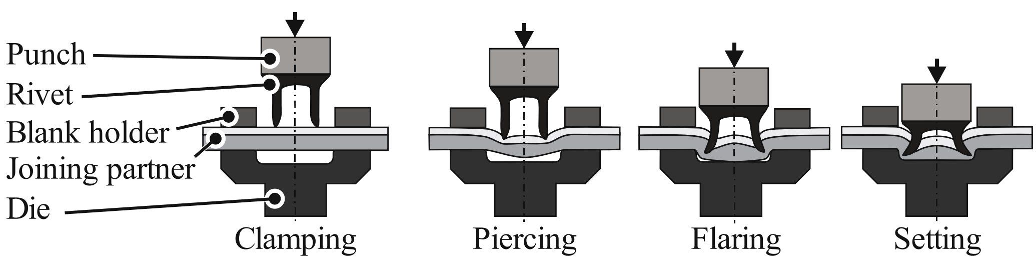


Fig. 13. Conventional semi-tubular self-piercing riveting according to [65].

joining process requires access from both sides of the joint due to the required punch and die and is limited in terms of the disturbance contours by the tools. High punch travel speeds enable short joining times and a high cycle rate in industrial applications. Furthermore, the process is very robust and offers good monitoring opportunities of quality criteria with the force-displacement curve. The joints are characterized by high quasi-static and dynamic load bearing capacities and the process provides the capability to join three joining partners. In particular, the joinability of different materials with varying melting points [66] and high-strength steels as well as hybrid joints is an important process feature [64].

The rigid characteristics are particularly due to the process design of the joining process. The conventional procedure for joining a new combination includes a sampling process in which the rivet-die-combination is selected. However, in the manufacture of multi-material systems in particular, it is a disadvantage to use different rivet-matrix combinations, since these represent an effort in the sampling process and require additional handling operations during the process [67]. In order to increase the opportunities for influencing the process and to expand the joining capabilities of individual rivet-die-combinations, the actuators in the process can be enhanced. In the case of semi-tubular self-piercing riveting, the axial movement of the joining punch is superimposed by a tumbling movement. The process is shown schematically in Figure 14.

This expands the parameter range of the influencing variables and the process can be controlled in a targeted way. These include in particular the tumbling angle, tumbling kinematics, tumbling velocity and tumbling onset. They all have a significant influence on the joining process, the resulting geometric joint formation and the load bearing capacity. When manufacturing these joints, one major challenge is the implementation of a tumbling punch in combination with the semi-tubular self-pierce riveting process. In [68] a tool concept is described which allows a completely freely configurable tumbling strategy consisting of different parameters to be adjusted. The concept is based on the combination of a rotating and a linear axis, which enables the system to access any point on a variable path of a circle. As a result, the configuration of the tumbling strategy is completely free and highly dynamic due to a decoupling of the adjustment mechanism from the force flow of the tool. In [69], investigations of a tumbling superimposed semi-tubular self-piercing riveting process of pure-art joints with an EN AW-6014 are shown. For this purpose, the tool set up in [68] is used and the parameters tumbling onset and tumbling angle are varied in several stages. The results are categorized according to the influence of the process superimposition on the joining process and the geometric joint formation. The variation of the tumbling angle shows a reduction of the joining force and a change of the geometrical joint properties in the form of the undercut, the rivet head end position and the residual bottom thickness. For the tumbling onset, it is observed that the process converges to the process end at different tumbling onsets and ends at similar force levels. The investigations prove that material flow control is possible by superposition and that the joining process becomes more versatile. In [68], investigations are carried

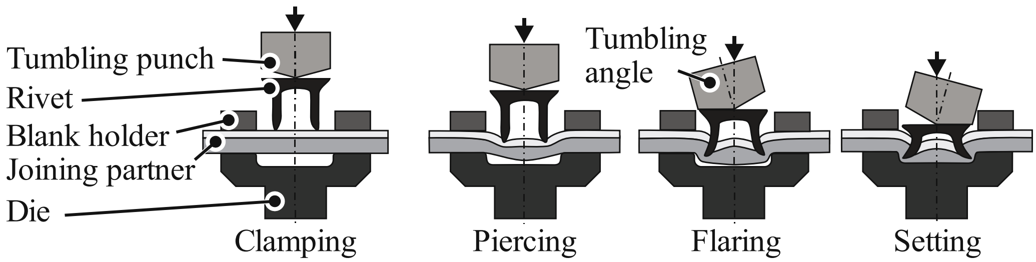
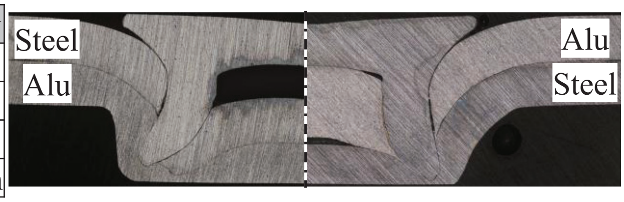


Fig. 14. Tumbling self-piercing riveting according to [68].

Tumbling strategy	
Angle α	6°
Kinematic	Circle
Velocity ω	240 °/s
Onset h_{TO}	3.5 mm



Joining configuration	
Rivet	C5.3x4.5
Die	FM 085 2117
Steel	HCT590X+Z
Aluminium	EN AW-6014

Fig. 15. Varying joining directions of hard and soft materials in multi-material systems.

out with multi-material systems using the dual-phase steel HCT590X and the aluminum alloy EN AW-6014, which confirm the results from [69] for the expanded materials. In addition, the spectrum of influencing parameters on the tumbling strategy is extended by the tumbling kinematics. It is shown that the properties of the joining process and the geometric joint formation are also influenced by this parameter and that the process superposition can be used to increase the versatility as well. Another parameter investigated in [70] is the tumbling velocity. This parameter shows that an adaptation of the tumbling speed in combination with the absolute number of revolutions, which represent the distance traveled in a circular motion, is a significant influencing parameter for increasing the versatility. In particular, the shaping of the rivet head is influenced by the tumbling velocity and, at higher speeds, more uniformly as a result of a higher number of increments in the joining process. In addition to the properties from the joining process and the geometric joint formation for the identification of material flow components by the process combination, the load bearing capacities of joints are an essential feature, since the transmission of forces is generally the primary function of a joint. In investigations in [71], the load bearing capacities of multi-material systems are analyzed with shear tensile tests and cross tensile tests according to [72]. The results show that the geometric joint formation has a significant influence on the load-bearing capacity and that this can be specifically controlled by the tumbling strategy, even for different multi-material systems. Furthermore, the difference to a conventionally joined connection is shown. It is concluded that the maximum transmissible forces are at a similar level for both tests, but the energy absorption is significantly higher for cross tensile test. The explanation for this is given as a shift in the form and force fit proportions in the joint. In addition to the load bearing capacities, the applicability of the identified and significant process characteristics is investigated in terms of different aspects. First, the total package thickness of the multi-material systems is varied. It is shown that the geometric joint formation for all joints shows an influence of the tumbling strategy and can be specifically adjusted within the process limits by this strategy. In addition, the aspect ratio of the sheet thickness of the punch-side and die-side joining partner is varied and limits in the joinability are identified. As an example, Figure 15 shows the differences of a joint with varying joining directions of hard and soft materials in multi-material systems when using a tumbling semi-tubular self-piercing riveting process. During this process, the tumbling strategy and the joining configuration are kept constant.

2.5 Manufacture of self-piercing rivets using high nitrogen steel

Semi-tubular self-piercing riveting is an established mechanical joining technology, which enables the joining of dissimilar materials by using rivets as mechanical fasteners. The production process for the manufacture of the rivets usually consists of several steps. Self-piercing rivets are formed from a wire in a multi-stage cold forming process, whereby high-strength boron steel is normally used as rivet material [63]. Subsequently, the rivets are hardened and tempered [73]. The heat treatment of the rivets is important to assure an adequate strength of the rivets in combination with a good ductility. These properties are an essential prerequisite for successful joining to prevent the buckling or an excessive compression of the rivet shank [39]. This is particularly the case when high-strength steels are to be joined. The rivet strength must be sufficient in relation to the strength of the sheets to be joined, otherwise the joinability cannot be guaranteed [74]. After heat treatment, frequently used rivets have a hardness of 480 HV ± 30 HV [75]. The rivets are thereafter coated in order to achieve a high corrosion resistance [76]. Because of the post process steps heat treatment and coating, which are necessary after the forming process, the rivet production is time-consuming, costly and energy-intensive. In particular, heat treatment processes in general

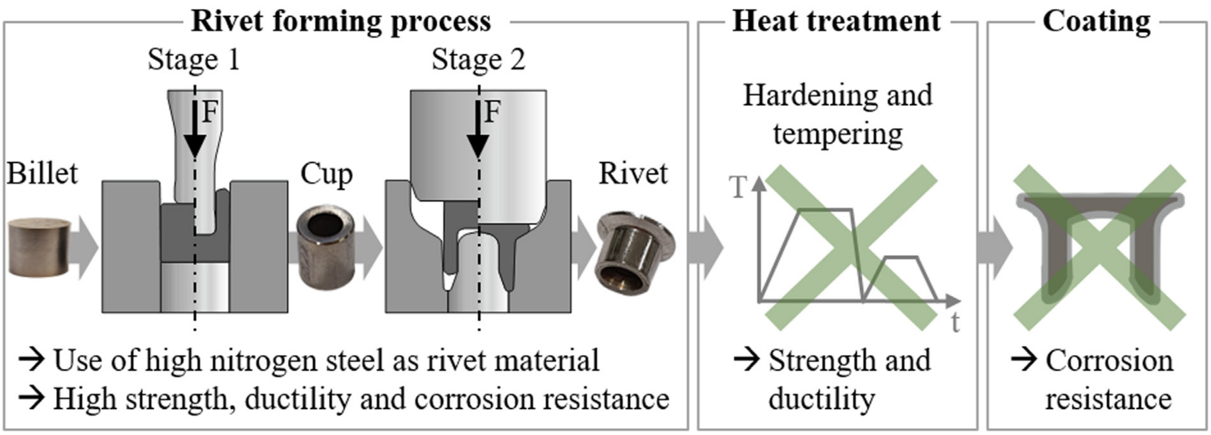


Fig. 16. New rivet manufacturing process according to [90].

cause a high energy consumption. The analysis of the energy consumption of a steel foundry in [77] showed that more than a third of the total gas consumption of the foundry is attributable to the heat treatment processes.

The use of alternative rivet materials offers the potential to shorten the process chain in rivet manufacture. The yield strength and the strain hardening of the rivet material have a great influence on the joining process and the joint formation including the specific joint parameters [78]. In the past, the suitability of austenitic stainless steel as rivet material has already been investigated [79]. A self-piercing rivet made of stainless steel is patented in [80]. Due to the use of stainless steel as rivet material, the post process steps can be omitted and thus the process chain can be shortened. A major disadvantage, however, is that the suitability of the rivets for joining high-strength steels is not ensured, as the strength of the rivets is not sufficient for this challenging joining task. In the case that the strength of the sheet is almost as high as the strength of the rivet, there is, among other things, the risk that the rivet shank is excessively compressed [63], which can even lead to the fact that the upper sheet is not cut. Furthermore, the buckling and the fracture of the rivet shank are typical defects when joining high-strength steel [81] as well as an insufficient interlock formation that especially occurs when using high-strength steel on the die side [82] because the rivet flaring is impeded in case of joining high-strength materials [83]. The use of rivets providing a higher hardness is not a solution. In [84] it is shown that buckling can be prevented by using rivets with a comparatively higher hardness, but that there is a risk of cracks in the rivet due to the reduced ductility.

A new approach is the use of high strain hardening materials like high nitrogen steel, which is characterized by a comparatively high nitrogen content, as rivet material. High nitrogen steels provide excellent mechanical properties like a high strength in combination with a high ductility and a good corrosion resistance [85], which is why they are used for highly-stressed components like retaining rings for turbo-generators [86]. With regard to the rivet manufacturing process, the use of high nitrogen steel as rivet material allows the shortening of the process chain, as the heat treatment and the coating are not necessary anymore because of the excellent mechanical properties of the material. Additionally, unlike the use of rivets made of conventional stainless steels, there is the possibility of joining high-strength steel because of the high strength of the rivets resulting from the high strain hardening of the high nitrogen steel. The high strain hardening is based on solid solution hardening due to the limitation of dislocation movement by the interstitially dissolved nitrogen [87]. As a result, challenging high tool loads need to be expected when forming high nitrogen steel, especially in multi-stage cold forming processes. Nevertheless, Noneder and Merklein [88] showed the feasibility of producing high performance components using high nitrogen steel in a five-stage industrial batch process by using an adequate forming strategy and tool design. Due to the small and fine geometry of self-piercing rivets and the associated extraordinary high tool loads during the rivet forming process, a special forming and tool concept is used for the rivet manufacture using high nitrogen steel, which was introduced in [89]. Furthermore, a new rivet geometry was developed in this context and was presented in [75]. The rivets are made of the high nitrogen steel 1.3815 that provides a nitrogen content of 7600 ppm and is manufactured by Energietechnik Essen GmbH. The new rivet manufacturing process consists of two forming stages, cup-backward extrusion in stage 1 to form the rivet shank and upsetting in stage 2 to form the rivet head and foot, as shown in Figure 16, which also illustrates the shortening of the process chain compared to the conventional rivet manufacturing process.

The results of the numerical analysis of the rivet manufacturing process in [89] show that contact normal stresses of more than 8500 MPa can occur in the counter punch in stage 2. This is critical with regard to the compressive strength of 8500 MPa of the tungsten carbide K01 used as tool material, which is already one of the available tungsten carbides with the highest strength. For this reason, special forming strategies are needed in order to manufacture self-piercing rivets using high nitrogen steel. On the basis of the material characterization in [91] it can be concluded that the yield strength and the true stress level during forming of 1.3815 can be reduced by forming the material at elevated temperature and that this is

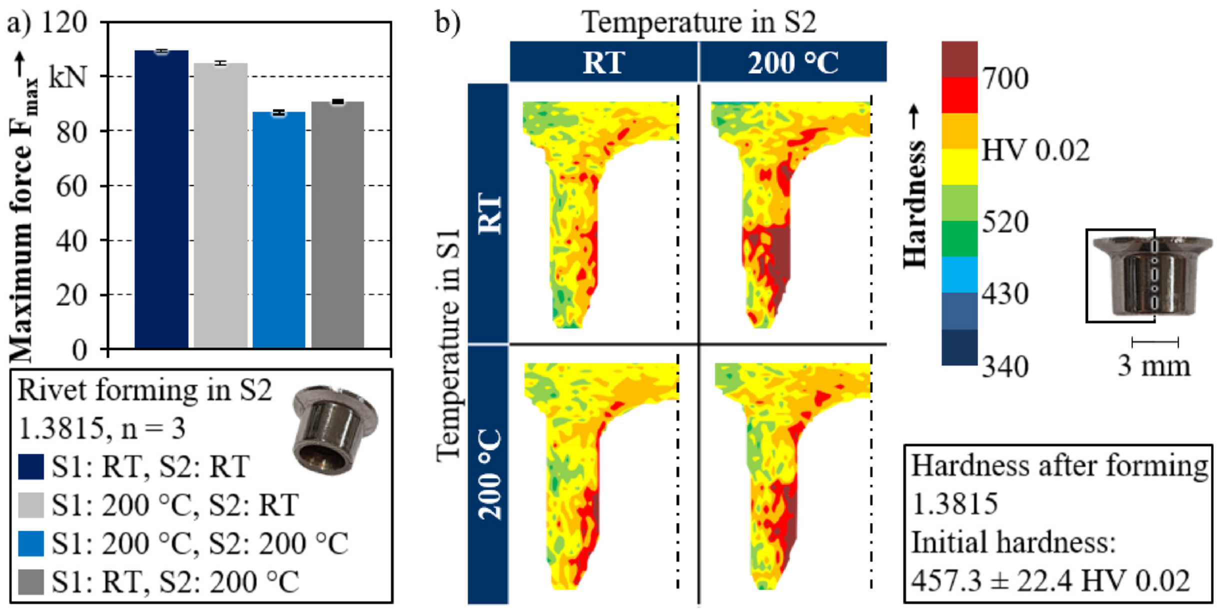


Fig. 17. (a) Maximum forces for rivet forming in dependence of the temperature combination of room temperature (RT) and 200 °C in stage 1 (S1) and stage 2 (S2), (b) Influence of the chosen temperature combination on the resulting rivet hardness according to [90].

already the case with a temperature increase up to 200 °C compared to room temperature. Consequently, the application of different forming temperatures in both forming stages was investigated in [90] in order to identify a suitable process-adapted temperature application for the rivet manufacture. For this purpose, the influence of various temperature combinations including room temperature and 200 °C in the two-stage rivet forming process on the necessary process forces but also on the resulting mechanical properties of the rivets after forming were analyzed. It was shown that the maximum forming force, which is needed to achieve a comparable rivet geometry at the end of the forming process, can be reduced if at least one of the both forming stages is carried out at 200 °C (see Fig. 17a).

Based on the results, it can be noted that forming the cups in stage 1 at room temperature followed by forming the rivets in stage 2 at 200 °C is an interesting approach with regard to the potential force reduction and thus the reduction of the tool loads. In this case, the maximum force is reduced by more than 20% in comparison if both stages are carried out at room temperature. Thus, in contrast to forming at 200 °C in both stages, energy can be saved, as a higher temperature needs to be applied in only one of the stages, while a considerable force reduction can be achieved compared to forming at room temperature in both stages.

Moreover, the investigations show that the approach offers the possibility to influence the resulting mechanical properties of the rivets after forming. This is demonstrated by the results of the hardness analysis of rivets that were formed using different temperature combinations in both forming stages (see Fig. 17b). In contrast to frequently used rivets providing a hardness of 480 HV ± 30 HV [75], the rivets made of the high nitrogen steel provide a mean hardness of at least 594 HV 0.02 in each of the cases investigated, which is beneficial in view of the intended use of the rivets for the joining of high-strength steel. As concerns the gradation of the hardness, overall, a mean difference of at least 284 HV 0.02 can be achieved depending on the temperature combination that is chosen for the two-stage rivet manufacture. Furthermore, it can be stated that the areas characterized by local hardness values of more than 700 HV 0.02 are larger if one of the two forming stages has been carried out at 200 °C. This effect is in accordance with the results obtained from the material characterization in [91], which showed that a higher hardening exponent and thus an elevated strengthening is reached when the high nitrogen steel is formed at 200 °C instead of room temperature. The hindered dislocation movement due to the temperature-induced diffusion processes of the interstitially dissolved nitrogen is a possible explanation for this effect. In [92] it is also assumed that the mobility of the nitrogen atoms increases with rising temperature above room temperature leading to an enhanced diffusion of the nitrogen, which can even result in the nitrogen being pinned at dislocations. The hardness distribution of the formed rivets is advantageous with regard to the joining process. The comparatively higher hardness values in the area of the rivet shank and the rivet foot are useful in order to prevent the unintentional excessive deformation when joining high-strength steel. The lower local hardness in the outer area of the rivet foot in combination with the higher local hardness in the inner area, following the function of a hinge, can facilitate the rivet flaring. The feasibility of joining using the new rivets made of the high nitrogen steel 1.3815 was demonstrated in [93] on the basis of joining tests using the high-strength steel HCT780X on the die side in combination with the aluminum alloy EN AW-5083 on the punch side as well as using HCT780X on both sides.

As the heat treatment can be omitted, the hardness distribution of the rivets remains intact in contrast to conventional heat treated rivets having homogeneous mechanical properties after the hardening and tempering. In summary, it can be stated that both the mean hardness level as well as the hardness distribution of the rivets is influenced by the process temperature during forming, particularly through the selection of different temperatures for the individual forming steps in the multi-stage rivet manufacturing process. It is clear that the choice of the forming operations and the rivet material represent the main factors influencing the rivet properties. However, the fact that a reduction of the maximum process forces and a change of the mechanical properties of the rivets can be achieved by a process-adapted temperature application can be used for process design and control in rivet production. This illustrates the great potential that is associated with the use of high nitrogen steel as rivet material, which opens the door to the production of customized rivets with a wide range of graded mechanical properties that can be adapted to the requirements of the subsequent joining process.

2.6 Data-based process control – mechanical joining 4.0

Since joining is usually one of the last steps within manufacturing chains of sheet metal assemblies, the properties of the components and therefore joining processes are influenced by the various prior production steps. For example, drawing leads to thinning and pre-straining of the sheets, resulting in properties, which differ from the initial condition, for which joints are usually sampled. The deviating properties are often more challenging for the processes as the formability of the sheets decreases. In addition, the resulting properties are also subject to deviations from the properties of semi-finished parts and of processes. Especially for high-strength materials, these circumstances may reduce process windows and therefore negatively affect the joint quality or even lead to failure.

Forming processes, which includes joining by forming operations, are usually bound to rigid tools, offering only small scope for adaptions. Moreover, adaptions require knowledge on the boundary conditions for each joint as well as on the influence of these conditions on the process results. Regarding forming operations, Purr [94], Havinga [95] and Heingärtner [96] have shown different approaches for the inline determination of deviations with and without the use of additional sensors. For example in [96], a loop, which allows the process control in deep drawing processes, is presented. A camera system records the draw-in of the sheet, which is correlated with the blank holder force. Hereby, the force can be adapted in situ in order to control the material flow. The underlying model was developed with the aid of numerical simulations. In [97], an advanced die system for self-piercing riveting, which includes a movable die bottom, is presented and combined with cyber-physical-systems, in order to ensure the joining quality even in the case of carrying boundary conditions.

The named publications aim to adapt the forming processes in order to maintain the part quality. In [98], an approach is shown, which aims to provide knowledge on the part properties as result of forming, cutting and clamping operations in order to adapt a subsequent joining process. Since the joining operation follows forming operations, it offers the opportunity to compensate for deviations along the process chain to a certain extent. In [98], a demonstrator geometry is deep drawn with different blank holder forces in order to set different part properties in the joining zone. After laser cutting the remaining flange, the part is clamped with another sheet metal component using a smart clamping device, which is equipped with force and angle sensors. The parts are then clinched. For a blank holder force of 130 kN, the boundary conditions in the flange are almost similar to the initial properties of the semi-finished parts (Fig. 18). Thus, the tool setup and parameters, which were determined with a standard sampling process, lead to a good joint quality without the occurrence of cracks [98]. By increasing the blank holder force to 800 kN, the conditions differ distinctly from the initial state. The higher restraining forces lead to distinct thinning and pre-straining of the sheet (Fig. 18). Using the determined parameters results in the failure of the joints [98].

The increased restraining force causes the enhancement of the necessary forming force. In addition, the higher forming force correlates with the strain-induced enhancement of the flow stresses and of residual stresses. On the other hand, the sheet thickness is reduced, which principally leads the reduction of the forming force as the loaded cross-section decreases. Therefore, these effects are opposing and difficult to isolate due to local variations of thinning and plastic strains.

Next to the displayed properties, the blank holder force during drawing also influences the springback behavior and the dimensional accuracy of the drawn part [98]. The increase of the blank holder force from 130 kN to 800 kN results in the reduction of springback and in the improved dimensional accuracy of the demonstrator geometry. This correlation can be determined in the clamping operation using smart clamping devices as the improved part geometry leads to the reduction of the measured residual gap [98].

Regarding the properties of semi-finished and finished components, blanking operations, which are conducted prior, during and after forming, allow the determination of sheet thicknesses, mechanical properties [99] and even pre-straining [100] with good accordance. However, due to the numerous influencing variables of forming operations, a mere correlation of globally recorded process data is not suitable for the reliable determination of local part properties at the joint area. Thus, an additional source of information is necessary to predict part properties in dependence of varying input variables. In [98], a continuous simulation accompanying the process chain, serves as information source. With knowledge on the process conditions, the process chain with the resulting deviations can be simulated and the joining result can be predicted allowing the determination of suitable process parameters. In addition, based on the numerical simulation of the

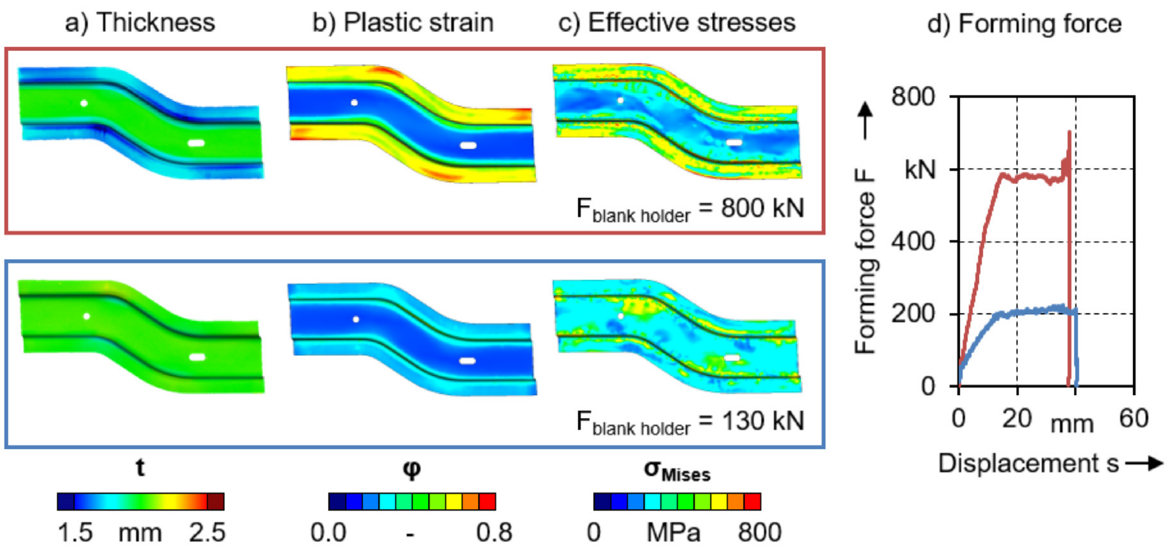


Fig. 18. (a) thickness determined with GOM ATOS, (b) plastic strain determined with Simufact.Forming, (c) effective stresses determined with Simufact.Forming and (d) forming forces in dependence of the blank holder force according to [98].

joining process, meta models are derived, which allow the analytical description of the correlation of process parameters and joint characteristics as well as of properties of the semi-finished parts and joint characteristics [98]. Using the meta models, the boundary conditions, which derive from previous processes, can be taken into account and a tool optimization for the particular use case can be performed [98]. By adapting the tool geometry with help of the derived meta models, sound joints could be produced even for a blank holder force of 800 kN and the resulting excessive thinning and pre-straining of the material (Fig. 19). After performing a target size optimization with the objectives to increase the neck thickness and the interlock at the same time, a punch radius of $R = 0.5$ mm and a bottom angle of $\beta = 1°$ were found to be suitable.

As the simulation of the whole process chain for specific boundary conditions is relatively time consuming in comparison to the cycle times, the in [98] presented approach to simulate the whole process chain in a continuous simulation is lacking real time capability. It is therefore only limited suited for the serial production of sheet metal assemblies. By using meta models, which allow the analytical description of process connections, real time capability is given. The meta models can be built based on a large variety of simulations with varying input parameters allowing the detailed modelling of the process behavior with lower effort in comparison to experimental data acquisition and with the focused variation of process parameters without disturbances and external influences [101]. The time consuming step to simulate the process chain is therefore shifted before the actual production. The derived meta models allow the interpolation also for unknown and not simulated cases and therefore the prediction of properties within a short period. The comprehensive understanding of the joining processes and cross-process relations forms the basis for the real-time process control in order to compensate for deviations and therefore to reduce reject. The process modelling can be facilitated by the use of machine learning methods. For example, approaches for joining processes are shown in [102] and [103]. An approach for self-piercing riveting is presented in [104] on the basis of local fuzzy pattern models with a multidimensional membership function that can be utilized for process control based on the prediction of a series of relevant output parameters. However, a remaining challenge is the linking of individual process models along a complete manufacturing chain.

3 Conclusions and outlook

In view of the increasing importance of environmental protection and sustainability in our society in the future, mechanical joining technologies will continue to play a central role in industrial production processes but also in scientific research. The main current challenges for mechanical joining technologies are existing process limits, caused among other things by the further development of innovative materials with ever higher strengths, high energy and resource consumption as well as a lack of process flexibility. The following key aspects for future trends according to the increasing demands for mechanical joining processes can be identified:
- **Lightweight design**: enhancement of existing process limits and opening up new fields of application.
- **Efficiency**: shortening of the process chains and minimization of energy and resource consumption.
- **Versatility and robustness**: use of adaptive tool designs and process control as well as reduction of the impact of interferences on processes and products.

Within this contribution, different approaches for various mechanical joining techniques with and without auxiliary element, which are based on these pillars addressing the current challenges as illustrated in

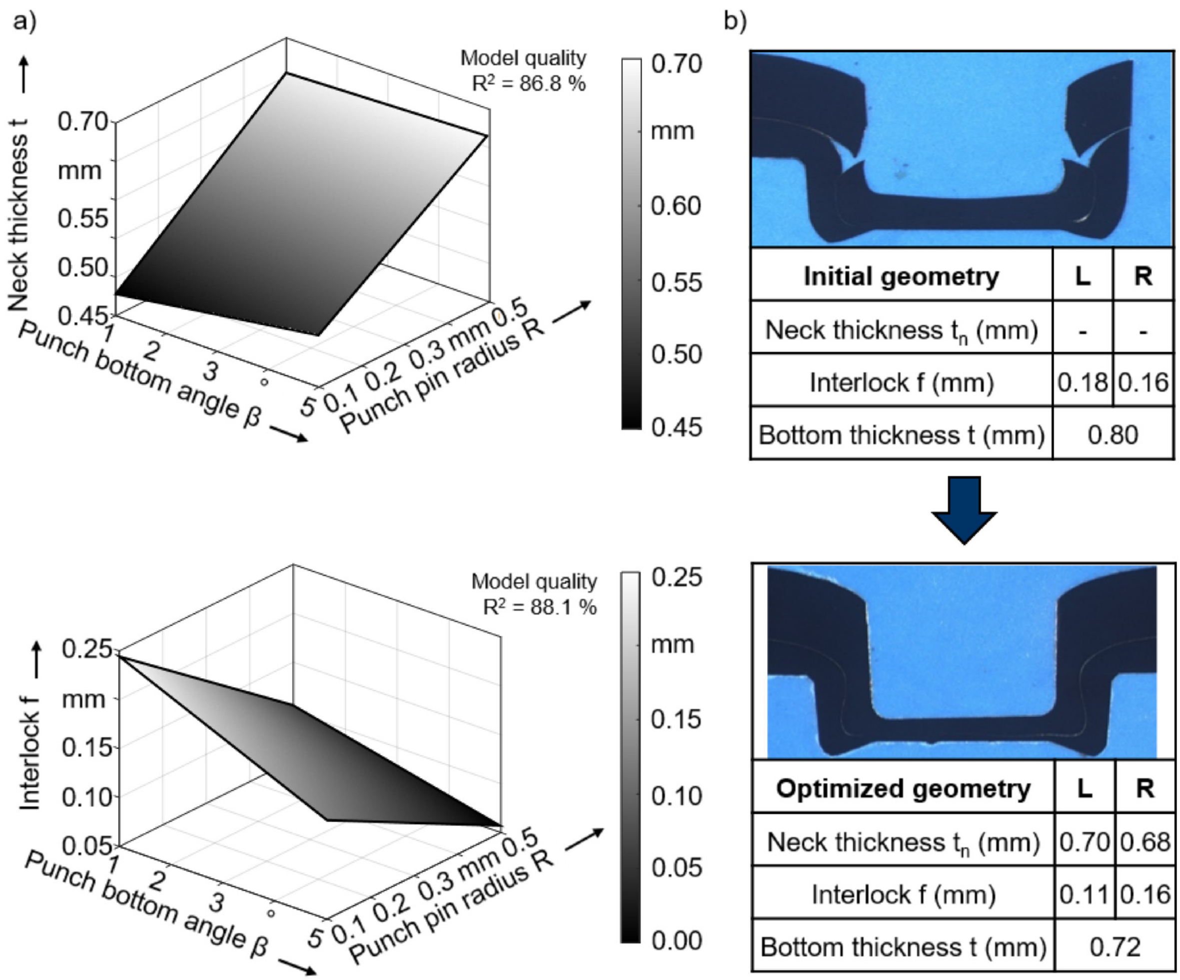


Fig. 19. (a) meta models for tool optimization and (b) joint geometry with standard tools and optimized tools for a blank holder force of $F_{\mathrm{bh}} = 800$ kN according to [98].

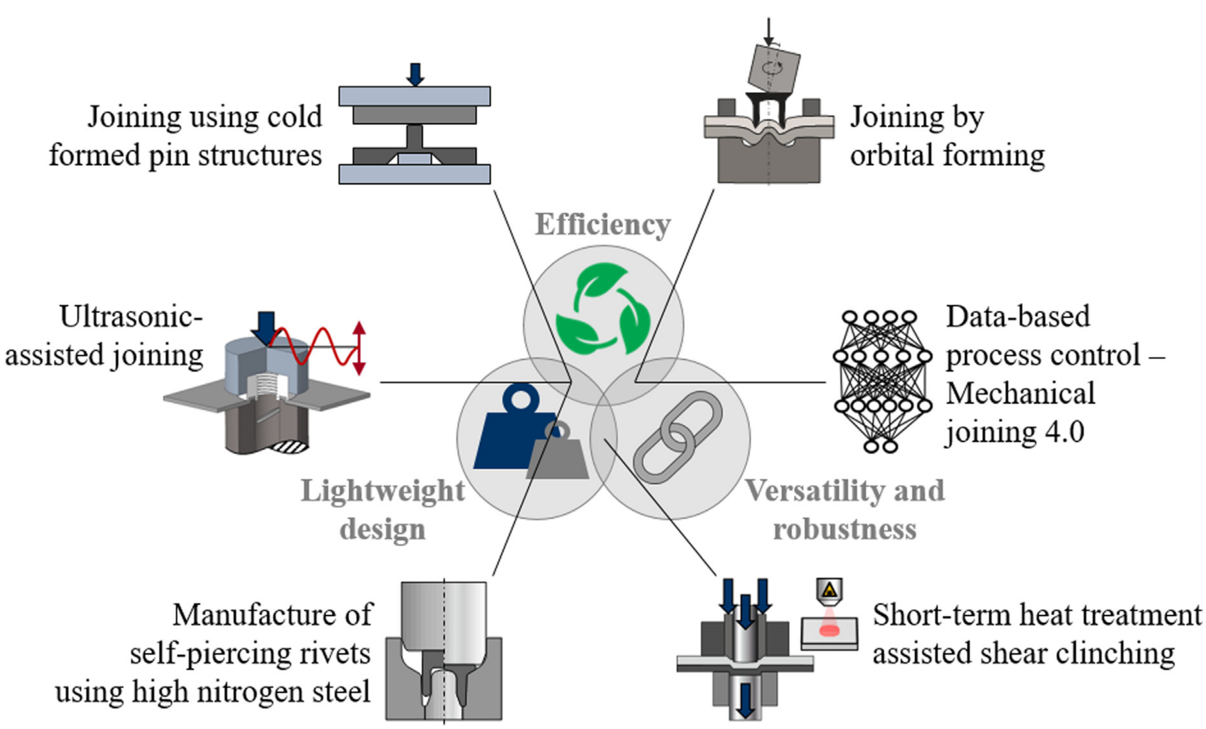


Fig. 20. Novel approaches based on the identified key aspects for the future development of mechanical joining processes.

Figure 20, are presented. In order to be able to respond to the new development of high-strength materials and the associated challenges, the process limits must be continuously expanded, which can be achieved, for example, by creating customized properties of the joints or the auxiliary elements. The shortening of the entire process chain, including the production of auxiliary elements, and the reduction of process forces contributes to the improvement of the process efficiency and resource protection. An increase in process robustness and versatility can be reached by creating more degrees of freedom and allowing an in-situ process adaptation.

In the future, joining of next generation high-strength materials will be a relevant topic. Regarding the efficiency enhancement, the consideration of the recycling of materials and joints taking into account the whole life cycle of products will become more and more important. This also includes the improvement of sustainability through the reduction of production rejects, which in turn is closely linked to the further increase of process robustness. A focus in this area should be placed on the continuous process monitoring including the targeted use of data, whereby the AI-supported deepening of process understanding could become a key factor for the development of self-regulating processes.

Conflict of interest

The authors certify that they have no financial conflict of interest (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc) in connection with this article.

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