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Joining by forming technologies: current solutions and future trends

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Abstract

The progressively more demanding needs of emissions and costs reduction in the transportation industry are pushing engineers towards the use of increasingly lightweight structures. This goal can be achieved only if dissimilar and/or new materials, including polymers and composites, are joined together to create complex structures. Conventional fusion welding processes have often been proven inadequate to this task because of the high heat input reducing the joint mechanical properties or even making the joining process impossible. Joining by forming technologies take advantage on the plastic deformation to create sound joints out of even very dissimilar materials. Over the last 25 years, several new processes, with increasing potential in effectively joining virtually every structural material, have been invented and developed. In the paper, a comprehensive overview of the most utilized joining by forming processes is given. For each process, an analysis of the current research trends and hot topics is provided, highlighting strengths and weaknesses for industrial applications.

Keywords Light alloys · Joining · Welding · Solid state · Clinching · Riveting

Introduction

In the last years, increasing pollution as well as progressive oil reserve depletion have led to energy saving and environmental impact minimization policies. These objectives can be pursued by employing materials with a diverse range of properties, which help designers to select the right material in the right place to achieve the desired structure performances [1]. In fact, the development of manufacturing technologies is leading to a wide use of innovative materials in various industry fields. Lightweight alloys, namely aluminum, magnesium and titanium alloys, are characterized by high strength/weight ratio thus allowing the production of light structures without using expensive composite materials. Such characteristics have been highly appreciated by the transportation industry because of the advantages they provide in terms of fuel consumption reduction and reduced emissions. For example, in the aeronautic and aerospace fields, besides Light Metal Alloys (LMAs), as newly and specifically developed aluminum alloys, also Polymer Matrix Composites (PMCs) have been extensively introduced and combined to LMAs. The potentiality in the automotive field has been proved in construction of race cars, where the extensive use of light alloys and carbon fiber reinforced plastics has resulted in car body lightening. Finally, in the naval industry, several examples can be found of dissimilar aluminum-steel joints and PMCs and LMAs joined components.

The growing use of these materials has led to the development of innovative joining techniques to produce complex structures[2] which enable “difficult to weld” or “non weldable” materials to be joined. Traditional welding techniques depend on melting the base material along the joining line. However, during the solidification of the weld, unwanted phenomena, i.e., segregation, dendritic recrystallization, gas bubbles (porosity) and formation of brittle intermetallic phases (IMCs) may occur compromising the joint resistance. This is a particularly limiting factor when dissimilar joints have to be produced as they are often characterized by significantly different melting temperatures and early joint failure due to the presence of IMCs is likely to occur.

In the last decades, researchers have been focusing on the development of new joining technologies to effectively address the issues of the melting-based welding techniques.

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A particularly interesting joining process classification embrace the so called "joining by forming" processes. Very different processes, characterized by extremely different process mechanics can be identified in this category. In fact, joining by forming can take place in cold or hot conditions, with or without "filler" material and with consumable or no consumable tools. However, for all the processes belonging to this category the parts joining occurs as a consequence of plastic deformation induced by proper joining machine either/both on the sheets to be joined or/and on a properly designed rivet or pin.

In this paper, joining by forming processes are divided into four main categories: mechanical fastening processes, friction-based processes, innovative joining processes (including forming or pre-forming of the materials) and hybrid joining processes, taking into account the combination of two or more techniques. For each category, besides a short description, the main advances and the current research trends will be presented and discussed.

Mechanical fastening processes

Self-piercing riveting

Mechanical fastening processes are indispensable for the joining of dissimilar materials, as the application of thermal joining techniques is limited in this case because of the differences regarding the melting temperatures of the materials. Self-piercing riveting is an established mechanical joining technology that is widely used, especially in the automotive sector due to the increasing importance of lightweight construction and multi material design. Two or more sheets are joined by creating force-fit and form-fit joints using rivets as mechanical fasteners [3]. The semi-tubular rivet pierces the punch-sided sheet and flares into the die-sided sheet leading to the formation of a mechanical interlock, as it is depicted in Fig. 1. As a consequence, no pre drilled hole is needed in contrast to conventional riveting. Besides semi tubular rivets, solid rivets can also be used, whereby the rivet pierces all the sheets. The interlock is created when the ring groove is filled by the die-sided material [3].

One of the main advantages of self-piercing riveting is that a wide range of similar and dissimilar materials can be joined. In recent years, the focus of a large number of investigations has been on the joinability of different material combinations. Self-piercing riveting can principally be used for the joining of aluminum alloys with mild steels [4], with copper alloys [5], with titanium [6] and magnesium alloys [7]. Mori et al. [8] optimized the shape of the die used for the joining process to open the possibility of joining the ultra-high strength steel SPFC980 and the aluminum alloy A5052. However, the joining becomes more difficult when there are large differences regarding the strength of the materials to be joined and the arrangement of the high strength steel has an impact on the joinability [9]. The application of self-piercing riveting is not limited to the joining of metals. In principle, the technique can also be used for the joining of aluminum alloys with plastics [10] and with fiberglass composites [11]. However, the laminate damage has to be taken into account when joining fiber-reinforced plastics by self-piercing riveting [12].

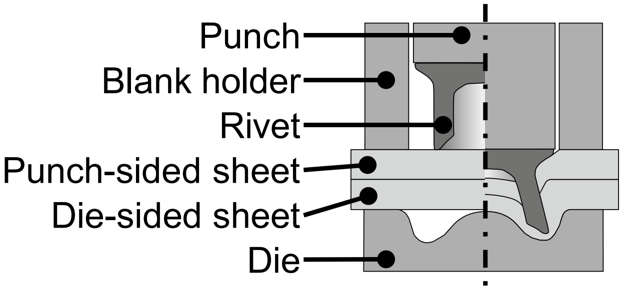


Fig. 1 Principle of the semi tubular self-piercing riveting process according to [3]

In view of the rising requirements regarding the passenger safety and the reduction of the vehicle weight, there is a need for innovative self-piercing riveting processes and new approaches in order to face the challenges of material mix with advanced materials in the future. A new joining by forming process, the so-called double-sided self-piercing riveting, provides the chance to overcome limitations concerning the joinable sheet thickness for dissimilar materials [13]. A tubular rivet is positioned between two sheets, the sheets are joined by flat parallel punches and the mechanical interlock is created by the flaring of the rivet, which makes the process independent of the thicknesses of the sheets [13].

Another new joining concept is self-locking self-pierce riveting, whereby modified solid rivets with an embossing contour below the rivet head are used, which is why no embossing ring on the die is needed [14]. The new process allows not only the joining of the ultra-high strength steel 22MnB5 with aluminum alloy, but also an increased flexibility of the process, as the die no longer needs to be adjusted in dependence of the material combination to be joined [14]. The efficiency and sustainability of the processes are further issues besides the extension of existing process limits, on which future research should concentrate because of the importance of environmental protection. This already starts with the rivet manufacturing process. By using high strain hardening materials like high nitrogen steel as rivet material, the conventionally necessary heat treatment and coating of the rivets after manufacturing can be omitted, as the new rivets provide an adequate strength and corrosion resistance without these post process steps [15]. Thus, it is possible not only to join high strength steel but also to shorten the energy-intensive and time-consuming rivet manufacturing process [15].

Recently, Ferreira et al. presented a new joining by forming process named as injection lap riveting, which combines machining and forming [16]. The process has two stages: first, a dovetail ring hole is machined in the lower sheet and afterwards a semi-tubular rivet is injected through the upper sheet into the dovetail hole of the lower sheet to obtain the interlocking. It is worth noting that, for the process, no fracture and formation of new surfaces occur. Hence, rivets made of harder materials are not needed. This is particularly relevant for hybrid electric busbars in which solely copper and aluminum must be used. Figure 2 shows a sketch of the process.

A further new approach is the process combination of tumbling and self-piercing riveting by applying a tumbling kinematic for the punch that allows a flexible process design without the need for tool change and leads to a high process robustness [17]. Furthermore, the digitalization of the processes is another trend. Machine learning methods can be used to predict appropriate process parameters and the expected joining result, which facilitates the experience-based and experimental joint design, especially for new material combinations [18]. In summary, the development of efficient and sustainable self-piercing riveting processes, which enable the joining of advanced materials and are robust against variability in inputs, will be a key aspect in the future.

Clinching

Clinching allows the highly productive and cost-efficient [19] joining by forming of two or more sheet metal components without auxiliary elements. During the process, the sheets are pushed into a die and subsequently upset, which leads to the formation of an interlock between the joining partners (Fig. 3). Thus, cohesion is based on a form and force fit. Forming of the interlock is promoted either by a ring groove in the die or by split dies with movable lamellas. The joint can be formed with and without cutting of the

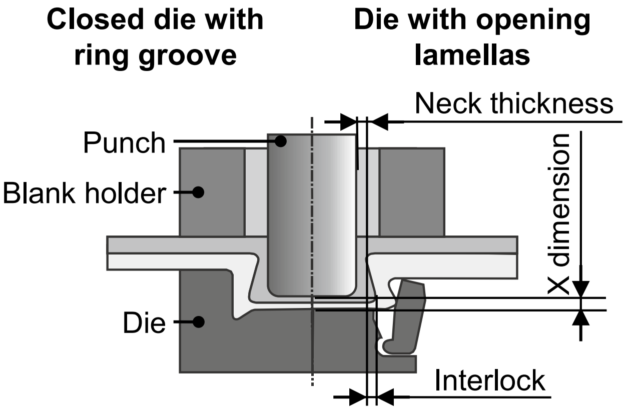
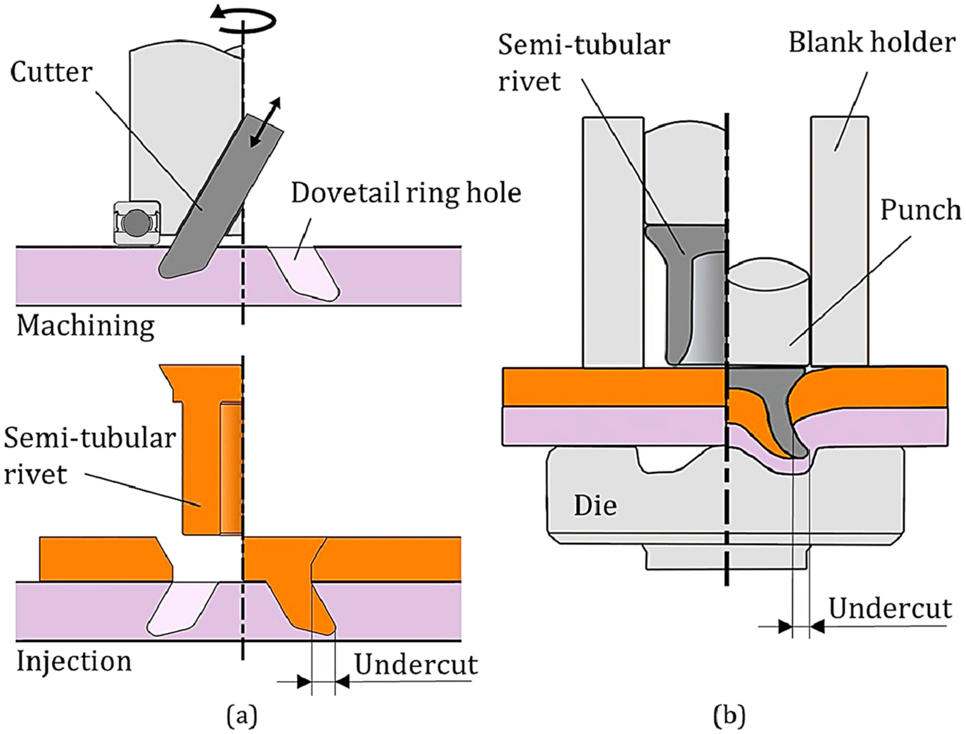


Fig. 3 Clinching tool and characteristic features of the joint according to [20]

Fig. 2 (**a**) Injection lap welding process sketch as compared to (**b**) conventional SPR



joining partners, while the shape of the joint is usually either round or square [20].

An important quality criterion of clinched joints is the resulting bottom thickness, which is addressed as X dimension [21]. The joint strength depends on the neck thickness as well as on the interlock [20]. Due to the protrusion of the joint, which is unfavorable for visible joints, flat clinching was developed. In a second subsequent process step, the clinched joint is flattened, using a flat die [22].

Even though the principle of clinching has already been mentioned in a patent in 1897 [23], its industrial application has only started in the late 20th century. Today, clinching is a state of the art joining method in the sheet metal processing industry and can be used for materials with thicknesses from 0.1 mm for single sheets and up to total thicknesses of 12 mm [21]. In [20] a tensile strength of 700 MPa is given as process limit. However, recent developments regarding the used tool geometries allow the clinching of sheet components with a tensile strength of 800 MPa [21] and even of 980 MPa in [24]. Usually, the material with the higher thickness and strength is placed on the punch side [21]. However, in [24] the high-strength material was placed on the die-side. The die depth was reduced in order to decrease tensile stresses and avoid failure, which resulted in a decreased formation of the interlock. An approach to increase the interlock by pre-forming of the die-sided joining partner is shown in [25]. If a flat die is used, materials with low ductility like cast aluminum can be joined, as compressive stresses are imposed throughout the whole process [20].

Another approach to increase the forming limits in clinching processes is the pre-conditioning of the joining partners by a heat treatment before the joining operation. For example, for AA7075 T6, an improvement of the joinability can be achieved by a short-term heat treatment at 250 °C for 3 s [26]. Clinching at elevated temperatures was presented in [27] for magnesium and in [28] for hardenable 6xxx aluminum. The increased part temperature results in the decline of the flow stress and the increase of the forming limit [28]. Thus, higher plastic strains can be achieved. In [29] a tool setup, which includes a laser as heat source in the punch, was presented. By increasing the sheet temperature, even hot stamped 22MnB5 could be joined. Lately, clinching of hybrid structures, consisting of metals and polymers, has come into focus. In [30] glass fiber reinforced plastics on the die-side were joined with AA6082 and AA5086 on the punch-side. Round grooved, split and flat dies as well as rectangular shear dies were used. The best results were achieved with split dies [30]. Yet, crumbles of the plastic remained in the slits. Generally, damaging of fiber reinforced plastics during the joining process is a challenge.

In order to overcome the limitations of clinching regarding the mechanical properties of the joining partners, further process variations have been developed. Clinching with pre-holing of the die-sided sheet allows the joining of high-strength materials, as the process is independent of the properties of the lower joining partner. Therefore, it is also suitable for joining of fiber reinforced plastics [31]. However, the exact retrieval of the hole is crucial for the joint quality. Punch clinching also allows the joining of materials with low ductility on the die-side. The punched slug of the lower joining partner remains within the joint. However, the load-bearing cross section is also solely formed by the upper sheet. Analyses for cast aluminum and magnesium were done in [32].

Another variation is shear-clinching (Fig. 4) [33]. The die-sided joining partner is indirectly shear cut during the process, while the upper sheet is pressed into the cut-out hole. Therefore, even ultra-high strength materials like hot stamped 22MnB5 can be joined in a single stage process. The suitability of shear-clinching for the joining of three sheets has recently been shown in [34]. However, the process is also limited by the mechanical properties of the punch-sided joining partner. In order to enhance the process limits, investigations on the short-term heat treatment of punch-sided high-strength AA7075 T6 were done in [35].

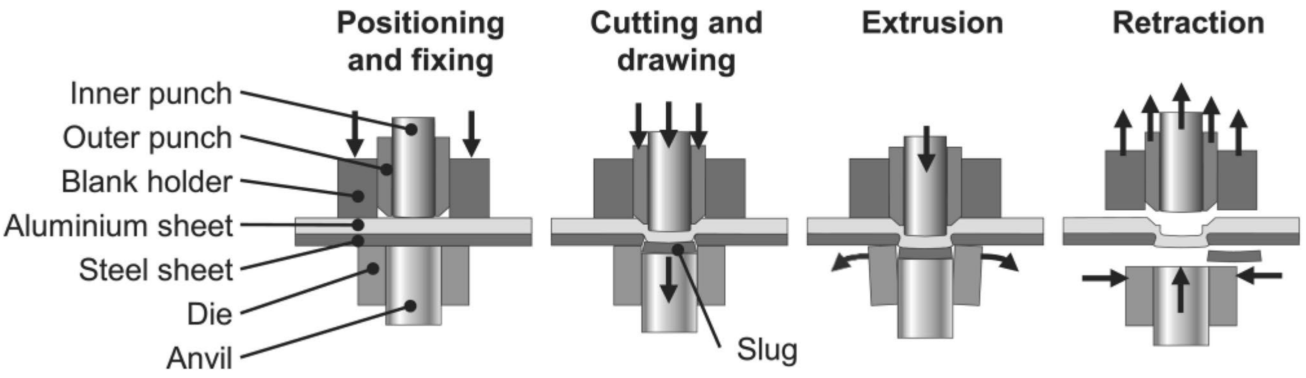


Fig. 4 Sketch of the shear clinching process [33]

A promising approach to not only grant the joinability, but also improve the joint characteristics is the locally limited heat treatment before the joining process, using a laser as heat source [35]. Further special applications of the clinching process are roller [36] and rotational clinching [37]. The assistance of the clinching process by superimposed ultrasonic in order to reduce the process force is shown in [36].

Due to the sensitivity of the clinching process towards aberrations of sheet thicknesses and the material strength, the process control has gained importance. In [38] an approach to determine the boundary conditions like the sheet thickness and pre-hardening as well as aberrations in previous process steps and providing the information for the clinching process is shown.

Friction based processes

Linear Friction Welding

Linear Friction Welding (LFW) is used to join non-axisymmetric thick parts. Although the process was first patented in 1929, it has never been actually used to produce parts up to a few years ago because of technical limitations in building proper machines. In the process, the two parts to be welded are put in a reciprocating motion, with large oscillation frequency, under a certain pressure. The heat generated by the friction forces work softens the material and eventually allows to get solid bonding conditions.

Four main phases can be identified in the process: (i) the initial phase, during which the reciprocating motion begins and the actual contact surface is less than 100% of the transverse sections of the specimens; (ii) the transition phase characterized by material softening and actual contact surface equal to 100% of the specimens transverse section; (iii) the equilibrium phase, which starts as the softened material is extruded under the applied pressure; (iv) the deceleration phase, when the reciprocating motion is stopped and additional pressure can be applied for a few seconds on the specimens in order to consolidate the weld (Fig. 5). The process is usually utilized for high added value products as the aeroengine bladed disks (blisks). Current research trends regard three main topics: the possibility to weld new and highly resistant materials, the production of dissimilar joints and the study of the residual stresses after the process.

Li et al. [40] studied the microstructural and mechanical properties of joints obtained out of S31042 heat-resistant steel blocks. Proper oscillation frequency, oscillation amplitude, pressure and process time were selected on the basis of preliminary tests. The results indicated that tensile properties similar to the one of the parent materials can be obtained, also due to the fine recrystallized grains and ultrafine NbCrN particles found in the weld nugget. Geng et al. [41] demonstrated the feasibility of LFW of GH4169 superalloy. In particular, a proper constitutive model to be implied in the numerical simulation of the process was developed, finding that the modified Field-Backofen model and Johnson-Cook model cannot properly describe the plastic flow stress evolution of GH4169 superalloy, especially at high strain rates occurring during the process, while the strain compensated Arrenius model resulted as the one allowing better matching between experimental and numerical results. Ma et al. [42] focused on the Ni-based GH3044 superalloy. Different tests were carried out with varying oscillation amplitude. They concluded that sound joints can be produced, with Ultimate Tensile Strength (UTS) comparable to the one of the base

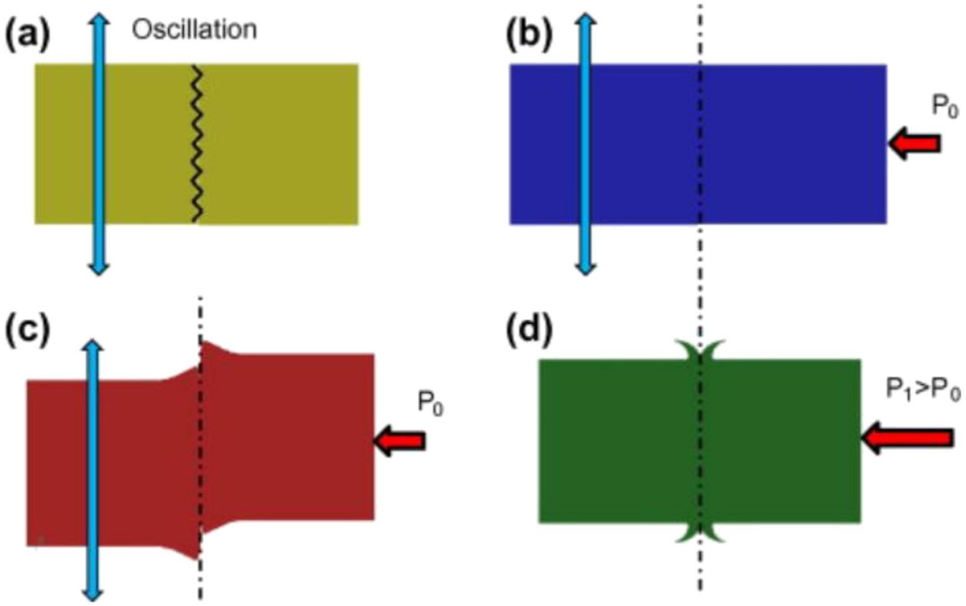


Fig. 5 Sketch of the four main phases of the LFW process: (**a**) initial phase, (**b**) transition phase, (**c**) equilibrium phase and (**d**) deceleration phase [39]

material. Oxides and grain size are strongly affected by the welding parameters, with finer grain size found in the nugget mainly due to dynamic recrystallization and limited continuous dynamic recrystallization. Finally, Masoumi et al. [43] proposed an analytical method, validated through axial shortening measurements, to determine process parameters in LFW of recently developed wrought Ni-based superalloy AD730™. The results indicate that post welding heat treatment is needed for the used alloy in order to maximize the mechanical properties both at room and high temperature.

As recent advances in welding dissimilar joints are regarded, Matsuda et al. [44] successfully welded AA5083 and AA6063 aluminum alloys to 304 stainless steel. Experimental tests were carried out under high oscillation frequency and different friction load and process time values. It was found that joint efficiency reached about 95% and 90% for the joints produced with AA5083 and AA6063, respectively. Too short processes times resulted in the formation of unwelded areas while too long process times produced excessive softening of the base alloy with consequent low joint strength. Boyat et al. [45] studied the dissimilar LFW of Ti–5Al–2Sn–2Zr–4Mo–4Cr (Ti17) and Ti–6Al–2Sn–4Zr–2Mo (Ti6242) under fixed process parameters, highlighting the microstructural mechanisms leading to the successful cohesion between the two dissimilar but mutually soluble titanium alloys considered. Finally, Ye et al. [46] investigated the dissimilar LFW of Ni-based superalloys IN718 and IN713LC. The different microstructures across the weld line were highlighted both in the as-welded and in the post welding heat-treated joints, finding increased microhardness for the heat treated specimens.

Due to the critical working conditions which parts produced by LFW usually undergo, residual stress prediction is a key point to process industrial widespread. Nunes at al. measured the residual stress, through the hole drilling method, in martensitic 18CrNiMo7-6 steel specimens in the following conditions: “as forged”, “as welded”, “as welded” without flash and post weld heat treated [47]. Interesting conclusions include that flash removal does not influence significantly the residual stress close to the weld center and post welding heat treatment switches the tensile stresses due to the welding process back into compressive, allowing to reach the highest values of compressive stresses close to the surface of the specimen. Buhr et al. [48] proposed a modelling approach to predict residual stress in LFW of Ti64 titanium alloy. Welds were produced with varying process parameters and the contour method was used to determine the residual stress, finding a strong correlation between the equilibrium temperature distribution and the residual stress field. Gadallah et al. [49] welded medium carbon steel (ISO-C45) with varying pressure measuring residual stresses by both X-Ray Diffraction (XRD) and contour method. It was found that both the methods were able to identify the effect of pressure, i.e., decreasing residual stress close to the center line was found with increasing pressure. Additionally, increasing full-width at half-maximum (FWHM) of the XRD peak and microhardness at the weld line was obtained with increasing pressure.

Friction Stir Welding

Friction Stir Welding FSW) was patented in 1991 by The Welding Institute. In the original formulation of the process, a non-consumable rotating tool is inserted between the two sheets to be welded and then moved along the seam. The heat, mainly produced by friction between the tool surface and the sheets, softens the material. In this way, the shoulder and the pin can stir the softened material through a combined roto-translational movement. As a solid-state welding process, FSW allows overcoming most of the main issues of traditional fusion welding processes, i.e., porosities, inclusions, distortions etc. For these reasons, during the last 30 years, FSW has been successfully used to weld hard-to-weld or unweldabe materials. Although first applied to aluminum alloys and butt joint configuration, the process has been demonstrated feasible also for several other materials, i.e., magnesium alloys, titanium alloys, copper, steels, etc. and joint configurations, i.e. lap, T-joints, fillet/corner joints, and others. The process can be considered mature for the above described “standard” applications, which mainly regard aeronautical, aerospace, automotive, naval and ground transportation industries. However, in the last few years several research topics have been developed and investigated by the research groups working in this field. Today, the most interesting research trends regards the possibility to weld polymers and composites, the possibility to produce Tailored Welded Blanks (TWBs) both in terms of different materials and different thickness and the introduction of newly developed processes obtained modifying standard FSW with the aim to overcome or minimize the actual process main limitations.

As far as FSW of polymers is concerned, Sheikh-Ahmad et al. [50] investigated the possibility to weld commercially available pipe-grade HDP-carbon black composite. The effect of the main process parameters was studied with the aim to overcome the main drawback given by the relatively low melting temperature of the used material, i.e., the melting occurring under the rotating shoulder and on the trailing side of the rotating pin. Derazkola et al. [51] demonstrated the feasibility of FSW of polycarbonate lap joints observing, for optimal process parameters selection, an opaque weld line due to rearrange of carbon chains and partial degradation of PC.

As FSW of metals is regarded, as previously observed, current research topics are focused on the production of TWBs. TWBs are obtained welding together two sheets of different thickness and/or materials and can be used for the stamping of optimized and advanced components allowing significant cost and weight reduction in the transportation industries. Recently, Moayedi et al. [52] focused on the weld orientation effects on the formability of tailor welded thin steel sheets. Low carbon stainless steel St 14 sheets with thickness of 1.2 and 1.4 mm were welded and specimens with different weld orientation were cut and evaluated by means of formability tests. They observed that the flow stress of the weld region is greater than the one of the base material due to fine grain formation. Additionally, the transverse weld orientation showed the best formability in uniaxial tension while the longitudinal weld orientation was the most formable.

Kesharwani et al. [53] produced two different aluminum TWBs using both different materials, i.e., AA5052-H32 and AA5754-H22, and different thickness, i.e., 2.0 and 2.5 mm, with optimized parameters. Then, they studied the formability of the produced joints with the aid of a dedicated numerical model. A different approach to TWBs was recently proposed by some of the authors [54] have recently developed an in-process tool rotation control in order to obtain constant mechanical properties along the weld seam using different thickness AZ31 magnesium alloy sheets. Mallieswaran et al. [55] focused on the optimization of the welding parameters with respect to joint strength. Dissimilar material TWBs were produced by welding AA1100 with AA6061 aluminum alloys. Statistical tools were used to establish a mathematical relation between process parameters and joint strength. Finally, Mehta et al. [56] studied Conventional and cooling assisted FSW of dissimilar 6 mm thick AA6061 aluminum alloy and AZ31B magnesium alloy, finding a beneficial effect of cooling both in terms of joint efficiency and maximum hardness.

As dissimilar joints are regarded, it is worth noting that new tool geometries can be developed in order to maximize the joint performance, especially when materials which present chemical incompatibilities and/or have significantly different melting temperatures have to be joined. In this respect, the so-called Friction Stir Scribe (FSS) process represents one of the most interesting advances recently developed (Fig. 6). Upadhyay et al. [57] showed the feasibility of the process in order to weld carbon fiber-reinforced polyamide (LCF50-PA66) and AA6022 aluminum alloy, AZ31 magnesium alloy and steel, as well as different aluminum alloys and different steels highlighting the presence of a continuous, rivet-like in situ mechanical interlocking feature produced during the process. Wang et al. [58] highlighted the correlations between welding parameters, hook height, joint strength and fracture position in dissimilar FSS of 6022-T4 aluminum alloy and electro galvanized mild steel. Recently, the same authors [59] studied the intermetallic compound at the interface between AA6022-T4 aluminum alloy sheets and DP600 steel sheets. Joint efficiency up to 98% was

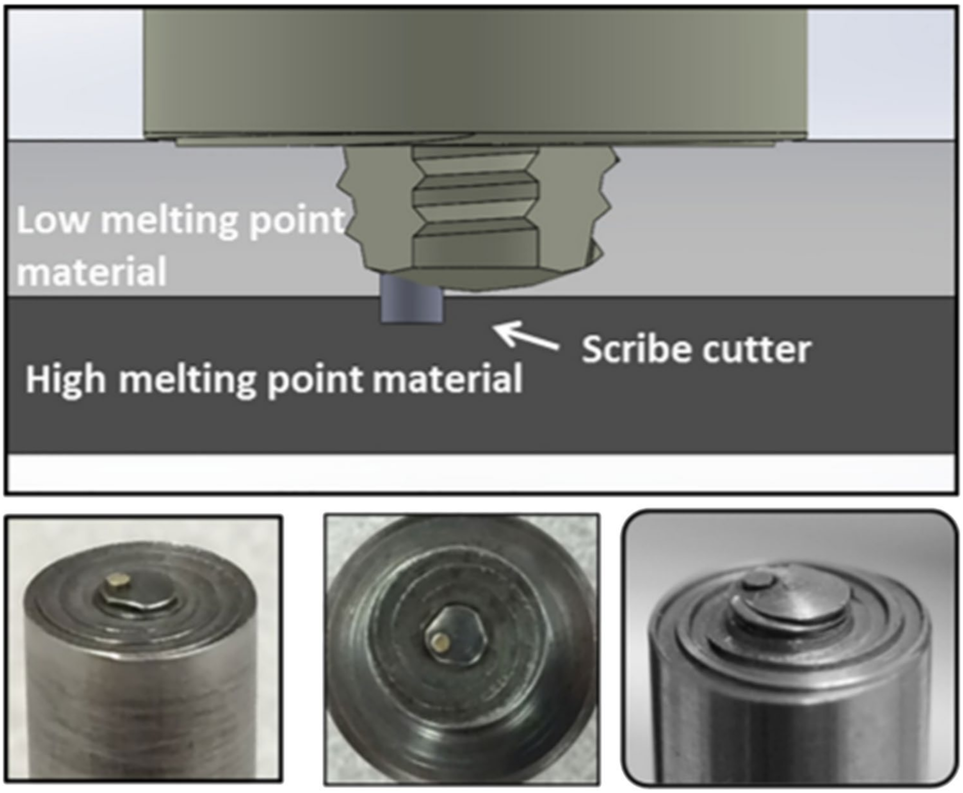


Fig. 6 Sketch of the Friction Stir Scribe process and utilized tool [57]

reached and a theoretical model for the prediction of the formation of intermetallic was presented.

Among the most interesting FSW-derived process there is Stationary Shoulder Friction Stir Welding (SSFSW). The process was developed by The welding Institute (TWI) with the aim to overcome the thickness reduction due to the effect of the rotating tool shoulder. Besides, as the tool slides on the top surface of the sheets instead of rotating, the heat input produced by the rotating pin is reduced with respect to traditional FSW, resulting in beneficial effects also for materials characterized by poor conductivity, e.g., titanium alloys. Weng et al. [60] studied the bonding interface behavior in SSFSW of AA2024 lap joints. Both experimental and numerical results showed that the shape of the joint, the peak temperature zone and the equivalent plastic strain zone are cylindrical in contrast with the pyramidal shape observed in traditional FSW, resulting in a more limited Thermo Mechanically Affected Zone (TMAZ) and Heat Affected Zone (HAZ) extension. Patel et al. [61] demonstrated the potential of the process in order to get grain refinement in AZ31 magnesium alloy sheets.

Bobbin tool FSW (BTFSW) was developed in order to increase the range of thickness weldable and to homogenize the microstructural properties across the plate thickness: in the process a tool made by two shoulders acting on both surfaces of the plate and connected by a pin is used. Xu et al. [62] compared conventional FSW and BTFSW in welding of 7085-T7452 alloy 12 mm thick plates. They found larger grain size and lower deformed grain fraction in the BTFSWed joints due to the lower strain rate. Wang et al. [63] added a further modification to the process, introducing a different rotation velocity between upper and lower should. The process, called dual-rotation bobbin tool friction stir welding (DBT-FSW) was developed in order to further enhance the mechanical properties of AA2198-T851 aluminum-lithium alloy joints (Fig. 7). The results indicated that larger process windows can be used to produce defect free joints with increased process stability. Finally, Li et al. [64] successfully applied BTFSW to 4 mm thick ZK60 magnesium alloy plates. Major findings are that, despite significant grain refinement, extensive softening occurs because of the dissolution of the precipitates induced by the heat input, resulting in joint efficiency around 80%.

Friction Stir Spot Welding

Friction Stir Spot Welding (FSSW) was developed as an alternative process to conventional spot welding/joining techniques, such as resistance welding or clinching, with the aim exploit the typical advantages of the FSW process in terms of low heat input and possibility to weld very dissimilar materials. In the process, the rotating tool is just plunged in the overlapped sheets and retracted with no feed rate. For these reasons as well as for the ease of implementation, FSSW has been intensively used by the transportation industries in the last years. As for the FSW process, research has recently moved into two main directions, i.e. the study of the capability of welding dissimilar materials and the development of new process variants able to enhance the properties of the produced joints.

Zhou et al. [65] studied the microstructural and mechanical properties of dissimilar FSSWed joints made out of 1060 aluminum and T2 copper 2 mm thick sheets. They found that both mechanical and metallurgical bonding can be obtained when proper tool rotation is selected, resulting in a continuous IMC layer with proper thickness. Mehta et al. [66] proposed a new strategy to repair the exit hole in dissimilar 6061 Aluminum alloy and AZ31B magnesium

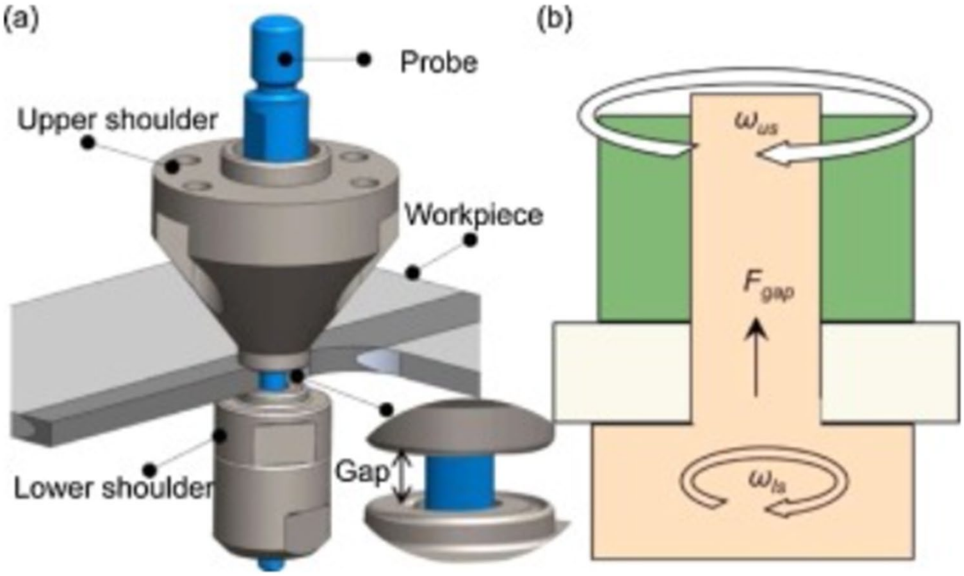


Fig. 7 Sketch of (**a**) the dual-rotation bobbin tool friction stir welding and (**b**) process principle [63]

alloy FSSW. The developed technique is based on the use of subsequent pinless tools with increasing shoulder diameter and allowed obtaining better mechanical properties with respect to conventional FSSW.

As far as FSSW process variants are regarded, a few techniques have been recently developed by different research groups, the most significant being Refill FSSW, double-sided FSSW and short traverse FSSW. Figure 8 shows a sketch of the above cited processes. In particular, in refill FSSW a

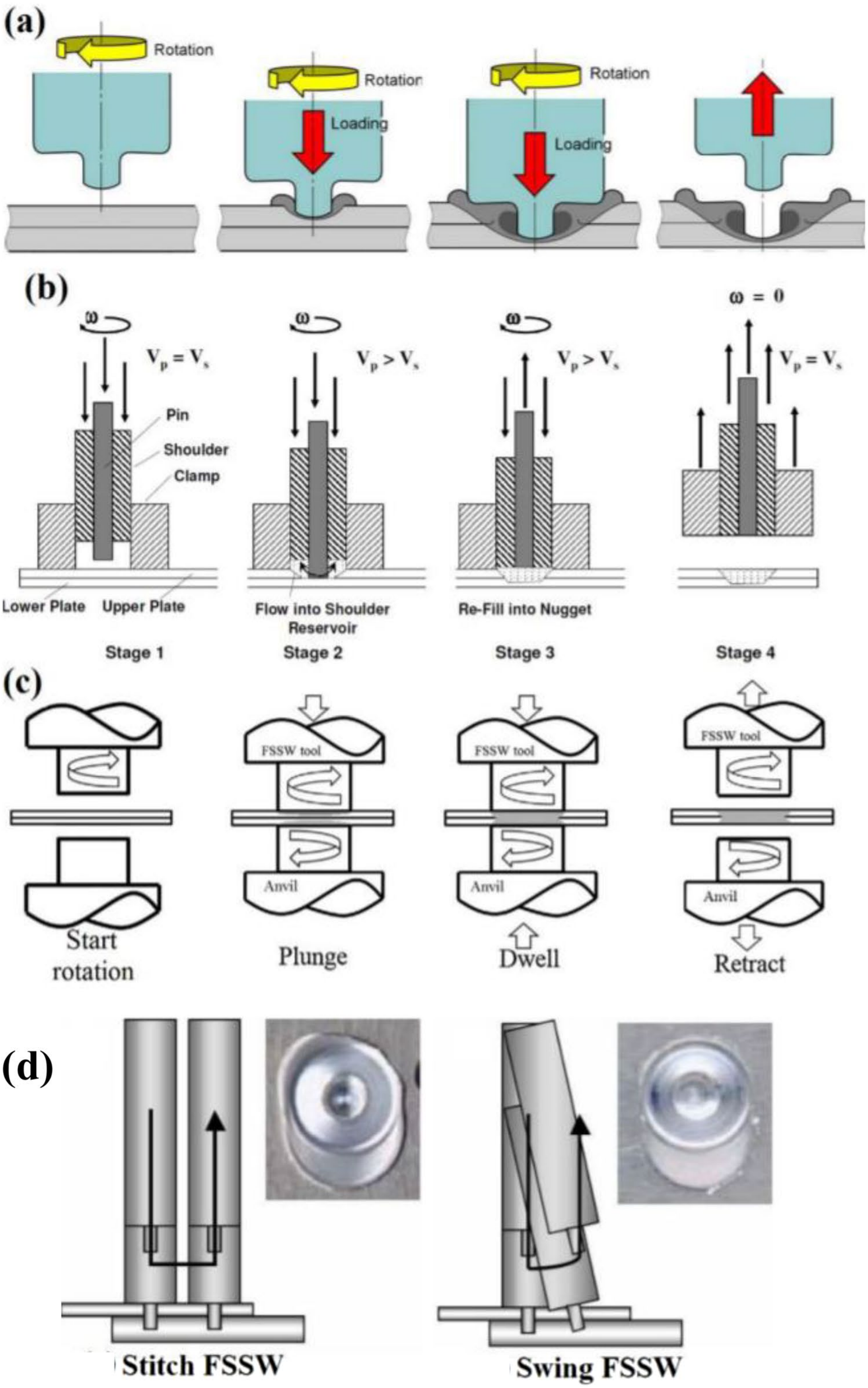


Fig. 8 Sketch of (**a**) conventional FSSW, (**b**) Refill FSSW, (**c**) double-sided FSSW and (**d**) short traverse FSSW [71]

dedicated machine is required, allowing for separate control of pin, sleeve and clamping. After conventional FSSW is carried out, the pin is retracted while the tool sleeve and the clamp still apply pressure on the sheets. In this way, an upward material flow is induced and the keyhole can be “refilled” thus overcoming one of the major drawbacks of conventional FSSW, i.e., the detrimental effects of the keyhole on the joint mechanical properties. Shen et al. [67] successfully welded AA6022-T4 and galvanized DP600 steel focusing on the effect of the tool sleeve temperature. The authors also indicated that the zinc coating on the steel sheet has beneficial effects on the overall joint strength as it generate a “brazing“ effect. Dong et al. [68] carried out refill FSSW on 2 mm-thick 5083 Al alloy and 1.8 mm-thick AZ31 Mg alloys under different process times finding that the bonding occurs through the liquid eutectic phase formed by the stirring of the sleeve. Double sided FSSW is a newer technique in which two tools similar to the one used for refill FSSW are placed on both sides of the overlapped joint. Wang et al. [69] demonstrated the feasibility of the process applied to dissimilar welding of AZ31 and ZK60 magnesium alloys, finding that the shearing at the interface between the pin and the sleeve enhances the mechanical resistance of the joints by promoting recrystallization.

Finally, some of the authors [70] have proposed a variation of the FSSW process in which a short path is assigned to the tool before retracting with the aim to enlarge the bonding area and increase the mechanical properties of the joints. They found increased performances and only slightly longer process times with respect to conventional FSSW.

Innovative joining processes

Joining with pin structures

When joining with pin structures, cylindrical structures protruding from the surface are often used to join components together. These are utilized in particular for joining dissimilar materials such as steels and fiber-reinforced plastics to increase the strength of the joints. However, pins are not only used to join metals and fiber-reinforced plastics, as research is also being conducted on the use of pin structures to join dissimilar metals such as steel and aluminum [72]. There are numerous processes for the production of pin structures, which can be categorized into additive, subtractive, formative and molding processes. These include additive manufacturing processes such as powder bed fusion with a laser beam [73], cold metal transfer [74], the surf-sculpt process [75], cold extrusion from the sheet metal plane [76] and metal injection molding [77].

The joining process when using pin structures is divided into two process steps, pin production and joining. There are different joining techniques depending on the material combinations used. In the production of multi-material systems made of steel and fiber-reinforced plastics, thermosets are frequently used as matrix material. Here, the pin structures are often integrated into dry fibers before they come into contact with the matrix through vacuum assisted resin infusion [78] and are subsequently cured. Furthermore, pre-impregnated sheets [78] are used as well. In addition to thermosets, thermoplastics are also used as the matrix material. Popp et al. [79] utilized glass fiber-reinforced polypropylene, which is heated locally by infrared radiation, to press additively manufactured pin structures into the composite in order to investigate the fiber rearrangement mechanisms.

In contrast, when joining dissimilar metals, caulking [76], in which the pin is inserted through a perforated joining partner and subsequently upset, and direct pin pressing [80], in which the cold extruded pin is pressed into an unperforated joining partner, can be used for joining. For this purpose, pin structures cold extruded from the sheet metal plane are utilized, which have a higher strength due to strain hardening.

Joining using plastic instability

Joining with plastic instability is based on the formation of plastic instability waves under axial pressure and the resulting beads that cause interlocking between the components, for instance, to join tubes together at their ends or to join tubes to sheets (Fig. 9). In [81], plastic instability is used to join sheet panels to tubular profiles at room temperature, replacing methods such as welding or bolting. The process presented in this paper is divided into two steps. First, the tube, which is supported on the top and bottom by dies separated by a defined gap, is axially loaded with pressure until an axisymmetric bead forms in the opening between the dies, as the material buckles under the compressive load [81]. In the subsequent step, the sheet panel is placed on the formed bead and the free upper end of the tube is upset with a tool until the connection and thus the desired clamping geometry is formed.

Alves et al. [82] also used this principle to join tubes at their ends at room temperature. The process itself is accomplished in one stroke by first placing two chamfered tubes, supported internally by a mandrel, in an upper and a lower die with a gap between them. The axial downward movement of the upper die presses the upper tube against the chamfer of the lower tube, causing the upper tube to bend outward past the lower tube. As the axial movement of the upper die progresses, the upper tube comes into contact with the lower die, which starts the plastic instability, and the upper and lower tubes form a bead that creates the joint and the interlock. Yu et al. [83] also studied compression instability joining for thin-walled tubes both numerically

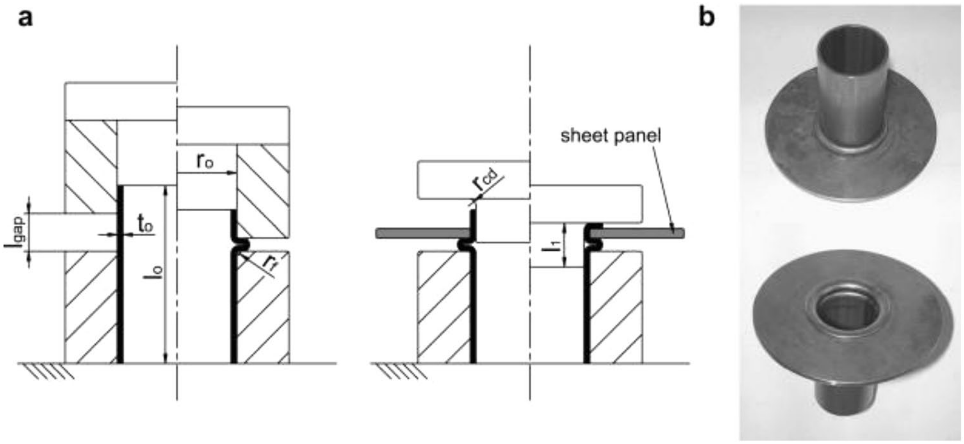


Fig. 9 Joining using plastic instability: (**a**) Sketch of the process and (**b**) application to a circular sheet joined to a tube [81]

and experimentally to investigate the influence of geometric parameters on the process and the subsequent joint strength.

Joining by a process combination of deep drawing and cold forging

Another innovative joining process is a combination of deep drawing and cold forging of multi-material components, as presented in [84]. In this process, a sheet is drawn around a massive component in a deep drawing tool that is placed above a conventional cold extrusion die. This four-stage process enables the production of massive components with shells made of different materials. In the first step, the sheet is conventionally deep-drawn by the core. In the second step, the joining components come into contact with the shoulder of the die, which causes the core body to be compressed. As soon as the core is in contact with the container wall, the third process step begins. The fourth stage consists of a conventional forward extrusion process with decreasing forming force. The process is characterized by a wide process window and thus allows a wide use of the so-called draw-forging process [85].

Cold welding by cold forging

Other innovative processes specifically use this mechanism for the manufacture of joints. The investigations presented in [86] show the joining mechanisms of the aluminum alloy AA1070 and a steel cylinder by cold welding on cold forging. To determine the joint quality, tensile tests were carried out with micro tensile specimen that were cut out of the bottom corner in the joining area. The test results showed that there was no influence of the punch speed on the tensile strength of the specimens. In the process introduced in [87], both joining partners with the same base material combination as described before are heat-treated, cleaned with acetone and then placed on top of each other in a conventional extrusion tool. The forming process creates a cold weld resulting in a joint between the two components. Basic investigations of the process address the influence of the heat treatment, the geometries of the joining partners and the surface treatments. Further, a new joining by forming technique is presented in [88] based on a sheet-bulk forming process [89]. The process consists of a combination of partial cutting, bending and form-fit joining and allows to produce lap joints in metal sheets.

Hybrid joining processes

Hybrid joining processes can be considered processes in which one or more of the techniques previously presented are used at the same time with the aim to further enhance the joint mechanical properties, taking advantage of the peculiar strengths of each technique.

One of the most representative categories of processes in this sector is represented by Friction Riveting. Using in different ways a combination of mechanical fastening and solid bonding results in the absence of pre-drilling and the use of both mechanical interlocking and metallurgical bonding to create strong joints able to withstand higher strain with respect to simply riveted or spot welded ones. A few techniques have been developed during the last years. Among the most promising, besides FricRiveting, Friction Stir Blind Riveting (FSBR), Friction Self-Piercing Riveting (FSPR), Rotation Friction Drilling Riveting (RFDR) and Rotation Friction Drilling Riveting (RFPR) can be acknowledged. Figure 10 shows a schematic of these processes.

Altmeyer at al. [90] investigated the mechanical and microstructural properties in FricRiveting of PEEK composite reinforced with 30% short carbon fibers with titanium grade 3 rotating rivets. The authors succeed in the production of joints with high resistance, characterized by pull-out force comparable with the strength of the base material used for the rivet. The high temperature and deformation rates resulted in the formation of seven different thermally and

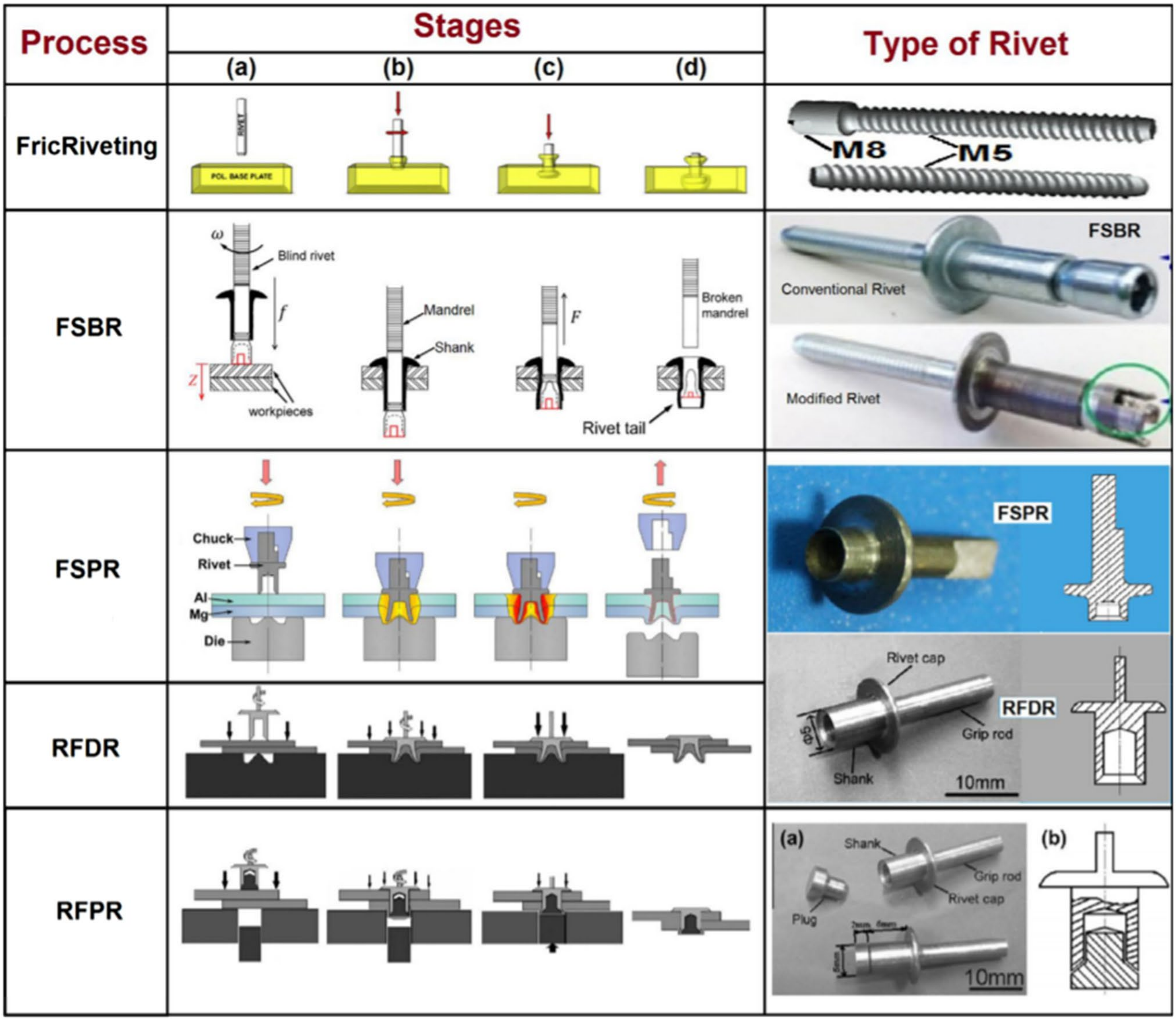


Fig. 10 Schematic of the different Friction Stir riveting "hybrid" processes and process phases: (**a**) preparation, (**b**) plunge, (**c**) joint consolidation and (**d**) tool pull off [71]

thermo-mechanically affected zones, both in the composite and in the metal side. Wang et al. [91] tested three different materials, i.e. Aluminum (AA5754-O), magnesium (AZ31B-H32), and injection molded CFRP with a blind rivet made of mild steel (body) and carbon boron steel (mandrel) with a zinc coating. The different failure modes were classified based on the joined material. For all the materials, three well-defined stages of mechanical behavior were distinguished: a linear stage (reversible response), an irreversible plastic deformation and the coalescence of damage and localized microcracking growth, resulting in joint failure.

Recently Ma et al. [92] highlighted the effects of the combined solid bonding and mechanical joining in FSPR of AA7075-T6 aluminum alloys. They found that, besides the technological parameters, also the hardness of the used rivet (made of 35CrMo) has a significant influence on the joint mechanical properties. Two different process conditions, i.e., a one stage process, with fixed rotational speed, and a two stages process, with initial high rotational speed and no rivet rotation in stage ii, were tested. They found that the two-stage process with small switch depth only produces solid-state bonding inside the rivet shank with no mechanical fastening. Han et al. [93] introduced rotation friction drilling riveting (RFDR) for 2 mm thick AZ31 magnesium alloy sheets obtaining higher shear strength and fatigue resistance with respect to conventional SPR joints produced at room temperature and at 180 °C. additionally, the authors highlighted the importance in the choice of the Rotation pressure applied on the rivet in order to maximize the mechanical performances of the produced joints.

As the processes characterized by the presence of a pin structure are regarded, despite the advantages that cold extrusion from the sheet metal plane offers for the production of metallic pin structures in terms of cycle times, integration into existing process chains and mechanical properties, processes such as additive manufacturing also have process-related advantages to offer. Particularly for small series, powder bed fusion (PBF-LB) [73] or direct energy deposition (DED-LB) [94] offer the possibility of manufacturing pin structures on sheet metal [79] or even on free-form surfaces of a component using multi-axis kinematics in the DED process. Due to the geometric design freedom that these processes offer due to the layer-by-layer production, the pin geometries can be specifically adapted, varied and combined without the need to change or replace tools. For this reason, these processes offer a high degree of customizability and flexibility, especially for small volume production.

Recently Baptista et al. presented a hybrid approach, based on additive manufacturing and forming for joining hollow section aluminum profiles to composite sheets, for applications n the transportation industry [95]. The process takes advantage of the Wire Arc Addittive Manufacturing (WAAM) process and is completed in two stages: first, the deposition of a tenon on the surface edge of two adjacent profiles by WAAM and then the compression of the tenon against the sheet to obtain the required mechanical interlocking.

Summary and outlook

It is well known that reducing CO_2 emissions is an urgent objective to pursue. In this respect, the manufacturing sector plays a relevant role in different stages of a product life cycle and must aim at gathering such challenges by finding out new guidelines for the production of effective structures. Joining is therefore a key process to enable such changes. In the paper, the most significant joining processes relying in several different ways on plastic deformation to generate a sound joint have been presented, classified and reviewed.

Over the last 25 years, several new technologies have been developed by modifying, exploiting and enhancing the existing processes. The significant number of papers that have been published in the last years proves the pushing interest of industry and the timely response of academia. Today, the main challenge seems to be the development of effective processes able to produce joints out of even very dissimilar materials with minimum environmental impact. Additional challenges that manufacturing engineers will have to face in the next years, include the mechanical joining of ultra high strength steels, characterized by strength above 1000 MPa, and hot stamped materials with strength up to 1900 MPa. For this, new materials for the joining elements or new process technologies are needed to meet the requirements. Furthermore, the increased scattering of materials properties (mechanical properties as well as geometrical ones including sheet thickness) lead to the need of more flexible and robust processes. In this way, research in data-driven process design and layout of process chains (i.e. material, forming, cutting, joining) has been started and seems to be a promising way into the future. Finally, considering the increasing market for AM products, it can be envisaged a need for proper and dedicated mechanical joining technologies for AM components and hybrid components (e.g. sheet and AM).

Indeed, based on the existing literature, it can be assessed that a leading technology enabling the effective joining of light alloys as well as polymer-based composite materials has not been identified yet. The proposed alternatives present encouraging results, but also drawbacks that must be overcome. Therefore, the right joining techniques must be defined for a specific application. Several joint solutions can be considered, moving from friction-based processes to mechanical fastening. In this context, the so called “hybrid processes”, taking advantage of the peculiar features of one or more existing process, seem a possible answer. As an example, friction riveting or processes based on joining with pin structures demonstrated high potential.

However, what solution is more performant and when one of these joints is more promising than the other one is still hard to be established and represent questions which the manufacturing community must answer in the next years.

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Declarations

Conflicts of interest/competing interests The authors declare that they have no conflict of interest.

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