9
Mechanical joining of magnesium alloys

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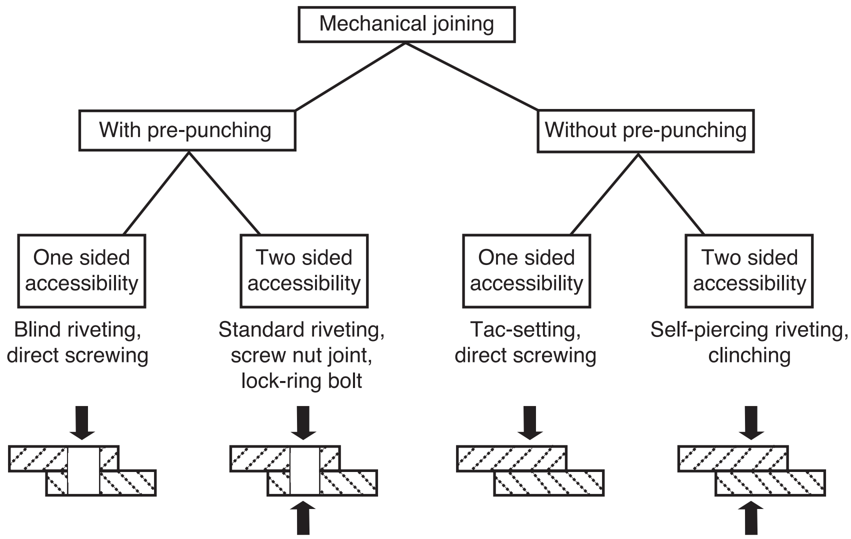
Abstract: In comparison to thermal joining techniques such as welding and soldering, mechanical joining techniques are remarkable for the fact that materials or auxiliary materials to be joined do not have to be converted into a molten state. Thus, the mechanical strength of the connection is achieved by form or force lock instead of material closure. Usually an auxiliary joining element is used to create the joint. Due to the ability to assemble a wide range of different materials, mechanical joining techniques have been established in various branches of industry, especially the automotive industry.

Key words: mechanical joining, riveting, blind riveting, direct screwing, tapping screws, tack-setting, lock-ring bolt, clinching, hemming, flanging, self-piercing riveting, fastener, magnesium.

9.1 Introduction

In comparison with thermal joining techniques, such as welding and soldering, mechanical joining techniques are remarkable for the fact that materials or auxiliary materials to be joined do not have to be converted into a molten state. Thus, the mechanical strength of the connection is achieved by form or force lock instead of material closure. Usually an auxiliary joining element is used to create the joint. Due to the ability to assemble a wide range of materials, mechanical joining techniques have been established in various branches of industry, especially the automotive industry. Here, lightweight constructions based on an intelligent multi-material design have been successfully put into practice for several years. The aim of such lightweight constructions is the reduction of vehicle weight which leads to less exhaust emission. Although environmentally worth striving for, this aim is contrary to the increasing demands of customers with regard to the security and comfort of vehicles.

The existing concepts for lightweight constructions in the automotive industry are characterized by the efficient and load-compatible application of different materials. Because of their relative density and their mechanical properties, semi-finished products consisting of magnesium are becoming more and more important for future material concepts. Now, the increasing variety of materials leads to necessary requirements on the different joining technologies. Moreover, the joining techniques have to fulfill different criteria such as costs, joint properties, joint strengths, automation capability, etc.



9.1 Classification of punctual mechanical joining techniques by criteria 'joining part preparation' and 'accessibility to the joining zone.'

All mechanical joining techniques mentioned in this chapter are specified in the fifth part of the DIN 8593 (2003). Here, 'joining by forming' is used as a general term for all production processes in which joining parts and/or auxiliary joining elements are locally or completely plastically deformed, and as a result, form locking connections with each other. In order to categorize mechanical joining techniques, the criteria 'joining part preparation' and 'accessibility to the joining zone' are appropriate.

Figure 9.1 gives an overview of the punctual mechanical joining techniques. For clarity, the following sections are structured according to this classification. The joining techniques listed are briefly described in the next section, and after that, the specialty of using magnesium is illustrated. At the end of the chapter, the linear hemming process and the combination of mechanical joining and adhesive bonding, the so-called hybrid joining, are detailed.

9.2 Technologies with pre-punching operation and one-sided accessibility

In this section, mechanical joining techniques are introduced, which only need accessibility from one side to the joining zone, but therefore a pre-punching or pre-drilling operation for the joining parts is required to execute the joining process. The two different techniques, blind riveting (also in combination with a functional element like a nut or a thread bolt), and direct screwing with thread forming screws are presented in this section.

9.2.1 Blind riveting

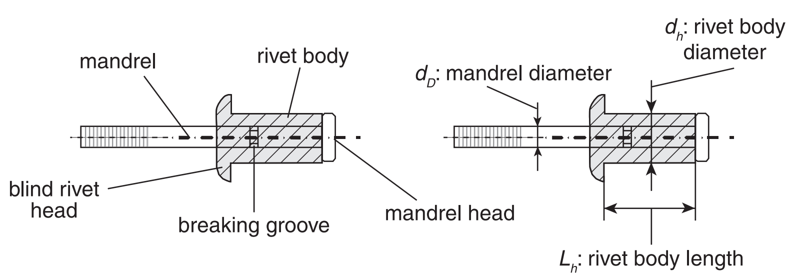
The joining technique blind riveting is especially characterized by the fact that only one-sided accessibility to the joining zone is required to produce a connection. This advantage and the high flexibility of this technique are the reasons why blind riveting often cannot be replaced by other joining techniques. One disadvantage of blind riveting is the higher preparation time compared to other mechanical joining techniques like self-piercing riveting or clinching, because a pre-punch operation is needed for the joining parts (Hahn and Klemens, 1996). DIN 14588 (2001) lists the exact terms of blind riveting. Normally, blind rivets consist of a rivet body and a mandrel which can be obtained in a pre-assembled state (see Fig. 9.2)

The rivet is processed by a setting tool. Besides manual converting machines, pneumatic hand setting tools or completely automated blind riveting machines are generally used in the industrial environment.

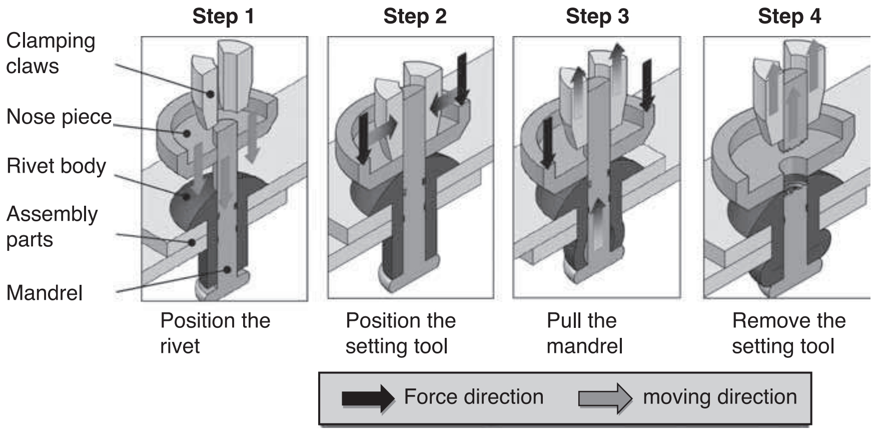
The blind rivet is inserted in the setting hole in order to be processed. Then, the mandrel is placed in the setting tool, and after the triggering, the clamping jaws in the setting tool grasp the mandrel and pull it supported on the rivet's head. The breakaway of the mandrel at a predetermined breaking point finishes the setting process. The geometrical design of the breaking point determines the maximum necessary setting force and, therefore, the required setting tool, too. During the setting process, the rivet body is plastically deformed regardless of the type of rivet used. The result is a form- and force-locked connection. This connection is permanent, that is, it can only be disassembled by the destruction of the blind rivet. Thereby, the substrates may or may not be damaged. The process steps of blind riveting and the most important terms of the joining system are shown in Fig. 9.3.

After finishing the setting process, the remaining mandrel normally stays force- and form-locked in the rivet's body. Additional terms describing the connection can be obtained from Fig. 9.4.

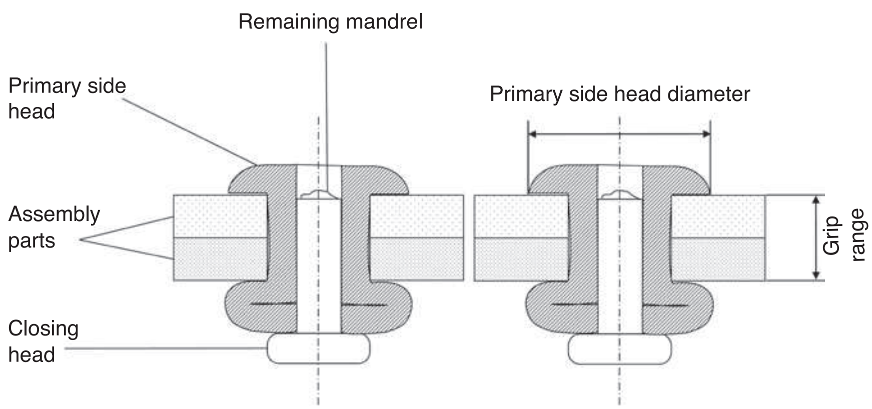
Besides different types of blind riveting, blind rivets can be produced out of different materials. Normally, blind rivets consist of a steel or aluminum body



9.2 Design and terms of an unprocessed body folding blind rivet (Hahn and Heger 2008).



9.3 Process steps of blind riveting (Hahn and Heger 2008).

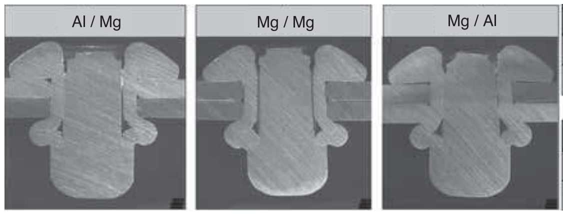


9.4 Design, terms and important dimensions of a blind riveting connection (Hahn and Heger 2008).

and a mandrel made of steel. But there also exist blind rivets made purely of aluminum or, for special applications, of titan. All blind rivets have in common that the material of the mandrel has a much higher strength than the material of the rivet body.

Hardly any other mechanical joining technique affects the magnesium substrates less than the blind riveting during the joining process. Because all holes are drilled or punched before the joining process starts, the corrosion protection of the components can be carried out before the blind rivet is inserted.

Joining partners or joining elements, which have a small potential difference to magnesium, have to be selected for the mechanical connection of magnesium and dissimilar materials in order to prevent a possible galvanic corrosion. Therefore,



Material		Thickness
Mg-alloy	AZ31	1,5 mm
Al-alloy	AlMg0,8Si0,9	1.5 mm

Joining element	
Mandrel: Al, Body: Al	
d_h = 6 mm	3 mm

9.5 Joining element characteristics of body folding blind rivet connections (Heger 2010).

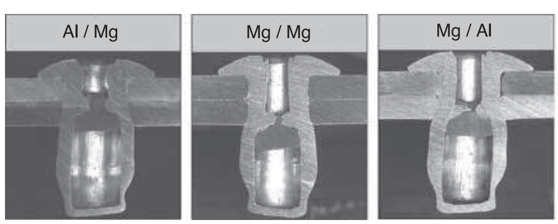
it is suggested that blind rivets with aluminum bodies be used. The reason for this is the difference in the electrochemical potential between magnesium and aluminum which is smaller than that between magnesium and steel.

In Fig. 9.5 and Fig. 9.6, the macroscopic samplings of two different types of blind rivets are illustrated. In each figure, three material combinations are shown: aluminum with magnesium, magnesium with magnesium and magnesium with aluminum. The blind rivet in Fig. 9.5 is a body folding blind rivet made of aluminum. This blind rivet is characterized by a high part of force closure within the connection. Moreover, the remaining mandrel covers the shear plane so that it can transmit the forces occurring from a tensile shear load and, thereby, increases the strength of the connection.

The rivet shown in Fig. 9.6 is a blind rivet with closed rivet body which is characterized by its leak-tightness. The connection gains additional tightness by the form-locked contact of the rivet body to the substrate at the side of the closing head.

9.2.2 Blind rivet nuts/blind rivet thread bolts

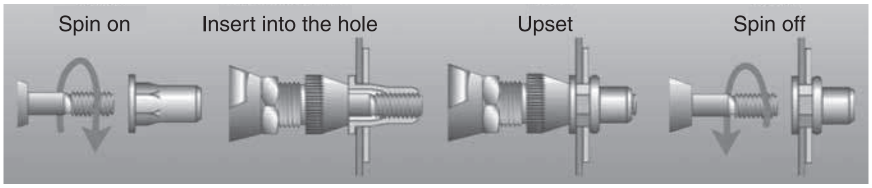
During blind riveting, the focus is on connecting two or more parts. In the joining techniques 'joining with blind rivet nuts' and 'joining with blind rivet thread bolts,' not only can components be connected but an attachment point like a nut body or a thread bolt can also be created. Because of the analogy of these two technologies, only the joining with blind rivet nuts is explained in the following sections. All



Material		Thickness
Mg-alloy	AZ31	1.5 mm
Al-alloy	AlMg0,8Si0,9	1.5 mm

Joining element	
Mandrel: Al, Body: Al	
d_h = 4 mm	3 mm

9.6 Joining element characteristics of blind rivet connections using blind rivets with closed rivet body (Heger 2010).



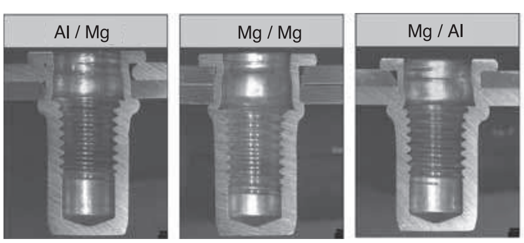
9.7 Process steps of processing a blind rivet nut (source: Böllhoff).

previous explanations for the blind riveting apply for the blind rivet nuts and thread bolts. It must be emphasized that all these elements can be processed manually, semi-automatically as well as fully automatically. The setting process of blind rivet nuts is slightly different because of the missing mandrel which is replaced by a modified setting tool. First, the nut is spun on the setting tool and then processed analogously to the blind riveting procedure. Finally, the setting process is finished with the spinning out of the nut from the setting tool (see Fig. 9.7).

Like blind rivets, blind rivet nuts can also be purchased in steel or aluminum. When using magnesium, an aluminum element should be preferred because of possible galvanic corrosion. Furthermore, blind rivet nuts with a closed body should be utilized to prevent the penetration of liquid media in the area of the screw thread (see Fig. 9.8).

9.2.3 Functional element Rivkle Elastic

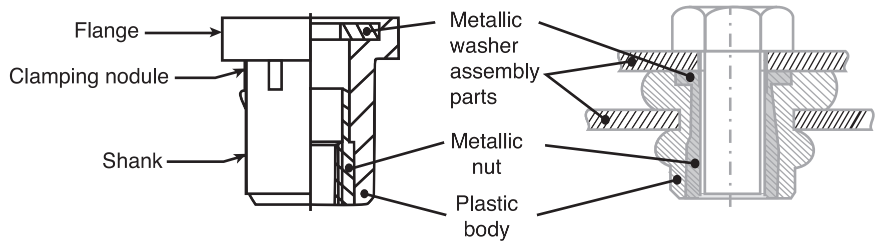
Another element which is similar to the principle of blind riveting is Rivkle Elastic produced by Wilhelm Böllhoff GmbH & Co. KG. This joining element consists of a metallic nut and a metallic washer which are overmolded with a body of plastic (see Fig. 9.9). First of all, the Rivkle Elastic is inserted into the pre-manufactured hole of a substrate. In a second step, another component in form of a cover sheet and with a pre-manufactured hole is arranged above the joining element. By means of a screw, which is finally added, the nut is pulled up until it is closely connected to the washer. As the plastic body is closely connected to the nut, it is compressed during the setting process. Thereby a bead is created which guarantees the form lock of the joining element.



Material		Thickness
Mg-alloy	AZ31	1.5 mm
Al-alloy	AlMg0,8Si0,9	1.5 mm

Joining element
Body: Al, M5
3 mm

9.8 Joining element characteristics of blind rivet nut connections using blind rivet nuts with closed rivet body (Heger 2010).



9.9 Functional element Rivkle Elastic in an unprocessed (left) and a processed (right) state (source: Böllhoff).

Material		Thickness
Mg-alloy	AZ31	1.5 mm
Al-alloy	AlMg3	1.5 mm

Joining element
RIVKLE Elastic, M5
5 mm

9.10 Joining element characteristic of a connection using the functional element Rivkle Elastic (Heger 2010).

The Rivkle Elastic is distinguished for its vibration-absorbing characteristics. Moreover, this element is especially suitable for joining of magnesium, due to the fact that the plastic body ensures a complete electrochemical isolation of other types of metal. Figure 9.10 shows an exemplary connection by means of Rivkle Elastic.

9.2.4 Direct screwing (thread-forming self-tapping screws)

In general, two essential process variants for the necessary joining part preparation are distinguished. One is the joining with hole- and thread-forming tapping screws which do not obligatorily require a pilot hole. A second process variant is the joining with thread-forming self-tapping screws which demand a pre-punch operation. Both the processes are described in this subsection.

The use of thread-forming self-tapping screws leads to a reduction in the process steps during the assembly, as the nut thread is shaped by the screw itself. Thread-forming self-tapping screws are often confused with thread-cutting self-tapping screws. The difference lies in swarf removal while cutting the thread as the thread-cutting screw is driven into the material, which does not apply to thread-forming screws. In the latter case, the substrate material is displaced downward into the groove of the thread. This results, for example, in a higher reliability toward self-loosening under vibration load because a form lock is produced via the thread-forming process. In comparison, the use of a conventional cut thread only leads to a force lock due to the frictional forces at the thread flanks.

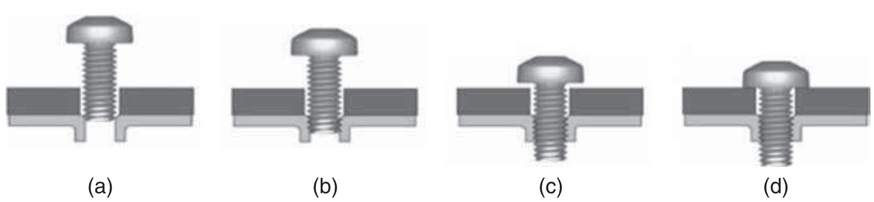
Thread-forming self-tapping screws can be purchased in different variants of steel and aluminum and with various coatings. The processing of such screws is depicted in Fig. 9.11.

Firstly, the screw is positioned above the pre-punched hole and pressed against it with its tip. Then the screwing process is activated using a spindle speed which is constant throughout the complete process. The screw now forces its way into the material. At the same time, the forming of the thread takes place and the screw is turned tight till the screw head rests against the connected component. Last, the screw is prestressed with a defined torque.

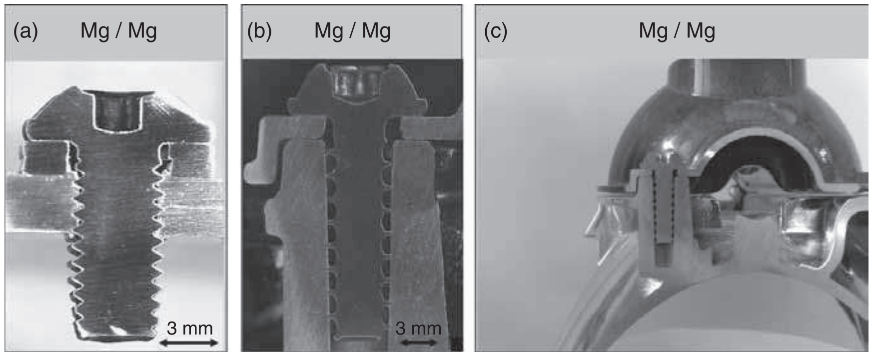
When producing screw joints with thread-forming self-tapping screws, five influence factors are of special importance:

- Difference between screw and hole diameter (cover of the flanks)
- Thread surface and thread lubrication
- Relation of thread-forming torque and overtorque (the bigger the difference, the bigger the process latitude)
- Sufficient strength of the screws
- Five percent rule (configuration to an elongation at fracture of at least five percent)

Figure 9.12 shows an example of the application of a thread-forming self-tapping screw in a magnesium component. Here, one can see a screw connection of two high-pressure die castings made out of magnesium alloy AZ91D, which are combined as a reflector system for the headlight of the current BMW 5 series. By means of this system, the two functions 'daytime running light' and 'position light' are realized by one light bulb.



9.11 Process steps of processing thread-forming self-tapping screws in prepunched joining parts: (a) position, (b) thread formation, (c) screw in, and (d) tighten (source: Betzer).



9.12 Joining element characteristics of screw connections using thread-forming self-tapping screws: (a) AZ31/AZ31 using aluminum screw Betzer Pentaform, (b) AZ91D/AZ91D using steel screw Ejot Delta PT, and (c) screw joint of piggyback reflector system within the headlamp of BMW 5 series (source: Hella KGaA/HDO GmbH).

9.3 Technologies with pre-punching operation and two-sided accessibility

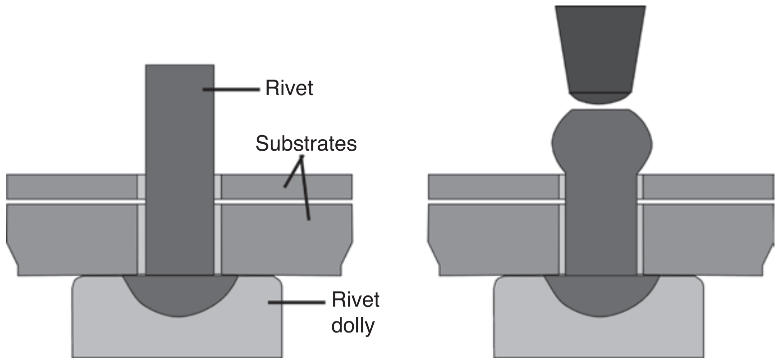
In this section, mechanical joining techniques are introduced, which need accessibility from both sides to the joining zone. Also a pre-punched or pre-drilled hole is required to execute the joining process. Three different techniques are presented that all need additional joining elements to create the connection.

9.3.1 Conventional riveting

Conventional riveting is known as one of the oldest metal forming joining techniques which increasingly has been replaced by welding processes in the past 80 years. Nevertheless, this joining method shows various characteristics which make it indispensable in security-sensitive connections even today. This is true for steel constructions of buildings and commercial vehicles as well as for the aerospace industry, due to the fact that the joining technique is especially suitable under cyclic load. Even the most modern aeroplanes are still produced by conventional riveting of sheet metal structures with solid rivets. The simple production as well as the easy way of checking their quality by visual inspection are two important reasons which make this process still practicable today.

Conventional riveting allows the establishing of force- and form-locked connections by deforming a solid, semi-tubular or tubular rivet. The substrates need to be prepunched and are not deformed throughout the joining process. Similar to the process of blind riveting, these joints are also permanent.

The production of a conventional riveted connection takes place when inserting the rivet into the prepunched hole of the components which are to be connected

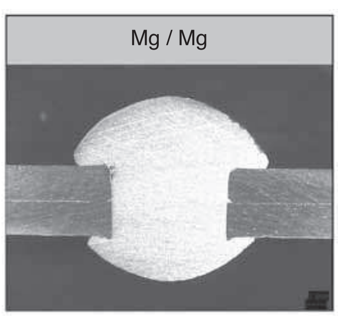


9.13 Process steps of conventional riveting using a solid rivet.

so that the rivet head lies flat against the above substrate. The connection is realized by deforming the opposite rivet shank into a closing head. The closing head can be formed through hammering, pressing, wobbling, rolling or blasting. The labeling of the rivets results from the upset form that the rivet head developed during production (universal, round, brazier, flat or countersunk rivet). Figure 9.13 shows an example of a conventional riveting procedure using a solid rivet.

Solid rivets can be produced out of different materials. The rivet material should consist of an alloy which is of the same type as the parts to be joined. But, the higher the stability of the rivet material, the more the necessary forming force will increase which is needed to form a closing head. Aluminum rivets with a diameter of 8 mm, for example, are still easily processable in a cold-forming process. Apart from solid rivets, there are different types of semi-tubular or tubular rivets which can be processed in a similar way.

Figure 9.14 shows an example of a conventional riveted magnesium connection using an aluminum solid rivet (AlMg5). The tensile shear strengths are comparable to those of blind riveted connections.



Material		Thickness
Mg-alloy	AZ31	1.5 mm

Joining element	
Rivet: AlMg5	
d = 6 mm	3 mm

9.14 Joining element characteristic of a conventional riveting connection using a solid rivet.

9.3.2 Screw nut joint

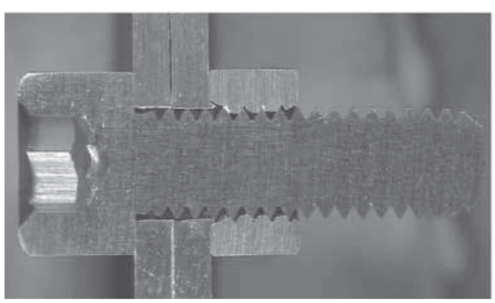
A screw joint is a detachable connection of two or more joining parts which are connected by one or several threaded bolts (usually screws) with a male thread and parts with a female thread (usually nuts). A screw joint is a force-locked connection, that is, when turning a screw into a component, the applied moment is converted into an axial load, which induces a preload by tightening the screw. Additionally, a clamping force is generated when using nuts for connections where the screw is pushed through the prepunched holes. Both preload force and clamping force cause an elastic tensioning of the joining parts, and hence a storage of force. Thereby a frictional force is generated within the thread and the screw cannot loosen itself. This process is called self-locking. The dimension of the frictional force depends on the friction angle. The screw-and-nut joint is the best-known mechanical joint for connecting a prepunched magnesium component with any other component.

Due to the effect of galvanic corrosion, one should not use screws of steel, or alternatively, add coatings or use washers in order to prevent corrosion. The application of aluminum screws is possible (compare Fig. 9.15). Because of the high notch sensitivity, bigger screw diameters should be used. In order to prevent the nut thread from pulling out, the minimum length of thread engagement for light metal screw joints is of special significance.

According to Mordike and Wiesner (2005), the maximum surface pressure beneath the screw head or within the thread contact of magnesium components should not exceed 100 MPa in order to obviate improper plastic deformation which might lead to a relaxation of preload force.

9.3.3 Lock-ring bolts

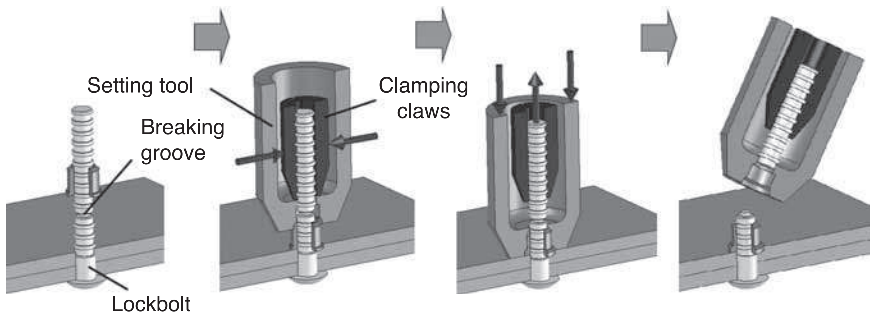
The lock-ring bolt system consists of two components – a lock-ring and a bolt. The various lock-ring bolts are used for highly stressed connections. The bolt consists of a rivet head and a shank with a predetermined breaking point. The bolt is plugged into the prepunched pars, and the lock-ring is slipped over the bolt. The appropriate lock-ring has to be pressed into the grooves of the bolt shank by a setting tool. In this way, the ring is formed into the grooves of the bolt. Axial pressure is balanced by



Material		Thickness
Mg-alloy	AZ31	1.5 mm

Joining element	
Screw: Al, Nut: Al	
M5	3 mm

9.15 Joining element characteristic of a screw nut joint.



9.16 Process steps of processing a lock-ring bolt (source: LWF).

clamping of the bolt. With this, additional stress to the joining parts can be avoided. The process is shown in Fig. 9.16. The connection is force- and form-locked. The bolt is under pretension and is dimensioned against shear fracture.

Originally, lock-ring bolt connections were developed for aircraft and aeronautics but are used extensively in the fields of structural-steel erection, crane construction, railway vehicle construction, commercial vehicle construction and shipbuilding. In contrast to screws, the original preload of the connection is permanently retained. Therefore, lock-ring bolt connections are vibration-resistant. The parallel grooves of the bolts avoid a preload reduction, even in the case of vibration load. Lock-ring bolt connections are permanent. The only way to separate the joined parts is to destroy the lock-ring.

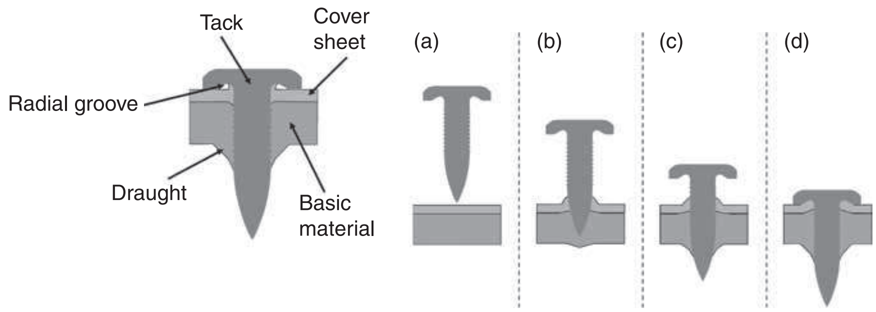
All materials that allow a manufacturing of a hole are able to be joined by lock-ring bolts. Thus, there are no special requirements for magnesium regarding formability or other properties. The material of the lock-ring bolt has to be adapted to the magnesium to attain an optimum strength and corrosion resistance. Lock-ring bolts made up of steel or aluminum are available with different coatings. As a result of the high-level strength, lock-ring bolt connections are suitable for parts with overall thicknesses of more than 3 mm.

9.4 Technologies without prepunching operation and one-sided accessibility

In this section, mechanical joining techniques are introduced, which only need accessibility from one side to the joining zone and no premanufactured hole. This clearly has advantages in terms of process times, costs and positioning accuracy. The two joining techniques, tack-setting and direct screwing by using hole- and thread-forming tapping screws, are depicted in the following subsections.

9.4.1 Tack-setting

During the process of tack-setting, a nail-like fastening element is inserted with high velocity into the materials to be joined. Its advantages are the one-sided



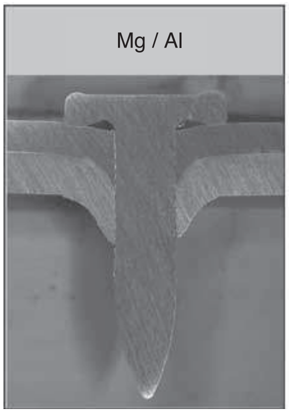
9.17 Terms of a tack-setting connection and process steps of tack-setting: (a) positioning, (b) entering, (c) penetration, and (d) fixing (source: Böllhoff).

access to the joining zone, the short process time and the possibility of connecting different materials. Thus, the flexibility of this technology with regard to the usage of various materials allows the connection of super high strength steels and also of magnesium alloys. The steps of the setting process can be described as follows: First of all, the element is positioned above the joining zone by the setting tool. After activating the joining process, the tack is accelerated up to 30 m/s by the pneumatically driven setting tool. When the element enters into the substrate, the material is displaced by the element. Thereby the typical rim hole is shaped around the base material. Parts of the base material rise up along the tack against the joining direction and, after finishing the setting process, remain in the provided radial groove of the tack. The setting process is finished when the head of the tack sits solidly on the cover sheet (cf. Fig. 9.17). Apart from the high force lock, the connection forms an additional form lock at the shank knurl of the tack due to the flow of the substrate materials. There are manual and fully automated setting tools available which can be used for tack-setting technology.

Especially when working with magnesium alloys it is important to use the magnesium component as cover sheet. Magnesium alloys are not suited as basic material because of the high deformation of the material and the visible cracks that appear during the shaping of the rim hole. Moreover, the joining zone should be of a very stiff design. The softer the joining zone, the more likely it is that cracks will appear underneath the set head of a magnesium cover sheet. Figure 9.18 shows a connection realized with a special aluminum tack. It was produced in order to minimize the electrochemical potential between the additional joining element and the substrates used.

9.4.2 Direct screwing (hole- and thread-forming tapping screws)

Direct screwing with hole- and thread-forming tapping screws means that a screw which connects two or more components is inserted without the necessity of a



Material		Thickness
Mg-alloy	AZ31	1.5 mm
Al-alloy	AlMg3	2.0 mm

Joining element	
Tac: Al	
d = 4 mm	3 mm ↔

9.18 Joining element characteristic of a tack-setting connection (source: Heger 2010).

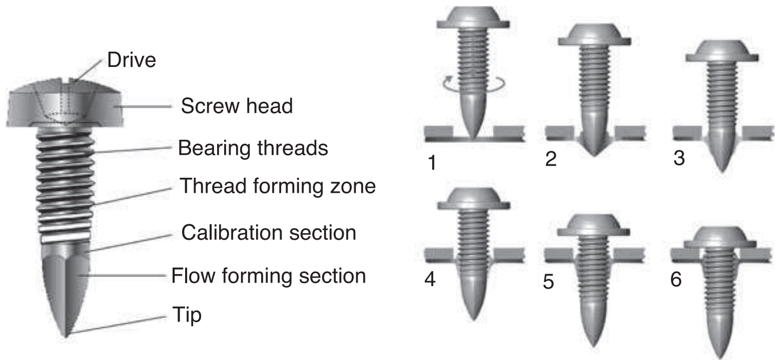
prepunched hole. There are two different variants of this technology that have to be distinguished. According to one variant, only the upper joining part is prepunched. The lower joining part is attached to the upper one by direct screwing. The second variant is an advancement of this first technology. Here, both joining parts are joined without a premanufactured hole. This second variant is preferred in the automotive industry because of the fact that there is no need of a cost-intensive prepunch operation. Moreover, this variant makes the positioning above the joining zone much easier. Thus, process time and process costs are minimized.

In this manner, two different kinds of screws are used in industrial applications: flow drill screws (FDS) and cold-forming screws.

Flow drill screws

The flow drill screw (FDS) is especially developed for such a type of joining process. One characteristic of the screw is the particular tip whose geometric design makes the joining possible (cf. Fig. 9.19).

At the beginning of the setting process, the element is set into rotation. As soon as the nominal rotation speed is reached, the screw is positioned on the joining part by an aligned axial feed force. Due to the frictional heat which is generated during this process, the material partially plasticizes. Now the screw can penetrate the material. Moreover, a rim hole is formed and expands according to and also against the feed force. Depending on the material and the process parameters, the dimension of the rim hole constitutes around the triple size of the joining part thickness. In the following phase, the cylindrical part of the screw forms the core hole based on the rim hole. Finally, the thread is formed by a non-cutting grooving and the screw is tightened by a defined tightening torque. As the joining zone cools down, the rim

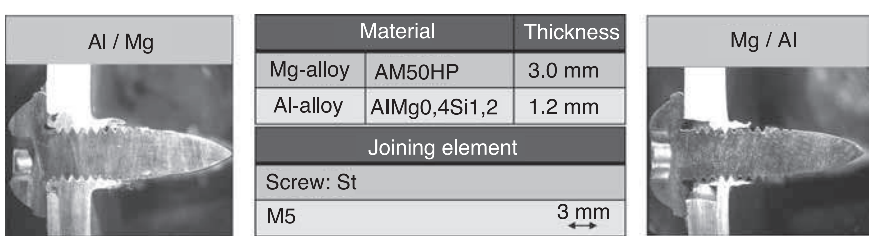


9.19 Functional sections of a flow forming screw and process steps of flow drill screwing with a pre-punched joining part at one side. (1) Heating the shield metal. (2) Penetration of the material with the conical tip of the screw. (3) Formation of the cylindrical passage. (4) Non-cutting tapping of dimensionally accurate nut threads. (5) Screwing through. (6) Tightening the screw with the set torque (source: EJOT).

hole contracts and covers the thread of the screw free from play. Thus, the connection gets a higher loosening torque which adds to the leak tightness of the joint. In contrast to most of the other mechanical joining techniques, the FDS can be unscrewed and replaced by another screw (Meschut 2007; DVS 2241–1).

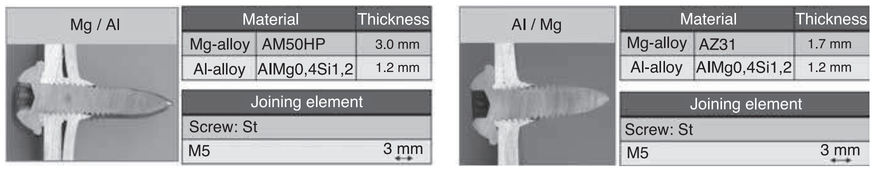
In the following paragraphs, the two different process variants are demonstrated. Figure 9.20 shows a flow drill screwing joint where the upper joining part is pre-punched. As said before, the length of the formed thread is dependent on the overall sheet thickness. Moreover, Fig. 9.20 shows that a direct screwing with magnesium results in good joining element characteristics due to the locally induced frictional heat which supports the high deformation in the thread zone. Heating is already part of the process and does not have to be additionally induced. Re-screwable magnesium joints with outstanding strength characteristics can therefore be manufactured.

Exemplary results of a flow drill screwing without a prepunched hole are shown in Fig. 9.21. Here, the quality criteria which can be derived from the macro grinding are fulfilled too. A slight gap between the joining sheets cannot be



Material		Thickness
Mg-alloy	AM50HP	3.0 mm
Al-alloy	AlMg0,4Si1,2	1.2 mm
Joining element		
Screw: St		
M5		

9.20 Joining element characteristics of flow drill screwing connections with a prepunched joining part at one side (source: Bruedgam et al. 2003).

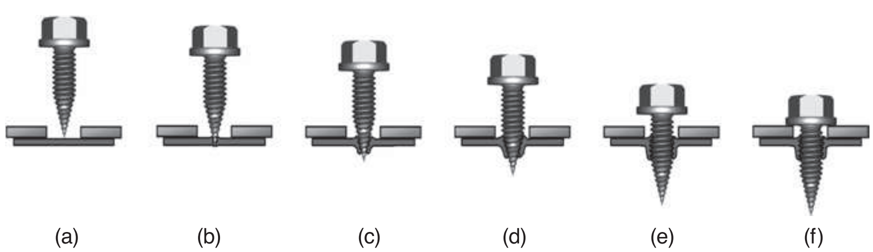


9.21 Joining element characteristics of flow drill screwing connections without pre-punching (source: Bruedgam et al. 2003).

completely obviated due to the thick magnesium sheet in the magnesium/aluminum connection. This formation of a gap can be regarded as noncritical as it does not reduce the strength of this joint. Finally, one can say that the technology flow drill screwing is appropriate when joining magnesium alloys.

Cold-forming screws

When using cold-forming screws, in comparison to FDS, the substrate material is not plasticized by heat. Here, the substrate material is plastically deformed by the geometry of the screw tip and the resulting surface pressure. After positioning the screw, the screw tip forms a hole into the joining part. As soon as the screw tip penetrates the substrate material, the threads form and pull the screw into the sheet. The rim hole is shaped into the sheet via the thread geometry of the screw. Throughout the process of screwing, the thread is formed into the rim hole by its non-cutting tapping, into which the screw is turned in further. The spindle is stopped when the favored tightening torque is reached (Fig. 9.22). In comparison to the process of flow drill screwing, the process mentioned here does only include a low frictional heat. Therefore, this process is suitable for magnesium materials to only a limited extent. The appropriateness of this process depends on the considered alloy as well as the thickness of the unpunched joining parts.



9.22 Process steps of processing a cold forming screw with a prepunched joining part at one side: (a) position, (b) form hole, (c) form rim, (d) form thread, (e) screw in, and (f) tighten (source: Betzer).

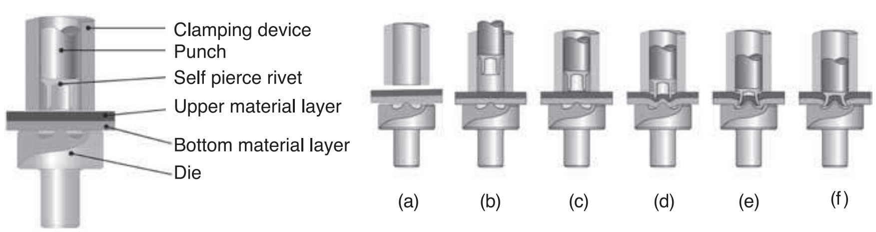
9.5 Technologies without prepunching operation and two-sided accessibility

The technologies described in this section are processes where the joining components are mechanically deformed to a considerable degree. As the ductility of magnesium alloys at room temperature is quite low, possible ways of improving those material properties are addressed here. A marked improvement in the characteristics of the joining components can be achieved by either locally heating the components or by accelerating the joining processes described below. A complete listing of all options can be found in Horstmann (2008). In practice, after considering costs, operational safety, process stability and process time, in particular, the method of heating by induction has been established. The acceleration of the setting process is generally realized by the use of accelerated masses driven by pressurized air.

9.5.1 Self-piercing riveting with semi-tubular rivet

In the past, the automotive industry has been consistently initiating innovative technologies for forming and joining processes. Modern and sustainable auto bodies built with new materials have been made possible by the advancements in joining technology. Having been developed for an aluminum body-in-white, semi-tubular, self-piercing rivets have also been proven successful in steel, aluminum, magnesium and plastic composite construction elements and are now an integral part of vehicles of every kind. High flexibility with regard to the multitude of materials used in composite construction is one of the key benefits which gives joining technology its outstanding status. During self-piercing riveting with semi-tubular rivets, two or more joining components are being connected with a joining element in a force and form locking manner. This process is executed without a prepunched hole and with two-sided accessibility. The main terms as well as an overview of the riveting process can be seen in Fig. 9.23.

The tool consisting of blank holder, punch and die is positioned over the joining zone. The die can vary in contour, size and depth depending on the joining task.



9.23 Terms and process steps of self-piercing riveting using a semi-tubular rivet: (a) positioning, (b) holding, (c) piercing, (d) stamping, (e) forming, and (f) setting (source: Böllhoff).

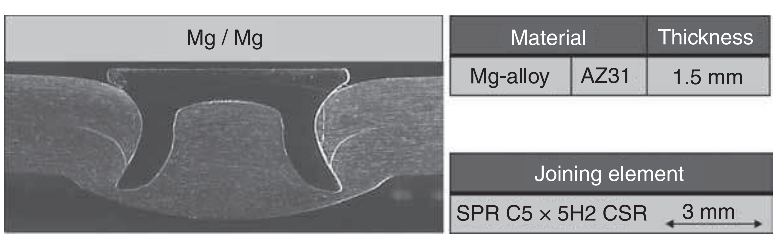
The stamping mechanism holding the riveting element is encased within a blank holder which fixes the components by pressing them with a predefined force. After triggering the setting process, the riveting element is pressed into the upper layer of material and punches it through. This cutting process is encouraged by the geometry of the cutting edge of the rivet. As the rivet meets the sheet metal facing the die, a radially directed flow process of the metal initiates. This deforms the joining element, causing it to wedge itself into the lower sheet metal without punching it through. In a final step, the joint is compressed in order to achieve a gap-free form- and force-locked joint. After reaching the maximum punch force or the preadjusted feed of the punch, the stamping mechanism is returned to its home position.

The main factors determining the quality of self-piercing riveting joints are a sufficient undercut of the joining element within the material facing the die as well as a gap-free joint of the rivet head to the material facing the punch.

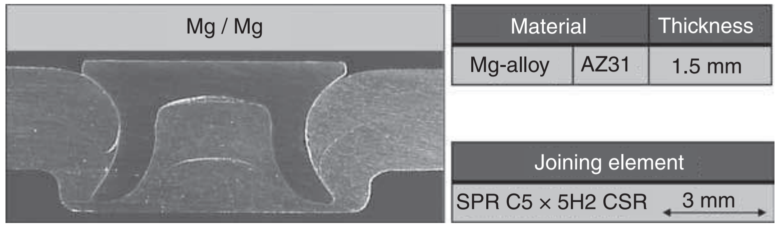
With regard to the processability of magnesium at room temperature, it is necessary to differentiate between different formations of the materials used in the joining process. Magnesium can generally be used as the material facing the punch, as that layer is merely punched through without being deformed too much. Depending on the thickness of the sheet metal and composition of the alloy, however, fissures below the snap head may occur. If magnesium is used as the material facing the die, the locally occurring deformation can be limited by choosing an extra small die. The joinability is limited, however, as external fissures of the snap head are frequently observed.

Figure 9.24 shows a joint set at room temperature. The material is a further developed variant of the AZ31 alloy used within the research project 'Mobil mit Magnesium' (Heger 2010). The alloy is characterized by an increased ductility and achieves a very good result at room temperature.

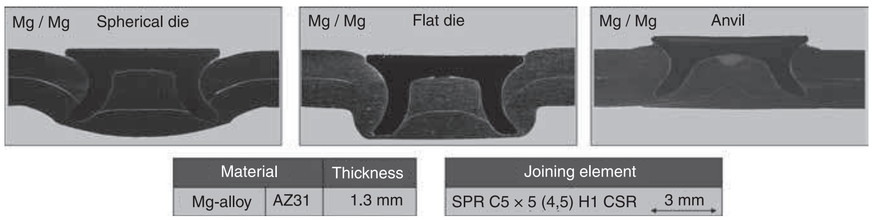
As described above, the joinability of magnesium alloys can be greatly improved by either locally heating the components or by accelerating the joining process. Considering costs, process time, installation space and operational safety, heating by induction has proven to be the best method of those described above.



9.24 Joining element characteristic of a self-piercing riveting connection using a semi-tubular rivet at room temperature (source: Heger 2010).



9.25 Joining element characteristic of a thermally supported self-piercing riveting connection using a semi-tubular rivet (source: Heger 2010).



9.26 Joining element characteristics of self-piercing riveting connections using a semi-tubular rivet within an accelerated setting process at room temperature; left: spherical die, center: flat die, right: anvil (source: Horstmann 2008).

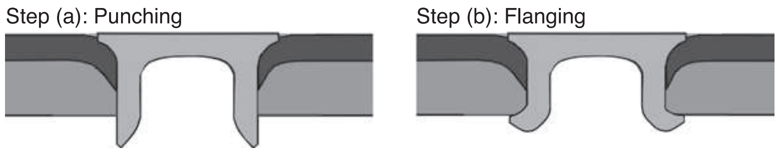
Figure 9.25 shows a monotype join of AZ31. Increasing the ductility by heating allows for a standard anvil/die used with conventional punch rivets.

Another possibility of increasing the joinability of magnesium alloys is by increasing the setting speed. This causes the joining components to heat locally upon penetration of the rivet and results in a gap-free joint which conforms to all specifications (cf. Fig. 9.26).

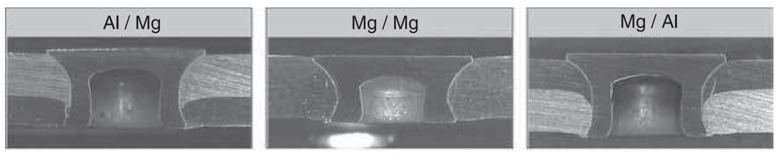
9.5.2 Flanging

Flanging is a process similar to self-piercing riveting with semi-tubular rivets but differs in the setting process and the characteristics of the joining element. Contrary to punch riveting with semi-tubular rivets, the hollow punch rivet is punched through all joining materials in one step. The element is deformed only slightly during this step. After removing the slug formed by the punching process, the protruding rivet is stamped with a flanging punch in a second step. This forms a force- and form-fitting joint as shown in Fig. 9.27. Figure 9.28 shows typical joints achieved by flanging.

The joints show no gap between the joining elements or the setting head and the element facing the punch. The resulting undercuts responsible for the form-fit and the stability of the joint are entirely comparable to the results achieved by punch riveting.



9.27 Process steps of flanging: (a) punching, and (b) flanging (source: Böllhoff).



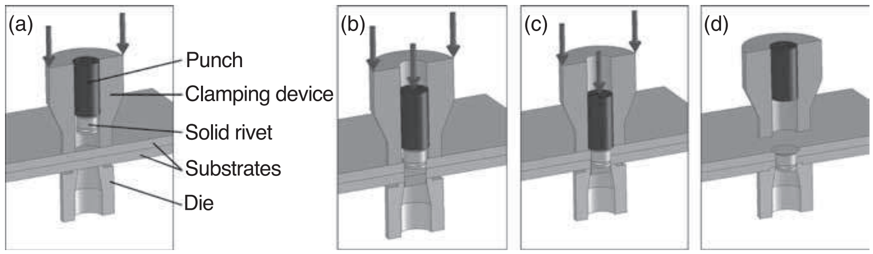
Material		Thickness	Joining element
Mg-alloy	AZ31	1.3 mm	SPR C5 × 4,5 H4 CSR
Al-alloy	Al 5042	2.0 mm	SPR C5 × 4,0 H2 CSR 3 mm

9.28 Joining element characteristics of flanging connections (source: Heger 2010).

9.5.3 Self-piercing riveting with solid rivet

Basically, the self-piercing riveting process with solid rivet is a cold-forming operation used to fasten two or more sheets of material by driving a solid rivet through the sheets. Joining parts are directly and permanently connected by form or force lock without premanufacturing a hole. The rivet itself is not deformed. The solid rivet produces the necessary hole itself while punching a small slug out of all joining parts. The sheets need to have two-sided accessibility for joining. Transmission of connection strength between joined parts is given exclusively by the rivet. As there is no requirement for predrilled holes in the sheet materials, the process eliminates the need for exact alignment between components and between components and rivet setting machinery.

While the setting tool moves to the joining spot, the rivet will be fed into the blank holder and vertically positioned to the surface of the joining parts. The blank holder fixes the parts before joining and serves a guiding and centering function for the rivet during the beginning of the joining process. The punch presses the rivet through the sheets. In this way, the solid rivet acts like a single-use punching tool. The pieces punched out are removed through the die. The ring-shaped die has a small offset at its inner diameter, which causes the material of the die-sided sheet to flow into the ring groove of the solid rivet. A complete filling of the ring groove provides the best mechanical properties of the joint, because of the undercut of the sheet material within the groove. Thereby the connection is established. The self-piercing riveting procedure using a solid rivet is pictured in Fig. 9.29.



9.29 Process steps of self-piercing riveting using a solid rivet (source: LWF).

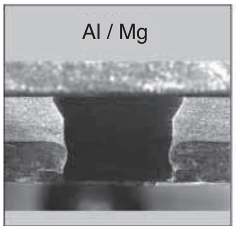
The length of the solid self-piercing rivet has to be aligned to the overall thickness of the joining zone. If this is done correctly, both sides of the joint are flushed with the surfaces of the joining parts. When joining materials of different thicknesses, the thicker sheet should be placed on the die side of the joint. The use of multi-application solid rivets offers the additional possibility to cover certain thickness variations of the parts. In this case, several ring grooves can be found on the rivet.

The material of the rivet needs to have a higher tensile strength and hardness than the material of the joining parts, because the punching is effected by the cutting edge of the rivet. Typical materials of the punch rivets are mild stainless steel as well as aluminum, but most of the rivets are heat-treated steels. To avoid electrochemical corrosion, the rivet manufacturers offer different coatings for their rivets especially in combination with aluminum substrates.

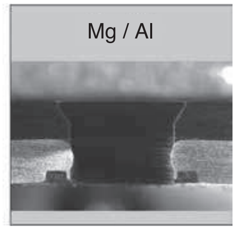
Compared to thermal joining techniques and also to self-piercing riveting with semi-tubular rivet, an important advantage of using solid pierce rivets is the high dimensional stability. The joining parts are only deformed locally while the die-sided material flows in the ring groove of the rivet. Because of its simple technology and reduced surface damage around the joining spot, especially on coated and painted parts, this connection is an economical alternative to resistance spot welding. This also applies to magnesium sheets. Due to the lower demand for deformability, it is more advantageous to place the magnesium sheet on the punch side of the joint. Depending on sheet thickness, alloy composition, joining temperature and tools that are used, good joining element characteristics can also be achieved by having magnesium on the die side of the joint (cf. Fig. 9.30).

9.5.4 Clinching

The technology of clinching is different from the other mechanical joining techniques as there is no use of an additional joining element to create the joint. Clinch technology can be divided into cutting and non-cutting processes. Besides dividing clinch systems according to their cutting ratio, they could also be classified according to their joining kinematics. Here, single-stage and multi-



Material		Thickness
Mg-alloy	AZ31	1.3 mm
Al-alloy	AlMg0,8Si0,9	1.5 mm
Joining element		
Solid rivet: 4 × 3		
		3 mm

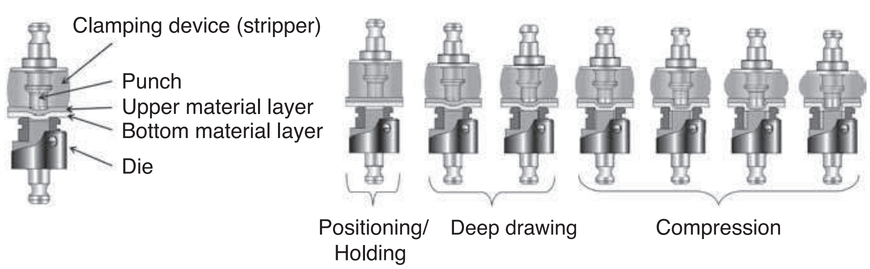


9.30 Joining element characteristics of self-piercing riveting connections using a solid rivet.

stage clinch processes are known. Owing to many advantages, such as quick process times and the good automation capability, mostly non-cutting round clinch processes manufactured in a single action are used in industrial applications. For joining magnesium, cutting clinch processes can be excluded, because they lead to an exposed cutting edge. This is not very positive for protection against corrosion. Therefore, only the single-stage, non-cutting clinching process is described in the following paragraphs.

Normally the clinch tool consists of a punch, a blank holder and a die (cf. Fig. 9.31). A distinction is made between different types of dies. The die can be one massive part with a cavity and a ring groove (closing die), or it can have moving die blades that are clamped together by springs (split die). These die blades enable expansion of the diameter and allow an outward flow of metal to create a form- and force-closed permanent interlocking. The blank holder fixes the joining parts before the punch is pressed into them and prevents distortion of the parts while joining is in progress.

The clinching procedure is done as follows. To start with, the parts to be joined are positioned between the punch and the die. Then a blank holder fixes the parts and presses them together without leaving any gaps. Now the actual joining process takes place. In a first step, the substrates are deep-drawn into the die. When the substrates reach the bottom of the die, a compression process is activated. Thereby a material flow is caused in radial directions due to high surface pressures. Along the way, a characteristic undercut is formed (cf. Fig. 9.31).



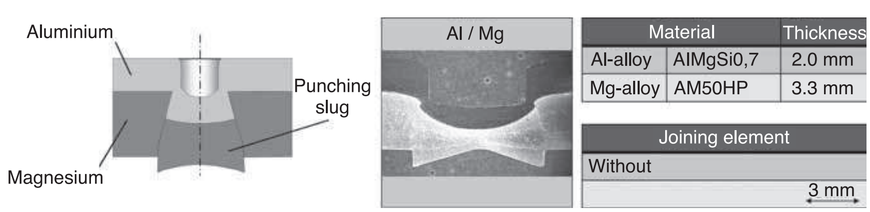
9.31 Process steps of clinching using a split die (source: Böllhoff).

Values which determine the quality of a clinch joint are the residual bottom thickness, neck thickness and the dimension of undercut. While the neck thickness has an influence on the maximum shear stress, the generated undercut affects the properties in head and peel tests. Because of form and force closure, clinch connections should be preferentially loaded with shear stress. Head and peel tests of clinch joints show much lower possible loads. Torsional stress should be generally avoided for single-spot connections, such as clinch connections.

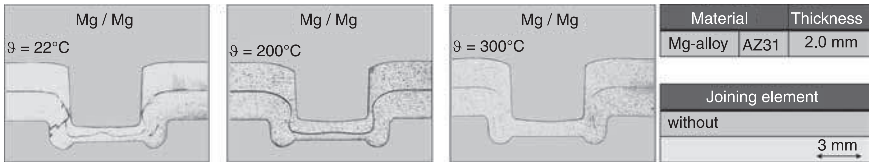
Because the technology of clinching creates a connection without adding an additional joining element, the materials to be joined have to be malleable. As a result of the necessary plastic deformation of the substrates, clinching of most of the magnesium alloys at room temperature is difficult to realize. The material tears apart in neck- and bottom-areas of the clinch joint. With an unmodified standard joining process, commercially available clinching systems achieve no sustainable connections (Hahn et al. 2001). Alternatively, however, special clinching processes are available that take into account the poor forming properties of magnesium alloys. These processes, for example punch clinching, are listed in Bruedgam et al. (2003) and can be executed at room temperature. In general, the created connections show much worse mechanical properties than connections which were conventionally manufactured at high substrate temperatures. An example of a joining element characteristic of a special clinching process is given in Fig. 9.32.

For common magnesium alloys, the deformation escalates at a temperature of above 225 °C, resulting from the thermal activation of additional slip systems in the lattice structure. Preheating of magnesium substrates leads to a broad extension of deformation and, thus, offers the chance to realize a high-quality clinch joint. The heating of the substrates before or during the clinching process can be performed by different heating concepts (Huebner 2005; Neugebauer et al. 2005; Hahn et al. 2009). Compared to other heating principles, one of the most efficient methods is the electromagnetic induction which has already been mentioned for the self-piercing riveting with semi-tubular rivet. Figure 9.33 displays characteristic joining elements of alloy AZ31 (sheet thickness: 2 mm each) which were created at different substrate temperatures.

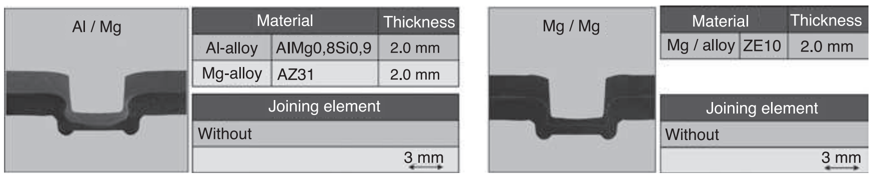
While the punch-sided disposition of magnesium leads to better mechanical properties for the self-piercing riveting, it is the other way around for



9.32 Terms and joining element characteristic of a punch clinching connection (source: Bruedgam et al. 2003).



9.33 Joining element characteristics of clinch connections using a closed die manufactured at different substrate temperatures.



9.34 Joining element characteristics of clinch connections using a closed die manufactured with a high (>100 m/s) setting velocity (source: Hahn et al. 2009).

the clinching process. The magnesium part should be arranged on the die-side during clinching.

In the same way as described for self-piercing riveting with a semi-tubular rivet, the malleability of magnesium in the clinching process can be significantly improved not only by heating of the substrates but also by accelerating the setting process to achieve extremely high deformation rates.

Hahn et al. (2009) exemplarily show a clinch joint, which has been successfully realized with an accelerated setting velocity of above 100 m/s. Figure 9.34 shows joining element characteristics of joints produced by such method.

9.6 Linear technology: hemming

In many industries, hemming is profitably used for joining thin metal sheets. The process of hemming is used to join two components by folding the edge of one over the other to create a mechanical interlock. Often the operation is deployed in combination with adhesive bonding to achieve a sealing of the fold and thus an improvement of the corrosion protection of the joining area as well as an improvement of the mechanical properties. Typical applications in the automotive industry are opening parts, for example, doors, hoods, sliding doors or tailgates, at which the flange of an outer panel is bent over the inner panel. With this technology sheets of different materials can be manufactured economically in small quantities.

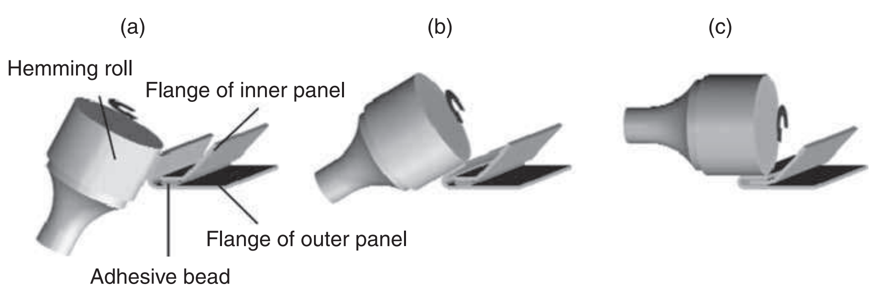
The hemming operation is usually a three-step process: flanging, prehemming and hemming. Flanging takes place during the drawing operation and consists of bending the sheet edge up to around 90 °C. Prehemming is done after the inner part is placed on the outer part and increases the angle of the sheet bend to around

135 °C to prepare for the next operation. Finally, the hemming tool folds the outer part over the inner part.

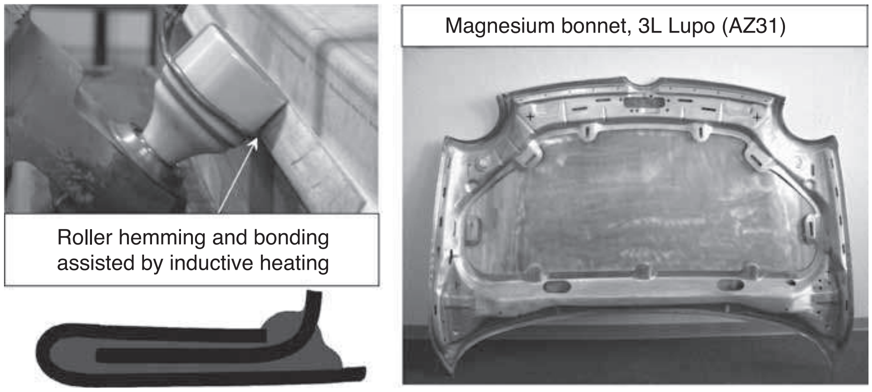
There are two main industrial hemming technologies, i.e. the classical hemming process, also known as tabletop hemming, and the roll-hemming process. The former is used in hemming units situated around the opening part. Hemming tools simultaneously assemble the opening part. The advantage of this method is the velocity at which it can be carried out, thus forwarding a very short cycle time. The latter uses a roller guided by a handling robot along the hemming line. The inclination of the robot head changes between the pre-hemming and hemming operations. The roller, which freely rotates around its revolution axis, progressively prehems and then hems the flanged edge of the opening part. The advantage of this method is the use of relatively light equipment. This method is very economical, if not taking the investment of the robot into account. The main drawbacks are the high cycle time and the hemming difficulties of parts with complex geometries. Finally, time is also shorter than for classical hemming because the programmer only modifies the roller trajectory in the problem area. Figure 9.35 illustrates the procedure for roller hemming and bonding using three hemming steps as an example.

Hemming of magnesium alloys is only difficult to realize because of the necessary procedural plastic deformation of the substrates. The material tears at the joining seam. Without modification of the joining process no adequate connections are achievable using the conventional or roller hemming process. This is rooted in a minor deformation of magnesium compared to steel and aluminum at room temperature. The anisotropic deformation characteristics of the hexagonal lattice structure of magnesium have a negative effect on the deformability, especially under multi-axial load.

For common magnesium alloys, a sufficient plastic malleability and, thus, a crack-free deformation is ensured at temperatures above 225 °C, resulting from the thermal activation of additional slip systems in the lattice structure. According to this, preheating of the folded edge can lead to a broad deformation of the material and thus offers the chance to realize a high-quality joint. The heating of



9.35 Process sequence of roller hemming and bonding: (a) first prehemming, (b) second prehemming, and (c) final hemming (source: LWF).



9.36 Magnesium sheet roller hemming using the example of a magnesium demonstrator bonnet (3L Lupo).

the substrates before or during the joining process can be performed by different heating concepts like hot air or inductive heating.

Using the example of a magnesium bonnet, Fig. 9.36 shows thermally supported magnesium sheet hemming, in which crack-free folded and mechanically bonded joints are produced in combination with an applied adhesive.

As a result of the high temperatures of more than 225 °C and the high degrees of deformation during a magnesium hemming process, high demands are also made on the applied surface coating system. Against the background of corrosion protection a delamination or burning of the coating layer must be avoided.

Due to the thermally supported process to deform the magnesium substrate, up to now a combination of roller hemming and adhesive bonding has not been possible from what is known so far, because the adhesive already shows a chemical reaction in the first prehemming step, when the material is heated to 225 °C. This leads to an insufficient deformation and wetting ability of the adhesive at the final hemming step, as the common curing temperatures of hot-curing systems in the automotive industry only reach values up to 180 °C. If the adhesive is exposed to such a high temperature, this can lead to an abrupt curing which has a harmful effect on the properties of the adhesive. In order to avoid precuring during the thermally supported prefolding steps, adhesives must be used whose reaction kinetics have been adapted to the process.

9.7 References

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